2011-09

Investigating the link between combat system capability and ship design

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http://hdl.handle.net/10945/5528

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

INVESTIGATING THE LINK BETWEEN COMBAT SYSTEM CAPABILITY AND SHIP DESIGN

by

Savannah G. Welch

September 2011

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704–0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE September 2011

3. REPORT TYPE AND DATES COVERED Master's Thesis

4. TITLE AND SUBTITLE Investigating the Link between Combat System Capability and Ship Design

5. FUNDING NUMBERS

6. AUTHOR(S) Savannah G. Welch

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943–5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)
N/A

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number _____N/A___________.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE
A

13. ABSTRACT (maximum 200 words)

The focus of this thesis is the examination of a method to supplement current combatant ship synthesis tools with combat system equipment and warfighting capability parameters. Current conceptual ship design tools lack an early integration of the naval architecture and the combat system aspects of a ship. Although the U.S. Navy's vision and the current JCIDS process involve designing ships based on warfighting capability using measures of effectiveness, the current ship synthesis tools lack the appropriate combat system parameters that will allow design for capability.

This study specifically investigates a link between a combat system capability and a ship design by conducting research and analysis on an existing combat system, a shipborne air search radar. A mathematical relationship was obtained between the radars detection ranges and their respective system weights. This equation describing the relationship between a combat system capability (radar detection range) and a naval architecture parameter (weight) was used to supplement an existing Excel-based ship synthesis tool. By inserting this into the model, the ships synthesized were able to change based on a desired combat system capability input from the user. Additionally, by modeling the radar detection range in a warfighting scenario in ExtendSim, the impacts of the radar detection range on warfighting effectiveness were computed. Therefore, it was demonstrated that a ship synthesis model could produce designs based on a user's input of a stakeholder-desired combat capability.

Using a single combat system and its corresponding measure of effectiveness in a single warfare area, this thesis shows as a proof of concept that combat system capability can be integrated into ship design. It lays the groundwork for creating an improved ship synthesis tool that includes complete sensitivity to capabilities from all the combat systems on the ship and how these selected parameters impact mission performance in a large spectrum of warfare areas. With this new ship synthesis model, designers can directly address stakeholder concerns, and can conduct trade off analyses for decision makers that result in an optimal ship design.

14. SUBJECT TERMS
Combat System Capability, Warfighting Effectiveness, Discrete Event Simulation, Ship Synthesis Tool, Naval Architecture Parameter, Naval Ship Design

15. NUMBER OF PAGES
109

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UU

NSN 7540–01–280–5500

Standard Form 298 (Rev. 2–89)
Prescribed by ANSI Std. 239–18

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INVESTIGATING THE LINK BETWEEN COMBAT SYSTEM CAPABILITY AND SHIP DESIGN

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
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LIST OF ACRONYMS AND ABBREVIATIONS

AAW	Anti Air Warfare
AD	Air Defense
ASM	Air to Surface Missile
ASSET	Advanced Surface Ship and Submarine Evaluation Tool
CAP	Combat Air Patrol
CBA	Capabilities-based Assessment
COA	Course of Action
CSE	Combat System Equations
DES	Discrete-Event Simulation
DRM	Design Reference Mission
EM	Electromagnetic
FFG	Frigate
HVU	High Value Unit
ICD	Initial Capabilities Document
IFF	Identification Friend or Foe
JCIDS	Joint Capabilities Integration & Development System
JROC	Joint Requirements Oversight Council
MBSE	Model-Based Systems Engineering
MIO	Maritime Interdiction Operations
MIT	Massachusetts Institute of Technology
MOE	Measure of Effectiveness
MOP	Measure of Performance

NFC	Naval Fire Control
NPS	Naval Postgraduate School
OMOE	Overall Measure of Effectiveness
OPSITS	Operational Situations
OPV	Offshore Patrol Vessel
P_K	Probability of Kill
RF	Radio Frequency
SAM	Surface to Air Missile
UNTL	Universal Naval Task List

ACKNOWLEDGMENTS

I would first like to acknowledge the kind financial support of the Naval Engineering Chair of Systems Engineering and the Department of Systems Engineering at the Naval Postgraduate School. This support allowed me to attend an international ship design workshop in Rome, Italy, in December 2010. This event expanded my understanding of the discipline and was a source of inspiration in choosing the area of research for my thesis.

I would like to thank a number of people at the Naval Postgraduate School for their support and guidance. I am grateful to LT James Drennan for his gracious support in helping me create my operational model in ExtendSim, as well as Mark Stevens and LT Matthew Horton for lending their time and knowledge in the use of ExtendSim. I would like to express gratitude to Dr. Robert Harney for his combat systems expertise shared in support of my research and to Mrs. Mary Vizzini for all her assistance in enhancing this thesis in its readability. My gratitude is extended to Dr. Eugene Paulo for not only his support as a second reader, but also in his efforts to organize the MBSE ship design group at Naval Postgraduate School. With utmost appreciation, I would like to thank Dr. Clifford Whitcomb for his vision, patience, and constant guidance throughout this whole process. His vast knowledge of ship design and dedicated time spent in expanding my understanding of it made this one of the most rewarding learning experiences for me at Naval Postgraduate School.

I would like to thank my husband, LT Brian Welch, for not only his love and support through this entire process, but also for his F-18 aviation expertise, which contributed in the making of the operational model. Finally, this all would not have been possible without the constant love and encouragement from my entire family and dear friends.

I. INTRODUCTION

As part of the U.S. defense acquisition process, the Joint Requirements Oversight Council (JROC) uses the Joint Capabilities Integration & Development System (JCIDS) to "identify the capabilities required by the warfighters to support the National Defense Strategy, the National Military Strategy, and the National Strategy for Homeland Defense [1]." Through this process, outlined in Figure 1, the JROC identifies the mission, required capabilities, and capability gaps in the very beginning during the capabilities-based assessment (CBA). Eventually, the warship designers receive the results of the CBA in the form of an initial capabilities document (ICD). In keeping with this process of filling capability gaps, warship designers are required to justify their designs based on that vehicle or weaponry's warfighting capabilities, particularly their design's ability to meet the capabilities set forth in the ICD.

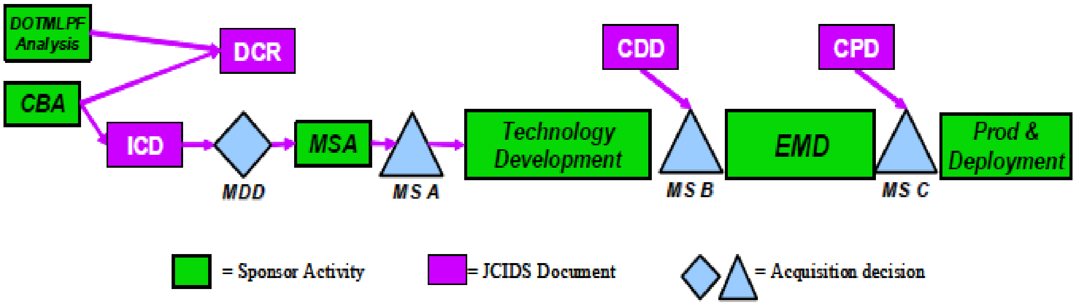


Figure 1. JCIDS Process and Acquisition Decisions (From [1])

Unfortunately, the lack of integration that exists between the combat system and ship parameters within the current ship design process is not conducive to properly conducting the JCIDS process. The early stage ship design usually takes place without accurate knowledge of how a combat system meets mission-related capability needs of the warfighter. The ship designers focus on the naval architecture aspects of the combat systems such as their weight, volume, center of gravity, power, and area, with no consideration for the actual warfighting capabilities or the associated technical variables of each combat or weapon system. On the other hand, combat system and weapons development proceeds largely without insight into the impact on the platform or the platform-caused constraints [2]. Therefore, what is lacking is a way of seeing early in the process how naval architecture and combat system choices impact one another [3].

This problematic separation of the combat system and ship designs exists at the fundamental level of conceptual design. It is rooted within the tools that ship designers use to conduct initial design. The current ship synthesis model of the Navy, Advanced Surface Ship and Submarine Evaluation Tool (ASSET), lacks any sensitivity to combat warfighting capability. Its inclusion of combat systems only pertains to those physical attributes that have an effect on the naval architecture, primarily weight, area, and stability. As a rough estimate, ASSET uses single data points of the weight, vertical centers of gravity, area, and power of specific existing combat systems, much like selecting a specific combat or weapon system from a catalog. Therefore, there is no way of seeing how these naval architecture parameters might change if a combat capability other than the one belonging to the specific data point might be desired. Furthermore, there is a desire to have the ship synthesis tools linked to mission effectiveness. Ideally, when changing a combat system performance parameter, the user could see the impacts that his decision would have on both the architecture of the ship design and the ship's warfighting effectiveness. In other words, the tools that ship designers are using to create the designs limit them in their ability to see the impacts of their choices. Additionally, the single data point entries for the combat systems leave little room for variability in the combat system physical characteristics used in the modeling.

The importance of concurrent mission analysis and engineering design in the optimization of a system is explained using a case of torpedo design. Researchers from the Georgia Institute of Technology found that the current torpedo design process, which consisted of disjointedness between the requirements development and engineering design, was not producing the most effective weapons. Through the simultaneous use of a torpedo synthesis program, which linked design variables to performance and size, and a submarine engagement model, which demonstrated mission performance effectiveness, they found a way to test their design space to prevent the creation of torpedoes that did not meet mission requirements without redesign. Their work revealed a new design paradigm, which highlighted a way to link the engagement model with the design tool [4]. Similarly, the work in this thesis aims to link the engagement (warfighting) model with the ship synthesis tool. In addition, it aims to link architectural characteristics to performance parameters within the ship synthesis tool.

A. BACKGROUND

Combatant capability, described by Rear Admiral Randolph King in 1974, is “the objectively stated system performance required by the operator to perform the intended mission when the ship is operating as an entity in the real world [5].” Figure 2 presents the important steps that were adhered to in ship design before 1965. It followed a sequential flow of preliminary design, contract design, followed by detail design. This sequence of steps would result in the naval architecture being determined in the first two steps and a much-constrained detailed design phase occurring afterward [5]. Combat capability, which King describes as “the reason of a warship’s existence,” had little to no bearing on this design sequence. Although the naval ship design models of today may take on a different appearance than that in Figure 2, the naval architecture practices where the selection or design of the hull comes first and all the necessary components are forced to fit inside its physical constraints still occurs [3].

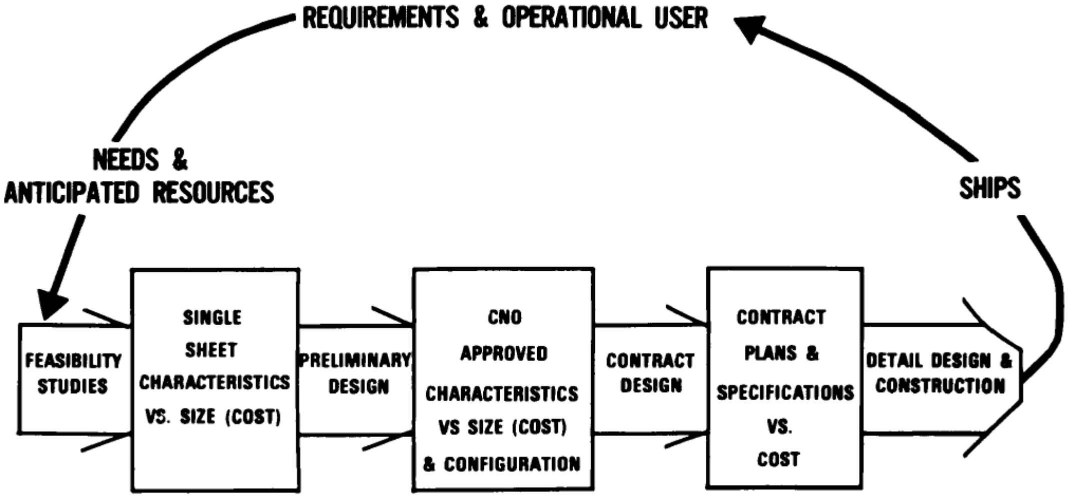


Figure 2. Pre-1965 Warship Design Sequence (From [5])

The idea of bringing capability into early stage ship design, ultimately coined as CBA, has been advocated extensively by many experts in the field of ship design throughout the years including Prout, Baker, and DeMattia Jr. in 1974, Rains in 1984, and Hockberger in 1996 [6], [7], [8]. The researchers promoted the identification and consideration of required capabilities early on in the ship design process. As the JCIDS process of 2009 provided by the U.S. Chairman of the Joint Chiefs of Staff indicates, as shown previously in this report, CBA has become a first step in the U.S. military's acquisition process.

One cannot speak of CBA without mentioning measures of performance (MOP) and measures of effectiveness (MOE). Simply described, MOPs are a measure of what a system does (such as radar range, speed, etc.) and MOEs are a measure of mission success (such as probability of survival) [9]. It has become a standard to establish MOEs in conjunction with the overall mission and operational requirements [8].

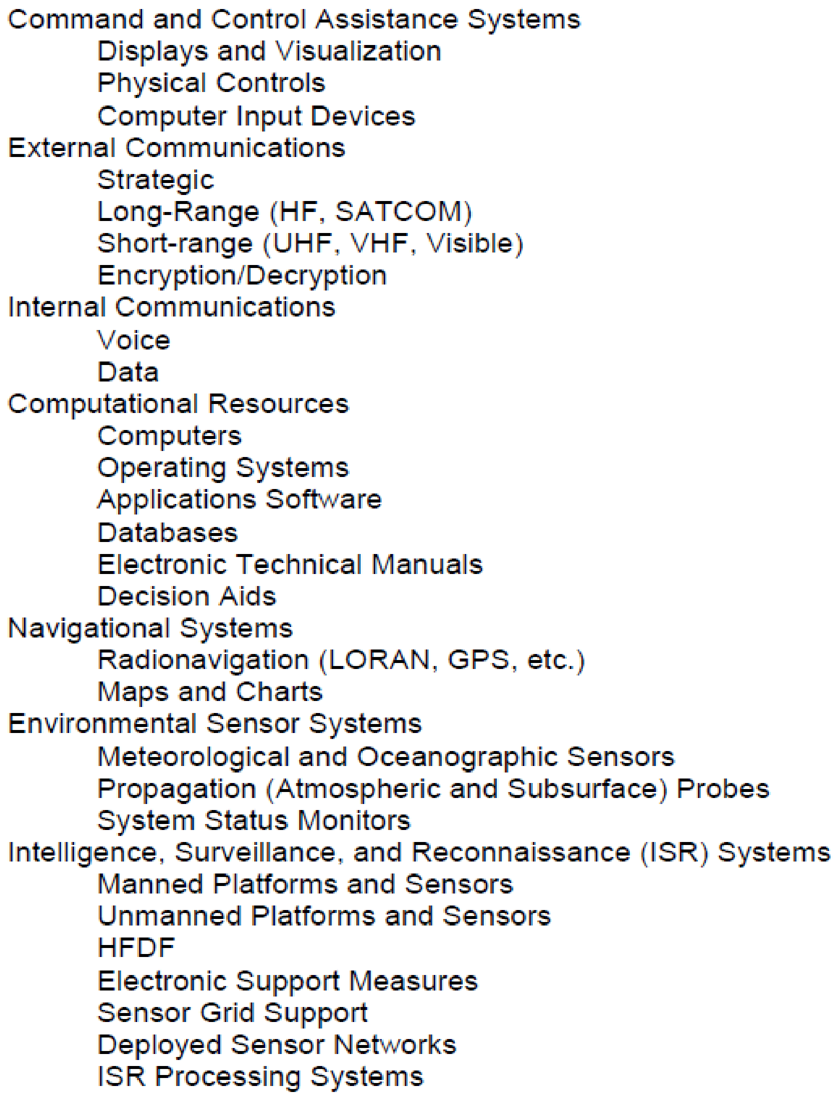
1. Combat Systems

Combat systems are described as "the integrated systems that give modern military units their enormous warfighting potential" [10]. Combat systems vary for each platform, but they have a general makeup that consists of the following: sensor systems, weapon systems, and command & control systems. A sensor system, whose primary function is detection and tracking, can take a number of forms including some of the following: radars (microwave, laser, synthetic aperture, etcetera), infrared search and tracking systems, electro-optical sensors, passive radio frequency sensors, acoustic sensors, magnetic and electric field sensors, nuclear, biological & chemical sensors, meteorological and oceanographic sensors, and several others [10]. For the purpose of this thesis, the author will focus on the conventional microwave radars commonly found on ships as the primary sensor system.

The weapon system, whose primary function is engagement of the target, can take on an even greater number of forms. Electromagnetic weapons commonly found on combatants are decoys and electronic warfare suites that provide jamming capabilities. Projectile weapons are generally the majority of weapons onboard a warship and they include many of the following: self-propelled projectiles (rockets, missiles, torpedoes), externally propelled projectiles (guns, artillery, bullets, shells), and thrown, dropped, or emplaced projectiles (bombs, mines, grenades) [10].

The command & control system, whose primary function is planning, directing, coordinating, and controlling, includes the following components outlined in Table 1.

Table 1. Command and Control Elements (From [10])



- Command and Control Assistance Systems
  - Displays and Visualization
  - Physical Controls
  - Computer Input Devices
- External Communications
  - Strategic
  - Long-Range (HF, SATCOM)
  - Short-range (UHF, VHF, Visible)
  - Encryption/Decryption
- Internal Communications
  - Voice
  - Data
- Computational Resources
  - Computers
  - Operating Systems
  - Applications Software
  - Databases
  - Electronic Technical Manuals
  - Decision Aids
- Navigational Systems
  - Radionavigation (LORAN, GPS, etc.)
  - Maps and Charts
- Environmental Sensor Systems
  - Meteorological and Oceanographic Sensors
  - Propagation (Atmospheric and Subsurface) Probes
  - System Status Monitors
- Intelligence, Surveillance, and Reconnaissance (ISR) Systems
  - Manned Platforms and Sensors
  - Unmanned Platforms and Sensors
  - HFDF
  - Electronic Support Measures
  - Sensor Grid Support
  - Deployed Sensor Networks
  - ISR Processing Systems

Elements of the command and control system are described as “anything that directly contributes to the ability to make intelligent decisions and execute actions (and is not a part of a mission sensor or a weapon)” [10].

Although the ship in Figure 3 is the Formidable Class frigate (FFG), it is a general representative of a warship’s combat system suite.

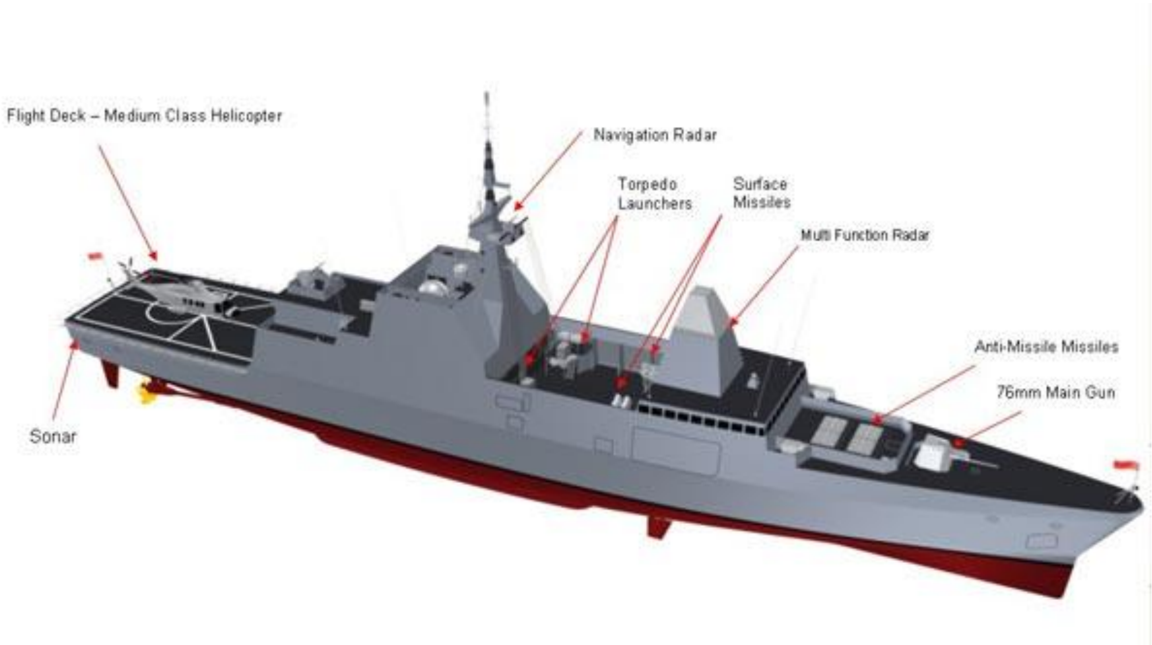


Figure 3. Combat System Elements for Formidable Class Frigate (From online database of weaponry, www.harpoondatabases.com)

Even though it contains other combat system elements, this figure highlights some of the major weapon and sensor systems. A navigation radar, a multi-function surface search radar, an air search radar, and a sonar system are the commonly found sensor systems on medium-sized warships. Most combatants come equipped with missiles to defend against air and surface threats, a long-range gun system, small caliber weapons, a close in weapon system, and torpedoes. The command and control system elements are generally housed inside the ship and therefore not shown in Figure 3. Each one of these elements brings a specific contribution to the ship's total warfighting effectiveness in the form of an MOE. The MOPs can include a radar's detection range or a weapon system's rounds per minute measurement. Ultimately, the combination of several of the ship's component MOPs, as variables in a warfighting simulation, results in an MOE for the ship's effectiveness in a particular mission area. An overall measure of effectiveness (OMOE) is determined based on the summation or combination MOEs of the ship's effectiveness over a large spectrum of mission areas.

2. Radar

Some discussion on the topic of radar is necessary since it is the primary combat system this thesis considers. Radar, a word derived from radio detection and ranging, finds its earliest beginnings in 1886, from which point it was refined throughout the years to become one of the greatest combat system elements in military warfare [11]. Because it provides early detection of targets and important target information such as range, velocity, and size, it has become an irreplaceable asset on almost every military platform. The basic elements of a radar system are shown in Figure 4.

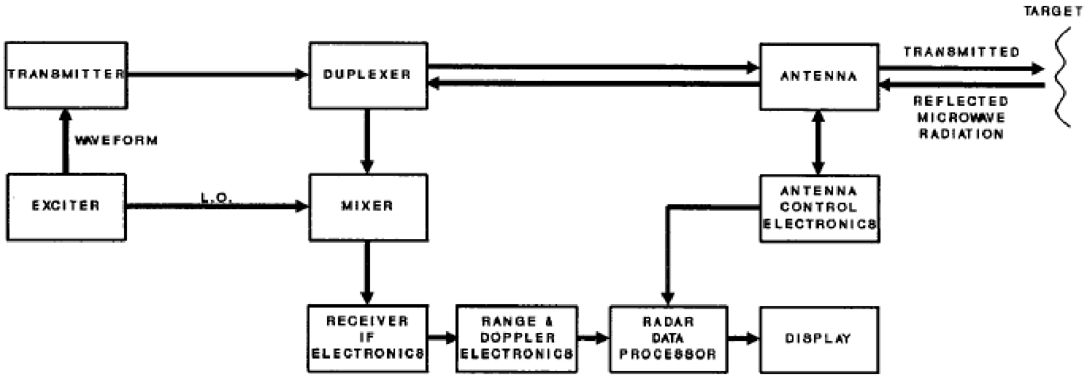


Figure 4. Basic Elements of a Generic Microwave Radar (From [10])

The transmitter generates a radio frequency (RF) waveform, which is routed to the antenna via a duplexer. The antenna then directs the beam of electromagnetic (EM) energy into the atmosphere in the direction at which it is pointed. The beam of RF energy is intercepted by the target and a certain amount of it is reflected back towards the antenna [11]. In Figure 4, it shows the same antenna both transmitting and receiving the RF energy, but there are cases where there are two separate antennas for each of the purposes. The receiving antenna amplifies the received signals and transmits it to the data processer so that it is conveyed to the operator in a useable format.

Many factors contribute to the resulting radar range as shown in Table 2. Characteristics of the receiver and transmitter, such as the power radiated, loss factors, diameters, temperature, bandwidth and noise figure influence the resulting radar range. The radar cross section of the target as a factor in the radar range equation indicates that the variables, which impact the results of the radar's performance cannot be completely controlled by the source of the radar. Therefore, the target that it is radiating also influences how far the radar is able to detect something. As is shown in Equation 1 and Table 2, the radar's range is determined by a number of variables with complex relationships.

$$R = \left[\frac{\pi P_T L_T L_R D_T^2 D_R^2 \sigma}{64kTBF\lambda^2 \cdot CNR} \right]^{1/4} \tag{1}$$

Table 2. Radar Range Equation and Variable Table (After [10])

Radar Range Equation Variable	
Symbol	**Meaning**
P_T	Source Radiated Power
L_T	Loss Factor of the Transmitter
L_R	Loss Factor of the Receiver
D_T	Transmitter Antenna Diameter
D_R	Receiver Antenna Diameter
σ	Radar Cross Section of Target
k	Boltzmann's Constant
T	Receiver Temperature
B	Receiver Bandwidth
F	Receiver Noise Figure
CNR	Carrier to Noise Ratio

B. SYSTEMS ENGINEERING APPROACH

A systems engineering approach becomes necessary when dealing with something as complex as naval ship design, which requires the integration of many subsystems into a single platform. Many systems engineering approaches exist and the implementation will vary based on the system being generated and the individuals involved. The author has chosen to examine the "Vee" model for the case of systems engineering a warship (see Figure 5). The operational requirements for the desired system, formulated based on the needs of the warfighter, feed into the first step of the "Vee" model. The definition of system requirements is based on those operational needs.

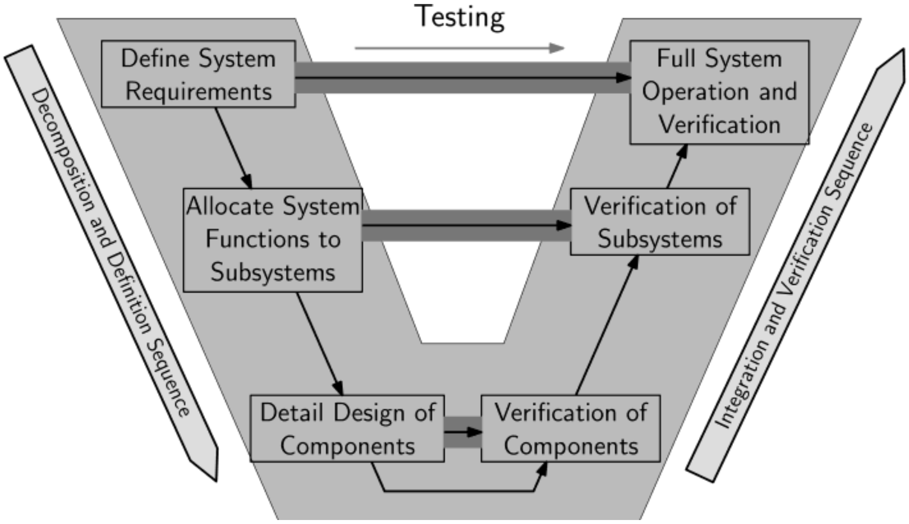


Figure 5. "Vee" Systems Engineering Process Model (From [12])

This thesis further implements a method using model-based systems engineering (MBSE), which is the "application of modeling to support systems requirements, design, analysis, verification and validation [13]." The MBSE design method allocates mission capabilities to operational activities to specific functions and requirements, and finally to alternative physical forms. Using MBSE during the CBA provides traceability from desired mission capabilities, as MOE, to resulting alternative physical ship design outcomes, as MOP, using models as the basis for engineering reasoning about system alternatives. The MBSE approach requires that the mission capabilities and operational scenarios first be defined, in conjunction with MOEs. One structured method to accomplish this is to use a Design Reference Mission (DRM) [14]. Ultimately, this method allows for functional versus physical ship design.

