Naval Ship Preliminary Arrangements for Operability and Reduced Vulnerability

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Thesis submitted to the Faculty of Virginia Polytechnic Institute
and State University in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

in

Ocean Engineering

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September 30, 2016
Blacksburg, Virginia

Keywords: Naval, ship, arrangements, vulnerability

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ABSTRACT

This thesis presents a process and tool that generates representative preliminary ship models and arrangements for use in vulnerability analysis in the Concept and Requirements Exploration (C&RE) process used at Virginia Tech. C&RE uses a Multi-Objective Genetic Optimization (MOGO) to explore the design space for non-dominated ship design solutions based on design effectiveness, risk, and cost. Vulnerability is assessed as part of the C&RE using a Preliminary Arrangements and Vulnerability (PA&V) model. Representative ship arrangements for specified combinations of ship system options are created based on operability needs, ship mission needs, and improved vulnerability. These are then analyzed for vulnerability and are used to calculate a representative Overall Measure of Vulnerability (OMOV) which is used to calculate the Overall Measure of Effectiveness (OMOE) in the MOGO.

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GENERAL AUDIENCE ABSTRACT

This thesis presents a process and tool for ship vulnerability analysis in early stage ship design. Vulnerability is defined as the probability of ship kill after taking damage from a weapon. The vulnerability is assessed on representative ships that are generated based on the systems required for the ship missions. The analysis results are used in the design process to compare different ship designs based on their effectiveness, risk, and cost. This thesis creates the representative ship arrangements based on expert opinion, ship characteristics, and a location damage analysis. This process considers the vulnerability of a design in calculating the effectiveness of the design to incorporate vulnerability early in the design process.

ACKNOWLEDGEMENTS

I would like to thank my graduate advisor, Dr. Alan Brown, for all that he has done to help me further my understanding of Naval Ship Design. Thank you for your guidance throughout my research and helping me with my paper edits.

I would also like to thank Dr. John Sajdak for overseeing my research throughout the last few years. Thank you for your advice and guidance.

I would like to thank Dr. Wayne Neu for being on my thesis committee and giving me very helpful advice on my report.

I would like to thank Grant Raisig for helping me to understand much more of the coding language that I needed for my research.

Thank you to my parents for always being there for me to complain to or talk to when I was frustrated. You have always encouraged me and helped me when I needed it. Thank you to my sister for always raising the bar and making me want to strive for more.

Thank you to David Goodfriend and Sean Stark for leading the way and helping on this collaborative research. Thank you for just smiling and dealing with me when I needed to talk through a problem aloud.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

AABB - Axis Aligned Bounding Block
AAW - Anti-Air Warfare
AHP – Analytical Hierarchy Process
ASAP - Advanced Survivability Assessment Program
ASM - Anti-Ship Missile
ASSET - Advanced Surface Ship and Submarine Evaluation Tool
ASUW - Anti-Surface Warfare
ASW - Anti-Submarine Warfare
BPM - Blast Propagation Module
C&RE - Concept and Requirements Exploration
CFD - Computational Fluid Dynamics
CIWS – Close-In Weapon System
CODAG - Combined Diesel and Gas
CONOPS - Concept of Operations
DBB – Design Building Blocks
DBD - Deactivation Block Diagram
DP - Design Parameter
DRM - Design Reference Mission
DV - Design Variable
HED - Hybrid Electric Drive
ICD - Initial Capabilities Document
IFF - Interrogator Friend or Foe
IPS - Integrated Power System
ISA - Intelligent Ship Arrangements
LOA - Length Overall
MC - Model Center
MOE - Measure of Effectiveness
MOGO - Multi-Objective Genetic Optimization
MOP - Measure of Performance
MOTISS - Measure of Total Integrated Ship Survivability
NDF - Non-Dominated Frontier
NMETL - Naval Mission Essential Task List
OEM - Operational Effectiveness Model
OMOE - Overall Measure of Effectiveness
OMOR - Overall Measure of Risk
OMOV - Overall Measure of Vulnerability
OpSits - Operational Situations
PA&V - Preliminary Arrangements and Vulnerability
PSYS - Power System
RBD - Reliability Block Diagram
ROC - Required Operational Capabilities
SDB - Subdivision Block
SSCS - Ship Space Classification System
SSG - Ship Service Generator

SSM - Ship Synthesis Model
VC - Vital Component
VIVA - Volumetric Integrated Vulnerability Analysis
VTPAM - Virginia Tech Preliminary Arrangements Model
VTVM - Virginia Tech Vulnerability Model
ZEDS - Zonal Electric Distribution System

CHAPTER 1 - INTRODUCTION

1.1 Motivation/Background/Purpose

In naval ship design, the concept design phase provides an important foundation for the entire ship design process. The concept design phase begins when the Navy determines a mission need and creates an Initial Capabilities Document (ICD). At this point, there is typically a very large design space from which a final design is to be selected. Many factors are considered in the selection process. Important objectives include cost, risk, and mission effectiveness. Although normally considered later in the design process, the importance of a naval ship's survivability and vulnerability in particular, necessitates that efforts be made to consider them at this early design stage. Survivability should be considered "during each phase of the ship design process, with considerations for the constraints on cost, schedule and performance" (Said, 1995). The vulnerability of a ship is largely determined by early design decisions and must be considered to avoid changing an entire design late in the process. Traditionally, vulnerability is not considered in the concept design phase because it requires more detail and analysis than is typically available or possible in early design stages when information on the design is limited. However, geometry, system architecture, and arrangements have a major impact on vulnerability (Brown and Sajdak, 2014) and because these characteristics are difficult and costly to change later in the design, they must be considered as early as possible.

The purpose of this thesis to describe research to develop a process and set of tools to generate a preliminary ship model that has sufficient detail for a vulnerability analysis in concept design.

1.1.1 Concept and Requirements Exploration (C&RE)

The Concept and Requirements Exploration (C&RE) process developed at Virginia Tech searches a user defined design space for non-dominated (Pareto-optimal) designs based on cost, risk, and effectiveness to select baseline designs and technologies for the next stage of design and establish initial performance and cost requirements. As shown in Figure 1-1, this process begins with the ICD and mission needs statement, identifies ship design parameters, generates ship design models, searches the design space, and creates a non-dominated frontier from which the user can choose a baseline design. The main steps of this process are “Mission Definition”, “Technology Review”, ‘Design Space Exploration”, “Build Models’, ‘Search Design Space’, and finally the design “Decision”.

Mission Definition is the step that gathers and refines all of the inputs for the design that are necessary to adequately define the mission. In this step, the documents for the ship mission are analyzed and the ship operational requirements based on mission needs are determined. This includes a large portion of the design space constraints and some ship characteristics.

In Technology Review relevant past, present, and near future ship technologies are identified and assessed.

In Design Space Exploration, different combinations of ship parameters are explored and representative designs are generated. This step explores hull options, propulsion and electrical options, and mission system options to determine compatible designs to be further analyzed.

In the Build Models step, synthesis response surface models are generated and assembled in a Ship Synthesis Model (SSM). Design models to calculate cost, risk, and effectiveness are also developed.

In the Search Design Space step, thousands of designs are synthesized, and their cost, risk, and effectiveness are compared to find non-dominated designs using a Multi-Objective Genetic Optimization (MOGO) and displayed as a non-dominated frontier (NDF) for the final step, Decision.

In the final Decision step, baseline designs are selected from the design space and ship requirements for these designs are defined.

Steps of the CR&E process specifically addressed in this thesis are outlined in red in Figure 1-1 and are called the Preliminary Arrangements and Vulnerability process (PA&V). The PA&V and the C&RE processes are discussed further in Chapter 2. The PA&V process is used to incorporate vulnerability into the concept design stage.

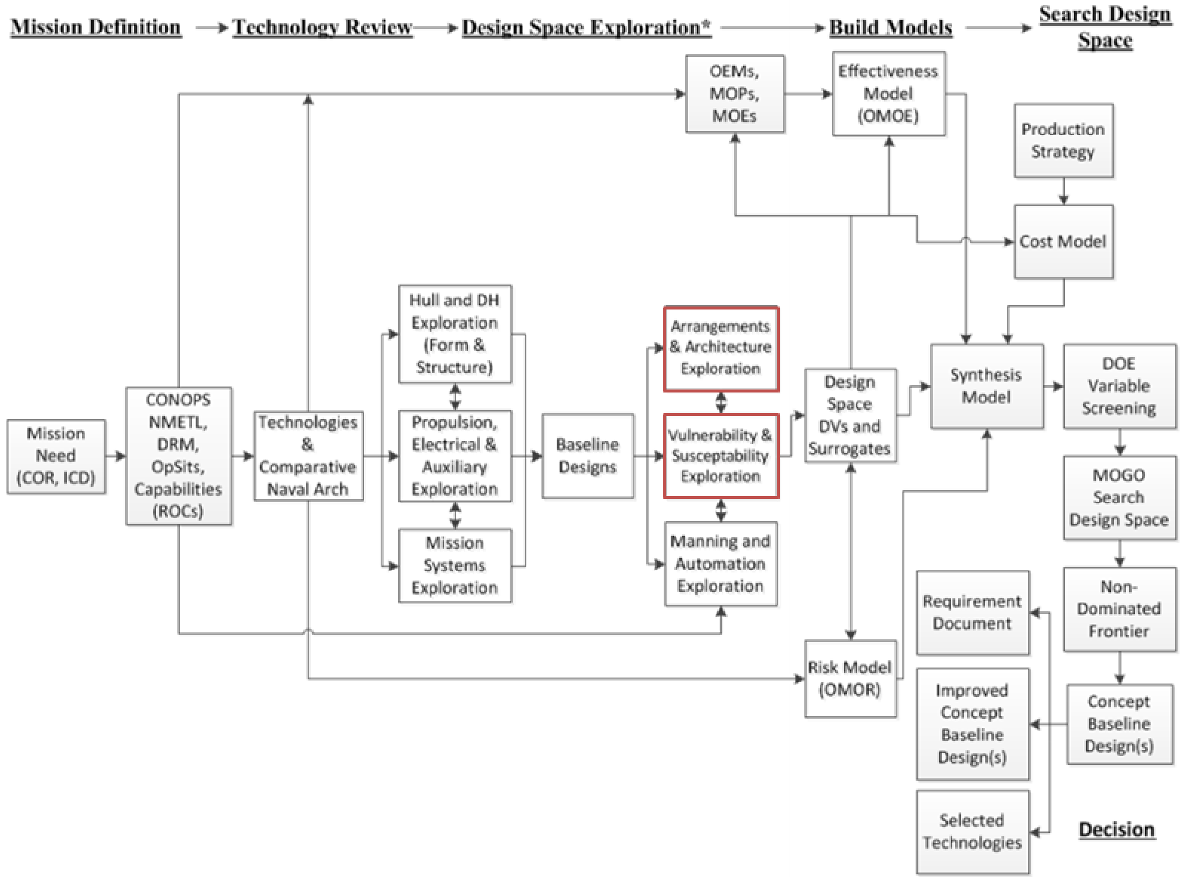


Figure 1-1 - Virginia Tech Concept and Requirements Exploration Module (C&RE)

1.1.2 Ship Vulnerability

Ship survivability can be broken down into three parts: susceptibility, vulnerability, and recoverability. Susceptibility is the probability of being hit by a weapon. Vulnerability is the probability of kill or loss of capability after being hit by a weapon, and recoverability is the probability of restoring a capability given kill. The focus of survivability within concept design is limited in this thesis to vulnerability as a vessel's vulnerability is predominantly dependent on the vessel's geometry, system architecture, and arrangements. These are particularly difficult to change in later design stages.

Vulnerability is usually analyzed later in the design process after arrangements have already been determined because the arrangements of equipment and components have a large impact on ship vulnerability and in concept exploration only limited arrangement definition is available. The most common way to assess vulnerability is to determine the ship capabilities and ship functionality remain after damage. In order to determine the total ship vulnerability, the ship must be subjected to many damage scenarios in many locations. Mission capability loss is calculated for each damage case and probabilities of kill given hit are calculated to determine the vulnerability for each capability and thus for the entire ship design.

1.1.3 Overview of VTPAM and VTVM

Ship vulnerability analysis is performed using a Vulnerability Model (VTVM), working with a Preliminary Arrangements Model (VTPAM) performing what we call a Preliminary Arrangements and Vulnerability (PA&V) process. This process was developed in collaboration with David Goodfriend (Goodfriend, 2015) and Sean Stark (Stark, 2016). In the PA&V process, shown in Figure 1-2, the mission system options and mechanical and electrical system options are used as the primary inputs to create representative design arrangements and assess ship vulnerability, which is then used in the ship synthesis model to calculate effectiveness.

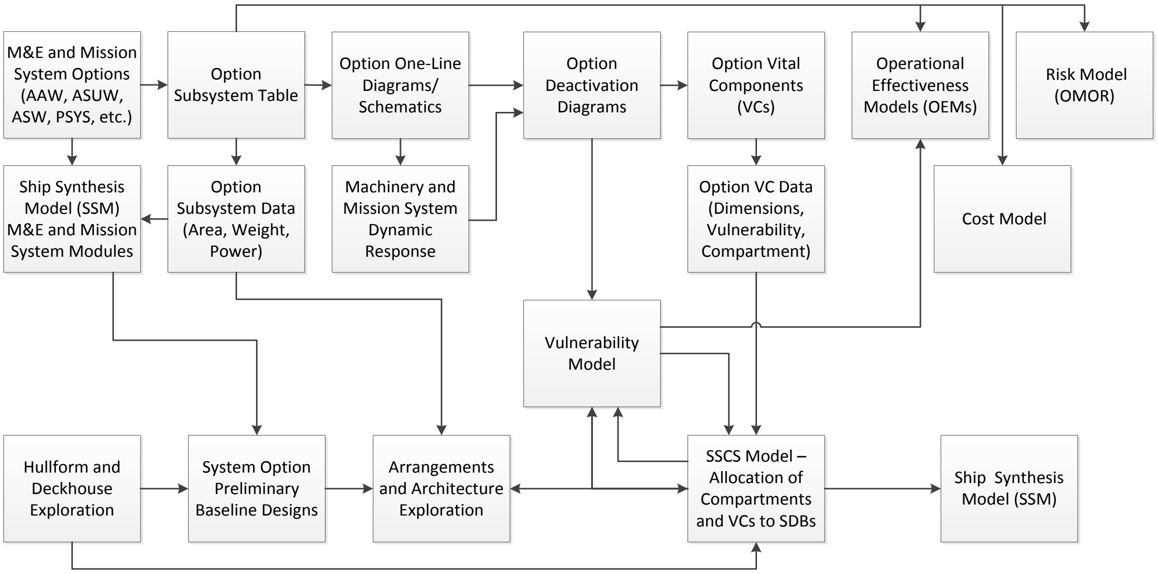


Figure 1-2 – Preliminary Arrangments and Vulnerability (PA&V) process

For the PA&V process, we assume that the systems, subdivisions, and arrangements are the main drivers for ship vulnerability given an adequately sized hullform with average shape characteristics. Vulnerability is calculated for all system option combinations and assessed in representative hullforms with preliminary arrangements based on operability and minimizing equipment hit probability. Representative vulnerability results are used later in the SSM as a function of system option selection only. This PA&V process is outlined below and further described in Sections 2.2 and 2.3.

The VTPAM process approximates necessary design variable and parameter values using payload and machinery system weights and space that are required for the specified Vital Components (VCs) and system combinations. The combined system weight is used to estimate displacement, and a displacement to length ratio (Δ/L^3) is used to estimate the overall length (LOA) of the representative ship. Other hullform parameters are given values based on mean values in the design space, and are the same for all designs. The size of the hullforms that are explored is determined by the systems that are specified for the design. VTPAM next defines a simplified representative hullform geometry that extends from deck to deck and bulkhead to bulkhead using subdivision blocks (SDBs) in the form of Axis Aligned Bounding Boxes (AABBs). An example of this is shown in Figure 1-3. This simplified hullform geometry is then assessed to determine the likelihood of damage to the subdivision blocks based on given threats and hit distributions.

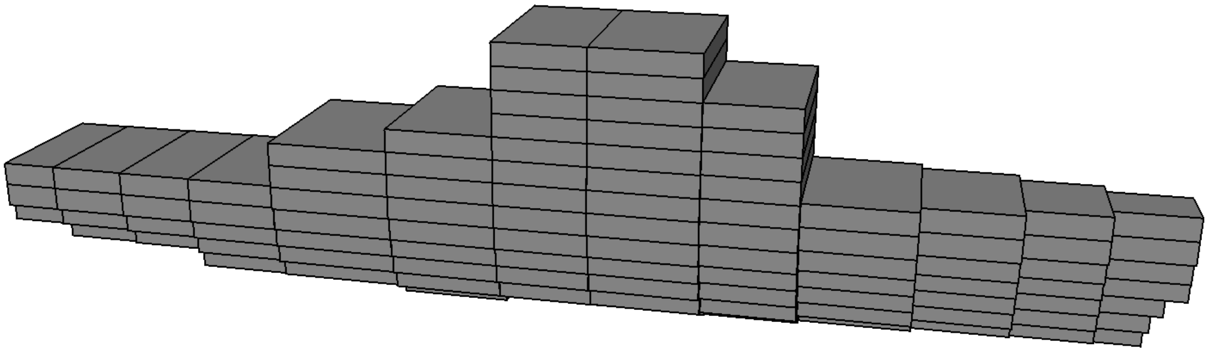


Figure 1-3 - Subdivision block model using Axis Aligned Bounding Boxes

The damage that is evaluated for these subdivision blocks is determined based on damage extents calculations as described in the thesis Definition of Damage Volumes for the Rapid Prediction of Ship Vulnerability to AIREX Weapon Effects (Stark, 2016). This process determines the probability of damage for each subdivision block for a range of threat parameters. For each threat a hit distribution is determined that is representative of the threat, and the extent of damage for these hits is assessed. An example of the hit distribution is shown in Figure 1-4. The damage results are then combined to determine the probability of damage for each of the subdivision blocks.

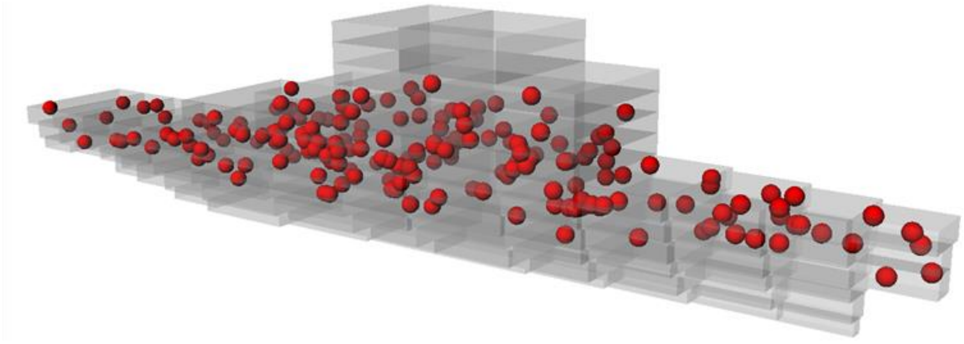


Figure 1-4 - Hit Distribution Example

The next step in VTPAM is to generate the representative preliminary arrangements. This is done by assigning compartments and their associated VCs to subdivision blocks based on operability and minimizing hit probability using the results of the initial SDB damage assessment. These representative hullforms and preliminary arrangements are then re-run in the damage assessment considering VC loss, system architecture and capability loss, and a vulnerability score for the specified system combination is determined by the VTVM.

The VTVM process was developed by David Goodfriend and is described in Exploration of System Vulnerability in Naval Ship Concept Design (Goodfriend, 2015). This vulnerability analysis method assesses loss of system capability using system deactivation block diagrams (DBDs). When a SDB is damaged by a threat, all VCs that are associated with it are considered deactivated, which can cause mission system capability to be lost. Probabilities of these system capability losses are then calculated and combined to determine the overall vulnerability of each representative design.

1.2 Literature Study

A number of existing programs and methods can accomplish parts of what the PA&V process was developed to perform. These programs and methods are used at different stages of design and use different principles to accomplish similar goals. Understanding these methods and programs provides some useful approaches, which were adapted in the PA&V process to a lesser level of detail and consistent with the C&RE framework. Functions of the PA&V process that have been addressed by others include automated ship arrangements, block geometries, vulnerability evaluation, system deactivation, 2.5D arrangements and network theory. These are discussed in the following sections.

1.2.1 Computer Based Naval Ship Arrangements

Generating a ship arrangement is usually a very manual effort in the ship design process. This is normally done by placing major compartments of the ship, then trying to fit together the rest of the ship like a puzzle. In order to determine the most efficient and accurate way to automate ship arrangements, it is important to understand other methods and efforts that have been used to generalize and speed up the process. Four recent methods are Intelligent Ship Arrangements (ISA, Parsons, 2008), the 2.5D packing approach (Oers, 2012), a Network Theory approach (Gillespie, 2012; Gillespie, 2013; Gillespie and Singer, 2013), and the Design Building Block (DBB) approach (Piperakis, 2012). These approaches use different methods to define multiple arrangement options for a single ship based on given ship parameters and systems, and select optimum or preferred options from these arrangements.

1.2.1.1 Intelligent Ship Arrangements

A recent approach to ship arrangements is described in “Intelligent Ship Arrangements: A New Approach to General Arrangement” (Parsons, 2008). This arrangement’s optimization system was developed at the University of Michigan and uses an optimization code to generate feasible arrangements that meet Navy requirements, standard design practices, and design specific needs. This is done in a two-step process, shown in Figure 1-5. The first step is allocation of spaces to general locations on the ship called “Zone-decks”. In the second step, spaces are arranged in detail to fit the compartments in the “Zone-deck” space. This very rigorous optimization system is computationally expensive, but some of the practices and ideas when simplified are potentially very useful to the VTPAM preliminary arrangements method.

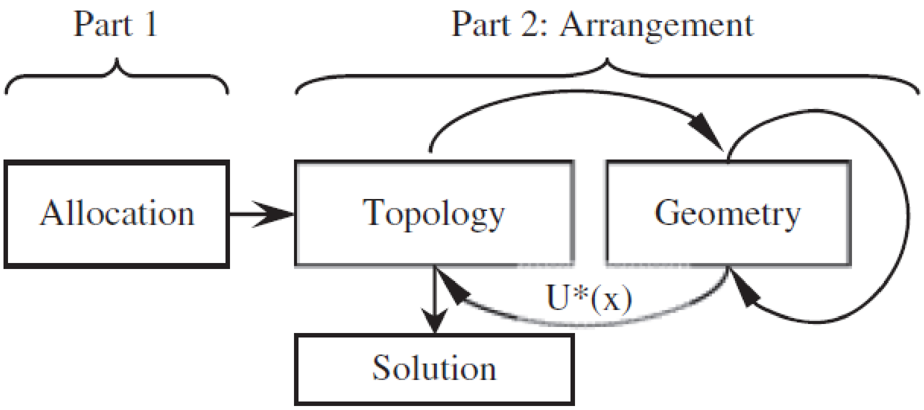


Figure 1-5 - ISA Optimization Process (Parsons, 2008)

The allocation optimization step of this approach searches all of the combinations of spaces being assigned to zones. This step uses Zone-deck area, global location, and adjacency/separation as the factors that determine the utility of each combination. The Zone-deck area constraint function considers the area of the spaces to be placed into each Zone-deck and compares the total to the area of each Zone-deck. This ensures that there is enough area to fit the spaces into the Zone-deck. The global location constraint function uses the space's preference to be in each Zone-deck based on the location of the Zone-deck in the ship. An example of this is shown in Figure 1-6. This allows for spaces to be placed in their preferred location on the ship. The final factor is the adjacency/separation constraint. This constraint function considers if the space in question prefers to be adjacent or separated from each other space. An example of this constraint is shown in Figure 1-7. All of these factors are then combined into a single cost function for each space. This function is used in a "hybrid agent/genetic algorithm" that optimizes the allocation of each space to a Zone-deck.

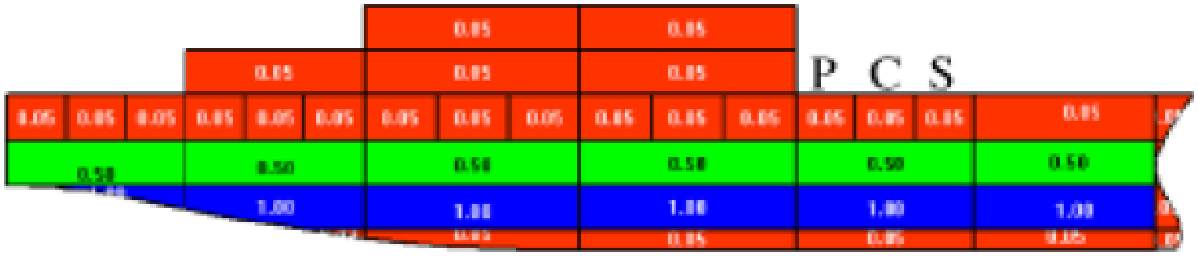


Figure 1-6 - ISA Global Location Goal example (Parsons, 2008)

Stern Bow

	–2	–1	0	+1	+2
+1	0.10	0.10	0.10	0.10	0.10
0	0.20	0.50	1.00	0.50	0.20
–1	0.10	0.10	0.10	0.10	0.10

Figure 1-7 - ISA Adjacency Constraint example showing space desires to be in the same location on the same deck (1 is most desired location) (Parsons, 2008)

Once the general location of each space is allocated into each Zone-deck, the method analyzes each Zone-deck and determines a detailed deck plan arrangement for each deck. The arrangements method starts with the Damage Control deck, and generates an optimized arrangement. It then moves on to the next Zone-deck until all spaces have been allocated and arranged. The arrangements method is also a two-step process as shown in Figure 1-5. The first loop is the topography optimization. This is where the spaces are placed fore and aft of each other. Then the geometry is detailed along with the shape of the space. The spaces are placed starting at the center of the Zone-deck and are optimized based on the user defined priorities. The arrangement considers if the Zone-deck has starboard and port passageways and/or athwartship passages. It also considers stairs and trunks if they are necessary for the Zone-deck. These features are predetermined for each Zone-deck by the user. The spaces that are arranged are allowed to be shaped as rectangles, T, L, C, and Z shapes. The arrangements optimization fits all of the spaces together and iterates until an arrangement is found. Each successful arrangement is given a utility value that represents how well the Zone-deck is arranged. This value is calculated based on required area, minimum overall dimension, minimum segment width, aspect ratios, perimeter, adjacencies, separations, and access separations. An example of an optimized Zone-deck is shown in Figure 1-8.

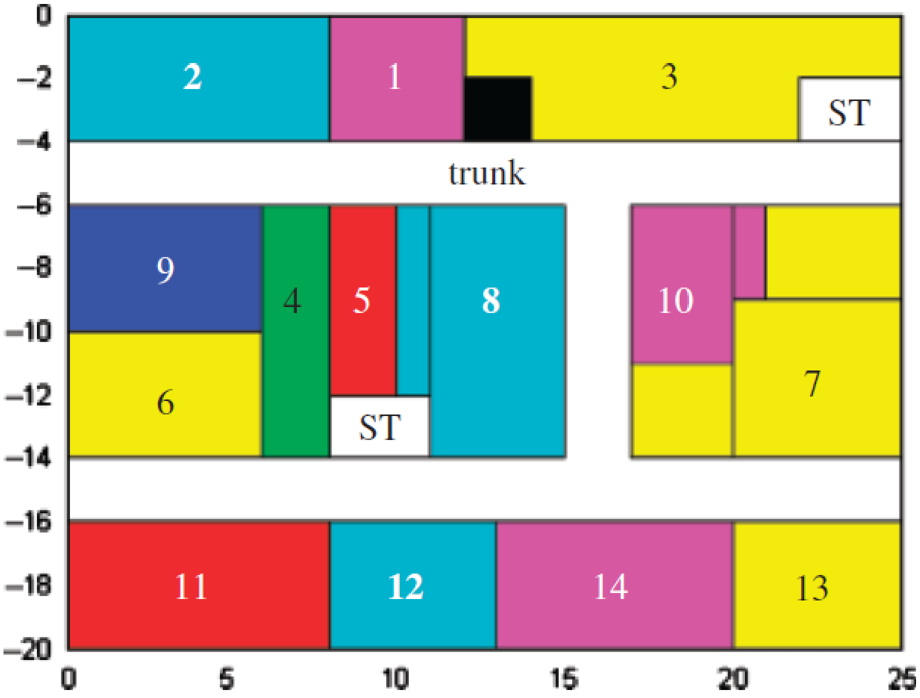


Figure 1-8 - ISA Arrangement example (Parsons, 2008)

The ISA method generates a very detailed ship arrangement for a single ship. The process is computationally intensive, and is too detailed for use in concept design. The VTPAM preliminary arrangements do not require an entire detailed arrangement, but the allocation step of the ISA method is potentially useful. The allocation of spaces to Zone-decks is a simplified way to assign spaces or compartments to areas of the ship. The optimization of space allocation is still more detailed than is required at this stage of design and for our simplified analysis. Other methods of accomplishing the space restraints are used in the Network and 2.5D Arrangements Modeling discussed in the next two sections.

1.2.1.2 Network Theory

An arrangements approach using Network Theory is described in “Approaching Ship Arrangements from a Non-Spatial Point of View Using Network Theory” (Gillespie, 2012). This approach uses a network of compartment relationship requirements to generate feasible arrangements. The method does not fully generate an arrangement, but arranges and simplifies the arrangement problem and provides guidance for a designer or an optimization program to finish the arrangements. It does not consider compartment size constraints. This approach is very different from current ship arrangement practices, but may be useful for our research using the method of space global location and adjacency preferences.

This Network Theory method requires each compartment to have a relationship between itself and every other compartment on the ship. These relationships are the requirement to be adjacent or separated from one another. These relationships are then used to “partition” compartments based on these preferences creating “partition nodes” as shown in Figure 1-9. Each node then represents multiple compartments that are ideally placed in the same structural zone. This step in the approach is done to consolidate the compartments and make the allocation to structural zones simpler. It is important to note that when creating the nodes, their global ship location preference and whether they fit in a single structural zone is not evaluated.

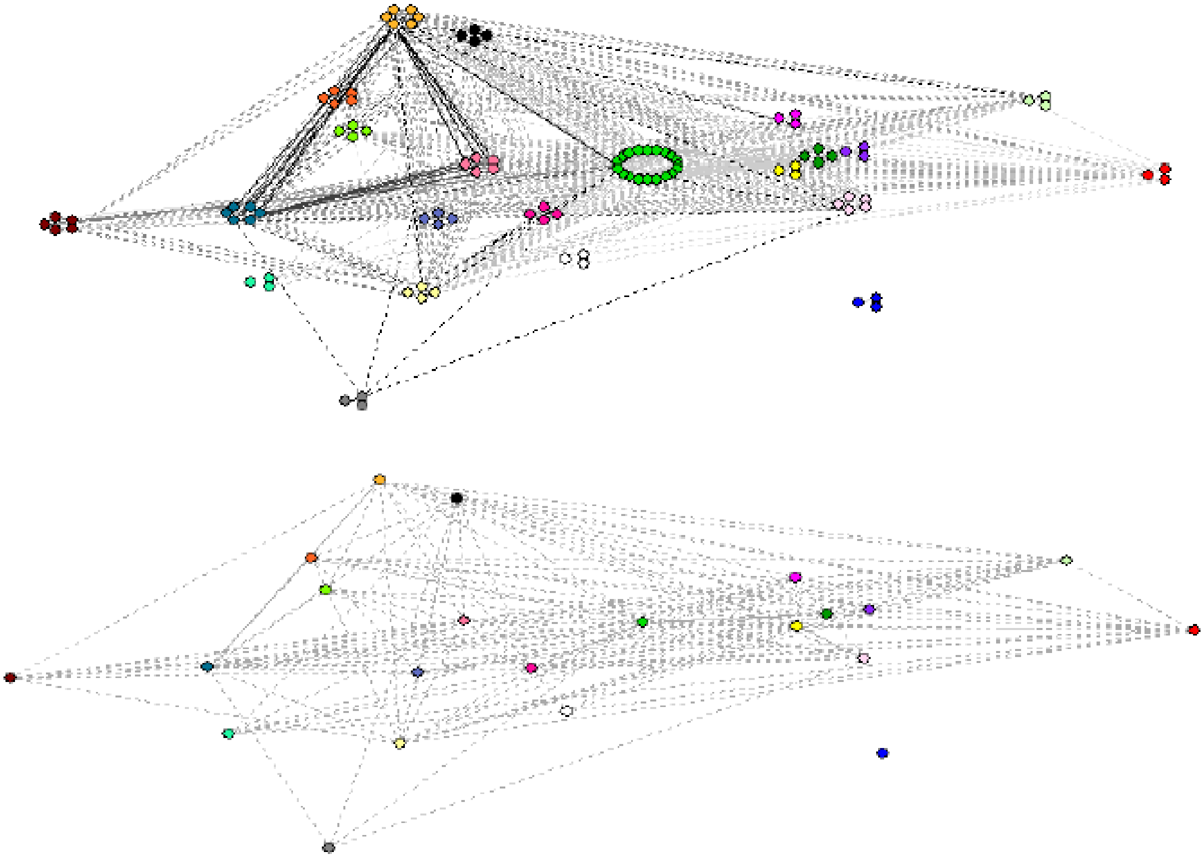
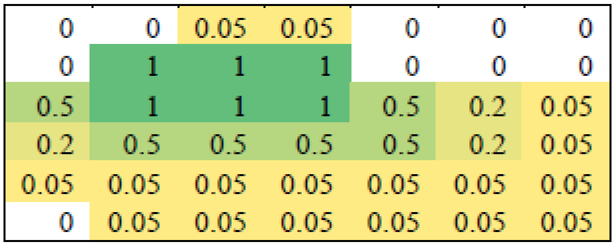


Figure 1-9 – Network Theory relationships between compartments (above) and the resulting partition nodes (below) (Gillespie, 2012)

Once the compartments are grouped into nodes, each node is analyzed and global location preferences are calculated using its assigned compartment preferences showing where it would ideally be placed, and where it would prefer not to be placed. An example of one set of single compartment location preferences is shown in Figure 1-10. The values in this example range from 0 to 1 where 0 is a location on the ship where the compartment cannot be placed and 1 is the most desired location on the ship. These compartment preferences are combined for compartments in each node to generate global cumulative zone preferences for each node. Each structural zone is a section of the ship that is determined by the user. These are usually defined between decks and bulkheads. An example of zone preferences for a single compartment node is shown in Figure 1-11. These values are used to place the nodes into the optimal structural zones generating a very simplified arrangement allocation. There is no consideration of whether an entire compartment group can fit in the structural zone that it prefers.



0	0	0.05	0.05	0	0	0
0	1	1	1	0	0	0
0.5	1	1	1	0.5	0.2	0.05
0.2	0.5	0.5	0.5	0.5	0.2	0.05
0.05	0.05	0.05	0.05	0.05	0.05	0.05
0	0.05	0.05	0.05	0.05	0.05	0.05

Figure 1-10 – Network Theory single compartment location preferences example (Gillespie, 2012)

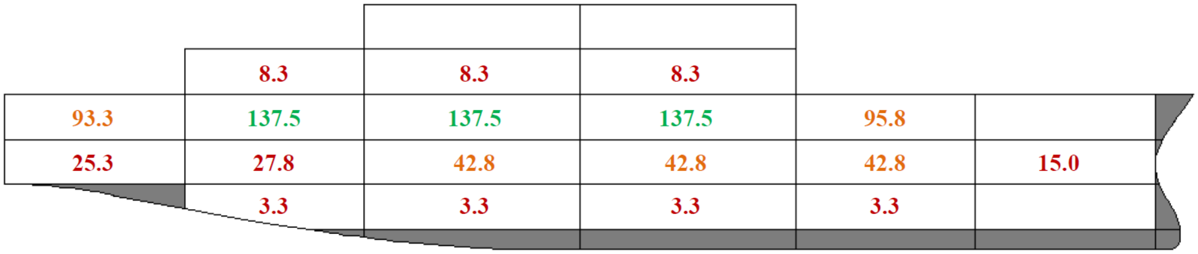


Figure 1-11 - Preference Values for a single Partition Node (Gillespie, 2012)

Preferences are then optimized by either the designer or an optimization agent such as the one used by ISA. The result is a ship that has groups of compartments that are separated from the majority of spaces that they need to be separated from, near spaces that they need to be near, and located in a preferred location on the ship. The compartment groups are assigned without consideration of whether they fit in the assigned locations.

Our VTPAM preliminary arrangements model uses some of the fundamentals described in this Network Theory approach. This Network Theory approach enables the grouping of compartments so that an entire group can be placed in the ship. This simplifies the allocation in the end, but there is no analysis of the size of the group to determine if there is enough space to fit the group in a particular location on the ship. VTPAM uses spatial preferences for each compartment to determine the arrangement allocation, but area requirements must also be met. Our method of analyzing how to use the space constraints is most similar to the 2.5D Arrangements Modeling discussed in the next section.

1.2.1.3 2.5D Arrangements Modeling

Another ship arrangements method that has been developed for monohulls is a 2.5D packing method described in "Simpler and Faster: A 2.5D Packing-Based Approach for Early Stage Ship Design" (Van Oers, 2012). This method modifies an earlier 3D packing technique to shorten the computational time. These packing techniques attempt to fit objects into their optimal location on the ship, similar to packing a suitcase. These objects include a ship envelope object, subdivision objects, equipment objects, system objects, and free area objects. After the objects are all packed, the combined weights and centers are used to evaluate the ship for draft and stability. If these do not meet the mission requirements, then the ship envelope object's width is increased incrementally and the packing is rerun until the draft and stability are met, or the ship is considered infeasible. This packing method was developed to be used for multiple designs in a user constrained design space where the hull and deckhouse envelopes are varied. A series of hull and deckhouse geometries is generated and each of these hulls is packed using this method in order to generate feasible designs for comparison.

The 2.5D method represents the ship envelope object (representing hull and deckhouse) in a 2D matrix using the x-z coordinate frame (longitudinal direction and vertical directions). At incremental x-z locations, the width of the envelope is measured and these widths determine if equipment, system, and free area objects can fit at that location. There are three “slices” in the ship to represent the port, starboard, and centerline slice translated into 2.5D. When an object is placed at an x-z location, the width of the object is subtracted from the chosen location on the “slice” that it is assigned. An example of the available widths and the remaining widths after equipment placement is shown in Figure 1-12 and Figure 1-13. This method places equipment objects into a predetermined ship design based on available area.

After all objects are placed, the weights and centers from all equipment are calculated and the design is analyzed for draft, initial stability, and hydrostatic performance and if the requirements for these are not met, then the ship envelope width is increased incrementally, and the packing process is rerun. This modification of the hull may have adverse effects on the resistance and power requirements for the ship. Any designs that are unable to generate a design where all of the equipment fit in the ship are infeasible. Only feasible ship designs in the design space then compared.

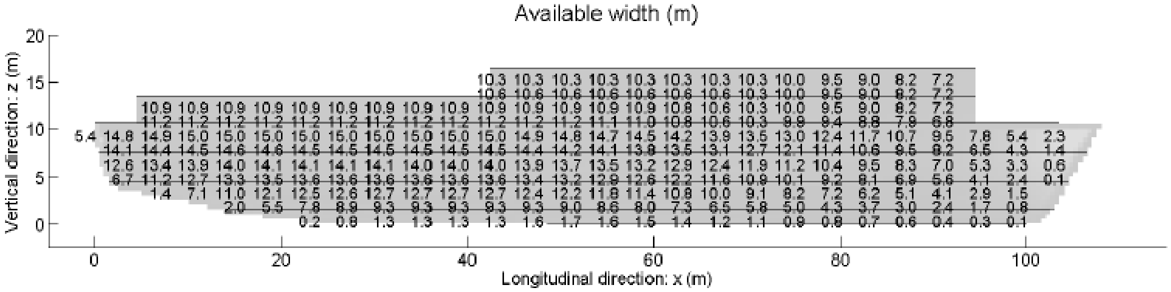


Figure 1-12 - 2.5D packing method available widths (Oers, 2012)

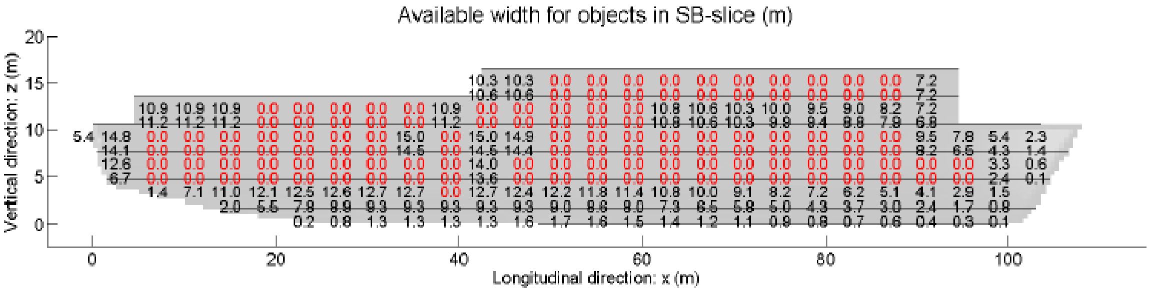


Figure 1-13 - 2.5D packing method available widths after object placement (Oers, 2012)

The 2.5D packing method allows for a rapid generation of ship arrangements for multiple ship parameters. This method was created for use with monohulls where width is the main driver for this method, so it is not known if multi-hull vessels can be used. This method is similar to the arrangement approach in VTPAM. The x-z location assignment method is very similar to the subdivisions that are generated, and a simplified area method allows for rapid location of compartments. VTPAM places entire compartments with their associated VCs into locations in the ship instead of individual equipment. One issue with the 2.5D packing method is the apparent lenience for objects to drastically move about the ship. The technique of adding and removing width allows for compartments to be added while still requiring there to be enough space for it. For VTPAM, it is very important that the ship have compartments placed in locations that are close to the user’s preferred locations for operability.

