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OMB No. 0704-0188

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<b>1. REPORT DATE (DD-MM-YYYY)</b> 30-03-2016		<b>2. REPORT TYPE</b> FINAL		<b>3. DATES COVERED (From - To)</b> 01-02-2011 to 30-06-2016	
<b>4. TITLE AND SUBTITLE</b> Investigating the Limitations of Advanced Design Methods through Real World Application				<b>5a. CONTRACT NUMBER</b>	
				<b>5b. GRANT NUMBER</b> N00014-11-1-0443	
				<b>5c. PROGRAM ELEMENT NUMBER</b> 16PR02073-00	
<b>6. AUTHOR(S)</b> Dr. Dimitri Mavris, Dr. Jean C Domercant, Mr. Stephen Edwards, Dr. Santiago Balestrini-Robinson, Mrs. Rebecca Douglas				<b>5d. PROJECT NUMBER</b> 1616626	
				<b>5e. TASK NUMBER</b>	
				<b>5f. WORK UNIT NUMBER</b>	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> Georgia Institute of Technology School of Aerospace Engineering Aerospace Systems Design Laboratory (ASDL) 275 Ferst Drive Atlanta, GA 30332-0150				<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b> Doc ID#: 116361	
<b>9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> Office of Naval Research ONR BD025 875 N. Randolph Street, Suite 1425 Arlington, VA 22203-1995				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> ONR/GIT/ASDL	
				<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b>	
<b>12. DISTRIBUTION / AVAILABILITY STATEMENT</b> Distribution Unlimited					
<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b> This final report details the results of the partnership between the Aerospace Systems Design Laboratory (ASDL) at the Georgia Institute of Technology ("Georgia Tech") and the Office of Naval Research (ONR) in continuing the development of advanced design methods and their application to revolutionary concepts. The methods pioneered include but are not limited to surrogate modeling in design applications, optimization, robust design simulation, strategic portfolio planning, technology impact forecasting and evaluation, as well as inverse design methods and capability-based design concepts. Prior funding has focused on developing the methods while actual applications have been incomplete and applied to simplified demonstration problems; The difficulty lies in that these prior applications are often done under strict non-disclosure agreements, therefore the findings cannot be published and shared. This highlights the need to apply ASDL methods to real world problems. The researchers have identified various problems that span the full spectrum of processes, methods and techniques developed at ASDL and are significantly different to ensure the broad applicability of the methods. These problem areas include ship design, Ballistic Missile Defense (BMD), Command & Control (C2), and space mission architectures.					
<b>15. SUBJECT TERMS</b> Naval Engineering, Advanced Systems Design, Modeling & Simulation					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b> UU	<b>18. NUMBER OF PAGES</b> 67	<b>19a. NAME OF RESPONSIBLE PERSON</b> Dr. Jean C Domercant
<b>a. REPORT</b> (U)	<b>b. ABSTRACT</b> (U)	<b>c. THIS PAGE</b> (U)			<b>19b. TELEPHONE NUMBER (include area code)</b> (404) 385-3381

**FINAL REPORT**

**AWARD NUMBER: N00014-11-1-0443**

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**Investigating the Limitations of Advanced Design Methods through Real World  
Application**

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March 31, 2016

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## **Introduction**

This final report details the results of the partnership between the Aerospace Systems Design Laboratory (ASDL) at the Georgia Institute of Technology (“Georgia Tech”) and the Office of Naval Research (ONR) in helping to ensure the continued training of the next generation of engineers that will contribute to the nation’s ongoing naval challenges. The Aerospace Systems Design Laboratory (ASDL) at the Georgia Institute of Technology has been at the forefront of the development of advanced design methods and their application to revolutionary concepts. The methods pioneered include but are not limited to surrogate modeling in design applications, optimization, robust design simulation, strategic portfolio planning, technology impact forecasting and evaluation, as well as inverse design methods and capability-based design concepts. Prior funding has focused in developing the methods and actual applications have been incomplete and applied to simplified demonstration problems; i.e. portions of the methods and techniques were applied to problems that did not reflect the full complexity of the problems of interest. When the methods were applied to realistic problems involving subject matter experts (SME), vested in a real world decision problem, the researchers realized that the processes, methods and techniques could be improved significantly. The difficulty lies in that these prior applications are often done under strict non-disclosure agreements, therefore the findings cannot be published and shared. This highlights the need to apply ASDL methods to real world problems.

The researchers have identified various problems that span the full spectrum of processes, methods and techniques developed at ASDL and are significantly different to ensure the broad applicability of the methods. The first task is based on an ONR NICOP with Orizzonte Sistemi Navali (OSN) tasked with developing a process and tools for integrating the evaluation of a ship’s mission effectiveness in the design process. OSN and its partners, CETENA and the University of Genoa collaborated with the Italian Navy to develop and test an environment to design ships and evaluate them according to their mission effectiveness. ASDL will provide guidance and apply the advanced design methods in order to expand the applicability, increase its computational efficiency and improve its ability to provide decision support to the critical stakeholders. The second task supported an analytical wargame for the US Joint Forces Command (USJFCOM) J9 Division, tasked with evaluating the effectiveness of the BMD system. This has been listed as one of NORTHCOM’s top priority Warfighter Challenges for 2011. J9 and NORTHCOM are investing significant resources in developing the analysis tools to support this effort. ASDL supported the wargame by developing real-time tradeoff environments based on those analysis tools, provide technical assistance during the workshops and host the event in its state-of-the-art collaborative design and visualization facilities.

The next project involved working with Joint Staff (JS) to in the area of Command & Control (C2). C2 is a necessary and critical component of war fighting, especially in today's joint war fighting environment. C2 is used in the planning, directing, coordination and control of forces and operations in the accomplishment of the mission. C2 is also largely responsible for enabling interoperability in military networks. Poor or non-existent interoperability can lead to degradation in combat effectiveness. The objective of this research is to develop an analytical framework for understanding and exploring C2 capability-based solutions across multiple missions and for multiple stakeholders. A Visual Command & Control Capability Analysis and Tradeoff Suite (VC3ATS) was developed to perform *dynamic* Command & Control (C2) and mission analysis with Joint Mission Thread (JMT) architectures for the purpose of comparing C2 alternatives in the single and multi-mission trade space.

The last project involved demonstrating and transferring Advanced Design Methodologies to a challenging mission architecture problem. This involved also collaborating with the NASA/Marshall Space Flight Center (MSFC) Advanced Concepts Office (ACO) in order to enhance NASA design practices and enable expanded trade study capabilities. This effort focuses on applications for in-space disciplinary analyses, Earth-to-orbit (ETO) modeling, and physics based engine modeling, enabling an encompassing look at a conceptual design for Mars exploration architecture. Opportunities associated with advanced manufacturing, materials, in-situ resource utilization (ISRU), and concepts of operation (CONOPS) were evaluated utilizing advanced technology impact forecasting methods. The challenge of developing a fully reusable transportation architecture for manned Mars missions was selected in order to provide a demonstration problem of current relevance to NASA. The Navy primarily benefits from being able to take the lessons learned from the methods development.

## **Objective**

These tasks address significant real world problems and were aligned with major efforts that were underway. This provided a unique opportunity to truly test methods developed in an academic environment. From these tests the methods were made not only more credible, but also easier to implement, more streamlined and robust.

## **Progress Statement Summary**

Funding provided by this grant supported the full-time research activities of undergraduate and graduate students who then became involved with and contributed to ongoing research projects in complex System of Systems (SoS) design, engineering, and architecting at ASDL. These students engaged in relevant research that was crucial in continuing the development of Advanced Design Methodologies and their application to revolutionary concepts. At the same time, these students were educated in state of the art systems design and decision making methods such as design of computer experiments, multidisciplinary analysis, advanced modeling and simulation techniques, and multi-criteria/multi-attribute decision making. The combination of the naval experience and systems design education will equip these students with the skills necessary to foster the cultural transformation that is necessary to keep up with the Navy's evolving challenges.

## **Detailed Progress Summary**

The grant was organized into the principal tasks (1) PRONTO ASNET NICOP (2) Advanced Design Methods in Support of BMD Wargaming, (3) Space Mission Architecting (4) Visual Command and Control Capability Analysis and Tradeoff Suite (VC3ATS).

### **PRONTO ASNET NICOP**

ONR has established a Naval International Cooperative Opportunities in Science and Technology Program (NICOP) with Orizzonte Sistemi Navali (OSN) and CETENA (both Fincantieri companies) and the University of Genoa. This NICOP is tasked with further developing and testing the Application System for Naval ship design and Evaluation and Testing (ASNET). To provide a realistic test problem, ONR and OSN decided to design an Offshore Patrol Vessel (OPV). The underlying goal of the project was to allow the designers of the OPV to obtain credible estimates of its effectiveness in conducting a wide range of missions, e.g., anti-air warfare (AAW) to fishery patrols, maritime interdiction operations (MIO), as a function of the ship design characteristics. In order for this to be effective, the stakeholder must obtain a near-immediate response from the analyses, which tend to become more computationally demanding as the analyses become more complex. This offered ASDL an ideal opportunity to apply its methods and techniques.

In order to meet the technical objective, a rapid cost-capability assessment framework for surface combatants was developed. This new modeling approach addresses multiple sources of uncertainty during conceptual design that were not previously captured such as price escalation, fluctuations in foreign exchange rates, and uncertainty in ship build scheduling. The approach also focuses on improving the

mathematical modeling of organic air asset availability for parametric ship designs under varying operating conditions. It is important to know when and under what conditions air assets such as rotorcraft may/may not be available to assist the ship during operations. The approach also investigates improved methodologies for formalizing the implementation and improving the efficiency of Agent Based Modeling. Specifically, the research seeks to address more rigorous ways of developing conceptual models for operational scenarios that will lead to improved modeling and simulation verification and validation.

A graphical tradeoff environment for rapid, defensible and traceable assessments was created. This is shown in Figure 1.

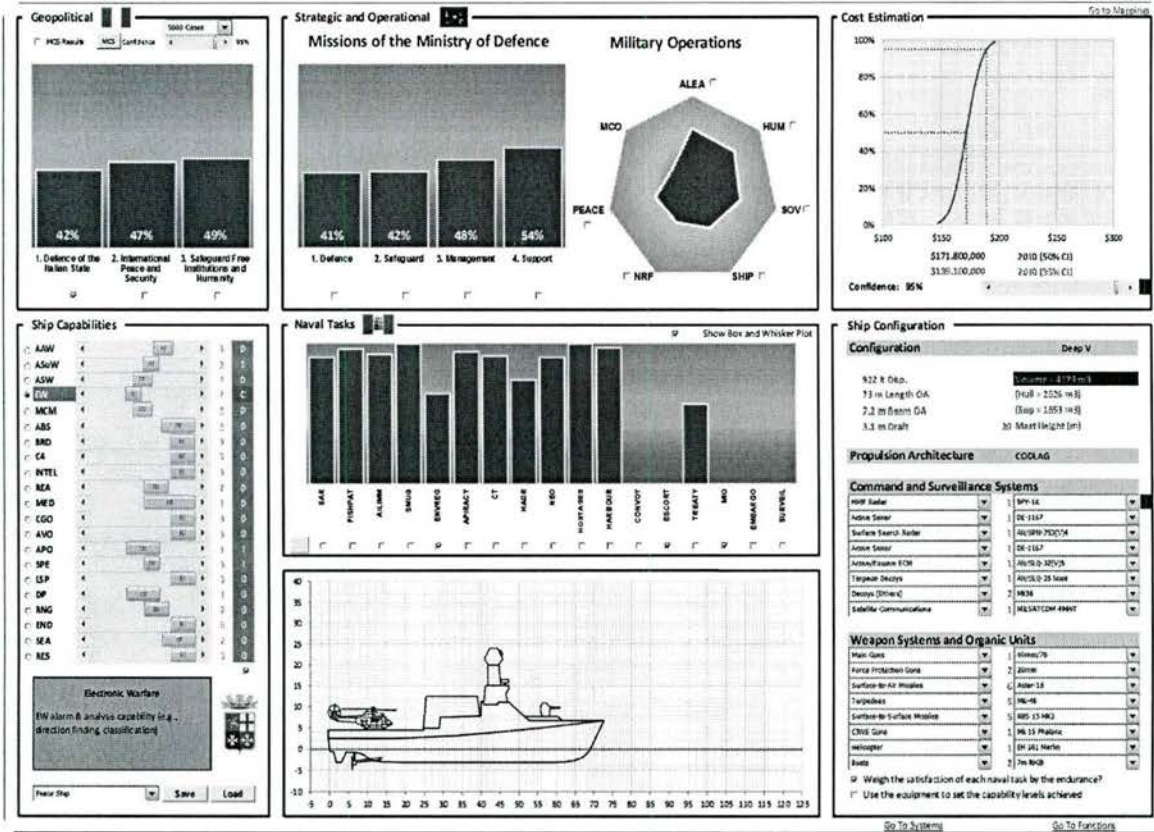


Figure 1. Graphical Tradeoff Environment

This tradeoff environment captures both quantitative modeling & simulation based analysis along with expert-based qualitative analysis to enable rapid relative cost estimation and risk assessment. A capability analysis is accomplished using an expert driven decomposition and criticality assessment. This is depicted in Figure 2.