Much research has been conducted using the MBSE approach for ship design in the Naval Postgraduate School (NPS) Systems Engineering Department. Gomez Torres showed through discrete event simulation how varying design parameters for an offshore patrol vessel (OPV) affected the OPV's performance in select mission areas [15]. Fox demonstrated through discrete modeling simulation and a ship synthesis model how varying design parameters impacted both the physical ship designs and mission performance in Maritime Interdiction Operations (MIO) [3]. This thesis follows the work of Gomez Torres and Fox in that it, too, will demonstrate a design parameter's impact on physical ship designs and warfighting effectiveness. In addition to the work performed on these topics, the thesis presents a ship synthesis tool that integrates combat system capabilities.

C. SCOPE OF THE THESIS

To bring system thinking into combatant ship design, there needs to be a modification to the ship synthesis tools utilized. The ideal ship synthesis tool would provide clarity for ship designers about the impacts of their decisions not only on the naval architecture of a ship design, but also on its corresponding combat capabilities. It would show a sensitivity of combat design parameters on naval architecture and vice versa. These impacts should also be translated into the language that is understood by the stakeholders, using appropriate warfighting MOEs. With the appropriate linkages being integrated into a ship synthesis tool, immediate impacts of designer decisions on stakeholder needs, warfighting capability impacts can become evident allowing for a clearer picture during trade off analysis and ultimately better-informed decision making.

The primary research questions are:

- Are there quantifiable relationships between aspects of naval architecture and combat system capabilities?

- If so, how can this relationship be implemented in a ship synthesis tool?
- Is it possible for a ship synthesis tool to show sensitivity to combat system capabilities?
- How can ship designers effectively trace the impact of ship design decisions on warfighting effectiveness?

This study investigates the link between combat system capabilities and ship design and ultimately its impact on warfighting effectiveness. In order to present a proof of concept, the thesis focuses on one combat system of choice and its impact on warfighting effectiveness in just one mission area. Specifically, this analysis features a frigate-sized combatant as a baseline reference ship for the ship synthesis model and warfighting operational model. The operational model is a simple simulation demonstrating the possible impact a combat system's parameter has on warfighting effectiveness. The results of the research are not recommendations for a particular ship design, but rather to demonstrate a process beneficial for ship design.

D. BENEFIT OF STUDY

The primary benefit of this study is demonstrating the possibility for integration of combat system capabilities into ship design. This is meant to be a foundation for which future research can build upon in order to refine the current ship design process. In accord with the recommendations from many naval ship design enthusiasts, it is meant to be a step forward in the direction of a "critically important," yet "elusive" goal, which is "understanding the simultaneous impact of requirements, product design variables, and emerging technologies during the concept formulation and development stages" [16].

E. METHOD

The method used for this study consists of four parts. First, an analysis of available data relevant to "real world" military use of radar was conducted. Secondly, a design reference mission (DRM) was created, following the results of the research, which brought focus to a specific combat system. Then, an existing ship synthesis model was used, with the addition of a mathematical equation found in the initial analysis part of the method. Finally, an operational model to demonstrate warfighting effectiveness was presented, which shows an MOE that can be traced to the combat capability used in the ship synthesis model.

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II. RADAR RESEARCH & ANALYSIS

As seen in the calculation of radar range, Equation 1, the influences of a specific variable on combat system's performance can be quite complicated, making it difficult to show mathematically the performance's relationship with a single factor. The open literature does not include information relating the physical design characteristics of a combat system, like a radar, to the parameters such as weight, volume, area, or input power needed. Therefore, the author chose to research the open literature for existing combat systems to determine if there was enough data to establish relationships or trends that could exist between some of the physical characteristics and performance characteristics. Although other combat systems would be valuable in this analysis, the author specifically focused on radar as the combat system of choice since radars are a major and critical component for surface combatant warfighting performance.

A. RESEARCH

The limiting factor to this entire study was the amount of available information about existing military combat systems. The goal of the research was to identify both performance and physical characteristics of existing military radars. After researching navy fire control (NFC) radars from around the world, the author concluded that the amount of available physical characteristic data for NFC radars is insufficient to conduct an analysis of all of their characteristic relationships. Therefore, the author focused on researching air surveillance radars, and concluded there was sufficient data available. Parameters such as frequency, detection range, power, scan rate, weight, volume, area, and antenna information were collected when available. The table of all the radar information collected is located in Appendix A.

Since this data was eventually to be integrated into a ship synthesis model, the author also researched the types of ships that these air search radars generally were housed in. From Indonesia's Todak Class missile attack craft (housing the Variant radar) at 446 LT shown in Figure 6 to the Russian Federation's Kuznetsov Class aircraft carrier (housing a Fregat radar) at 58,500 LT shown in Figure 7, the 16 air search radars used for the data baseline, shown in Table 3, reside in a large spectrum of different-sized ships from many different countries [17].

Figure 6. Todak Class Missile Attack Craft (From [17])

Figure 7. Kuznetsov Class Aircraft Carrier (From [17])

Although these radars are placed into over 47 different classes of ships in over 25 different countries, they are most frequently found aboard ships comparable in size to a frigate (FFG). Therefore, the German Sachsen Class FFG (housing the SMART-L radar) at 5600 LT shown in Figure 8 was used as a baseline reference ship for the ship synthesis and operational models. Its average size and SM-2 capabilities made it an ideal reference ship for both the ship synthesis and operational models [17].

Figure 8. Sachsen Class Frigate (From [17])

B. ANALYSIS

Using the data from the 16 different air search radars listed in Table 3, the author performed several different evaluations, comparing the relationships between radar range, power, frequency, total weight, antenna surface area, total area occupied, and total volume [17]. From these evaluations, the most promising relationships resulting from this analysis were that of maximum radar detection range versus total radar weight and total radar weight versus radar power, shown in Figures 9 and 10, respectively. The results of the other analyses are found in Appendix B.

Table 3. Air Search Radars used in the Analysis

Air Search Radar	**Maximum Range**	**Total Weight**	**Power**
DA05	135 km	3.2213 LT	Not Available
DA08	125 km	4.2843 LT	Not Available
EL/M-2228S (2D HP AMDR)	70 km	1.7096 LT	15 kW
EL/M-2228S (3D AMDR)	70 km	2.116 LT	21 kW
Fregat-MAE	130 km	4.5539 LT	30 kW
Fregat-MAE-1	125 km	3.6603 LT	30 kW
Fregat-MAE-4K	58 km	2.679 LT	30 kW
MW08	55 km	2.116 LT	Not Available
Podberyozovik-ET1	300 km	7.0538 LT	45 kW
Podberyozovik-ET2	240 km	5.4466 LT	45 kW
Pozitiv-ME1	110 km	3.1495 LT	45 kW
Pozitiv-ME1.2	50 km	2.116 LT	45 kW
RAN 20S	120 km	3.7252 LT	Not Available
RSR 210N	55 km	1.929 LT	Not Available
SMART-L	400 km	11.3863 LT	140 kW
VARIANT	70 km	0.8464 LT	8.1 kW

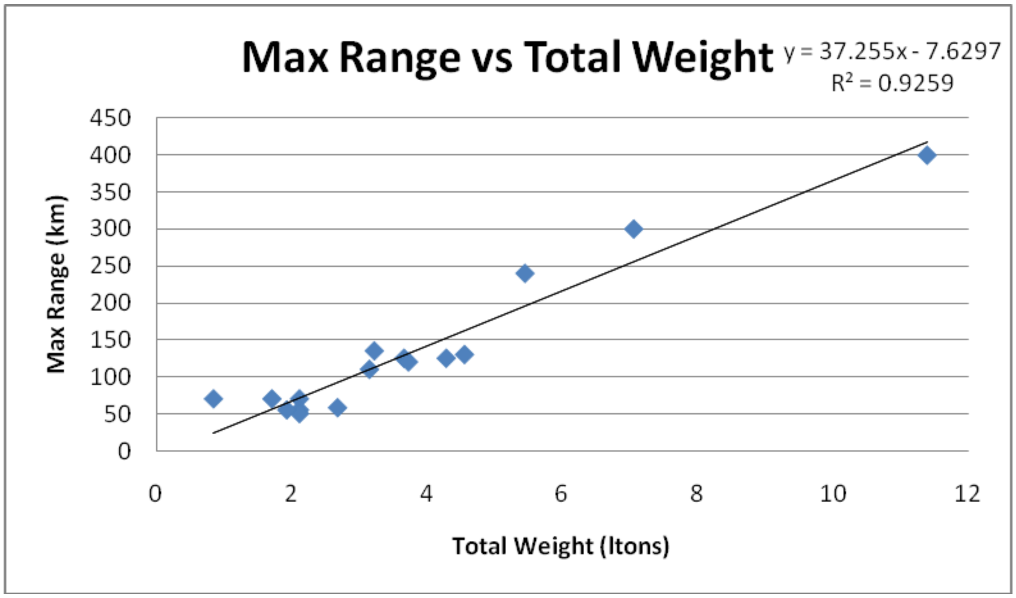

Figure 9. Radar Weight and Detection Range Relationship

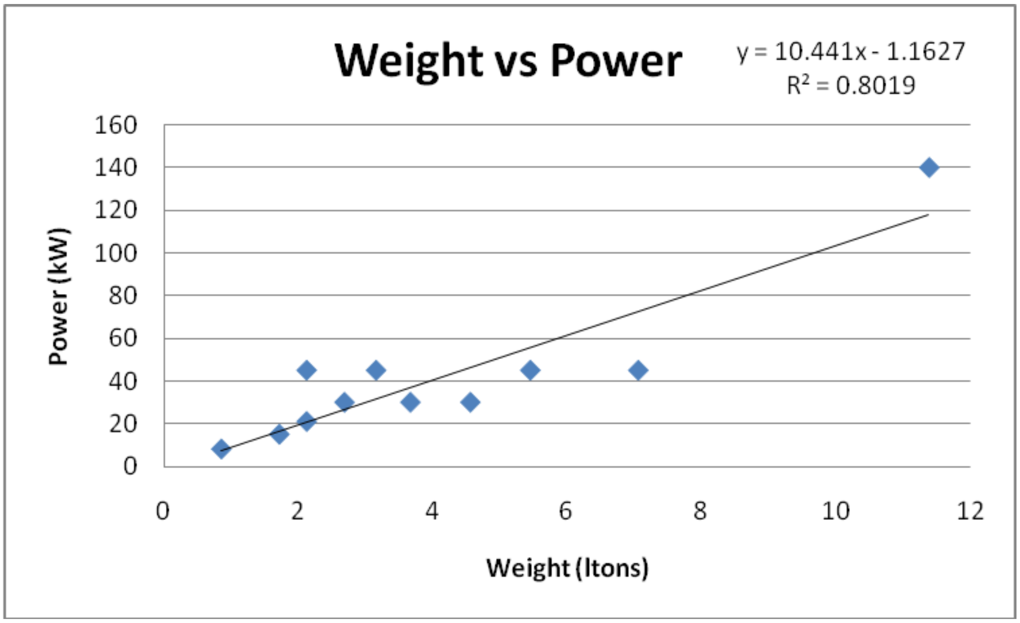

Figure 10. Radar Weight and Power Relationship

The R^2 value of 0.9259 in Figure 9 indicates that a close relationship exists between maximum detection range and weight for the air search radars researched. In Figure 10, the R^2 value of 0.8019 also demonstrates a close relationship between radar weight and radar power for the air search radars. Equation 2 and 3, derived from the Excel plots in Figures 9 and 10, express these relationships and will be inserted into the ship synthesis model because they link a combat system parameter with ship naval architecture parameters.

$$\text{Radar Range} = 37.255(\text{Radar Weight}) - 7.6297 \tag{2}$$

$$\text{Radar Power} = 10.441(\text{Radar Weight}) - 1.1627 \tag{3}$$

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III. DESIGN REFERENCE MISSION

As the Navy pushes to find a more cost-effective way to create systems that fulfill a greater amount of missions around the world, it has become evident that there is a need for a DRM concept during the design process. A DRM is used to "define the projected threat and operating environment baseline for a rigorous systems engineering process [14]." Although it can vary based on what type of DRM used, it generally considers aspects such as operational situations (OPSITS), physical environment, and threat characterization [14]. For the purpose of this thesis, the author created a DRM for a hypothetical situation. It is a simple example of a DRM, which serves as a foundation for operational and ship synthesis models.

A. INTRODUCTION TO ANTI-AIR WARFARE (AAW)

History reveals the great impact that combat systems technology, such as ship-borne radar, has had on naval warfare. For example, the Battle of Empress Augusta Bay in 1943 during World War II demonstrates in particular how radar enabled U.S. ships to successfully defend themselves against impending Japanese air attacks [18]. In this particular case in history, four light cruisers and four destroyers were able to not only survive against 100 attacking Japanese aircraft with minimal damage, but inflicted a substantial amount of damage on the Japanese [18]. This example shows that radar, through its early warning capabilities, has become an essential piece of the AAW mission.

AAW is one of the many missions of a surface warship. The objective of AAW is "to protect the task force from enemy air attack [19]." In conducting the AAW mission, units must conduct air defense (AD), which is defined in Joint Publication 1–02 as "defensive measures designed to destroy attacking enemy aircraft or missiles in the atmosphere, or to nullify or reduce the effectiveness of such attack [20]." This process can be split into three parts: detecting and identifying the enemy aircraft, controlling the sensor and weapon systems, and engaging the threat [21]. The intricacy of this process depends on the number of sensor and weapon systems available for use in this mission. It can be as simple as the air search radar and surface-to-air missiles (SAM) of just one combatant in self defense or it can be as complex as the many sensor and weapon systems of an entire task force, which could additionally include combat air patrol (CAP), in the defense of a high value unit (HVU). For the overarching purpose of demonstrating a method in ship design, this thesis focuses on the simple example of a surface ship conducting air defense of its own unit.

B. OPERATIONAL SITUATION (OPSIT)

For the purposes of this thesis, the following fictional scenario will be examined. As a major theater of war has been in the Middle East, the author selected this as the location for a proposed threat situation:

After many years of ongoing war in Iraq and Afghanistan, the United States now faces a third major conflict with Persian Gulf State, Country X. After both FFGs, *USS Reuben James* (FFG 57) and *USS Kauffman* (FFG 59), were each hit by an air-to-surface missile (ASM) from a single attack fighter aircraft from Country X within one week of each other, the 5th Fleet Combatant Commander (COCOM) has directed assets to engage any identified enemy aircraft within range. Both FFGs were conducting an independent operation of offshore oil platform defense when they were attacked. Because of the continued importance of Iraqi oil platform defense and the United States' inability to meet the AD requirements with the current class of FFGs used, the Maritime Component Commander (MCC) has directed that the new class of FFGs, comparable to the Sachsen Class baseline FFG be used. The importance of their SM-2 capabilities for AAW was a determining factor for this decision.

The physical environment that the ship will operate in is the Persian Gulf. Its large hydrocarbon reserve, 500 species of fish, and strategic location amongst 8 surrounding countries make it a frequently transited area for large oil and shipping tankers and numerous small dhows [22]. Its average water depth is 50 m, its length is 1000 km, and width across ranges from 200 to 300 km [22]. Therefore, Country X is not far from the location of most naval assets within the Gulf. Its climate is hot and arid with temperatures getting into 100° F in the summer. Days vary in sea state and visibility.

The main threat for this OPSIT is Country X's fighter attack aircraft. They are comparable in size and performance to the U.S.'s F-18 Superhornets. Its most threatening weapon for the U.S.'s new class of FFG is its long-range, high speed, fire-and-forget ASM. But because of its need for multiple types of ordnance and limited payload capacity, Country X's aircraft generally only carry one of these ASMs at a time. Country X's newly acquired fighter aircraft generally operate independently due to their inexperience and lack of doctrine. Their tactics seem to consist of approaching the target with little concern of minimizing their exposure, delivering the one ASM near the area of the target, and immediately conducting an egress from the target area back towards their home base [21]. They generally conduct their attacks on days with good visibility and only during daylight hours because most of them are inexperienced tactical pilots.

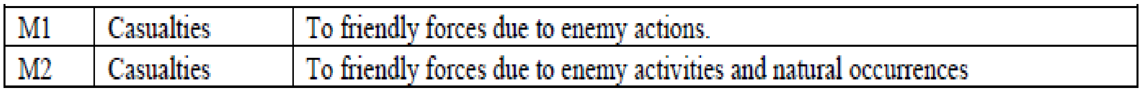
C. MEASURES OF EFFECTIVENESS (MOE)

In keeping with a systems engineering approach to ship design, there are a certain number of aspects that must be established from the very beginning, such as problem definition, needs statement, operational requirements, and MOEs. In the formalized JCIDS process, the CBA, which identifies the capabilities, should be created in conjunction with how those capabilities will be measured, in terms of MOEs. The MOEs provide a metric for how well the system will meet those operational requirements. In the end, the stakeholders and decision makers often care more about how well the system will perform operationally against threats (MOE), versus what it can do on its own (MOP).

In this study, the author has defined the problem, the mission, and the operational requirements in the DRM. The ship to be designed will take on the AAW mission so that it may conduct AD in the protection of itself against the aircraft threats. This ship to be designed will need the capabilities in order to meet the operational requirements that were set forth in order to be successful in that mission. Therefore, the next step is in defining how to measure this system's success in the AAW mission.

In defining the MOE for this mission, the Universal Naval Task List (UNTL) was consulted to verify it was in alignment with the official requirements for mission success. Naval Tactical Task (NTA) 6 "Protect the Force" defined the objective of the design ship's mission well. The stated objective is "to protect the tactical forces fighting potential so that it can be applied at the appropriate time and place" and it includes "those measures the force takes to remain viable and functional by protecting itself from the effects of or recovery from enemy activities [23]." Table 4 shows the UNTL measures for this particular task.

Table 4. Measures for Naval Tactical Task "Protect the Force" (From [23])



M1	Casualties	To friendly forces due to enemy actions.
M2	Casualties	To friendly forces due to enemy activities and natural occurrences

In selecting areas for consideration in determining the scope of this thesis, the number of casualties due to enemy activities and natural occurrences (M2) was omitted to focus on this research's primary purpose, which is to integrate combat capability into a ship synthesis model. Natural occurrences were not considered as a threat in the OPSIT. Therefore, the author only focused on M1, the casualties to friendly forces due to enemy actions. In the case of the scenario of the "designed ship," in which it is protecting itself from an incoming enemy aircraft and its ASM, the number of friendly force casualties will either be one or zero since there is only one ship that makes up the "friendly force." When examining this OPSIT in a warfighting simulation, it is assumed that the probability of being killed when hit is one for both the U.S. FFG and Country X's aircraft. By repeating the simulation several times, the sum of the instances that the "friendly" ship endures a casualty divided by the number of simulation repetitions reveals the probability of the ship being killed. This is shown in Equation 4. This is then subtracted from one in order to give a probability of survival, which is shown in Equation

5. In conclusion, the MOE for this study is the ship's probability of survival, P_S, against the incoming enemy aircraft equipped with its ASM.

$$P_{\text{Being Killed}} = \frac{\text{Number of Times Ship Hit}}{\text{Number of Simulation Runs}} \qquad (4)$$

$$P_S = 1 - P_{\text{Being Killed}} \qquad (5)$$

There are numerouos MOPs that impact this mission such as detection range for the ship's radar, SAM range, or the speed of the aircraft just to name a few. Because the purpose of this study is to examine the impacts of changing the shipborne radar's detection range on warfighting effectiveness, the MOP of interest in this study is the detection range of the ship's air search radar.

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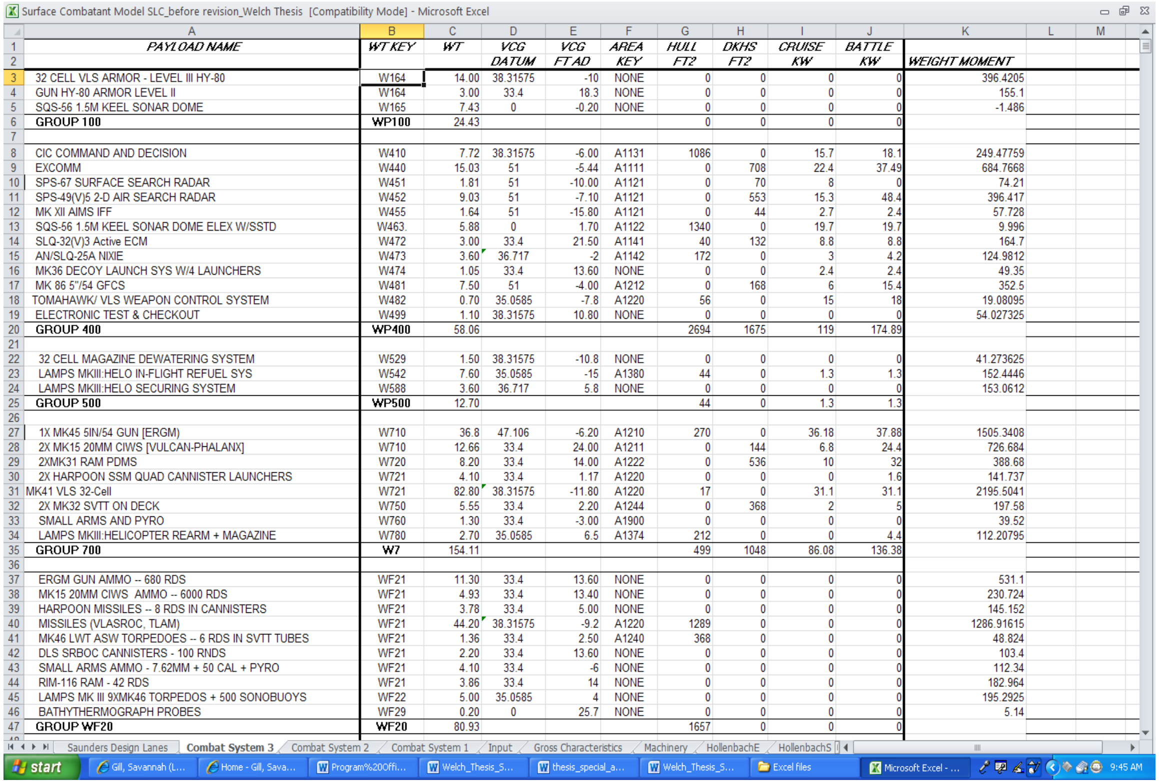
IV. SHIP SYNTHESIS MODEL

The third part of the method involves the use of an Excel-based ship synthesis model that was provided to the author by Professor Whitcomb. The model was initially developed over many years by the Naval Construction and Engineering faculty and students from the Massachusetts Institute of Technology (MIT) 13A Program, (now 2N Program), and refined by Professor Whitcomb in the past several years using the results of ship research at the University of Michigan and the Naval Postgraduate School (NPS). The Excel ship synthesis tool provides a reasonable "first order approximation of a concept's feasibility" [24]. The model uses a collection of worksheets within one Excel file to perform mathematical calculations based on the basic principles of naval architecture. Under the "Inputs" worksheet, the user enters the ship's naval architecture gross characteristics (displacement, prismatic coefficients, etc.), performance-type requirements (such as speed), machinery requirements, space requirements, weight requirements for structures and payload, manning requirements, and cost constraints. The results, found in the "Evaluation" worksheet, are the characteristics of the synthesized ship based on the user's input requirements. The "Evaluation" worksheet also indicates if the ship is feasible based on some basic rules of naval architecture. For a breakdown of all the worksheets, refer to Appendix C.

Unfortunately, this model, like most existing ship synthesis tools, is lacking any sensitivity to combat system design variables. As shown in Figure 11, its combat system worksheets only provide single data points for specific U.S. pieces of combat systems equipment. For example, in the surface search radar category, the SPS-67's unique characteristics of weight, vertical centers of gravity, area, and power are listed. Therefore, every ship synthesized with this model is assumed to have a surface search radar with the same characteristics of an SPS-67. What happens when the user wants a surface search radar with different capabilities? In this way, the model provides no variability in the combat system portions of the model, but acts much like selecting specific examples of combat systems from a catalog.