1.2.1.4 Design Building Blocks (DBBs)

The Design Building Block (DBB) approach is a method that is similar to AABB allocation and compartments to a ship, but it proceeds from the inside-out instead of the outside (hull) in. The DBBs are discrete elements that represent ship’s functions, sub-functions, and other elements. This method is performed manually by the designer and places DBBs into the ship based on “appropriate” criteria that incudes consideration for system architecture instead of sequentially for weight and space. This method allows a more through consideration of alternative arrangements. Figure 1-14 shows a summary of the DBB method.

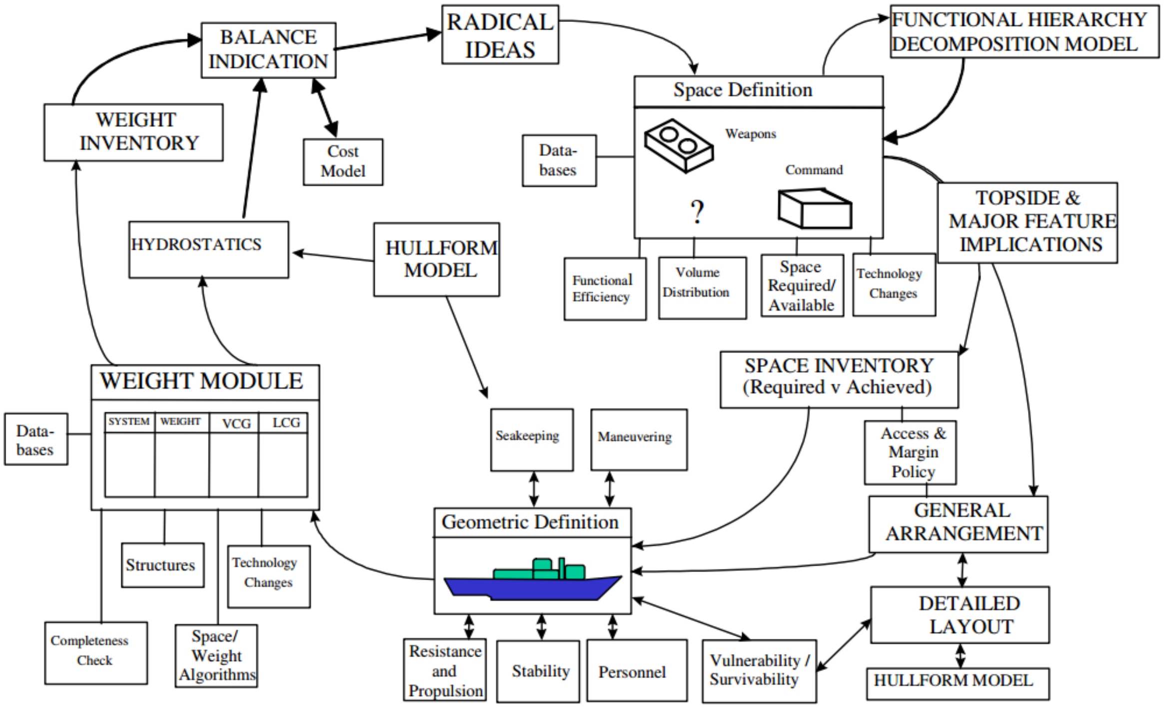


Figure 1-14 - DBB Approach Summary (Piperakis, 2012).

1.2.2 Existing Vulnerability Evaluation Tools

The purpose of our PA&V process is to locate compartments by priority in preferred locations, adjust locations to improve compartment hit probability, and assess system vulnerability for use in ship synthesis. In order for this to be accomplished, a system vulnerability analysis method is required. The vulnerability analysis method used in our PA&V process is most similar to the techniques that are used in the program Measure of Total Integrated Ship Survivability (MOTISS) (Sajdak and Raisig, 2011). Other programs that are available are the Advanced Survivability Assessment Program (ASAP) (Freitas, 2012) the Volumetric Integrated Vulnerability Analysis (VIVA) (Doerry, 2007), SURVIVE (Schofield, 2009), SURVIVE Lite, SURMA (SURMA, 2016), and PREVENT (Heywood and Lear, 2006). SURVIVE Lite has been used in a University College London (UCL) Design Research Centre (DRC) Study with DBBs for early stage design. This study is described in Section 1.2.2.5. Each of these tools uses a ships geometry, arrangements, vital component locations, and system architecture to evaluate the ship for vulnerability. These programs are designed to be used later in the design process. PA&V requires more simplified method that can be used in concept design.

1.2.2.1 Measure of Total Integrated Ship Survivability (MOTISS)

The Measure Of Total Integrated System Survivability (MOTISS) program is an analysis tool used to assess ship survivability during all stages of design. It uses Axis Aligned Bounding Boxes (AABBs) to represent ship geometry (compartmentation), vital components (VC), crew, distributed systems such as power and fuel oil, secondary detonators, etc. as shown in Figure 1-15. These AABBs represent the ship and all its components as boxes that approximate their size, shape, and location. AABBs are used to simplify 3D analysis by making all objects orthogonal to each other allowing for faster projectile ray tracing and blast propagation. In early stage design analyses, the ship is analyzed using a Damage Ellipsoid that defines the damage extents. This type of analysis is most often run as a vulnerability only analysis which provides an analysis of the damage caused by the initial threat (damage ellipsoid), but does not run the simulation through time. Typically everything that is touched by this ellipsoid is deactivated or killed; however a probability of being killed when touched by the ellipsoid may also be applied. Figure 1-16 shows an example of the Damage Ellipsoid. The ellipsoid's size is determined based only on the threat and defines the extent of damage that would result from the given threat. This definition of damage extents by damage ellipsoid is conducted in place of ballistic tracking, blast propagation, and component lethality application at this low fidelity analysis. VC AABBs must be intersected directly, not just their surrounding structure. This method is a much faster method to approximate ship VC and hull damage caused by a threat detonation than the higher fidelity MOTISS analyses used as the ship design process moves forward.

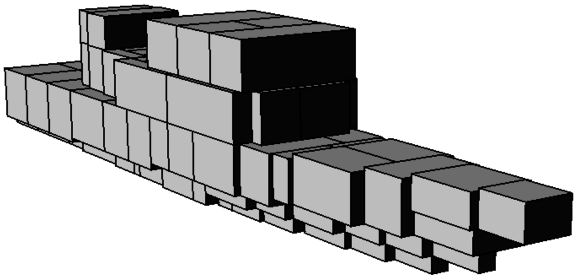


Figure 1-15 - Example of a MOTISS AABB Model

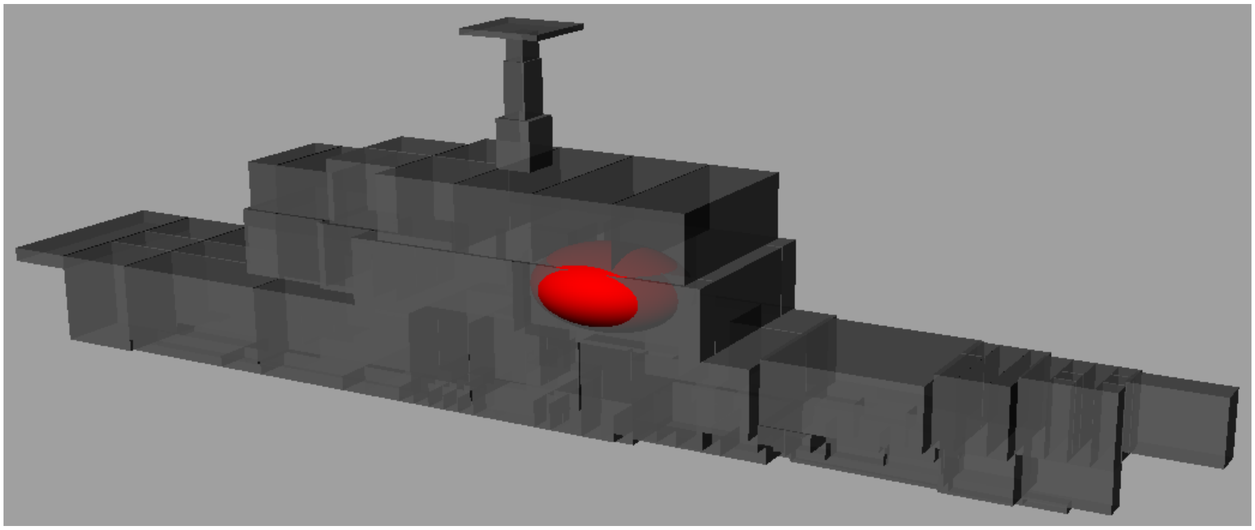


Figure 1-16 - MOTISS Damage Ellipsoid example

As the ship design process moves forward both the MOTISS model and the techniques and damage mechanisms implemented during a MOTISS analysis see an increase in fidelity. Detailed ship structure including materials, plate thicknesses and stiffening along with insulation are added to the MOTISS model. The distributed systems model is expanded to include additional systems and valves/switches are inserted where necessary to along for system realignment and control (both automatic and manual operated by crew). Vital components can now be assessed not solely based on their physical availability, but also by their ability to maintain sufficient inputs/outputs of fuel oil, fresh water, etc. coming from the distributed systems. Damage control systems, such as fire suppression and dewatering are added along with the specific details of their operation. A detailed crew movements model is incorporated comprised of all doors, hatches, ladders, etc. along with a routing system which defines how crew members may move throughout the vessel. Crew actions such as damage control party actions, firefighting team deployment, etc. may be defined. These model additions along with further incorporated environmental (both internal and external) data, component specific lethality criteria (kinetic energy, thermal, shock and saturation limits) etc. now along for a higher fidelity vulnerability and recoverability analysis. In the full vulnerability/recoverability MOTISS analysis mode, time is introduced so that the threat hits the ship, detonates, and the blast propagation (along with ballistic penetration and/or jetting) is analyzed and continues or is stopped as it damages structure and VCs. After the initial damage has been fully determined, the program now begins a full recoverable routine which assesses the progression of fire and flooding in the ship along with any secondary detonations. As VCs are damaged, ship systems are assessed and when they can no longer function, they are deactivated. As the time-based analysis continues, the systems may be deactivated if their VCs are deactivated or lose their necessary inputs, depending on their architecture. During this analysis, crew members are being moved throughout the vessel as needed to realign systems, fight fires, attend to flooding etc. This method uses many analyses to assess ship system status after hits which provides sufficient data for probabilistic results to be calculated.

The VTPA&V process uses similar techniques to the MOTISS analysis tool. The use of AABBs to represent the ship supports a rapid vulnerability analysis. The analysis of ship system loss determines the functionality of the ship after a hit so these results can be used to assess vulnerability in the PA&V process. The MOTISS high fidelity vulnerability/recoverability analysis method uses small increments of time and tracks damage at many time steps. This is too detailed for early stage design where less detailed comparisons between ships are sufficient for early design decisions. A Modified Damage Ellipsoid analysis technique is used by the PA&V for vulnerability analysis, which adjusts the damage extents to consider the ship structure in addition to the threat characteristics, but it calculates damage extents based on energy dissipation, not in a time-based propagation which is much faster.

1.2.2.2 Advanced Survivability Assessment Program (ASAP)

The Advanced Survivability Assessment Program (ASAP) was developed by the Naval Surface Warfare Center, Carderock Division as a tool to simulate AIREX and UNDEX threats on US Navy surface ships (Freitas, 2015). These threats are assessed using physics-based codes called Data Driven Modules (DDMs) which are developed separately from ASAP then incorporated to consider specific physical phenomena. The damage from these threats are simulated through a Computational Fluid Dynamics (CFD) code called the Blast Propagation Module (BPM) that is contained in a probabilistic wrapper that uses modeled VC locations. The geometry of the ship and VCs are resolved using a tetrahedral grid approach that utilizes cell-centered elements, which are nonaligned grid blocks. The BPM threats are modeled using equivalent TNT to determine the explosive products of detonation. This program calculates and reports the static and dynamic pressures, impulse, and records the velocity, pressure, wave speed, and density of the blast through time.

To save computational time, the blast for the PA&V process does not propagate through time, but the extents of the damage are determined based on energy dissipation. The PA&V process also uses AABBs to represent the ship instead of the tetrahedral grid, and VCs are not explicitly modeled in the PA&V process.

1.2.2.3 Volumetric Integrated Vulnerability Assessment (VIVA)

The Volumetric Integrated Vulnerability Assessment (VIVA) program was developed to study the vulnerability of a ship by damaging compartments, with the deactivation of ship systems and missions resulting from this. This method is not currently in use, but has some similar methods to the vulnerability assessment for the PA&V process. The methodology for this program is shown in Figure 1-17. The ships are modeled using ship synthesis programs such as the Advanced Surface Ship and Submarine Evaluation Tool (ASSET) and a hit point distribution is determined from the threat parameters as shown in Figure 1-18. The damage and the fire spread are then calculated as described in Figure 1-19. The program determines the Probability of Ship Loss, Mission Loss, and Mobility Loss after the ship is hit. The PA&V process uses a similar vulnerability definition that uses ship system, and mission system loss for vulnerability calculation.

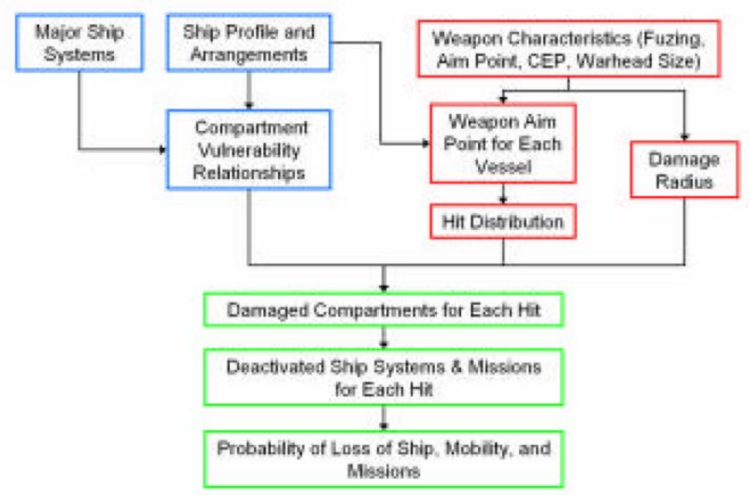


Figure 1-17 - Methodology of VIVA (Doerry, 2007)

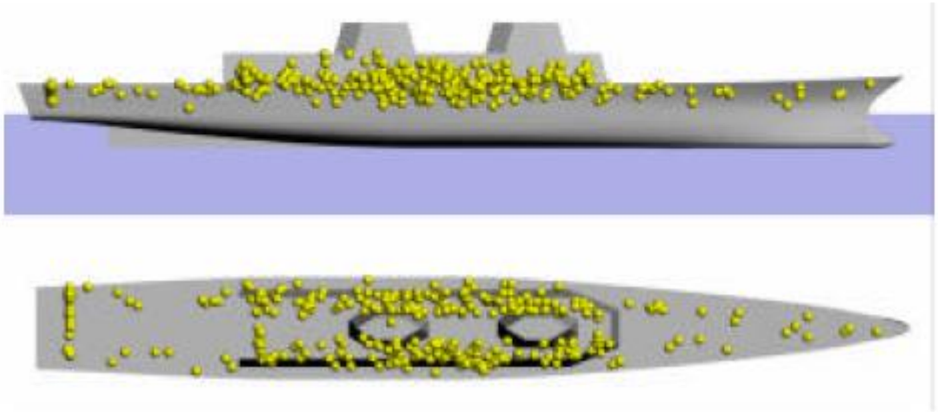


Figure 1-18 - VIVA Hit Distribution example (Doerry, 2007)

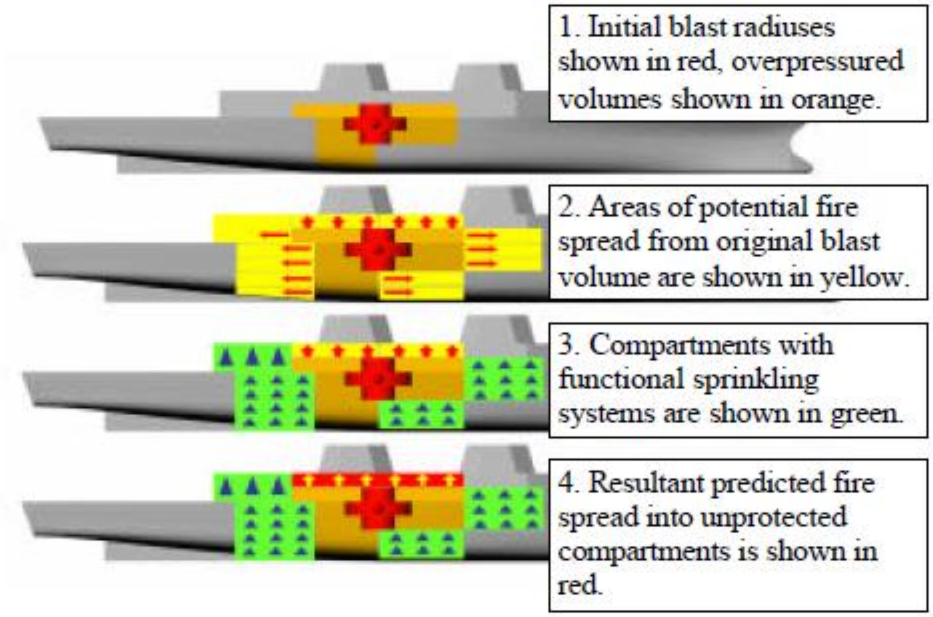


Figure 1-19 - VIVA Fire Spread Model (Doerry, 2007)

1.2.2.4 Brief Overview of Other Vulnerability Evaluation Tools

There are other survivability evaluation tools that are currently in use or have been used recently and some of these have been used in ship design applications. Some use methods that are similar to the VTPA&V process. These include SURVIVE, SURVIVE lite, SURMA, and Prevent. These tools are briefly described below. They use similar geometry to define the ship and ship systems and similar analysis components, but our C&RE approach, level of detail, and need for fully hands-off execution of many designs requires a very different implementation and different analysis methods. The most complete early-stage design implementation of survivability tools was recently performed by the University College London Design Research Centre (Piperakis, 2012). This study is described in Section 1.2.2.5.

“SURVIVE is the UK’s naval platform survivability tool” (Schofield, 2009). The general method that SURVIVE uses is illustrated in Figure 1-20. The inputs for the SURVIVE analysis include a ship represented by cuboid-shaped building blocks similar to the AABBs that are used in the VTPA&V, but generated from the inside-out and not the outside-in and not necessarily aligning with SDBs. Vital components (VCs) are represented by simple shapes or user-defined shapes. These are not required to be axis-aligned. The VTPA&V does not use shapes, but simply assigns VCs to compartments and subsequently to SDBs. The SURVIVE ship functionally is specified by logical systems using these VCs. The threat(s) and susceptibility scenarios are defined by user inputs and these determine the hit distribution of the analysis. This hit distribution is based on susceptibility results, or the user can choose to use a uniform grid distribution. SURVIVE analyses the damage including, weapon penetration, internal and external blast, fragmentation, underwater shock, whipping, and bubble effects. The flooding and stability, structural damage, fire and smoke, and magazine detonations are tracked though time based on the damages from the threat(s). The vital equipment and systems vulnerability is checked and the recoverability from damage is analyzed.

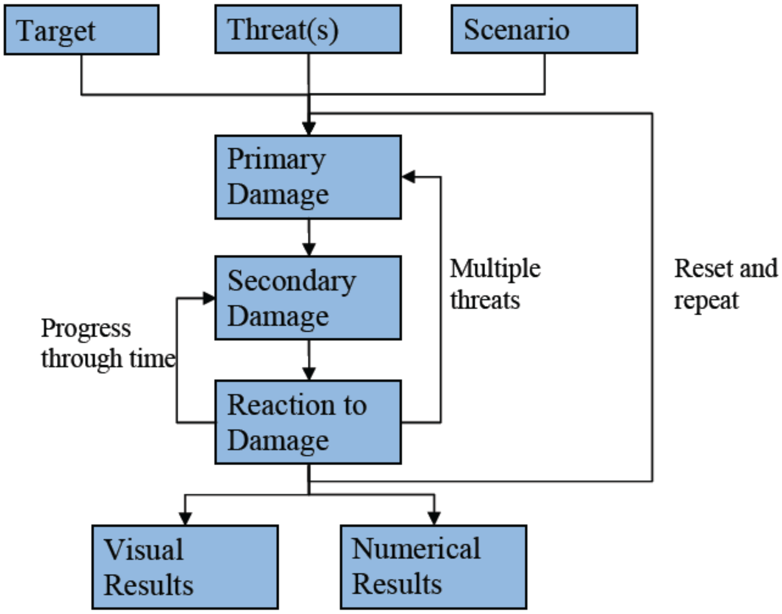


Figure 1-20 – SURVIVE simulation method

SURVIVE Lite is a version of the SURVIVE program that was created to quickly assess ship vulnerability in early stage design. This version uses a grid approach for the hit distribution and simplified ship systems. SURVIVE Lite is capable of being used with only major systems without the modeling of cables and piping. It is for these reasons that this vulnerability assessment was chosen as the vulnerability assessment to be used with the Design Building Block approach described in Section 1.2.1.4 for an early stage design process used by University College London (Piperakis, 2012), described in Section 1.2.2.5.

SURMA is the Survivability Manager Application and analysis survivability including susceptibility, vulnerability, and recoverability (SURMA, 2016). SURMA uses preexisting compartment arrangements to create the ship model. The susceptibility is assessed through considering underwater magnetic signatures and radar cross section. AIREX vulnerability is assessed using detonation pressure histories and quasi-static pressure build-ups for confined blasts. SURMA also analyzes UNDEX threat damage. In the current PA&V process, UNDEX is not considered. A single degree of freedom dynamic structural response is calculated and the structural loss is analyzed. If flooding occurs, a stability analysis is performed. Equipment are checked for kill and system functionality is analyzed. After the damage is assessed, a recoverability analysis is performed.

"PREVENT stands for PREliminary Vulnerability Evaluation of eNemy Threats" (Heywood and Lear, 2006) and is a simplified tool to assess the effects of blast, fragmentation, underwater shock, and flooding. This is done using 2D ship and pseudo- 3D analysis. The input for PREVENT is shown in Figure 1-21. The ship is defined by decks and transverse sections based on user defined dimensions creating a grid of “cells”. Compartments are assigned to these “cells” by the user. The structure of the decks and bulkheads at “cell” boundaries is defined as thin, medium, and thick. Equipment is assigned to a “cell” by a number and the lethality of the equipment is defined. Hit distribution is defined by selecting the “cell” that a hit will detonate inside. Vulnerability is assessed by comparing the blast overpressures, shock accelerations, flooding, and fragmentation limits with the equipment’s lethality. This causes equipment loss, and system loss. The system loss then determines vulnerability.

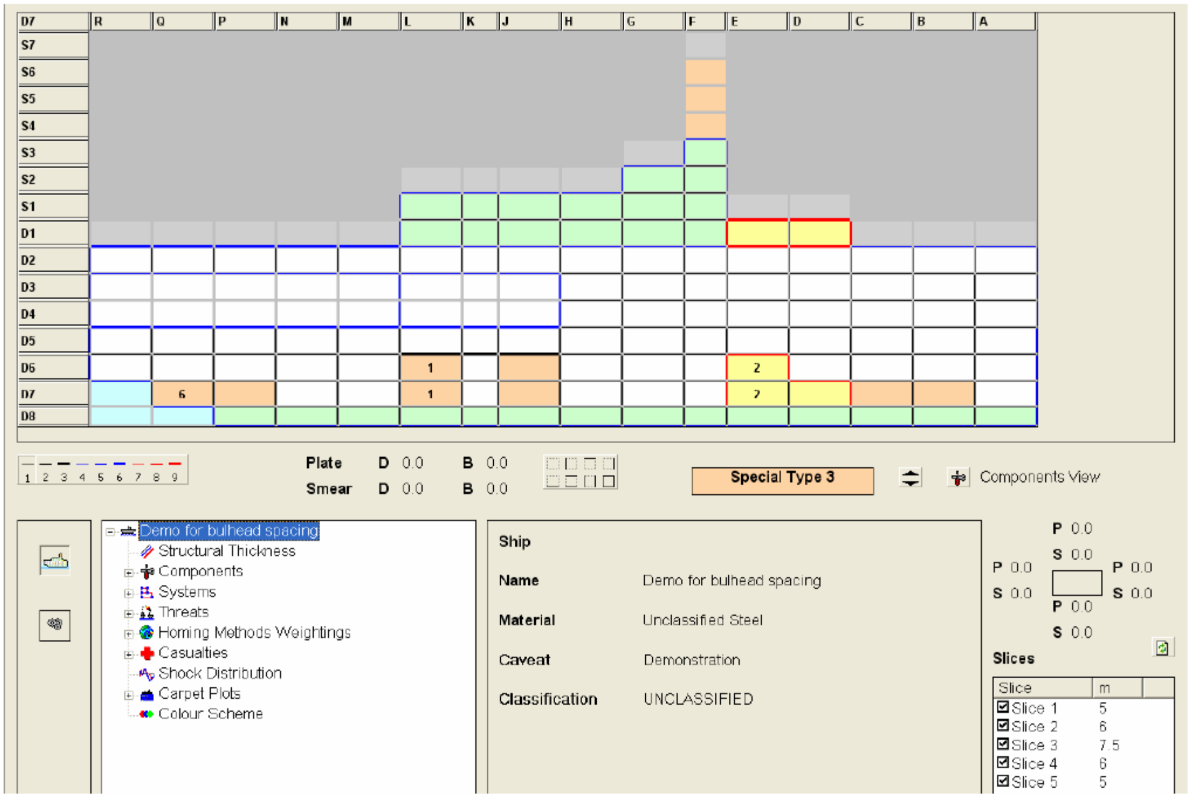


Plate D 0.0 B 0.0

Smear D 0.0 B 0.0

Ship

Name Demo for bulhead spacing

Material Unclassified Steel

Caveat Demonstration

Classification UNCLASSIFIED

Slice	m
☑ Slice 1	5
☑ Slice 2	6
☑ Slice 3	7.5
☑ Slice 4	6
☑ Slice 5	5

Figure 1-21 - PREVENT User Interface

1.2.2.5 University College London Design Research Centre Study

The University College London Design Research Centre proposed an approach to incorporate survivability in early stage design that is similar to the PA&V process. This method is described in the paper Integrated Approach to Naval Ship Survivability in Preliminary Ship Design (Piperakis, 2012) and integrates preexisting design and survivability programs to generate a design considering survivability. This approach uses the architecturally oriented Design Building Block (DBB) approach to generate a preliminary ship design as described in Section 1.2.1.4. The design is analyzed for susceptibility, vulnerability and recoverability. The susceptibility is determined using SPECTRE and Combat Systems Effectiveness Exercise (CSEE). The vulnerability is determined using SURVIVE Lite (described in Section 1.2.2.4). The vulnerability is rolled up to two major capabilities "Move" and "Fight". The fight system is made up of Gun, ASM, Aft SAM, Fwd SAM, and Helicopter systems. The recoverability of the design is estimated using Performance Measures (PMs) that are calculated in SURVIVE Lite and Paramarine. The result of this integrated design approach is a ship design created using DBBs with a survivability metric value that is used to improve ship survivability early in the design process. This is very similar to what the VTPA&V process does, but the process is not as automated.

1.3 Thesis Objective

It is the objective of this thesis to develop and describe a method to generate a preliminary ship arrangement model that has sufficient detail for a vulnerability analysis in concept design. This is accomplished in the context of a PA&V process.

1.4 Thesis Outline

Chapter 1 of this thesis describes the need, basics, and fundamentals for this research and where and how it fits into the design process. Chapter 2 describes the current Virginia Tech concept design (C&RE), PA&V process, and VTVM, and where this research is used. Chapter 3 describes the development and steps of the VTPAM process, and the creation of the representative hullform geometry and preliminary arrangements. Chapter 4 is a case study where VTPAM is used in the PA&V process to create a feasible ship that can be used to evaluate vulnerability. The discussion of the results and conclusions of this thesis are presented in Chapter 5 along with some future work that can help VTPAM.

CHAPTER 2 - C&RE CONSIDERING VULNERABILITY

2.1 Concept and Requirements Exploration (C&RE)

Virginia Tech's C&RE process shown in Figure 1-1 determines a non-dominated frontier that represents the relationship between cost, effectiveness, and risk for non-dominated (best effectiveness for given cost and risk) designs in the design space. The non-dominated frontier is used to select the most appropriate designs for further development and assessment. The C&RE process starts with the mission needs and the Initial Capabilities Document (ICD), identifies ship design parameters, generates ship design models, searches the design space, and creates a Non-Dominated Frontier (NDF) of possible ship designs. From this, baseline concept designs can be selected and ship requirements can be determined.

The C&RE process begins by expanding on the ICD by developing a Concept of Operations (CONOPS), Naval Mission Essential Task List (NMETL), Design Reference Mission (DRM), Operational Situations (OpSits), and Required Operational Capabilities, (ROCs). These are used to create Operational Effectiveness Models (OEMs), Measures of Performance (MOPs), and Measures of Effectiveness (MOEs). Once this is complete, pertinent technologies are identified and a complete study of similar ships is done. This study compares the characteristics and technologies of existing ships that have similar mission needs and uses these to establish a baseline representative design at the start of Hull and Deckhouse Exploration, Propulsion, Electrical, and Auxiliary Exploration, and Mission Systems Exploration. These explorations use the characteristics and technologies to explore and refine the design space. This includes hullform and deckhouse geometry, structures, propulsion systems, electrical systems, and mission systems (ie. AAW, ASW, ASUW).

The process then continues with an Arrangements and Architecture Exploration, Vulnerability and Susceptibility Exploration, and Manning and Automation Exploration. The Arrangements and Architecture Exploration is the primary focus of this thesis and is done using a Preliminary Arrangements and Vulnerability (PA&V) process. Designs with various combinations of systems options and representative arrangements are assessed in a vulnerability exploration, which analyzes each system combination and representative design for vulnerability. These explorations determine Design Variable (DV) ranges and Design Parameter (DP) values that define the design space for ship synthesis and calculate system option vulnerability values for assessing effectiveness.

The Ship Synthesis Model assembles designs and analyzes them for feasibility, cost, risk, and effectiveness. It is used in a Multi-Objective Genetic Optimization (MOGO) to search the design space and identify a non-dominated frontier that spans the range of feasible ship design options, and represents the trade offs between feasible design cost, risk, and effectiveness. The Ship Synthesis Model is shown in Figure 2-1 as it is implemented in Phoenix Integration’s Model Center program.

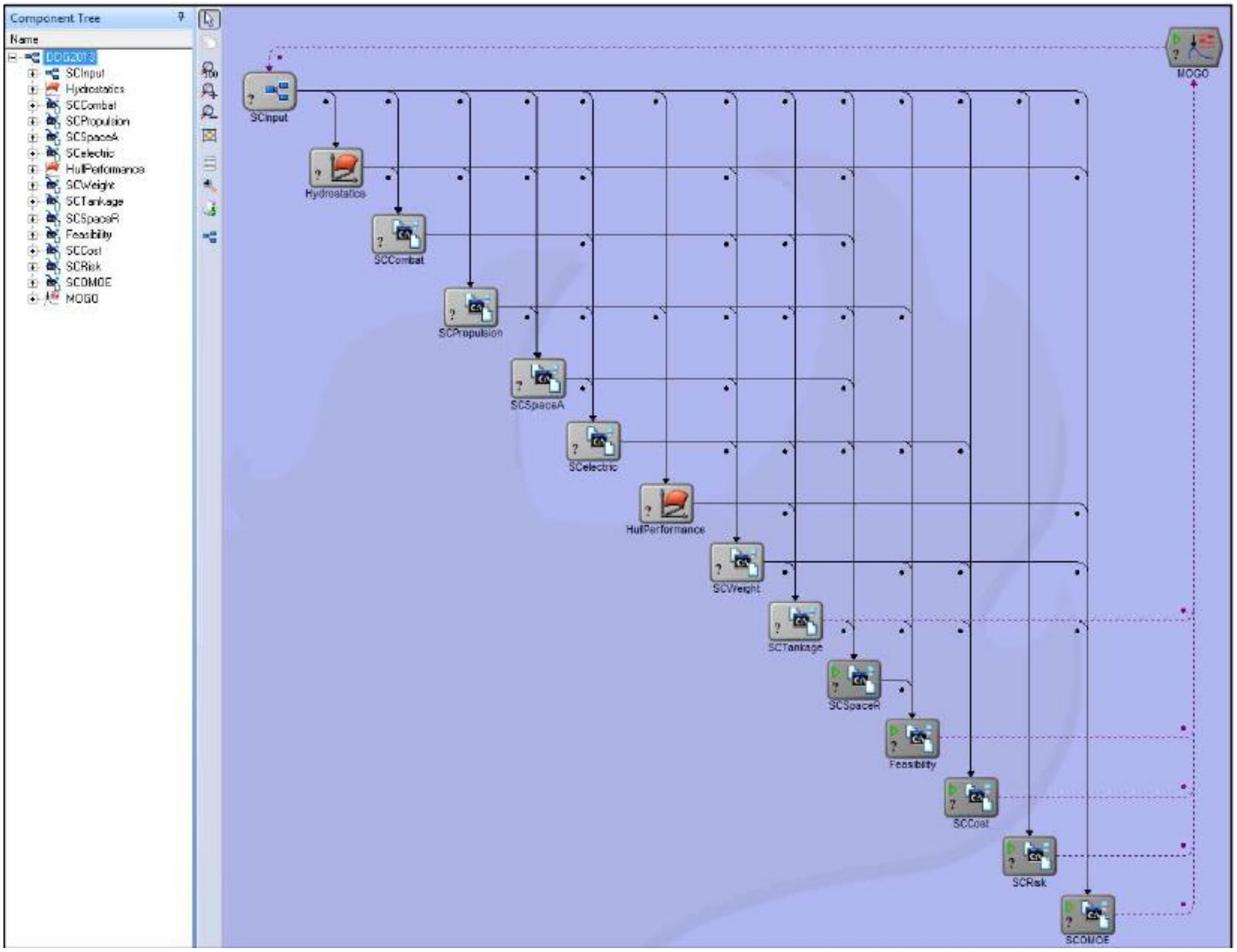


Figure 2-1 - Ship Synthesis Model and MOGO in Model Center (MC)

Typical non-dominated frontiers are shown in Figure 2-2 and Figure 2-3. The data points in these figures each represent feasible non-dominated ships for the design space. They are represented in 2-D and 3-D so that the relationship for risk, cost, and effectiveness can be visualized. Figure 2-2 shows the 3-D frontier, which has effectiveness on the vertical axis, with technology risk and total ownership cost on the horizontal axes. Figure 2-3 is the 2-D representation with effectiveness on the vertical axis, cost on the horizontal axis, and risk shown in a color based depiction where red is the highest risk and blue is the lowest risk. There is no single optimal design, but often preferred designs fall on the extremes of the frontier and at sharp decreases in effectiveness/cost and effectiveness/risk slopes in the graphs called “knees”.

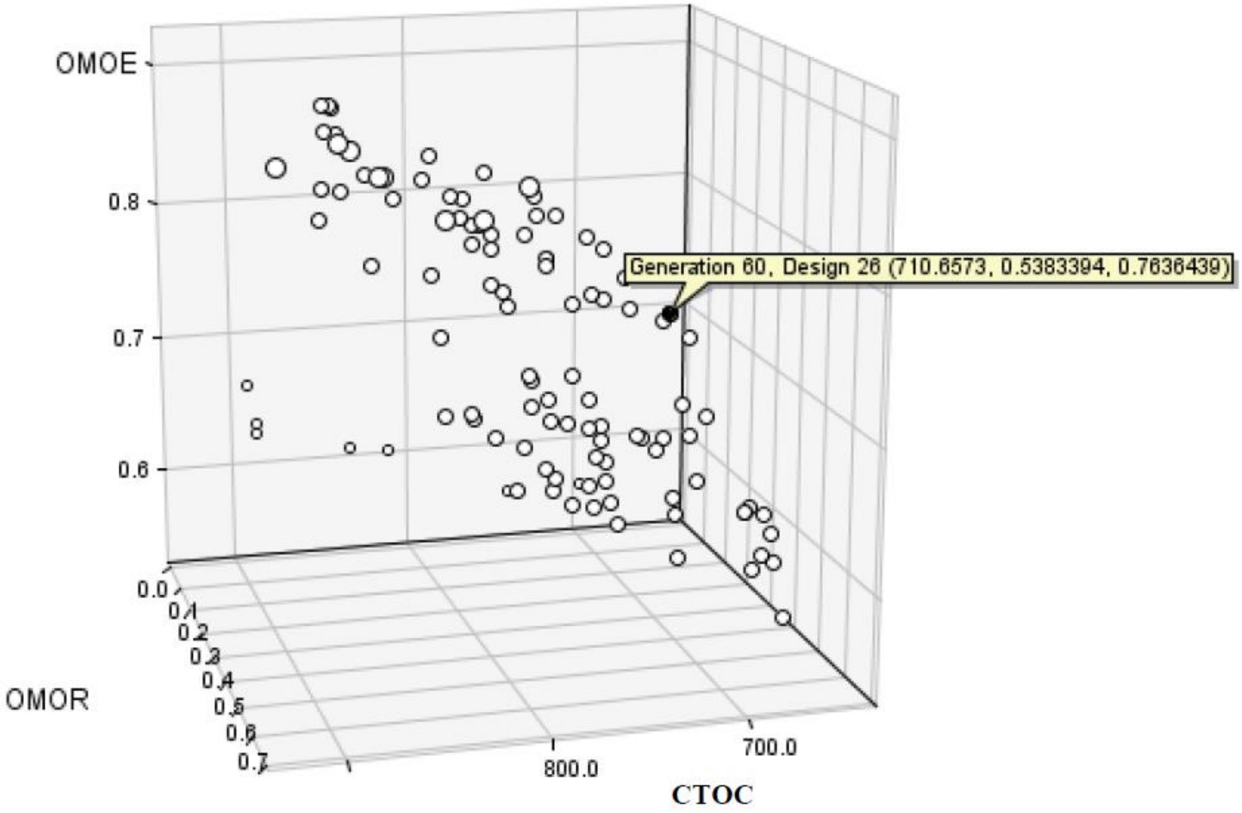


Figure 2-2 – 3-D Non-Dominated Frontier

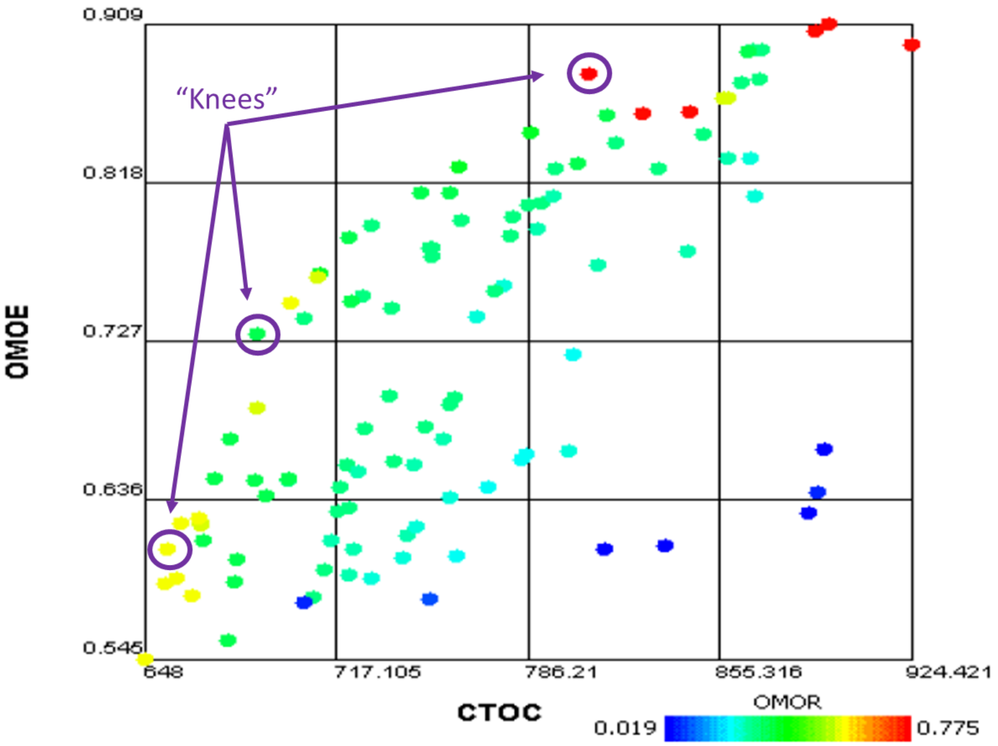


Figure 2-3 - 2-D Non-Dominated Frontier

2.2 Preliminary Arrangements and Vulnerability (PA&V) Process

This thesis focuses on the Preliminary Arrangements and Vulnerability (PA&V) Process and particularly the preliminary arrangements model (VTPAM) which is part of the C&RE Process. This section provides and overview of the PA&V process including VTPAM. VTPAM is discussed in detail in Chapter 3. The PA&V process is outlined in red in Figure 1-1, and is made up of two parts, preliminary arrangements and vulnerability assessment. Vulnerability results from this process are also used later in the C&RE ship effectiveness analysis. Since the MOGO and SSM must evaluate thousands of designs when searching the design space, we assume that vulnerability is most sensitive to system option selection, architecture, and arrangements in the ship to reduce the number of design variables and the resulting analysis time in the PA&V process.