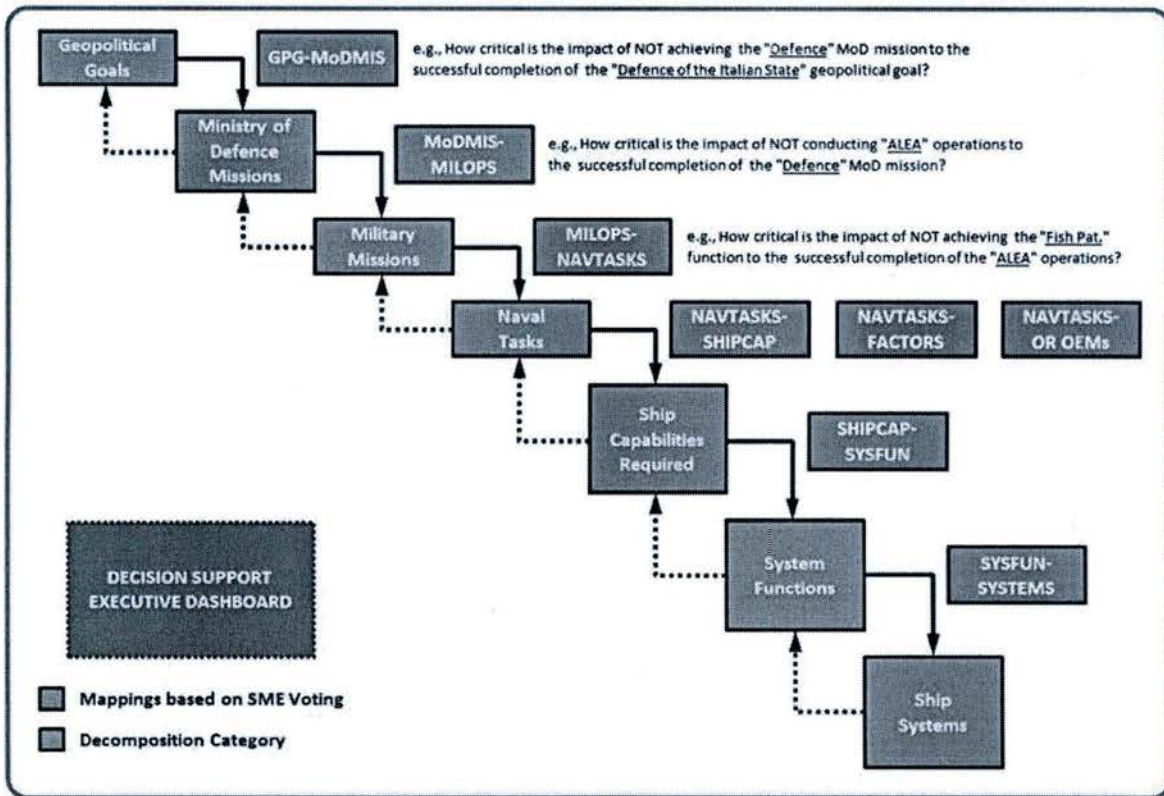


Figure 2. Expert Driven Decomposition & Criticality Assessment

A one week-long workshop was conducted with 16 Naval Officers ranging in rank from Rear Admiral to Lieutenant, representing extensive operational experience. The workshop provided a structured process to elicit subject matter expert (SME) knowledge to develop a model of the value of different ship capabilities under a variety of conditions. This can be seen in Figure 3.



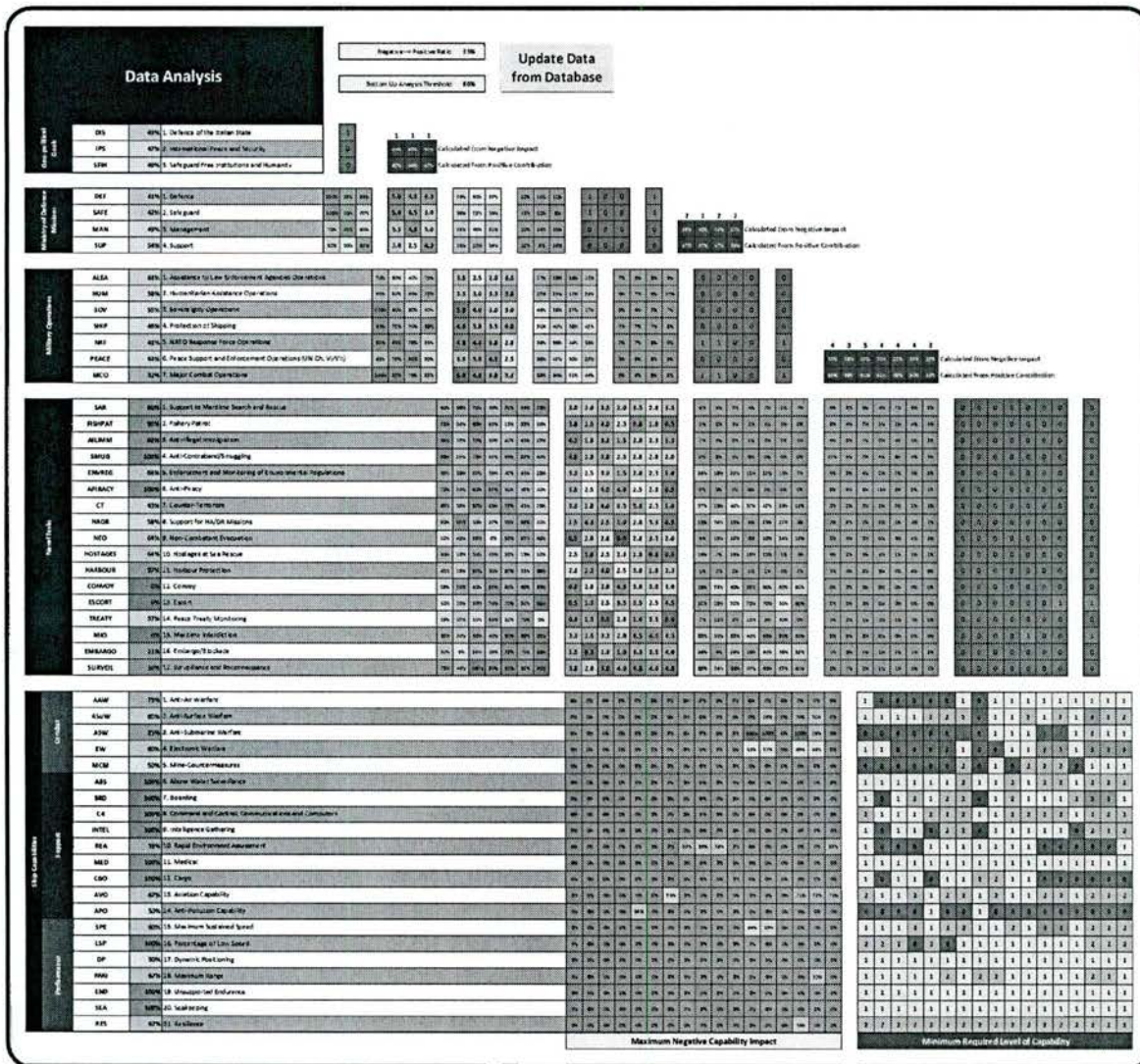


Figure 3. Expert-Based Capability Analysis

Overall, the integrated analysis provides decision makers the ability to trace the impact of requirements from the systems level all the way up to tactical and even high-level strategic goals. This represents a complete capability assessment that includes the entire range of stakeholder requirements.

Continued development of the assessment framework focused on three distinct areas. First, a new cost modeling approach was fully integrated into the graphical tradeoff environment to enhance both probabilistic cost estimating and budget risk mitigation. Second, methods to improve modeling of the ship motion was investigated in collaboration with Virginia Tech in order to help explore the feasibility and validity of mathematical models for the operational availability of aerial vehicles operating from naval

assets. This would result in more accurate probabilistic evaluation models to capture the effectiveness contribution from naval assets under varying operational conditions. Lastly, continued progress was made in the area of operational modeling and integrating the analysis results along with methods for additional statistical analysis into the graphical tradeoff environment.

### Focus Area 1: Probabilistic cost estimating and budget risk mitigation

At the beginning of this phase of the effort the cost estimation portion of the graphical tradeoff environment provided a confidence estimation of the total cost of the OPV design by displaying cost using a Cumulative Distribution Function (CDF). This is shown in Figure 4.

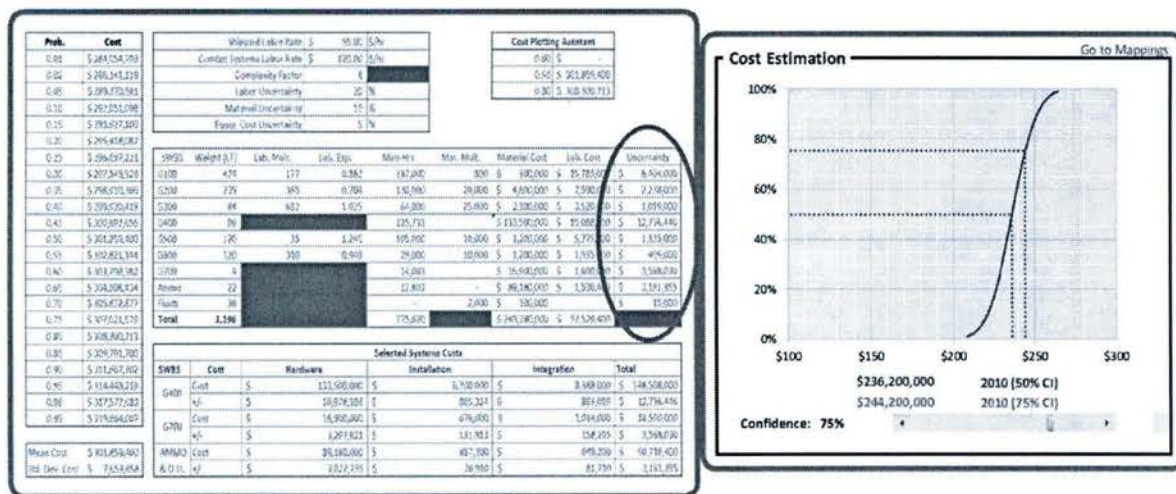


Figure 4. Original Cost Estimation Display

Thus, decision makers could specify a desired confidence level when assessing the anticipated future cost OPV designs during the decision making process. However, this approach was limited to normal distributions to model cost uncertainty that were specific to each type of equipment captured in the overall systems cost. In order to grant decision makers the ability to provide rapid cost vs. capability tradeoffs while also dealing with multiple sources of uncertainty present during conceptual design, a more comprehensive probabilistic approach to capturing costs is necessary. These sources of cost uncertainty can be categorized as follows:

- Weight estimates of Ship Work Breakdown Structure (SWBS) subgroups
  - Group 100 – Group 700
- Regressions for Cost Estimating Relations (CERs)
  - 2 sets of CERs – Product Oriented Design and Construction (PODAC) cost model
- Future price of commodities such as steel
- Cost of ship systems
  - For international navies especially, many mission systems are purchased from foreign suppliers
- Inflation/Escalation
  - Escalation defined as the general increase in costs/ prices over a period of time
  - Distinguished from inflation and the risk-free discount rate
  - Both economy-driven & customer-driven escalation components can outpace inflation
- Requirements & regulations
- Foreign exchange rates
- Ship build schedule

By giving decision makers the ability to distinctly assess the impact of different sources of uncertainty mitigation plans can be more effectively developed in order to manage risk. This was realized by creating an updated cost analysis methodology and integrating it into the graphical tradeoff environment. The updated cost analysis requires the following inputs

- User Inputs: Labor rates, ship design complexity factor & labor/material/equipment cost uncertainty percentages
- Ship weight estimations from the ship design tab of the graphical tradeoff environment
- Cost estimates grouped by systems from the systems tab of the graphical tradeoff environment
- Inputs based on regression of historical trends for use in the CER equations.

Based on these inputs, a more comprehensive probabilistic cost analysis can then be performed. The results of the analysis are integrated into the graphical tradeoff environment. This can be seen in Figure 3.