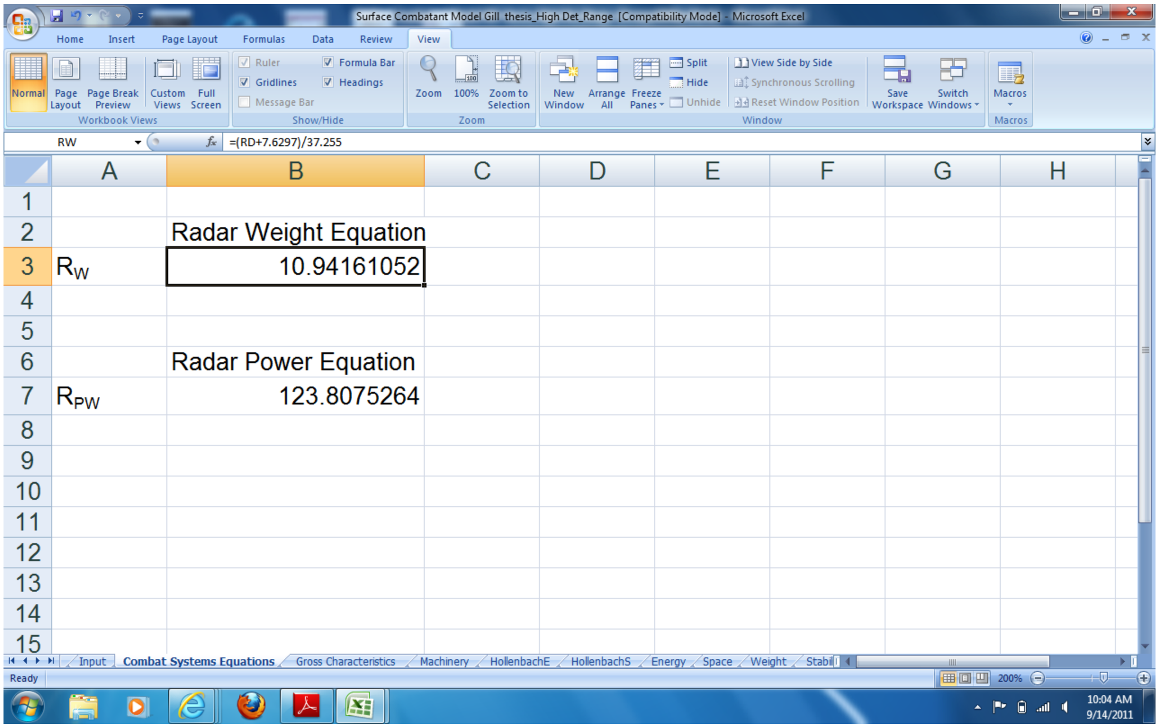

Surface Combatant Model SLC_before revision_Welch Thesis [Compatibility Mode] - Microsoft Excel

	A	B	C	D	E	F	G	H	I	J	K
1–2	PAYLOAD NAME	WT KEY	WT	VCG DATUM	VCG FT AD	AREA KEY	HULL FT2	DKHS FT2	CRUISE KW	BATTLE KW	WEIGHT MOMENT
3	32 CELL VLS ARMOR - LEVEL III HY-80	W164	14.00	38.31575	-10	NONE	0	0	0	0	396.4205
4	GUN HY-80 ARMOR LEVEL II	W164	3.00	33.4	18.3	NONE	0	0	0	0	155.1
5	SQS-56 1.5M KEEL SONAR DOME	W165	7.43	0	-0.20	NONE	0	0	0	0	-1.486
6	**GROUP 100**	**WP100**	24.43				0	0	0	0	
7											
8	CIC COMMAND AND DECISION	W410	7.72	38.31575	-6.00	A1131	1086	0	15.7	18.1	249.47759
9	EXCOMM	W440	15.03	51	-5.44	A1111	0	708	22.4	37.49	684.7668
10	SPS-67 SURFACE SEARCH RADAR	W451	1.81	51	-10.00	A1121	0	70	8	0	74.21
11	SPS-49(V)5 2-D AIR SEARCH RADAR	W452	9.03	51	-7.10	A1121	0	553	15.3	48.4	396.417
12	MK XII AIMS IFF	W455	1.64	51	-15.80	A1121	0	44	2.7	2.4	57.728
13	SQS-56 1.5M KEEL SONAR DOME ELEX W/SSTD	W463.	5.88	0	1.70	A1122	1340	0	19.7	19.7	9.996
14	SLQ-32(V)3 Active ECM	W472	3.00	33.4	21.50	A1141	40	132	8.8	8.8	164.7
15	AN/SLQ-25A NIXIE	W473	3.60	36.717	-2	A1142	172	0	3	4.2	124.9812
16	MK36 DECOY LAUNCH SYS W/4 LAUNCHERS	W474	1.05	33.4	13.60	NONE	0	0	2.4	2.4	49.35
17	MK 86 5"/54 GFCS	W481	7.50	51	-4.00	A1212	0	168	6	15.4	352.5
18	TOMAHAWK/ VLS WEAPON CONTROL SYSTEM	W482	0.70	35.0585	-7.8	A1220	56	0	15	18	19.08095
19	ELECTRONIC TEST & CHECKOUT	W499	1.10	38.31575	10.80	NONE	0	0	0	0	54.027325
20	**GROUP 400**	**WP400**	58.06				2694	1675	119	174.89	
21											
22	32 CELL MAGAZINE DEWATERING SYSTEM	W529	1.50	38.31575	-10.8	NONE	0	0	0	0	41.273625
23	LAMPS MKIII:HELO IN-FLIGHT REFUEL SYS	W542	7.60	35.0585	-15	A1380	44	0	1.3	1.3	152.4446
24	LAMPS MKIII:HELO SECURING SYSTEM	W588	3.60	36.717	5.8	NONE	0	0	0	0	153.0612
25	**GROUP 500**	**WP500**	12.70				44	0	1.3	1.3	
26											
27	1X MK45 5IN/54 GUN [ERGM)	W710	36.8	47.106	-6.20	A1210	270	0	36.18	37.88	1505.3408
28	2X MK15 20MM CIWS [VULCAN-PHALANX]	W710	12.66	33.4	24.00	A1211	0	144	6.8	24.4	726.684
29	2XMK31 RAM PDMS	W720	8.20	33.4	14.00	A1222	0	536	10	32	388.68
30	2X HARPOON SSM QUAD CANNISTER LAUNCHERS	W721	4.10	33.4	1.17	A1220	0	0	0	1.6	141.737
31	MK41 VLS 32-Cell	W721	82.80	38.31575	-11.80	A1220	17	0	31.1	31.1	2195.5041
32	2X MK32 SVTT ON DECK	W750	5.55	33.4	2.20	A1244	0	368	2	5	197.58
33	SMALL ARMS AND PYRO	W760	1.30	33.4	-3.00	A1900	0	0	0	0	39.52
34	LAMPS MKIII:HELICOPTER REARM + MAGAZINE	W780	2.70	35.0585	6.5	A1374	212	0	0	4.4	112.20795
35	**GROUP 700**	**W7**	154.11				499	1048	86.08	136.38	
36											
37	ERGM GUN AMMO -- 680 RDS	WF21	11.30	33.4	13.60	NONE	0	0	0	0	531.1
38	MK15 20MM CIWS AMMO -- 6000 RDS	WF21	4.93	33.4	13.40	NONE	0	0	0	0	230.724
39	HARPOON MISSILES -- 8 RDS IN CANNISTERS	WF21	3.78	33.4	5.00	NONE	0	0	0	0	145.152
40	MISSILES (VLASROC, TLAM)	WF21	44.20	38.31575	-9.2	A1220	1289	0	0	0	1286.91615
41	MK46 LWT ASW TORPEDOES -- 6 RDS IN SVTT TUBES	WF21	1.36	33.4	2.50	A1240	368	0	0	0	48.824
42	DLS SRBOC CANNISTERS - 100 RNDS	WF21	2.20	33.4	13.60	NONE	0	0	0	0	103.4
43	SMALL ARMS AMMO - 7.62MM + 50 CAL + PYRO	WF21	4.10	33.4	-6	NONE	0	0	0	0	112.34
44	RIM-116 RAM - 42 RDS	WF21	3.86	33.4	14	NONE	0	0	0	0	182.964
45	LAMPS MK III 9XMK46 TORPEDOS + 500 SONOBUOYS	WF22	5.00	35.0585	4	NONE	0	0	0	0	195.2925
46	BATHYTHERMOGRAPH PROBES	WF29	0.20	0	25.7	NONE	0	0	0	0	5.14
47	**GROUP WF20**	**WF20**	80.93				1657	0	0	0	

Figure 11. Combat System Worksheet for Excel-based Ship Synthesis Tool

A. MODEL REVISION

The equations formulated in the first step of the thesis method were integrated into the ship synthesis model. Equation 2, relating radar detection range and radar weight, and Equation 3, relating radar power and radar weight, were inserted into a newly created worksheet titled “Combat Systems Equations” (shown in Figure 12).

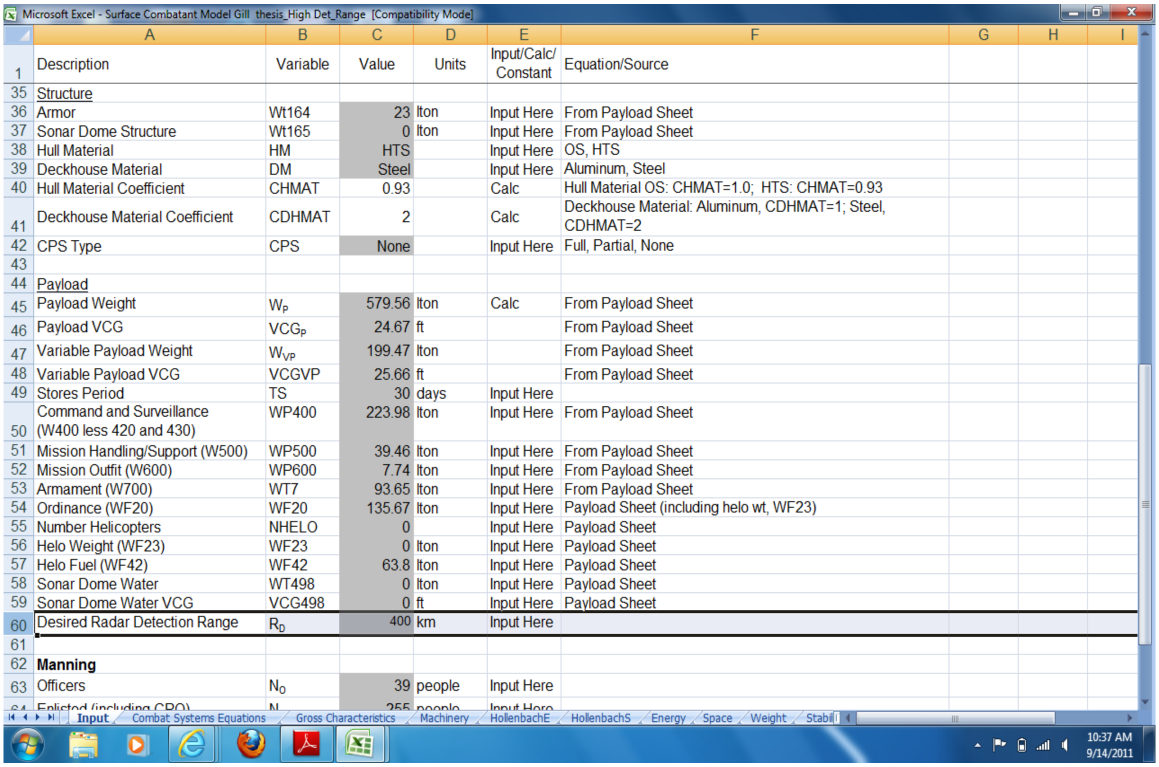


RW f_x =(RD+7.6297)/37.255

	A	B
1		
2		Radar Weight Equation
3	R_W	10.94161052
4		
5		
6		Radar Power Equation
7	R_{PW}	123.8075264

Figure 12. Combat Systems Equations Worksheet of Excel-based Ship Synthesis Tool

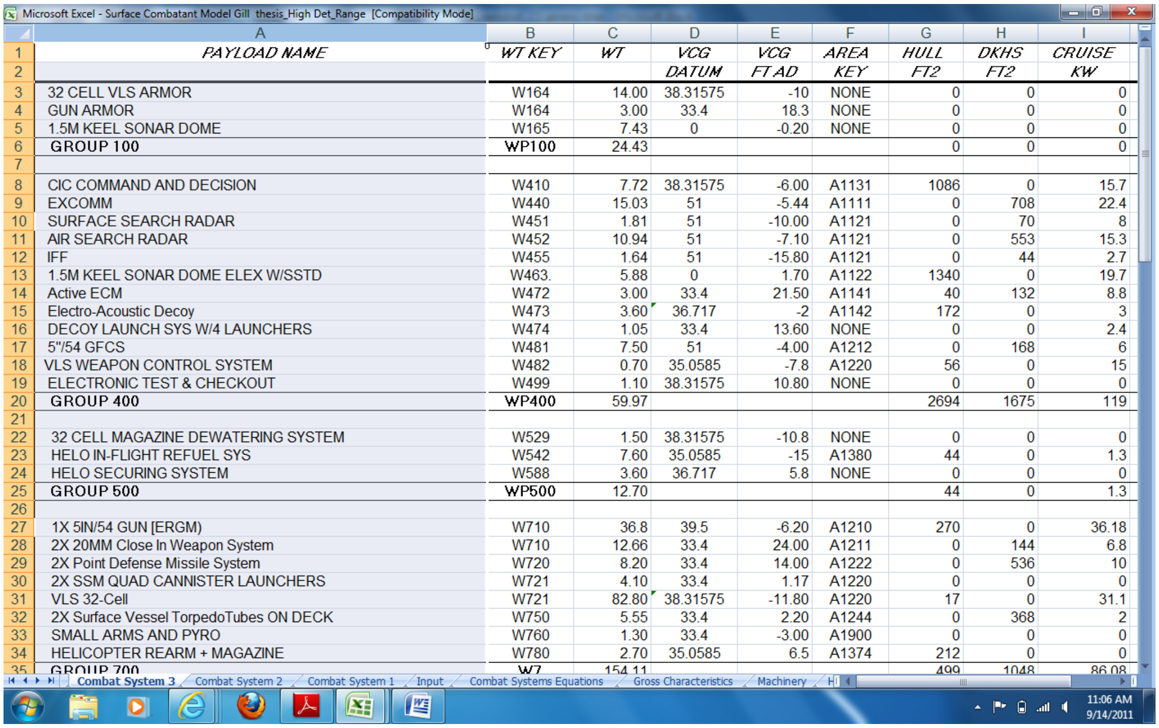
As shown in Figure 13, what this offers as an improvement to the original model is that the user is now able to enter in the desired radar detection range in the "Input" worksheet. Once this radar detection range is used in a warfighting simulation, such as a discrete event simulation of a warfighting scenario as an operational model, a direct link now exists between the ship synthesis model and a warfighting effectiveness model.



	A	B	C	D	E	F
1	Description	Variable	Value	Units	Input/Calc/ Constant	Equation/Source
35	Structure					
36	Armor	Wt164	23	lton	Input Here	From Payload Sheet
37	Sonar Dome Structure	Wt165	0	lton	Input Here	From Payload Sheet
38	Hull Material	HM	HTS		Input Here	OS, HTS
39	Deckhouse Material	DM	Steel		Input Here	Aluminum, Steel
40	Hull Material Coefficient	CHMAT	0.93		Calc	Hull Material OS: CHMAT=1.0; HTS: CHMAT=0.93
41	Deckhouse Material Coefficient	CDHMAT	2		Calc	Deckhouse Material: Aluminum, CDHMAT=1; Steel, CDHMAT=2
42	CPS Type	CPS	None		Input Here	Full, Partial, None
43						
44	Payload					
45	Payload Weight	W_P	579.56	lton	Calc	From Payload Sheet
46	Payload VCG	VCG_P	24.67	ft		From Payload Sheet
47	Variable Payload Weight	W_{VP}	199.47	lton		From Payload Sheet
48	Variable Payload VCG	VCGVP	25.66	ft		From Payload Sheet
49	Stores Period	TS	30	days	Input Here	
50	Command and Surveillance (W400 less 420 and 430)	WP400	223.98	lton	Input Here	From Payload Sheet
51	Mission Handling/Support (W500)	WP500	39.46	lton	Input Here	From Payload Sheet
52	Mission Outfit (W600)	WP600	7.74	lton	Input Here	From Payload Sheet
53	Armament (W700)	WT7	93.65	lton	Input Here	From Payload Sheet
54	Ordinance (WF20)	WF20	135.67	lton	Input Here	Payload Sheet (including helo wt, WF23)
55	Number Helicopters	NHELO	0		Input Here	Payload Sheet
56	Helo Weight (WF23)	WF23	0	lton	Input Here	Payload Sheet
57	Helo Fuel (WF42)	WF42	63.8	lton	Input Here	Payload Sheet
58	Sonar Dome Water	WT498	0	lton	Input Here	Payload Sheet
59	Sonar Dome Water VCG	VCG498	0	ft	Input Here	Payload Sheet
60	Desired Radar Detection Range	R_D	400	km	Input Here	
61						
62	**Manning**					
63	Officers	N_O	39	people	Input Here	
64	Enlisted (including CPO)	N	255	people	Input Here	

Figure 13. Worksheet for User Input Supplemented with Radar Range on Excel-based Ship Synthesis Tool

The “Combat Systems Equations” worksheet takes the user’s input for “Desired Radar Detection Range” from the “Input” worksheet and calculates the resulting weight and power of the radar. This resulting weight and power are then automatically inserted into the “Combat Systems” worksheet under the appropriate columns in the “Air Search Radar” row. These updated values are used in the ship synthesis calculations. Therefore, although it is only for the air search radar’s values of weight and power, the ship synthesis model is now capable of varying its values based on a combat system capability. In addition to the combat system relationship equations presented here, further coordinates and parameters could be inserted into this “Combat Systems Equations (CSE)” worksheet. This would eliminate the use of unique, unchanging data points for each combat system. Ideally, each of the combat systems’ naval architecture characteristics would change with the differing system capabilities entered into the CSE worksheet by the user. Additionally, since the combat systems’ architectural characteristics would change based on the user's input, the "Combat Systems" worksheet would have generic titles for each system, as what is shown in Figure 14 versus the specific combat system names that are shown in the "Combat System" worksheet of Figure 11.



	A	B	C	D	E	F	G	H	I
1	PAYLOAD NAME	WT KEY	WT	VCG	VCG	AREA	HULL	DKHS	CRUISE
2				DATUM	FT AD	KEY	FT2	FT2	KW
3	32 CELL VLS ARMOR	W164	14.00	38.31575	-10	NONE	0	0	0
4	GUN ARMOR	W164	3.00	33.4	18.3	NONE	0	0	0
5	1.5M KEEL SONAR DOME	W165	7.43	0	-0.20	NONE	0	0	0
6	GROUP 100	WP100	24.43				0	0	0
7									
8	CIC COMMAND AND DECISION	W410	7.72	38.31575	-6.00	A1131	1086	0	15.7
9	EXCOMM	W440	15.03	51	-5.44	A1111	0	708	22.4
10	SURFACE SEARCH RADAR	W451	1.81	51	-10.00	A1121	0	70	8
11	AIR SEARCH RADAR	W452	10.94	51	-7.10	A1121	0	553	15.3
12	IFF	W455	1.64	51	-15.80	A1121	0	44	2.7
13	1.5M KEEL SONAR DOME ELEX W/SSTD	W463.	5.88	0	1.70	A1122	1340	0	19.7
14	Active ECM	W472	3.00	33.4	21.50	A1141	40	132	8.8
15	Electro-Acoustic Decoy	W473	3.60	36.717	-2	A1142	172	0	3
16	DECOY LAUNCH SYS W/4 LAUNCHERS	W474	1.05	33.4	13.60	NONE	0	0	2.4
17	5"/54 GFCS	W481	7.50	51	-4.00	A1212	0	168	6
18	VLS WEAPON CONTROL SYSTEM	W482	0.70	35.0585	-7.8	A1220	56	0	15
19	ELECTRONIC TEST & CHECKOUT	W499	1.10	38.31575	10.80	NONE	0	0	0
20	GROUP 400	WP400	59.97				2694	1675	119
21									
22	32 CELL MAGAZINE DEWATERING SYSTEM	W529	1.50	38.31575	-10.8	NONE	0	0	0
23	HELO IN-FLIGHT REFUEL SYS	W542	7.60	35.0585	-15	A1380	44	0	1.3
24	HELO SECURING SYSTEM	W588	3.60	36.717	5.8	NONE	0	0	0
25	GROUP 500	WP500	12.70				44	0	1.3
26									
27	1X 5IN/54 GUN [ERGM)	W710	36.8	39.5	-6.20	A1210	270	0	36.18
28	2X 20MM Close In Weapon System	W710	12.66	33.4	24.00	A1211	0	144	6.8
29	2X Point Defense Missile System	W720	8.20	33.4	14.00	A1222	0	536	10
30	2X SSM QUAD CANNISTER LAUNCHERS	W721	4.10	33.4	1.17	A1220	0	0	0
31	VLS 32-Cell	W721	82.80	38.31575	-11.80	A1220	17	0	31.1
32	2X Surface Vessel TorpedoTubes ON DECK	W750	5.55	33.4	2.20	A1244	0	368	2
33	SMALL ARMS AND PYRO	W760	1.30	33.4	-3.00	A1900	0	0	0
34	HELICOPTER REARM + MAGAZINE	W780	2.70	35.0585	6.5	A1374	212	0	0
35	GROUP 700	W7	154.11				499	1048	86.08

Figure 14. Revised "Combat Systems" Worksheet with Generic Titles

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V. OPERATIONAL MODEL

This analysis uses discrete-event simulation for the operational model of the ship being designed. Discrete-event simulation (DES) is “the modeling of a system as it evolves over time by a representation where the state variables change instantaneously at separated points in time [25].” An attribute of a DES model is that it is event-based. Changes in time and states of variables occur through event. The operational model was constructed using ExtendSim, which is a modeling tool that uses a library of building components, called blocks, to model discrete-event systems. In this study, the warfighting scenario described above was modeled as a Monte Carlo simulation, which is a statistical model that uses repeated random samplings from a probability distribution to characterize parts of that system [26]. This random sampling from a distribution is used in parts of the model that require human interaction and cannot be deterministically represented.

A. MODEL DEVELOPMENT

The objective of the operation in this model is for the ship to conduct successful point defense against an incoming aircraft threat. The ship’s course of action (COA) chosen for this model is to engage the incoming aircraft and/or missile threat with its primary SAM once it has done the following three actions: detects the aircraft or missile, identifies it as hostile, and tracks it within ship firing range. The enemy aircraft’s COA chosen for this model is to engage the ship with its primary ASM once it is within the aircraft’s firing range. The only changing variable within this model is the MOP of interest, the detection range of the ship’s air search radar. All other variables that would normally have impact on the outcome of the model remain constant.

1. Model Scope

Because the purpose of the thesis is to show a way of implementing combat system capability into ship design, the operational model created is a very basic simulation to demonstrate warfighting effectiveness. The MOE values resulting from the operational model are used to show how a ship synthesis tool can be supplemented with them and are not meant for use in an actual combatant design. The following statements describe specific boundaries of the model:

- The model is based solely on speed and range, not three-dimensional geometry.
- The model is based on only one mission area (point defense in AAW).
- The model only evaluates P_S of ship.
- The model is focusing only on the aircraft's standard ASM and the ship's standard SAM for its defensive capabilities and does not consider the other weapon system assets.

2. Model Assumptions

The intent of this model is not to predict with certainty the outcome of a warfighting situation in order to influence a Commanding Officer's decision, but rather to present a simple, yet realistic way of demonstrating one MOP's impact on a specific MOE for a specific mission. Therefore, the following assumptions are made in the model:

- The ship is stationary.
- The ship is at its highest level of combat readiness; ship has intelligence that air attack is imminent and all watchstanders are very alert.
- The ship utilizes a Shoot-Look-Shoot Doctrine.
- The aircraft's tactics consist of shooting only 1 ASM when it reaches its firing range and will immediately change course and return to its home base.
- The aircraft's radar detection range is greater than its firing range.
- If the ship or aircraft is hit, $P_S = 0$.
- The $P_{Detection}$ of both the ship and aircraft's radar is equal to 1.
- All environmental and time factors (weather, sea state, visibility, temperature, etc.) are ideal for ship and aircraft combat system and weapon performance.

B. MODEL LOGIC

The model was constructed using the logic in Figure 15. The ship radar's detection range is the MOP of interest and is the only number that is varied throughout the simulation trials. In this scenario, this range is the maximum range at which a fighter-sized aircraft can be detected. The range, at which air search radars are capable of detecting missiles, is generally much smaller. Therefore, at the beginning of the simulation, the ship radar's missile detection range is calculated based on the following equation:

$$Missile\ Detection\ Range = \frac{Detection\ Range + 33.438}{6.3565} \tag{6}$$

This equation was formed based on an evaluation of the relationship between several existing radars' known detection ranges for both aircraft and missiles. Further details of this evaluation are found in Appendix D. The first event is the creation of the target that the radar is detecting. This is based on the ship's radar detection range that has been entered by the user. If the ship's radar detection range is greater than the aircraft's firing range, the ship will detect the aircraft first. Therefore, the initial target created is the enemy aircraft. However, if the ship's radar detection range is less than the aircraft's firing range, the initial target created is the incoming anti-ship missile (based on the assumption that the enemy aircraft's tactics are to shoot only 1 ASM and immediately increase distance away from the ship and return to home base). From that point, the simulation can go one of the following ways:

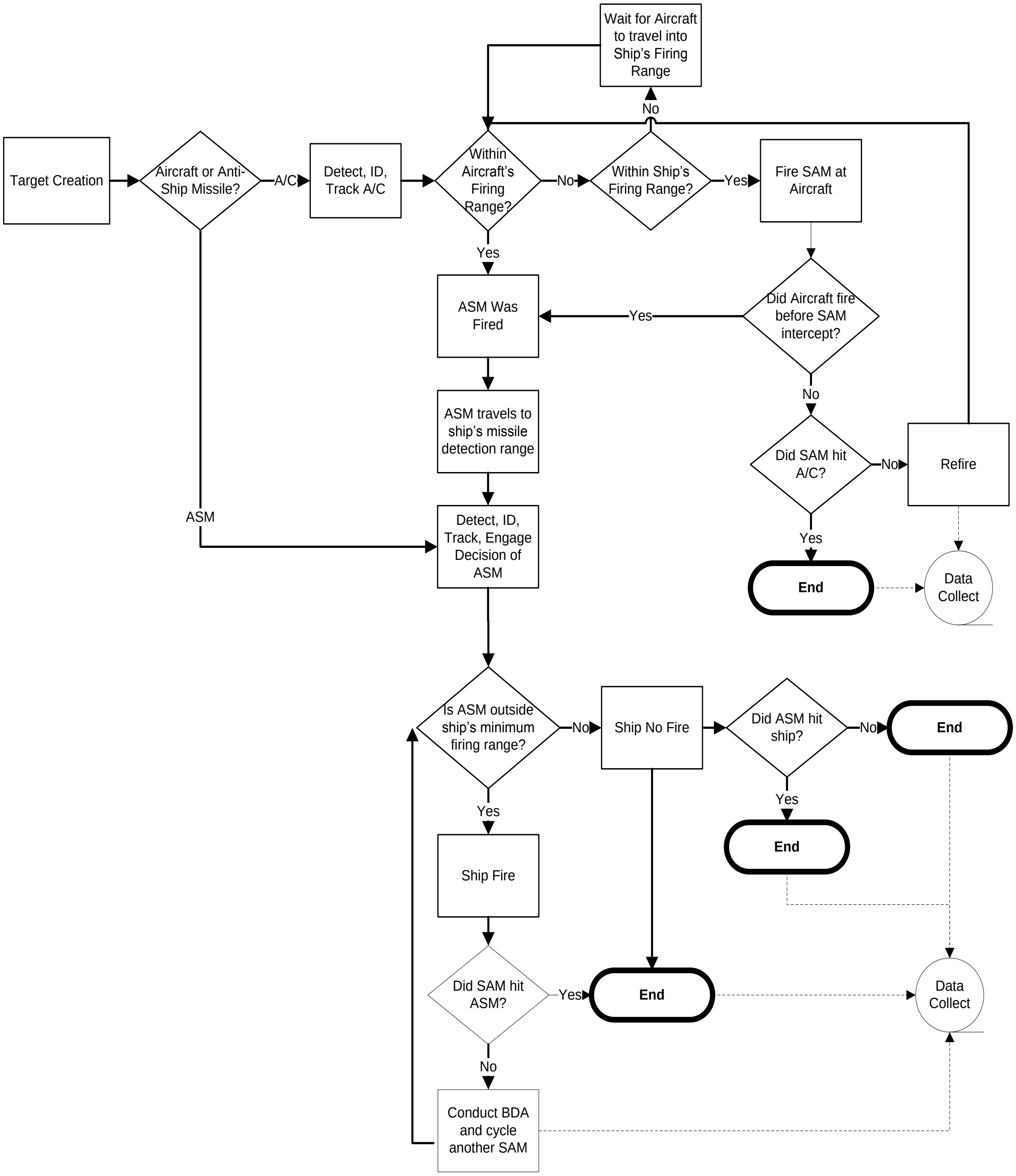

Figure 15. Logic Diagram for Operational Model

If the initial target detected is the enemy aircraft:

- The ship hits the aircraft with its SAM before the aircraft reaches its firing range
- The ship does not hit the aircraft with its SAM before the aircraft reaches its firing range, but successfully hits the incoming ASM before it reaches the ship's minimum firing range
- The ship does not hit the aircraft with its SAM before the aircraft reaches its firing range, does not hit the incoming ASM before it reaches the ship's minimum firing range, and the ASM successfully hits the ship
- The ship does not hit the aircraft with its SAM before the aircraft reaches its firing range, does not hit the incoming ASM before it reaches the ship's minimum firing range, but the ASM misses the ship

If the initial target detected is the ASM:

- The ship hits the incoming ASM before it reaches the ship's minimum firing range
- The ship does not hit the ASM before it reaches the ship's minimum firing range and the ASM hits the ship
- The ship does not hit the ASM before it reaches the ship's minimum firing range, but the ASM misses the ship

Ultimate outcomes of operational model:

- Aircraft hit; ship not hit
- ASM hit; ship not hit
- ASM not hit; ship hit
- Neither ASM nor ship hit

The outcomes for each of the variables under consideration are recorded into an Excel database where they are averaged over the number of iterations performed in the simulation. A screenshot of the Excel database can be found in Appendix E. The MOE probability of ship survival is calculated using Equations 4 and 5 previously discussed. Throughout the model, random samplings from a normal distribution take place at the points where human involvement determine that event's length of time. The time for a skilled operator to detect, track and identify the threat (which could be as simple as the receipt of an Identification Friend or Foe (IFF) code or as time-consuming as multiple verbal queries and warnings) and the time for a Commanding Officer or Tactical Action Officer to make the decision to engage both bring a great source of variability to the modeling scenario. A screenshot of the actual operational model in ExtendSim is found in Appendix F.