Only one hullform variable, LOA, is used. Representative ships are generated for each combination of system options (250+ options), sized based on displacement by varying LOA and keeping other hullform DVs, mostly ratios, constant for all representative designs. Vulnerability (used for the OMOV) is assessed for each representative design/system combination and these OMOVs are used in the MOGO OMOE calculation for all designs based on their system combinations only. Preliminary arrangements and vulnerability assessment are not performed for all MOGO designs which saves significant computational time.. The PA&V process is shown in Figure 2-4. The ModelCenter model for execution this process is shown in Figure 2-5.

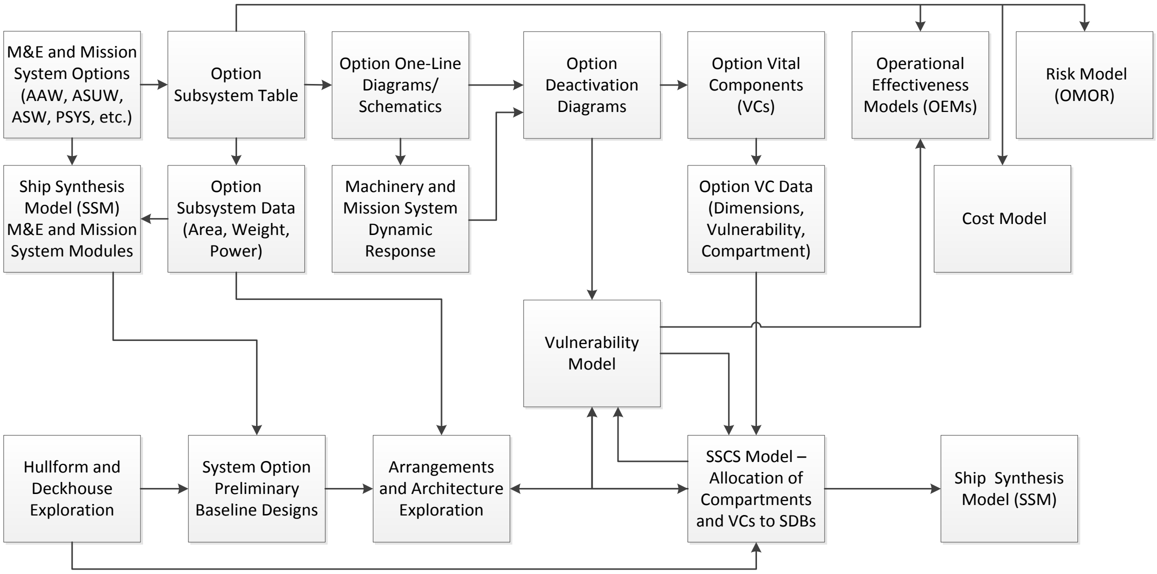


Figure 2-4 - Preliminary Arrangements and Vulnerability (PA&V) Process

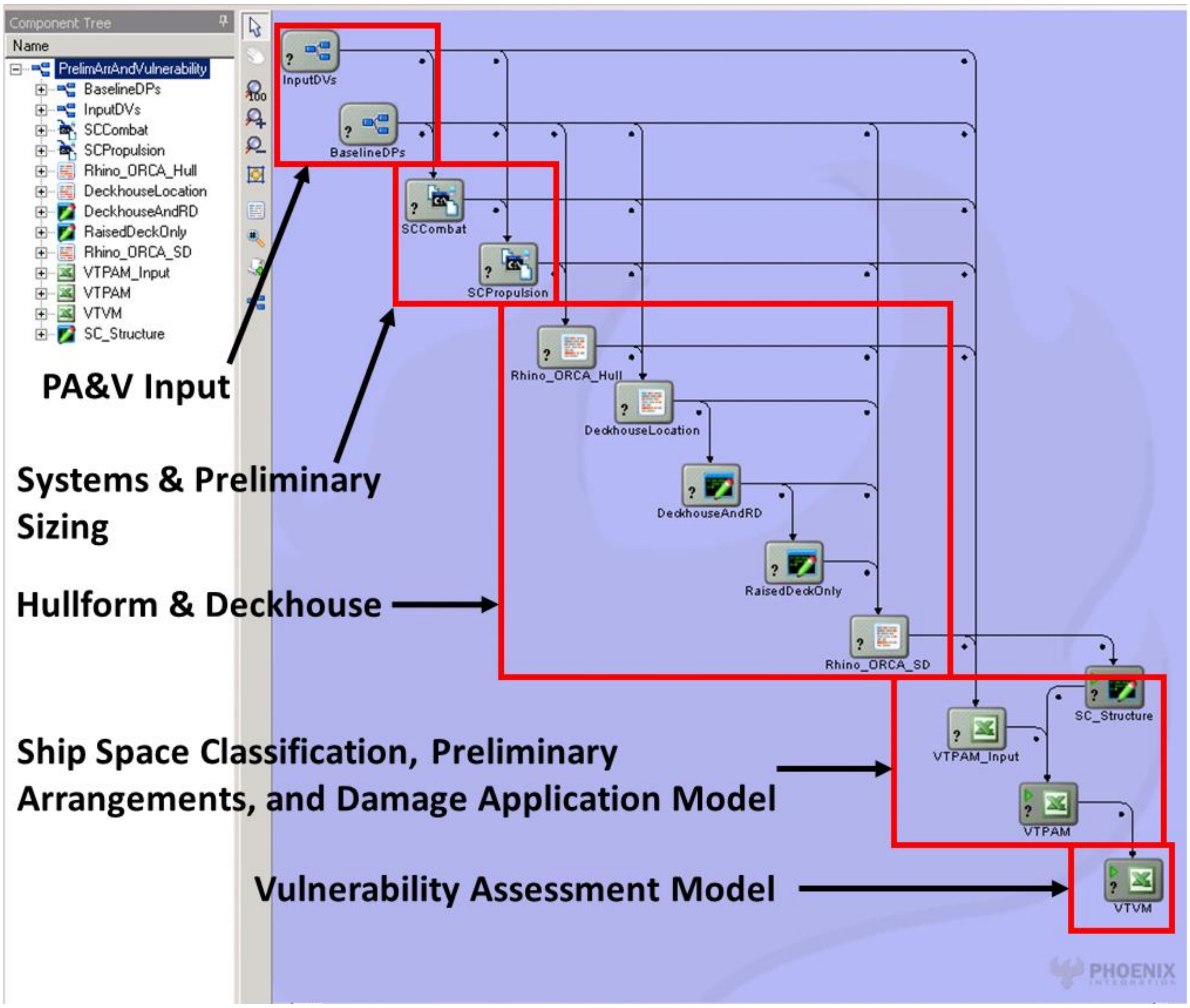


Figure 2-5 - Preliminary Arrangements and Vulnerability Exploration Model in ModelCenter

The PA&V process begins with the mission specified in the DRM and OpSits documents, selects technologies, and defines options for power, propulsion, and combat systems consistent with those chosen for the C&RE. These options include data for system and component weight, volume, Vital Components (VCs) and system architecture consistent with the preliminary Design Variables (DVs) and Design Parameters (DPs) that make up the design space being analyzed. These inputs are used to create feasible representative hullforms and preliminary arrangements that are used to evaluate vulnerability. These inputs also determine the compartments required on each representative design and prioritized preferred locations for each of these compartments.

The hullform is created in Rhino/ORCA3D based on the hullform DVs and DPs as a 3-Dimensional geometry with decks and bulkheads. An example of this hullform is shown Figure 2-6. Subdivision is created considering design space geometric characteristics, the floodable length, tankage, and general large space locations (i.e. for machinery rooms). These locations are determined using simplified parametrics (Winyall 2012).

Figure 2-6 - Preliminary 3-D Hullform with major subdivisions

The hull and subdivision are used in the Virginia Tech Preliminary Arrangements Model (VTPAM) to create a simplified subdivision block (SDB) geometry of the ship as shown in Figure 2-7, where the x, y, and z locations of the subdivision intersections are used to define Axis Aligned Bounding Boxes (AABBs) that represent subdivision blocks between adjacent bulkheads and decks. This simplified geometry is used by the VTPAM to generate preliminary arrangements, assign compartment and VCs locations, and evaluate vulnerability. This model has less than a 10% error in the representation of the curvilinear 3-D hullform volume, which is suitable for concept design exploration.

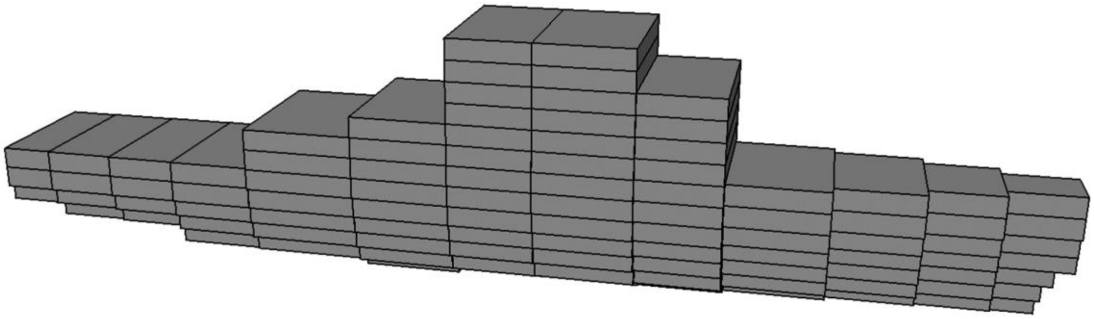


Figure 2-7 - Subdivision block model using Axis Aligned Bounding Boxes

The AABB model is then analyzed in a simplified hit assessment. This hit assessment considers only the ship geometry and the threat parameters. The method for this hit assessment is described in Definition of Damage Volumes for the Rapid Prediction of Ship Vulnerability to AIREX Weapon Effects (Stark, 2016) and is discussed in Section 3.2.3. Multiple threats are analyzed for each design. For each threat a hit distribution (approximately 250 hits) is generated based on the given threat parameters. An example of results from one threat hit distribution is given in Figure 2-8. Damage extents are calculated for each hit in the hit distribution and a probability of damage is calculated for each SDB for each threat. Figure 2-9 shows an example of the probability of damage probability for each SDB based on the hit distribution of a single threat. These probability of damage probabilities are normalized for all threats based on each threat's probability of encounter. These collective SDB hit probabilities are used to adjust compartment locations after an initial placement based only on operational preferences and required area.

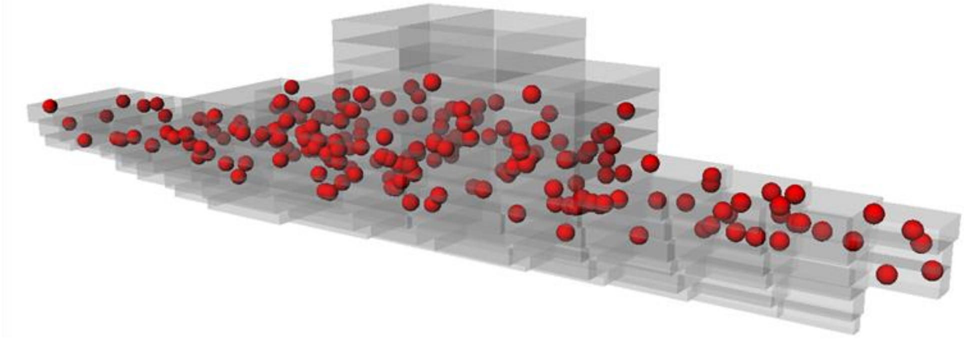


Figure 2-8 - Initial Damage Assessment Hit Distribution Example

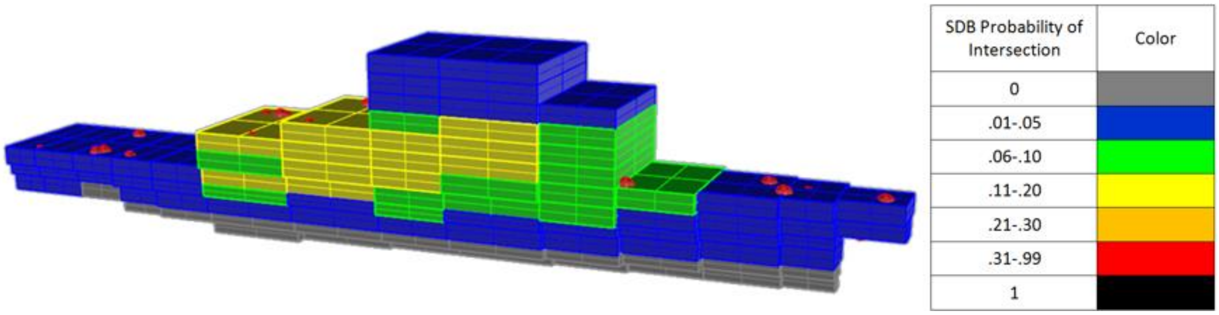
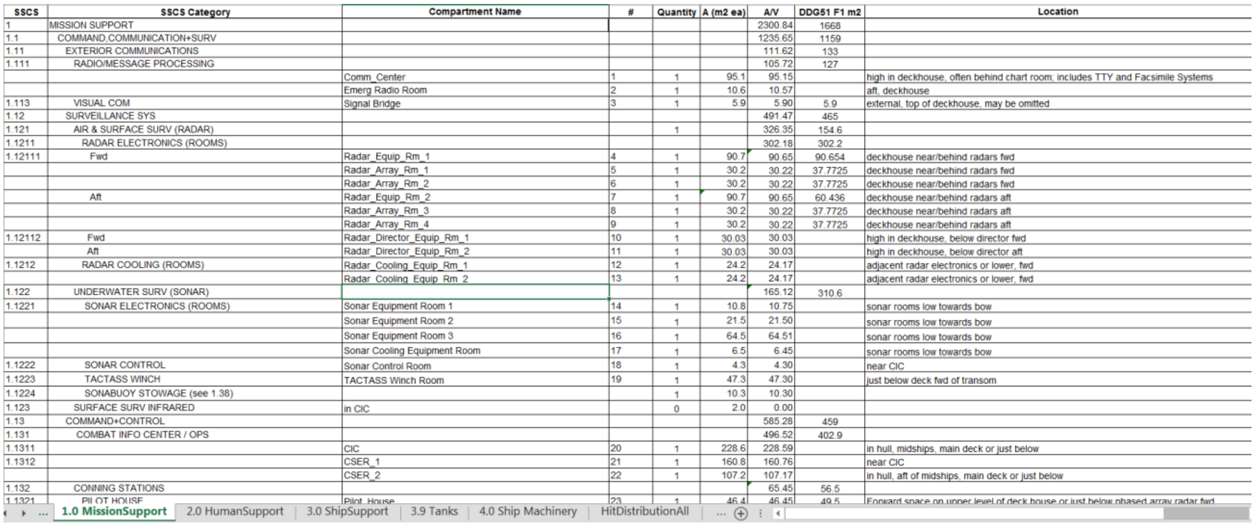


Figure 2-9 - Initial Damage Assessment SDB Damage Probability Score Example

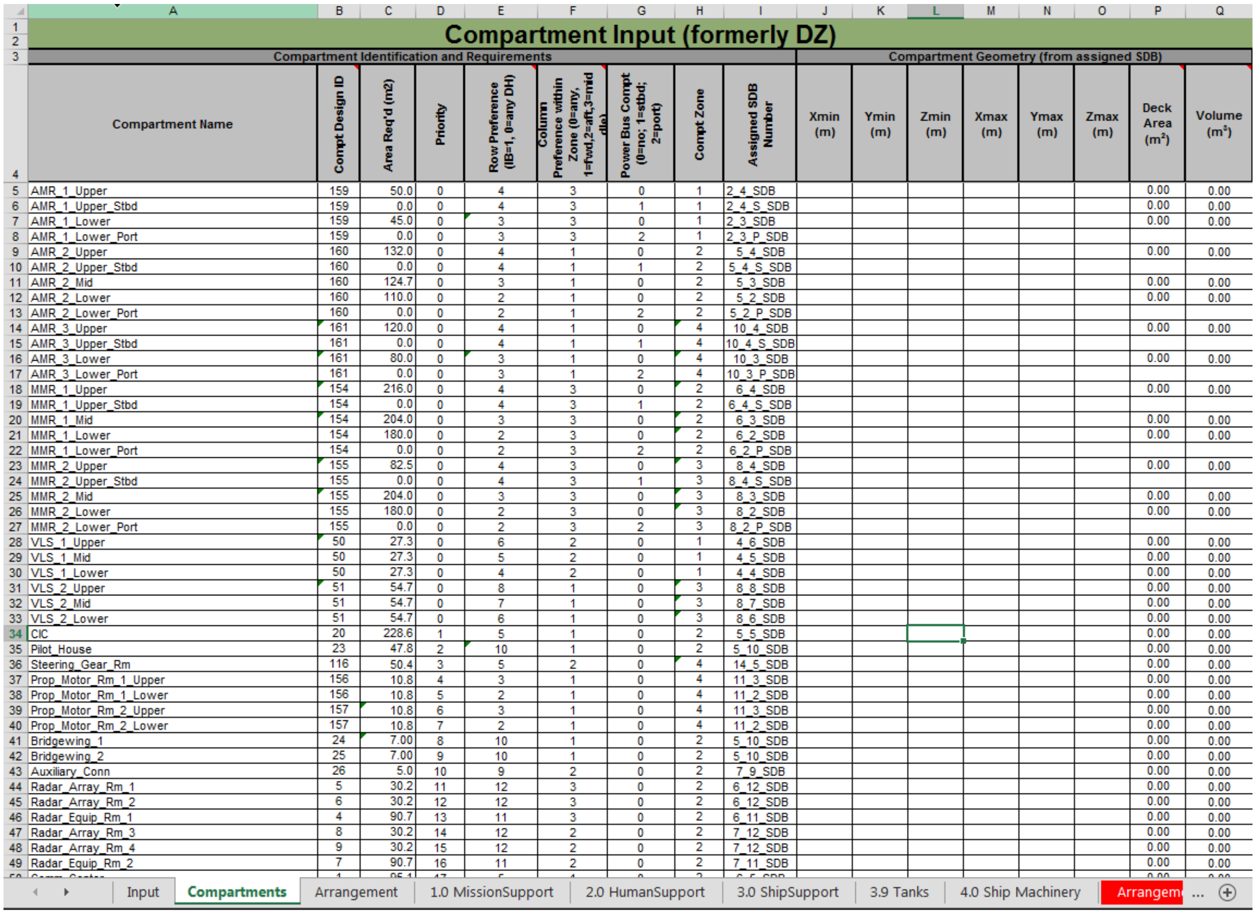
The preliminary arrangements are created based on required compartment area, compartment operational location priority in the SDB model, and the SDB hit probabilities. The compartment areas are calculated based on ship and ship system characteristics for the VCs that are located in each compartment. VCs are assigned to SDBs along with their compartments. Worksheets in VTPAM are used to specify the priorities and preferred locations for each compartment and to calculate required area. An example of one of these sheets for calculating area or space is shown in Figure 2-10. Five Ship Space Classification System (SSCS) worksheets estimate the area needed for mission support, human support, ship support, tankage, and ship machinery compartments.



SSCS	SSCS Category	Compartment Name	#	Quantity	A (m2 ea)	A/V	DDG51 F1 m2	Location
1	MISSION SUPPORT					2300.84	1668	
1.1	COMMAND,COMMUNICATION+SURV					1235.65	1159	
1.11	EXTERIOR COMMUNICATIONS					111.62	133	
1.111	RADIO/MESSAGE PROCESSING					105.72	127	
		Comm_Center	1	1	95.1	95.15		high in deckhouse, often behind chart room; includes TTY and Facsimile Systems
		Emerg Radio Room	2	1	10.6	10.57		aft, deckhouse
1.113	VISUAL COM	Signal Bridge	3	1	5.9	5.90	5.9	external, top of deckhouse, may be omitted
1.12	SURVEILLANCE SYS					491.47	465	
1.121	AIR & SURFACE SURV (RADAR)			1		326.35	154.6	
1.1211	RADAR ELECTRONICS (ROOMS)					302.18	302.2	
1.12111	Fwd	Radar_Equip_Rm_1	4	1	90.7	90.65	90.654	deckhouse near/behind radars fwd
		Radar_Array_Rm_1	5	1	30.2	30.22	37.7725	deckhouse near/behind radars fwd
		Radar_Array_Rm_2	6	1	30.2	30.22	37.7725	deckhouse near/behind radars fwd
	Aft	Radar_Equip_Rm_2	7	1	90.7	90.65	60.436	deckhouse near/behind radars aft
		Radar_Array_Rm_3	8	1	30.2	30.22	37.7725	deckhouse near/behind radars aft
		Radar_Array_Rm_4	9	1	30.2	30.22	37.7725	deckhouse near/behind radars aft
1.12112	Fwd	Radar_Director_Equip_Rm_1	10	1	30.03	30.03		high in deckhouse, below director fwd
	Aft	Radar_Director_Equip_Rm_2	11	1	30.03	30.03		high in deckhouse, below director aft
1.1212	RADAR COOLING (ROOMS)	Radar_Cooling_Equip_Rm_1	12	1	24.2	24.17		adjacent radar electronics or lower, fwd
		Radar_Cooling_Equip_Rm_2	13	1	24.2	24.17		adjacent radar electronics or lower, fwd
1.122	UNDERWATER SURV (SONAR)					165.12	310.6	
1.1221	SONAR ELECTRONICS (ROOMS)	Sonar Equipment Room 1	14	1	10.8	10.75		sonar rooms low towards bow
		Sonar Equipment Room 2	15	1	21.5	21.50		sonar rooms low towards bow
		Sonar Equipment Room 3	16	1	64.5	64.51		sonar rooms low towards bow
		Sonar Cooling Equipment Room	17	1	6.5	6.45		sonar rooms low towards bow
1.1222	SONAR CONTROL	Sonar Control Room	18	1	4.3	4.30		near CIC
1.1223	TACTASS WINCH	TACTASS Winch Room	19	1	47.3	47.30		just below deck fwd of transom
1.1224	SONABUOY STOWAGE (see 1.38)			1	10.3	10.30		
1.123	SURFACE SURV INFRARED	in CIC		0	2.0	0.00		
1.13	COMMAND+CONTROL					585.28	459	
1.131	COMBAT INFO CENTER / OPS					496.52	402.9	
1.1311		CIC	20	1	228.6	228.59		in hull, midships, main deck or just below
1.1312		CSER_1	21	1	160.8	160.76		near CIC
		CSER_2	22	1	107.2	107.17		in hull, aft of midships, main deck or just below
1.132	CONNING STATIONS					65.45	56.5	
1.1321	PILOT HOUSE	Pilot_House	23	1	46.4	46.45	49.5	Forward space on upper level of deck house or just below phased array radar fwd

Figure 2-10 – VTPAM "MissionSupport" Classification Sheet

The VTPAM Compartment sheet is shown in Figure 2-11. This sheet specifies compartment priorities and operational location preferences. Multiple compartment locations with sufficient area are considered. Of these locations, the one with the least likelihood of being hit (determined from the SDB hit probabilities) is chosen as the location of the compartment. If no suitable location is found, the ship is considered infeasible for this analysis which requires designer intervention. With properly sized hull and deckhouse, this rarely happens. Once all of the compartments are assigned, the design is sent to the VTVM for vulnerability analysis. An example of the finished arrangements is shown in Figure 2-12. VTPAM and its development are discussed in more detail in Chapter 3.

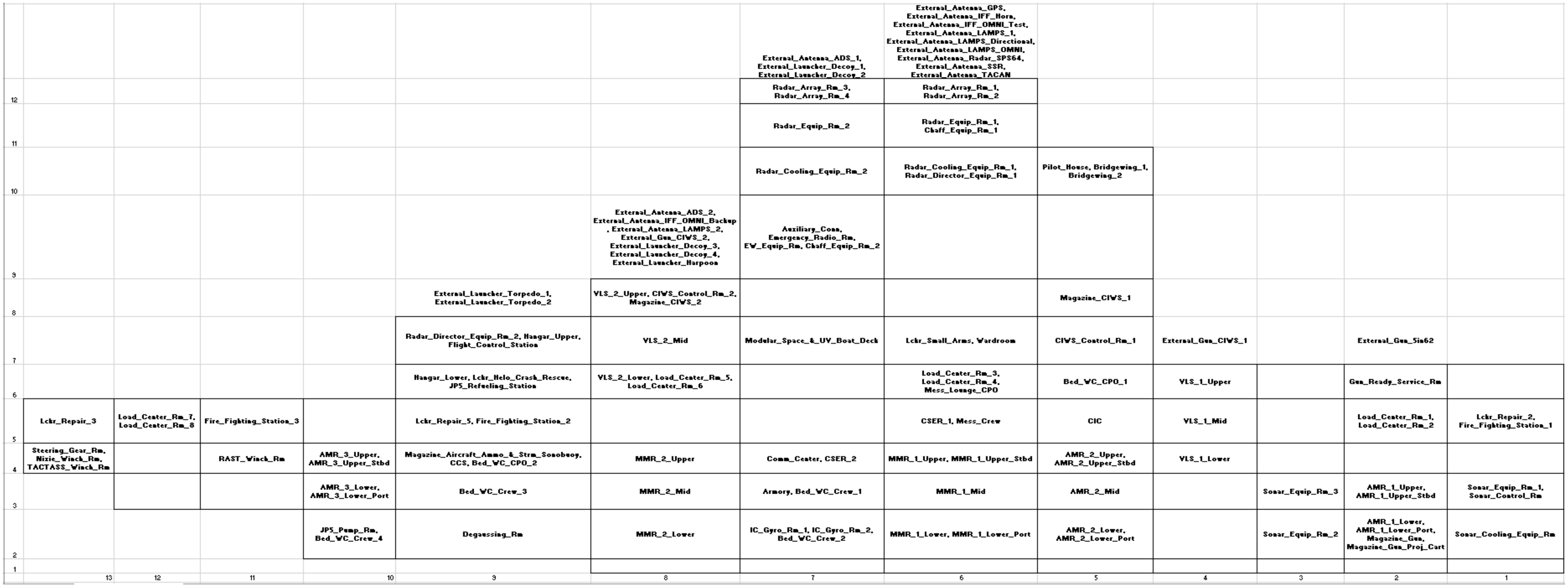


Compartment Input (formerly DZ)

Compartment Identification and Requirements | Compartment Geometry (from assigned SDB)

	Compartment Name	Compt Design ID	Area Req'd (m2)	Priority	Row Preference (IB=1, 0=any DH)	Column Preference within Zone (0=any, 1=fwd,2=aft,3=middle)	Power Bus Compt (0=no; 1=stbd; 2=port)	Compt Zone	Assigned SDB Number	Xmin (m)	Ymin (m)	Zmin (m)	Xmax (m)	Ymax (m)	Zmax (m)	Deck Area (m^2)	Volume (m^3)
5	AMR_1_Upper	159	50.0	0	4	3	0	1	2_4_SDB							0.00	0.00
6	AMR_1_Upper_Stbd	159	0.0	0	4	3	1	1	2_4_S_SDB							0.00	0.00
7	AMR_1_Lower	159	45.0	0	3	3	0	1	2_3_SDB							0.00	0.00
8	AMR_1_Lower_Port	159	0.0	0	3	3	2	1	2_3_P_SDB								
9	AMR_2_Upper	160	132.0	0	4	1	0	2	5_4_SDB							0.00	0.00
10	AMR_2_Upper_Stbd	160	0.0	0	4	1	1	2	5_4_S_SDB								
11	AMR_2_Mid	160	124.7	0	3	1	0	2	5_3_SDB							0.00	0.00
12	AMR_2_Lower	160	110.0	0	2	1	0	2	5_2_SDB							0.00	0.00
13	AMR_2_Lower_Port	160	0.0	0	2	1	2	2	5_2_P_SDB								
14	AMR_3_Upper	161	120.0	0	4	1	0	4	10_4_SDB							0.00	0.00
15	AMR_3_Upper_Stbd	161	0.0	0	4	1	1	4	10_4_S_SDB								
16	AMR_3_Lower	161	80.0	0	3	1	0	4	10_3_SDB							0.00	0.00
17	AMR_3_Lower_Port	161	0.0	0	3	1	2	4	10_3_P_SDB								
18	MMR_1_Upper	154	216.0	0	4	3	0	2	6_4_SDB							0.00	0.00
19	MMR_1_Upper_Stbd	154	0.0	0	4	3	1	2	6_4_S_SDB								
20	MMR_1_Mid	154	204.0	0	3	3	0	2	6_3_SDB							0.00	0.00
21	MMR_1_Lower	154	180.0	0	2	3	0	2	6_2_SDB							0.00	0.00
22	MMR_1_Lower_Port	154	0.0	0	2	3	2	2	6_2_P_SDB								
23	MMR_2_Upper	155	82.5	0	4	3	0	3	8_4_SDB							0.00	0.00
24	MMR_2_Upper_Stbd	155	0.0	0	4	3	1	3	8_4_S_SDB								
25	MMR_2_Mid	155	204.0	0	3	3	0	3	8_3_SDB							0.00	0.00
26	MMR_2_Lower	155	180.0	0	2	3	0	3	8_2_SDB							0.00	0.00
27	MMR_2_Lower_Port	155	0.0	0	2	3	2	3	8_2_P_SDB								
28	VLS_1_Upper	50	27.3	0	6	2	0	1	4_6_SDB							0.00	0.00
29	VLS_1_Mid	50	27.3	0	5	2	0	1	4_5_SDB							0.00	0.00
30	VLS_1_Lower	50	27.3	0	4	2	0	1	4_4_SDB							0.00	0.00
31	VLS_2_Upper	51	54.7	0	8	1	0	3	8_8_SDB							0.00	0.00
32	VLS_2_Mid	51	54.7	0	7	1	0	3	8_7_SDB							0.00	0.00
33	VLS_2_Lower	51	54.7	0	6	1	0	3	8_6_SDB							0.00	0.00
34	CIC	20	228.6	1	5	1	0	2	5_5_SDB							0.00	0.00
35	Pilot_House	23	47.8	2	10	1	0	2	5_10_SDB							0.00	0.00
36	Steering_Gear_Rm	116	50.4	3	5	2	0	4	14_5_SDB							0.00	0.00
37	Prop_Motor_Rm_1_Upper	156	10.8	4	3	1	0	4	11_3_SDB							0.00	0.00
38	Prop_Motor_Rm_1_Lower	156	10.8	5	2	1	0	4	11_2_SDB							0.00	0.00
39	Prop_Motor_Rm_2_Upper	157	10.8	6	3	1	0	4	11_3_SDB							0.00	0.00
40	Prop_Motor_Rm_2_Lower	157	10.8	7	2	1	0	4	11_2_SDB							0.00	0.00
41	Bridgewing_1	24	7.00	8	10	1	0	2	5_10_SDB							0.00	0.00
42	Bridgewing_2	25	7.00	9	10	1	0	2	5_10_SDB							0.00	0.00
43	Auxiliary_Conn	26	5.0	10	9	2	0	2	7_9_SDB							0.00	0.00
44	Radar_Array_Rm_1	5	30.2	11	12	3	0	2	6_12_SDB							0.00	0.00
45	Radar_Array_Rm_2	6	30.2	12	12	3	0	2	6_12_SDB							0.00	0.00
46	Radar_Equip_Rm_1	4	90.7	13	11	3	0	2	6_11_SDB							0.00	0.00
47	Radar_Array_Rm_3	8	30.2	14	12	2	0	2	7_12_SDB							0.00	0.00
48	Radar_Array_Rm_4	9	30.2	15	12	2	0	2	7_12_SDB							0.00	0.00
49	Radar_Equip_Rm_2	7	90.7	16	11	2	0	2	7_11_SDB							0.00	0.00

Figure 2-11 - VTPAM "Compartment" Sheet



							External_Antenna_ADS_1, External_Launcher_Decoy_1, External_Launcher_Decoy_2	External_Antenna_GPS, External_Antenna_IFF_Horn, External_Antenna_IFF_OMNI_Test, External_Antenna_LAMPS_1, External_Antenna_LAMPS_Directional, External_Antenna_LAMPS_OMNI, External_Antenna_Radar_SPS64, External_Antenna_SSR, External_Antenna_TACAN					
12							Radar_Array_Rm_3, Radar_Array_Rm_4	Radar_Array_Rm_1, Radar_Array_Rm_2					
11							Radar_Equip_Rm_2	Radar_Equip_Rm_1, Chaff_Equip_Rm_1					
10							Radar_Cooling_Equip_Rm_2	Radar_Cooling_Equip_Rm_1, Radar_Director_Equip_Rm_1	Pilot_House, Bridgewing_1, Bridgewing_2				
9						External_Antenna_ADS_2, External_Antenna_IFF_OMNI_Backup, External_Antenna_LAMPS_2, External_Gun_CIWS_2, External_Launcher_Decoy_3, External_Launcher_Decoy_4, External_Launcher_Harpoon	Auxiliary_Conn, Emergency_Radio_Rm, EW_Equip_Rm, Chaff_Equip_Rm_2						
8					External_Launcher_Torpedo_1, External_Launcher_Torpedo_2	VLS_2_Upper, CIWS_Control_Rm_2, Magazine_CIWS_2			Magazine_CIWS_1				
7					Radar_Director_Equip_Rm_2, Hangar_Upper, Flight_Control_Station	VLS_2_Mid	Modular_Space_&_UV_Boat_Deck	Lckr_Small_Arms, Wardroom	CIWS_Control_Rm_1	External_Gun_CIWS_1		External_Gun_5in62	
6					Hangar_Lower, Lckr_Helo_Crash_Rescue, JP5_Refueling_Station	VLS_2_Lower, Load_Center_Rm_5, Load_Center_Rm_6		Load_Center_Rm_3, Load_Center_Rm_4, Mess_Lounge_CPO	Bed_WC_CPO_1	VLS_1_Upper		Gun_Ready_Service_Rm	
5	Lckr_Repair_3	Load_Center_Rm_7, Load_Center_Rm_8	Fire_Fighting_Station_3		Lckr_Repair_5, Fire_Fighting_Station_2			CSER_1, Mess_Crew	CIC	VLS_1_Mid		Load_Center_Rm_1, Load_Center_Rm_2	Lckr_Repair_2, Fire_Fighting_Station_1
4	Steering_Gear_Rm, Nixie_Winch_Rm, TACTASS_Winch_Rm		RAST_Winch_Rm	AMR_3_Upper, AMR_3_Upper_Stbd	Magazine_Aircraft_Ammo_&_Strm_Sonobuoy, CCS, Bed_WC_CPO_2	MMR_2_Upper	Comm_Center, CSER_2	MMR_1_Upper, MMR_1_Upper_Stbd	AMR_2_Upper, AMR_2_Upper_Stbd	VLS_1_Lower			
3				AMR_3_Lower, AMR_3_Lower_Port	Bed_WC_Crew_3	MMR_2_Mid	Armory, Bed_WC_Crew_1	MMR_1_Mid	AMR_2_Mid		Sonar_Equip_Rm_3	AMR_1_Upper, AMR_1_Upper_Stbd	Sonar_Equip_Rm_1, Sonar_Control_Rm
2				JP5_Pump_Rm, Bed_WC_Crew_4	Degaussing_Rm	MMR_2_Lower	IC_Gyro_Rm_1, IC_Gyro_Rm_2, Bed_WC_Crew_2	MMR_1_Lower, MMR_1_Lower_Port	AMR_2_Lower, AMR_2_Lower_Port		Sonar_Equip_Rm_2	AMR_1_Lower, AMR_1_Lower_Port, Magazine_Gun, Magazine_Gun_Proj_Cart	Sonar_Cooling_Equip_Rm
1													
	13	12	11	10	9	8	7	6	5	4	3	2	1

Figure 2-12 - VTPAM Arrangements Sheet with compartment assignment outputs

2.3 Virginia Tech Vulnerability Model (VTVM)

The Virginia Tech Vulnerability Model (VTVM) uses the ship preliminary arrangements, ship geometry, and ship requirements from VTPAM and models the ship systems, components and architecture to assess their vulnerability in the ship. Vulnerability is analyzed based on mission system capabilit loss caused mainly by Vital Component (VC) loss. Deactivation block diagrams (DBDs) define the system architecture of each mission system.

Since compartments are assigned to SDBs in VTPAM, and VCs are assigned to compartments, VCs are also assigned to SDBs. While the exact location in a subdivision block is not specified, it is assumed for this analysis that if the subdivision block in which a VC is located is damaged, the subdivision block is deactivated and isolated causing all of the VCs in the subdivision block to be deactivated. Once a VC is deactivated, there is the potential that a ship system may also be deactivated and mission capability lost. An example Close-in Weapon System (CIWS) DBD is shown in Figure 2-13. These DBDs are visual representations of the mission system architecture that VTVM uses to analyze the vulnerability of a ship based on capability loss from VC deactivation caused by weapon hit. The overall ship mission capability system is shown in Figure 2-14.

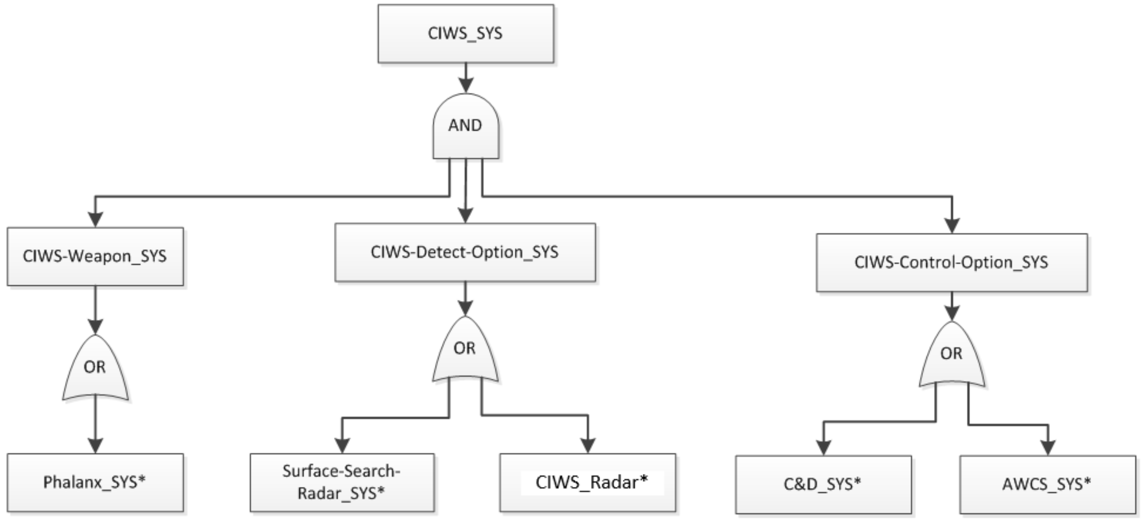


Figure 2-13 - CIWS System DBD

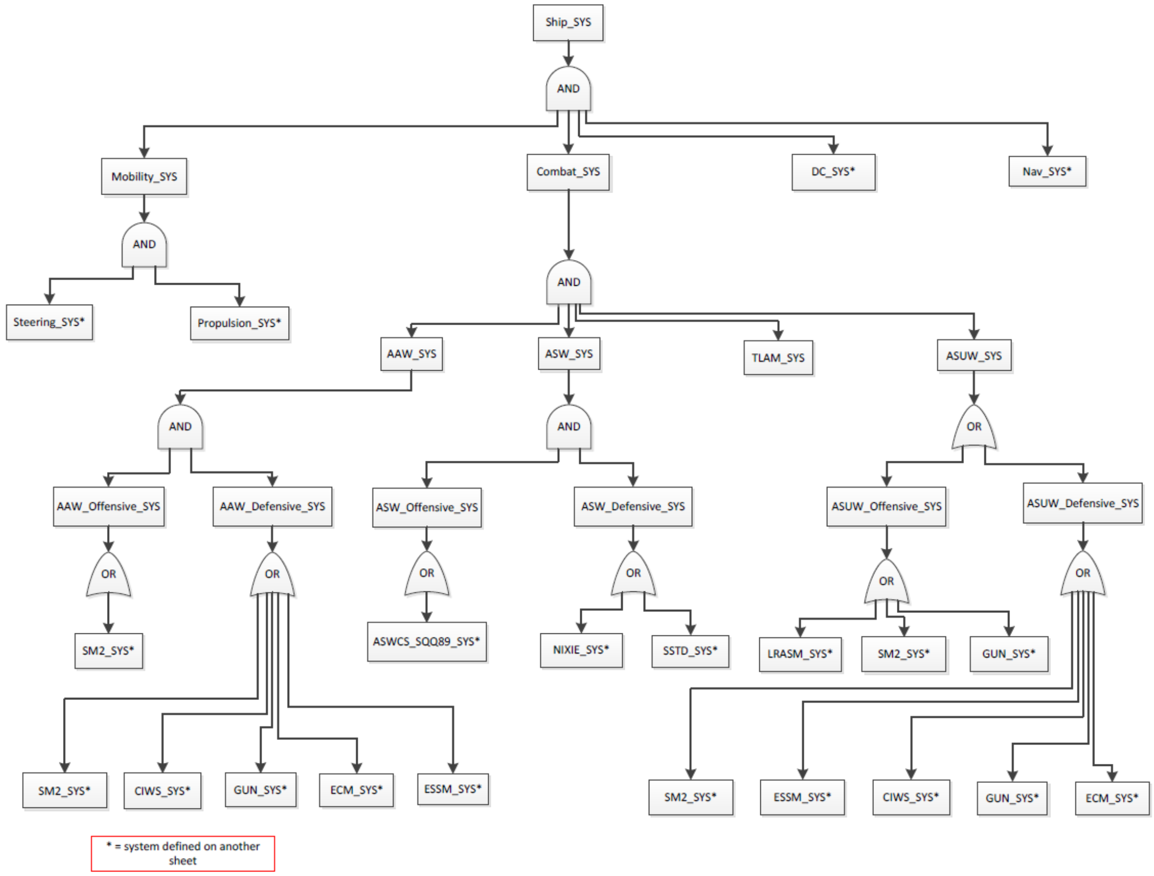


Figure 2-14 - Overall Ship Mission Capability DBD

These DBDs were created from ITEM DBD text files (Goodfriend, 2015). Each system architecture specifies mission capabilities that are dependent on the sub-mission level VCs and sub-systems. These sub-systems are also comprised of VCs. The ship mission capabilities include damage control, propulsion, combat systems, and navigation.