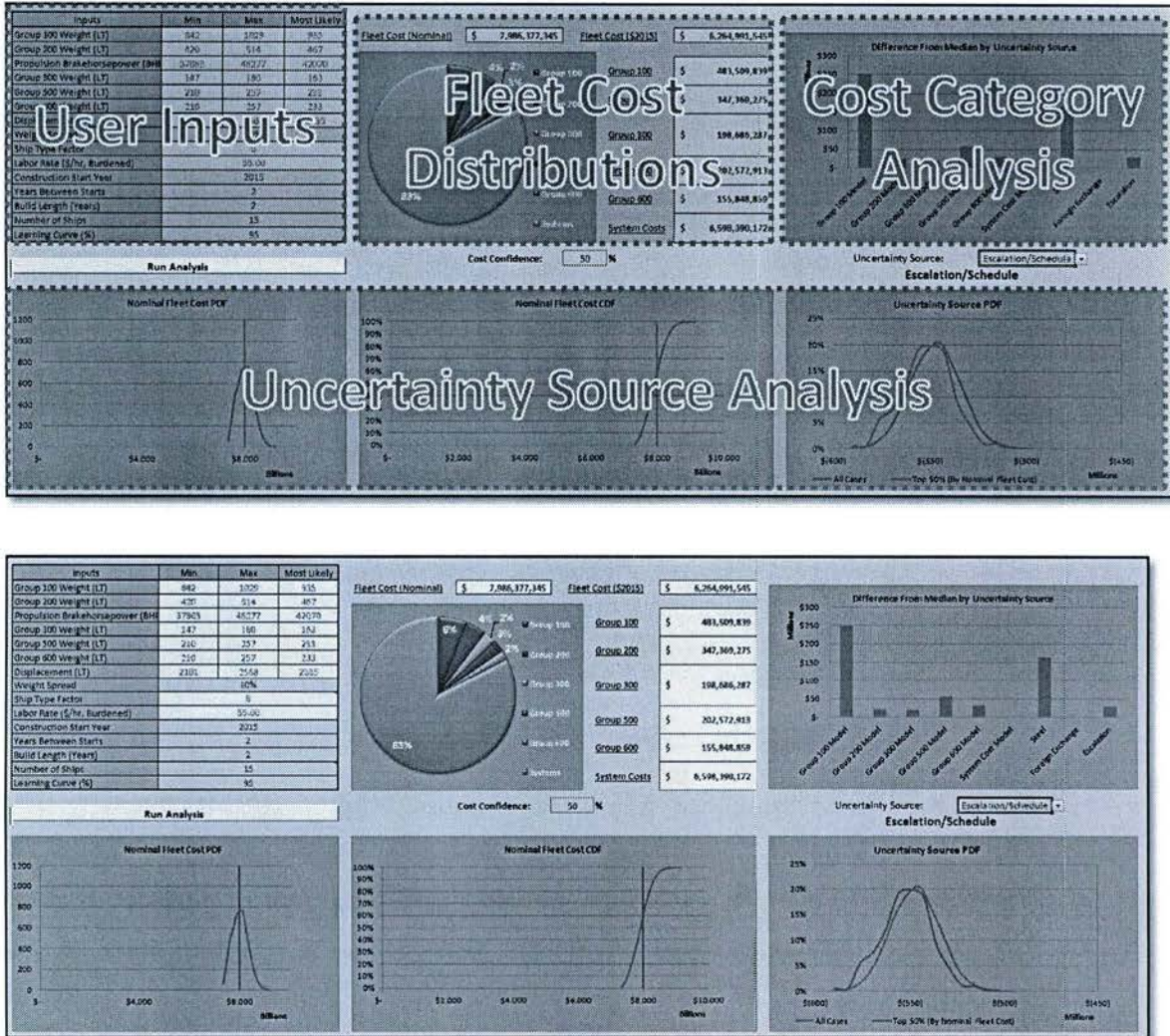
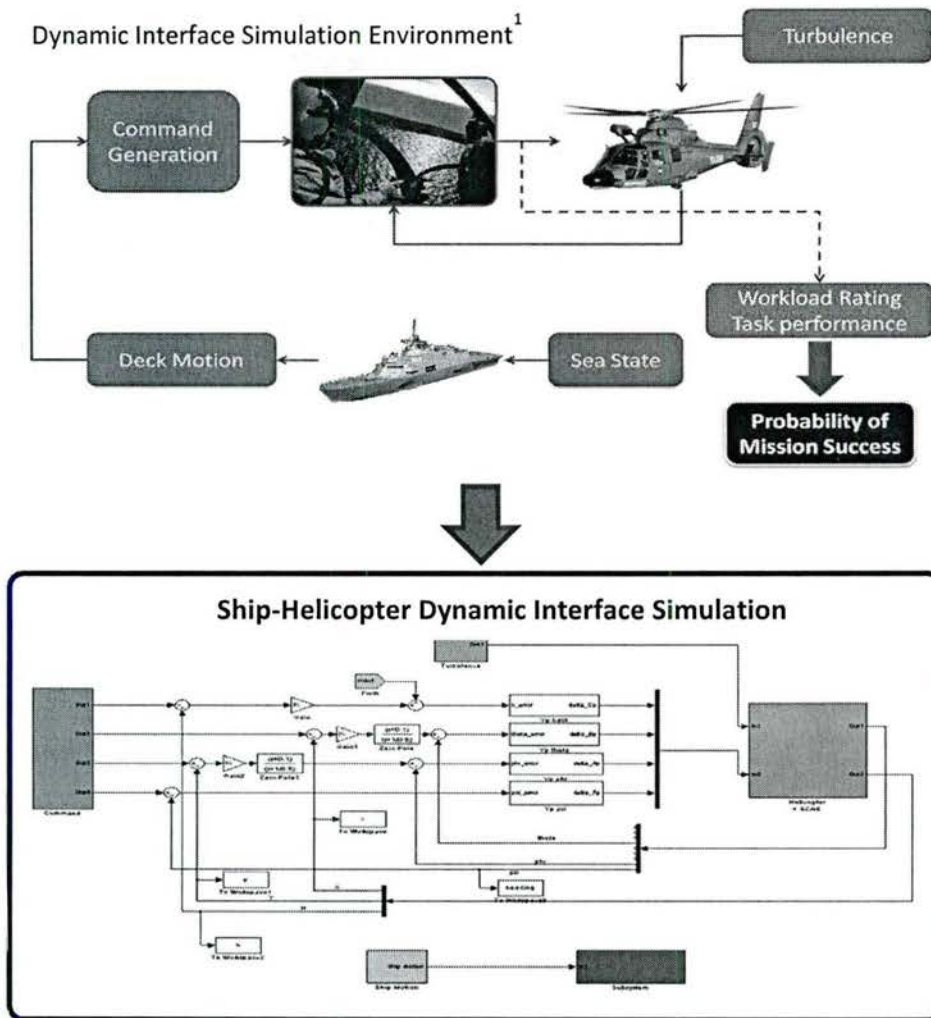


Figure 5. Comprehensive Cost Analysis Dashboard Display

The end result is the ability to retain the rapid relative cost estimation and risk assessment capability while also providing a comprehensive assessment of risks associated with uncertainties in the CER regressions, parameter estimates, foreign currency exchange rate fluctuations, and shipbuilding learning curves. This provides an even greater measure of confidence in the cost estimations and confidence levels displayed by the CDF.

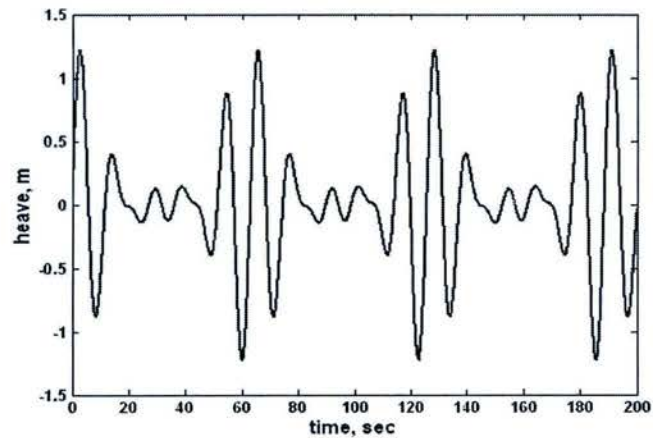
**Focus Area 2: Improved ship motion modeling for mathematical modeling of organic air asset availability**

Continued progress was also made in creating efficient models to assess the likelihood of operating organic rotorcraft from a monohull ship under varying operating conditions such as ship motion, low visibility & poor visual cues, restricted landing areas, airwake turbulence and helicopter motion. A dynamic interface simulation environment was developed that uses ship motion time histories to provide a probabilistic analysis of organic air asset availability [1]. It also uses a quantification of pilot workload using standard deviations of control stick position and velocity to quantify a Workload Rating (WR). An overview is provided in Figure 6.



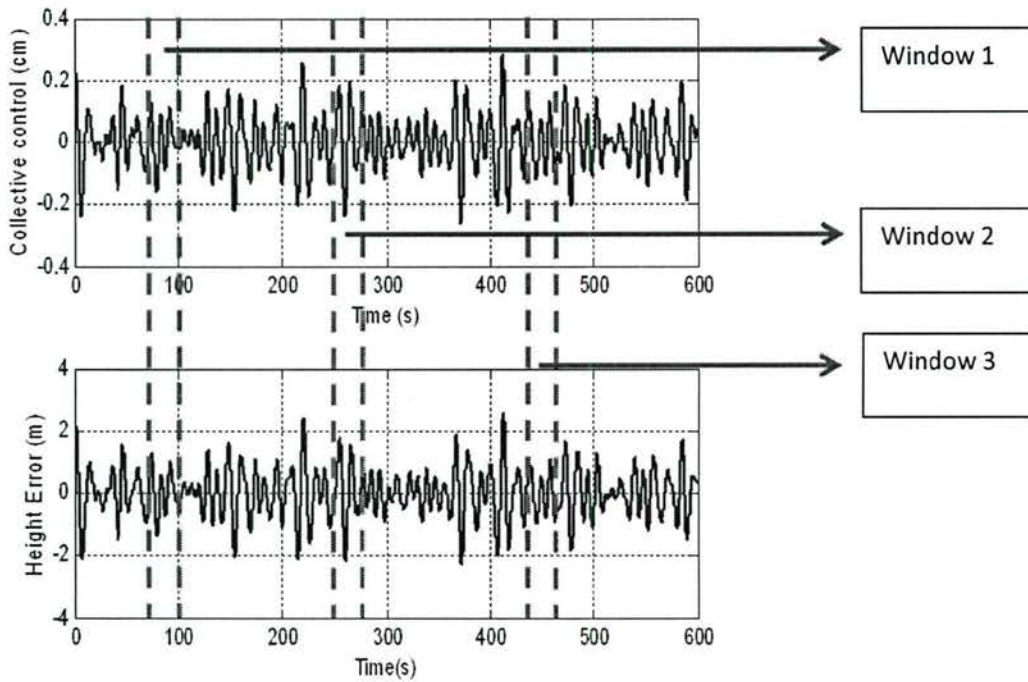
**Figure 6. SimuLink Dynamic Interface Simulation Environment**

An example of a ship motion time history from Ref. 1 for a TMV Fast Ferry in the heave direction can be seen in Figure 7.



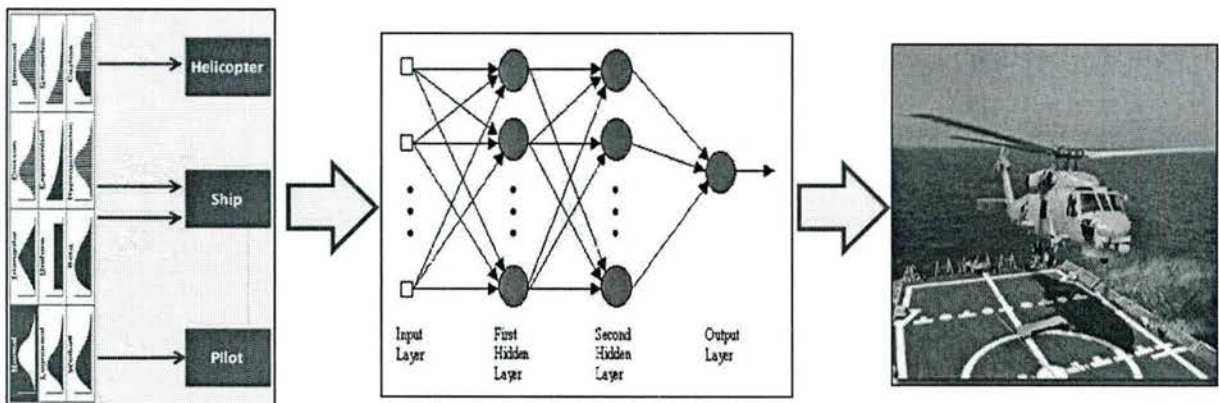
**Figure 7. TMV 114 Fast Ferry Heave Ship Motion Time History**

Ship motion time histories are needed in order to run the dynamic interface simulation environment for a given set of simulation conditions such as ship design variables, sea state, pilot delay, etc. From the developed time histories, a random sampling technique can be used as a simulation input to determine if a helicopter can land on the ship deck during the simulation time window.



**Figure 8. Technique for Random Sampling of Ship Motion Time Histories**

Based on these values obtained at each time window, it becomes possible to determine the pilot workload rating and the maximum tracking error that occurs as the pilot attempts to land the helicopter. This can be quantified as a Mission Success Rating (MSR) percentage [1]. An Artificial Neural Network (ANN) regression is used. The ANN is a feed-forward design with two hidden layers that uses sigmoidal/linear basis functions. The output from the ANN is a prediction of the landing success rate.



**Figure 9. Artificial Neural Network Regression for Determining Mission Success Rate**

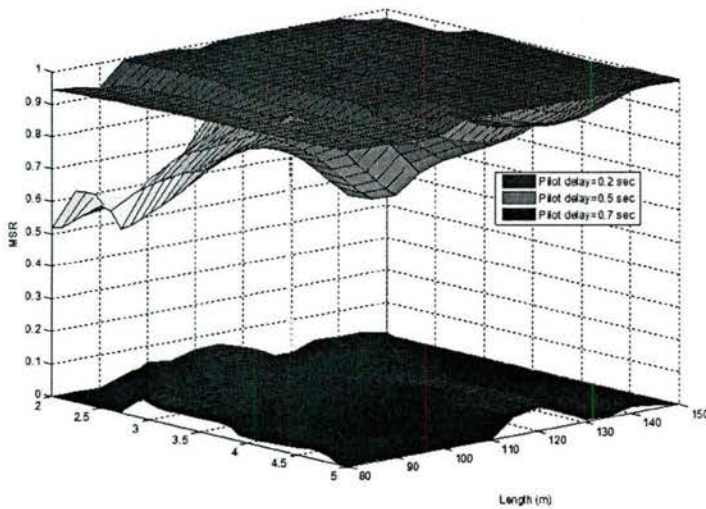
The following figure is an example of the output that results from the simulation results. The helicopter used in this simulation is a BO-105 helicopter. The ship motion histories used are from the TMV 114 Fast Ferry. Additionally, the pilot model used is an optimal control model with a response delay of 0.2 seconds [1].