C. MODEL PARAMETERS

Table 5 shows the parameters that were held constant through every iteration of the model simulation. Some of the parameters were selected based on research of actual aircraft, ship, and missile parameters from *Jane's Fighting Ships* and *Jane's All the World's Aircraft*.

Table 5. Parameter Values used in the Operational Model

Constant Parameters	**Value**
Maximum Aircraft Firing Range	100 km (54 nm)
Maximum Ship Firing Range	150 km (81 nm)
Minimum Ship Firing Range	2 km (1.08 nm)
Aircraft Velocity	0.3087 km/s (0.9M)
SAM Velocity	0.8575 km/s (2.5M)
ASM Velocity	0.686 km/s (2M)
SAM P_K of Aircraft	0.65
SAM P_K of ASM	0.6
ASM P_K of Ship	0.85

The values were also deemed realistic by a qualified Surface Warfare Officer and F-18 Weapon Systems Officer. The author was unable to find probability of kill ($P_{K)}$ information and therefore picked reasonable values based on expert opinion, but in an actual modeling case, real data would be used. In determining the normal distributions' means and standard deviations for the human-based activities, the author consulted with a qualified Anti-Air Warfare Coordinator.

VI. RESULTS

Once the operational model was constructed and refined and the "real world" parameters were added, the simulation was run 1000 times for several detection ranges going from 10 km to 400 km. The probability of survival, P_S, was calculated for each detection range and the results are shown in Figure 16.

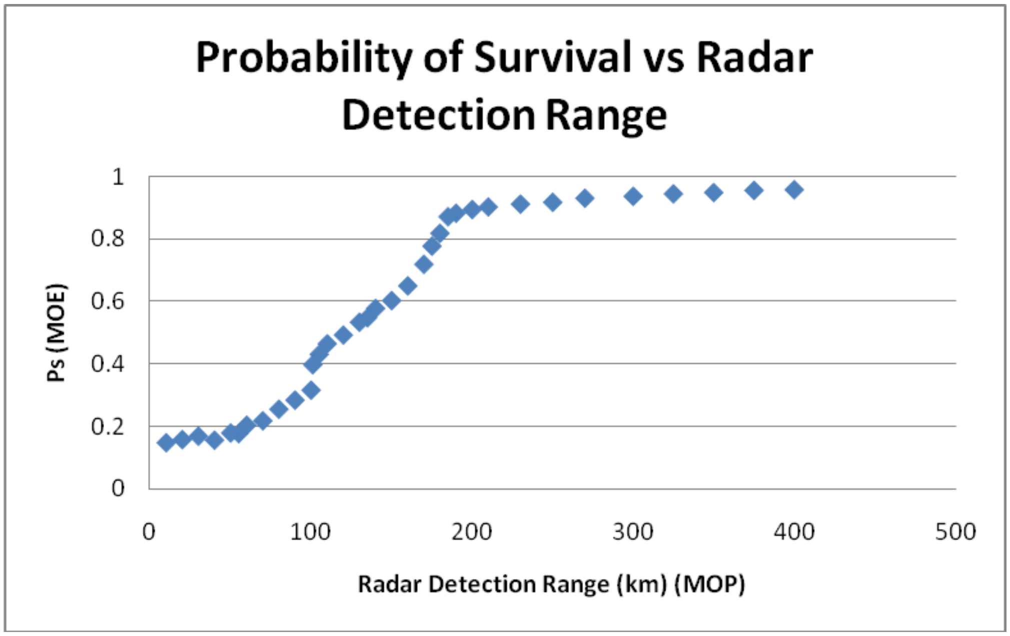

Figure 16. Plot of P_S versus Radar Detection Range in Results from Operational Model

The knee of the curve is around the 190 km area, which means that increasing the detection range of the radar more than 190 km does not result in as great of a return in probability of survival of the ship. Because the author used an equation for calculating the radar's missile detection range based on the radar's maximum detection range, there continues to be an increase in P_S of the ship as detection range increases even though it is not as pronounced after the 190 km point. The importance of the 190 km point can be described in the logic and parameter choice of the model. From detection ranges of 190 km and greater, the ship has the greatest amount of opportunities to shoot down the aircraft before it can even fire one of its ASMs. From 190 km and greater, the ship is able to detect the aircraft far enough in advance so that its radar operator can detect, track, and identify the target through IFF and possibly verbal queries and warnings, and the Commanding Officer and/or Tactical Action Officer can make the difficult decision on engagement, all before the aircraft has reached the 150 km maximum ship firing range. The curve's not quite perfectly smooth shape is based on the variability involved in the parts of the model that require human interaction. These parts use the random samplings from a normal distribution in order to determine the amount of time for that certain event.

The values for P_S from Figure 16 were used as the MOE for warfighting effectiveness of the ship to be designed. After warfighting effectiveness information was collected, the author developed ships using the ship synthesis tool based on a user's requirement for an air search radar of low, medium, and high detection range. The results are summarized below in Table 6. Screenshots of the "Evaluation" worksheets for these three ships synthesized can be found in Appendix E.

Table 6. Ship Synthesis Information for Low, Medium, and High Air Search Radar Detection Ranges

Ship Synthesis Results			
Air Search Radar Range	**Total Ship Full Load Weight**	**Ship Survivability in AAW**	**Cost**
High (400 km)	4840 LT	96%	$677.69 M
Medium (135 km)	4826.7 LT	55%	$673.66 M
Low (55 km)	4822.7 LT	18%	$670.63 M

In order for the ship to achieve a 96% PS in the AAW scenario, it needs a combat capability of 400 km (air search radar detection range), which results in an overall ship weight of 4840 ltons. As shown in Table 6, going from a ship with a low radar detection range to a high radar detection range increases its warfighting effectiveness by nearly

80%, but only increases its weight by about 17 tons. These are the types of observations that ship designers, stakeholders, and decision makers need in order to conduct proper trade off analyses when building a ship.

In demonstrating what this modeling tool is capable of, it should be noted that this analysis focused specifically on the air search radar and its individual impact. Additionally, the ships synthesized were based on the Sachsen Class FFG, which belongs under the "Combat Systems 2" worksheet of the ship synthesis model. The Sachsen Class FFG is representative of the average of the ships that housed the radars used in this analysis and its additional information can be found in Appendix H. Because the research conducted here examined closely a particular scenario, it must be understood that claims made here are limited to the scenarios in question. In other words, while it does indicate what might take place between one ship and one aircraft, it does not speak to how well the ship would do in other warfare areas. Finally, the cost shown in Table 6 is the total lead ship acquisition cost and is calculated by the ship synthesis model solely based on weights of parts of the ship and not on other costly factors, such as combat systems software. Therefore, the costs shown may not be indicative of the actual costs.

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VII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Historically, ship synthesis models, such as Asset and the Excel-based model used in this thesis, have only accounted for combat systems through inserted single data points that included only physical characteristics like weight, volume, area, and input power. These tools are void of any sensitivity to combat system design variables that relate to their performance as combat and weapon systems. Through this thesis, it was shown as a proof of concept that it is possible to integrate combat system design parameters directly into a ship synthesis tool. By finding a quantitative relationship between radar detection range and radar weight, the author discovered a link between combat system design parameters and naval architecture parameters that can be used to directly couple to operational simulation models to determine warfighting MOE. Implementing this quantitative relationship into the ship synthesis model provides a way to show variability in the combat systems architecture characteristics based on the combat system parameter inputs. By measuring the warfighting effectiveness of the combat system design parameter at different values, the author then links the combat system design parameter to what is pertinent to the stakeholders and decision makers, the MOE. As a result, stakeholders have an enhanced ability to evaluate a combat system parameter, such as a radar range, based on its impacts on both the actual ship's naval architecture and warfighting effectiveness, which allows them to conduct trade-offs on variables of direct concern and therefore make more informed decisions.

B. RECOMMENDATIONS

If the proof of concept outlined here were expanded, further research should examine any or all of the ship's combat systems and warfighting effectiveness measures in all warfare areas. Therefore, the ship synthesis model used would have the "Combat Systems Equations" worksheet populated with equations describing every relationship between each combat system's input parameters and its naval architecture characteristics. Additionally, the "Combat System" worksheets would no longer contain single data points for a unique existing combat system, but would instead be a list of generic names for essential pieces of ship combat systems equipment and their data values would change based on the user's input for their parameters.

Since the author only focused her research on air search radars, a future recommendation is to research other pieces of combat systems equipment, such as surface search radars, multifunction radars, sonar, missiles, close-in weapon systems, guns, torpedoes, and several others. The next step in an analysis of this kind would be to determine if there is a relationship between any of their physical characteristics, such as weight, volume, or size, and any of their performance parameters. Any clear relationships found would be gathered together in much the same way as was done in this thesis in the "Combat Systems Equations" worksheet section.

Additionally, the author only focused on one MOE for one particular mission area during her evaluation of the warfighting effectiveness of her combat system parameter. This research could be expanded to show how combat and weapon systems beyond radar range affect other mission scenarios, such as anti-surface warfare (ASuW) or maritime interdiction operation (MIO). MOE's other than ship survivability could be explored as well. Expanding the number of warfare areas and MOEs analyzed would provide relevant information that would enable a decision maker to understand and therefore analyze the impact of a change to overall ship design.

The Excel-based ship synthesis model is a math-based tool that allows ship designers to test different concept designs for feasibility based on the principles of naval architecture. The method outlined in this thesis consists of the following:

- Conducting research and analysis on the physical and functional parameters for existing combat systems
- Supplementing the ship synthesis model with mathematical relationships found from the previous analysis

- Demonstrating the combat system functional parameter’s impact on warfighting effectiveness through the use of an operational model
- Linking the impacts of a combat capability on both the ship design and warfighting effectiveness

By using this method for future research in other combat systems, warfare areas, and MOEs, the ship synthesis tool can provide enough information to enable decision makers to make better-informed choices to meet the requirements of CBA and the current JCIDS process.

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APPENDIX A: AIR SEARCH RADAR INFORMATION COLLECTED DURING RESEARCH

Table 7 shows the air search radar information that was collected during the author's research. Although initially there were more radars investigated, these specifically were the radars used in the analysis of the thesis. As can be seen by the blank cells in the table, the amount of information varied for each radar. Therefore, all the radars listed in Table 7 had range and weight data available that was useful in the analysis of this relationship. Other comparisons were made between the other categories of information available but are discussed further in Appendix B. Because Table 7 is a very long and wide Excel spreadsheet, it is broken up into several pages. The first two pages include the type, frequency, range, scan rate, weight, and power requirements for all 16 air search radars from top to bottom alphabetically arranged. The third, fourth, and fifth pages of Table 7 include the dimensions, antenna information, class of ships carrying the radar, the country flags of those ships, the radar's functions, and the manufacturer of the radar for all 16 air search radars in the same order as before.

Name	Type	Freq	Range	Scan Rate	Weight	Power Req
DA05	high power, med range surveillance	2–4 GHz	135 km		3273 kg	
DA08	horn fed parabolic reflector	3–4 GHz	125 km	15 rpm	1100 kg (top), 3253 kg (rem)	
EL/M-2228S (2D HP AMDR)	2-D HP, Automatic Missile Detection Radar (AMDR); pulse Doppler multimode	2 - 4 GHz	20 km (auto threat alert of incoming missile), 70 km (fighter), 100 km (instrm)	12 or 24 rpm	237 kg (ant), 1500 kg (below decks)	15 kVa
EL/M-2228S (3D HP AMDR)	3-D, HP, AMDR; pulse Doppler multimode	2 - 4 GHz	20 km (auto threat alert of incoming missile), 70 km (fighter), 100 km (instrm)	12 or 24 rpm	550 kg (ant), 1600 kg (below deck)	21 kVA
Fregat-MAE	3-D, 1 channel, baseline	2 - 3 GHz	27 or 30 km (missile), 125 or 130 km (fighter), rad horizon (ship)	15 rpm	2.2 t (ant), 2.9 t (below decks)	30 kW
Fregat-MAE-1	3-D, 1 channel, variant of MAE + electronic beam stabilisation	2 - 3 GHz	27 km (missile), 125 km (fighter), radar horizon (ship)	15 rpm	1 t (ant), 3.1 t (below decks)	30 kW
Fregat-MAE-4K	3-D, 1 channel, lightweight, variant of MAE-1	6 - 8 GHz	17 km (missile), 58 km (fighter), radar horizon (ship)	30 rpm	0.4 t (ant), 2.6 t (below decks)	30 kW
MW08	3D short to medium range surveillance and target acquis	4–6 GHz	55 km (fighter)		650 kg (above deck), 1500 kg (below deck)	
Podberyozovik-ET1	3-D, solid state	4 - 8 GHz	55 km (missile), 300 km (fighter), radar horizon (ship)	6 or 12 rpm	3.2 t (below deck), 4.7 t (ant)	45 kW

Table 7. Air Search Radar Information (Continued over next 4 pages)

Name	**Type**	**Freq**	**Range**	**Scan Rate**	**Weight**	**Power Req**
Podberyozovik-ET2	3-D, solid state	4–8 Ghz	45 km (missile), 240 km (fighter), radar horizon (ship)	6 or 12 rpm	2.9 t (ant), 3.2 t (below deck)	45 kW
Pozitiv-ME1 (Strut Curve?)	3D flat phased array	X	110km (air), 15 km (anti ship missile)	2,5,10,20 cycle sec	1460 kg (above), 1740 kg (below)	
Pozitiv-ME1.2 (Strut Curve?)	3D flat phased array	X	50 km (air), 13–15 km (aship missile)	1, 2, 5	750 kg (above), 1400 (below)	
RAN 20S	2-D, solid state, med range, air and surface search radar	2–4 GHz	52 km (28 rpm, instr) ; 120 km (14 rpm, instr)	14 rpm and 28 rpm	240 kg (below deck ant group control unit), 300 kg (rcvr), 1325 kg (trnsmtr), 1920 kg (above deck ant group)	
RSR 210N	2-D, lightweight	8 - 12.5 GHz	185m-10km (helo cont), 1–25km (gunfire support), 1–30km (anti-air), 2–55 km (air surveillance)	15 rpm, 30 rpm, 60 rpm	<560 kg (ant/pedestal assmbly), < 1400 kg (below deck elements)	
SMART-L Multibeam Radar	Multibeam Radar	1–2 GHz	65 km (missile), 400 km (a/c, max)	12 rpm	72 kg (humid contr), 120 kg (climate contr unit), 200 kg (drive contr unit),231 kg (B/C video proc cab), 275 kg (vid proc cab A), 2,640 kg (transm cab), 7800 kg (antenna)	(440 V, 60 hz, 3phase,130 kVA), (115V, 60hz, 3phase, 10 kVA)
VARIANT	dual band, 2D surveill and target indic radar	4–6 GHz, 8–10 GHz	60 km (air), 70 km (surface)	14 and 28 rpm	180 kg (search process cab), 230 kg (interf proc cab), 450 kg (ant sys)	(115 V, 60hz, 3phase, 3.9 kVA), (115 V, 60hz, 1 phase, 1.2 kVA), (440V, 60 hz, 3 phase, 3 kVA)

Name	Dimensions	Antenna Info	Class of Ships	Countries	Function	Manufacturer
DA05		horn fed parabolic reflector	FFG, corv, patrol ships	Argentina, Bulgaria, Egypt, Finland, Indonesia, Ireland, South Korea, Malaysia, Morocco, Spain, Thailand	air surveillance and target indication	Thales Nederland, Hengelo, Netherlands
DA08			DDG, FFG, corv, Amph Trnspt dock, CG	Argentina, Bangladesh, Canada, Malaysia, Netherlands, Pakistan, Peru, Portugal, Turkey	med-long range surv, target indication to WCS	Thales Nederland, Hengelo, Netherlands
EL/M-2228S (2D HP AMDR)		2-D HP, cosec^2 lightweight reflector on masthead	DDG	Chile	missile (sea skim) detection, air/surf surveillance	Elta Systems Ltd (sub of Israel Aeorospace Ind), Ashdod
EL/M-2228S (3D HP AMDR)		3-D HP, reflector + multibeam array on masthead	DDG	Chile	missile (sea skim) detection, air/surf surveillance	Elta Systems Ltd (sub of Israel Aeorospace Ind), Ashdod
Fregat-MAE	16 m^2 Area		survey ship, DDG, FFG, carrier, CG, amphibious transort dock, missile range ship	China, India, Russia, Ukraine	multi-function 3D naval surveillance radar	Rosoboronexport, Moscow; State Unitary Enterprise-State Moscow Plant 'Salyut', Moscow.
Fregat-MAE-1	16 m^2 Area		survey ship, DDG, FFG, carrier, CG, amph transort dock, missile range ship	China, India, Russia, Ukraine	multi-function 3D naval surveillance radar	Rosoboronexport, Moscow; State Unitary Enterprise-State Moscow Plant 'Salyut', Moscow.

Name	**Dimensions**	**Antenna Info**	**Class of Ships**	**Countries**	**Function**	**Manufacturer**
Fregat-MAE-4K	20 m^2 Area		survey ship, DDG, FFG, carrier, CG, amph trns dock, missile range ship	China, India, Russia, Ukraine	multi-function 3D naval surveillance radar	Rosoboronexport, Moscow; State Unitary Enterprise-State Moscow Plant
MW08		stripeline array (rcv and transmit)	FFG, DDG, Corv, FAC	Greece, South Korea, Oman, Portugal, Turkey	short to med range surveillance	Thales Nederland, Hengelo, Netherlands
Podberyozovik-ET1	area occupied 30 m^2	7.16 X 6.26 m; narrow trns/rcptn beams, low sidlobe	CG	Russia	air and surface surveillance and targeting radar	Rosoboronexport, Moscow; State Unitary Enterprise-State Moscow Plant
Podberyozovik-ET2	area occupied 30 m^2	7.16 X 2.92 m; low sidelobe and narrow trns/rcptn beams	CG	Russia	air and surface surveillance and targeting radar	Rosoboronexport, Moscow; State Unitary Enterprise-State Moscow Plant
Pozitiv-ME1 (Strut Curve?)				Russia		Rosoboronexport, Moscow; State Unitary Enterprise-State Moscow Plant
Pozitiv-ME1.2 (Strut Curve?)				Russia		Rosoboronexport, Moscow; State Unitary Enterprise-State Moscow Plant

Name	**Dimensions**	**Antenna Info**	**Class of Ships**	**Countries**	**Function**	**Manufacturer**
RAN 20S	1370 X 700 X 5090 mm (bel deck ant group cont unit), 1850 X 700 X 645 mm (rcvr), 2109 X 700 X 2180 mm (trnsmtr), 2740 X 778 X 5090 mm (above deck ant group) HWD	roll and pitch stabilised ant group, conformal array that is mounted on a 2 axis stabilisd platform	FFG, corv	Brazil	med range, air and surface search radar	Selex Sistemi Integrati SpA, Rome
RSR 210N	1.8 X 2.1 X 0.9 m (below decks elem), 1.8 (ht) X 1.5 m (swept radius, ant),	planar array ant, stabilised pitch and roll; 1.8 m (ht) X 1.5 m (swept radius, antenna)	FFG	Norway	air/sea surveillance	Reutech Radar Systems, Stellenbosch
SMART-L Multibeam Radar		planar array ant	FFG, amph	Denmark, Germany, South Korea, Netherlands	air/surf surveillance and target desig	Thales Nederland, Hengelo, Netherlands
VARIANT	WHD 745 X 1859 X 446 mm (search and interf proc cab, each), 2353 (W) X 1970 (H) mm (ant syst)	double pill box	FFG, FAC, Amphib dock, large patrol craft	Bangladesh, Greece, Indonesia, Netherlands	automat fast reaction sensor, provides info to weapon sys	Thales Nederland, Hengelo, Netherlands

APPENDIX B: OTHER RESULTS FROM AIR SEARCH RADAR ANALYSES

Figures 9 and 10 showed the two analyses that resulted in the most promising relationships. The following figures are plots of the other analyses that were conducted based on the information researched in Appendix A, but did not result in strongly correlated relationships.

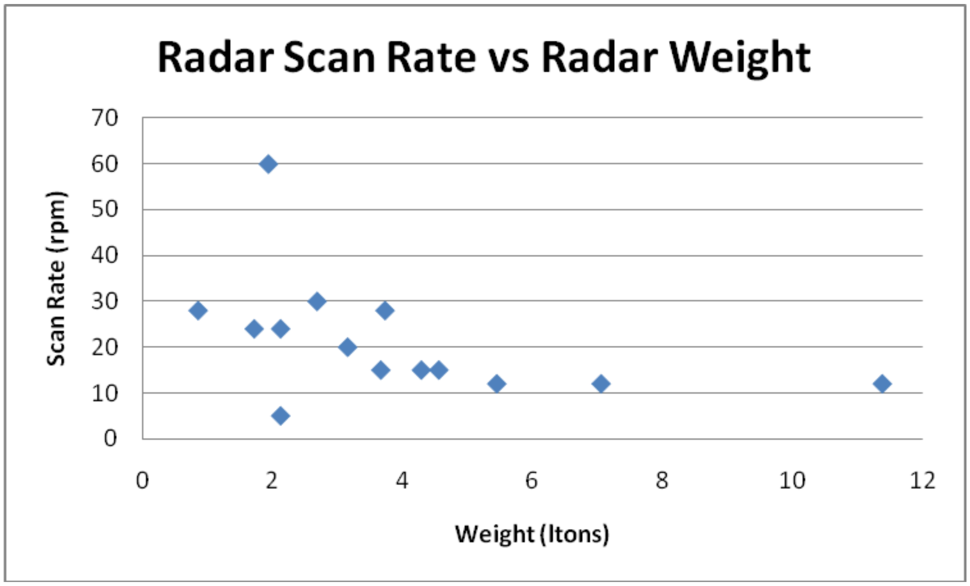

Figure 17. Analysis of Radar Scan Rate versus Radar Weight

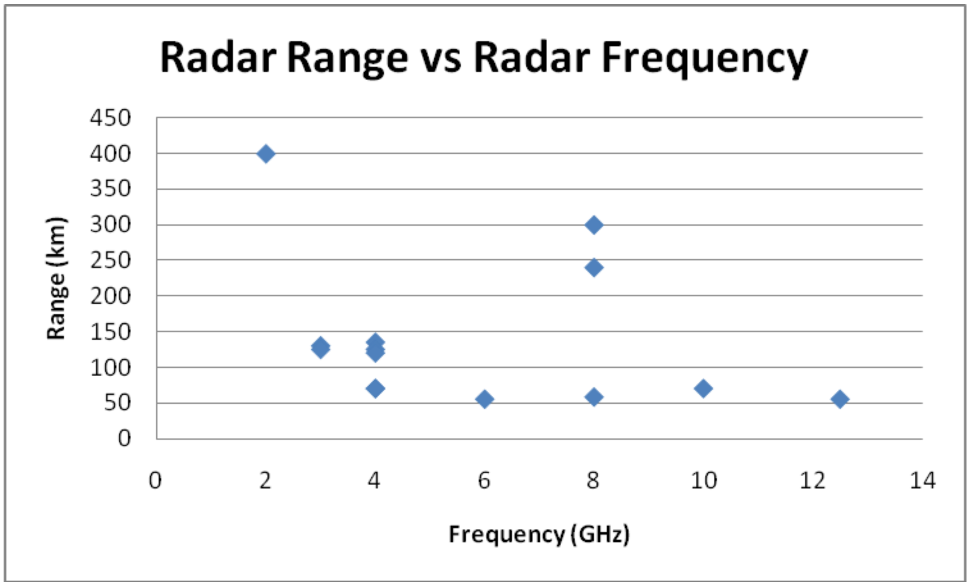

Figure 18. Analysis of Radar Range versus Radar Frequency

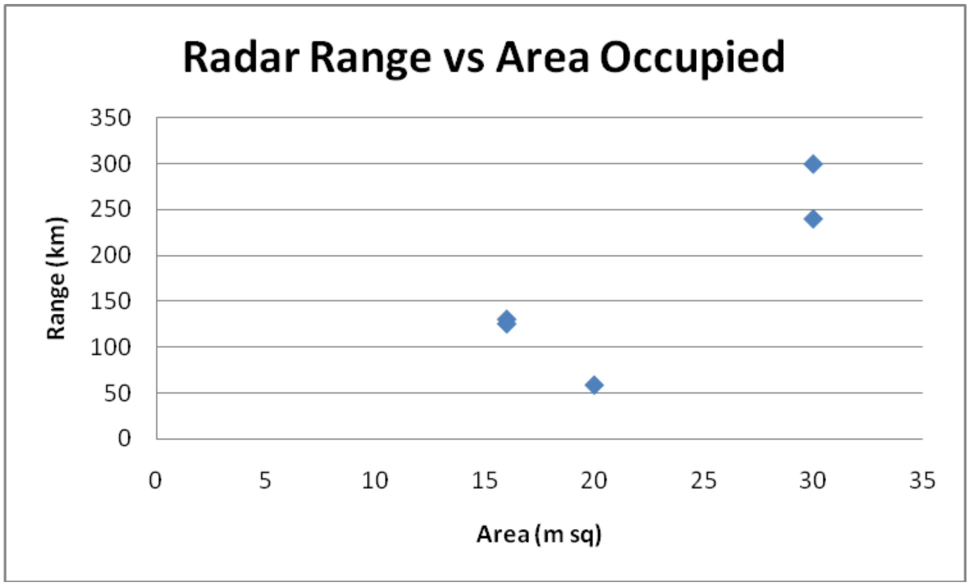

Figure 19. Analysis of Radar Range versus Radar Area Occupied

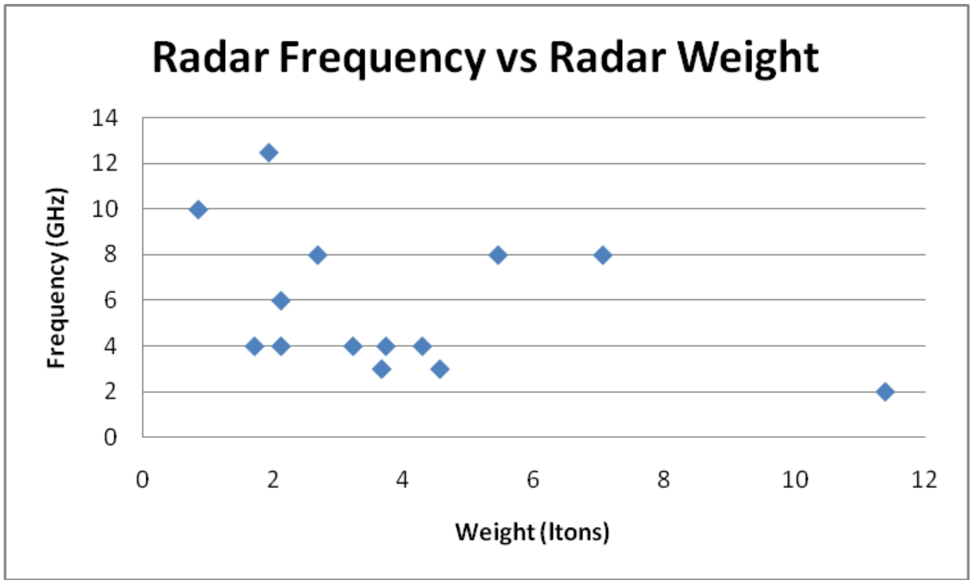

Figure 20. Analysis of Radar Frequency versus Radar Weight

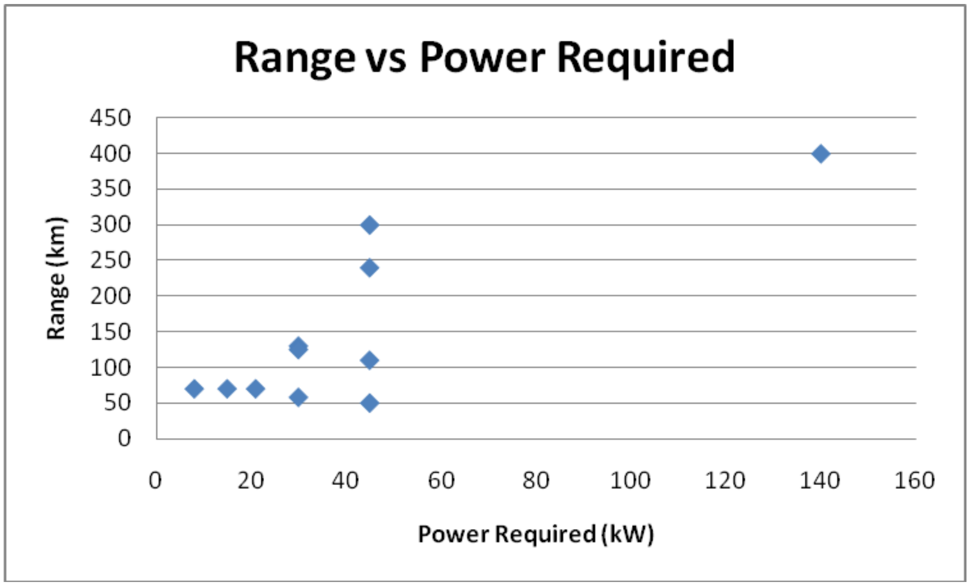

Figure 21. Analysis of Radar Range versus Radar Power

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APPENDIX C: BREAKDOWN OF THE WORKSHEETS OF THE EXCEL-BASED SHIP SYNTHESIS MODEL

The Excel-based ship synthesis model used in this thesis is a collection of 18 worksheets that together perform mathematical calculations based on the principles of naval architecture. Based on the user's inputs under the "Input" worksheet, the other worksheets accept the input variables and perform calculations, and finally the results of the synthesized ship are displayed in the "Evaluation" worksheet for users to view. The following figures show a screenshot of each of the worksheets and a brief description is provided.