The damage that is specified for SDB, compartment, and VC deactivation is the same damage that was previously used in VTPAM to calculate SDB hit probabilities. If a SDB is deactivated from the damage, the VCs that are associated with it are also deactivated. This is done under the assumption that if a compartment takes damage, the first step in damage control would be to isolate the area rendering the VCs deactivated. VC deactivations for a particular hit that cause a system loss are tracked and marked as causing a mission failure for that particular threat hit. These mission failures are tallied and the overall mission loss results for all threats and all hits are used to determine the Overall Measure of Vulnerability for the specified system option combination.

The resulting VC and system loss for each damage case are used to determine the Vulnerability Measures of Performance (VMOP) as a statistical metric of the ship mission availability after hit. Analytical Hierarchy Process (AHP) and expert opinion are used to determine the Overall Measure of Vulnerability (OMOV) based on the individual system VMOPs. The top level OMOV DBD is shown in Figure 2-15. OMOV scores represent the vulnerability for any design that is comprised of the same mission system options. All combinations of system options are analyzed for their OMOV using the PA&V process. This assumes that the systems, arrangements, and architecture are the main drivers for vulnerability. This assumption is required so that thousands of designs can be given a vulnerability score without requiring large computational time. The validity of this assumption will be analyzed in future work.

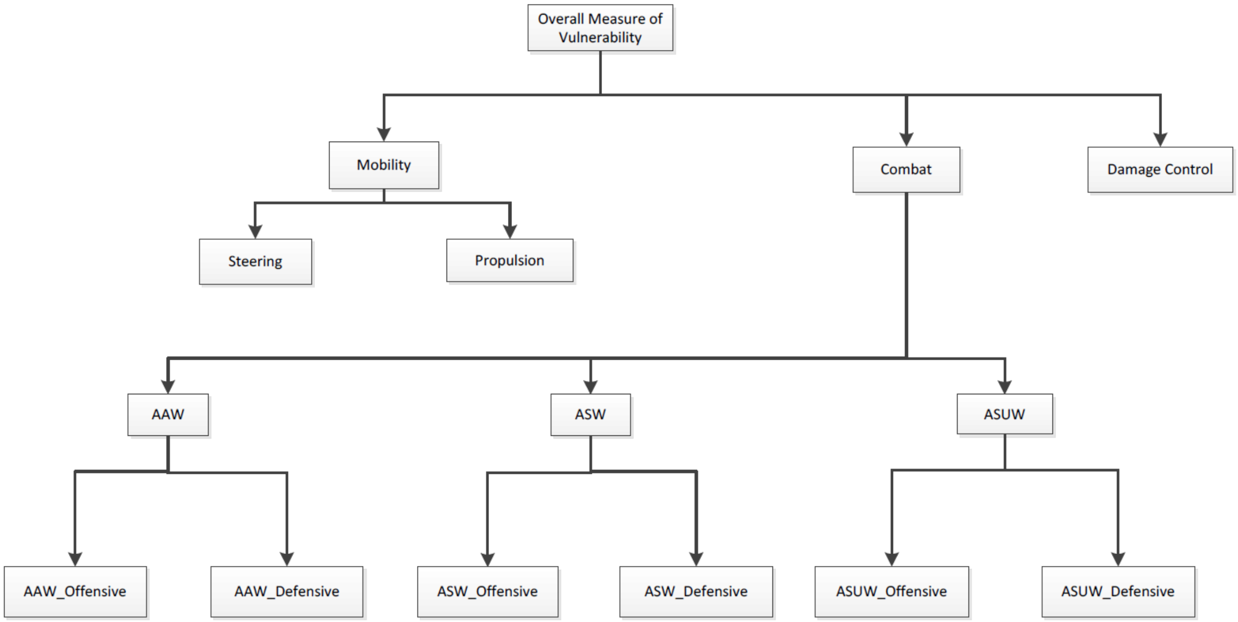


Figure 2-15 - OMOV DBD Architecture

CHAPTER 3 - Virginia Tech Preliminary Arrangement Model (VTPAM)

The Virginia Tech Preliminary Arrangement Model (VTPAM) transforms a 3D hullform into a representative ship model composed of SDBs in Rhino and MS Excel, and uses ship operability and SDB hit probability to generate a concept design preliminary arrangement that is used in a simplified ship vulnerability analysis. The representative geometric model made up of AABBs incudes hull, deckhouse and mast. Compartments and their related VCs are assigned to SDBs in this model based on required area, operability, and hit probability. This is done in many steps that use multiple Excel macros based on basic design practices, assumptions, ship parameters and geometry in Rhino. Many of these assumptions simplify the details and geometry that usually would be considered later in the ship design process. This chapter describes the methods used to create the 3D AABB hullform and generate representative preliminary arrangements.

3.1 Assumptions

VTPAM assumptions are made to save computational time or deal with the lack of detail in concept design. The first step in the VTPAM begins with a three dimensional hullform in Rhino and approximates the hullform using Axis Aligned Bounding Boxes (AABBs) as shown in Figure 1-15. These boxes represent the 3-D hullform, but do not have exact measurements from the curvilinear hullform. The geometry does not include the very bow of the ship. This study considers warfighting mission capabilities only, and the missing bow does not contain vital compartments or components. The ship structure is not represented explicitly in the AABBs, but the damage extents calculation considers the structural design when assessing threat damage. In this version of VTPAM the damage extents analysis is limited to AIREX threats. These are threats that only hit and detonate above the ship waterline. The quality of results from VTPAM depends very much on the quality of user inputs. The ship arrangements are largely based on the priorities and preferred location for compartments specified by the user. The biggest assumption is that system vulnerability in a balanced design depends primarily on subdivision, arrangements, and system architecture. Hullform shape beyond overall length and displacement has only second order effects.

There are also some simplifications that are made to the model and analysis process in order to save time and fit into the C&RE architecture. It is assumed that these simplification do not have a major impaction system vulnerability. This is partly demonstrated by Sean Stark in his thesis Definition of Damage Volumes for the Rapid Prediction of Ship Vulnerability to AIREX Weapon Effects (Stark, 2016). The validity of these assumptions and simplifications is also stated as future work to be done on this research. These simplifications are as follows:

- The system model does not include piping, cabling, or shafting.
- System architecture loss is based on deactivation only, and has no flow or capacity loss considered.
- Deactivation of a SDB also deactivates all associated VCs.

3.2 VTPAM Process

The VTPAM process is a multi step process that uses Microsoft Excel and Rhino to input a hullform and a list of compartment priorities, represent it in a simplified way, and create a preliminary arrangement that can be analyzed for vulnerability. The process is very linear, but each step has many parts. The overall process is shown in Figure 3-1.

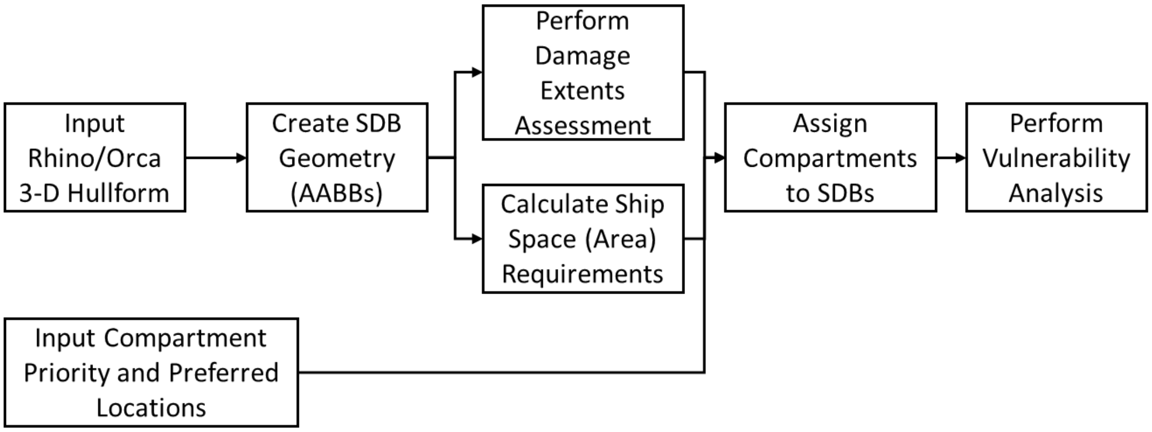
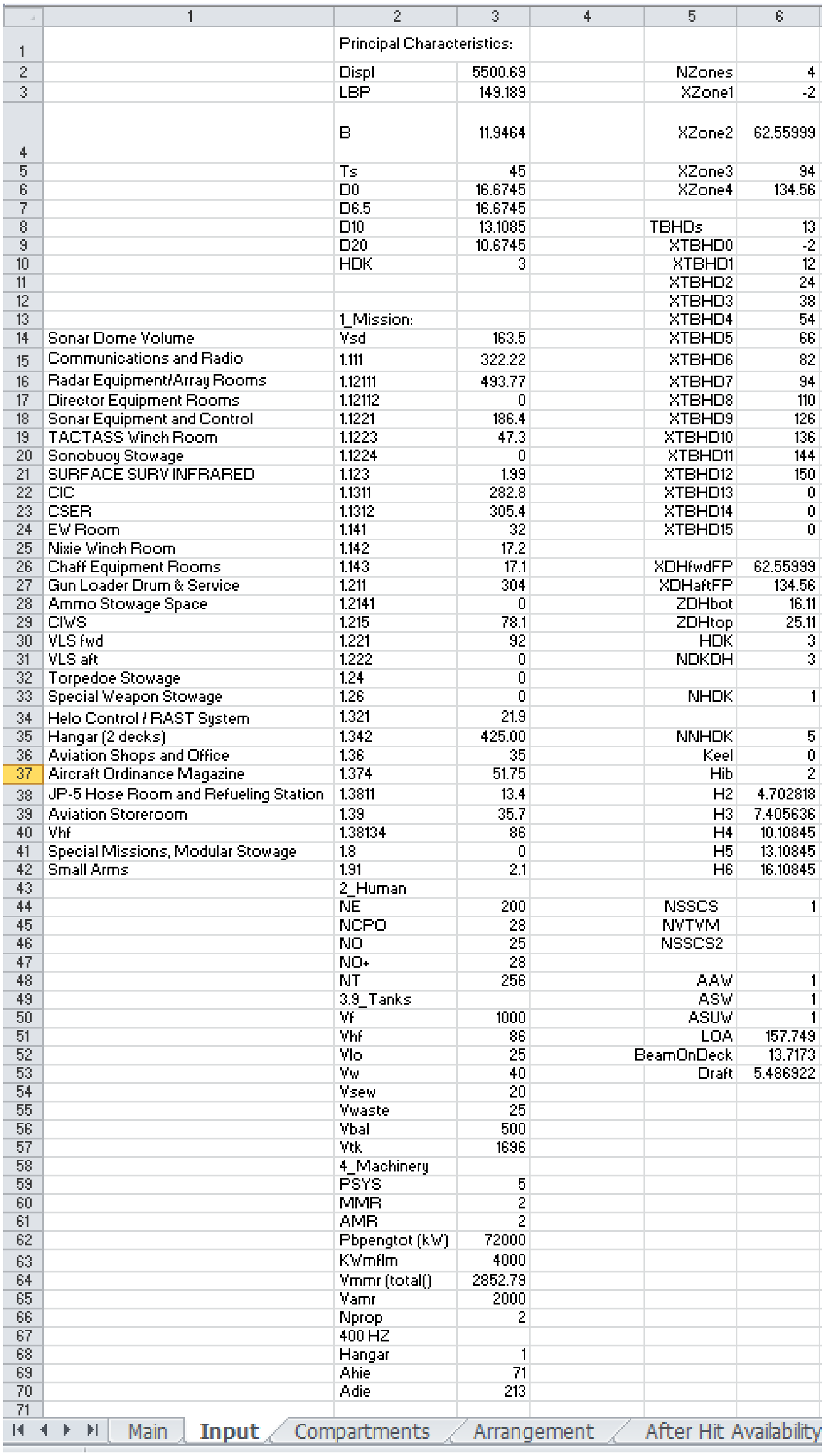


Figure 3-1 - VTPAM Process Outline

3.2.1 Input Rhino/Orca 3-D Hullform

The inputs for the VTPAM hullform are from the PA&V model shown in Figure 2-5. These include ship characteristics that are written into Excel, and a 3D hullform model in Rhino that VTPAM replicates with AABBs. The ship characteristics are written to the Input sheet in VTPAM which is shown in Figure 3-2. The ship values are read from other Model Center PA&V modules. The most important of these values for geometry are damage control Zone locations, transverse bulkhead (TBHD) locations, deck heights, and the deckhouse dimensions. These values are stored in columns 5 and 6 and determine the locations and dimensions of the subdivision blocks. The other principle characteristics in columns 2 and 3 are used to determine area requirements and other parameters for the arrangements. These values are used later in the VTPAM process and are discussed in Section 3.2.5.



	1	2	3	4	5	6
1		Principal Characteristics:				
2		Displ	5500.69		NZones	4
3		LBP	149.189		XZone1	-2
4		B	11.9464		XZone2	62.55999
5		Ts	45		XZone3	94
6		D0	16.6745		XZone4	134.56
7		D6.5	16.6745			
8		D10	13.1085		TBHDs	13
9		D20	10.6745		XTBHD0	-2
10		HDK	3		XTBHD1	12
11					XTBHD2	24
12					XTBHD3	38
13		1_Mission:			XTBHD4	54
14	Sonar Dome Volume	Vsd	163.5		XTBHD5	66
15	Communications and Radio	1.111	322.22		XTBHD6	82
16	Radar Equipment/Array Rooms	1.12111	493.77		XTBHD7	94
17	Director Equipment Rooms	1.12112	0		XTBHD8	110
18	Sonar Equipment and Control	1.1221	186.4		XTBHD9	126
19	TACTASS Winch Room	1.1223	47.3		XTBHD10	136
20	Sonobuoy Stowage	1.1224	0		XTBHD11	144
21	SURFACE SURV INFRARED	1.123	1.99		XTBHD12	150
22	CIC	1.1311	282.8		XTBHD13	0
23	CSER	1.1312	305.4		XTBHD14	0
24	EW Room	1.141	32		XTBHD15	0
25	Nixie Winch Room	1.142	17.2			
26	Chaff Equipment Rooms	1.143	17.1		XDHfwdFP	62.55999
27	Gun Loader Drum & Service	1.211	304		XDHaftFP	134.56
28	Ammo Stowage Space	1.2141	0		ZDHbot	16.11
29	CIWS	1.215	78.1		ZDHtop	25.11
30	VLS fwd	1.221	92		HDK	3
31	VLS aft	1.222	0		NDKDH	3
32	Torpedoe Stowage	1.24	0			
33	Special Weapon Stowage	1.26	0		NHDK	1
34	Helo Control / RAST System	1.321	21.9			
35	Hangar (2 decks)	1.342	425.00		NNHDK	5
36	Aviation Shops and Office	1.36	35		Keel	0
37	Aircraft Ordinance Magazine	1.374	51.75		Hib	2
38	JP-5 Hose Room and Refueling Station	1.3811	13.4		H2	4.702818
39	Aviation Storeroom	1.39	35.7		H3	7.405636
40	Vhf	1.38134	86		H4	10.10845
41	Special Missions, Modular Stowage	1.8	0		H5	13.10845
42	Small Arms	1.91	2.1		H6	16.10845
43		2_Human				
44		NE	200		NSSCS	1
45		NCPO	28		NVTVM	
46		NO	25		NSSCS2	
47		NO+	28			
48		NT	256		AAW	1
49		3.9_Tanks			ASW	1
50		Vf	1000		ASUW	1
51		Vhf	86		LOA	157.749
52		Vlo	25		BeamOnDeck	13.7173
53		Vw	40		Draft	5.486922
54		Vsew	20			
55		Vwaste	25			
56		Vbal	500			
57		Vtk	1696			
58		4_Machinery				
59		PSYS	5			
60		MMR	2			
61		AMR	2			
62		Pbpengtot (kW)	72000			
63		KWmflm	4000			
64		Vmmr (total()	2852.79			
65		Vamr	2000			
66		Nprop	2			
67		400 HZ				
68		Hangar	1			
69		Ahie	71			
70		Adie	213			
71						

Figure 3-2 - VTPAM Inputs from PA&V Process

For the geometry inputs, each transverse bulkhead location (x coordinate) is given from forward to aft starting in row 8. These are used to locate the forward and aft x location of each SDB. VTPAM is limited to a maximum of fifteen transverse bulkheads. The deck information starts at row 32 and moves from the keel of the ship to the top of the hull. VTPAM is limited to a maximum of five decks in the hull. The intersections of decks and bulkheads with the hull determine the offsets that are used to create the SDBs. The method for creating these SDBs is described in Section 3.2.2.1.

The deckhouse is created using the input values starting at row 26. These values determine the bulkhead location and where the forward and aft faces of the deckhouse are located. The lower deck height, upper deck height, and number of decks in the deckhouse are also listed. This allows the deckhouse to be created at the intersections of these bulkheads and decks with the sides of the deckhouse similar to the hull. The forward and aft deckhouse extents are required to be located on a hull bulkhead location. The starting deck of the deckhouse is also required to be the upper deck of the hullform so that the deckhouse sits correctly on the ship. The assumptions of the deckhouse creation and the method are discussed in Section 3.2.2.2. All of these values are used to create the ship geometry based on SDBs in the form of AABBs.

3.2.2 SDB Geometry Creation

Once the inputs are determined for VTPAM, the next step is the creation of the ship geometry using SDBs. This is done in multiple steps as depicted in Figure 3-3. Each of these steps has an associated Excel VBA macro, described further in this section.

Figure 3-3 - SDB Geometry Step of the VTPAM Process

The 3-D hullform model in Rhino is used to determine the width of each subdivision block in the hull, as described in Section 3.2.2.1. Once the hull SDBs are determined, the deckhouse is generated using the parameters and the sizes determined by the user inputs. The mast is then created on top of the deckhouse using design practices for standard placement. Additional SDBs are added to the bow of the ship that maintain deck height continuity, but adjusted between the bulkhead locations to create a more accurate model based on volume. The final step is the definition of external SDBs to provide a location for topside VCs on the ship. Each of these geometry build steps create a separate piece of the ship. An example of the final geometry is shown in Figure 3-4. As SDB extents are determined, the data is written and stored on the VTPAM Input Sheet shown in Figure 3-5. Once all of these processes are complete, a geometrically defined ship to be used in the assessment of preliminary damage and preliminary arrangements.

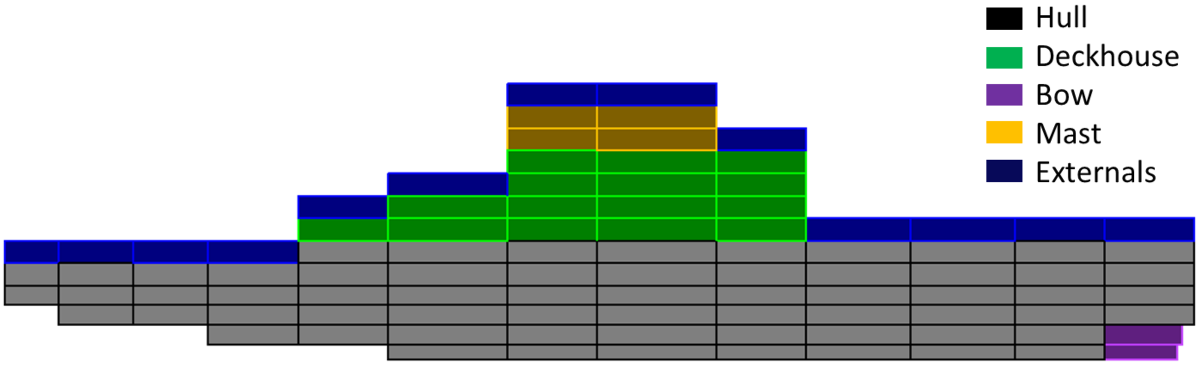
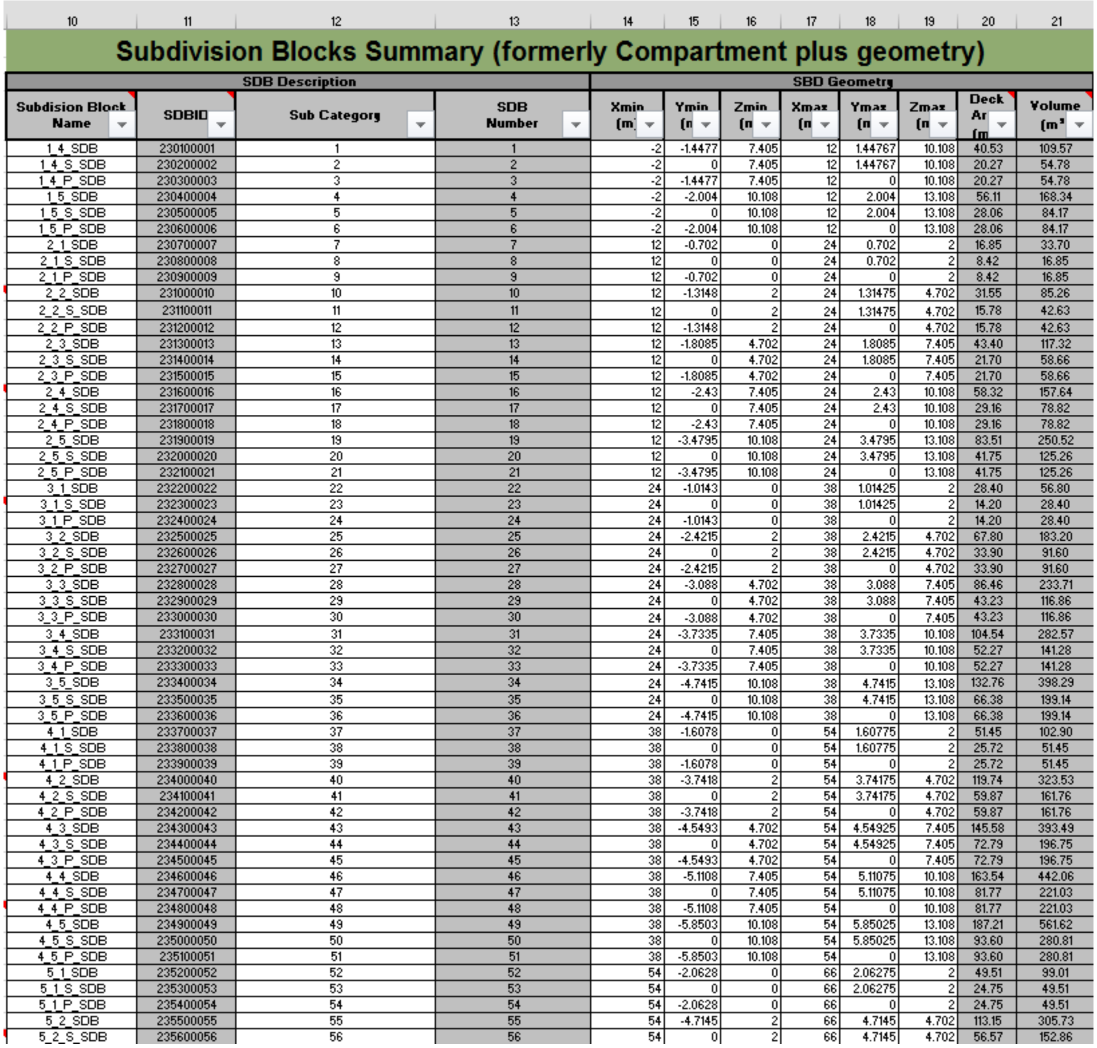


Figure 3-4 - Example of final AABB geometry



Subdivision Blocks Summary (formerly Compartment plus geometry)

10	11	12	13	14	15	16	17	18	19	20	21
SDB Description				SBD Geometry							
Subdision Block Name	SDBID	Sub Category	SDB Number	Xmin (m	Ymin (n	Zmin (n	Xmax (n	Ymax (n	Zmax (n	Deck Ar (m	Volume (m³
1_4_SDB	230100001	1	1	-2	-1.4477	7.405	12	1.44767	10.108	40.53	109.57
1_4_S_SDB	230200002	2	2	-2	0	7.405	12	1.44767	10.108	20.27	54.78
1_4_P_SDB	230300003	3	3	-2	-1.4477	7.405	12	0	10.108	20.27	54.78
1_5_SDB	230400004	4	4	-2	-2.004	10.108	12	2.004	13.108	56.11	168.34
1_5_S_SDB	230500005	5	5	-2	0	10.108	12	2.004	13.108	28.06	84.17
1_5_P_SDB	230600006	6	6	-2	-2.004	10.108	12	0	13.108	28.06	84.17
2_1_SDB	230700007	7	7	12	-0.702	0	24	0.702	2	16.85	33.70
2_1_S_SDB	230800008	8	8	12	0	0	24	0.702	2	8.42	16.85
2_1_P_SDB	230900009	9	9	12	-0.702	0	24	0	2	8.42	16.85
2_2_SDB	231000010	10	10	12	-1.3148	2	24	1.31475	4.702	31.55	85.26
2_2_S_SDB	231100011	11	11	12	0	2	24	1.31475	4.702	15.78	42.63
2_2_P_SDB	231200012	12	12	12	-1.3148	2	24	0	4.702	15.78	42.63
2_3_SDB	231300013	13	13	12	-1.8085	4.702	24	1.8085	7.405	43.40	117.32
2_3_S_SDB	231400014	14	14	12	0	4.702	24	1.8085	7.405	21.70	58.66
2_3_P_SDB	231500015	15	15	12	-1.8085	4.702	24	0	7.405	21.70	58.66
2_4_SDB	231600016	16	16	12	-2.43	7.405	24	2.43	10.108	58.32	157.64
2_4_S_SDB	231700017	17	17	12	0	7.405	24	2.43	10.108	29.16	78.82
2_4_P_SDB	231800018	18	18	12	-2.43	7.405	24	0	10.108	29.16	78.82
2_5_SDB	231900019	19	19	12	-3.4795	10.108	24	3.4795	13.108	83.51	250.52
2_5_S_SDB	232000020	20	20	12	0	10.108	24	3.4795	13.108	41.75	125.26
2_5_P_SDB	232100021	21	21	12	-3.4795	10.108	24	0	13.108	41.75	125.26
3_1_SDB	232200022	22	22	24	-1.0143	0	38	1.01425	2	28.40	56.80
3_1_S_SDB	232300023	23	23	24	0	0	38	1.01425	2	14.20	28.40
3_1_P_SDB	232400024	24	24	24	-1.0143	0	38	0	2	14.20	28.40
3_2_SDB	232500025	25	25	24	-2.4215	2	38	2.4215	4.702	67.80	183.20
3_2_S_SDB	232600026	26	26	24	0	2	38	2.4215	4.702	33.90	91.60
3_2_P_SDB	232700027	27	27	24	-2.4215	2	38	0	4.702	33.90	91.60
3_3_SDB	232800028	28	28	24	-3.088	4.702	38	3.088	7.405	86.46	233.71
3_3_S_SDB	232900029	29	29	24	0	4.702	38	3.088	7.405	43.23	116.86
3_3_P_SDB	233000030	30	30	24	-3.088	4.702	38	0	7.405	43.23	116.86
3_4_SDB	233100031	31	31	24	-3.7335	7.405	38	3.7335	10.108	104.54	282.57
3_4_S_SDB	233200032	32	32	24	0	7.405	38	3.7335	10.108	52.27	141.28
3_4_P_SDB	233300033	33	33	24	-3.7335	7.405	38	0	10.108	52.27	141.28
3_5_SDB	233400034	34	34	24	-4.7415	10.108	38	4.7415	13.108	132.76	398.29
3_5_S_SDB	233500035	35	35	24	0	10.108	38	4.7415	13.108	66.38	199.14
3_5_P_SDB	233600036	36	36	24	-4.7415	10.108	38	0	13.108	66.38	199.14
4_1_SDB	233700037	37	37	38	-1.6078	0	54	1.60775	2	51.45	102.90
4_1_S_SDB	233800038	38	38	38	0	0	54	1.60775	2	25.72	51.45
4_1_P_SDB	233900039	39	39	38	-1.6078	0	54	0	2	25.72	51.45
4_2_SDB	234000040	40	40	38	-3.7418	2	54	3.74175	4.702	119.74	323.53
4_2_S_SDB	234100041	41	41	38	0	2	54	3.74175	4.702	59.87	161.76
4_2_P_SDB	234200042	42	42	38	-3.7418	2	54	0	4.702	59.87	161.76
4_3_SDB	234300043	43	43	38	-4.5493	4.702	54	4.54925	7.405	145.58	393.49
4_3_S_SDB	234400044	44	44	38	0	4.702	54	4.54925	7.405	72.79	196.75
4_3_P_SDB	234500045	45	45	38	-4.5493	4.702	54	0	7.405	72.79	196.75
4_4_SDB	234600046	46	46	38	-5.1108	7.405	54	5.11075	10.108	163.54	442.06
4_4_S_SDB	234700047	47	47	38	0	7.405	54	5.11075	10.108	81.77	221.03
4_4_P_SDB	234800048	48	48	38	-5.1108	7.405	54	0	10.108	81.77	221.03
4_5_SDB	234900049	49	49	38	-5.8503	10.108	54	5.85025	13.108	187.21	561.62
4_5_S_SDB	235000050	50	50	38	0	10.108	54	5.85025	13.108	93.60	280.81
4_5_P_SDB	235100051	51	51	38	-5.8503	10.108	54	0	13.108	93.60	280.81
5_1_SDB	235200052	52	52	54	-2.0628	0	66	2.06275	2	49.51	99.01
5_1_S_SDB	235300053	53	53	54	0	0	66	2.06275	2	24.75	49.51
5_1_P_SDB	235400054	54	54	54	-2.0628	0	66	0	2	24.75	49.51
5_2_SDB	235500055	55	55	54	-4.7145	2	66	4.7145	4.702	113.15	305.73
5_2_S_SDB	235600056	56	56	54	0	2	66	4.7145	4.702	56.57	152.86

Figure 3-5 - VTPAM SDB geometry (shown on the Input Sheet of VTPAM)

3.2.2.1 Hull Geometry from 3D Model

The geometry for the hull is created using an Excel VBA code that works with the 3D Rhino model. This code measures the width of the 3D model at each of the specified SDB x-min and x-max, z-min z-max locations in Rhino. This is done in Rhino by first creating a line that extends across the ship at the intersections of the deck and bulkheads. The intersection of these lines and the hull determines the width at the given locations. These widths are then averaged and used as the single width of the representative AABB. This process is shown in Figure 3-6.

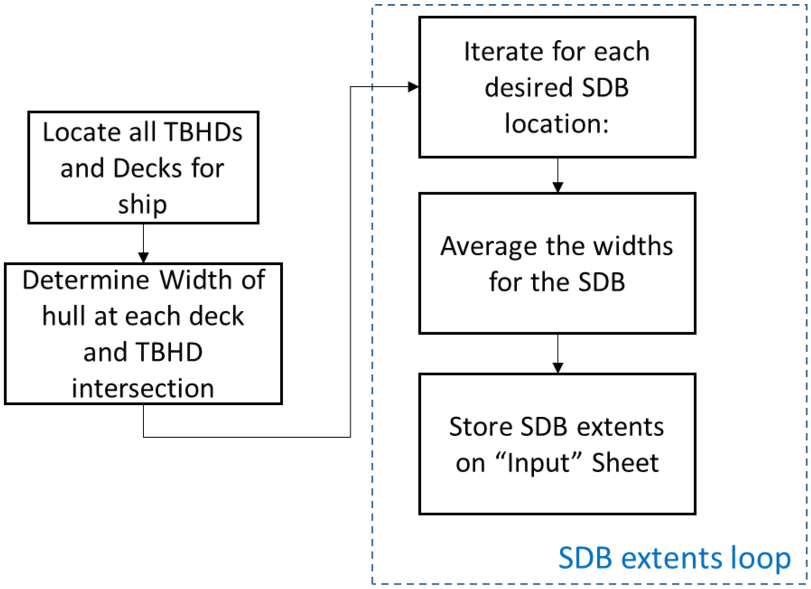


Figure 3-6 - Hull Geometry Creation Process

Once the widths are measured and averaged, the extents of each AABB are used to define three subdivision blocks (SDB) that represents the AABB from port to starboard, the port width to centerline, and the starboard width to centerline. These are separated so that VCs that are separated port/starboard in the same full SDB, such as for electric power, can be placed in separate SDBs for damage assessment and deactivation without having to provide actual x, y, and z locations for individual VCs.

The calculation of the AABB and SDB extents is an average of the breadths at each of the intersections of transverse bulkhead and decks. Since the ship is curvilinear, these averages do not exactly represent the volume of the given space or the exact useable area of the AABB. It is assumed in VTPAM that since this is designed for use at concept design for a very rapid assessment, the error in these values does not affect the vulnerability results in a significant way. SDB volume results are within 10% of the curvilinear values, which is be helpful in future flooding and damage stability calculations.

3.2.2.2 Deckhouse and Mast Geometry

As shown in Figure 3-3, once the hull SDBs are created, VTPAM uses the inputs from the PA&V to create the deckhouse and the mast. The deckhouse is required to be built on the top of the hull consistent with hull dimensions and the mast is then built on top of the deckhouse. The deckhouse and mast build processes are shown in Figure 3-7 and Figure 3-8 respectively.

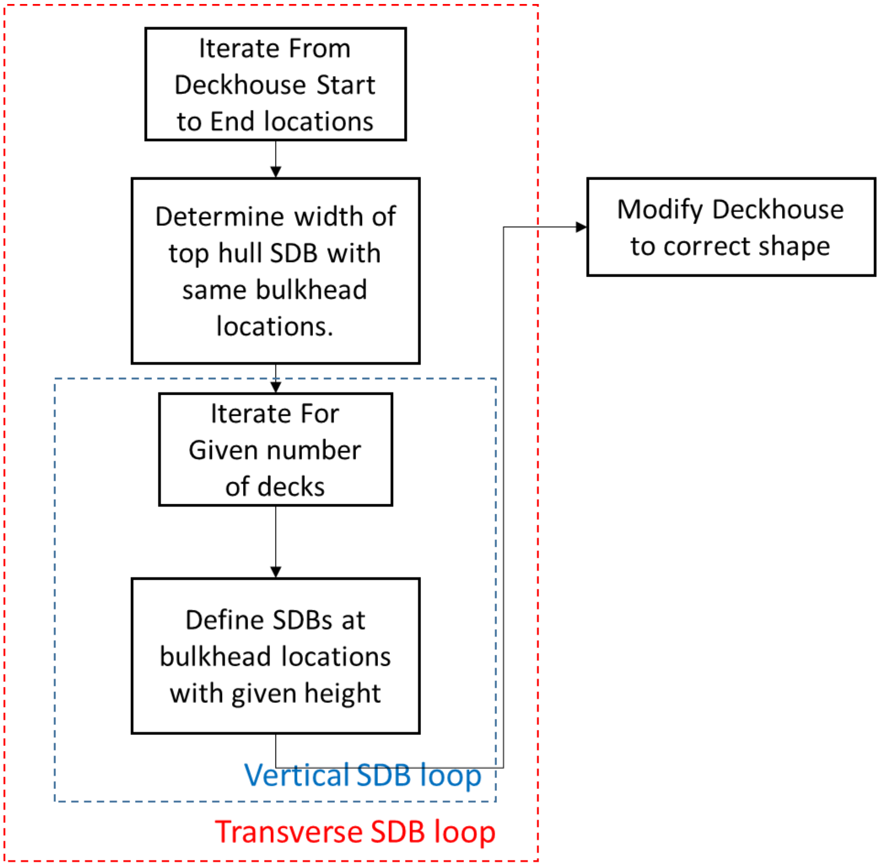


Figure 3-7 - Deckhouse Geometry Creation Process

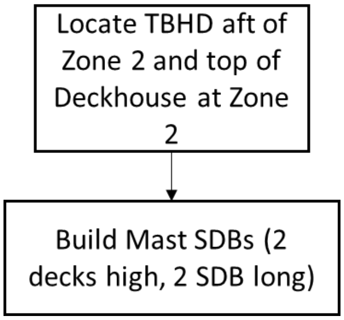


Figure 3-8 - Mast Geometry Creation Process

The deckhouse extends from the user defined forward face to the aft face, but is split into separate SDBs at each bulkhead that it crosses. It then extends up from the top deck of the hull by the specified deck heights for the given number of decks in the deckhouse as shown in Figure 3-8. Once this block envelope of the deckhouse is created, it is modified so that the ship has a deckhouse that more accurately represents the shape of deckhouses that are currently used in naval ship design to provide lines of sight for various antennas and weapons. The deckhouse is also trimmed to define a hangar at the aft end that it is two decks high by removing the subdivisions in the decks above the hangar location as shown in Figure 3-10.

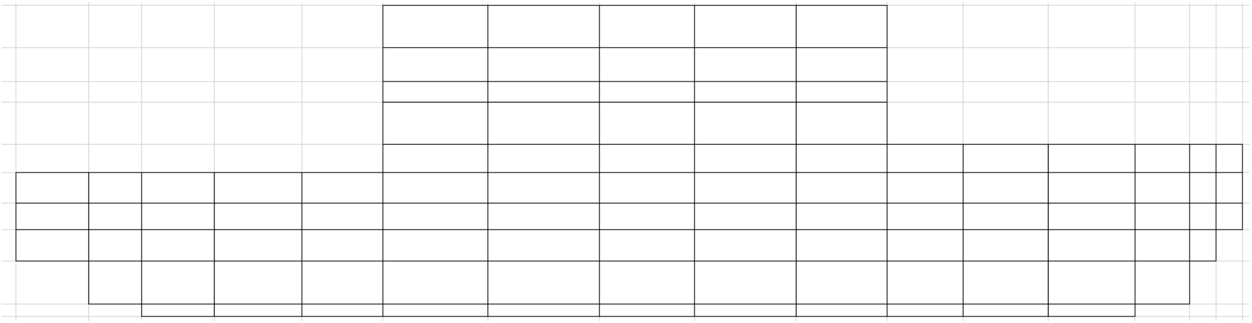


Figure 3-9 - Step 1: Basic block deckhouse

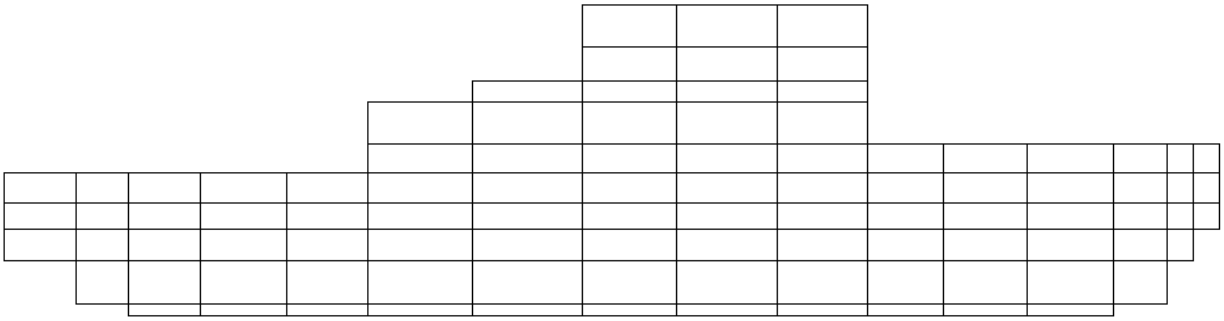


Figure 3-10 - Step 2: Deckhouse Trimming

Once the deckhouse is defined, SDBs representing the mast are placed on top. The mast is located at a standard location on the upper deck of the deckhouse and is two bulkheads long and two decks high at the aft end of Zone 2 in a four-damage zone ship as shown in Figure 3-11. These SDBs are considered external and are where the antennas and other mast specific VCs are placed so that they are considered in the vulnerability analysis.