MSR	beta=0												
	Hs	1	2	3	4	5	6	7	8	9	10	11	12
Tz													
5		100	100										
6		100	100	100	100	100	100						
7		100	100	100	100	100	100	97.5	0.5	0			
8		100	100	100	100	100	94	55	4.5	0	0	0	
9		100	100	100	100	100	96.5	90	0.5	0	0	0	0
10		100	100	100	100	100	52.5	47	5	0	0	0	0
MSR	beta=(1/2)pi												
	Hs	1	2	3	4	5	6	7	8	9	10	11	12
Tz													
5		100	0										
6		100	0	0	0	0	0						
7		100	0	0	0	0	0	0	0	0			
8		100	57	0	0	0	0	0	0	0	0	0	
9		100	100	0	0	0	0	0	0	0	0	0	0
10		100	100	1	0	0	0	0	0	0	0	0	0

Figure 10. Mission Success Ratings for Helicopter Landing

The MSR values displayed in each of the colored boxes are for varying levels of significant wave height (Hs) and zero upcrossing period (Tz), while beta indicates the direction of seas. The following figure provides an example graphical display of the ANN surrogate model results.





- Conditions:
  - BO-105 Helicopter
  - 0 degree heading
  - Landing pad – 80% length, center line
  - Sea state: 2m significant wave height, 10 second zero crossing frequency
  - GMT (transverse metric height) – 2.7 meters
  - Tn (roll natural period) – 4.5 seconds

**Figure 11. Sample ANN Surrogate Modeling Results**

Initially, simplified hydrodynamics were used to obtain the ship motion. This method simplified the shape of the hull to a rectangular prism. During this period of the effort the focus was on improving the modeling of the ship motion, since the dynamic interface between the ship environment and the helicopter is vital to correctly developing the proper modeling and simulation tools. There was collaboration with Virginia Tech to utilize existing modeling & simulation tools to obtain power spectral density (PSD) plots of ship motion for various monohull surface ships. A PSD describes how the power of a signal or time series is distributed over different frequencies. A PSD can be described using Equation 1:

$$(1) \quad \Phi(w) = |H(w)|^2 S(w)$$

Where:

- $\Phi(w)$ : Power Spectral Density (PSD) of ship motions
- $H(w)$ : Frequency response function
- $S(w)$ : PSD of sea waves
- Inputs for heave and pitch response functions
  - Draft, length, breadth, Froude number, heading, box coefficient, etc.
- Inputs for roll response function

- Draft, length, breadth, Froude number, heading, box coefficient, transverse met centric height, roll time constant, etc.
- Sea wave model: JONSWAP spectrum model (Joint North Sea Wave Observation Project). See Ref. [2]. Sea states are characterized by frequencies and amplitudes of waves.

Example PSD's of the heave, roll and pitch motions for a TMV 114 Fast Ferry are provided in the following figures from Ref. [2]:

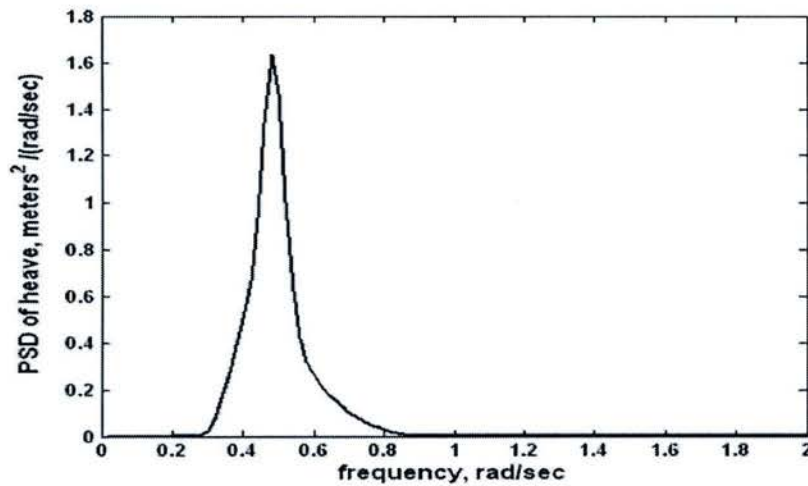


Figure 12. TMV 114 Fast Ferry Heave PSD

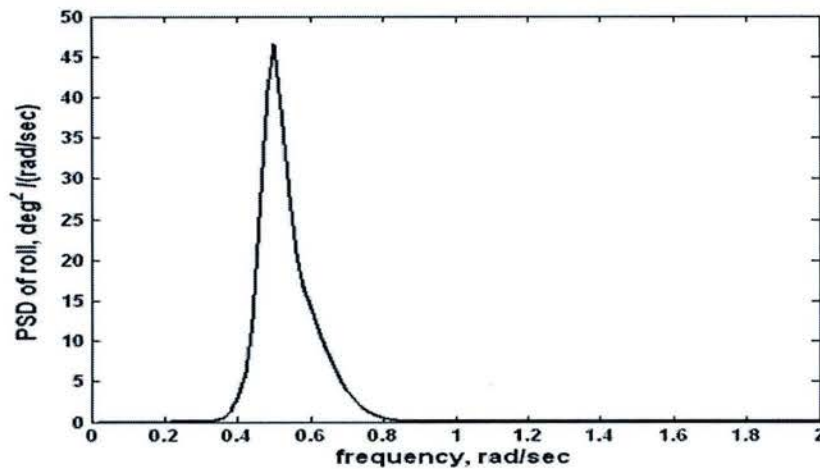


Figure 13. TMV 114 Fast Ferry Roll PSD

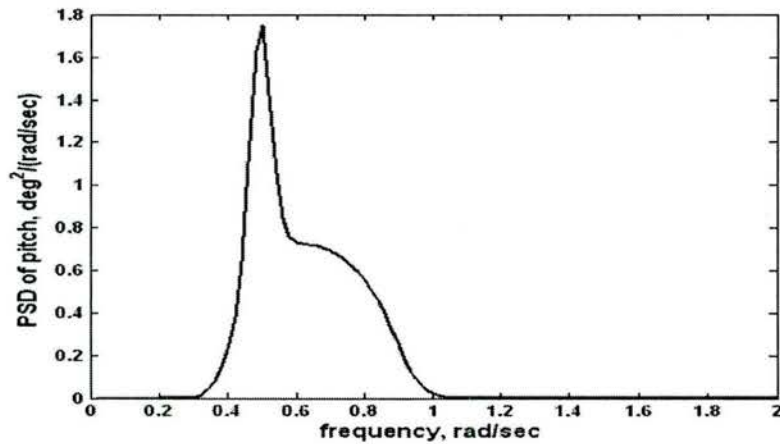


Figure 14. TMV 114 Fast Ferry Pitch PSD

Figure 13 illustrates the goal, namely to identify a technique to translate PSD plots into ship motion time histories.

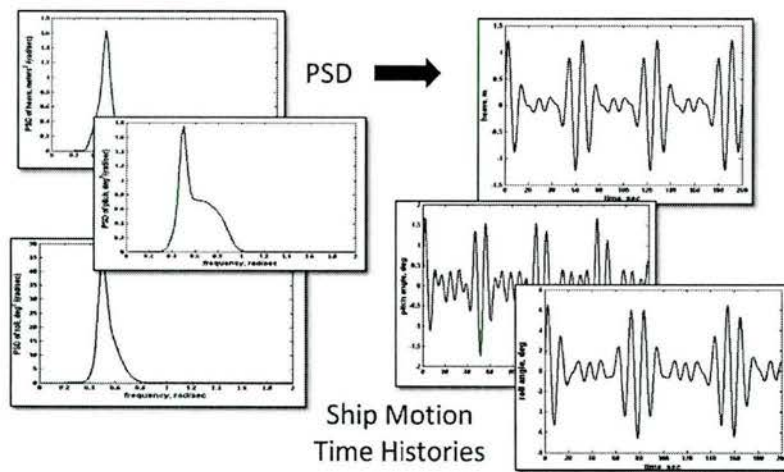


Figure 15. TMV 114 Fast Ferry Pitch PSD

A technique for generating the time histories so as to simulate the ship motions over time was identified in Ref. [3]. In summary, the first step is to integrate the PSD over frequency. Then, one can select frequencies

$\omega_1$  and  $\omega_n$  as follows:

$$\int_0^{\omega_1} \Phi_m(s) ds = 0.05 \int_0^{\infty} \Phi_m(s) ds \quad (2)$$

$$\int_0^{\omega_n} \Phi_m(s) ds = 0.99 \int_0^{\infty} \Phi_m(s) ds \quad (3)$$

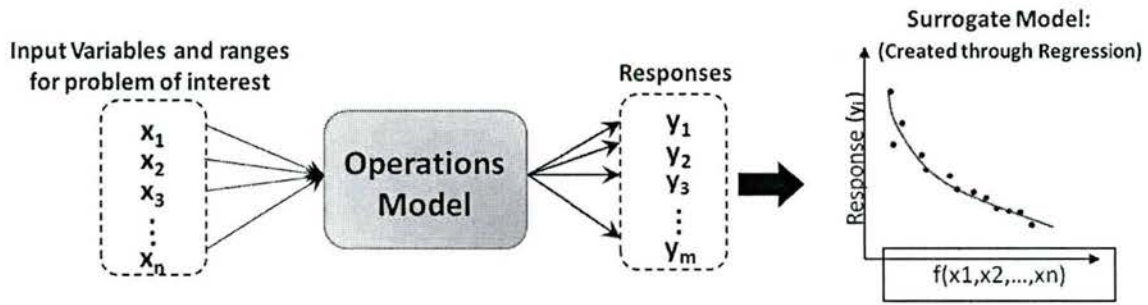
Now,  $\omega_2, \dots, \omega_{n-1}$  can be equally distributed between  $\omega_1$  and  $\omega_n$ . Amplitudes  $a_k$  at the select frequencies are obtained as follows:

$$a_k = \left( 2 \int_{\omega_{k-1}}^{\omega_k} \Phi_m(s) ds \right)^{1/2}, \quad k = 1, 2, \dots, n \quad (4)$$

Equations (2)–(4) imply that the PSDs calculated in Eq. (1) are represented as the sum of  $n$  sinusoidal signals, whose amplitudes are condensed so that the frequency distribution over power closely match that of the integrated PSD. However, it should be noted that information on the relative phase of each motion's time history is lost with this technique. In the end, though, one can obtain heave ( $h_s$ ), pitch ( $\theta_s$ ), and roll ( $\phi_s$ ) of the ship in the form of time series. In this analysis, motion variables of a ship follow the definitions and sign conventions given in Ref. 0.

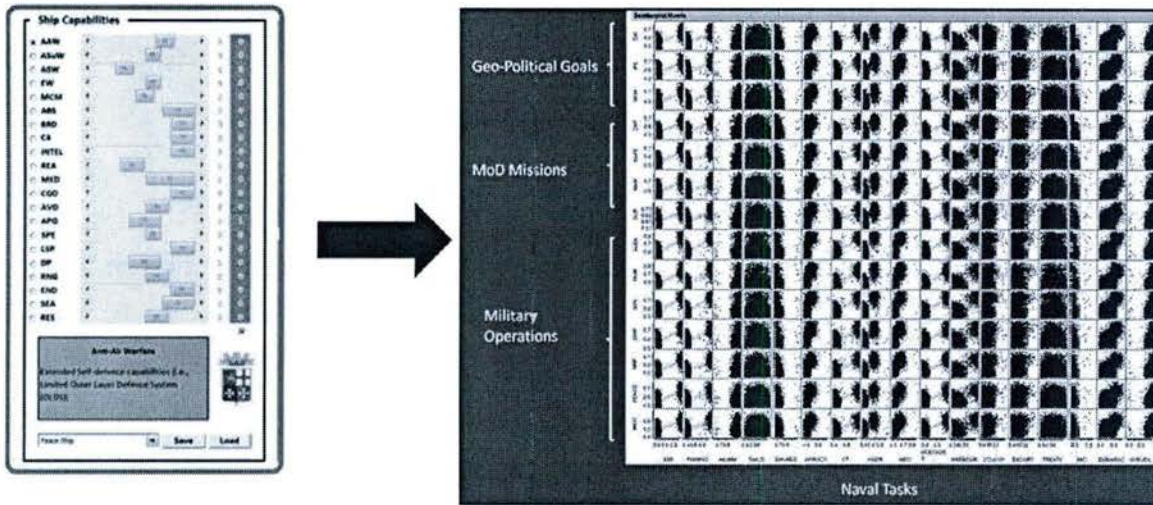
### ***Focus Area 3: Operational Modeling***

The future OPV will be required to carry out a number of Naval tasks, including search and rescue, maritime interdiction, conduct embargos and blockades, engage in Anti-Surface and Anti-Aircraft Warfare (ASuW & AAW), perform fishery patrols, provide non-combatant evacuation (NEO) and even anti-piracy, to name a few. In order to perform a capabilities-based analysis, collaboration with other entities such as Naval Postgraduate School and personnel from OSN, CETENA and the University of Genoa was necessary to create the necessary operational models to assess OPV capability. These models were then incorporated into the graphical tradeoff environment using surrogate modeling techniques so that real-time analysis and exploration of the entire design space could be conducted. Surrogate modeling enables rapid manipulation of any modeling and simulation tools. This allows highly accurate, equation-based regressions of complex codes with negligible (but measurable) loss in accuracy of the original tools. The surrogate model can then be executed in fractions of a second instead of hours or days.