In Figure 22, the first worksheet, "Saunders Design Lanes" shows plots of several design lanes for important naval architecture parameters that are used throughout the model. These plots show visually the standard for U.S. naval surface vessels and are a quick reference for ship designers for feasibility of selection.

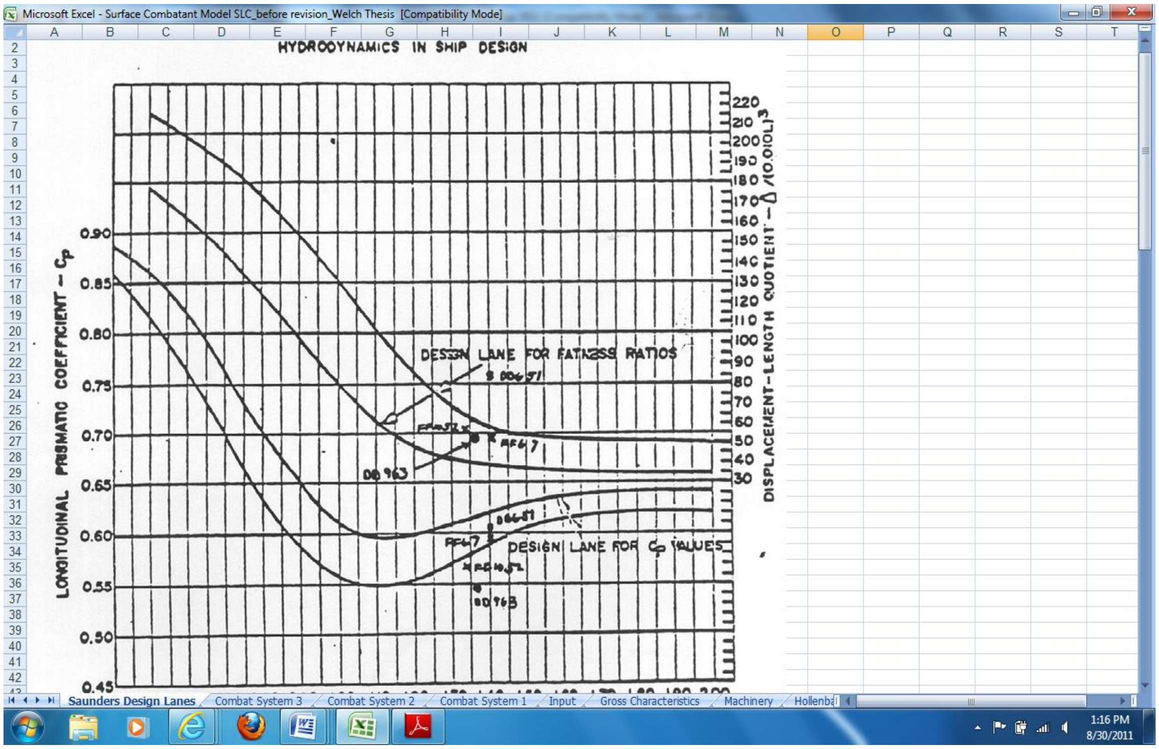
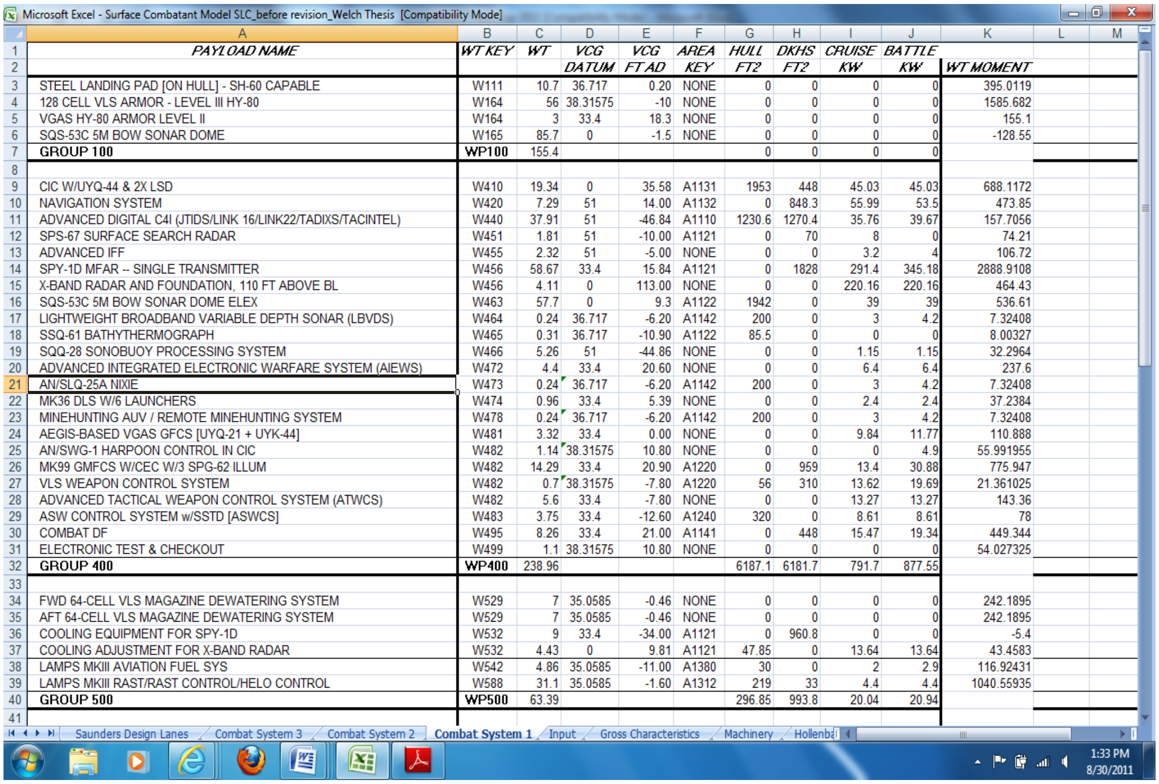


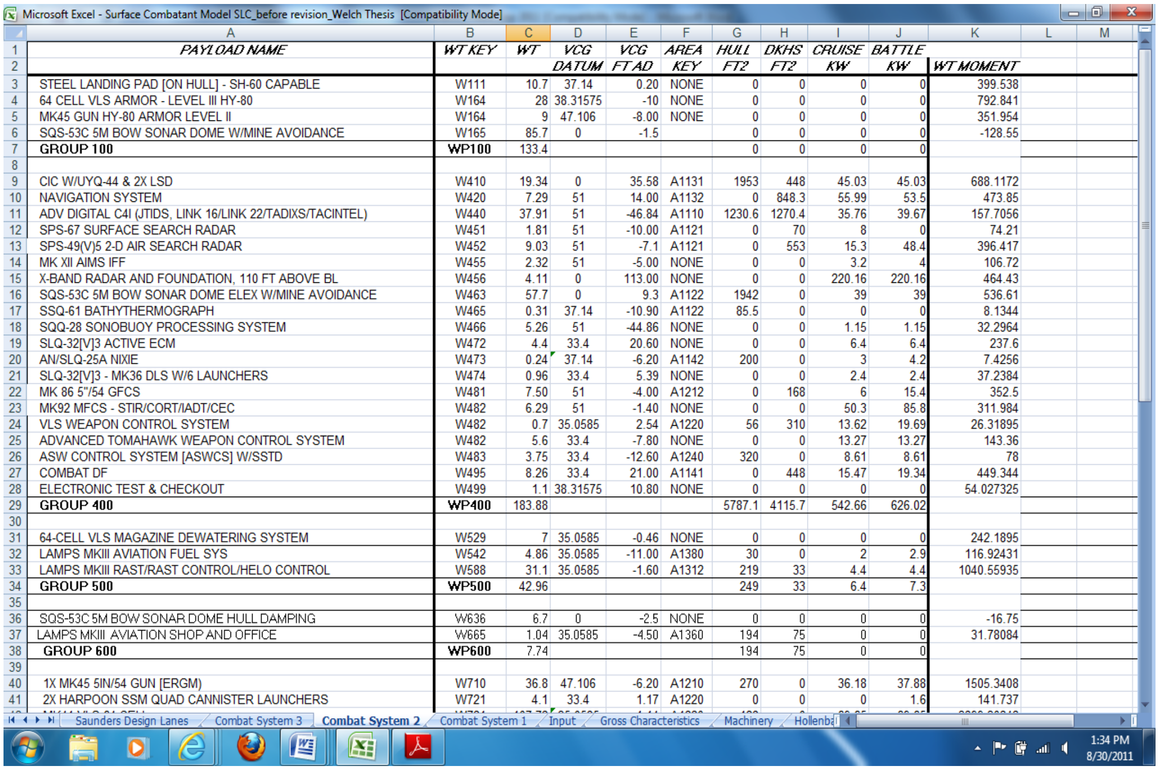
Figure 22. Screenshot of "Saunders Design Lane" Worksheet

The combat system information of the ship being synthesized is found in either one of three worksheets, “Combat System 1,” “Combat System 2,” or “Combat System 3.” Figures 23, 24, 25 show how all three of them are arranged with the name of the combat system on the very left column and the weight, vertical center of gravity, area, power, and weight moment listed in the same row to the right of each one. The three different options of combat system worksheets represent the use of a large, medium, or small combat system suite for the ship being synthesized. For example, the number of vertical launching system (VLS) cells goes from 32, 64, and 128 for combat system 3, 2, and 1 respectively. The differences in combat system suite makeup can be seen by examining Figures 23, 24, and 25. combat system worksheets all calculate the total sum of combat system payload weight as well as the vertical center of gravity for payload and variable payload.


Microsoft Excel - Surface Combatant Model SLC_before revision_Welch Thesis [Compatibility Mode]

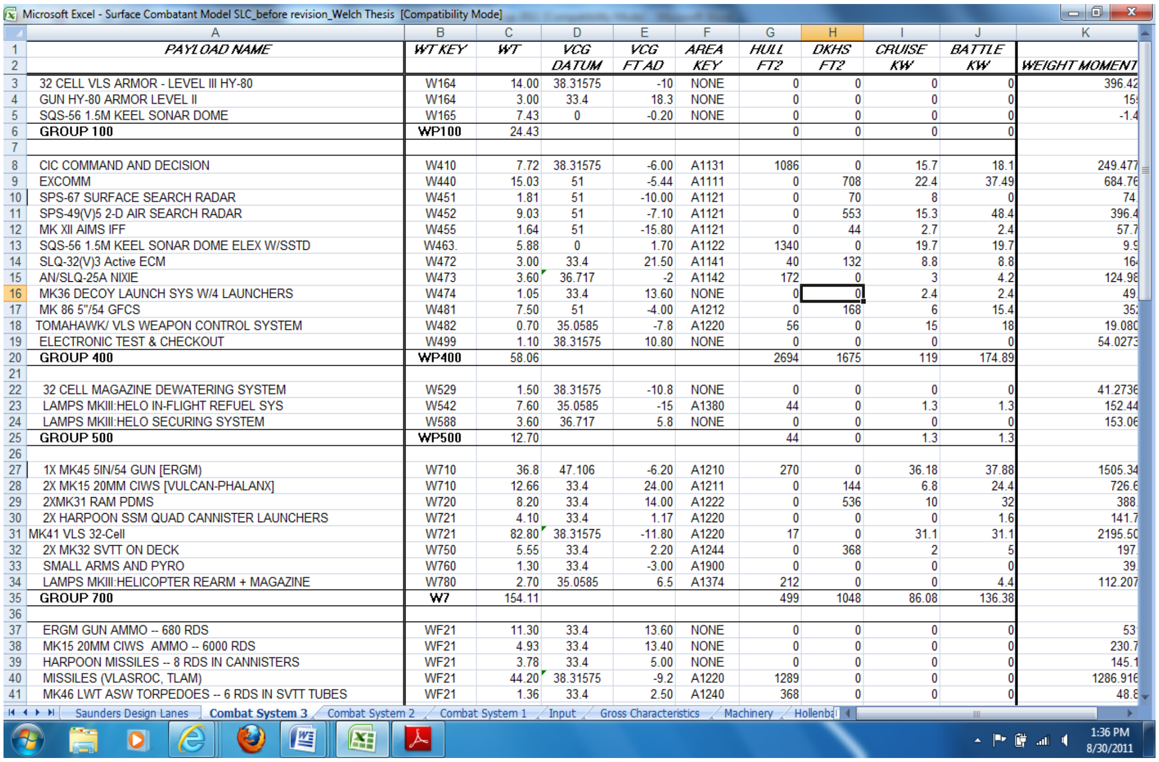
	A	B	C	D	E	F	G	H	I	J	K	L	M
1	*PAYLOAD NAME*	*WT KEY*	*WT*	*VCG*	*VCG*	*AREA*	*HULL*	*DKHS*	*CRUISE*	*BATTLE*			
2				*DATUM*	*FT AD*	*KEY*	*FT2*	*FT2*	*KW*	*KW*	*WT MOMENT*		
3	STEEL LANDING PAD [ON HULL] - SH-60 CAPABLE	W111	10.7	36.717	0.20	NONE	0	0	0	0	395.0119		
4	128 CELL VLS ARMOR - LEVEL III HY-80	W164	56	38.31575	-10	NONE	0	0	0	0	1585.682		
5	VGAS HY-80 ARMOR LEVEL II	W164	3	33.4	18.3	NONE	0	0	0	0	155.1		
6	SQS-53C 5M BOW SONAR DOME	W165	85.7	0	-1.5	NONE	0	0	0	0	-128.55		
7	**GROUP 100**	**WP100**	155.4				0	0	0	0			
8													
9	CIC W/UYQ-44 & 2X LSD	W410	19.34	0	35.58	A1131	1953	448	45.03	45.03	688.1172		
10	NAVIGATION SYSTEM	W420	7.29	51	14.00	A1132	0	848.3	55.99	53.5	473.85		
11	ADVANCED DIGITAL C4I (JTIDS/LINK 16/LINK22/TADIXS/TACINTEL)	W440	37.91	51	-46.84	A1110	1230.6	1270.4	35.76	39.67	157.7056		
12	SPS-67 SURFACE SEARCH RADAR	W451	1.81	51	-10.00	A1121	0	70	8	0	74.21		
13	ADVANCED IFF	W455	2.32	51	-5.00	NONE	0	0	3.2	4	106.72		
14	SPY-1D MFAR -- SINGLE TRANSMITTER	W456	58.67	33.4	15.84	A1121	0	1828	291.4	345.18	2888.9108		
15	X-BAND RADAR AND FOUNDATION, 110 FT ABOVE BL	W456	4.11	0	113.00	NONE	0	0	220.16	220.16	464.43		
16	SQS-53C 5M BOW SONAR DOME ELEX	W463	57.7	0	9.3	A1122	1942	0	39	39	536.61		
17	LIGHTWEIGHT BROADBAND VARIABLE DEPTH SONAR (LBVDS)	W464	0.24	36.717	-6.20	A1142	200	0	3	4.2	7.32408		
18	SSQ-61 BATHYTHERMOGRAPH	W465	0.31	36.717	-10.90	A1122	85.5	0	0	0	8.00327		
19	SQQ-28 SONOBUOY PROCESSING SYSTEM	W466	5.26	51	-44.86	NONE	0	0	1.15	1.15	32.2964		
20	ADVANCED INTEGRATED ELECTRONIC WARFARE SYSTEM (AIEWS)	W472	4.4	33.4	20.60	NONE	0	0	6.4	6.4	237.6		
21	AN/SLQ-25A NIXIE	W473	0.24	36.717	-6.20	A1142	200	0	3	4.2	7.32408		
22	MK36 DLS W/6 LAUNCHERS	W474	0.96	33.4	5.39	NONE	0	0	2.4	2.4	37.2384		
23	MINEHUNTING AUV / REMOTE MINEHUNTING SYSTEM	W478	0.24	36.717	-6.20	A1142	200	0	3	4.2	7.32408		
24	AEGIS-BASED VGAS GFCS [UYQ-21 + UYK-44]	W481	3.32	33.4	0.00	NONE	0	0	9.84	11.77	110.888		
25	AN/SWG-1 HARPOON CONTROL IN CIC	W482	1.14	38.31575	10.80	NONE	0	0	0	4.9	55.991955		
26	MK99 GMFCS W/CEC W/3 SPG-62 ILLUM	W482	14.29	33.4	20.90	A1220	0	959	13.4	30.88	775.947		
27	VLS WEAPON CONTROL SYSTEM	W482	0.7	38.31575	-7.80	A1220	56	310	13.62	19.69	21.361025		
28	ADVANCED TACTICAL WEAPON CONTROL SYSTEM (ATWCS)	W482	5.6	33.4	-7.80	NONE	0	0	13.27	13.27	143.36		
29	ASW CONTROL SYSTEM w/SSTD [ASWCS]	W483	3.75	33.4	-12.60	A1240	320	0	8.61	8.61	78		
30	COMBAT DF	W495	8.26	33.4	21.00	A1141	0	448	15.47	19.34	449.344		
31	ELECTRONIC TEST & CHECKOUT	W499	1.1	38.31575	10.80	NONE	0	0	0	0	54.027325		
32	**GROUP 400**	**WP400**	238.96				6187.1	6181.7	791.7	877.55			
33													
34	FWD 64-CELL VLS MAGAZINE DEWATERING SYSTEM	W529	7	35.0585	-0.46	NONE	0	0	0	0	242.1895		
35	AFT 64-CELL VLS MAGAZINE DEWATERING SYSTEM	W529	7	35.0585	-0.46	NONE	0	0	0	0	242.1895		
36	COOLING EQUIPMENT FOR SPY-1D	W532	9	33.4	-34.00	A1121	0	960.8	0	0	-5.4		
37	COOLING ADJUSTMENT FOR X-BAND RADAR	W532	4.43	0	9.81	A1121	47.85	0	13.64	13.64	43.4583		
38	LAMPS MKIII AVIATION FUEL SYS	W542	4.86	35.0585	-11.00	A1380	30	0	2	2.9	116.92431		
39	LAMPS MKIII RAST/RAST CONTROL/HELO CONTROL	W588	31.1	35.0585	-1.60	A1312	219	33	4.4	4.4	1040.55935		
40	**GROUP 500**	**WP500**	63.39				296.85	993.8	20.04	20.94			
41													

Figure 23. Screenshot of Large Combat System Suite of “Combat System 1” Worksheet



	A	B	C	D	E	F	G	H	I	J	K
1	*PAYLOAD NAME*	*WT KEY*	*WT*	*VCG*	*VCG*	*AREA*	*HULL*	*DKHS*	*CRUISE*	*BATTLE*	
2				*DATUM*	*FT AD*	*KEY*	*FT2*	*FT2*	*KW*	*KW*	*WT MOMENT*
3	STEEL LANDING PAD [ON HULL] - SH-60 CAPABLE	W111	10.7	37.14	0.20	NONE	0	0	0	0	399.538
4	64 CELL VLS ARMOR - LEVEL III HY-80	W164	28	38.31575	-10	NONE	0	0	0	0	792.841
5	MK45 GUN HY-80 ARMOR LEVEL II	W164	9	47.106	-8.00	NONE	0	0	0	0	351.954
6	SQS-53C 5M BOW SONAR DOME W/MINE AVOIDANCE	W165	85.7	0	-1.5		0	0	0	0	-128.55
7	**GROUP 100**	**WP100**	133.4				0	0	0	0	
8											
9	CIC W/UYQ-44 & 2X LSD	W410	19.34	0	35.58	A1131	1953	448	45.03	45.03	688.1172
10	NAVIGATION SYSTEM	W420	7.29	51	14.00	A1132	0	848.3	55.99	53.5	473.85
11	ADV DIGITAL C4I (JTIDS, LINK 16/LINK 22/TADIXS/TACINTEL)	W440	37.91	51	-46.84	A1110	1230.6	1270.4	35.76	39.67	157.7056
12	SPS-67 SURFACE SEARCH RADAR	W451	1.81	51	-10.00	A1121	0	70	8	0	74.21
13	SPS-49(V)5 2-D AIR SEARCH RADAR	W452	9.03	51	-7.1	A1121	0	553	15.3	48.4	396.417
14	MK XII AIMS IFF	W455	2.32	51	-5.00	NONE	0	0	3.2	4	106.72
15	X-BAND RADAR AND FOUNDATION, 110 FT ABOVE BL	W456	4.11	0	113.00	NONE	0	0	220.16	220.16	464.43
16	SQS-53C 5M BOW SONAR DOME ELEX W/MINE AVOIDANCE	W463	57.7	0	9.3	A1122	1942	0	39	39	536.61
17	SSQ-61 BATHYTHERMOGRAPH	W465	0.31	37.14	-10.90	A1122	85.5	0	0	0	8.1344
18	SQQ-28 SONOBUOY PROCESSING SYSTEM	W466	5.26	51	-44.86	NONE	0	0	1.15	1.15	32.2964
19	SLQ-32[V]3 ACTIVE ECM	W472	4.4	33.4	20.60	NONE	0	0	6.4	6.4	237.6
20	AN/SLQ-25A NIXIE	W473	0.24	37.14	-6.20	A1142	200	0	3	4.2	7.4256
21	SLQ-32[V]3 - MK36 DLS W/6 LAUNCHERS	W474	0.96	33.4	5.39	NONE	0	0	2.4	2.4	37.2384
22	MK 86 5"/54 GFCS	W481	7.50	51	-4.00	A1212	0	168	6	15.4	352.5
23	MK92 MFCS - STIR/CORT/IADT/CEC	W482	6.29	51	-1.40	NONE	0	0	50.3	85.8	311.984
24	VLS WEAPON CONTROL SYSTEM	W482	0.7	35.0585	2.54	A1220	56	310	13.62	19.69	26.31895
25	ADVANCED TOMAHAWK WEAPON CONTROL SYSTEM	W482	5.6	33.4	-7.80	NONE	0	0	13.27	13.27	143.36
26	ASW CONTROL SYSTEM [ASWCS] W/SSTD	W483	3.75	33.4	-12.60	A1240	320	0	8.61	8.61	78
27	COMBAT DF	W495	8.26	33.4	21.00	A1141	0	448	15.47	19.34	449.344
28	ELECTRONIC TEST & CHECKOUT	W499	1.1	38.31575	10.80	NONE	0	0	0	0	54.027325
29	**GROUP 400**	**WP400**	183.88				5787.1	4115.7	542.66	626.02	
30											
31	64-CELL VLS MAGAZINE DEWATERING SYSTEM	W529	7	35.0585	-0.46	NONE	0	0	0	0	242.1895
32	LAMPS MKIII AVIATION FUEL SYS	W542	4.86	35.0585	-11.00	A1380	30	0	2	2.9	116.92431
33	LAMPS MKIII RAST/RAST CONTROL/HELO CONTROL	W588	31.1	35.0585	-1.60	A1312	219	33	4.4	4.4	1040.55935
34	**GROUP 500**	**WP500**	42.96				249	33	6.4	7.3	
35											
36	SQS-53C 5M BOW SONAR DOME HULL DAMPING	W636	6.7	0	-2.5	NONE	0	0	0	0	-16.75
37	LAMPS MKIII AVIATION SHOP AND OFFICE	W665	1.04	35.0585	-4.50	A1360	194	75	0	0	31.78084
38	**GROUP 600**	**WP600**	7.74				194	75	0	0	
39											
40	1X MK45 5IN/54 GUN [ERGM)	W710	36.8	47.106	-6.20	A1210	270	0	36.18	37.88	1505.3408
41	2X HARPOON SSM QUAD CANNISTER LAUNCHERS	W721	4.1	33.4	1.17	A1220	0	0	0	1.6	141.737

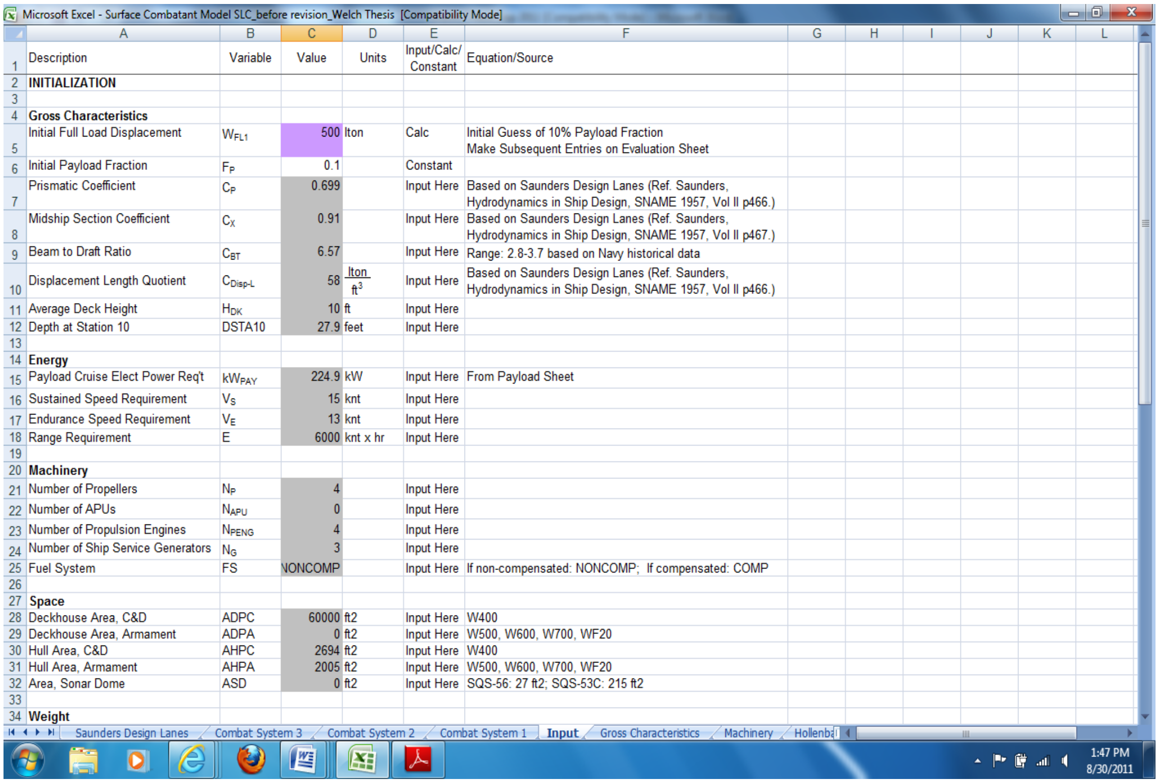
Figure 24. Screenshot of Medium Combat System Suite of “Combat System 2” Worksheet