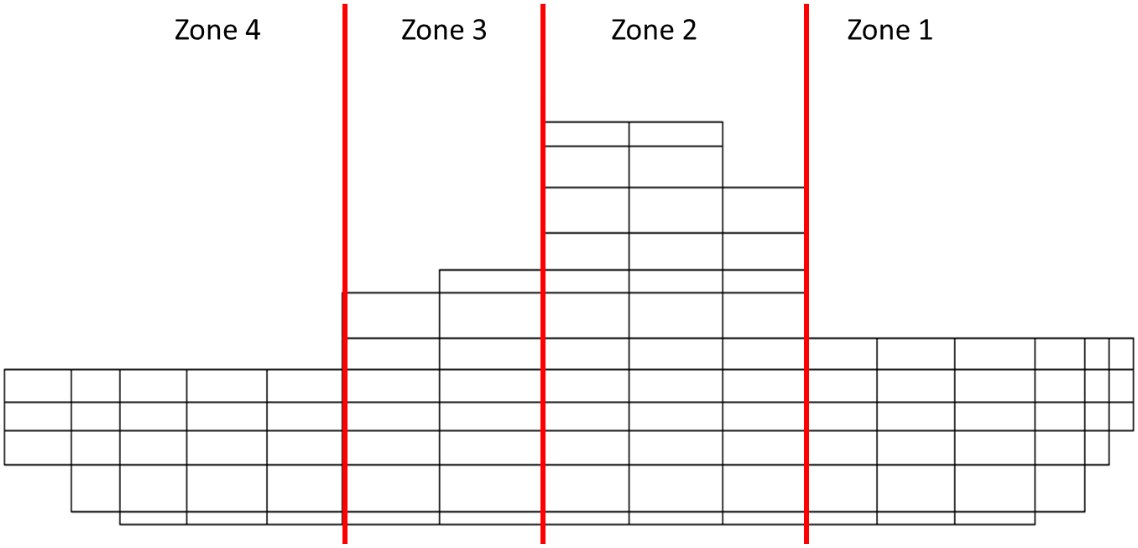


Figure 3-11 - Step 3: Mast creating and final geometric profile of the ship

3.2.2.3 Bow Geometry

At this point in the VTPAM geometry process, the main structure of the ship is defined, but for a more accurate hydrostatic model, the bow needs to be more defined. Figure 3-12 shows the SDBs without a more defined bow, and Figure 3-13 shows the model with the bow defined. The process to define the bow is similar to the original SDB geometry creation, but it measures the forward extent of SDBs. The process is shown in Figure 3-14.

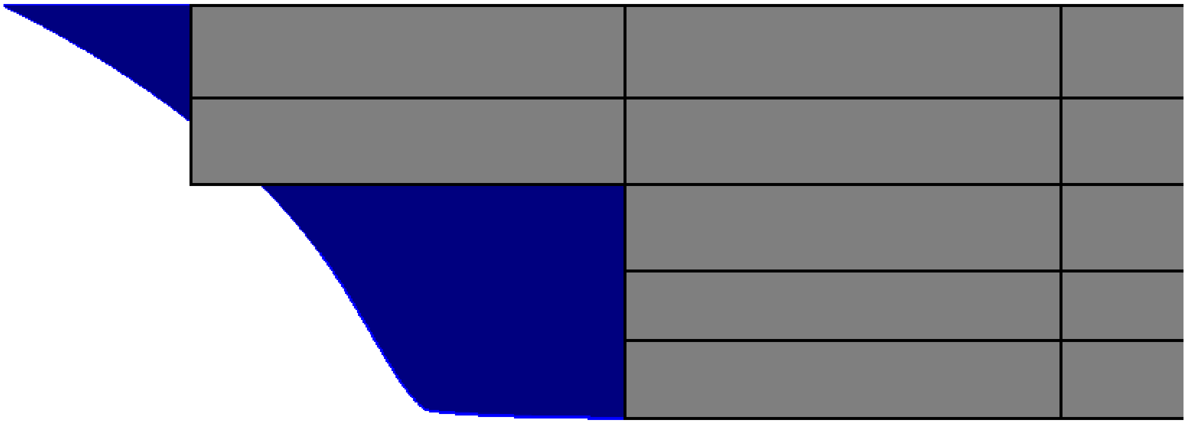


Figure 3-12 - SDB model without bow modification

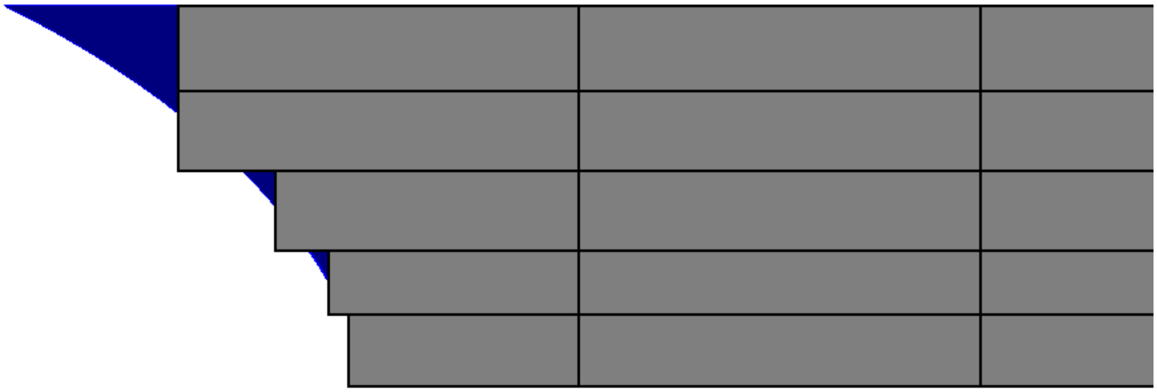


Figure 3-13- SDB model with bow modification

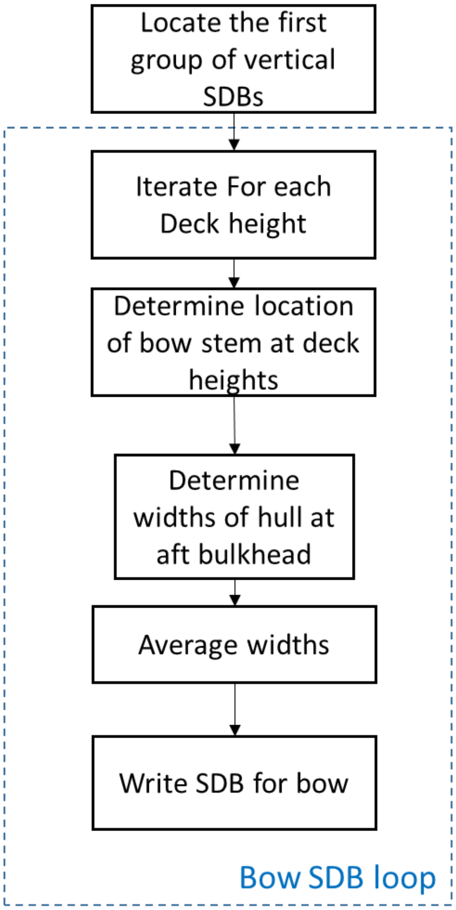


Figure 3-14 - Bow Geometry Creation Process

The bow creation process measures the widths of additional SDBs at their aft bulkheads and the x location of where the bow stem intersects each deck. X intersections between decks are averaged to determine the forward extent of the SDB. The width is also averaged as it is in the hull geometry creation with a zero width at the stem. This bow creation allows for a more accurate model so that when a flooding analysis is added to the vulnerability analysis, the model more accurately represents the underwater shape and volume.

3.2.2.4 External SDB Geometry

Since the vulnerability assessment allocates VCs to SDBs based on the compartment assignment, a method was determined to include external VCs that are not placed in internal compartments or on the mast. This is done by adding a layer of special topside SDBs to the top of the ship for VCs that are placed on the exposed decks. These SDBs do not have surrounding structure but they are exposed to topside hits. The process that was used to locate and define these SDBs is shown in Figure 3-15.

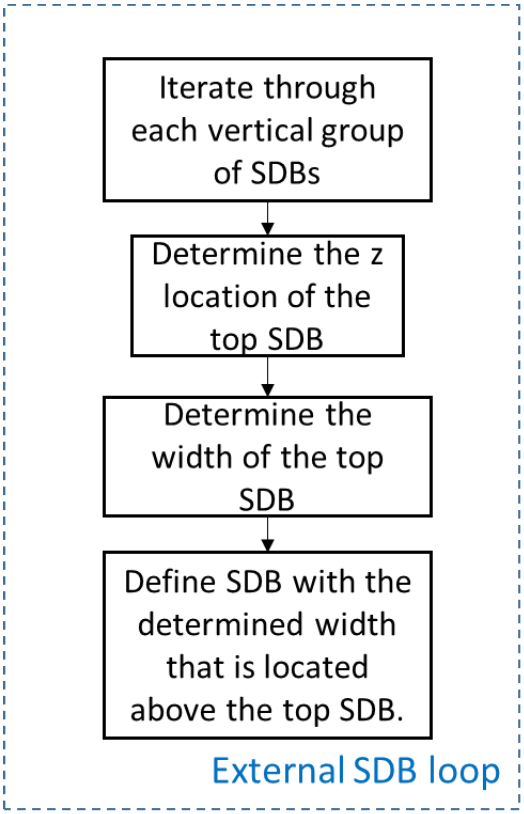
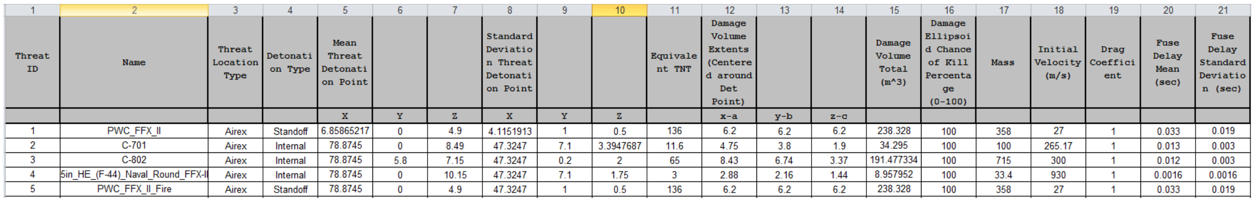


Figure 3-15 – External SDB Geometry Creation Process

3.2.3 SDB Damage Extents Assessment

The method that is used for calculating hit probabilities and damage extents is described in Definition of Damage Volumes for the Rapid Prediction of Ship Vulnerability to AIREX Weapon

Effects (Stark, 2016). This process uses the geometry of the ship and the chosen threats to generate the SDB damage extents for each threat based on the threat parameters. The threat parameters are defined in the Threat Library sheet of VTPAM, shown in Figure 3-17. The user chooses the main threats for the ship mission and VTPAM calculates hit distributions for each threat.



1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Threat ID	Name	Threat Location Type	Detonation Type	Mean Threat Detonation Point			Standard Deviation Threat Detonation Point			Equivalent TNT	Damage Volume Extents (Centered around Det Point)			Damage Volume Total (m^3)	Damage Ellipsoid Chance of Kill Percentage (0-100)	Mass	Initial Velocity (m/s)	Drag Coefficient	Fuse Delay Mean (sec)	Fuse Delay Standard Deviation (sec)
				X	Y	Z	X	Y	Z		x-a	y-b	z-c							
1	PWC_FFX_II	Airex	Standoff	6.85865217	0	4.9	4.1151913	1	0.5	136	6.2	6.2	6.2	238.328	100	358	27	1	0.033	0.019
2	C-701	Airex	Internal	78.8745	0	8.49	47.3247	7.1	3.3947687	11.6	4.75	3.8	1.9	34.295	100	100	265.17	1	0.013	0.003
3	C-802	Airex	Internal	78.8745	5.8	7.15	47.3247	0.2	2	65	8.43	6.74	3.37	191.477334	100	715	300	1	0.012	0.003
4	5in_HE_(F-44)_Naval_Round_FFX-II	Airex	Internal	78.8745	0	10.15	47.3247	7.1	1.75	3	2.88	2.16	1.44	8.957952	100	33.4	930	1	0.0016	0.0016
5	PWC_FFX_II_Fire	Airex	Standoff	78.8745	0	4.9	47.3247	1	0.5	136	6.2	6.2	6.2	238.328	100	358	27	1	0.033	0.019

Figure 3-16 - VTPAM Threat Library Sheet

The hit parameters include the mean and standard deviation of the x and z hit location distribution, mean and standard deviation of the detonation fusing, threat velocity, and internal/standoff detonation type. These hit parameters are used with an assumed random Gaussian distribution to generate random hit points based on the mean and standard deviation. The location of a point is checked to make sure that it is inside one of the SDBs, that the hit has not missed the ship. If no SDB is found, then the hit location process is rerun. Since this is a vulnerability analysis assuming a hit, a hit location is required. The beam of the SDB is then recorded, and the z location of the point is compared to the design waterline to ensure that the hit is above the waterline since only AIREX threats are considered. If the threat has fragmentation, only external SDBs are checked. For each threat, 200+ hits are assessed, and for each hit, the damage extents are determined.

The process used to calculate damage extents is shown in Figure 3-18. Before applying damage extents to a particular design, two unique representative damage extent models are defined, one for the hull and one for the deckhouse. These models are developed for a particular threat and for the structure and subdivision of the particular design. These representative SDBs are sized to represent the subdivision of the actual SDBs in the hull/deckhouse, and their bounding panels are sized based on the scantlings and deck heights of the hull/deckhouse near midship. A “grid” of these representative SDBs is created and hit detonations are simulated at the center and corners of the center SDB in the grid. These detonation locations are shown in Figure 3-17. Damage extent is calculated based on how many decks and bulkheads are ruptured by the damage using an energy-dissipation based algorithm. Excess energy beyond what is required to rupture the grid boundaries is used to estimate how much further the damage might extend if the boundary had been further away. When applying the results to the actual design and hit locations, the damage extents are interpolated from the center and corner values calculated in the representative SDB grid. The damage extents are also scaled based on SDB size difference between the actual SDB hit location and the representative SDB sizes using a ratio of the cubic root of their volumes. This method was validated against a series of detailed MOTISS test runs.

This method is applied to all hits. Any SDB that is intersected by the adjusted damage extents is considered deactivated with its VCs for that analysis. An example of the resulting SDB deactivation from a single hit is shown in Figure 3-20. The damage extents and hit distribution are recorded on the Hit Distribution Sheet, shown in Figure 3-19.

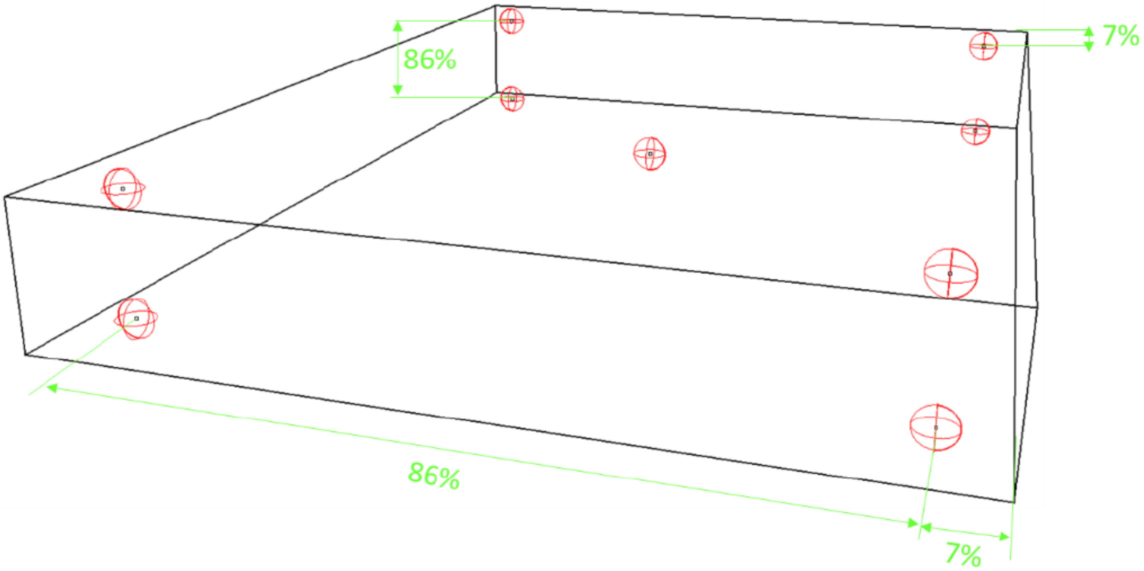


Figure 3-17 - Internal Blast Damage Extent Nodes (Stark, 2016)

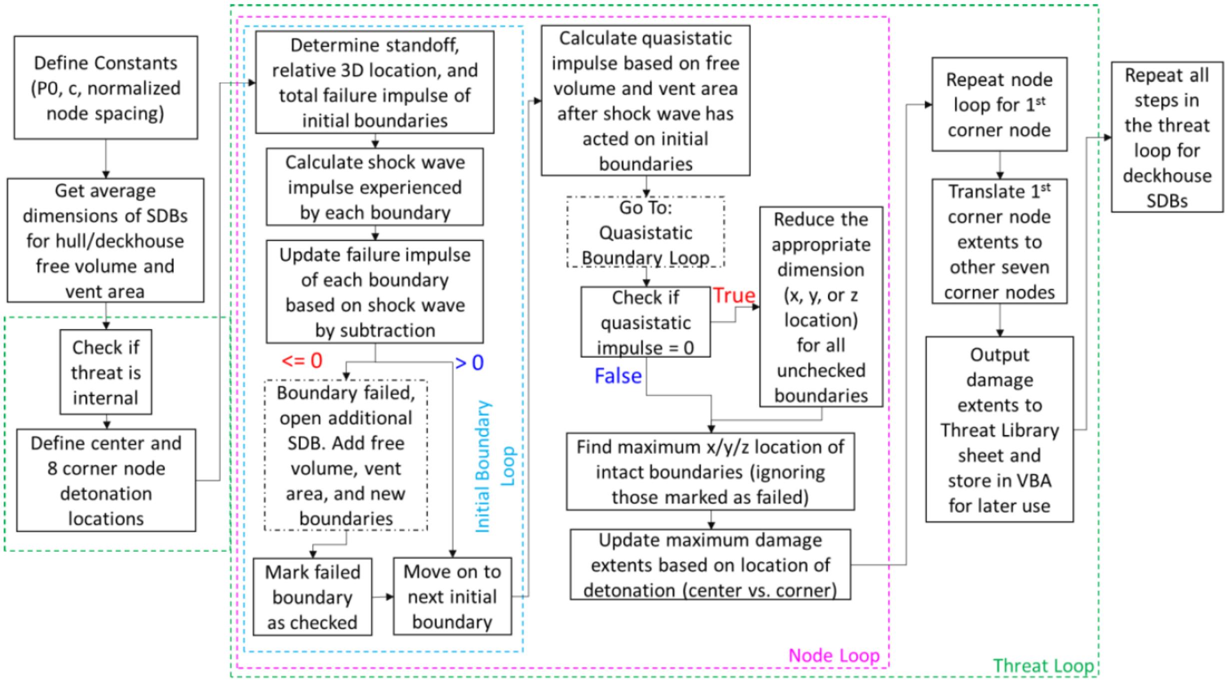
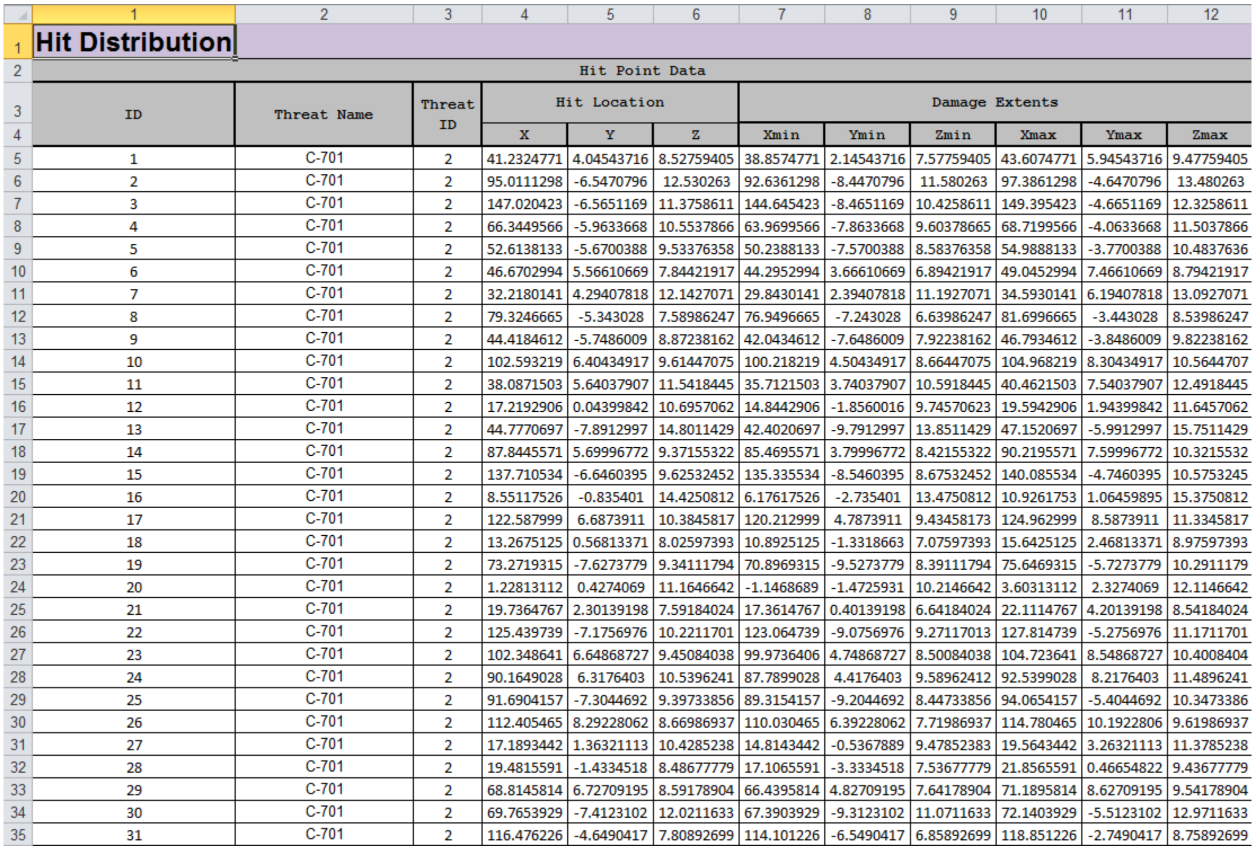


Figure 3-18 - Internal Damage Extent Calculation Process (Stark, 2016)



	1	2	3	4	5	6	7	8	9	10	11	12
1	Hit Distribution											
2	Hit Point Data											
3	ID	Threat Name	Threat ID	Hit Location			Damage Extents					
4				X	Y	Z	Xmin	Ymin	Zmin	Xmax	Ymax	Zmax
5	1	C-701	2	41.2324771	4.04543716	8.52759405	38.8574771	2.14543716	7.57759405	43.6074771	5.94543716	9.47759405
6	2	C-701	2	95.0111298	-6.5470796	12.530263	92.6361298	-8.4470796	11.580263	97.3861298	-4.6470796	13.480263
7	3	C-701	2	147.020423	-6.5651169	11.3758611	144.645423	-8.4651169	10.4258611	149.395423	-4.6651169	12.3258611
8	4	C-701	2	66.3449566	-5.9633668	10.5537866	63.9699566	-7.8633668	9.60378665	68.7199566	-4.0633668	11.5037866
9	5	C-701	2	52.6138133	-5.6700388	9.53376358	50.2388133	-7.5700388	8.58376358	54.9888133	-3.7700388	10.4837636
10	6	C-701	2	46.6702994	5.56610669	7.84421917	44.2952994	3.66610669	6.89421917	49.0452994	7.46610669	8.79421917
11	7	C-701	2	32.2180141	4.29407818	12.1427071	29.8430141	2.39407818	11.1927071	34.5930141	6.19407818	13.0927071
12	8	C-701	2	79.3246665	-5.343028	7.58986247	76.9496665	-7.243028	6.63986247	81.6996665	-3.443028	8.53986247
13	9	C-701	2	44.4184612	-5.7486009	8.87238162	42.0434612	-7.6486009	7.92238162	46.7934612	-3.8486009	9.82238162
14	10	C-701	2	102.593219	6.40434917	9.61447075	100.218219	4.50434917	8.66447075	104.968219	8.30434917	10.5644707
15	11	C-701	2	38.0871503	5.64037907	11.5418445	35.7121503	3.74037907	10.5918445	40.4621503	7.54037907	12.4918445
16	12	C-701	2	17.2192906	0.04399842	10.6957062	14.8442906	-1.8560016	9.74570623	19.5942906	1.94399842	11.6457062
17	13	C-701	2	44.7770697	-7.8912997	14.8011429	42.4020697	-9.7912997	13.8511429	47.1520697	-5.9912997	15.7511429
18	14	C-701	2	87.8445571	5.69996772	9.37155322	85.4695571	3.79996772	8.42155322	90.2195571	7.59996772	10.3215532
19	15	C-701	2	137.710534	-6.6460395	9.62532452	135.335534	-8.5460395	8.67532452	140.085534	-4.7460395	10.5753245
20	16	C-701	2	8.55117526	-0.835401	14.4250812	6.17617526	-2.735401	13.4750812	10.9261753	1.06459895	15.3750812
21	17	C-701	2	122.587999	6.6873911	10.3845817	120.212999	4.7873911	9.43458173	124.962999	8.5873911	11.3345817
22	18	C-701	2	13.2675125	0.56813371	8.02597393	10.8925125	-1.3318663	7.07597393	15.6425125	2.46813371	8.97597393
23	19	C-701	2	73.2719315	-7.6273779	9.34111794	70.8969315	-9.5273779	8.39111794	75.6469315	-5.7273779	10.2911179
24	20	C-701	2	1.22813112	0.4274069	11.1646642	-1.1468689	-1.4725931	10.2146642	3.60313112	2.3274069	12.1146642
25	21	C-701	2	19.7364767	2.30139198	7.59184024	17.3614767	0.40139198	6.64184024	22.1114767	4.20139198	8.54184024
26	22	C-701	2	125.439739	-7.1756976	10.2211701	123.064739	-9.0756976	9.27117013	127.814739	-5.2756976	11.1711701
27	23	C-701	2	102.348641	6.64868727	9.45084038	99.9736406	4.74868727	8.50084038	104.723641	8.54868727	10.4008404
28	24	C-701	2	90.1649028	6.3176403	10.5396241	87.7899028	4.4176403	9.58962412	92.5399028	8.2176403	11.4896241
29	25	C-701	2	91.6904157	-7.3044692	9.39733856	89.3154157	-9.2044692	8.44733856	94.0654157	-5.4044692	10.3473386
30	26	C-701	2	112.405465	8.29228062	8.66986937	110.030465	6.39228062	7.71986937	114.780465	10.1922806	9.61986937
31	27	C-701	2	17.1893442	1.36321113	10.4285238	14.8143442	-0.5367889	9.47852383	19.5643442	3.26321113	11.3785238
32	28	C-701	2	19.4815591	-1.4334518	8.48677779	17.1065591	-3.3334518	7.53677779	21.8565591	0.46654822	9.43677779
33	29	C-701	2	68.8145814	6.72709195	8.59178904	66.4395814	4.82709195	7.64178904	71.1895814	8.62709195	9.54178904
34	30	C-701	2	69.7653929	-7.4123102	12.0211633	67.3903929	-9.3123102	11.0711633	72.1403929	-5.5123102	12.9711633
35	31	C-701	2	116.476226	-4.6490417	7.80892699	114.101226	-6.5490417	6.85892699	118.851226	-2.7490417	8.75892699

Figure 3-19 - VTPAM Hit Distribution Sheet

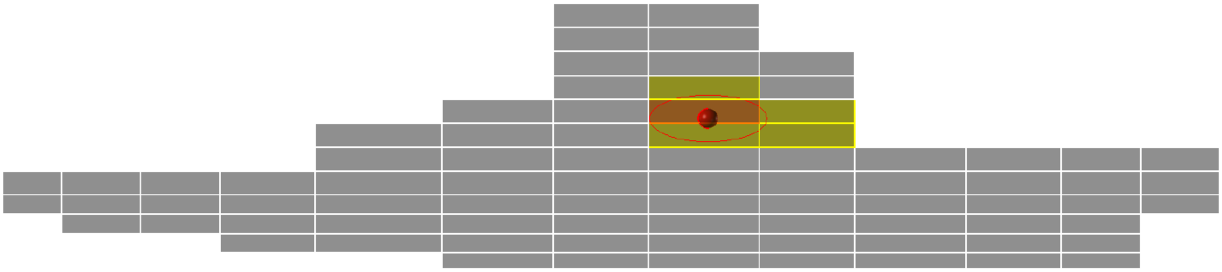
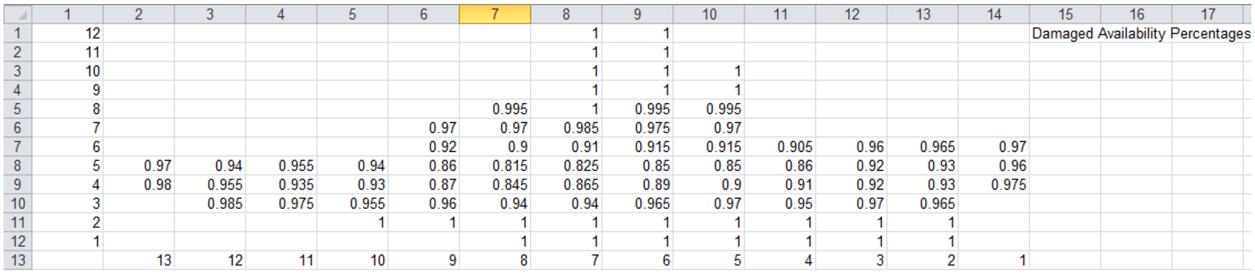


Figure 3-20 - Example of Damage Extents and Resulting SDB Deactivation

Once all the damage extents analyses are completed, a percentage is calculated that represents the probability of being hit for each SDB that includes the damage from all threats. This is the probability of each SDB hit given ship hit. In addition, it represents the susceptibility of each SDB. One minus this probability represents the SDB availability and is listed on the After Hit Availability sheet shown in Figure 3-21. The availability score is from 0 to 1 where 1 is a SDB that is never impacted by the damage extents in any analysis. These locations are the least vulnerable spaces on the ship. This availability is used to assign compartments to the safest locations in the ship to decrease the vulnerability of the ship for the defined set of threats and hit distributions.

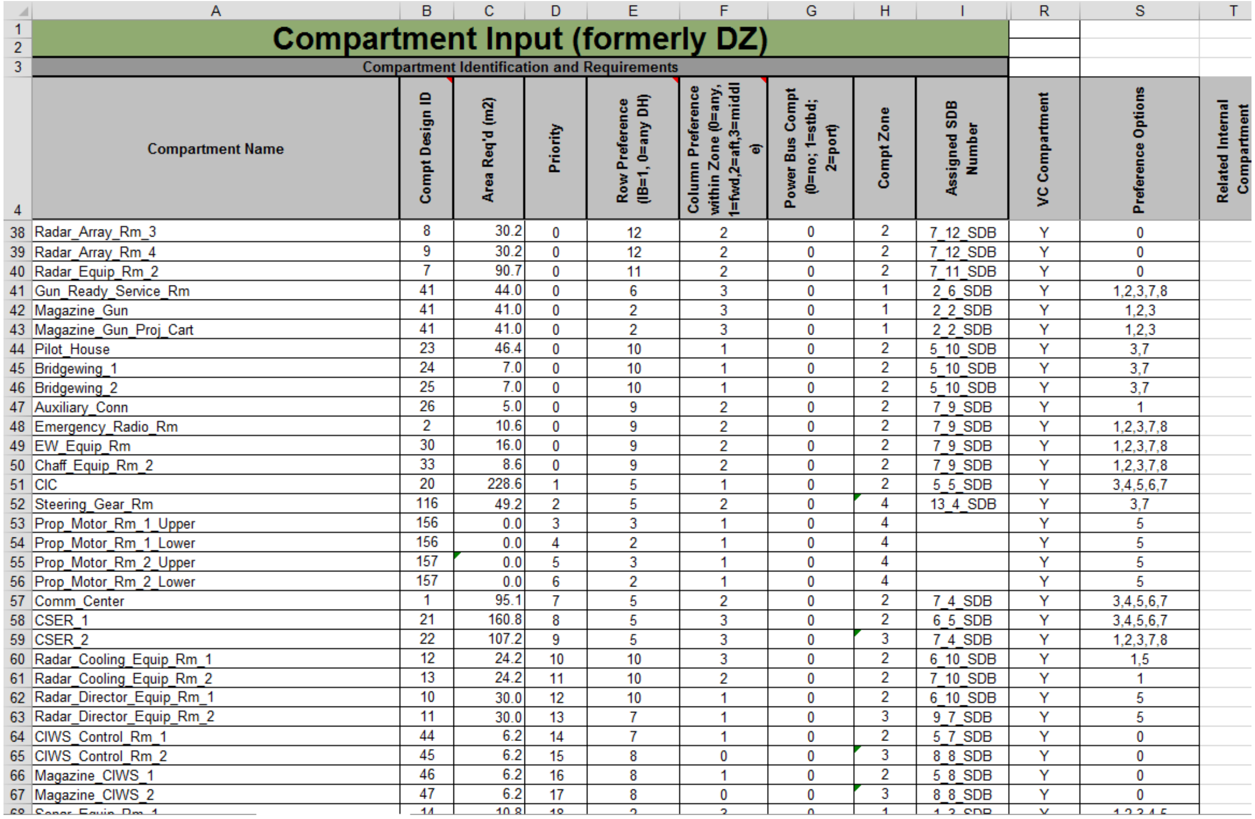


	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	12							1	1						Damaged Availability Percentages		
2	11							1	1								
3	10							1	1	1							
4	9							1	1	1							
5	8						0.995	1	0.995	0.995							
6	7					0.97	0.97	0.985	0.975	0.97							
7	6					0.92	0.9	0.91	0.915	0.915	0.905	0.96	0.965	0.97			
8	5	0.97	0.94	0.955	0.94	0.86	0.815	0.825	0.85	0.85	0.86	0.92	0.93	0.96			
9	4	0.98	0.955	0.935	0.93	0.87	0.845	0.865	0.89	0.9	0.91	0.92	0.93	0.975			
10	3		0.985	0.975	0.955	0.96	0.94	0.94	0.965	0.97	0.95	0.97	0.965				
11	2				1	1	1	1	1	1	1	1	1				
12	1						1	1	1	1	1	1	1				
13		13	12	11	10	9	8	7	6	5	4	3	2	1			

Figure 3-21 –VTPAM After Hit SDB Availability Sheet

3.2.4 Space Requirements and Compartment Priority and Preferred Location Inputs

The compartment required area, priority, and preferred location for operability are used as the primary criteria for compartment assignment to SDB. Area requirements for each compartment are calculated using ship and system characteristics so that they can be assigned to SDBs that have sufficient free area to fit the compartment. Compartments are assigned in user defined priority order to the least vulnerable location that has sufficient area and is preferred by the compartment. These inputs are displayed on the Compartment Sheet shown in Figure 3-22.



Compartment Input (formerly DZ)

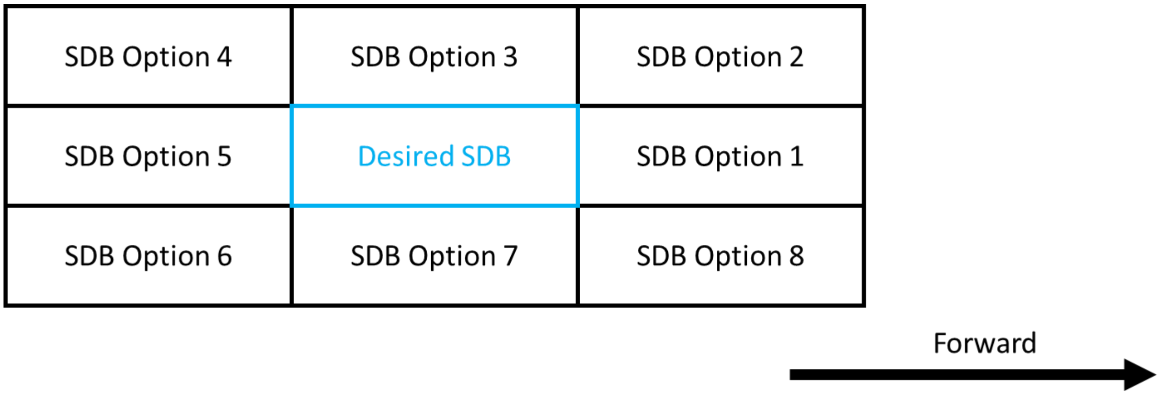
Compartment Identification and Requirements

4	Compartment Name	Compt Design ID	Area Req'd (m2)	Priority	Row Preference (IB=1, 0=any DH)	Column Preference within Zone (0=any, 1=fwd,2=aft,3=middle)	Power Bus Compt (0=no; 1=stbd; 2=port)	Compt Zone	Assigned SDB Number	VC Compartment	Preference Options	Related Internal Compartment
38	Radar_Array_Rm_3	8	30.2	0	12	2	0	2	7_12_SDB	Y	0	
39	Radar_Array_Rm_4	9	30.2	0	12	2	0	2	7_12_SDB	Y	0	
40	Radar_Equip_Rm_2	7	90.7	0	11	2	0	2	7_11_SDB	Y	0	
41	Gun_Ready_Service_Rm	41	44.0	0	6	3	0	1	2_6_SDB	Y	1,2,3,7,8	
42	Magazine_Gun	41	41.0	0	2	3	0	1	2_2_SDB	Y	1,2,3	
43	Magazine_Gun_Proj_Cart	41	41.0	0	2	3	0	1	2_2_SDB	Y	1,2,3	
44	Pilot_House	23	46.4	0	10	1	0	2	5_10_SDB	Y	3,7	
45	Bridgewing_1	24	7.0	0	10	1	0	2	5_10_SDB	Y	3,7	
46	Bridgewing_2	25	7.0	0	10	1	0	2	5_10_SDB	Y	3,7	
47	Auxiliary_Conn	26	5.0	0	9	2	0	2	7_9_SDB	Y	1	
48	Emergency_Radio_Rm	2	10.6	0	9	2	0	2	7_9_SDB	Y	1,2,3,7,8	
49	EW_Equip_Rm	30	16.0	0	9	2	0	2	7_9_SDB	Y	1,2,3,7,8	
50	Chaff_Equip_Rm_2	33	8.6	0	9	2	0	2	7_9_SDB	Y	1,2,3,7,8	
51	CIC	20	228.6	1	5	1	0	2	5_5_SDB	Y	3,4,5,6,7	
52	Steering_Gear_Rm	116	49.2	2	5	2	0	4	13_4_SDB	Y	3,7	
53	Prop_Motor_Rm_1_Upper	156	0.0	3	3	1	0	4		Y	5	
54	Prop_Motor_Rm_1_Lower	156	0.0	4	2	1	0	4		Y	5	
55	Prop_Motor_Rm_2_Upper	157	0.0	5	3	1	0	4		Y	5	
56	Prop_Motor_Rm_2_Lower	157	0.0	6	2	1	0	4		Y	5	
57	Comm_Center	1	95.1	7	5	2	0	2	7_4_SDB	Y	3,4,5,6,7	
58	CSER_1	21	160.8	8	5	3	0	2	6_5_SDB	Y	3,4,5,6,7	
59	CSER_2	22	107.2	9	5	3	0	3	7_4_SDB	Y	1,2,3,7,8	
60	Radar_Cooling_Equip_Rm_1	12	24.2	10	10	3	0	2	6_10_SDB	Y	1,5	
61	Radar_Cooling_Equip_Rm_2	13	24.2	11	10	2	0	2	7_10_SDB	Y	1	
62	Radar_Director_Equip_Rm_1	10	30.0	12	10	1	0	2	6_10_SDB	Y	5	
63	Radar_Director_Equip_Rm_2	11	30.0	13	7	1	0	3	9_7_SDB	Y	5	
64	CIWS_Control_Rm_1	44	6.2	14	7	1	0	2	5_7_SDB	Y	0	
65	CIWS_Control_Rm_2	45	6.2	15	8	0	0	3	8_8_SDB	Y	0	
66	Magazine_CIWS_1	46	6.2	16	8	1	0	2	5_8_SDB	Y	0	
67	Magazine_CIWS_2	47	6.2	17	8	0	0	3	8_8_SDB	Y	0	

Figure 3-22 - VTPAM Compartment Sheet

All compartments with VCs or high priority are located. Compartments with priority equal to zero are the first compartments to be located. They must be assigned to their preferred location, and may not have any other compartments (other than other priority zero compartments) in the same SDB. Each compartment is required to have a row (deck) and column (subdivision within zone) preference. A row preference of 1 indicates the ship inner bottom with row numbers increasing going up deck by deck. In this study, the ship is divided into four damage control zones, and each compartment preference specifies a zone. A compartment cannot to be placed outside its zone. The column preference is a preference within the zone and specifies if the compartment should be initially located forward, aft, or in the middle of the assigned zone. The "Power Bus Compt" column specifies if the compartment has any power requirements that require it to be on the port or starboard side of the ship. These compartments are assigned to SDBs that only extend form the port to centerline, or from the starboard to centerline. This allows the ship to have separate port and starboard power busses that are somewhat isolated from each other. These preferences determine the initial compartment location based on their operability, ship mission, and standard practices.