**Figure 16. Surrogate Modeling Based Approach for Operations Model Integration**

Traditional Operations Research/Analysis (OR/OA) approaches rely on simple analytical formulations for mapping the measures of effectiveness of a system. As the missions and tasks modeled become more complex, models that capture these complexities must be developed, or the modeler must simplify and abstract the situation to create useful and credible models that will support decision making. Traditional OR/OA models may not suffice, and over time have become more complex, e.g., using numerical optimization, discrete event simulation, and agent-based modeling and simulation (ABM&S). These techniques are newer, more complex, and demanding in terms of implementation and evaluation. In order to aid the decision maker during design space exploration, different statistical analysis techniques were investigated for their applicability in this regard. The first technique focused on investigating statistical correlations between different levels in the hierarchy that consists of several mappings from geopolitical goals to military missions and naval tasks down through ship systems previously depicted in Figure 2. The goal is to capture hidden trades early on in the design process with varying ship capability levels used as an input. This can be seen in the following figure.



**Figure 17. Statistical Analysis of Ship Capability Level vs. Performance**

As seen in Figure 17, there are clear trends exhibited in the design space that may be exploited. However, to make this information more useful to the decision maker, additional investigation into automating the statistical analysis for various analytical objectives must be investigated and refined.

Lastly, techniques were explored for formalizing the implementation and improving the use of Agent Based Models (ABM). Traditional ABM applications use many instantiations of a simple agent to study aggregate behaviors that are difficult to predict from the study of the agents in isolation. Rather than being a completely scientific exercise, the creation and execution of agent-based models still retains elements of art. Anti-piracy was determined to be a good candidate for testing due to the interactions that can occur between agents and the relevancy to OPV design requirements. Figure 18 demonstrates the number of recorded pirate attacks against commercial vessels off the coast of Somalia in 2009 [5]. Figure 19 also shows an overlay of an internationally recommended transit corridor (IRTC).

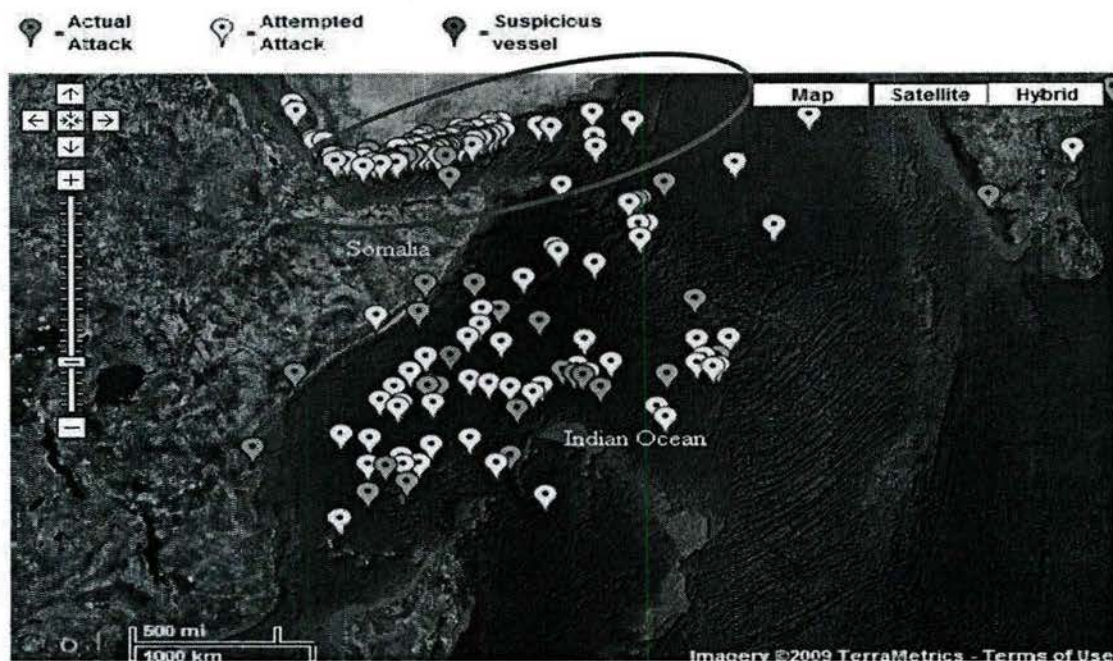


Figure 18. 2009 Somali Pirating Attacks

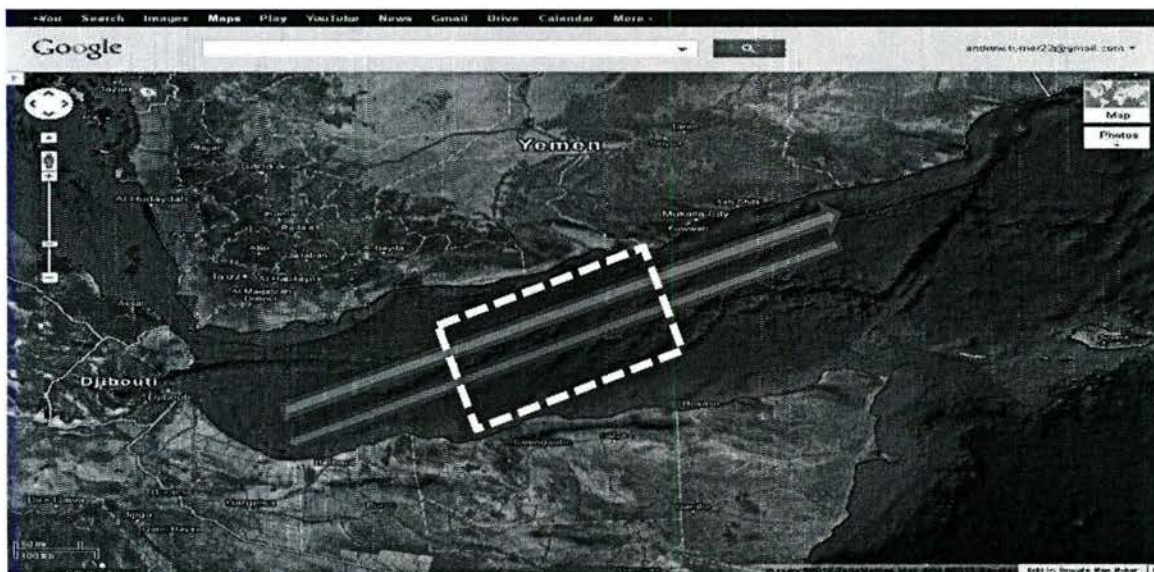


Figure 19. Internationally Recommended Transit Corridor (IRTC).

An ABM was created using the NetLogo M&S tool. The ABM scenario was modeled with various numbers of tankers and container ships transiting the IRTC. An OPV and helicopter can then be simulated as agents patrolling the IRTC to disrupt and deter pirate attacks. An additional layer of complexity is added by the

presence of fishing vessels that can be used by pirates to mask their approach. Figure 20 gives a graphical overview of the ABM.

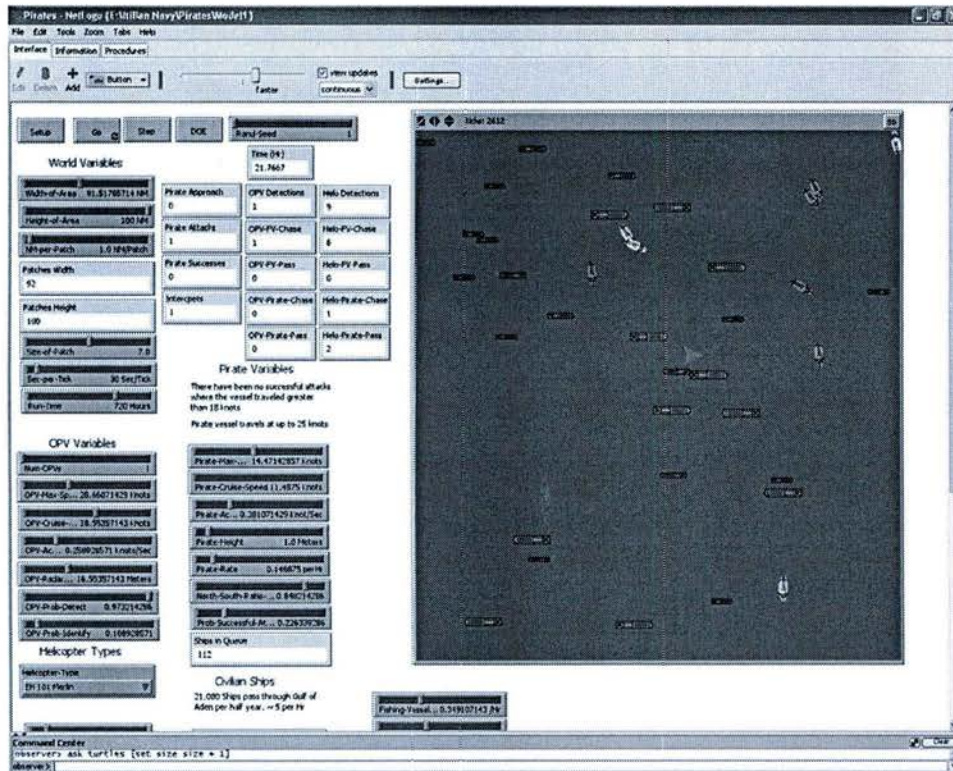


Figure 20. NetLogo Agent Based Anti-Piracy Model

A Measure of Effectiveness (MOE) was developed in order to quantify the impact of the OPV. The MOE is shown in Equation 5:

$$(5) \quad MOE = \left( 1 - \frac{\text{Number Intercepted} + \text{Number Escaped}}{\text{Number Pirates}} \right) \left( \frac{\text{Number Attacks}}{\text{Number Pirates}} \right)$$

The simulation uses the following criteria in determining the MOE for each engagement.

- Approaches: Visual contact has been made between the civilian cargo ship and the pirates
- Attacks: The pirate vessel catches the civilian ship and attempts to board
- Successes: The pirates successfully take the ship



- Escapes: The pirate vessel is scared off by the patrol ship
- Number Pirates: The total number of pirates during the scenario

Figure 21 provides an accounting of the 29 factors that can be varied in the execution of the model. Ranges for each variable were estimated using open source information.

Variable	Min	Max	Units
Width-of-Area	100	200	Nm
OPV-Max-Speed	20	30	Knots
OPV-Cruise-Speed	10	20	Knots
OPV-Acceleration	0.1	0.3	Knots/Sec
OPV-Radar-Height	13	23	Meters
OPV-Prob-Detect	0	1	%
OPV-Prob-Identify	0	1	%
Helo-Down-Time	0.5	12	Hr
Helo-Land-Time	120	1200	Sec
Helo-Launch-Time	120	1200	Sec
Helo-Altitude	50	500	Feet
Helo-Prob-Detect	0	1	%
Helo-Prob-Identify	0	1	%
Helo-Endurance	2	8	Hr
Helo-Range	500	1000	Nm
Helo-Cruise-Speed	50	100	Knots
Helo-Max-Speed	100	150	Knots
Helo-Acceleration	1	10	Knots/Sec
Pirate-Max-Speed	12	25	Knots
Pirate-Cruise-Speed	5	12	Knots
Pirate-Acceleration	0.1	0.3	Knots/Sec
Pirate-Rate	0.0003	0.001	/(Hr-Nm)
North-South-Ratio-Pirates	0	1	%
Prob-Successful-Attack	0.05	0.3	%
Transit-Rate-Large-Oil	1	2	/Hr
Transit-Rate-Medium-Oil	1	2	/Hr
Transit-Rate-Small-Oil	1	2	/Hr
Fishing-Vessel-Rate	0.001	0.01	/(Hr-Nm)
Dist-OPV	10	25	Nm

**Figure 21. Anti-Piracy Model Factors**

This represents a complex model with many inputs that affect the interaction of the different agents within the simulation. Modeling and simulation environments that are stochastic in nature present a multitude of problems in the creation of surrogate or meta-models, notably the reduction of the quality of fit due to statistical error. The first issue is in determining the minimum number of repetitions required for interval estimates to hold true regardless of interval width. These intervals are then used for meta-model regressions. Four measures were examined. Sample mean and variance interval coverage accuracy was studied by varying skewness, kurtosis, desired coverage, and sample size within the Pearson family of distributions. Binomial proportion and quantile interval coverage accuracy was studied with the standard normal with varying sample size, desired coverage, and quantile level. Finally, heuristic measures to determine how repetitions are related to the quality of the meta-model fit were developed based on the experimentation with a canonical problem. The ratio of confidence interval width to the range of sample measures was found to be an indicator of the impact of statistical error on the quality of model fit. Regression methods of weighted least squares (WLS), ordinary least squares for constant sample sizes, and constant interval widths were compared. The WLS method is suggested for stochastic regressions of simulations. A detailed explanation of the methodology can be found in Ref. [6]. Based on this methodology, 40 repetitions were determined to be an adequate number. A design of experiments (DoE) was then constructed in order to aid in constructing the surrogate model. A summary is provided here:

- The DoE used was a Latin Hypercube Sampling (LHS) DoE
  - 290 LHS points were created
    - 10 per factor (29 factors examined)
    - Maximum Correlation: 0.0043
  - Model runtime: 720 Hr (30 Days)
  - Repetitions: 40
    - Shown by past research that this is more than sufficient for mean estimates used in conjunction with weighted linear regressions weighted on inverse of confidence interval
  - 2 DOE sets (with helicopter and without helicopter)

The results of operations of the OPV both with and without the helicopter were then analyzed. For the case of the OPV operating with the helicopter, the OPV/helicopter patrol pattern used is shown in Figure 22.