	A	B	C	D	E	F	G	H	I	J	K
1	*PAYLOAD NAME*	*WT KEY*	*WT*	*VCG*	*VCG*	*AREA*	*HULL*	*DKHS*	*CRUISE*	*BATTLE*	
2				*DATUM*	*FT AD*	*KEY*	*FT2*	*FT2*	*KW*	*KW*	*WEIGHT MOMENT*
3	32 CELL VLS ARMOR - LEVEL III HY-80	W164	14.00	38.31575	-10	NONE	0	0	0	0	396.42
4	GUN HY-80 ARMOR LEVEL II	W164	3.00	33.4	18.3	NONE	0	0	0	0	15
5	SQS-56 1.5M KEEL SONAR DOME	W165	7.43	0	-0.20	NONE	0	0	0	0	-1.4
6	**GROUP 100**	**WP100**	24.43				0	0	0	0	
7											
8	CIC COMMAND AND DECISION	W410	7.72	38.31575	-6.00	A1131	1086	0	15.7	18.1	249.477
9	EXCOMM	W440	15.03	51	-5.44	A1111	0	708	22.4	37.49	684.76
10	SPS-67 SURFACE SEARCH RADAR	W451	1.81	51	-10.00	A1121	0	70	8	0	74.
11	SPS-49(V)5 2-D AIR SEARCH RADAR	W452	9.03	51	-7.10	A1121	0	553	15.3	48.4	396.4
12	MK XII AIMS IFF	W455	1.64	51	-15.80	A1121	0	44	2.7	2.4	57.7
13	SQS-56 1.5M KEEL SONAR DOME ELEX W/SSTD	W463.	5.88	0	1.70	A1122	1340	0	19.7	19.7	9.9
14	SLQ-32(V)3 Active ECM	W472	3.00	33.4	21.50	A1141	40	132	8.8	8.8	16
15	AN/SLQ-25A NIXIE	W473	3.60	36.717	-2	A1142	172	0	3	4.2	124.98
16	MK36 DECOY LAUNCH SYS W/4 LAUNCHERS	W474	1.05	33.4	13.60	NONE	0	0	2.4	2.4	49.
17	MK 86 5"/54 GFCS	W481	7.50	51	-4.00	A1212	0	168	6	15.4	35
18	TOMAHAWK/ VLS WEAPON CONTROL SYSTEM	W482	0.70	35.0585	-7.8	A1220	56	0	15	18	19.080
19	ELECTRONIC TEST & CHECKOUT	W499	1.10	38.31575	10.80	NONE	0	0	0	0	54.0273
20	**GROUP 400**	**WP400**	58.06				2694	1675	119	174.89	
21											
22	32 CELL MAGAZINE DEWATERING SYSTEM	W529	1.50	38.31575	-10.8	NONE	0	0	0	0	41.2736
23	LAMPS MKIII:HELO IN-FLIGHT REFUEL SYS	W542	7.60	35.0585	-15	A1380	44	0	1.3	1.3	152.44
24	LAMPS MKIII:HELO SECURING SYSTEM	W588	3.60	36.717	5.8	NONE	0	0	0	0	153.06
25	**GROUP 500**	**WP500**	12.70				44	0	1.3	1.3	
26											
27	1X MK45 5IN/54 GUN [ERGM)	W710	36.8	47.106	-6.20	A1210	270	0	36.18	37.88	1505.34
28	2X MK15 20MM CIWS [VULCAN-PHALANX]	W710	12.66	33.4	24.00	A1211	0	144	6.8	24.4	726.6
29	2XMK31 RAM PDMS	W720	8.20	33.4	14.00	A1222	0	536	10	32	388.
30	2X HARPOON SSM QUAD CANNISTER LAUNCHERS	W721	4.10	33.4	1.17	A1220	0	0	0	1.6	141.7
31	MK41 VLS 32-Cell	W721	82.80	38.31575	-11.80	A1220	17	0	31.1	31.1	2195.50
32	2X MK32 SVTT ON DECK	W750	5.55	33.4	2.20	A1244	0	368	2	5	197.
33	SMALL ARMS AND PYRO	W760	1.30	33.4	-3.00	A1900	0	0	0	0	39.
34	LAMPS MKIII:HELICOPTER REARM + MAGAZINE	W780	2.70	35.0585	6.5	A1374	212	0	0	4.4	112.207
35	**GROUP 700**	**W7**	154.11				499	1048	86.08	136.38	
36											
37	ERGM GUN AMMO -- 680 RDS	WF21	11.30	33.4	13.60	NONE	0	0	0	0	53
38	MK15 20MM CIWS AMMO -- 6000 RDS	WF21	4.93	33.4	13.40	NONE	0	0	0	0	230.7
39	HARPOON MISSILES -- 8 RDS IN CANNISTERS	WF21	3.78	33.4	5.00	NONE	0	0	0	0	145.1
40	MISSILES (VLASROC, TLAM)	WF21	44.20	38.31575	-9.2	A1220	1289	0	0	0	1286.916
41	MK46 LWT ASW TORPEDOES -- 6 RDS IN SVTT TUBES	WF21	1.36	33.4	2.50	A1240	368	0	0	0	48.8

Figure 25. Screenshot of Small Combat System Suite of “Combat System 3” Worksheet

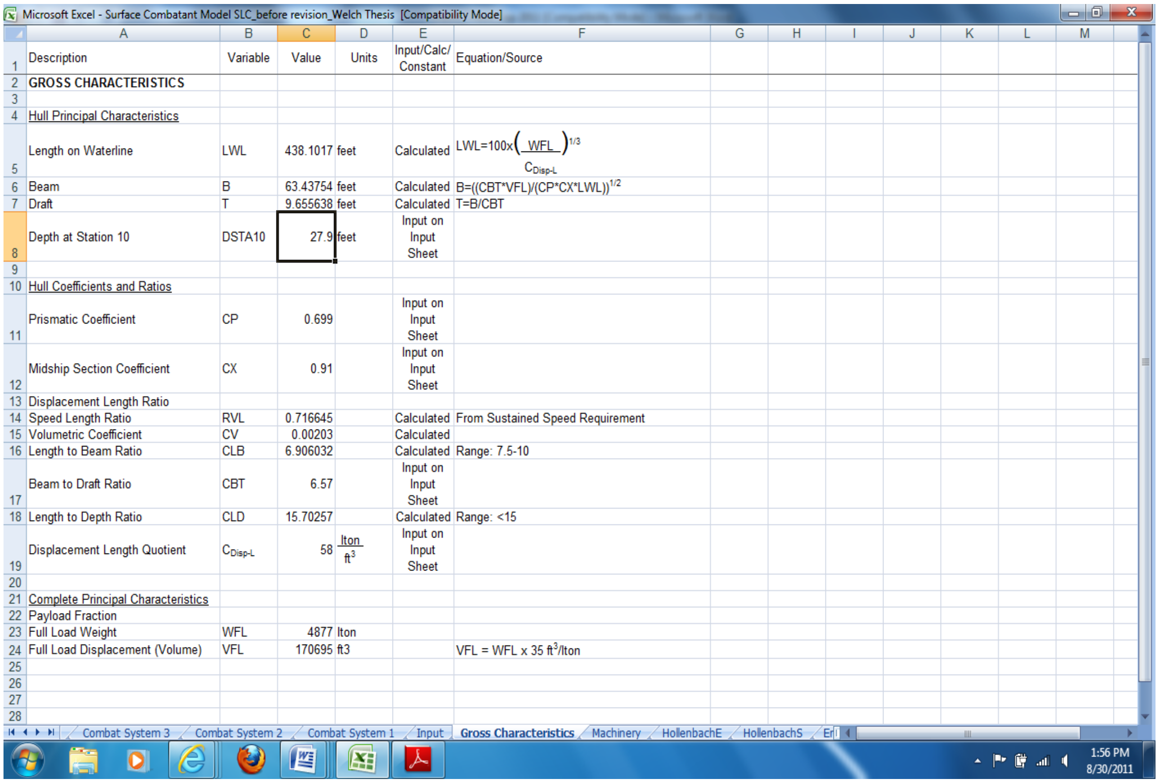
Figure 26 shows the “Input” worksheet where the user enters in information that it desires the ship to be synthesized to have. It includes naval architecture gross characteristics, such as prismatic coefficient and beam to draft ratio, energy requirements, propulsion requirements, area and weight requirements, manning requirements, and any cost constraints. These inputs are then used in other worksheets as variables in their equations to calculate parameters for the ship being synthesized.



	A	B	C	D	E	F
1	Description	Variable	Value	Units	Input/Calc/ Constant	Equation/Source
2	**INITIALIZATION**					
3						
4	**Gross Characteristics**					
5	Initial Full Load Displacement	W_{FL1}	500	lton	Calc	Initial Guess of 10% Payload Fraction Make Subsequent Entries on Evaluation Sheet
6	Initial Payload Fraction	F_P	0.1		Constant	
7	Prismatic Coefficient	C_P	0.699		Input Here	Based on Saunders Design Lanes (Ref. Saunders, Hydrodynamics in Ship Design, SNAME 1957, Vol II p466.)
8	Midship Section Coefficient	C_X	0.91		Input Here	Based on Saunders Design Lanes (Ref. Saunders, Hydrodynamics in Ship Design, SNAME 1957, Vol II p467.)
9	Beam to Draft Ratio	C_{BT}	6.57		Input Here	Range: 2.8-3.7 based on Navy historical data
10	Displacement Length Quotient	$C_{Disp\text{-}L}$	58	$\frac{\text{lton}}{\text{ft}^3}$	Input Here	Based on Saunders Design Lanes (Ref. Saunders, Hydrodynamics in Ship Design, SNAME 1957, Vol II p466.)
11	Average Deck Height	H_{DK}	10	ft	Input Here	
12	Depth at Station 10	DSTA10	27.9	feet	Input Here	
13						
14	**Energy**					
15	Payload Cruise Elect Power Req't	kW_{PAY}	224.9	kW	Input Here	From Payload Sheet
16	Sustained Speed Requirement	V_S	15	knt	Input Here	
17	Endurance Speed Requirement	V_E	13	knt	Input Here	
18	Range Requirement	E	6000	knt x hr	Input Here	
19						
20	**Machinery**					
21	Number of Propellers	N_P	4		Input Here	
22	Number of APUs	N_{APU}	0		Input Here	
23	Number of Propulsion Engines	N_{PENG}	4		Input Here	
24	Number of Ship Service Generators	N_G	3		Input Here	
25	Fuel System	FS	NONCOMP		Input Here	If non-compensated: NONCOMP; If compensated: COMP
26						
27	**Space**					
28	Deckhouse Area, C&D	ADPC	60000	ft2	Input Here	W400
29	Deckhouse Area, Armament	ADPA	0	ft2	Input Here	W500, W600, W700, WF20
30	Hull Area, C&D	AHPC	2694	ft2	Input Here	W400
31	Hull Area, Armament	AHPA	2005	ft2	Input Here	W500, W600, W700, WF20
32	Area, Sonar Dome	ASD	0	ft2	Input Here	SQS-56: 27 ft2; SQS-53C: 215 ft2
33						
34	**Weight**					

Figure 26. Screenshot of "Input" Worksheet

Figure 27 shows the "Gross Characteristics" worksheet. It conducts mathematical calculations on the variables that were entered in the "Input" worksheet in order to find hull principal characteristics, such as the beam and the draft measurements, hull coefficients and ratios, such as the volumetric coefficient, and overall principal characteristics, such as full load displacement.

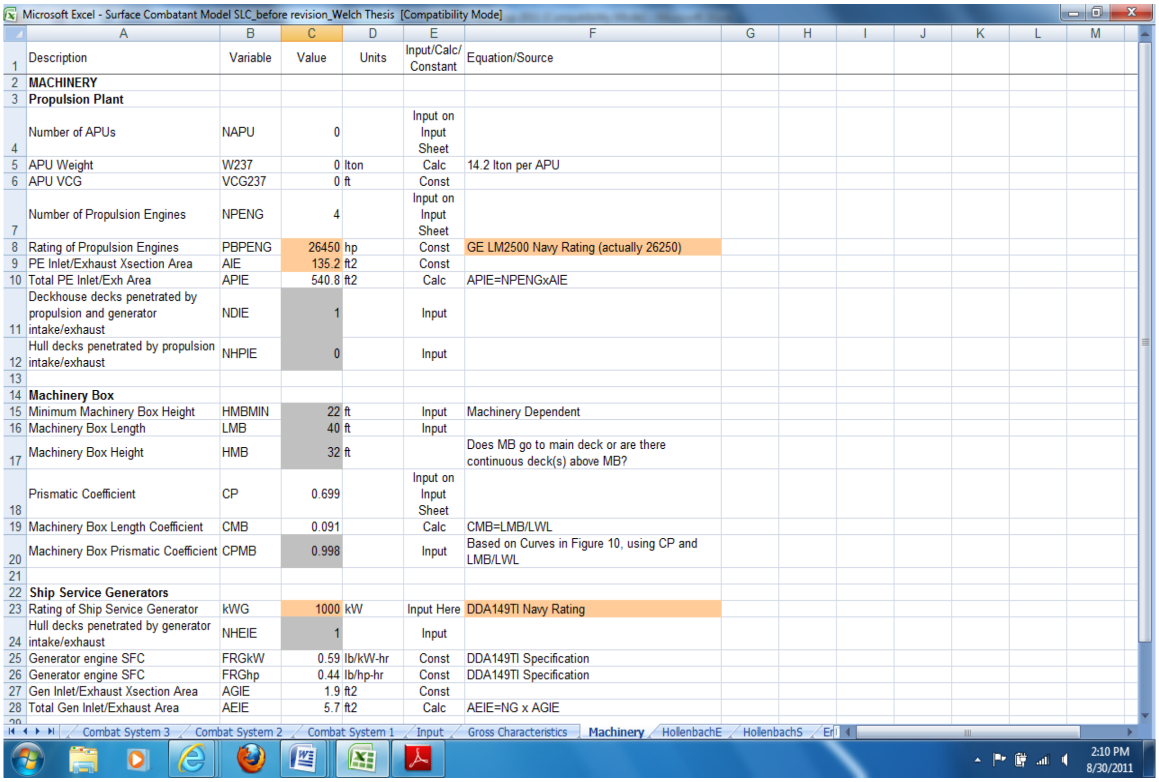


Microsoft Excel - Surface Combatant Model SLC_before revision_Welch Thesis [Compatibility Mode]

	A	B	C	D	E	F
1	Description	Variable	Value	Units	Input/Calc/ Constant	Equation/Source
2	**GROSS CHARACTERISTICS**					
3						
4	Hull Principal Characteristics					
5	Length on Waterline	LWL	438.1017	feet	Calculated	$LWL=100x\left(\frac{WFL}{C_{Disp-L}}\right)^{1/3}$
6	Beam	B	63.43754	feet	Calculated	$B=((CBT*VFL)/(CP*CX*LWL))^{1/2}$
7	Draft	T	9.655638	feet	Calculated	T=B/CBT
8	Depth at Station 10	DSTA10	27.9	feet	Input on Input Sheet	
9						
10	Hull Coefficients and Ratios					
11	Prismatic Coefficient	CP	0.699		Input on Input Sheet	
12	Midship Section Coefficient	CX	0.91		Input on Input Sheet	
13	Displacement Length Ratio					
14	Speed Length Ratio	RVL	0.716645		Calculated	From Sustained Speed Requirement
15	Volumetric Coefficient	CV	0.00203		Calculated	
16	Length to Beam Ratio	CLB	6.906032		Calculated	Range: 7.5-10
17	Beam to Draft Ratio	CBT	6.57		Input on Input Sheet	
18	Length to Depth Ratio	CLD	15.70257		Calculated	Range: <15
19	Displacement Length Quotient	C_{Disp-L}	58	$\frac{lton}{ft^3}$	Input on Input Sheet	
20						
21	Complete Principal Characteristics					
22	Payload Fraction					
23	Full Load Weight	WFL	4877	lton		
24	Full Load Displacement (Volume)	VFL	170695	ft3		VFL = WFL x 35 ft^3/lton
25						
26						
27						
28						

Figure 27. Screenshot of "Gross Characteristics" Worksheet

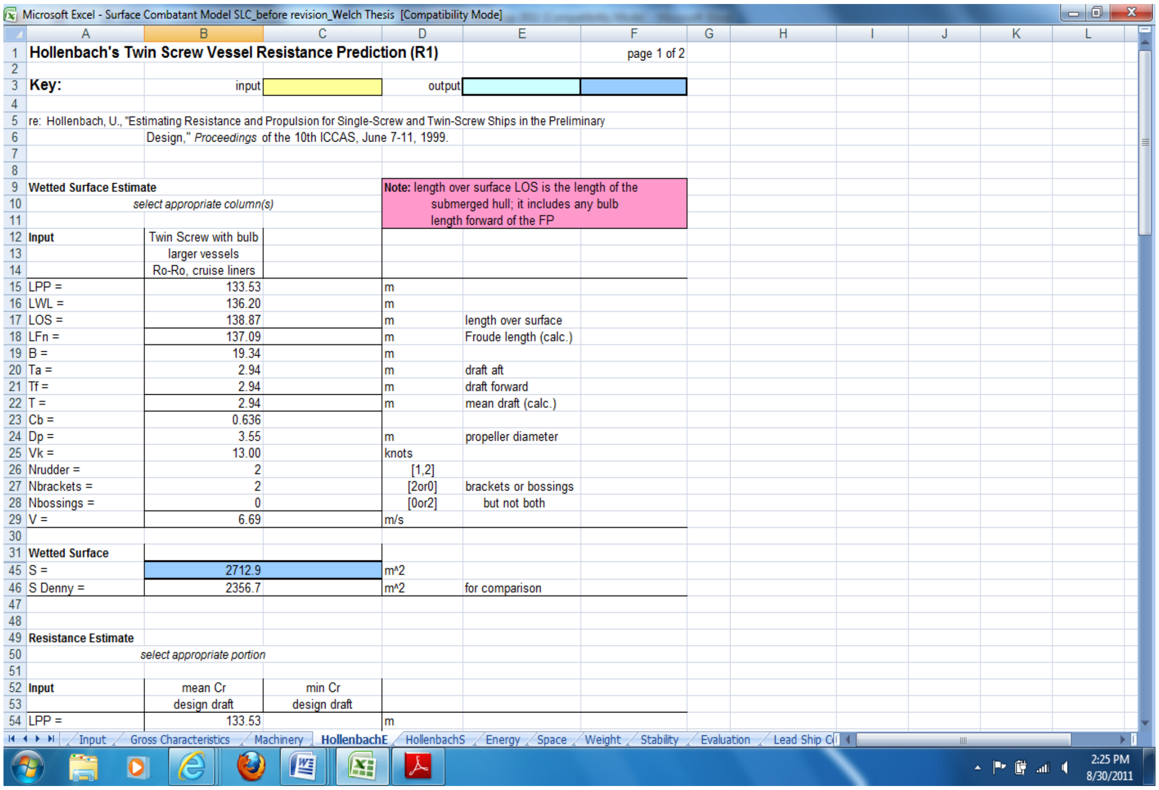
Figure 28 shows the "Machinery" worksheet. It allows the user to enter specific information about the propulsion plant, machinery box, and ship service generators. It also lists other propulsion-related constants used in calculations.



	A	B	C	D	E	F
1	Description	Variable	Value	Units	Input/Calc/ Constant	Equation/Source
2	**MACHINERY**					
3	**Propulsion Plant**					
4	Number of APUs	NAPU	0		Input on Input Sheet	
5	APU Weight	W237	0	lton	Calc	14.2 lton per APU
6	APU VCG	VCG237	0	ft	Const	
7	Number of Propulsion Engines	NPENG	4		Input on Input Sheet	
8	Rating of Propulsion Engines	PBPENG	26450	hp	Const	GE LM2500 Navy Rating (actually 26250)
9	PE Inlet/Exhaust Xsection Area	AIE	135.2	ft2	Const	
10	Total PE Inlet/Exh Area	APIE	540.8	ft2	Calc	APIE=NPENGxAIE
11	Deckhouse decks penetrated by propulsion and generator intake/exhaust	NDIE	1		Input	
12	Hull decks penetrated by propulsion intake/exhaust	NHPIE	0		Input	
13						
14	**Machinery Box**					
15	Minimum Machinery Box Height	HMBMIN	22	ft	Input	Machinery Dependent
16	Machinery Box Length	LMB	40	ft	Input	
17	Machinery Box Height	HMB	32	ft		Does MB go to main deck or are there continuous deck(s) above MB?
18	Prismatic Coefficient	CP	0.699		Input on Input Sheet	
19	Machinery Box Length Coefficient	CMB	0.091		Calc	CMB=LMB/LWL
20	Machinery Box Prismatic Coefficient	CPMB	0.998		Input	Based on Curves in Figure 10, using CP and LMB/LWL
21						
22	**Ship Service Generators**					
23	Rating of Ship Service Generator	kWG	1000	kW	Input Here	DDA149TI Navy Rating
24	Hull decks penetrated by generator intake/exhaust	NHEIE	1		Input	
25	Generator engine SFC	FRGkW	0.59	lb/kW-hr	Const	DDA149TI Specification
26	Generator engine SFC	FRGhp	0.44	lb/hp-hr	Const	DDA149TI Specification
27	Gen Inlet/Exhaust Xsection Area	AGIE	1.9	ft2	Const	
28	Total Gen Inlet/Exhaust Area	AEIE	5.7	ft2	Calc	AEIE=NG x AGIE

Figure 28. Screenshot of the “Machinery” Worksheet

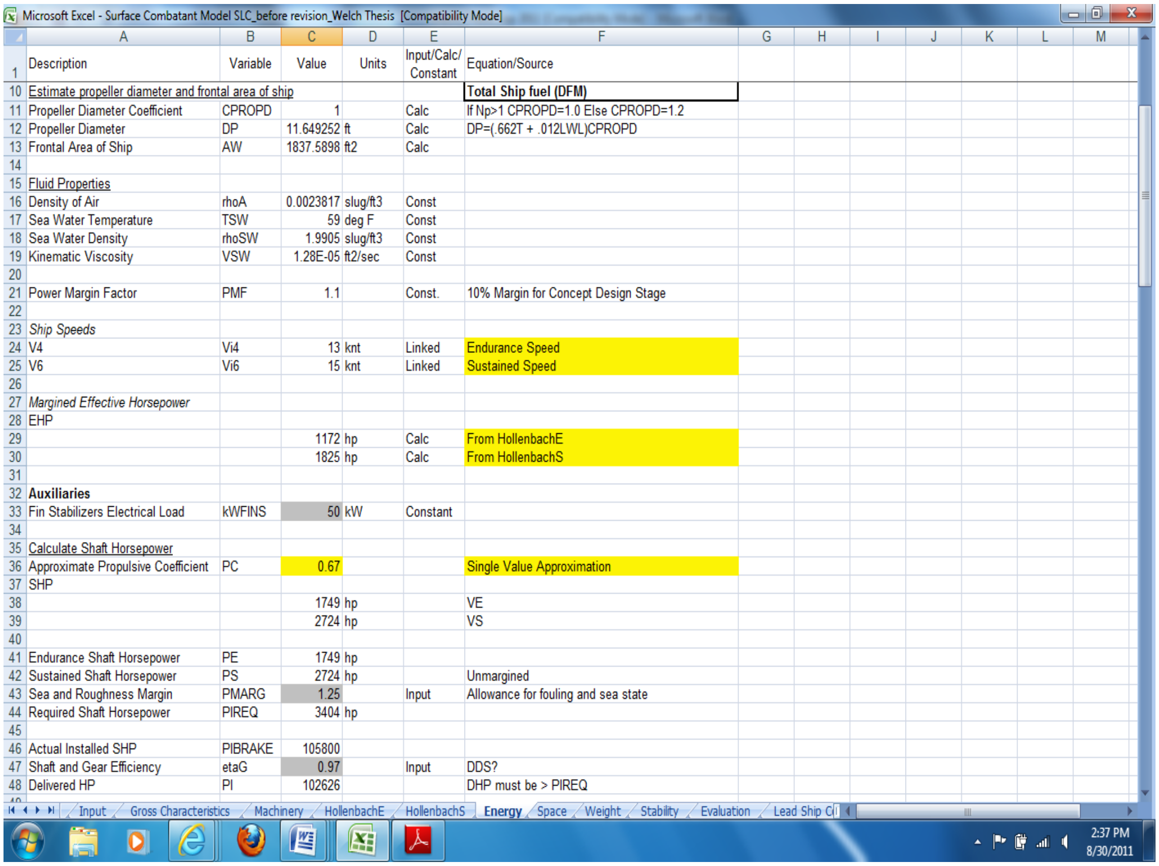
Figure 29 displays the “HollenbachE” worksheet where a number of mathematical calculations are performed in order to make resistance predictions. They are based on a method proposed by Hollenbach in estimating twin screw vessel resistance.