The final compartment input is relocation options. These options represent adjacent SDBs to be evaluated to locate the least vulnerable location. There are 8 possible adjacent SDBs, 1 being directly forward, 3 is directly above, 5 is directly aft, and 7 is directly below. The even numbers are the corner adjacencies. These are shown in Figure 3-23. Possible relocation options are different for each compartment depending on operability.



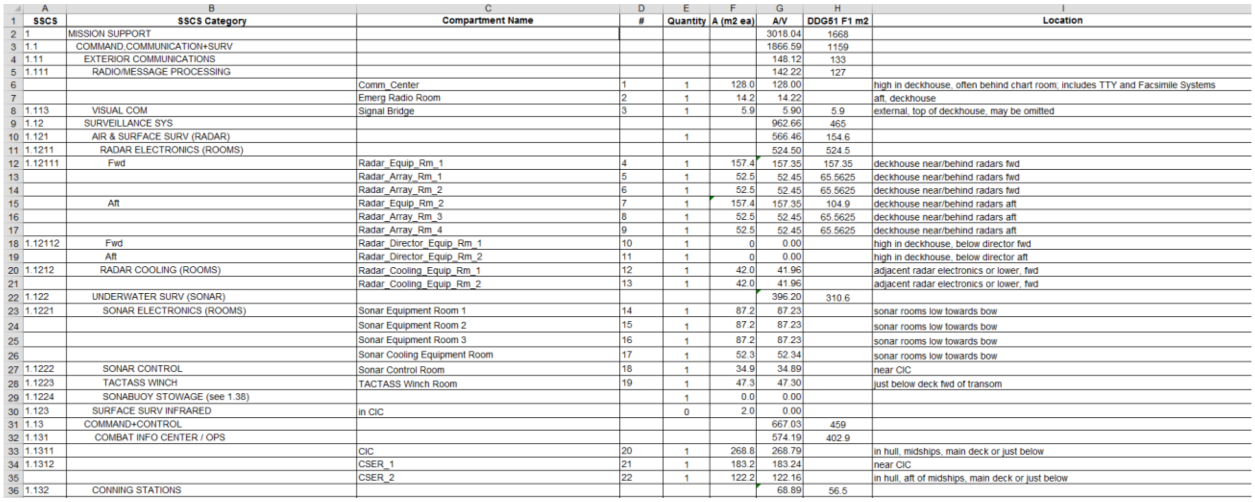
SDB Option 4	SDB Option 3	SDB Option 2
SDB Option 5	Desired SDB	SDB Option 1
SDB Option 6	SDB Option 7	SDB Option 8

Figure 3-23 - Compartment Preference Option Numbering System

3.2.5 Area Requirement Calculations

Required arrange able area is calculated for each compartment to ensure that adequate area is available for it to be placed in a SDB. The calculation of these areas is done by the Ship Space Classification System (SSCS) Worksheets. An example of one SSCS Worksheet is shown in

Figure 3-24. These calculations use area data for combat and machinery systems, various ship characteristics and manning requirements to calculate required compartment area using simple regression based parametric equations. These values are then passed to the Compartments Sheet and used in the arrangements generation.



	A	B	C	D	E	F	G	H	I
1	**SSCS**	**SSCS Category**	**Compartment Name**	**#**	**Quantity**	**A (m2 ea)**	**A/V**	**DDG51 F1 m2**	**Location**
2	1	MISSION SUPPORT					3018.04	1668	
3	1.1	COMMAND,COMMUNICATION+SURV					1866.59	1159	
4	1.11	EXTERIOR COMMUNICATIONS					148.12	133	
5	1.111	RADIO/MESSAGE PROCESSING					142.22	127	
6			Comm_Center	1	1	128.0	128.00		high in deckhouse, often behind chart room; includes TTY and Facsimile Systems
7			Emerg Radio Room	2	1	14.2	14.22		aft, deckhouse
8	1.113	VISUAL COM	Signal Bridge	3	1	5.9	5.90	5.9	external, top of deckhouse, may be omitted
9	1.12	SURVEILLANCE SYS					962.66	465	
10	1.121	AIR & SURFACE SURV (RADAR)			1		566.46	154.6	
11	1.1211	RADAR ELECTRONICS (ROOMS)					524.50	524.5	
12	1.12111	Fwd	Radar_Equip_Rm_1	4	1	157.4	157.35	157.35	deckhouse near/behind radars fwd
13			Radar_Array_Rm_1	5	1	52.5	52.45	65.5625	deckhouse near/behind radars fwd
14			Radar_Array_Rm_2	6	1	52.5	52.45	65.5625	deckhouse near/behind radars fwd
15		Aft	Radar_Equip_Rm_2	7	1	157.4	157.35	104.9	deckhouse near/behind radars aft
16			Radar_Array_Rm_3	8	1	52.5	52.45	65.5625	deckhouse near/behind radars aft
17			Radar_Array_Rm_4	9	1	52.5	52.45	65.5625	deckhouse near/behind radars aft
18	1.12112	Fwd	Radar_Director_Equip_Rm_1	10	1	0	0.00		high in deckhouse, below director fwd
19		Aft	Radar_Director_Equip_Rm_2	11	1	0	0.00		high in deckhouse, below director aft
20	1.1212	RADAR COOLING (ROOMS)	Radar_Cooling_Equip_Rm_1	12	1	42.0	41.96		adjacent radar electronics or lower, fwd
21			Radar_Cooling_Equip_Rm_2	13	1	42.0	41.96		adjacent radar electronics or lower, fwd
22	1.122	UNDERWATER SURV (SONAR)					396.20	310.6	
23	1.1221	SONAR ELECTRONICS (ROOMS)	Sonar Equipment Room 1	14	1	87.2	87.23		sonar rooms low towards bow
24			Sonar Equipment Room 2	15	1	87.2	87.23		sonar rooms low towards bow
25			Sonar Equipment Room 3	16	1	87.2	87.23		sonar rooms low towards bow
26			Sonar Cooling Equipment Room	17	1	52.3	52.34		sonar rooms low towards bow
27	1.1222	SONAR CONTROL	Sonar Control Room	18	1	34.9	34.89		near CIC
28	1.1223	TACTASS WINCH	TACTASS Winch Room	19	1	47.3	47.30		just below deck fwd of transom
29	1.1224	SONABUOY STOWAGE (see 1.38)			1	0.0	0.00		
30	1.123	SURFACE SURV INFRARED	in CIC		0	2.0	0.00		
31	1.13	COMMAND+CONTROL					667.03	459	
32	1.131	COMBAT INFO CENTER / OPS					574.19	402.9	
33	1.1311		CIC	20	1	268.8	268.79		in hull, midships, main deck or just below
34	1.1312		CSER_1	21	1	183.2	183.24		near CIC
35			CSER_2	22	1	122.2	122.16		in hull, aft of midships, main deck or just below
36	1.132	CONNING STATIONS					68.89	56.5	

Figure 3-24 - Example of SSCS Area Requirement Calculations

3.2.6 Compartment Assignments

Once the geometry, SDB damage availabilities, and compartment preferences are defined and compartment required areas are calculated, the ship is ready for preliminary arrangements. VTPAM uses this information to determine operable and least vulnerable locations for each compartment. The process for this is shown in Figure 3-25.

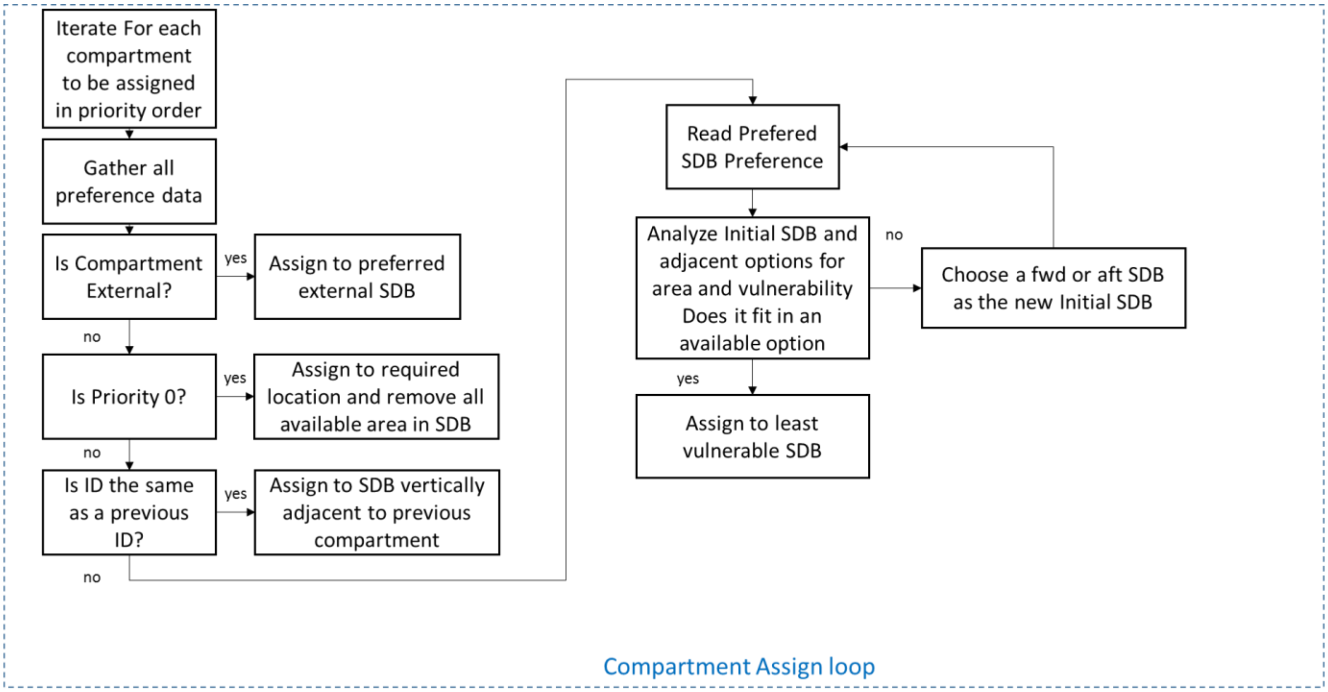


Figure 3-25 – Compartment Assignment Process

VTPAM processes each vital compartment in priority order as shown on the Compartment Sheet in Figure 3-22, and reads the row and column within zone preferences to locate the preferred SDB. This SDB location is evaluated based on required area, post hit availability, and allowable surrounding SDB locations. The SDB chosen as the location for the compartment has the highest hit availability that meets the required area. The SDB available area is reduced by the area of the compartment. If the initial preferred SDB and all of the preference options do not have enough area for the compartment, then the initial preference is modified along the same deck first, then up or down and the compartment is reanalyzed until a location with available area is found. If there is no SDB with enough available area found within the zone or hull/deckhouse, then the code identifies the ship as infeasible. Each compartment must be placed in specified zone and in the hull or deckhouse as specified.

There are three types of compartments that are exceptions to this method. The first type is external compartments that are used to define locations for external VCs. These compartments are placed in one of the external SDBs that were created in Section 3.2.2.4. If the compartment requires an external SDB, it is placed in the external SDB that is above a desired internal compartment that has already been assigned, or it is placed in an external SDB as specified at the forward, middle, or aft location of a desired zone. Either filling in the “Related Internal Compartment” column with the desired compartment ID marks external compartments or a zero in the column to mark a desired zone is needed. The second exception is compartments that have a Priority of zero. This signifies that the compartment is required to be placed in its desired location and that nothing else can be placed there. This is done by assigning the compartment then making the available area equal to zero so that no other compartments can be placed in that SDB. The final exception is compartments that must be vertically aligned. These are given an ID that is the same as the previous ID. If they cannot be vertically aligned, then both compartments must move until they can fit. This is done for compartments that span multiple decks such as the hangar.

3.2.7 Results/Output

The preliminary arrangements function in the PA&V process creates representative feasible ship arrangements considering operability and post-hit availability. Representative arrangements are created for multiple system options and architectures so that their vulnerability may be assessed. These feasible arrangements are used in the VTVM for vulnerability analysis.

This allows VCs to be assigned to SDBs in the ship. Once the VCs are located, the damage extents can be analyzed and the VCs can be analyzed for deactivation. Once a VC is deactivated, each ship required system is analyzed for deactivation for each damage scenario. This allows the ship's capabilities to be analyzed and a vulnerability score to be generated for each ship. This score is very dependent on the location of the VCs and thus the preliminary arrangements and geometry.

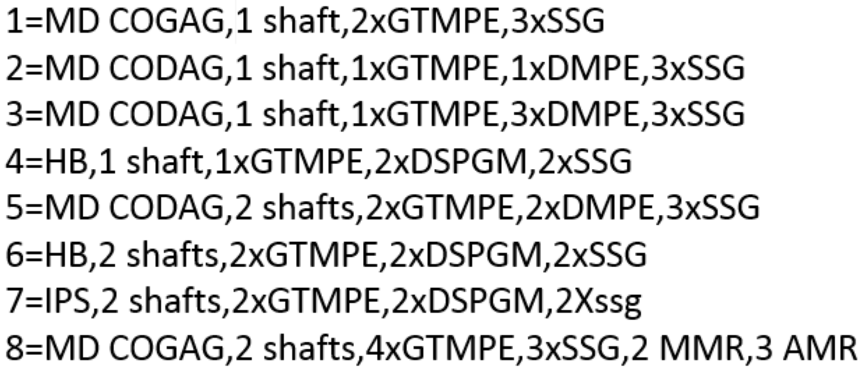
CHAPTER 4 - CASE STUDY

A case study of a notional DDGX was performed using the C&RE process to assess the PA&V process in early stage design. This case study followed the process starting with the Initial Capabilities Document (ICD) through the MOGO as shown in Figure 1-1. This process determined mission requirements from the ICD and considered three power and propulsion systems, a set of combat system options, and a preliminary arrangements generated by the methods described in Chapter 3.

4.1 Ship Propulsion System Options

This case study was a modification to a previous DDG study where vulnerability was not considered. The previous study considered eight propulsion options that are shown in Table 4-1. In order to simplify the process but still assess the vulnerability influence on the design, this case study only considers three of these propulsion options, options 5, 6, and 7.

Table 4-1 – Power and Propulsion System Options from previous DDG study



1=MD COGAG,1 shaft,2xGTMPE,3xSSG
2=MD CODAG,1 shaft,1xGTMPE,1xDMPE,3xSSG
3=MD CODAG,1 shaft,1xGTMPE,3xDMPE,3xSSG
4=HB,1 shaft,1xGTMPE,2xDSPGM,2xSSG
5=MD CODAG,2 shafts,2xGTMPE,2xDMPE,3xSSG
6=HB,2 shafts,2xGTMPE,2xDSPGM,2xSSG
7=IPS,2 shafts,2xGTMPE,2xDSPGM,2Xssg
8=MD COGAG,2 shafts,4xGTMPE,3xSSG,2 MMR,3 AMR

The CODAG option for this case study uses a two shaft mechanical drive configuration where diesel engines are used for cruise speed and gas turbines are used for sprint speed. The architecture for the vulnerability requirements for this system option is shown in Figure 4-1. This RBD shows that only one functional shaft line is needed to maintain propulsion after damage. The shaft lines also require the propulsion control system, the reduction gear system, the shaft and bearing systems, the propulsor system, the MPE group system, the seawater cooling systems, and the fuel oil service system to remain functional.

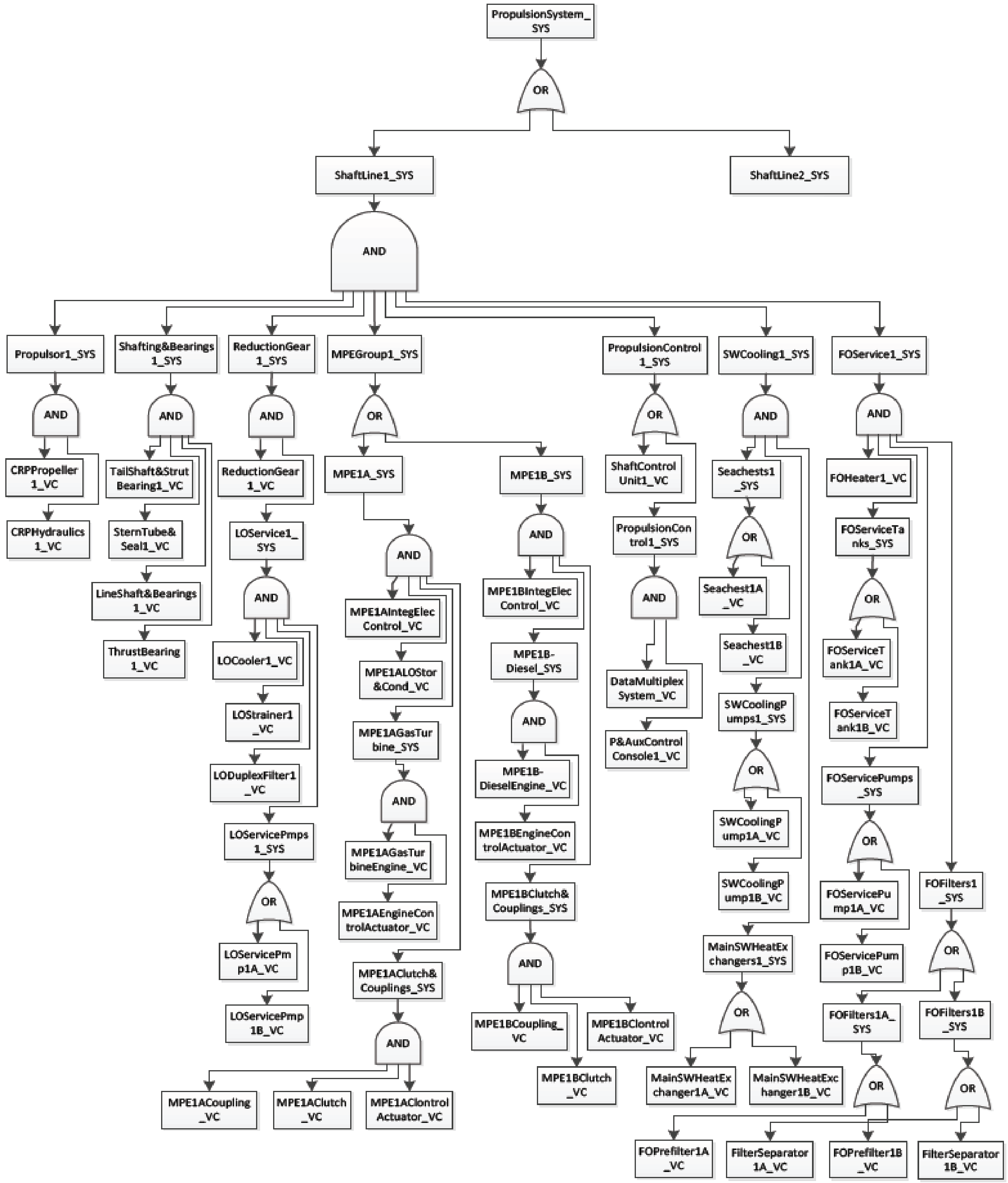


Figure 4-1 - RBD Architecture for CODAG System (Propulsion Option 5)

The Integrated Power System generates electric power for ship service and to power the motors that are used for propulsion. The power is generated by gas turbine and diesel power generation modules (PGMs and SPGMs) which generate 4160 VAC power (McCoy, 2009). This power is distributed by a zonal electrical distribution system (ZEDS) to ship systems and variable speed Propulsion Motor Modules (PMMs) driving fixed pitch propellers. This method eliminates the need for gearbox and CRP propeller systems. This power system also allows for more freedom of generator placement since they do not need to be in line with the propulsors. IPS provides acoustic signature reduction by decoupling the engine noise from the surrounding water. The ability to use large amounts of power in short bursts is also advantageous for future weapon technologies like rail-guns because the power can be rerouted from propulsion to these weapons. These advantages make IPS useful for ship missions that require high speed, low signatures, and high-energy weapons. The RBD architecture for this system is shown in Figure 4-2. Similar to CODAG, the IPS RBD requires one of two shaft lines to be functional to maintain power and propulsion after damage. The shaft lines also require the propulsion control system, the shaft and bearing systems, the propeller system, and the PMM system to remain functional. The ZEDS electrical power distribution for this system is discussed in Section 4.2, and is shown in Figure 4-5.

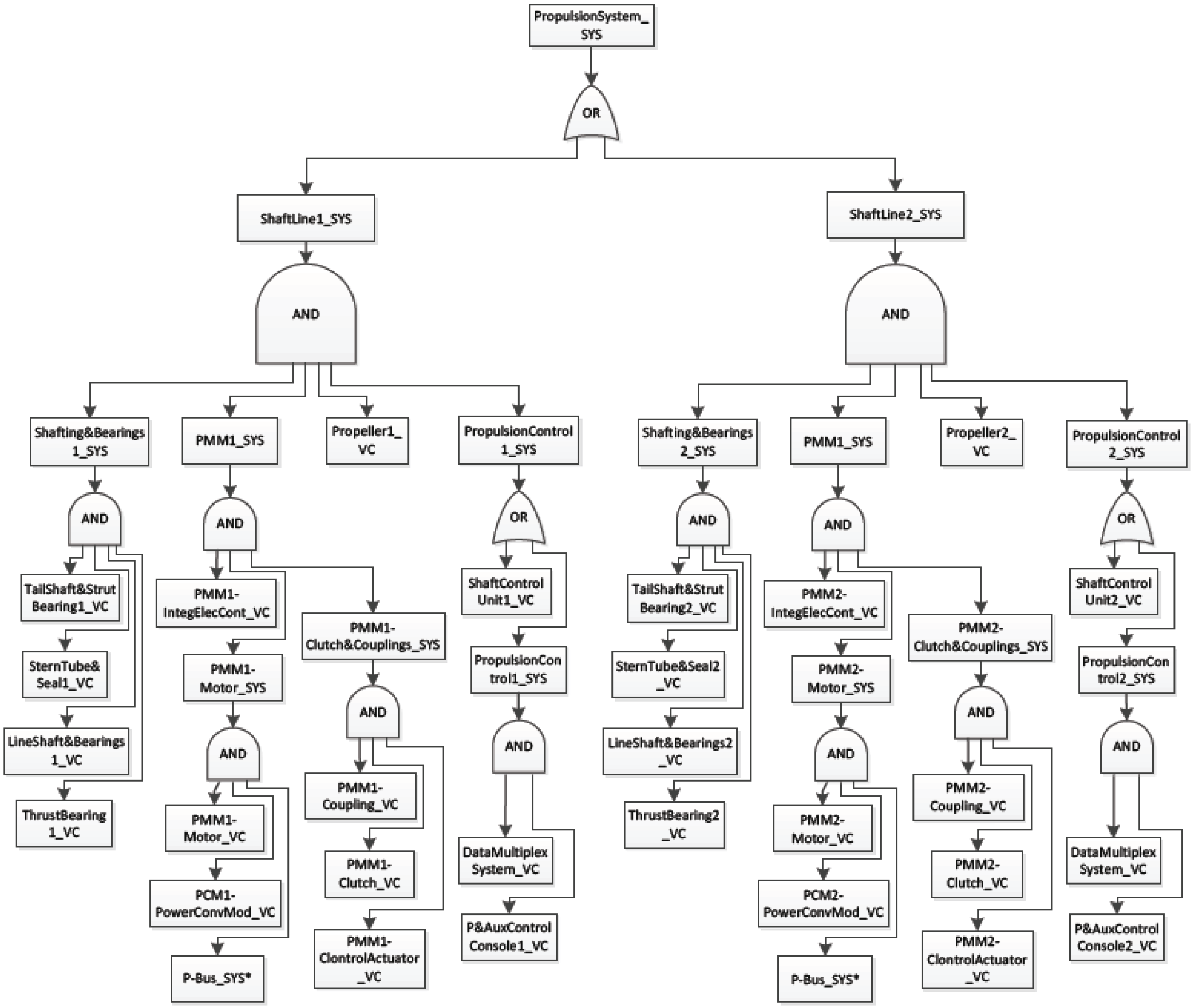


Figure 4-2 - RBD Architecture for IPS System (Propulsion Option 7)

Hybrid Electric Drive Option 6 uses a combination of mechanical and electric propulsion. The gas turbines are used for boost mechanical propulsion and electric power is used for ship service power and secondary propulsion with propulsion motors supplying power to the reduction gears connected in parallel to the gas turbines. The architecture of this propulsion and power system is shown in Figure 4-3 (Steele, 2011). The RBD requires one of two shaft lines to be functional to maintain power and propulsion after damage. The shaft lines also require the propulsion control system, the shaft and bearing systems, the propeller system, the seawater cooling system, the reduction gear system, the MP group system, and the fuel oil service system to remain functional. The electrical power distribution for this system is discussed in Section 4.2 and is shown in Figure 4-6.

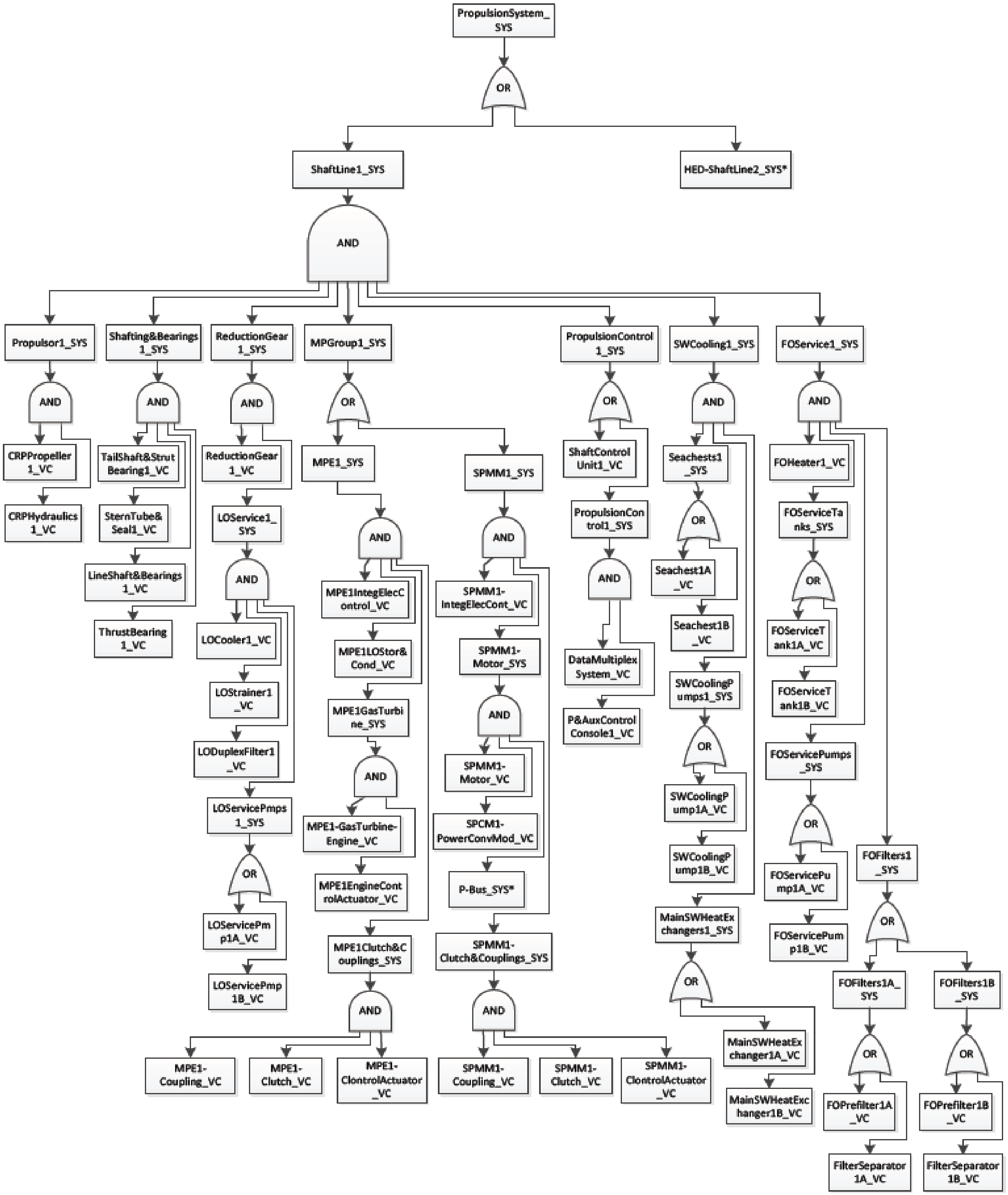


Figure 4-3 – Example RBD Architecture for IPS System (Propulsion Option 6)

4.2 Ship Power Generation and Distribution System

Each of the propulsion and power systems described in Section 4.1 has a corresponding power generation and distribution system that is described in this section. RBDs for these distribution systems are incorporated in the ship RBDs and contribute to ship survivability by providing redundant and distributed sources of power.

The Zonal Electric Distribution System (ZEDS) provides power to the ship in four damage control and power zones. Each zone has two redundant vital load centers and a ship service generator (SSG) that is connected through a switchboard. Each of these load centers receives power form two power conversions modules and bus switchboards that are redundant and separated port and starboard. The bus switchboards receive power from the generator in their own zone or from the bus in either direction around the ship. This is be shown in Figure 4-4. Each of the busses in this ZEDS configuration are 480 VAC.

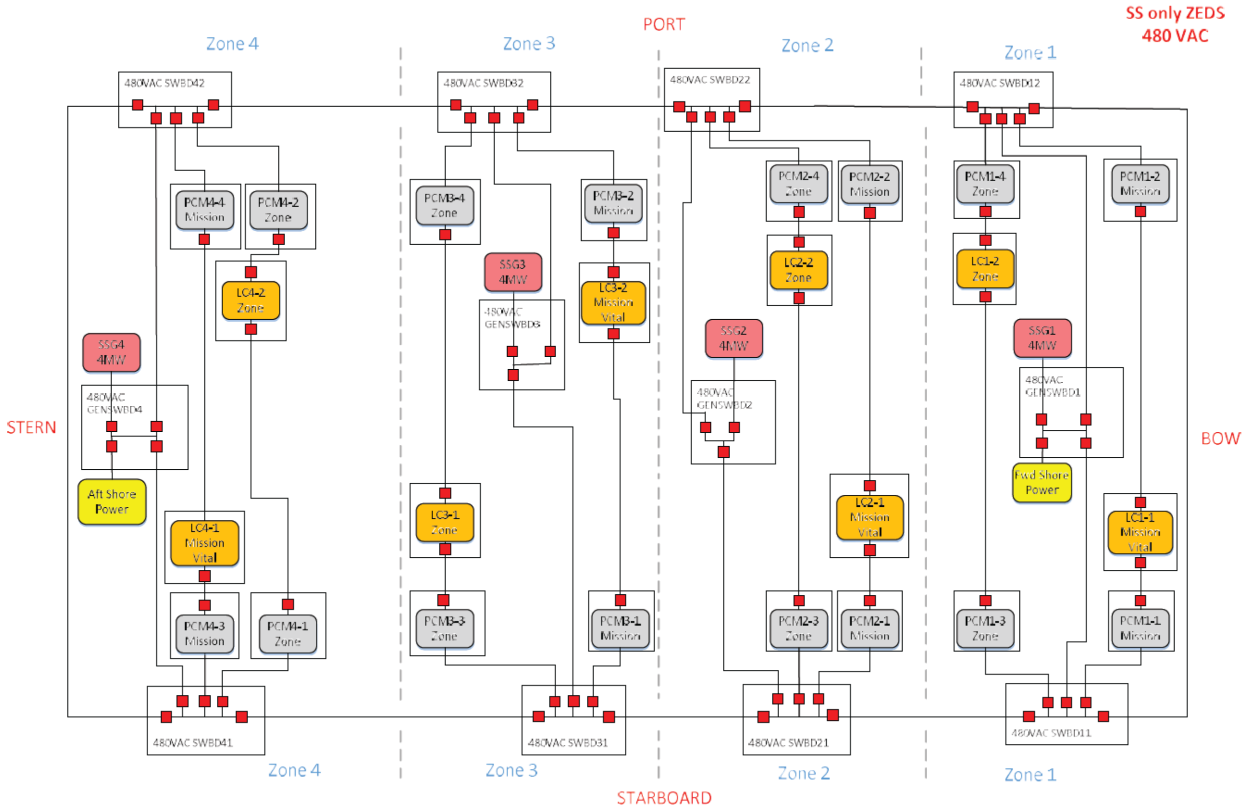


Figure 4-4 - Zonal Electric Distruiution (modified from Bradshaw and Robinson, 2013)

Similar to the ship service ZEDS power distribution, the Integrated Power System (IPS) Dual Ring Bus ZEDS also provides power to the ship in four zones, each with two vital load centers and a generator switchboard. Unlike the ZEDS, the IPS ZEDS in zones 2 and 3 receiver power from two Power Generation Modules (PGMs), and two Secondary Power Generation Modules (SPGMs), and distribute power to a propulsion bus and the zonal bus. As discussed in Section 4.1, redundant bus connections, local power options and power conversion modules provide power to the load centers giving each two sources of power. These busses operate at 4160VAC. This power distribution system is shown in Figure 4-5.

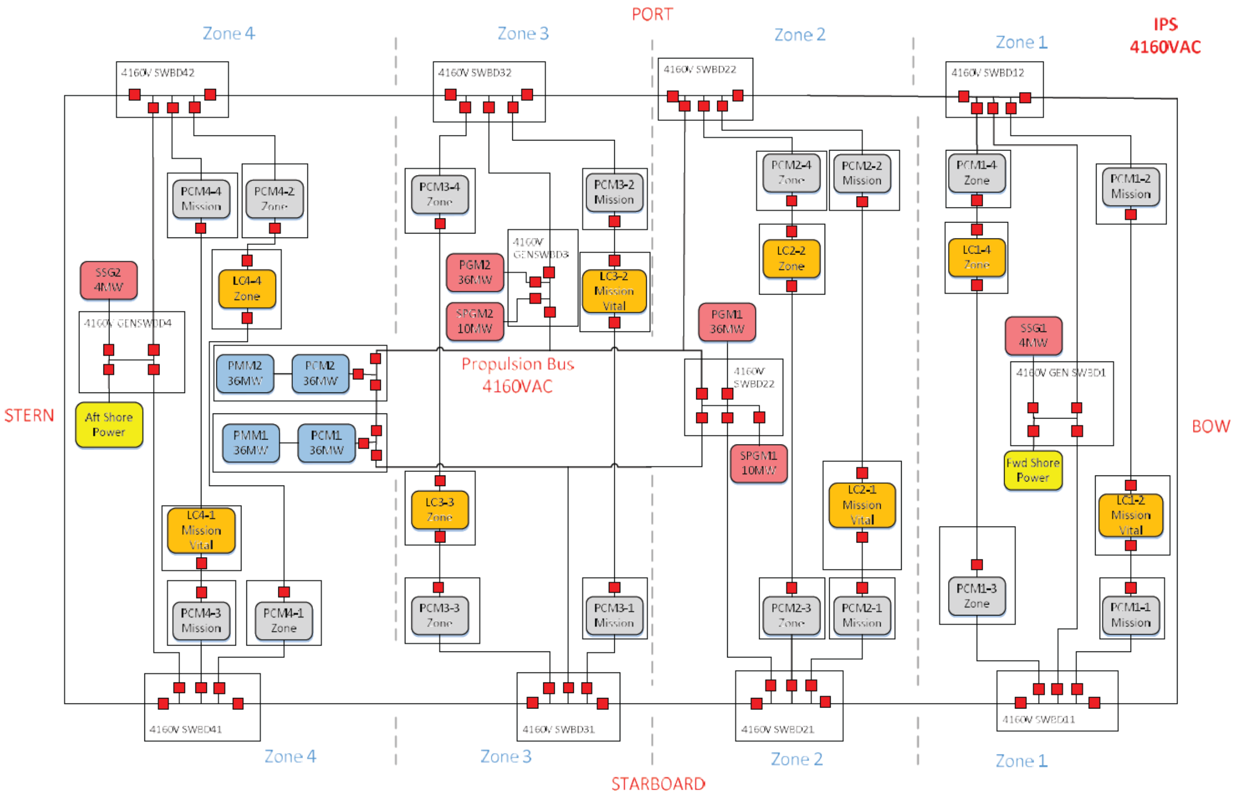


Figure 4-5 - IPS Dual Ring Bus Distribution System (from Bradshaw and Robinson, 2013)

Similar to the other power generation systems, the Hybrid Electric Drive (HED) Dual Ring Bus also provides power to the ship in four zones each with two vital load centers. For the HED, each zone has one ship service generator or SPGM with connections to both port and starboard busses. Since the HED is a hybrid of ZEDS and IPS, it has diesel SPGMs providing electric power from a propulsion bus to the propulsion motors connected to reduction gears and to the ship service bus. Ship service power is also provided to redundant load centers in each zone from bus connections or local power options as described in Section 4.1. The busses operate at 4160VAC. This power distribution system is shown in Figure 4-6.

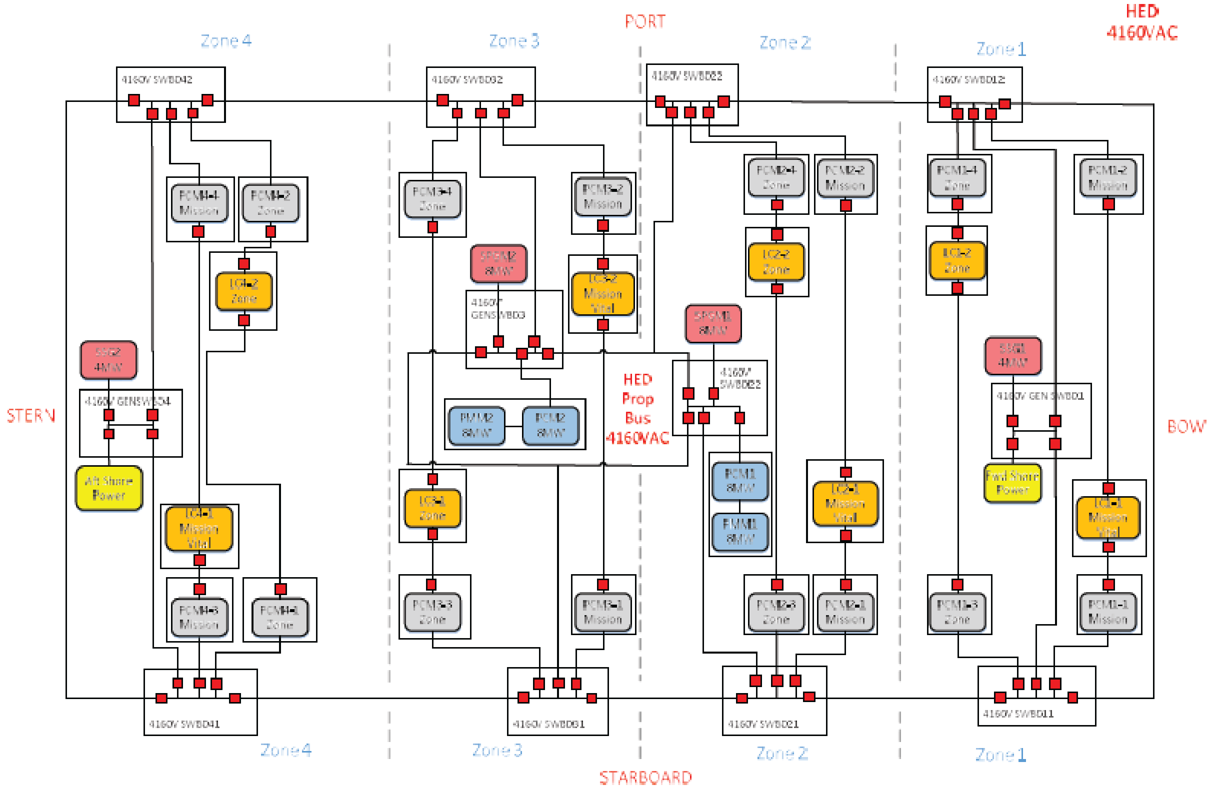


Figure 4-6 – Hybrid Dual Ring Bus Distribution System (Bradshaw and Robinson, 2013)

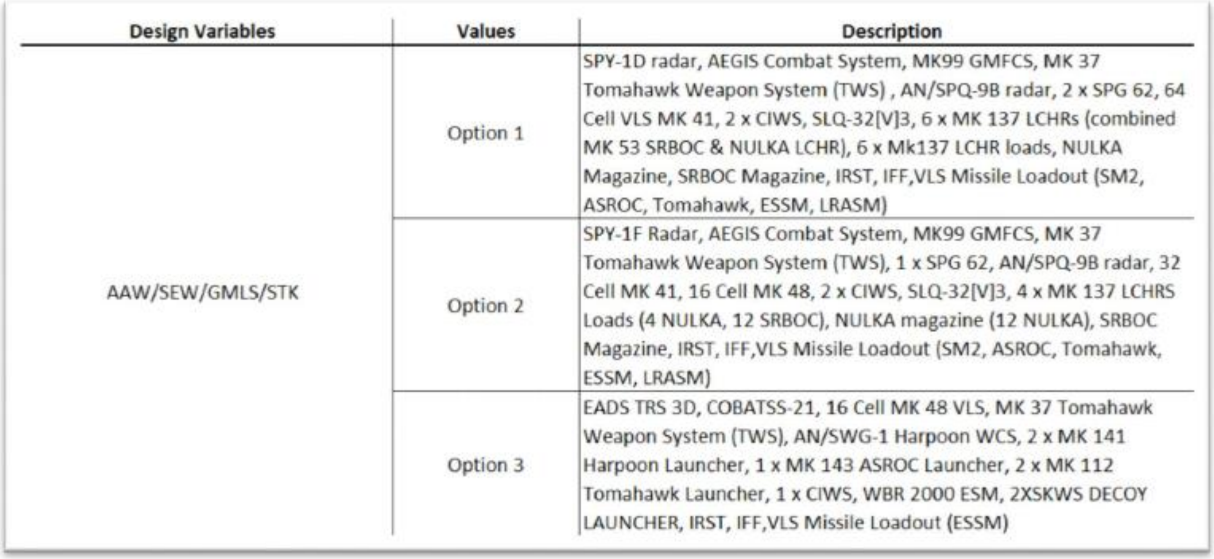
4.3 Ship Combat Systems

The combat system options chosen for this case study are described in the following sections. Each war fighting area combat system provides both offense and defensive capabilities and is separated into three options. The first option provides goal capabilities meaning the most complete and proficient suite to complete the ship mission. The third provides threshold capabilities, meaning the minimum capabilities to complete the ship missions. The second provides capabilities between goal and threshold. This case study uses only the goal option for each warfighting mission area.