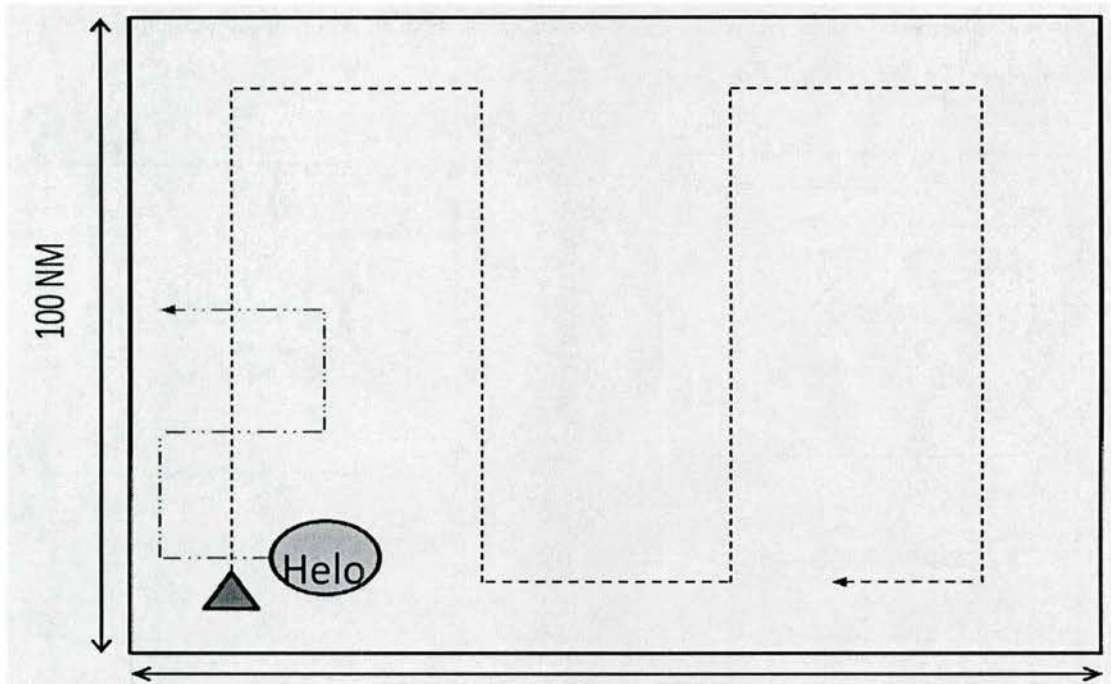


Figure 22. Combined OPV/Helicopter Search Pattern

Figure 23 provides the results of the surrogate model regression quality of fits for the OPV/Helicopter patrol combination. Figure 24 depicts the influence of different variables.

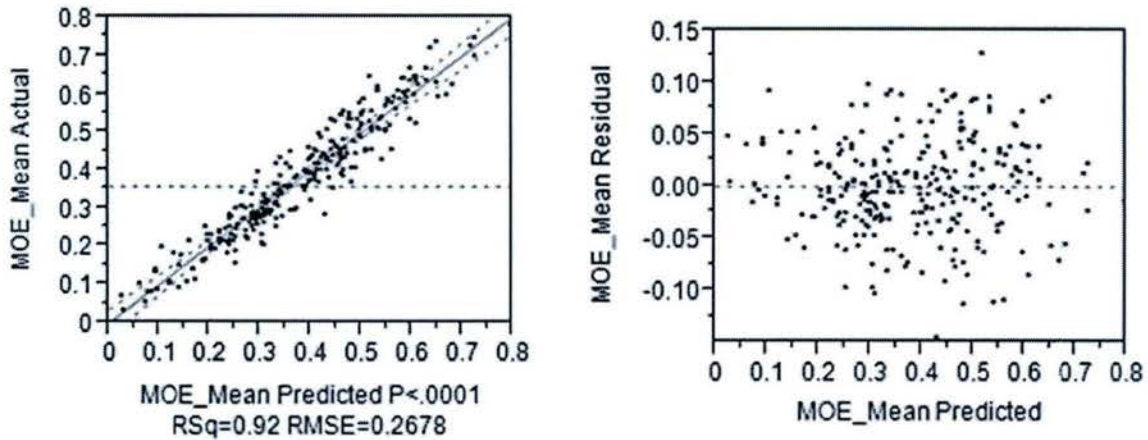


Figure 23. OPV/Helicopter Actual by Predicted and Residual by Predicted Plots for Surrogate Model Goodness of Fit

Sorted Parameter Estimates				
Term	Estimate	Std Error	t Ratio	Prob> t
Pirate-Max-Speed	0.0435889	0.001223	35.66	<.0001*
Width-of-Area	0.0015651	0.000063	24.86	<.0001*
Helo-Prob-Identify	-0.182573	0.009638	-18.94	<.0001*
OPV-Prob-Identify	-0.109867	0.009654	-11.38	<.0001*
Helo-Endurance	-0.015233	0.001609	-9.47	<.0001*
OPV-Max-Speed	-0.005321	0.000976	-5.45	<.0001*
Pirate-Cruise-Speed	-0.007543	0.001446	-5.22	<.0001*
OPV-Cruise-Speed	-0.004613	0.000991	-4.65	<.0001*
(Helo-Prob-Identify-0.51114)*(Helo-Endurance-5.02165)	-0.026119	0.00567	-4.61	<.0001*
Transit-Rate-Small-Oil	0.0451134	0.009808	4.60	<.0001*
(OPV-Prob-Identify-0.50255)*(Helo-Endurance-5.02165)	0.0259138	0.005703	4.54	<.0001*
Helo-Altitude	-9.111e-5	2.149e-5	-4.24	<.0001*
(Helo-Down-Time-6.26853)*(Helo-Prob-Identify-0.51114)	0.0125335	0.003064	4.09	<.0001*
Helo-Down-Time	0.0034127	0.000842	4.05	<.0001*
(OPV-Cruise-Speed-15.0021)*(Pirate-Cruise-Speed-8.62127)	0.0017568	0.00051	3.44	0.0007*
(Width-of-Area-121.08)*(Pirate-Max-Speed-15.6337)	9.6277e-5	2.828e-5	3.40	0.0008*
(Helo-Altitude-277.954)*(Helo-Endurance-5.02165)	-2.781e-5	1.259e-5	-2.21	0.0281*
(OPV-Max-Speed-24.9676)*(Transit-Rate-Small-Oil-1.49727)	-0.004682	0.003469	-1.35	0.1783
(OPV-Prob-Identify-0.50255)*(Helo-Prob-Identify-0.51114)	0.0054744	0.033341	0.16	0.8697

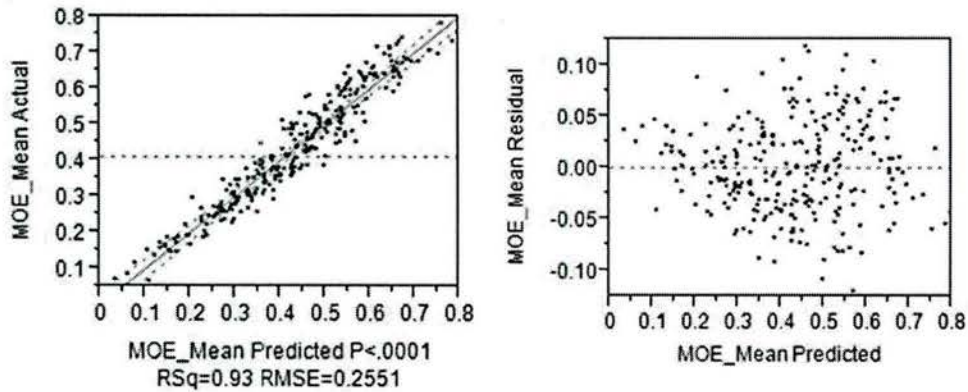
Figure 24. OPV/Helicopter Parameter Estimates

The results of the analysis show that an R-squared value of 0.92 and the scattering pattern of the residuals provide an adequate surrogate model fit. Also, the most influential variable is the maximum speed of the pirate boats. This is intuitive since the faster the pirates travel the easier it is for them to overtake the cargo

ships. The analysis also shows that a significant portion of the response is controllable. This includes the following:

- **Operations**
- Reduce vehicle search area → More vehicles in the area
- **Performance**
- Improve identification of pirates
- Keeps eyes in the sky
- Increase OPV max speed
- Increase OPV cruise speed

The following figures are the results from running the simulation when there is no helicopter available for use by the OPV. Figure 25 provides the results of the surrogate model regression quality of fits while Figure 26 depicts the influence of different variables.



**Figure 25. OPV without Helicopter Actual by Predicted and Residual by Predicted Plots for Surrogate Model Goodness of Fit**

Sorted Parameter Estimates				
Term	Estimate	Std Error	t Ratio	Prob> t
Pirate-Max-Speed	0.0464847	0.00116	40.07	<.0001*
Width-of-Area	0.0016274	6.077e-5	26.78	<.0001*
OPV-Prob-Identify	-0.227694	0.009206	-24.73	<.0001*
OPV-Cruise-Speed	-0.008378	0.000946	-8.85	<.0001*
(Width-of-Area-121.652)*(Width-of-Area-121.652)	-9.6e-6	1.583e-6	-6.07	<.0001*
(Pirate-Acceleration-0.19988)*(Transit-Rate-Medium-Oil-1.49823)	0.7314182	0.156427	4.68	<.0001*
Transit-Rate-Small-Oil	0.0363189	0.009334	3.89	0.0001*
(OPV-Cruise-Speed-15.0408)*(OPV-Prob-Identify-0.50124)	-0.01032	0.003226	-3.20	0.0015*
(Width-of-Area-121.652)*(Pirate-Max-Speed-15.7437)	8.442e-5	2.647e-5	3.19	0.0016*
(OPV-Cruise-Speed-15.0408)*(Pirate-Cruise-Speed-8.59919)	0.0014593	0.000487	3.00	0.0030*
Pirate-Cruise-Speed	-0.00384	0.001349	-2.85	0.0048*
Transit-Rate-Large-Oil	0.0260468	0.009309	2.80	0.0055*
Transit-Rate-Medium-Oil	0.0192691	0.009144	2.11	0.0360*
Pirate-Acceleration	-0.092602	0.045769	-2.02	0.0441*
(Transit-Rate-Large-Oil-1.49623)*(Transit-Rate-Small-Oil-1.50047)	0.032897	0.032421	1.01	0.3112

**Figure 26. OPV without Helicopter Parameter Estimates**

The results of this analysis show that an R-squared value of 0.93 and the scattering pattern of the residuals provide an adequate surrogate model fit. Also, the most influential variable is the maximum speed of the pirate boats. This was also seen in the scenario when the OPV was patrolling with the helicopter. The analysis also shows that a significant portion of the response is also controllable in this case. This includes the following:

- **Operations**
- Reduce vehicle search area → More vehicles in the area
- **Performance**
- Improve identification of pirates
- Increase OPV cruise speed
- Note: OPV Max speed not as important

In contrast to what was observed in the case of the OPV operating with the helicopter, OPV max speed plays less of a role in mission success. This analysis has determined that in situations where the OPV will be patrolling without a helicopter OPV cruise speed is more important. OPV maximum speed gains increased importance when operating with a helicopter since the OPV must be able to quickly relocate to an area

designated by the forward patrolling helicopter in order to disrupt pilot activities. Overall, importing the results of this ABM allows decision makers to estimate the impact of the systems level design all the way up to tactical and even higher-level strategic goals. This also requires the continued study of complex modeling and simulation techniques such as ABM in order to more efficiently design, use, and integrate them into the decision making process.

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### **BMD Wargaming Task**

The main objective of the BMD task was to adapt Georgia Tech's Aerospace Systems Design Laboratory (ASDL) advanced design techniques to facilitate the construction of an analytical environment capable of performing real-time trades of interest to decision makers leveraging the analytical collaboration facilities of ASDL. Many of the advanced design methods and know-how that were applied for this project have been developed through other ONR-funded ASDL projects. The Ballistic Missile Defense Phased Adaptive Approach (BMD PAA) (renamed HDBAS - Homeland Defense using the Ballistic Missile Defense System against Southwest Asia) is a U.S. Northern Command (USNORTHCOM) Warfighter Challenge within the FY11 Joint Concept Development and Experimentation Campaign Plan, conducted by the Joint Staff-led Joint and Coalition Warfighting (JCW) group (formerly known as USJFCOM J7). The goal of this effort is to leverage the USJFCOM Warfighter Challenge as case study to better understand the suitability of using surrogate modeling within defense modeling and simulation applications. It is hoped that a better

understanding of the specifics surrounding the acceptable uses and limitations of the various types of advanced methods will be obtained.

The researchers followed a regimented approach (see Figure 1: HDBAS Work Plan) to developing the necessary tools to support the HDBAS wargame.