	A	B	C	D	E	F
1	**Hollenbach's Twin Screw Vessel Resistance Prediction (R1)**					page 1 of 2
2						
3	**Key:**	input	🟨	output	🟦	🟦
4						
5	re: Hollenbach, U., "Estimating Resistance and Propulsion for Single-Screw and Twin-Screw Ships in the Preliminary					
6		Design," *Proceedings* of the 10th ICCAS, June 7-11, 1999.				
7						
8						
9	**Wetted Surface Estimate**			**Note:** length over surface LOS is the length of the		
10		*select appropriate column(s)*		submerged hull; it includes any bulb		
11				length forward of the FP		
12	**Input**	Twin Screw with bulb				
13		larger vessels				
14		Ro-Ro, cruise liners				
15	LPP =	133.53		m		
16	LWL =	136.20		m		
17	LOS =	138.87		m	length over surface	
18	LFn =	137.09		m	Froude length (calc.)	
19	B =	19.34		m		
20	Ta =	2.94		m	draft aft	
21	Tf =	2.94		m	draft forward	
22	T =	2.94		m	mean draft (calc.)	
23	Cb =	0.636				
24	Dp =	3.55		m	propeller diameter	
25	Vk =	13.00		knots		
26	Nrudder =	2		[1,2]		
27	Nbrackets =	2		[2or0]	brackets or bossings	
28	Nbossings =	0		[0or2]	but not both	
29	V =	6.69		m/s		
30						
31	**Wetted Surface**					
45	S =	2712.9		m^2		
46	S Denny =	2356.7		m^2	for comparison	
47						
48						
49	**Resistance Estimate**					
50		*select appropriate portion*				
51						
52	**Input**	mean Cr	min Cr			
53		design draft	design draft			
54	LPP =	133.53		m		

Figure 29. Screenshot of “HollenbachE” Worksheet

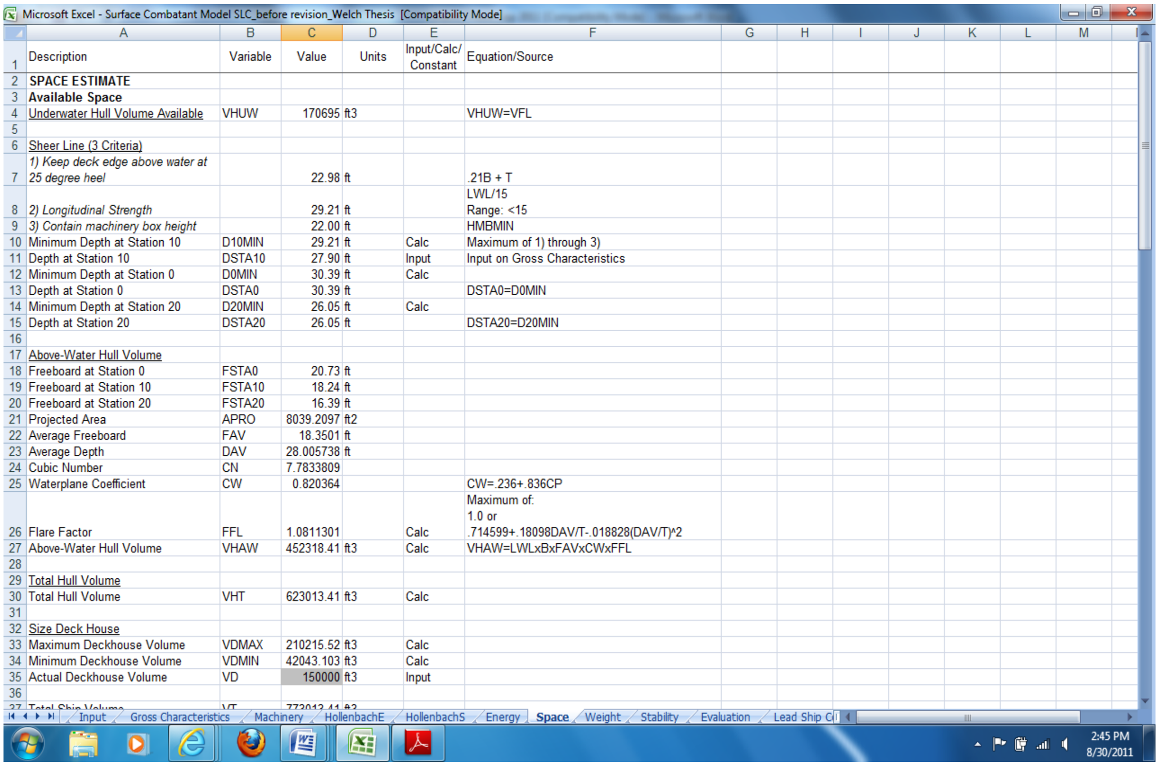
Figure 30 displays the “Energy” worksheet, which performs a number of calculations in order to determine such things as a propeller diameter estimate, effective horsepower, shaft horsepower, fuel requirements, electric load, electric fuel requirement and total ship fuel.



	A	B	C	D	E	F
1	Description	Variable	Value	Units	Input/Calc/ Constant	Equation/Source
10	Estimate propeller diameter and frontal area of ship					**Total Ship fuel (DFM)**
11	Propeller Diameter Coefficient	CPROPD	1		Calc	If Np>1 CPROPD=1.0 Else CPROPD=1.2
12	Propeller Diameter	DP	11.649252	ft	Calc	DP=(.662T + .012LWL)CPROPD
13	Frontal Area of Ship	AW	1837.5898	ft2	Calc	
14						
15	Fluid Properties					
16	Density of Air	rhoA	0.0023817	slug/ft3	Const	
17	Sea Water Temperature	TSW	59	deg F	Const	
18	Sea Water Density	rhoSW	1.9905	slug/ft3	Const	
19	Kinematic Viscosity	VSW	1.28E-05	ft2/sec	Const	
20						
21	Power Margin Factor	PMF	1.1		Const.	10% Margin for Concept Design Stage
22						
23	*Ship Speeds*					
24	V4	Vi4	13	knt	Linked	Endurance Speed
25	V6	Vi6	15	knt	Linked	Sustained Speed
26						
27	*Margined Effective Horsepower*					
28	EHP					
29			1172	hp	Calc	From HollenbachE
30			1825	hp	Calc	From HollenbachS
31						
32	**Auxiliaries**					
33	Fin Stabilizers Electrical Load	kWFINS	50	kW	Constant	
34						
35	Calculate Shaft Horsepower					
36	Approximate Propulsive Coefficient	PC	0.67			Single Value Approximation
37	SHP					
38			1749	hp		VE
39			2724	hp		VS
40						
41	Endurance Shaft Horsepower	PE	1749	hp		
42	Sustained Shaft Horsepower	PS	2724	hp		Unmargined
43	Sea and Roughness Margin	PMARG	1.25		Input	Allowance for fouling and sea state
44	Required Shaft Horsepower	PIREQ	3404	hp		
45						
46	Actual Installed SHP	PIBRAKE	105800			
47	Shaft and Gear Efficiency	etaG	0.97		Input	DDS?
48	Delivered HP	PI	102626			DHP must be > PIREQ

Figure 30. Screenshot of "Energy" Worksheet

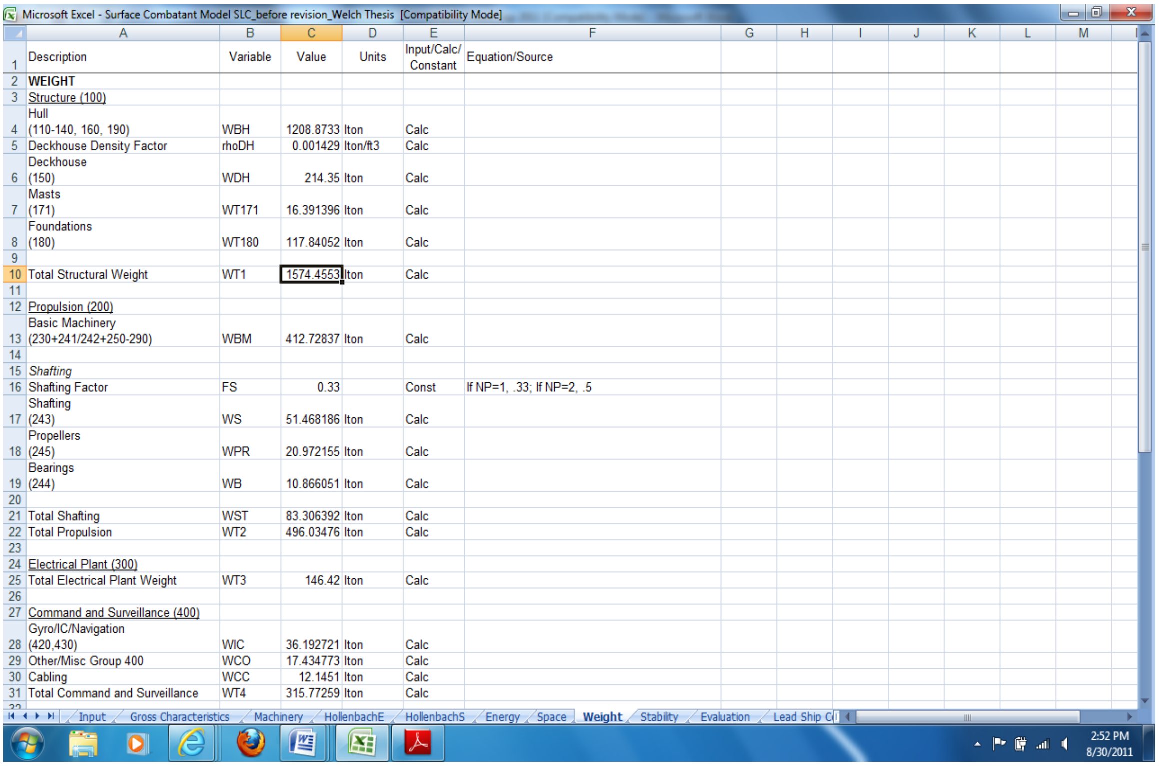
In Figure 31, the "Space" worksheet provides estimates based on user input of the underwater hull volume, above water hull volume, total hull volume, deck house size, machinery box size, tankage sizes, payload and living deck areas, hull habitability areas, hull stores area, and other important areas.



	Description	Variable	Value	Units	Input/Calc/ Constant	Equation/Source
2	**SPACE ESTIMATE**					
3	**Available Space**					
4	Underwater Hull Volume Available	VHUW	170695	ft3		VHUW=VFL
5						
6	Sheer Line (3 Criteria)					
7	*1) Keep deck edge above water at 25 degree heel*		22.98	ft		.21B + T
8	*2) Longitudinal Strength*		29.21	ft		LWL/15 Range: <15
9	*3) Contain machinery box height*		22.00	ft		HMBMIN
10	Minimum Depth at Station 10	D10MIN	29.21	ft	Calc	Maximum of 1) through 3)
11	Depth at Station 10	DSTA10	27.90	ft	Input	Input on Gross Characteristics
12	Minimum Depth at Station 0	D0MIN	30.39	ft	Calc	
13	Depth at Station 0	DSTA0	30.39	ft		DSTA0=D0MIN
14	Minimum Depth at Station 20	D20MIN	26.05	ft	Calc	
15	Depth at Station 20	DSTA20	26.05	ft		DSTA20=D20MIN
16						
17	Above-Water Hull Volume					
18	Freeboard at Station 0	FSTA0	20.73	ft		
19	Freeboard at Station 10	FSTA10	18.24	ft		
20	Freeboard at Station 20	FSTA20	16.39	ft		
21	Projected Area	APRO	8039.2097	ft2		
22	Average Freeboard	FAV	18.3501	ft		
23	Average Depth	DAV	28.005738	ft		
24	Cubic Number	CN	7.7833809			
25	Waterplane Coefficient	CW	0.820364			CW=.236+.836CP
26	Flare Factor	FFL	1.0811301		Calc	Maximum of: 1.0 or .714599+.18098DAV/T-.018828(DAV/T)^2
27	Above-Water Hull Volume	VHAW	452318.41	ft3	Calc	VHAW=LWLxBxFAVxCWxFFL
28						
29	Total Hull Volume					
30	Total Hull Volume	VHT	623013.41	ft3	Calc	
31						
32	Size Deck House					
33	Maximum Deckhouse Volume	VDMAX	210215.52	ft3	Calc	
34	Minimum Deckhouse Volume	VDMIN	42043.103	ft3	Calc	
35	Actual Deckhouse Volume	VD	150000	ft3	Input	
36						

Figure 31. Screenshot of “Space” Worksheet

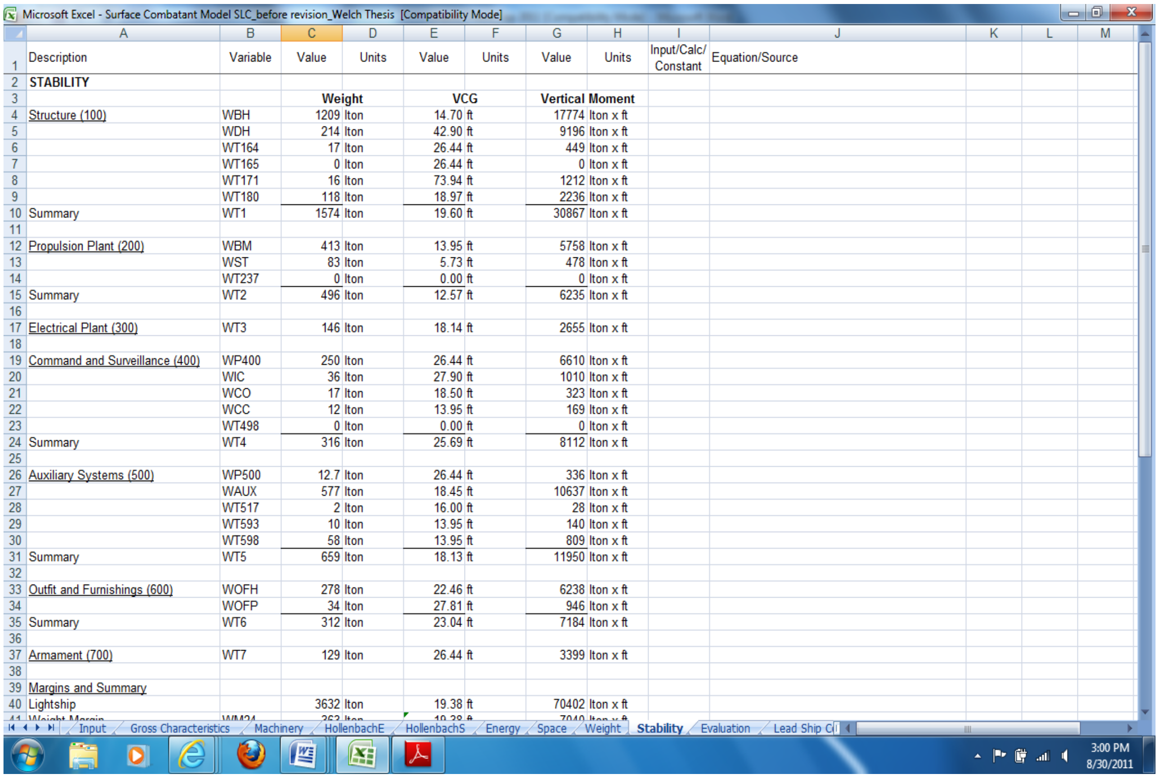
Figure 32 shows the “Weight” worksheet, which calculates the weights of the major ship group components. These groups include the following: Group 100 Structure, Group 200 Propulsion, Group 300 Electrical Plant, Group 400 Command and Surveillance, Group 500 Auxiliary Systems, Group 600 Outfit and Furnishings, and additional loads such as stores and crew.



	Description	Variable	Value	Units	Input/Calc/ Constant	Equation/Source
2	**WEIGHT**					
3	Structure (100)					
4	Hull (110-140, 160, 190)	WBH	1208.8733	lton	Calc	
5	Deckhouse Density Factor	rhoDH	0.001429	lton/ft3	Calc	
6	Deckhouse (150)	WDH	214.35	lton	Calc	
7	Masts (171)	WT171	16.391396	lton	Calc	
8	Foundations (180)	WT180	117.84052	lton	Calc	
9						
10	Total Structural Weight	WT1	1574.4553	lton	Calc	
11						
12	Propulsion (200)					
13	Basic Machinery (230+241/242+250-290)	WBM	412.72837	lton	Calc	
14						
15	*Shafting*					
16	Shafting Factor	FS	0.33		Const	If NP=1, .33; If NP=2, .5
17	Shafting (243)	WS	51.468186	lton	Calc	
18	Propellers (245)	WPR	20.972155	lton	Calc	
19	Bearings (244)	WB	10.866051	lton	Calc	
20						
21	Total Shafting	WST	83.306392	lton	Calc	
22	Total Propulsion	WT2	496.03476	lton	Calc	
23						
24	Electrical Plant (300)					
25	Total Electrical Plant Weight	WT3	146.42	lton	Calc	
26						
27	Command and Surveillance (400)					
28	Gyro/IC/Navigation (420,430)	WIC	36.192721	lton	Calc	
29	Other/Misc Group 400	WCO	17.434773	lton	Calc	
30	Cabling	WCC	12.1451	lton	Calc	
31	Total Command and Surveillance	WT4	315.77259	lton	Calc	

Figure 32. Screenshot of the "Weight" Worksheet

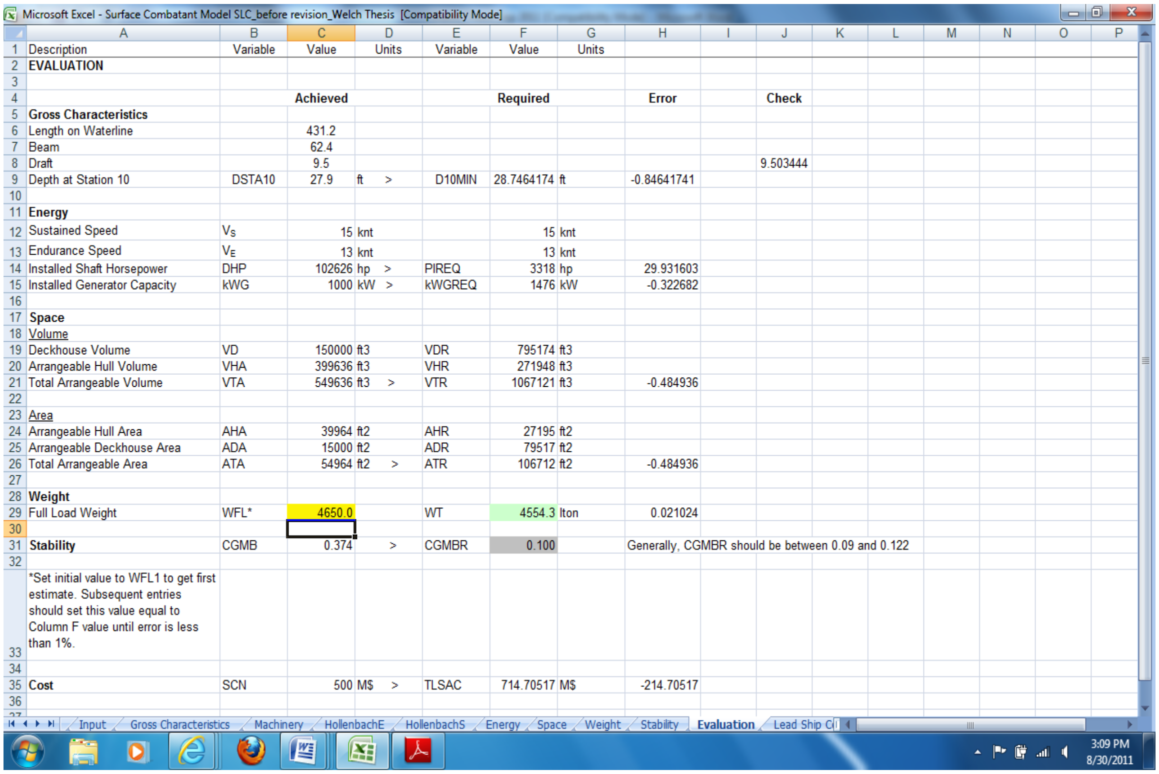
Figure 33 displays the "Stability" worksheet, which takes the weight, vertical center of gravity, and vertical moment information from all the major groups of the ship and calculates total ship stability characteristics. The major ship groups used are the following: structure, propulsion plant, electrical plant, command and surveillance, auxiliary systems, outfit and furnishings, armament, and loads.


Microsoft Excel - Surface Combatant Model SLC_before revision_Welch Thesis [Compatibility Mode]

	A	B	C	D	E	F	G	H	I	J
1	Description	Variable	Value	Units	Value	Units	Value	Units	Input/Calc/ Constant	Equation/Source
2	**STABILITY**									
3			**Weight**		**VCG**		**Vertical Moment**			
4	Structure (100)	WBH	1209	lton	14.70	ft	17774	lton x ft		
5		WDH	214	lton	42.90	ft	9196	lton x ft		
6		WT164	17	lton	26.44	ft	449	lton x ft		
7		WT165	0	lton	26.44	ft	0	lton x ft		
8		WT171	16	lton	73.94	ft	1212	lton x ft		
9		WT180	118	lton	18.97	ft	2236	lton x ft		
10	Summary	WT1	1574	lton	19.60	ft	30867	lton x ft		
11										
12	Propulsion Plant (200)	WBM	413	lton	13.95	ft	5758	lton x ft		
13		WST	83	lton	5.73	ft	478	lton x ft		
14		WT237	0	lton	0.00	ft	0	lton x ft		
15	Summary	WT2	496	lton	12.57	ft	6235	lton x ft		
16										
17	Electrical Plant (300)	WT3	146	lton	18.14	ft	2655	lton x ft		
18										
19	Command and Surveillance (400)	WP400	250	lton	26.44	ft	6610	lton x ft		
20		WIC	36	lton	27.90	ft	1010	lton x ft		
21		WCO	17	lton	18.50	ft	323	lton x ft		
22		WCC	12	lton	13.95	ft	169	lton x ft		
23		WT498	0	lton	0.00	ft	0	lton x ft		
24	Summary	WT4	316	lton	25.69	ft	8112	lton x ft		
25										
26	Auxiliary Systems (500)	WP500	12.7	lton	26.44	ft	336	lton x ft		
27		WAUX	577	lton	18.45	ft	10637	lton x ft		
28		WT517	2	lton	16.00	ft	28	lton x ft		
29		WT593	10	lton	13.95	ft	140	lton x ft		
30		WT598	58	lton	13.95	ft	809	lton x ft		
31	Summary	WT5	659	lton	18.13	ft	11950	lton x ft		
32										
33	Outfit and Furnishings (600)	WOFH	278	lton	22.46	ft	6238	lton x ft		
34		WOFP	34	lton	27.81	ft	946	lton x ft		
35	Summary	WT6	312	lton	23.04	ft	7184	lton x ft		
36										
37	Armament (700)	WT7	129	lton	26.44	ft	3399	lton x ft		
38										
39	Margins and Summary									
40	Lightship		3632	lton	19.38	ft	70402	lton x ft		

Figure 33. Screenshot of “Stability” Worksheet

In Figure 34, the “Evaluation” worksheet displays an evaluation of the results achieved compared to the required results of the synthesized ship for the user. It allows the user to make adjustments to different parts and compare how close he is to the desired results.



	A	B	C	D	E	F	G	H	I	J
1	Description	Variable	Value	Units	Variable	Value	Units			
2	**EVALUATION**									
3										
4			**Achieved**			**Required**		**Error**		**Check**
5	**Gross Characteristics**									
6	Length on Waterline		431.2							
7	Beam		62.4							
8	Draft		9.5							9.503444
9	Depth at Station 10	DSTA10	27.9	ft >	D10MIN	28.7464174	ft	-0.84641741		
10										
11	**Energy**									
12	Sustained Speed	V_S	15	knt		15	knt			
13	Endurance Speed	V_E	13	knt		13	knt			
14	Installed Shaft Horsepower	DHP	102626	hp >	PIREQ	3318	hp	29.931603		
15	Installed Generator Capacity	kWG	1000	kW >	kWGREQ	1476	kW	-0.322682		
16										
17	**Space**									
18	Volume									
19	Deckhouse Volume	VD	150000	ft3	VDR	795174	ft3			
20	Arrangeable Hull Volume	VHA	399636	ft3	VHR	271948	ft3			
21	Total Arrangeable Volume	VTA	549636	ft3 >	VTR	1067121	ft3	-0.484936		
22										
23	Area									
24	Arrangeable Hull Area	AHA	39964	ft2	AHR	27195	ft2			
25	Arrangeable Deckhouse Area	ADA	15000	ft2	ADR	79517	ft2			
26	Total Arrangeable Area	ATA	54964	ft2 >	ATR	106712	ft2	-0.484936		
27										
28	**Weight**									
29	Full Load Weight	WFL*	4650.0		WT	4554.3	lton	0.021024		
30										
31	**Stability**	CGMB	0.374	>	CGMBR	0.100		Generally, CGMBR should be between 0.09 and 0.122		
32										
33	*Set initial value to WFL1 to get first estimate. Subsequent entries should set this value equal to Column F value until error is less than 1%.									
34										
35	**Cost**	SCN	500	M$ >	TLSAC	714.70517	M$	-214.70517		
36										

Figure 34. Screenshot of the “Evaluation” Worksheet

The “Summary” worksheet will be shown and explained for the ships that were designed in this study in Appendix G. The remaining worksheets pertain to cost, which was not in the scope of this thesis, but would be quite useful in ship design analysis.

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APPENDIX D: CALCULATION OF MISSILE DETECTION RANGE

To make the operational model more realistic, the author distinguished between the range at which the radar detected the enemy fighter aircraft and the range at which it detects the incoming enemy missile. In reality, the range at which a radar can see a missile is much less than the range at which it can see something as big as an aircraft. Therefore, in order to make the missile detection range adjust to the user's input of the maximum detection range, the author conducted an analysis on maximum radar detection range and missile detection range for existing radars. The analysis was conducted only on those air search radars from Table 7 that had missile detection range available and these are listed in Table 8.

Table 8. Air Search Radars Used in Maximum Detection Range-Missile Detection Range Analysis

Radar Name	Maximum Range	Missile Detection Range
EL/M-2228S (2D HP AMDR)	70	20
EL/M-2228S (3D AMDR)	70	20
Fregat-MAE	150	27
Fregat-MAE-1	150	27
Fregat-MAE-4K	58	17
Podberyozovik-ET1	300	55
Podberyozovik-ET2	240	45
Pozitiv-ME1	110	15
Pozitiv-ME1.2	50	13
SMART-L	400	65

The information in Table 8 was compared and plotted in Excel and is shown in Figure 35.

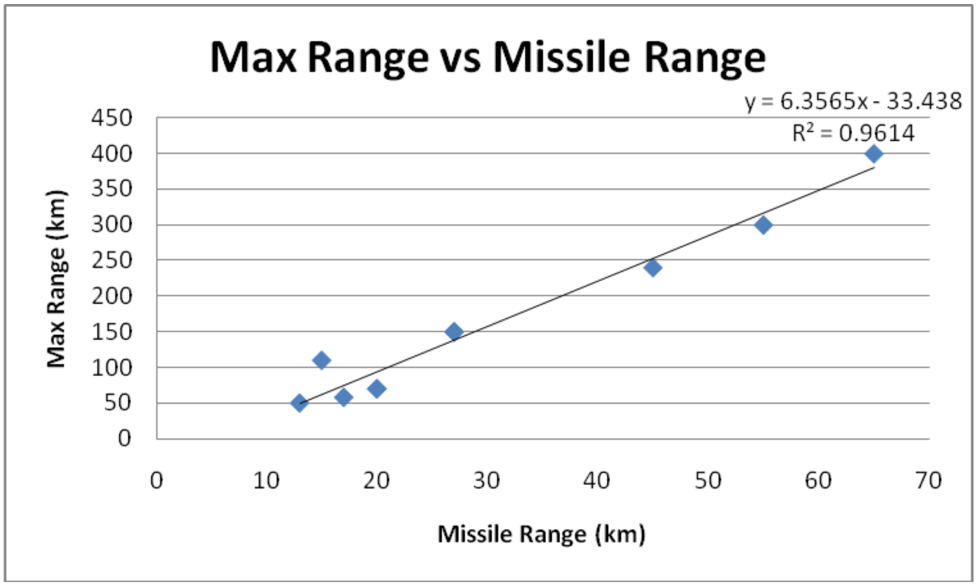
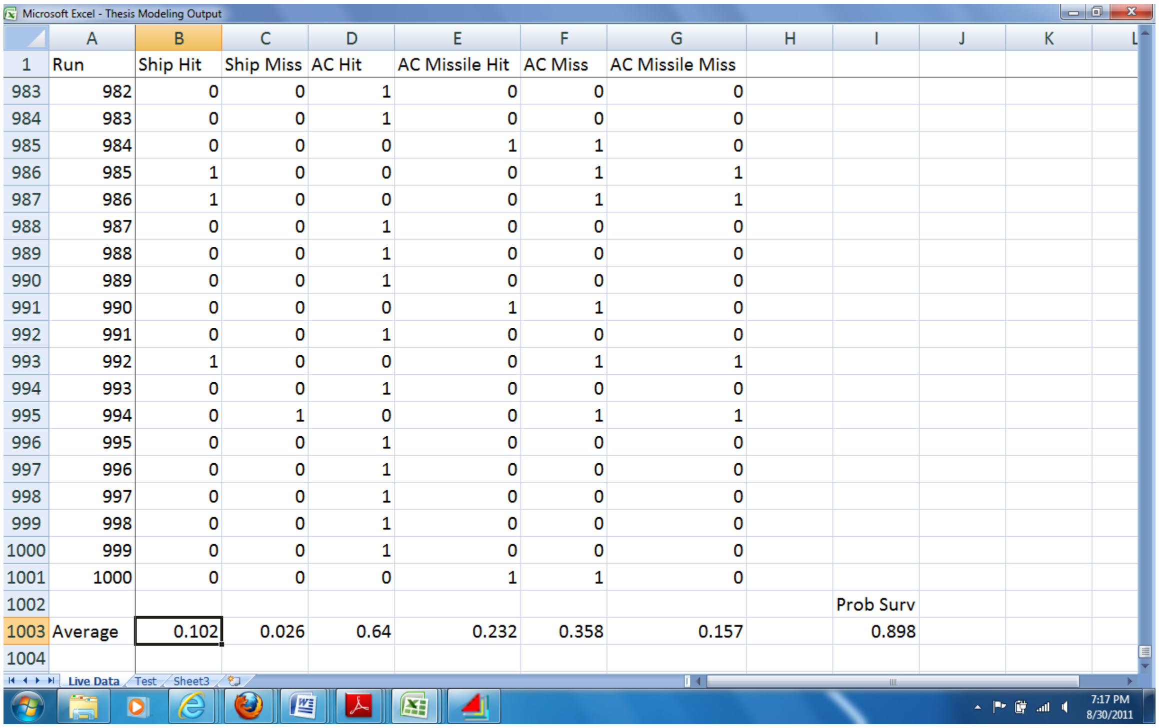


Figure 35. Analysis of Maximum Detection range versus Missile Detection Range for Air Search Radars in Table 8

As shown in Figure 35, there is a very close relationship between maximum detection range and missile detection range for the air search radars. Therefore, the equation expressing this relationship shown in Figure 35 was inserted into the operational model. When the user enters a desired detection range, the program automatically calculates by way of the equation the missile detection range and uses it during the simulation.