4.3.1 Anti-Air Warfare (AAW)

The main functions that are required for an Anti-Air Warfare (AAW) system are detect, control, and engage. Each of the options in the AAW system options accomplishes each of these to some level of performance. These weapon suites generally include a radar system, Interrogator Friend or Foe (IFF) system, fire control systems, and short, medium, and long range air weapon systems. The AAW options are listed in Table 4-2. Option 1 is used for this case study. The RBD for this option is shown in Figure 4-7.

Table 4-2 – AAW System Options



Design Variables	Values	Description
AAW/SEW/GMLS/STK	Option 1	SPY-1D radar, AEGIS Combat System, MK99 GMFCS, MK 37 Tomahawk Weapon System (TWS) , AN/SPQ-9B radar, 2 x SPG 62, 64 Cell VLS MK 41, 2 x CIWS, SLQ-32[V]3, 6 x MK 137 LCHRs (combined MK 53 SRBOC & NULKA LCHR), 6 x Mk137 LCHR loads, NULKA Magazine, SRBOC Magazine, IRST, IFF,VLS Missile Loadout (SM2, ASROC, Tomahawk, ESSM, LRASM)
	Option 2	SPY-1F Radar, AEGIS Combat System, MK99 GMFCS, MK 37 Tomahawk Weapon System (TWS), 1 x SPG 62, AN/SPQ-9B radar, 32 Cell MK 41, 16 Cell MK 48, 2 x CIWS, SLQ-32[V]3, 4 x MK 137 LCHRS Loads (4 NULKA, 12 SRBOC), NULKA magazine (12 NULKA), SRBOC Magazine, IRST, IFF,VLS Missile Loadout (SM2, ASROC, Tomahawk, ESSM, LRASM)
	Option 3	EADS TRS 3D, COBATSS-21, 16 Cell MK 48 VLS, MK 37 Tomahawk Weapon System (TWS), AN/SWG-1 Harpoon WCS, 2 x MK 141 Harpoon Launcher, 1 x MK 143 ASROC Launcher, 2 x MK 112 Tomahawk Launcher, 1 x CIWS, WBR 2000 ESM, 2XSKWS DECOY LAUNCHER, IRST, IFF,VLS Missile Loadout (ESSM)

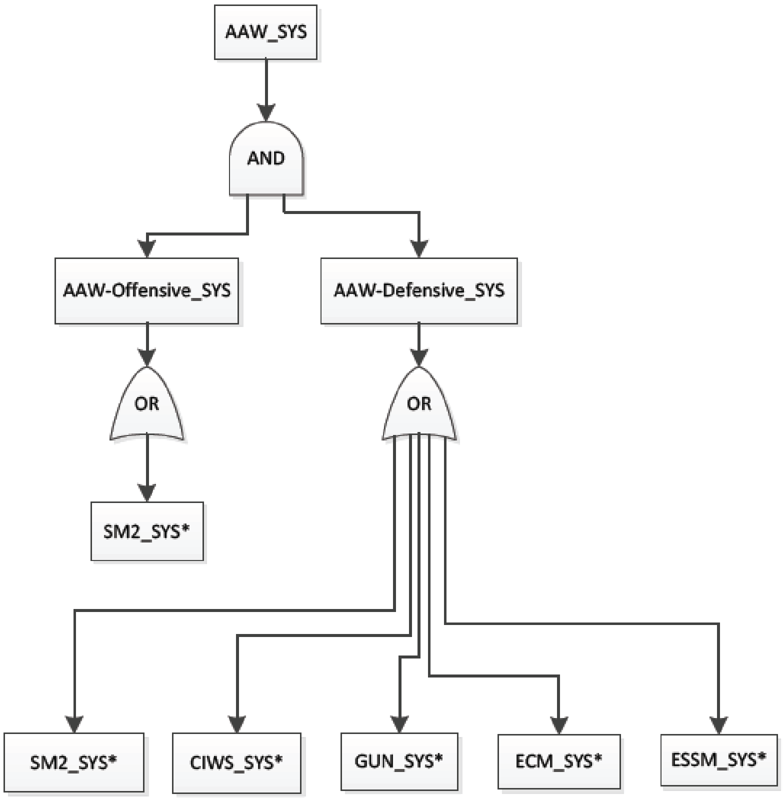
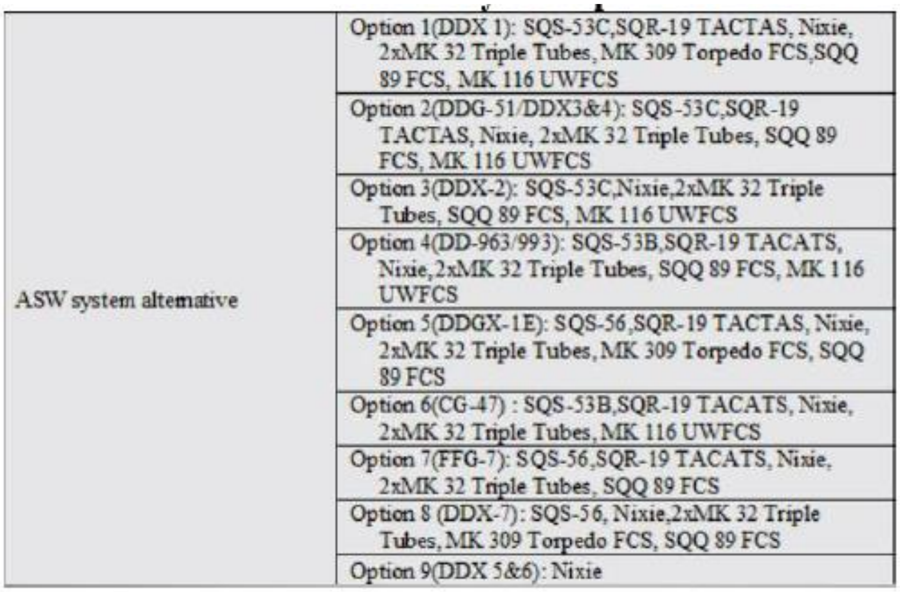


Figure 4-7 - AAW RBD System Architecture

4.3.2 Anti-Submarine Warfare (ASW)

The main functions that are required for an Anti-Submarine Warfare (ASW) system are also detect, control, and engage. Each of the options in the ASW system options accomplishes each of these to some level of performance. The ASW targets are primarily submarines since enemy weapons such as torpedoes are extremely difficult to detect and intercept. A typical weapon suite includes sonar for tracking, torpedo tubes for engagement, fire control systems, underwater countermeasures, and LAMPS helos with sonobuoys and lightweight (LW) torpedoes for engage or intercept. The ASW options are listed in Table 4-3. Option 1 is used for this case study. The RBD for this option is shown in Figure 4-8 and Figure 4-9.

Table 4-3 - ASW System Options



ASW system alternative	Option 1(DDX 1): SQS-53C,SQR-19 TACTAS, Nixie, 2xMK 32 Triple Tubes, MK 309 Torpedo FCS,SQQ 89 FCS, MK 116 UWFCS
	Option 2(DDG-51/DDX3&4): SQS-53C,SQR-19 TACTAS, Nixie, 2xMK 32 Triple Tubes, SQQ 89 FCS, MK 116 UWFCS
	Option 3(DDX-2): SQS-53C,Nixie,2xMK 32 Triple Tubes, SQQ 89 FCS, MK 116 UWFCS
	Option 4(DD-963/993): SQS-53B,SQR-19 TACATS, Nixie,2xMK 32 Triple Tubes, SQQ 89 FCS, MK 116 UWFCS
	Option 5(DDGX-1E): SQS-56,SQR-19 TACTAS, Nixie, 2xMK 32 Triple Tubes, MK 309 Torpedo FCS, SQQ 89 FCS
	Option 6(CG-47) : SQS-53B,SQR-19 TACATS, Nixie, 2xMK 32 Triple Tubes, MK 116 UWFCS
	Option 7(FFG-7): SQS-56,SQR-19 TACATS, Nixie, 2xMK 32 Triple Tubes, SQQ 89 FCS
	Option 8 (DDX-7): SQS-56, Nixie,2xMK 32 Triple Tubes, MK 309 Torpedo FCS, SQQ 89 FCS
	Option 9(DDX 5&6): Nixie

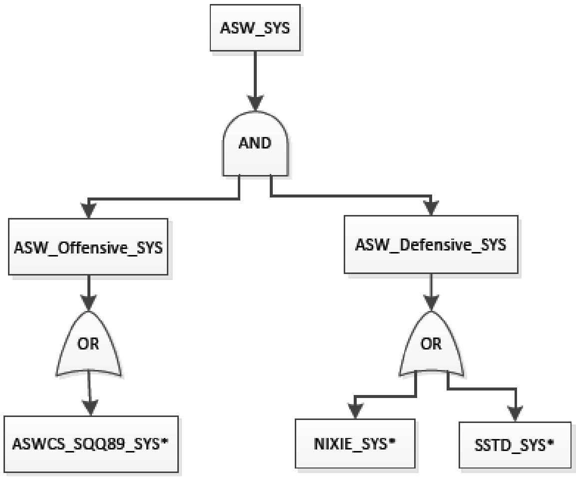


Figure 4-8 - ASW RBD System Architecture

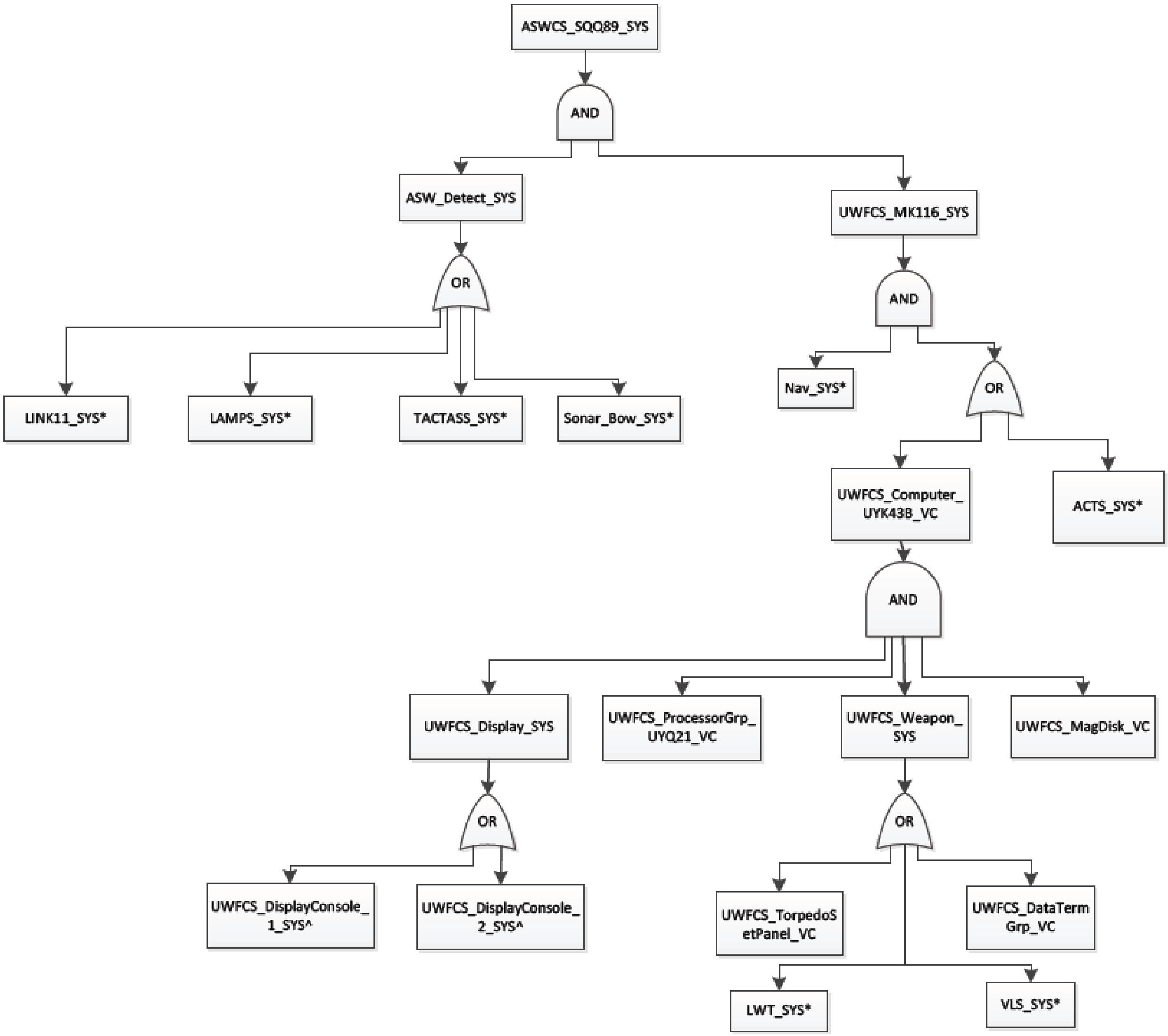
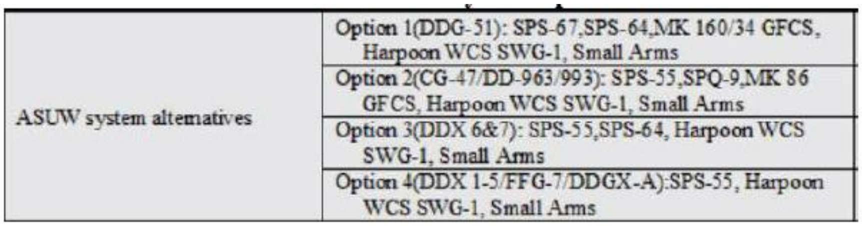


Figure 4-9 - ASWCS SQQ89 System RBD

4.3.3 Anti-Surface Warfare (ASUW)

The main functions that are required for an Anti-Surface Warfare (ASUW) system are also detect, control, and engage. Each of the options in the ASUW system options accomplishes each of these to some level of performance. A typical ASUW weapon suite includes Surface Search Radar for tracking, ASMs, projectiles, and small arms for engagement, and Gun or Missile control systems. The ASW options are listed in Table 4-4. Option 1 is used for this case study. The RBD for this option is shown in Figure 4-10.

Table 4-4 - ASUW System Options



ASUW system alternatives	Option 1(DDG-51): SPS-67,SPS-64,MK 160/34 GFCS, Harpoon WCS SWG-1, Small Arms
	Option 2(CG-47/DD-963/993): SPS-55,SPQ-9,MK 86 GFCS, Harpoon WCS SWG-1, Small Arms
	Option 3(DDX 6&7): SPS-55,SPS-64, Harpoon WCS SWG-1, Small Arms
	Option 4(DDX 1-5/FFG-7/DDGX-A):SPS-55, Harpoon WCS SWG-1, Small Arms

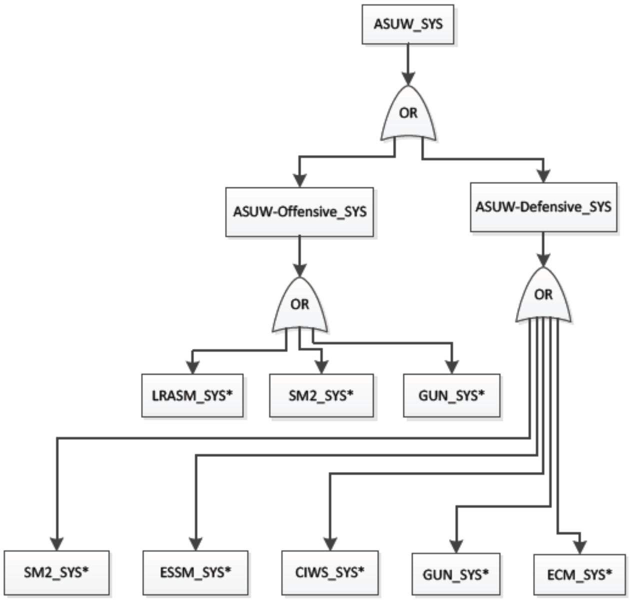


Figure 4-10 - ASUW RBD Systems Architecture

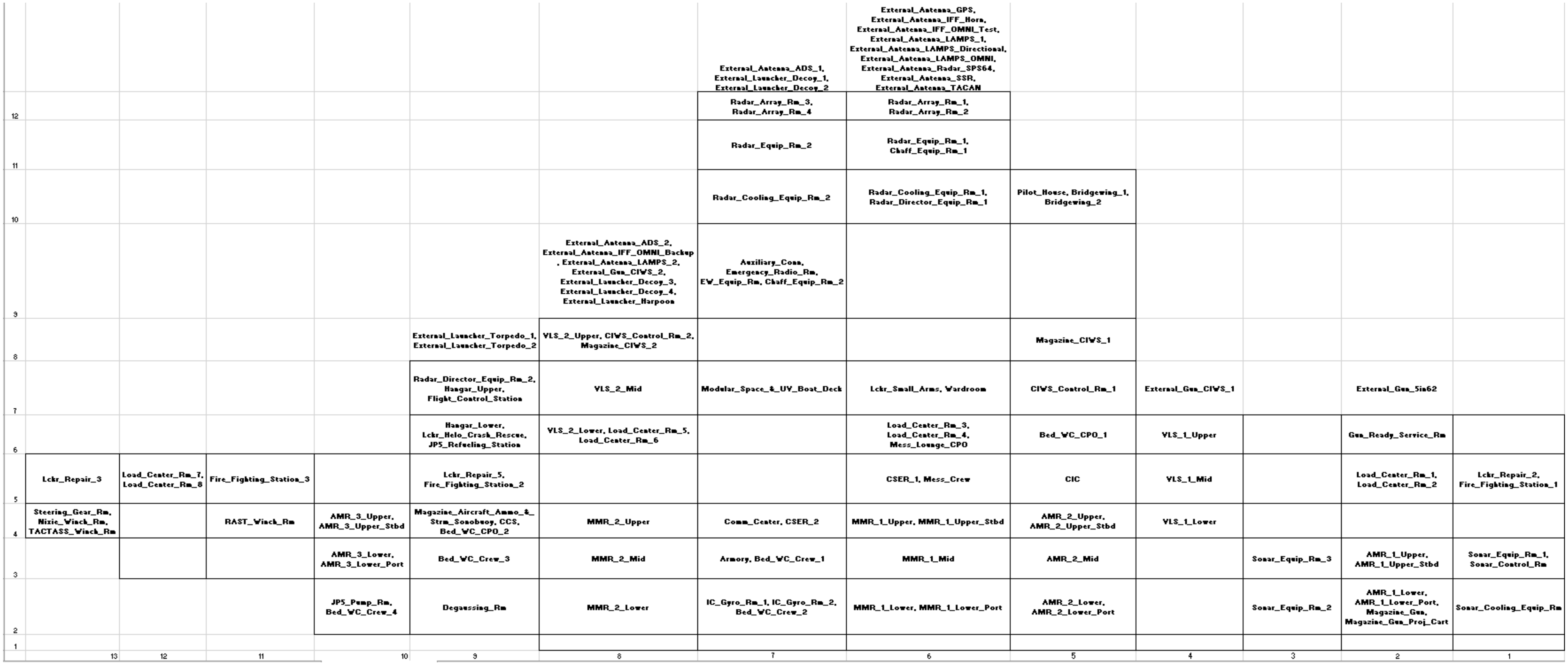
4.4 DDGX PA&V Process and Overall Measure of Vulnerability Overview

The systems options discussed above are used in the PA&V process to generate system representative designs and calculate an Overall Measure of Vulnerability (OMOV) score for each option combination. For this case study, three representative designs are generated which only differ in propulsion and power system options (PSYS). These PSYS options were Options 5, 6, and 7 (CODAG, HED, IPS) from Table 4-1 as discussed in Section 4.1 through Section 4.2. After the PA&V analysis, thousands of designs are synthesized in the Ship Synthesis Module (SSM) and the appropriate OMOV value associated with each PSYS option is used to calculate the OMOE for designs using that option. The Multi-Objective Genetic Optimization (MOGO) is performed to search the design space and generate the design non-dominated frontier that compares the cost, effectiveness (including vulnerability), and risk of non-dominated designs.

The representative designs are named according to the system options that are chosen for each design in the following order: AAW, ASUW, ASW, Power, and Propulsion. This means that the design that uses AAW Option 1, ASUW Option 1, ASW Option 1, Power Option 5, and Propulsion Option 5 would be named 11155. This is the design that uses the CODAG PSYS option in this case study, and the other designs are named 11166 and 11177. This numerical naming convention is very helpful when hundreds of designs are being compared and all system option combinations are considered.

4.5 DDGX Baseline Preliminary Arrangements

Representative design characteristics are determined based on the mission need and system requirements in the PA&V process that is performed before the MOGO. Since each of the designs has the same combat systems, they each have similar characteristics. These are used with the compartment priorities and preferences to generate the preliminary arrangements using the methods discussed in Chapter 3 and calculate vulnerability. Arrangements for the representative designs are shown in Figure 4-11 through Figure 4-13.



	13	12	11	10	9	8	7	6	5	4	3	2	1
							External_Antenna_ADS_1, External_Launcher_Decoy_1, External_Launcher_Decoy_2	External_Antenna_GPS, External_Antenna_IFF_Horn, External_Antenna_IFF_OMNI_Test, External_Antenna_LAMPS_1, External_Antenna_LAMPS_Directional, External_Antenna_LAMPS_OMNI, External_Antenna_Radar_SPS64, External_Antenna_SSR, External_Antenna_TACAN					
12							Radar_Array_Rm_3, Radar_Array_Rm_4	Radar_Array_Rm_1, Radar_Array_Rm_2					
11							Radar_Equip_Rm_2	Radar_Equip_Rm_1, Chaff_Equip_Rm_1					
10							Radar_Cooling_Equip_Rm_2	Radar_Cooling_Equip_Rm_1, Radar_Director_Equip_Rm_1	Pilot_House, Bridgewing_1, Bridgewing_2				
9						External_Antenna_ADS_2, External_Antenna_IFF_OMNI_Backup, External_Antenna_LAMPS_2, External_Gun_CIWS_2, External_Launcher_Decoy_3, External_Launcher_Decoy_4, External_Launcher_Harpoon	Auxiliary_Conn, Emergency_Radio_Rm, EW_Equip_Rm, Chaff_Equip_Rm_2						
8					External_Launcher_Torpedo_1, External_Launcher_Torpedo_2	VLS_2_Upper, CIWS_Control_Rm_2, Magazine_CIWS_2			Magazine_CIWS_1				
7					Radar_Director_Equip_Rm_2, Hangar_Upper, Flight_Control_Station	VLS_2_Mid	Modular_Space_&_UV_Boat_Deck	Lckr_Small_Arms, Wardroom	CIWS_Control_Rm_1	External_Gun_CIWS_1		External_Gun_5in62	
6					Hangar_Lower, Lckr_Helo_Crash_Rescue, JP5_Refueling_Station	VLS_2_Lower, Load_Center_Rm_5, Load_Center_Rm_6		Load_Center_Rm_3, Load_Center_Rm_4, Mess_Lounge_CPO	Bed_WC_CPO_1	VLS_1_Upper		Gun_Ready_Service_Rm	
5	Lckr_Repair_3	Load_Center_Rm_7, Load_Center_Rm_8	Fire_Fighting_Station_3		Lckr_Repair_5, Fire_Fighting_Station_2			CSER_1, Mess_Crew	CIC	VLS_1_Mid		Load_Center_Rm_1, Load_Center_Rm_2	Lckr_Repair_2, Fire_Fighting_Station_1
4	Steering_Gear_Rm, Nixie_Winch_Rm, TACTASS_Winch_Rm		RAST_Winch_Rm	AMR_3_Upper, AMR_3_Upper_Stbd	Magazine_Aircraft_Ammo_&_Strm_Sonobuoy, CCS, Bed_WC_CPO_2	MMR_2_Upper	Comm_Center, CSER_2	MMR_1_Upper, MMR_1_Upper_Stbd	AMR_2_Upper, AMR_2_Upper_Stbd	VLS_1_Lower			
3				AMR_3_Lower, AMR_3_Lower_Port	Bed_WC_Crew_3	MMR_2_Mid	Armory, Bed_WC_Crew_1	MMR_1_Mid	AMR_2_Mid		Sonar_Equip_Rm_3	AMR_1_Upper, AMR_1_Upper_Stbd	Sonar_Equip_Rm_1, Sonar_Control_Rm
2				JP5_Pump_Rm, Bed_WC_Crew_4	Degaussing_Rm	MMR_2_Lower	IC_Gyro_Rm_1, IC_Gyro_Rm_2, Bed_WC_Crew_2	MMR_1_Lower, MMR_1_Lower_Port	AMR_2_Lower, AMR_2_Lower_Port		Sonar_Equip_Rm_2	AMR_1_Lower, AMR_1_Lower_Port, Magazine_Gun, Magazine_Gun_Proj_Cart	Sonar_Cooling_Equip_Rm
1													

Figure 4-11 – 11155 Case Study Preliminary Arrangements

							External_Antenna_ADS_1, External_Launcher_Decoy_1, External_Launcher_Decoy_2	External_Antenna_GPS, External_Antenna_IFF_Horn, External_Antenna_IFF_OMNI_Test, External_Antenna_LAMPS_1, External_Antenna_LAMPS_Directional, External_Antenna_LAMPS_OMNI, External_Antenna_Radar_SPS64, External_Antenna_SSR, External_Antenna_TACAN					
12							Radar_Array_Rm_3, Radar_Array_Rm_4	Radar_Array_Rm_1, Radar_Array_Rm_2					
11							Radar_Equip_Rm_2	Radar_Equip_Rm_1, Chaff_Equip_Rm_1					
10							Radar_Cooling_Equip_Rm_1, Radar_Cooling_Equip_Rm_2	Radar_Director_Equip_Rm_1	Pilot_House, Bridgewing_1, Bridgewing_2				
9						External_Antenna_ADS_2, External_Antenna_IFF_OMNI_Backup, External_Antenna_LAMPS_2, External_Gun_CIWS_2, External_Launcher_Decoy_3, External_Launcher_Decoy_4, External_Launcher_Harpoon	Auxiliary_Conn, Emergency_Radio_Rm, EW_Equip_Rm, Chaff_Equip_Rm_2						
8					External_Launcher_Torpedo_1, External_Launcher_Torpedo_2	VLS_2_Upper, CIWS_Control_Rm_2, Magazine_CIWS_2			Magazine_CIWS_1				
7					Radar_Director_Equip_Rm_2, Hangar_Upper, Flight_Control_Station, Modular_Space_&_UV_Boat_Deck	VLS_2_Mid		Lckr_Small_Arms, Wardroom	CIWS_Control_Rm_1	External_Gun_CIWS_1		External_Gun_5in62	
6					Hangar_Lower, Lckr_Helo_Crash_Rescue, JP5_Refueling_Station	VLS_2_Lower, Load_Center_Rm_5, Load_Center_Rm_6	CSER_1, Bed_WC_CPO_1	CIC, Load_Center_Rm_3, Load_Center_Rm_4, Mess_Lounge_CPO		VLS_1_Upper		Gun_Ready_Service_Rm	
5	Lckr_Repair_3	Load_Center_Rm_7, Load_Center_Rm_8	Fire_Fighting_Station_3		Lckr_Repair_5, Fire_Fighting_Station_2			Mess_Crew		VLS_1_Mid		Load_Center_Rm_1, Load_Center_Rm_2	Lckr_Repair_2, Fire_Fighting_Station_1
4	Steering_Gear_Rm, Nixie_Winch_Rm, TACTASS_Winch_Rm		RAST_Winch_Rm	AMR_3_Upper, AMR_3_Upper_Stbd	Magazine_Aircraft_Ammo_&_Strm_Sonobuoy, CCS, Bed_WC_CPO_2	MMR_2_Upper	Comm_Center, CSER_2	MMR_1_Upper, MMR_1_Upper_Stbd	AMR_2_Upper, AMR_2_Upper_Stbd	VLS_1_Lower			
3				AMR_3_Lower, AMR_3_Lower_Port	Bed_WC_Crew_3	MMR_2_Mid	Armory, Bed_WC_Crew_1	MMR_1_Mid	AMR_2_Mid		Sonar_Equip_Rm_3	AMR_1_Upper, AMR_1_Upper_Stbd	Sonar_Equip_Rm_1, Sonar_Control_Rm
2				JP5_Pump_Rm, Bed_WC_Crew_4	Degaussing_Rm	MMR_2_Lower	IC_Gyro_Rm_1, IC_Gyro_Rm_2, Bed_WC_Crew_2	MMR_1_Lower, MMR_1_Lower_Port	AMR_2_Lower, AMR_2_Lower_Port		Sonar_Equip_Rm_2	AMR_1_Lower, AMR_1_Lower_Port, Magazine_Gun, Magazine_Gun_Proj_Cart	Sonar_Cooling_Equip_Rm
1													
	13	12	11	10	9	8	7	6	5	4	3	2	1

Figure 4-12 - 11166 Case Study Preliminary Arrangements

								External_Antenna_ADS_1, External_Launcher_Decoy_1, External_Launcher_Decoy_2	External_Antenna_GPS, External_Antenna_IFF_Horn, External_Antenna_IFF_OMNI_Test, External_Antenna_LAMPS_1, External_Antenna_LAMPS_Directional, External_Antenna_LAMPS_OMNI, External_Antenna_Radar_SPS64, External_Antenna_SSR, External_Antenna_TACAN					
12								Radar_Array_Rm_3, Radar_Array_Rm_4	Radar_Array_Rm_1, Radar_Array_Rm_2					
11								Radar_Equip_Rm_2	Radar_Equip_Rm_1, Chaff_Equip_Rm_1					
10								Radar_Cooling_Equip_Rm_1, Radar_Cooling_Equip_Rm_2	Radar_Director_Equip_Rm_1	Pilot_House, Bridgewing_1, Bridgewing_2				
9							External_Antenna_ADS_2, External_Antenna_IFF_OMNI_Backup, External_Antenna_LAMPS_2, External_Gun_CIWS_2, External_Launcher_Decoy_3, External_Launcher_Decoy_4, External_Launcher_Harpoon	Auxiliary_Conn, Emergency_Radio_Rm, EW_Equip_Rm, Chaff_Equip_Rm_2						
8						External_Launcher_Torpedo_1, External_Launcher_Torpedo_2	VLS_2_Upper, CIWS_Control_Rm_2, Magazine_CIWS_2			Magazine_CIWS_1				
7						Radar_Director_Equip_Rm_2, Hangar_Upper, Flight_Control_Station, Modular_Space_&_UV_Boat_Deck	VLS_2_Mid		Lckr_Small_Arms, Wardroom	CIWS_Control_Rm_1	External_Gun_CIWS_1		External_Gun_5in62	
6						Hangar_Lower, Lckr_Helo_Crash_Rescue, JP5_Refueling_Station	VLS_2_Lower, Load_Center_Rm_5, Load_Center_Rm_6		Load_Center_Rm_3, Load_Center_Rm_4	CIC	VLS_1_Upper		Gun_Ready_Service_Rm	
5		Lckr_Repair_3	Load_Center_Rm_7, Load_Center_Rm_8	Fire_Fighting_Station_3		Lckr_Repair_5, Fire_Fighting_Station_2			CSER_1, Mess_Crew, Mess_Lounge_CPO	Bed_WC_CPO_1	VLS_1_Mid		Load_Center_Rm_1, Load_Center_Rm_2	Lckr_Repair_2, Fire_Fighting_Station_1
4	Steering_Gear_Rm, Nixie_Winch_Rm, TACTASS_Winch_Rm			RAST_Winch_Rm	AMR_3_Upper, AMR_3_Upper_Stbd	Magazine_Aircraft_Ammo_&_Strm_Sonobuoy, CCS, Bed_WC_CPO_2	MMR_2_Upper	Comm_Center, CSER_2	MMR_1_Upper, MMR_1_Upper_Stbd	AMR_2_Upper, AMR_2_Upper_Stbd	VLS_1_Lower			
3				Prop_Motor_Rm_1_Upper, Prop_Motor_Rm_2_Upper	AMR_3_Lower, AMR_3_Lower_Port	Bed_WC_Crew_3	MMR_2_Mid	Armory, Bed_WC_Crew_1	MMR_1_Mid	AMR_2_Mid		Sonar_Equip_Rm_3	AMR_1_Upper, AMR_1_Upper_Stbd	Sonar_Equip_Rm_1, Sonar_Control_Rm
2					Prop_Motor_Rm_1_Lower, Prop_Motor_Rm_2_Lower, JP5_Pump_Rm	Degaussing_Rm, Bed_WC_Crew_4	MMR_2_Lower	IC_Gyro_Rm_1, IC_Gyro_Rm_2, Bed_WC_Crew_2	MMR_1_Lower, MMR_1_Lower_Port	AMR_2_Lower, AMR_2_Lower_Port		Sonar_Equip_Rm_2	AMR_1_Lower, AMR_1_Lower_Port, Magazine_Gun, Magazine_Gun_Proj_Cart	Sonar_Cooling_Equip_Rm
1														
	14	13	12	11	10	9	8	7	6	5	4	3	2	1

Figure 4-13 - 11177 Case Study Preliminary Arrangements

These arrangements each have two Main Machinery Rooms (MMRs), three Auxiliary Machinery Rooms (AMRs), and eight load centers with two in each zone as required by the propulsion and power systems. The 11177 Case Study (IPS) also has propulsion motor rooms. Each of these arrangements are feasible where the machinery rooms, pilothouse, VLS, radar, and antennas are all located close to standard practice locations. This shows that the PA&V process generates ship arrangements that meet the system requirements and represent a good starting point for the design process.

The vulnerability of each of these arrangements was then analyzed using two threat scenarios. The first was a sea skimming missile that penetrates the hull and damages internally near the waterline. The second was an anti-radiation missile that targets the topside of the ship. The parameters for each of these threats are given in Table 4-5. An example of the hit distribution for the sea skimming ASM and Anti-Radiation missile is shown for one of the representative designs in Figure 4-14. This distribution is used to determine the probability of intersection and damage for each subdivision block. An example of the combined probability of each subdivision block's intersection with the hit damage extents is shown on one of the study designs in Figure 4-15 with the color code given in Table 4-6.

Table 4-5 - Case Study Threat Parameters

Name	Threat Location Type	Detonation Type	Mean Threat Detonation Point			Standard Deviation Threat Detonation Point			Mass	Initial Velocity (m/s)
			X	Y	Z	X	Y	Z		
Sea-Skimming ASM	Airex	Internal	80.3187	0	11.46	40.15935	1	3.33333333	870	310
Anti-Radiation ASM	Airex	Fragmenting	80.3187	0	21.46	48.19122	1	8.58425676	907	857.5

Drag Coefficient	Fuse Delay Mean (sec)	Fuse Delay Standard Deviation (sec)	Equivalent TNT (kg)	Casing Weight (kg)	Avg. Casing Thickness (m)	Avg. Casing Inner Diameter (m)	Casing Density (kg/m^3)	Fragment Drag Coefficient	Threat Probability of Encounter
1	0.019	0.006	165	0	0	0	0	0	0.8
1	0.013	0.003	205	90	0.02	0.1	7860	1	0.8

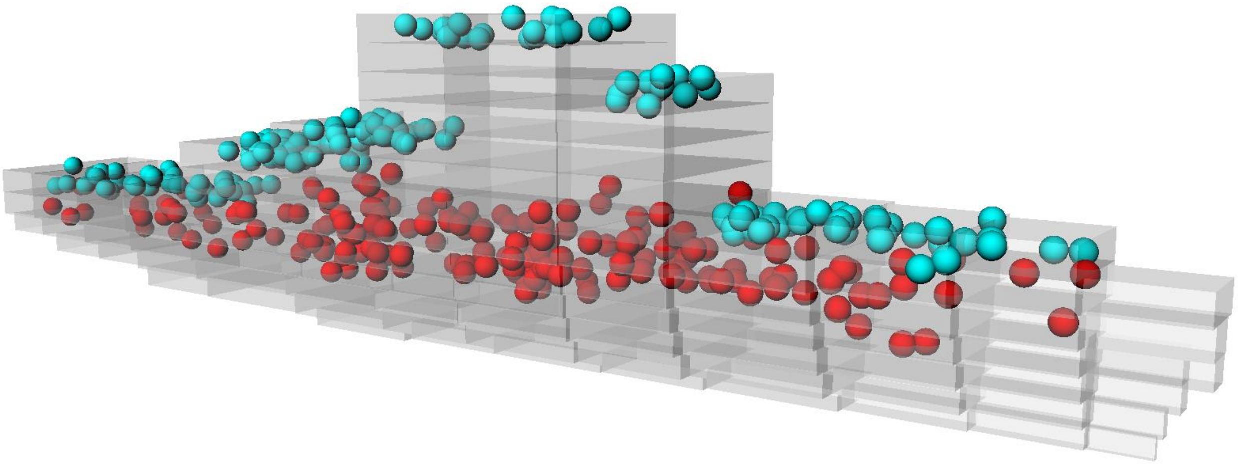


Figure 4-14 - Case Study Hit Distribution with Sea-Skimming ASM (red) and Anti-Radiation ASM (cyan)

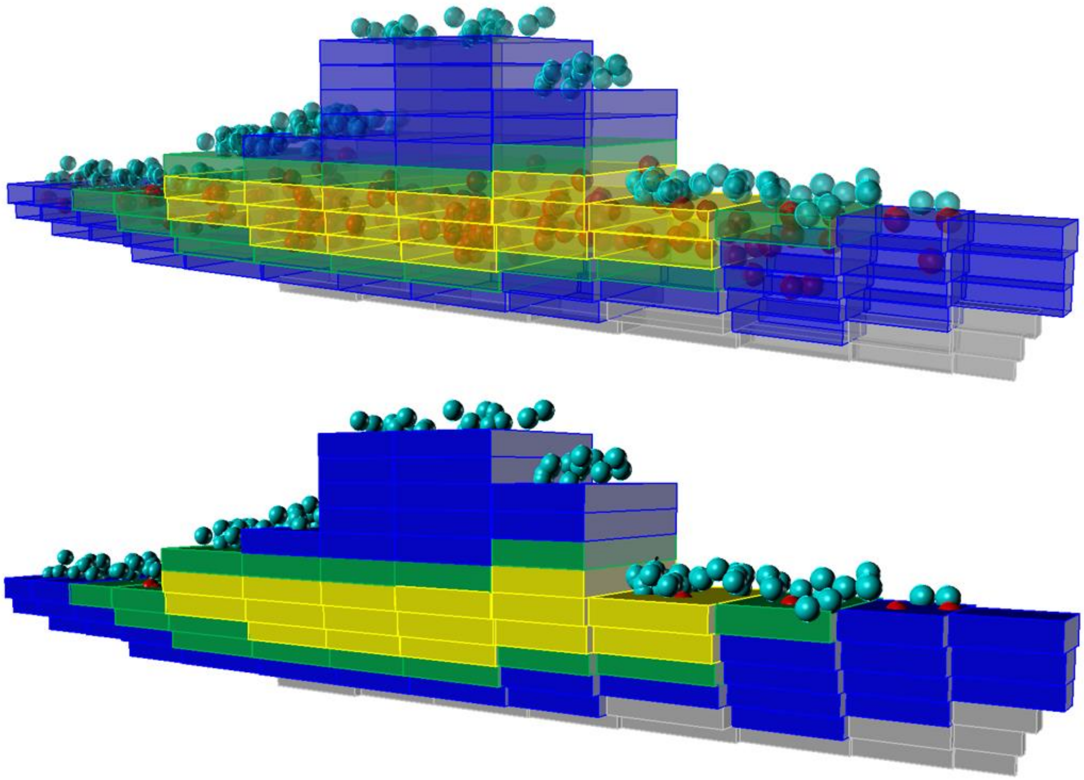
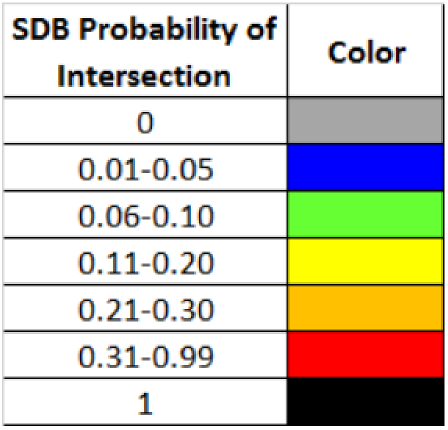


Figure 4-15 - Case Study Probability of Damage Intersection

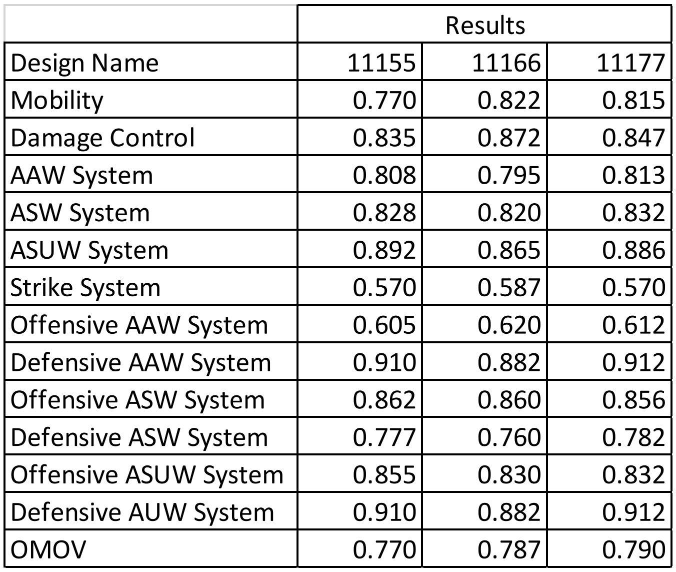
Table 4-6 - SBD Probability of Intersection Color Code



SDB Probability of Intersection	Color
0	▩
0.01-0.05	🟦
0.06-0.10	🟩
0.11-0.20	🟨
0.21-0.30	🟧
0.31-0.99	🟥
1	⬛

The three representative designs that are used in this case study were then analyzed for their system vulnerability that results from being hit by the threats described above. The results for this analysis are shown in Table 4-7 for each system capability. Since the PSYS options also vary the power systems of the ship, this causes differences in combat systems vulnerability. The AAW and ASW vulnerability show this most clearly. The CODAG (11155) power and propulsion system has the lowest score for mobility because it is the least redundant and the most mechanically driven design causing more vulnerable areas on the ship. The three designs have similar overall scores ranging from 0.770 to 0.790 with the most vulnerable being the CODAG PSYS option (design 11155) and the least vulnerable being the IPS PSYS option (11177). This is likely due to the strong redundancy of IPS.