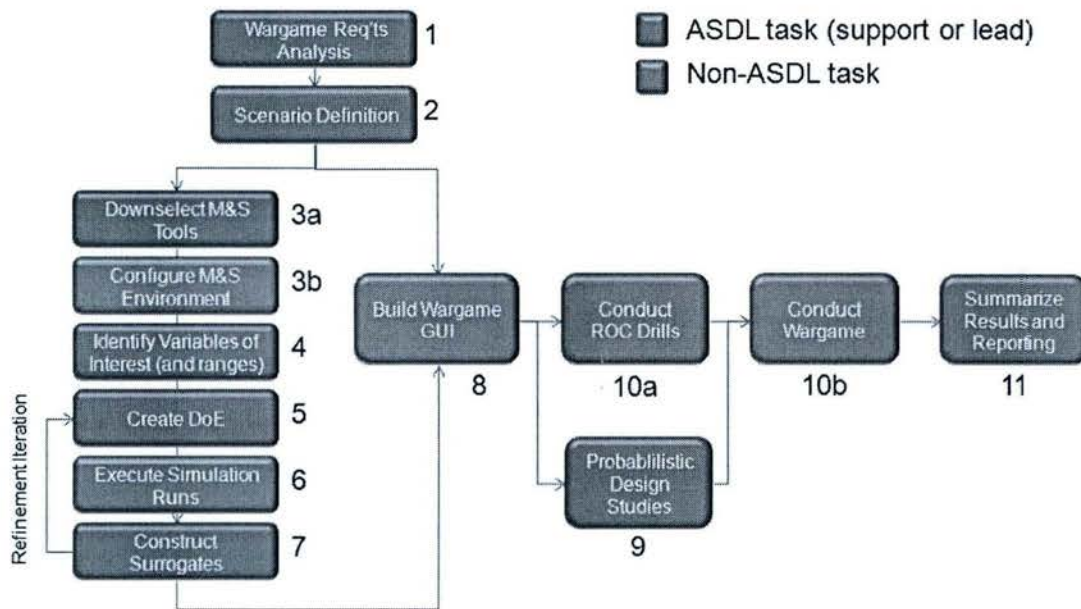


Figure 1: HDBAS Work Plan

*Step 1 – Wargame Requirements Analysis*

The first step in the proposed process is a thorough analysis of the problem space. The wargame requirements call for the input from three phases of analysis: (1) **Development**, (2) **Assessment**, and (3) **Solutions**. The Development Phase will include single threat scenarios. The Assessment Phase will include raids as well as more detailed single threat analysis. The objective of this phase is to identify gaps and vulnerabilities in the proposed PAA. The Solutions Phase will address these gaps and vulnerabilities that have been identified. Steps 3-7 will be repeated for each phase. Step 8 will include the analytical GUI of all three phases. Requirements for the types of trade studies the decision makers would like to perform during the analytic wargame, the necessary “dials” that the analyses should have available for adjustment to support such trades, and the types of performance metrics the decision-makers are interested in seeing



will be developed and stated explicitly. This step is critical because it drives the requirements for all subsequent steps.

#### *Step 2 – Scenario Definition*

During the scenario definition step the team will produce a detailed description of the range of scenarios to be modeled in order to support the analytical wargame. A definition of available blue forces, constraints on force apportionment and deployment, list and prioritization of defended assets, threat epoch characteristics, and possible launch locations and trajectories will be agreed upon.

#### *Step 3 – Construction of M&S Environment*

This step will focus on identifying and constructing a modeling and simulation environment suitable for generating the data required to create the surrogate models needed to support the analytical wargame. Existing tools with extensive support, such as SAIC-owned WILMA, could most likely be setup and run very quickly, but contractor time might be expensive. Other existing tools, like EADSIM, might require climbing a steep learning curve, and take longer to get setup and calibrated for this problem, but offer the ability to run and rerun cases as needed at no additional cost. A detailed M&S tradeoff will need to be performed to settle upon the best overall compromise.

#### *Step 4 – Identify Variables of Interest*

The trades identified during the wargame requirements analysis are mapped to specific variables available in the created M&S environment. Appropriate ranges for the variables are identified according to the scenario definitions obtained in step 2. The performance metrics (responses) are likewise mapped to specific output variables available in the created M&S environment. An analysis plan must then be created to determine which performance metrics will need to be modeled using surrogate models and which, if any, can be quickly calculated based on the output of said surrogates.

#### *Step 5 – Create Design of Experiments (DoE)*

Subject to the number of identified input variables, and restrictions on the number of simulations or the allowed total runtime, a DoE is constructed to ensure that the simulation runs provide the greatest amount of statistically significant data and capture the variability of the responses to the greatest degree possible. This step provides the run matrix to be used in executing the simulations.

#### *Step 7 – Construct Surrogate Models*

Various non-linear regression techniques will be employed to construct a transfer function that relates the identified inputs and responses. The surrogate models give the analyst the ability to execute data

calls nearly instantaneously to the level of fidelity of the underlying M&S tools used to create them. This enables the use of real-time probabilistic analysis techniques that were previously prohibited by the long runtimes of the BMD M&S tools.

#### *Step 8 – Build Wargame GUI*

A graphical user interface (GUI) will be created to leverage the power of the surrogate models in support of the analytical wargame. The GUI will be designed such that it is able to visually convey the probabilistic output of the surrogate model analyses in a meaningful way, while at the same time enabling real-time interaction with the input variables and underlying assumptions. The GUI will make full use of the functionality of ASDL's analytical facilities, the CoVE and CoDE, described below.

#### *Step 9 – Perform Probabilistic Studies*

Once the surrogate models have been created, they can be used in place of the underlying modeling and simulation tools to perform probabilistic analysis and design studies using many thousands of surrogate-model-generated data points. The goal of this step is to explore the decision space and gain an understanding of the performance of the BMD system being studying and put forth recommendations about how to maximize its performance.

#### *Step 10 – Conduct Wargame*

The final step of the proposed approach is the actual conduct of the analytical wargame. ASDL is preparing to use the Secure COVE facility. The high resolution displays and ample seating are ideal for allowing decision makers to collaboratively perform real-time trade studies.

ASDL developed and tested a Rapid Tradeoff Visualization Tool (RTVT) to support Development Phase analysis. Additionally, ASDL co-authored a detailed 17-page whitepaper entitled 'Understanding the Metrics – A Survey of Metrics for Use in SoS-Level BMD Decision Making' and distributed to leadership. Because of the complexity of the BMD system, many metrics exist to describe the performance of the system at various levels. Particular importance is given to the distinction between single-threat scenario performance metrics and multiple-threat raid performance metrics. It is shown that single threat scenario metrics such as Probability of Engagement Success ( $P_{ES}$ ) and Single Shot Probability of Kill ( $P_{SSK}$ ) are unacceptable for use as multiple-threat-scenario metrics. Probability of Zero Leakers ( $P_{ZL}$ ) is then presented as a viable multiple-shot-scenario metric and its limitations explained. Expected Number of Leakers ( $E(L)$ ) is introduced as a way to overcome the limitations of  $P_{ZL}$  without requiring any additional data. Finally, Raid Protection Level (RPL) and Average Raid Protection Level (RPL) are presented as a viable

way of describing the expected defensibility of a particular point within a raid. Examples are provided throughout to show that incorrect selection of scenario-level metrics can drastically change the outcome of the study. This whitepaper has been supported by MDA, NORTHCOM, JCW and SAIC. The whitepaper was endorsed by senior leadership (including Lt. Gen. Obering) and a draft is included in the appendix.

### **Run Matrix Design**

Run Matrix size was a significant issue that needed to be addressed

- Evaluating all possible combinations within the trade space is very computationally expensive
  - The ~6 million combinations represented by the variables in the table to the right would take 4160 hours to run at 1 minute/case on 24 processors
- Not all combinations within the trade space are of interest, so evaluating all possible combinations is not even desirable

A method is needed for intelligently selecting which combinations to evaluate, while simultaneously reducing the Run Matrix size

Previous approach relied on a “smart” design, reducing the number of cases by manually pruning the run matrix

- Only variable combinations that are directly relevant to the study are evaluated
- This approach produces an order of magnitude reduction in the required cases
- Results are biased by running only those cases which are seen as most likely
- Statistical significance of the results is lost as branches of the trade space are pruned

ASDL introduced Design of Experiments (DOE) into the Run Matrix Design approach

- Enables order of magnitude reduction of required cases, similar to manual pruning
- Maintains an uncorrelated Run Matrix, maximizing the amount of information gathered with the cases evaluated

ASDL briefings on the fundamentals of DOE enabled the transition from the old approach

- Design of Experiments (DOE) is:
  - Purposeful changes to the inputs to a process in order to observe the corresponding changes in the outputs
    - Inputs also called *design variables* or *factors*
    - Outputs also called *responses*
  - A set of runs *designed* to maximize information and minimize experimental effort

#### Key Concepts and Terminology

- Correlation: Statistically induced non-independence of input variables
- Orthogonality: Implies zero correlation between experimental factors
  - i.e. A purely orthogonal design is used to maintain the independence of independent variables

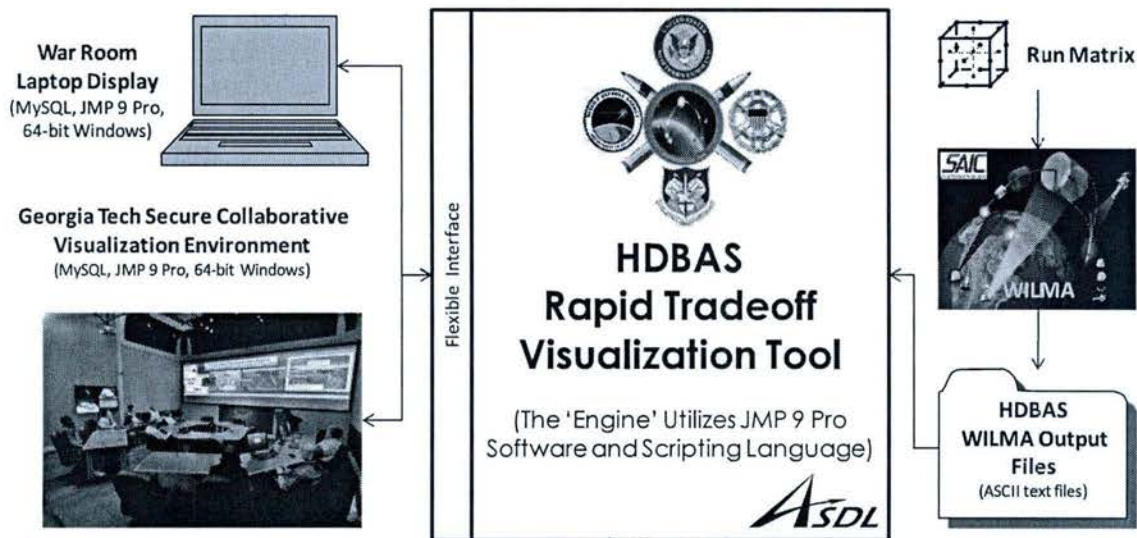
Resulting Run Matrix Design Options:

<u>Design</u>	<u># of Cases</u>	<u>Pros</u>	<u>Cons</u>
Full Factorial	~ 900,000	<ul style="list-style-type: none"> <li>Quantifies performance for every possible combination</li> </ul>	<ul style="list-style-type: none"> <li>Computationally expensive</li> <li>Evaluates many unlikely combinations</li> </ul>
Manual Pruning	~ 166,000	<ul style="list-style-type: none"> <li>Reduced # of Cases when compared to Full Factorial</li> <li>Evaluates all cases of interest and only those cases</li> </ul>	<ul style="list-style-type: none"> <li>Cannot answer "what-if" questions that were not explicitly stated at the start</li> <li>Results become biased and statistical significance is lost as branches of the trade space are pruned</li> </ul>
Nearly Orthogonal Arrays	~ 50,000	<ul style="list-style-type: none"> <li>Specified cases can be incorporated into the Run Matrix generation</li> <li>Can answer "what-if" questions throughout the trade space</li> <li>Provides guidance for selection subsequent study cases</li> </ul>	<ul style="list-style-type: none"> <li>Does not provide for a 1-to-1 comparison between Blue Force architectures</li> </ul>
Taguchi Arrays	~ 120,000	<ul style="list-style-type: none"> <li>Provides a 1-to-1 comparison between Blue Force architectures</li> <li>Can answer "what-if" questions throughout the trade space</li> <li>Provides guidance for selection subsequent study cases</li> </ul>	<ul style="list-style-type: none"> <li>Less efficient than OA Option 1</li> <li>Additional cases needed to quantify the impact of interactions</li> </ul>

### Rapid Tradeoff Visualization Tool

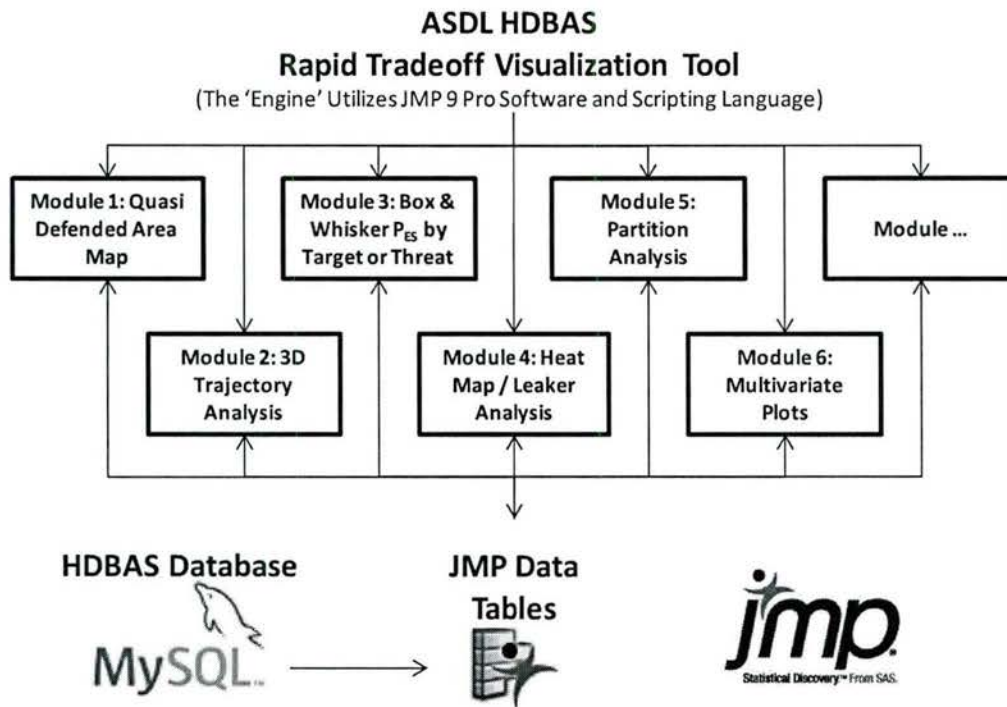
The data analysis for this project leveraged the experience of ASDL in creating interactive, dynamic data visualization tools / GUI. The use of these visual displays, in conjunction with advanced visual analytics techniques will allow the analyst to view the data in bulk, find trends and patterns, and examine the influence of assumptions more easily than traditional approaches to data analysis.