APPENDIX E: EXCEL DATABASE FOR OPERATIONAL MODEL OUTPUT

Figure 36 shows the Excel database that received the results from the ExtendSim program. With each iteration of the operational model, the results were recorded in each row. A number was placed under the column for the number of times the following actions occurred in that particular simulation trial: the ship being hit, the missile missing the ship, the aircraft being hit, the aircraft missile being shot down, the ship's missile missing the aircraft, and the ship's missile missing the aircraft's missile. Although all the information was a good indicator for the author on the workings of the model, the "Ship Hit" column was of most interest for the sake of the study. The MOE for this mission is the probability of the ship surviving this encounter with an enemy aircraft. Therefore, P_S was calculated by subtracting the average of the "Ship Hit" column from 1.



	A	B	C	D	E	F	G	H	I	J	K
1	Run	Ship Hit	Ship Miss	AC Hit	AC Missile Hit	AC Miss	AC Missile Miss				
983	982	0	0	1	0	0	0				
984	983	0	0	1	0	0	0				
985	984	0	0	0	1	1	0				
986	985	1	0	0	0	1	1				
987	986	1	0	0	0	1	1				
988	987	0	0	1	0	0	0				
989	988	0	0	1	0	0	0				
990	989	0	0	1	0	0	0				
991	990	0	0	0	1	1	0				
992	991	0	0	1	0	0	0				
993	992	1	0	0	0	1	1				
994	993	0	0	1	0	0	0				
995	994	0	1	0	0	1	1				
996	995	0	0	1	0	0	0				
997	996	0	0	1	0	0	0				
998	997	0	0	1	0	0	0				
999	998	0	0	1	0	0	0				
1000	999	0	0	1	0	0	0				
1001	1000	0	0	0	1	1	0				
1002									Prob Surv		
1003	Average	0.102	0.026	0.64	0.232	0.358	0.157		0.898		
1004											

Figure 36. Screenshot of Excel Database for Operational Model Output

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APPENDIX F: SCREENSHOTS OF OPERATIONAL MODEL

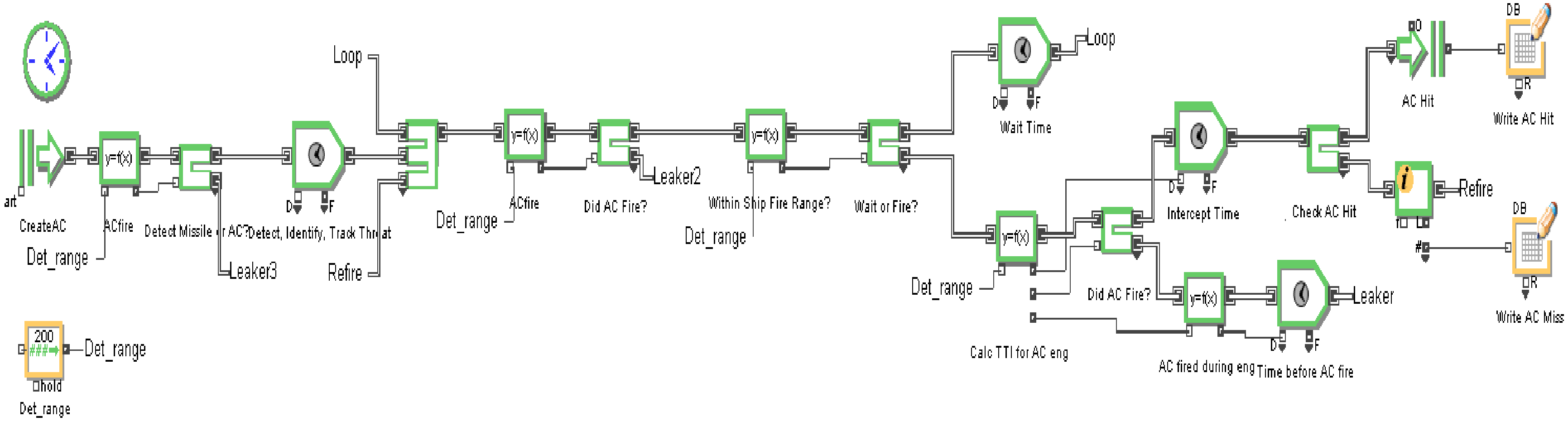

Figure 37. Aircraft Detection and Engagement Section

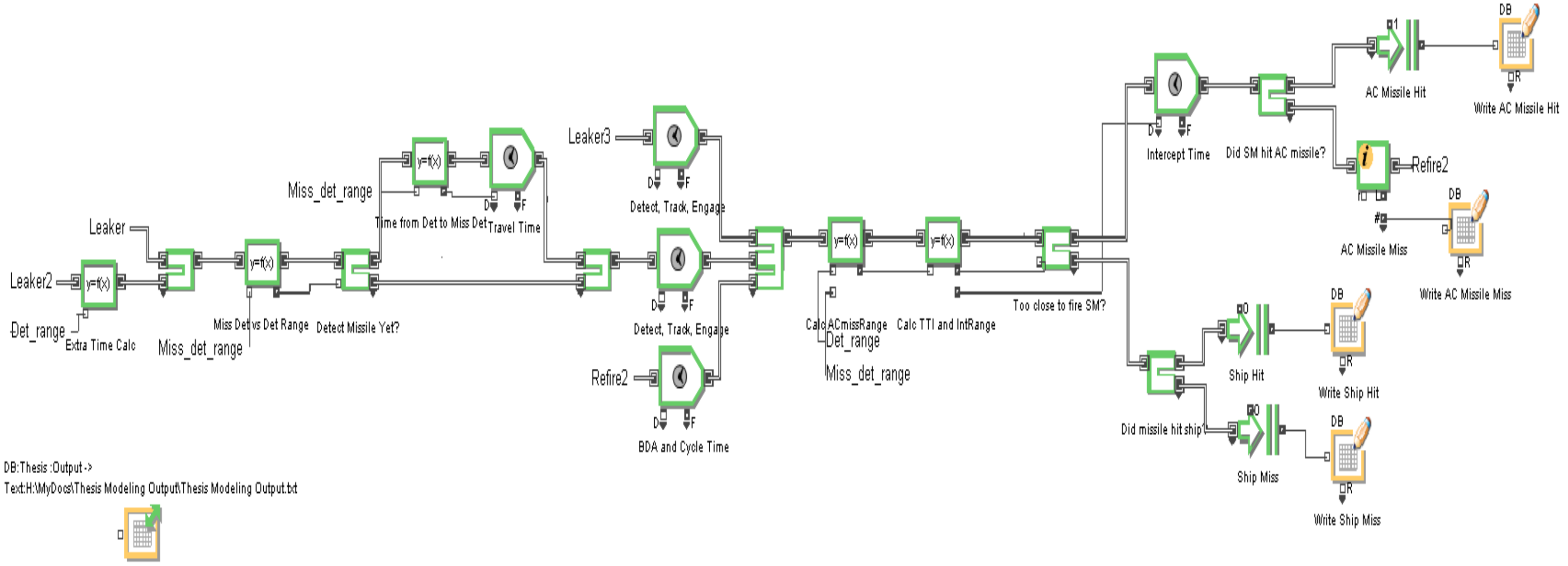

Figure 38. Missile (ASM) Detection and Engagement Section

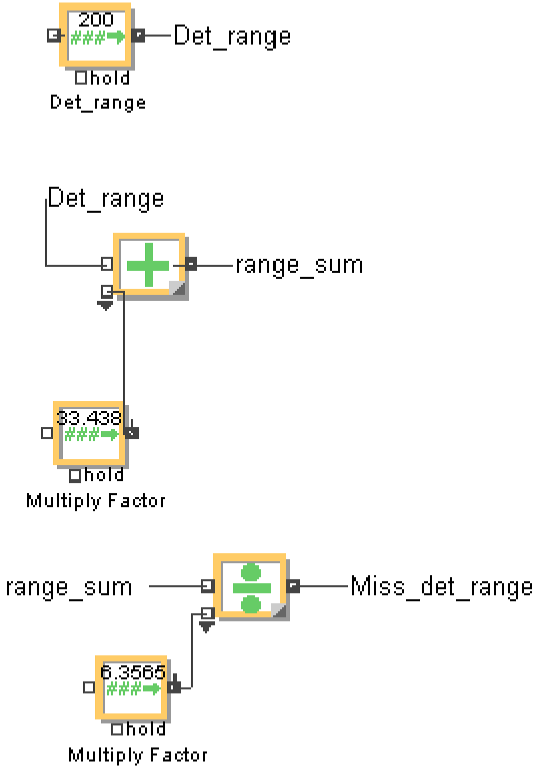

Figure 39. Radar Detection Range User Input and Missile Detection Range Calculation Section

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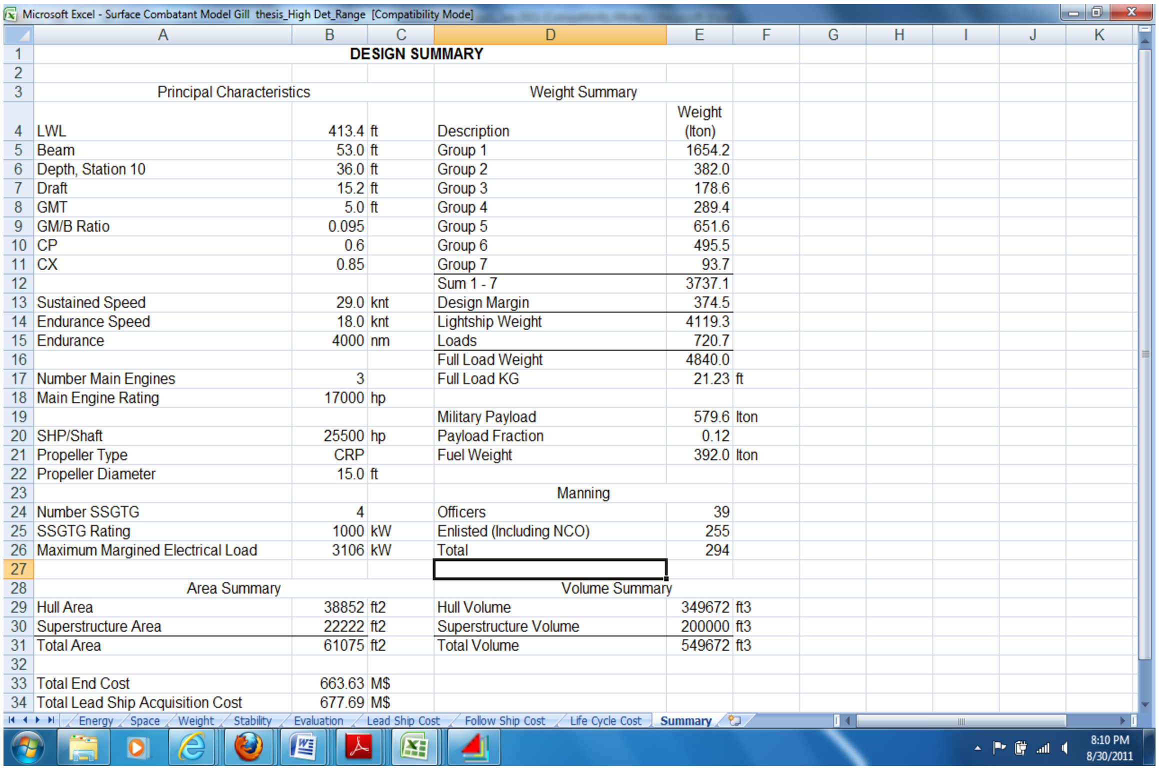
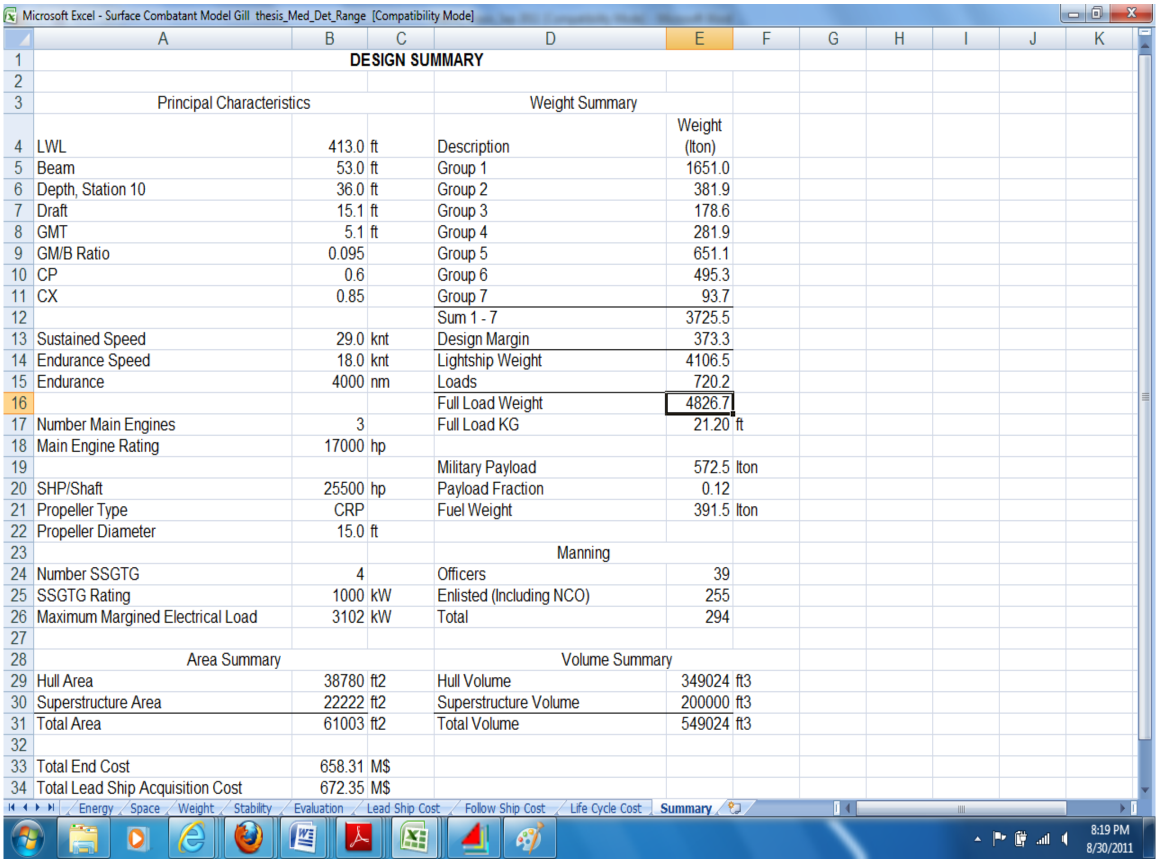
APPENDIX G: DESIGN SUMMARY FOR SHIPS SYNTHESIZED WITH HIGH, MEDIUM, AND LOW AIR SEARCH RADAR DETECTION RANGES

The following figures are screenshots of the “Summary” worksheets in Excel for the three ships synthesized in this study with high, medium, and low detection ranges.



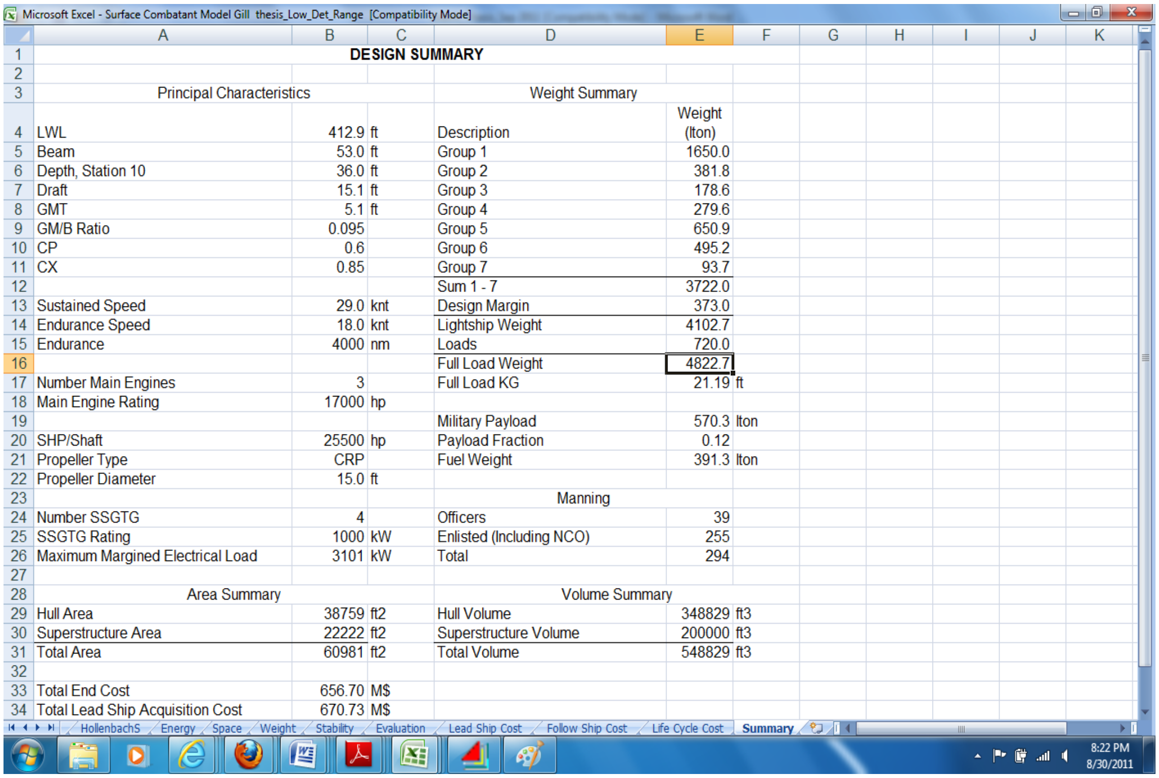
	A	B	C	D	E	F
1	**DESIGN SUMMARY**					
2						
3	Principal Characteristics			Weight Summary		
4	LWL	413.4	ft	Description	Weight (lton)	
5	Beam	53.0	ft	Group 1	1654.2	
6	Depth, Station 10	36.0	ft	Group 2	382.0	
7	Draft	15.2	ft	Group 3	178.6	
8	GMT	5.0	ft	Group 4	289.4	
9	GM/B Ratio	0.095		Group 5	651.6	
10	CP	0.6		Group 6	495.5	
11	CX	0.85		Group 7	93.7	
12				Sum 1 - 7	3737.1	
13	Sustained Speed	29.0	knt	Design Margin	374.5	
14	Endurance Speed	18.0	knt	Lightship Weight	4119.3	
15	Endurance	4000	nm	Loads	720.7	
16				Full Load Weight	4840.0	
17	Number Main Engines	3		Full Load KG	21.23	ft
18	Main Engine Rating	17000	hp			
19				Military Payload	579.6	lton
20	SHP/Shaft	25500	hp	Payload Fraction	0.12	
21	Propeller Type	CRP		Fuel Weight	392.0	lton
22	Propeller Diameter	15.0	ft			
23				Manning		
24	Number SSGTG	4		Officers	39	
25	SSGTG Rating	1000	kW	Enlisted (Including NCO)	255	
26	Maximum Margined Electrical Load	3106	kW	Total	294	
27						
28	Area Summary			Volume Summary		
29	Hull Area	38852	ft2	Hull Volume	349672	ft3
30	Superstructure Area	22222	ft2	Superstructure Volume	200000	ft3
31	Total Area	61075	ft2	Total Volume	549672	ft3
32						
33	Total End Cost	663.63	M$			
34	Total Lead Ship Acquisition Cost	677.69	M$			

Figure 40. Screenshot of “Summary” Worksheet for Ship with High Air Search Radar Detection Range (400 km)



	A	B	C	D	E	F
1		DESIGN SUMMARY				
2						
3	Principal Characteristics			Weight Summary		
4	LWL	413.0	ft	Description	Weight (lton)	
5	Beam	53.0	ft	Group 1	1651.0	
6	Depth, Station 10	36.0	ft	Group 2	381.9	
7	Draft	15.1	ft	Group 3	178.6	
8	GMT	5.1	ft	Group 4	281.9	
9	GM/B Ratio	0.095		Group 5	651.1	
10	CP	0.6		Group 6	495.3	
11	CX	0.85		Group 7	93.7	
12				Sum 1 - 7	3725.5	
13	Sustained Speed	29.0	knt	Design Margin	373.3	
14	Endurance Speed	18.0	knt	Lightship Weight	4106.5	
15	Endurance	4000	nm	Loads	720.2	
16				Full Load Weight	4826.7	
17	Number Main Engines	3		Full Load KG	21.20	ft
18	Main Engine Rating	17000	hp			
19				Military Payload	572.5	lton
20	SHP/Shaft	25500	hp	Payload Fraction	0.12	
21	Propeller Type	CRP		Fuel Weight	391.5	lton
22	Propeller Diameter	15.0	ft			
23				Manning		
24	Number SSGTG	4		Officers	39	
25	SSGTG Rating	1000	kW	Enlisted (Including NCO)	255	
26	Maximum Margined Electrical Load	3102	kW	Total	294	
27						
28	Area Summary			Volume Summary		
29	Hull Area	38780	ft2	Hull Volume	349024	ft3
30	Superstructure Area	22222	ft2	Superstructure Volume	200000	ft3
31	Total Area	61003	ft2	Total Volume	549024	ft3
32						
33	Total End Cost	658.31	M$			
34	Total Lead Ship Acquisition Cost	672.35	M$			

Figure 41. Screenshot of “Summary” Worksheet for Ship with Medium Air Search Radar Detection Range (135 km)



	A	B	C	D	E	F
1	**DESIGN SUMMARY**					
2						
3	Principal Characteristics			Weight Summary		
4	LWL	412.9	ft	Description	Weight (lton)	
5	Beam	53.0	ft	Group 1	1650.0	
6	Depth, Station 10	36.0	ft	Group 2	381.8	
7	Draft	15.1	ft	Group 3	178.6	
8	GMT	5.1	ft	Group 4	279.6	
9	GM/B Ratio	0.095		Group 5	650.9	
10	CP	0.6		Group 6	495.2	
11	CX	0.85		Group 7	93.7	
12				Sum 1 - 7	3722.0	
13	Sustained Speed	29.0	knt	Design Margin	373.0	
14	Endurance Speed	18.0	knt	Lightship Weight	4102.7	
15	Endurance	4000	nm	Loads	720.0	
16				Full Load Weight	4822.7	
17	Number Main Engines	3		Full Load KG	21.19	ft
18	Main Engine Rating	17000	hp			
19				Military Payload	570.3	lton
20	SHP/Shaft	25500	hp	Payload Fraction	0.12	
21	Propeller Type	CRP		Fuel Weight	391.3	lton
22	Propeller Diameter	15.0	ft			
23				Manning		
24	Number SSGTG	4		Officers	39	
25	SSGTG Rating	1000	kW	Enlisted (Including NCO)	255	
26	Maximum Margined Electrical Load	3101	kW	Total	294	
27						
28	Area Summary			Volume Summary		
29	Hull Area	38759	ft2	Hull Volume	348829	ft3
30	Superstructure Area	22222	ft2	Superstructure Volume	200000	ft3
31	Total Area	60981	ft2	Total Volume	548829	ft3
32						
33	Total End Cost	656.70	M$			
34	Total Lead Ship Acquisition Cost	670.73	M$			

Figure 42. Screenshot of “Summary” Worksheet for Ship with Low Air Search Radar Detection Range

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APPENDIX H: SACHSEN CLASS FRIGATE INFORMATION

Table 9. Sachsen Class Frigate Information (After [12])

Sachsen Class (Type 124) FFGHM	
Displacement (full load)	5690 tonnes (5600.1 (uk) t) (6272.2 t (short)) (5690000 kg)
Length (overall)	143 m (469 ft)
Length (waterline)	132.2 m (434 ft)
Beam (overall)	17.4 m (57 ft)
Draught (hull)	6.9 m (22.6 ft)
Speed (top)	29 kt (53.7 km/h) (33.4 mph)
Range (Standard)	4000 n miles (7408 km) (4603.1 miles) at 18 kt (33.3 km/h) (20.7 mph)
Crew Capacity	255
Officer Capacity	39
Machinery	CODAG; 1 GE LM 2500 gas turbine; 31,514 hp (23.5 MW); 2 MTU 20V 1163 TB 93 diesels; 20,128 hp(m) (14.8 MW); 2 shafts; cp props
Missiles	**SSM:** 8 McDonnell Douglas Harpoon Block 1D 2 (twin); active radar homing to 95 km (51 n miles) at 0.9 Mach; warhead 227 kg. **SAM:** Mk 41 VLS (32 cells) 24 Raytheon Standard SM-2 Block IIIA; command/inertial guidance; semi-active radar homing to 167 km (90 n miles) at 2.5 Mach. 32 Evolved Sea Sparrow RIM 162B; semi-active radar homing to 18 km (9.7 n miles) at 3.6 Mach; warhead 39 kg. 2 RAM RIM-116 launchers. 21 cell Mk 49 launchers; passive IR/anti-radiation homing to 9.6 km (5.2 n miles) at 2.5 Mach; warhead 9.1 kg. 42 missiles.
Guns	1 Otobreda 76 mm/62 IROF; 108 rds/min to 16 km (8.6 n miles) anti-surface; 12 km (6.5 n miles) anti-aircraft; weight of shell 6 kg. 2 Mauser 27 mm. 4–12.7 mm MGs.
Torpedoes	6–324 mm (2 triple) Mk 32 Mod 7 tubes. Eurotorp Mu 90 Impact.
Physical Countermeasures	**Decoys:** 4 Rheinmetall MASS-4L decoy launchers.
Electronic Countermeasures	**ESM/ECM:** EADS Fl 1800S-II; intercept and jammer
Radars	**Air search:** SMART L 3D; D-band. **Air/surface search:** Thales APAR phased array; I/J-band. **Navigation**: 2 SAM 9600M; E/I-band. IFF: Mk XII.
Sonars	Atlas DSQS-21B (Mod); bow-mounted; active search; medium frequency.
Combat Data Systems	CDS F 124; Link 11/16.
Electro-optic Systems	MSP optronic director
Helicopters	2 NH90 NFH or 2 Westland Super Lynx Mk 88A.

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