Table 4-7 - OMOV Analysis Results (higher is less vulnerability)



	Results		
Design Name	11155	11166	11177
Mobility	0.770	0.822	0.815
Damage Control	0.835	0.872	0.847
AAW System	0.808	0.795	0.813
ASW System	0.828	0.820	0.832
ASUW System	0.892	0.865	0.886
Strike System	0.570	0.587	0.570
Offensive AAW System	0.605	0.620	0.612
Defensive AAW System	0.910	0.882	0.912
Offensive ASW System	0.862	0.860	0.856
Defensive ASW System	0.777	0.760	0.782
Offensive ASUW System	0.855	0.830	0.832
Defensive AUW System	0.910	0.882	0.912
OMOV	0.770	0.787	0.790

An Overall Measure of Effectiveness (OMOE) value is calculated for each design. Each MOP in the OMOE is given a value weight and equation (4-1) is used to calculate the OMOE for each design.

$$\boldsymbol{OMOE = \sum_1^n VMOP_n * MOP_n} \tag{4-1}$$

The weight for each MOP used in this calculation are given in Table 4-8. The OMOV scores from Table 4-7 are used as one of these MOPs weighted by a value of 0.062. The OMOV scores for each representative design are then used for designs with the same system combinations.

Table 4-8 - OMOE MOP Weights

MOP	Weight
AAW & CCC	0.156
Acoustic Signature	0.065
ASUW/NSFS	0.083
ASW/MCM	0.084
C4ISR	0.087
Endurance Range	0.053
IRS Signature	0.058
Magnetic Signature	0.051
NBC	0.054
Provisions Duration	0.05
RCS	0.08
Seakeeping	0.061
Sustained Speed	0.056
Vulnerability	0.062

4.6 Comparison of MOGO Results with and without OMOV

In order to assess the effects of including vulnerability in the C&RE process, a comparison is made between the non-dominated frontier results for ships with and without vulnerability included in the MOGO. This is done using two complete Multi-Objective Genetic Optimizations (MOGOs) with the design variables values in Table 4-9 and Table 4-10.

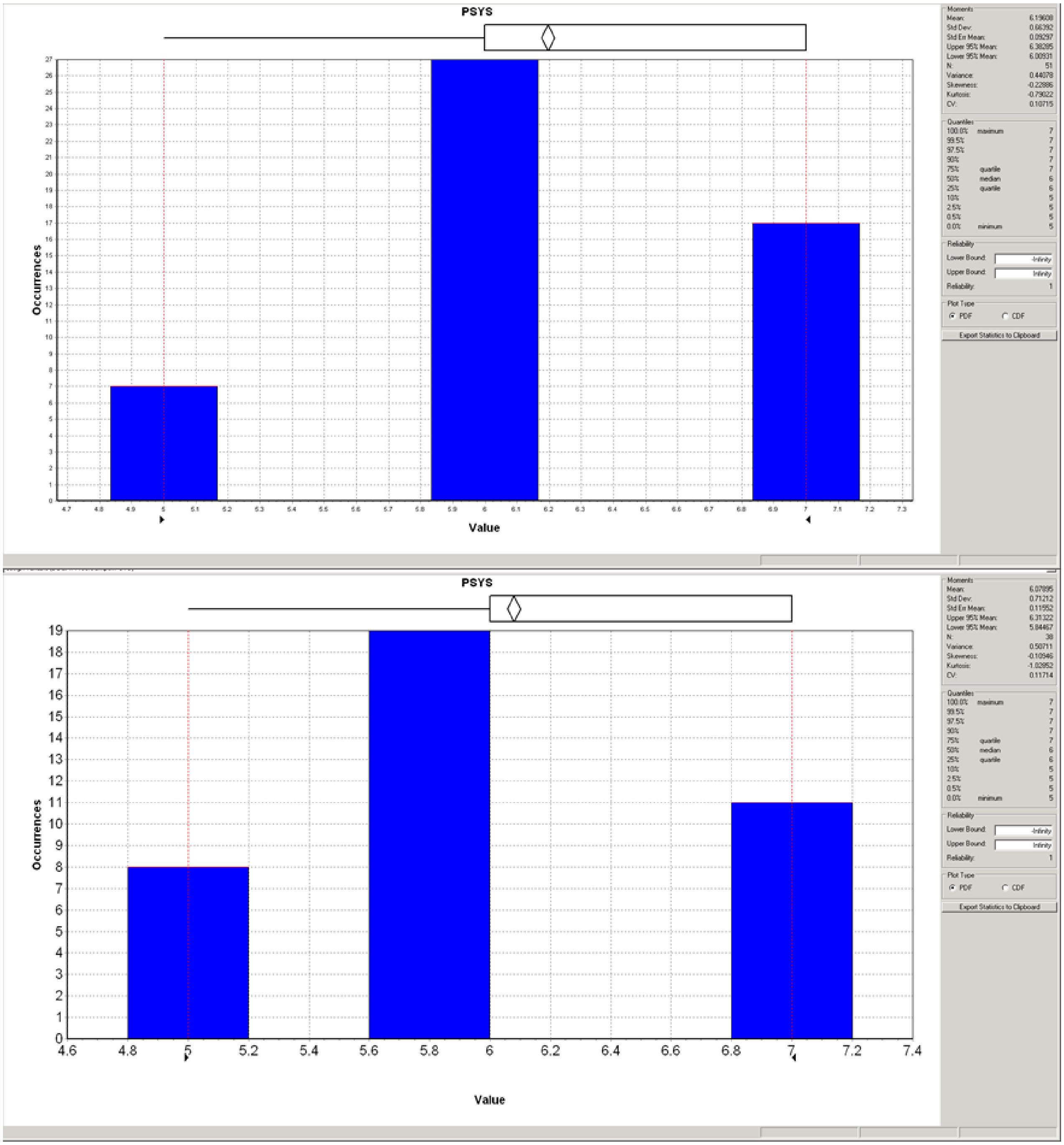
Table 4-9 - MOGO Design Variables and Bounds

Variable	Lower Bound	Upper Bound
LOA	130.0	165.0
MAINT	1.0	3.0
LtoB	7.1	7.7
BtoT	3.3	3.6
LongPrismaticControl	0.3	0.4
StemRake	35.0	45.0
SectionTightness	0.4	1.0
DeadriseMid	0.2	0.3
FullnessFwd	0.3	0.6
Vdmin	3000.0	6000.0

Table 4-10 - MOGO System Design Options

Variable	Lower Bound	Upper Bound
CDHMAT	1	3
PSYS	5	7
GTMPE	1	2
DMPE	1	4
SSGENG	1	3
Ts	35	60
CCC	1	2
AIR	1	2
Ncps	0	2
Ndegaus	0	1

The non-dominated designs for these MOGO analyses are shown in Figure 4-16 through Figure 4-19. Figure 4-16 shows the histograms for the PSYS preference if vulnerability is and is not considered. This shows that there is a tendency in both to use the HED PSYS option, but if vulnerability is included, there is a further preference shift from CODAG to IPS. Figure 4-17 shows the histograms for OMOE if vulnerability is and is not considered and shows an increase in OMOE if vulnerability is included. Figure 4-18 shows the histograms for OMOR if vulnerability is and is not considered. This figure shows that there is a decrease in OMOR when moving from IPS to HED due to the decrease in risk. Figure 4-19 shows the histograms for ship acquisition cost if vulnerability is and is not considered. This shows a decrease in follow-ship acquisition cost (Cfola) when shifting from IPS to HED.



```
Moments
Mean:                6.19608
Std Dev:             0.66392
Std Err Mean:        0.09297
Upper 95% Mean:      6.38285
Lower 95% Mean:      6.00931
N:                        51
Variance:            0.44078
Skewness:           -0.22886
Kurtosis:           -0.79022
CV:                  0.10715

Quantiles
100.0%   maximum           7
99.5%                      7
97.5%                      7
90%                        7
75%      quartile          7
50%      median            6
25%      quartile          6
10%                        5
2.5%                       5
0.5%                       5
0.0%     minimum           5

Reliability
Lower Bound:       -Infinity
Upper Bound:        Infinity
Reliability:               1

Plot Type
● PDF        ○ CDF
```

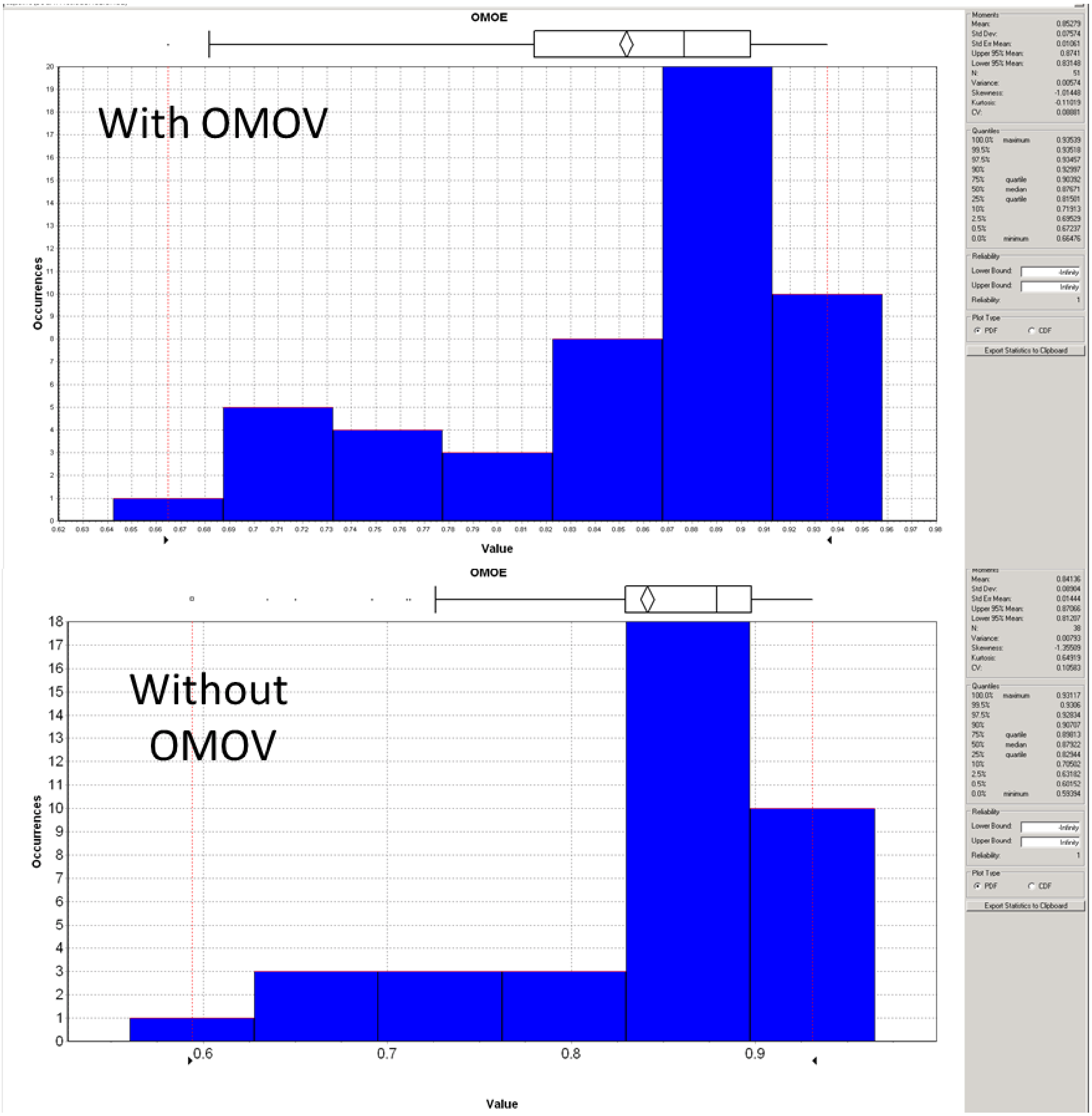
```
Moments
Mean:                6.07895
Std Dev:             0.71212
Std Err Mean:        0.11552
Upper 95% Mean:      6.31322
Lower 95% Mean:      5.84467
N:                        38
Variance:            0.50711
Skewness:           -0.10946
Kurtosis:           -1.02852
CV:                  0.11714

Quantiles
100.0%   maximum           7
99.5%                      7
97.5%                      7
90%                        7
75%      quartile          7
50%      median            6
25%      quartile          6
10%                        5
2.5%                       5
0.5%                       5
0.0%     minimum           5

Reliability
Lower Bound:       -Infinity
Upper Bound:        Infinity
Reliability:               1

Plot Type
● PDF        ○ CDF
```

Figure 4-16 - Case Study MOGO PSYS Results Histogram (w/o OMOV; w/ OMOV)



Moments	
Mean:	0.85279
Std Dev:	0.07574
Std Err Mean:	0.01061
Upper 95% Mean:	0.8741
Lower 95% Mean:	0.83148
N:	51
Variance:	0.00574
Skewness:	-1.01448
Kurtosis:	-0.11019
CV:	0.08881

Quantiles		
100.0%	maximum	0.93539
99.5%		0.93518
97.5%		0.93457
90%		0.92997
75%	quartile	0.90392
50%	median	0.87671
25%	quartile	0.81501
10%		0.71913
2.5%		0.69529
0.5%		0.67237
0.0%	minimum	0.66476

Reliability
Lower Bound: -Infinity
Upper Bound: Infinity
Reliability: 1

Plot Type
● PDF ○ CDF

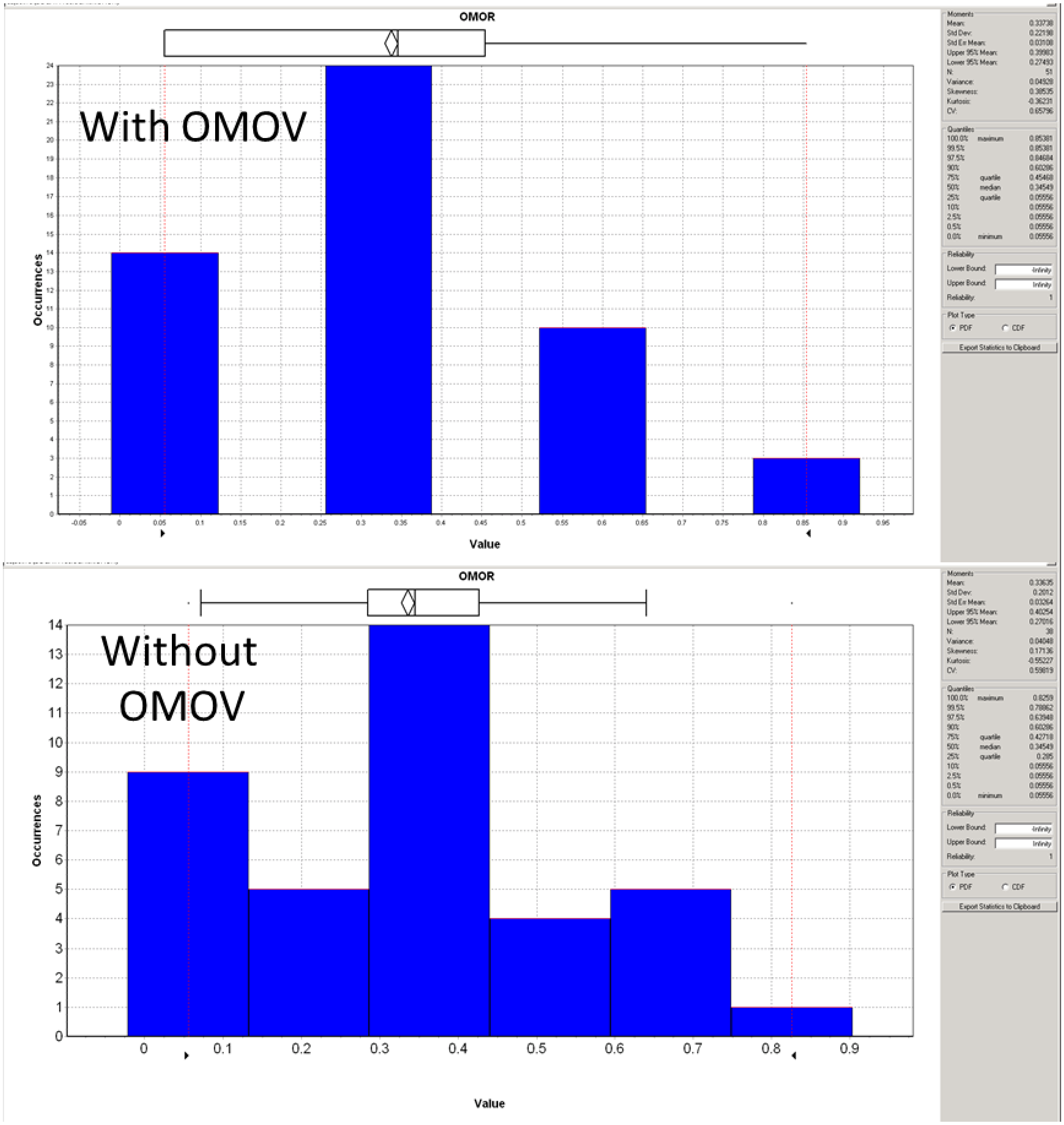
Moments	
Mean:	0.84136
Std Dev:	0.08904
Std Err Mean:	0.01444
Upper 95% Mean:	0.87066
Lower 95% Mean:	0.81207
N:	38
Variance:	0.00793
Skewness:	-1.35509
Kurtosis:	0.64919
CV:	0.10583

Quantiles		
100.0%	maximum	0.93117
99.5%		0.9306
97.5%		0.92834
90%		0.90707
75%	quartile	0.89813
50%	median	0.87922
25%	quartile	0.82944
10%		0.70502
2.5%		0.63182
0.5%		0.60152
0.0%	minimum	0.59394

Reliability
Lower Bound: -Infinity
Upper Bound: Infinity
Reliability: 1

Plot Type
● PDF ○ CDF

Figure 4-17 - Case Study MOGO OMOE Results Histogram (w/o OMOV; w/ OMOV)



Moments	
Mean:	0.33738
Std Dev:	0.22198
Std Err Mean:	0.03108
Upper 95% Mean:	0.39983
Lower 95% Mean:	0.27493
N:	51
Variance:	0.04928
Skewness:	0.38535
Kurtosis:	-0.36231
CV:	0.65796

Quantiles		
100.0%	maximum	0.85381
99.5%		0.85381
97.5%		0.84684
90%		0.60286
75%	quartile	0.45468
50%	median	0.34549
25%	quartile	0.05556
10%		0.05556
2.5%		0.05556
0.5%		0.05556
0.0%	minimum	0.05556

Reliability
Lower Bound: -Infinity
Upper Bound: Infinity
Reliability: 1

Plot Type
● PDF ○ CDF

Export Statistics to Clipboard

Moments	
Mean:	0.33635
Std Dev:	0.2012
Std Err Mean:	0.03264
Upper 95% Mean:	0.40254
Lower 95% Mean:	0.27016
N:	38
Variance:	0.04048
Skewness:	0.17136
Kurtosis:	-0.55227
CV:	0.59819

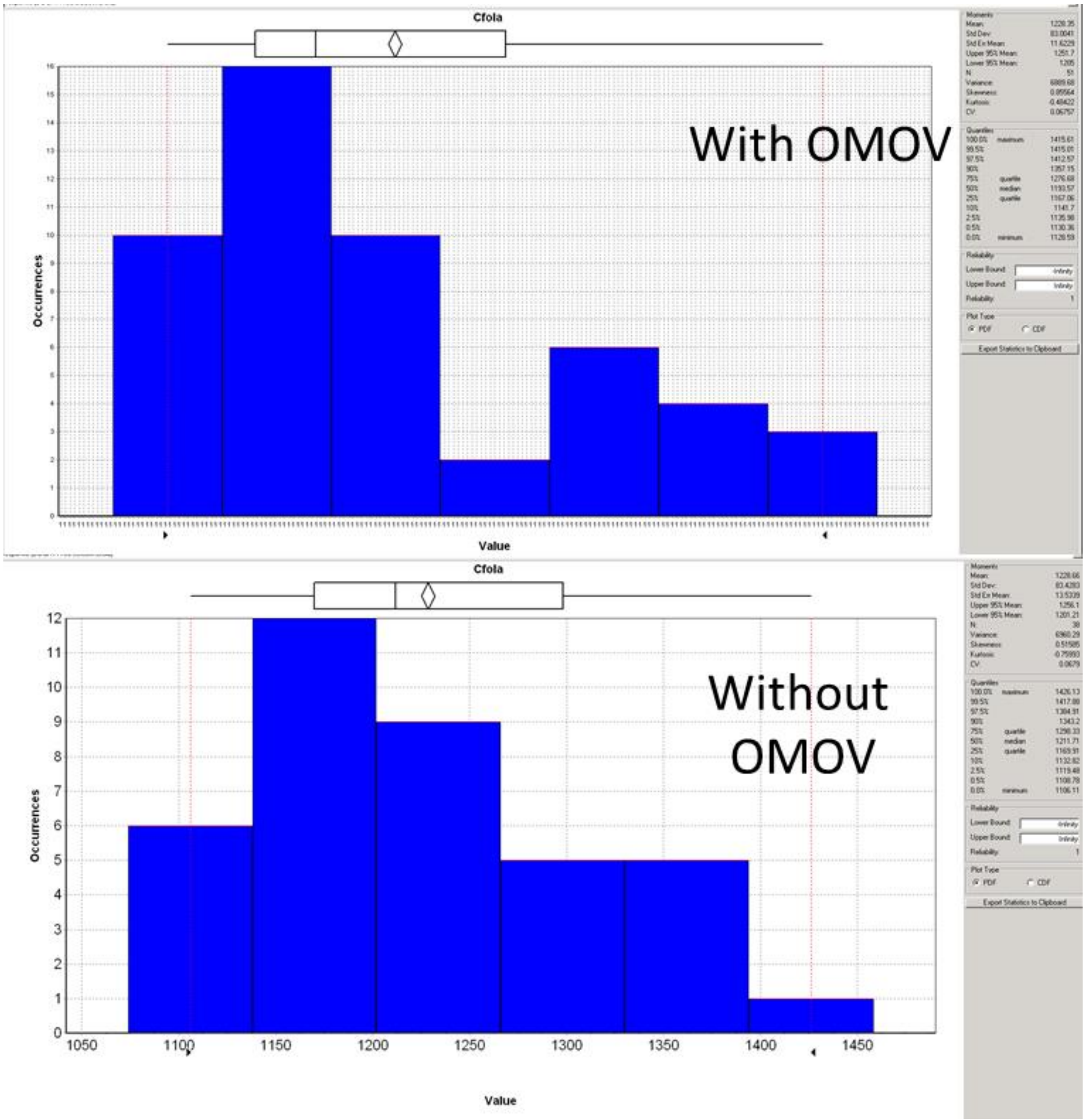
Quantiles		
100.0%	maximum	0.8259
99.5%		0.78862
97.5%		0.63948
90%		0.60286
75%	quartile	0.42718
50%	median	0.34549
25%	quartile	0.285
10%		0.05556
2.5%		0.05556
0.5%		0.05556
0.0%	minimum	0.05556

Reliability
Lower Bound: -Infinity
Upper Bound: Infinity
Reliability: 1

Plot Type
● PDF ○ CDF

Export Statistics to Clipboard

Figure 4-18 - Case Study MOGO OMOR Results Histogram (w/o OMOV; w/ OMOV)



```
Moments
Mean                      1228.35
Std Dev                   83.0041
Std Err Mean              11.6229
Upper 95% Mean             1251.7
Lower 95% Mean               1205
N                              51
Variance                  6889.68
Skewness                  0.85564
Kurtosis                 -0.48422
CV                        0.06757
Quantiles
100.0%   maximum          1415.61
99.5%                     1415.01
97.5%                     1412.57
90%                       1357.15
75%      quartile         1276.68
50%      median           1193.57
25%      quartile         1167.06
10%                        1141.7
2.5%                      1135.98
0.5%                      1130.36
0.0%     minimum          1128.59
Reliability
Lower Bound              -Infinity
Upper Bound               Infinity
Reliability                     1
Plot Type
● PDF        ○ CDF
Export Statistics to Clipboard
```

```
Moments
Mean                      1228.66
Std Dev                   83.4283
Std Err Mean              13.5339
Upper 95% Mean             1256.1
Lower 95% Mean            1201.21
N                              38
Variance                  6960.29
Skewness                  0.51585
Kurtosis                 -0.75993
CV                         0.0679
Quantiles
100.0%   maximum          1426.13
99.5%                     1417.88
97.5%                     1384.91
90%                        1343.2
75%      quartile         1298.33
50%      median           1211.71
25%      quartile         1169.91
10%                       1132.82
2.5%                      1119.48
0.5%                      1108.78
0.0%     minimum          1106.11
Reliability
Lower Bound              -Infinity
Upper Bound               Infinity
Reliability                     1
Plot Type
● PDF        ○ CDF
Export Statistics to Clipboard
```

Figure 4-19 - Case Study MOGO Cfola Results Histogram (w/o OMOV; w/ OMOV)

The probability of PSYS selection when vulnerability is used and when it is not is summarized in Table 4-11. This shows an increase in IPS and HED selection and decrease in CODAG when vulnerability is selected.

Table 4-11 - PSYS Selection Probability in ND Set

	Probability of System Selection	
PSYS	Without OMOV	With OMOV
5 (CODAG)	0.211	0.137
6 (HED)	0.500	0.529
7 (IPS)	0.289	0.333

The mean values for each of these characteristics when vulnerability is used and when it is not are summarized in Table 4-12. These show the impact on the effectiveness and risk when the vulnerability is considered by changing a single system option.

Table 4-12 – Characteristic Mean Values for ND Set

	Mean Value	
Characteristic	No OMOV	OMOV
PSYS	6.079	6.196
OMOV	0.845	0.786
OMOE	0.845	0.853
OMOR	0.336	0.337
Cfola	$1229M	$1228M

The non-dominated frontier results for the MOGO with and without vulnerability are shown in Figure 4-20 through Figure 4-22. Figure 4-20 shows the effectiveness versus cost of these designs. These figures show an increase in effectiveness and decrease in cost when vulnerability is considered. Figure 4-21 shows the non-dominated frontier comparing effectiveness, cost, and OMOV. This figure shows that most designs have a high OMOV, and the lower effective designs have the lowest OMOV. It also shows a similar OMOV for designs that have similar effectiveness regardless of cost. Figure 4-22 shows the non-dominated frontier that compares effectiveness, cost, and PSYS. This shows the effectiveness and cost comparison depending on which system was used. Generally, the CODAG has the lowest effectiveness and cost, and the IPS had the highest effectiveness. For some of the designs, the HED and IPS had similar effectiveness, but the HED had a lower cost.

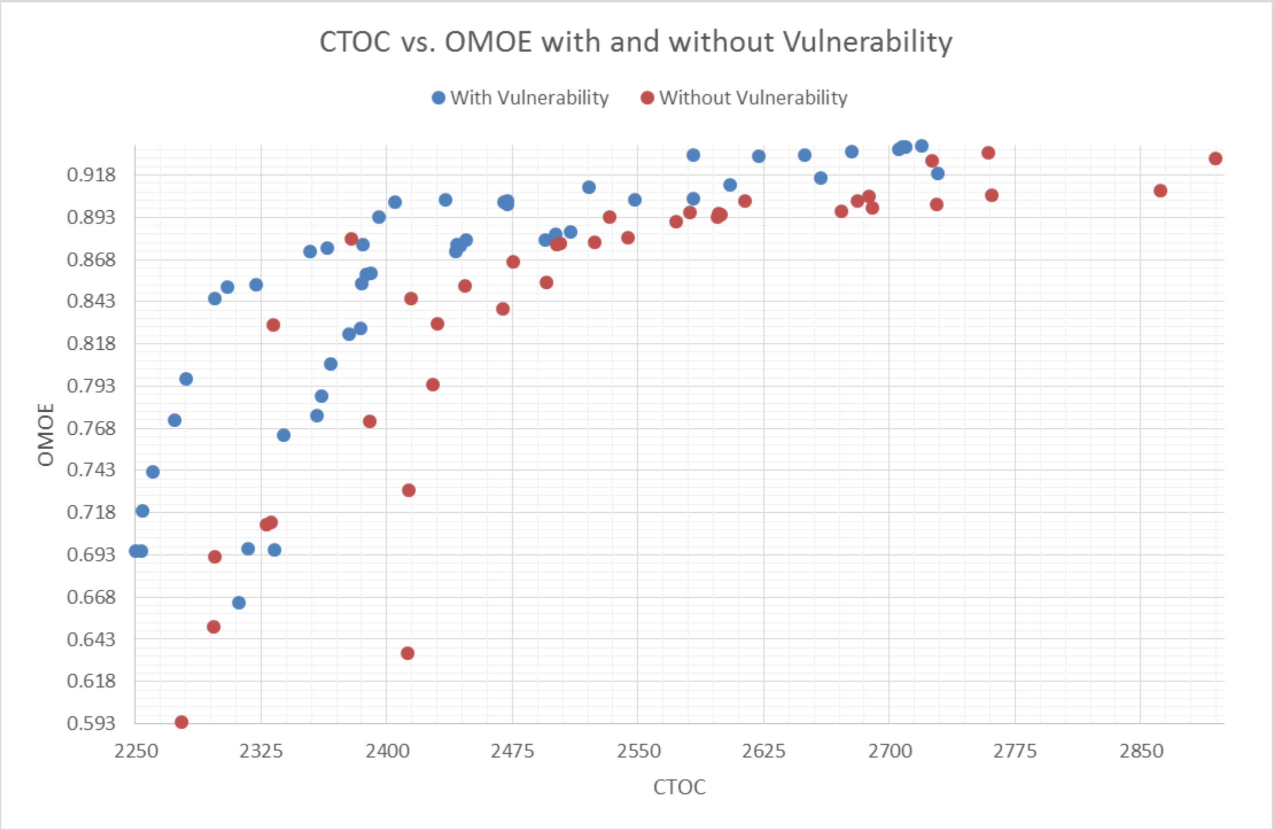


Figure 4-20 - Non-Dominated Frontier comparing with and without vulnerability (OMOE for these plots includes OMOV)

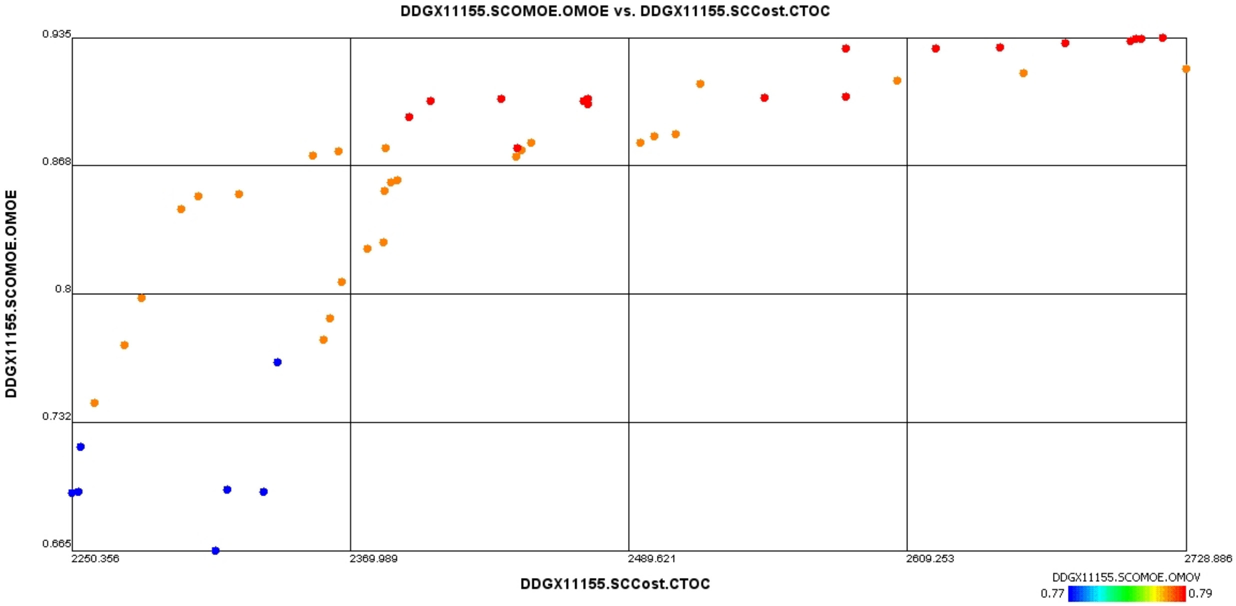


Figure 4-21 – DDGX Effectiveness vs Cost and OMOV (with Vulnerability)

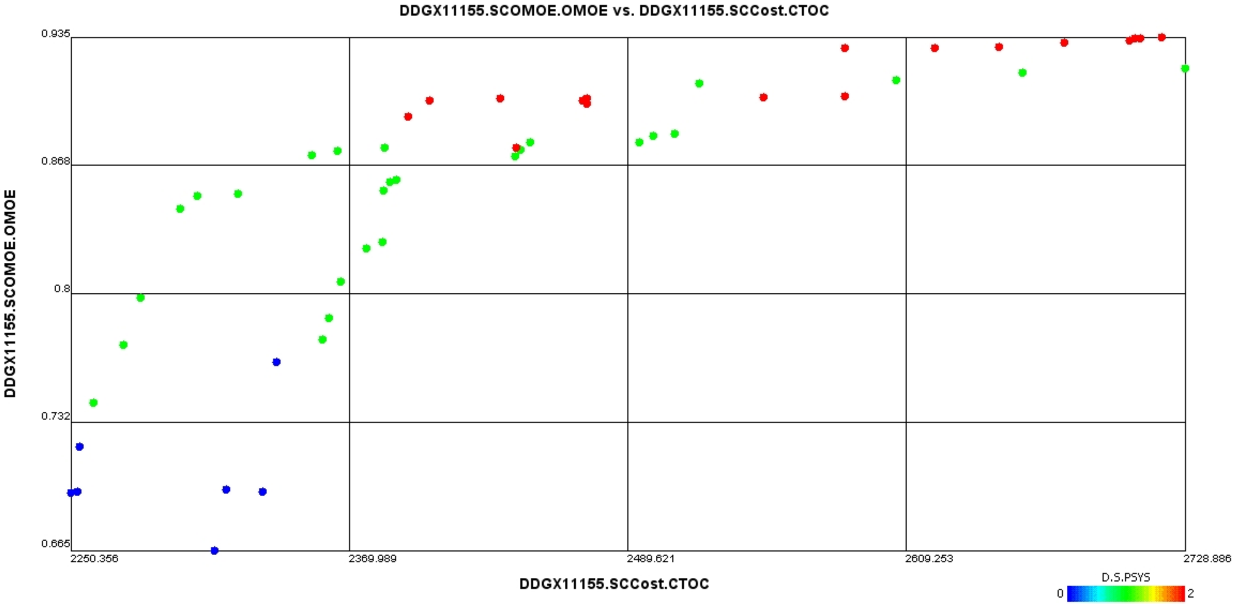


Figure 4-22 - DDGX Effectiveness vs Cost and PSYS (with Vulnerability)

CHAPTER 5 - CONCLUSIONS AND FUTURE WORK

This thesis presents a process and tool that generates a representative preliminary ship model and arrangement for use with a concept design vulnerability analysis. This Preliminary Arrangement and Vulnerability (PA&V) process replicates the geometry of the ship in an AABB form, assesses damage extents given threats, and arranges the ship to meet operability needs, ship mission needs, and improved vulnerability. An Overall Measure of Vulnerability (OMOV) is calculated for each representative design and applied in ship synthesis and the calculation of effectiveness to the assessment of all designs in the design space. To simplify the process, Axis Aligned Bounding Boxes (AABBs) are used to represent the ship as subdivision blocks (SDBs). In addition, compartments and VCs are assigned to these SDBs instead of using exact locations in the ship and vulnerability analysis is adapted to this level of detail so that thousands of ships can be analyzed in a reasonable amount of time in concept exploration.

5.1 Conclusions

As a result of this research, we have tentatively concluded that:

1. The representative designs that are created for assessing the vulnerability of system combinations are feasible designs and adequately represent the geometry and arrangements of the design.
2. The results from the case study show that when only one system (PSYS) was varied, the inclusion of the OMOV in the OMOE has a significant influence on the non-dominated design selection.

The limits of the applicability of the preliminary arrangements process for large variations of concept design parameters will be assessed further as the method is used in more explorations. This will be done by varying more ship parameters and including different system combinations. More explorations are required before it can be definitely stated that the inclusion of vulnerability in concept design improves the design of the ship, but this thesis shows that there is an influence in the results for this exploration and it should be considered in concept design.

5.2 Limitations

Limitations and assumptions of this methodology include:

1. It has not been fully assessed whether omitting the explicit geometry and location of VCs provides sufficient results for the comparison of concept designs. This will require additional validation. Results obtained thus far are encouraging.
2. The arrangements are adjusted using the hit probability of ship SDBs without compartments. Ideally, the arrangements would be optimized so that the vulnerability is assessed after each arrangement, and the model is rearranged based on these results. The impact of this simplification should be assessed.
3. This application of the PA&V methodology only considers AIREX threats. UNDEX effects are not assessed.
4. Distributed system (cabling and piping) that run throughout the ship connecting VCs are not considered explicitly. This simplification is significant and may require at least some approximate solution.

5.3 Future Work

Future work to improve the methodology of this thesis includes:

1. Assess the impact of not considering cabling and piping routing and develop a method or strategy to deal with significant inaccuracies.
2. Use MANA based OEMs instead of the expert opinion based OMOE to apply vulnerability results and determine the effectiveness directly.
3. Develop a similar damage extents method for UNDEX weapon effects.
4. Determine the flooding that occurs after damage and evaluate the stability in the vulnerability assessment.
5. Consider system flow through variables and capacities vice simple 0 and 1 deactivation.

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