Data generated in each phase of the study is stored within a database structure. With the volume of data expected, this ensured intuitive and responsive access to all data from within the visualization interface. Output files in the form of ASCII text files will be imported into the database using custom written scripts that will be implemented in the visualization tool. All database management was performed within the visualization tool framework. This enabled all post-processing and analysis operations to be performed on a single system, minimizing data transfers and streamlining the overall process. An overview of the integrated framework is shown in Figure 2.



**Figure 2: The Integrated BMD PAA Rapid Tradeoff Visualization Tool Framework**

One or more visualization tools with customizable layouts were created to support the analysis of the results of each phase. These interfaces allowed for the study of relationships among the assumptions, scenario configurations, and BMDS performance metrics. Central to the visualizations for each phase is a map feature with the ability to display overlaid data in both two dimensions and three dimensions. User interaction with the maps as well as other analysis modules in the visualization interface will automatically query the database of simulation inputs and outputs to display the geographic differences in performance of various BMD configurations. This tool will provide the user with the ability to rapidly sort through uninteresting/non-limiting cases and quickly find troublesome areas that need to be examined in the Assessment Phase. An example data structure is presented in Figure 3.



**Figure 3: HDBAS Rapid Tradeoff Visualization Tool Example Modules and Data Structure**

The modules for the RTVT are custom, developed for use for HDBAS. JMP has many built in JMP Scripting Language (JSL) functions and visualizations but this was a fairly large development effort. The current list of modules is as follows:

1. **Box Plots:** In the JMP dashboard, a box plot is used to visualize the Probability of Engagement Success (PES) of the entire BMDS of defending a specific targeted site or defending against a specific threat site. The individual data points in these hypothetical box plots represent the average PES for a single interceptor shot at a threat missile launched from a specific threat site to a specific targeted site using a unique BMDS architecture.
2. **Scatter Plot Matrix:** An nxn matrix with 2D comparisons of any combination of user selected input and output variables. It is very useful for constraint analysis, inverse design, and to find trends and correlations with large sets of data. Data can be color coded by discrete scenario variables like threat type, launch location, etc.

3. Heat Map: The heat map module is responsible for analyzing the probability of engagement success (PES) for asset architectures and displaying the information as a series of colors which identify relative value of PES for threat-aim site pairings. The heat map analysis presents data in the form of a series of (n x m) matrices where the rows and columns display the launch and aim points included in the given study. Each matrix of launch-aim points identifies a single BMDS asset architecture (i.e. radar locations and types as well as interceptor type). The user will be able to select what threat architecture they would like to view via drop down menu.

4. Engagement Sequence Group (ESG) Analysis: The purpose of an ESG analysis is to determine what the placement of assets was during a specific defense sequence. This allows the determination as to what assets was the best performing and at what locations they performed best at. This allows the person to make intelligent trades in order to ensure that the best assets (Radars, Space based assets ...) are placed at the best locations performing appropriate roles in the ESG (such as Commit, Track, Update,) such that the desired PES can be achieved. To that end, a simple visualization was needed to quickly see which roles were being filled and what assets filled those roles with different scenarios. A cell plot function was used for the visualization.

5. Principal Component Analysis: Principal Component Analysis (PCA) is a method used to reduce the dimensionality of a set of data. One application of this method is to define the overall variability of a set of data. When confronted with large sums of data that happens to be stochastic, this method could aid in the determination of how many repetitions are required to obtain the desired confidence intervals. Another application is the visual display of the data. By reducing the dimensionality one can better understand the behaviors. For example a 15 dimensional space could be represented as a 3 dimensional space while observing the majority of the variability of the space. However, the transformations made can result in very confusing metrics. Another application is to use PCA to aid in selection Measure of Effectiveness or Performance of a system. This may not happen however, because variables that need to be maximized and minimized could be correlated along the same principal factor. This method could be used to aid other metrics that are limited by the number to dimensions that can be used. Examples of this are Partition Analysis and Heat Map.

6. Partition Analysis: Partition Analysis is a technique often used as a data mining tool. PA is good for finding relationships within the data without having a defined model. In addition, PA is useful when dealing with large amounts of data. In general a PA will determine the factors that control the greatest



variability on the response. This can be useful for determining which factors to investigate further. In this application, the PA will be utilized in determining the main drivers of launch and aim points. This analysis may result in the identification of critical assets or even launch windows. In addition, PA could be used to determine which aim points have sufficiently similar PES under defined conditions that they could be evaluated as nearly identical. PA could also be used to break up the space as a series of launch to target “corridors” to determine which routes are able to produce the best radar track of threats.

7. Cluster Analysis: Cluster Analysis (CA) is the process to dividing a set of data containing  $n$  pieces of data into  $k$  sets of data. CA can be used to help identify key elements or patterns in the data. An example would be to cluster by probability of kill, which will show similarities in cases that may have completely different launch and target sites. This allows the analyst to compare and evaluate variables that may have a considerable impact on probability of kill regardless of the launch or target site. Another foreseeable use of cluster analysis would be to cluster based upon the time the threat is identified. This analysis would allow for the identification of areas or target sites where tracking the threat early on in the engagement is difficult. For this example, the relationship between the time of identification to the probability of kill, time of intercept, and radar track quality could easily be examined.

8. PES versus Intercept Time: A PES versus intercept time plot displays exactly what its name claims, the overall system PES as a function of the time when the lethal threat was intercepted. In the case of this plot, the system is defined as a single interceptor shot. The plot is split into multiple windows each showing PES curves per a single interceptor launch point. Each curve represents a unique system architecture. Furthermore, as the same system architecture may be used to set up the shot from each launch site, the curves are color coded to the system architecture. This allows for single architecture performance to be compared across launch sites.

9. Engagement Timeline: An engagement timeline analysis is useful for examining a series of events over a time. Events are plotted on the Y axis while time is plotted on the X axis. The time period that an event that occurs appears as a bar. This method examines one engagement sequence group at a time.

10. Analysis of Variance: Analysis of Variance (ANOVA) is a statistical modeling method in which the variance of data is clustered into sections in order to explain the sources of the variation. In essence, the variance is attributed to certain variables, which gives the user an indication to which variables are the strong contributors of change.

11. 3D Trajectory Visualization: This displays one or more trajectories over a 3D map for comparison. This module still needs a lot of work and will be continued after the project ramps up in April. The additional work will be to add Meta data (such as launch window information, radar search volumes, etc.) to the curves.

It is important to note that the modules can be used independently, but when used together, the visual analytical capability is greatly improved. An example would be to looking across the executed trade space to determine critical factors and areas of improvement (solutions) that would have the biggest impact across this space.

The analysis environment built in JMP makes a very large number of analysis approaches and usage paths available. The sequence in which each of the modules is used is influenced by everything from the specific questions being asked to the analyst's personal preference or style. It is likely that a number of key approaches will be identified and standardized during the course of this study. However, several notional analysis approaches are provided below to serve as examples of the flexibility available to the analyst. An example path was posed:

1. Observe interesting feature on Map module; use the mouse to select the cases that make up that feature and highlight them with a different color
2. Plot key parameters and metrics in the Scatter Plot Matrix in order to identify unique attributes of the cases of interest which show up with the highlight color applied
3. Use filters to remove unrelated cases from being plotted in the modules
4. Examine the Trajectories plot to see if any additional intuition can be gained based on the geometry of the engagement, the radar locations, etc.
5. Use the Timeline Decision Aid, Battlespace Plot and Parallel Plot to compare cases and better understand the effects which were observed at the beginning
6. Use filters to bring all of the data back into play, and use

## Summary

The RTVT was created using methods to support analysis of large data sets. ASDL experimented with different database designs and efficient ways of accessing the data to support rapid tradespace analysis. Different modules were created so that the data can be analyzed in bulk and in different groups to support performance and fault analysis. The RTVT was used during the Development Phase for benchmarking and for assisting with the Assessment phase run matrix design.

## Visual Command and Control Capability Analysis Tradeoff Suite (VC3ATS)

The Visual Command & Control Capability Analysis and Tradeoff Suite (VC3ATS) task seeks to perform *dynamic* Command & Control (C2) and mission analysis with Joint Mission Thread (JMT) architectures for the purpose of comparing C2 alternatives in the single and multi-mission trade space. This will result in a formalized methodology that will produce traceable, defensible results while analyzing both process and materiel alternatives.

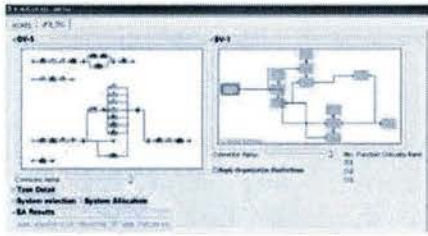
VC3ATS utilizes standardized, static Department of Defense Architecture Framework (DoDAF) products as a means of providing JMT generic data descriptions. These JMT descriptions, which are described as being at the “Tier 1” level, are completely reusable. In contrast, DoDAF products developed at the “Tier 2” level, for example, are much more specific and serve as subsets to Tier 1 information. Furthermore, the use of static Tier 1 related DoDAF products are then leveraged to allow for the automatic or semi-automatic generation of C2 and mission analyses, which are then used for the purpose of C2 portfolio tradeoffs. Figure 1 provides an overview of the structured decomposition analysis framework used by VC3ATS.

The successful implementation of this C2 analysis framework requires the development of specific methods and techniques that will enhance the decision makers’ ability to perform meaningful comparisons of competing C2 architectures. Specifically, VC3ATS focuses on 3 key approaches that will enhance the analysis of military C2. These approaches include:

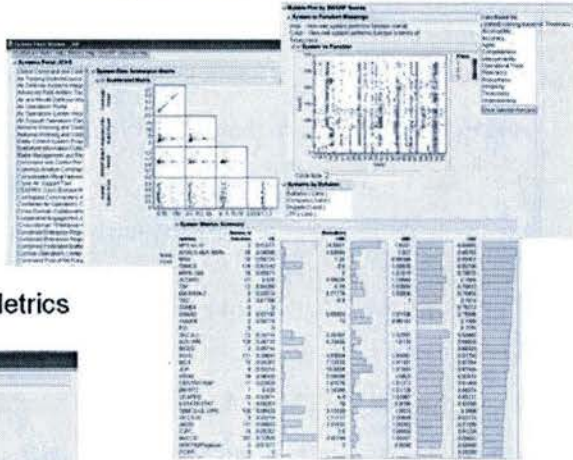
1. The generation of feasible architectures
2. Analyzing C2 performance and mission effectiveness
3. Making C2 attributes measurable and useful

VC3ATS provides an interactive visual environment to aid in the generation and analysis of feasible architectures. An example of this can be seen in Figure 1:

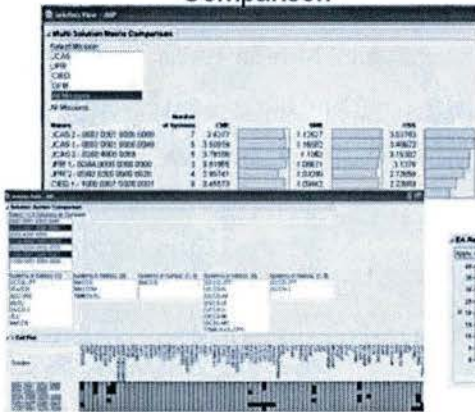
### Interactive OV-5 & SV-1 for Solution Development



### C2 System Metrics and Comparison



### C2 Portfolio & Multi-Mission Metrics Comparison



### Experimental: Business Process Model Executable Architecture Platform

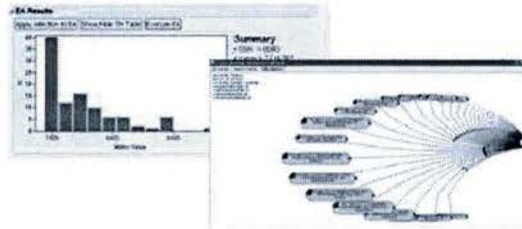


Figure 1. Interactive Visual Environment Screenshots

The current analysis framework uses the operational sequence diagram of related tasks/functions as the ‘work horse’ of the analysis framework. Continued progress has been made in including additional DoDAF products and provided data sets in order to improve the generation of feasible architectures. Specifically, the research was conducted in cooperation with the Deputy Director, Command and Control Integration (DD C2K) Joint Staff (J6) to incorporate additional “Tier 2” level architecture data. Also, the scope of the analysis was broadened with the inclusion of additional JMT data so that both single and multi-JMT analysis could be conducted. Further development of the analysis framework resulted in the refinement of the analysis methodology to include both top-down and bottom-up perspectives. User sessions were then conducted with Joint Staff (J6) where valuable feedback was obtained for possible future development of VC3ATS. Finally, objectives for the next phase of VC3ATS development were identified, provided that funding is renewed for the next FY.

Previous developmental phases of VC3ATS operated with limited data set availability. However, VC3ATS is now at a critical crossroads where more data is becoming available at the same time as VC3ATS analytical capability is improving. For example, through collaboration with the Deputy Director, Command and Control Integration (DD C2K) Joint Staff (J6) “Tier 2” JMT data became available. A description of the different Tiers can be seen in Figure 2.

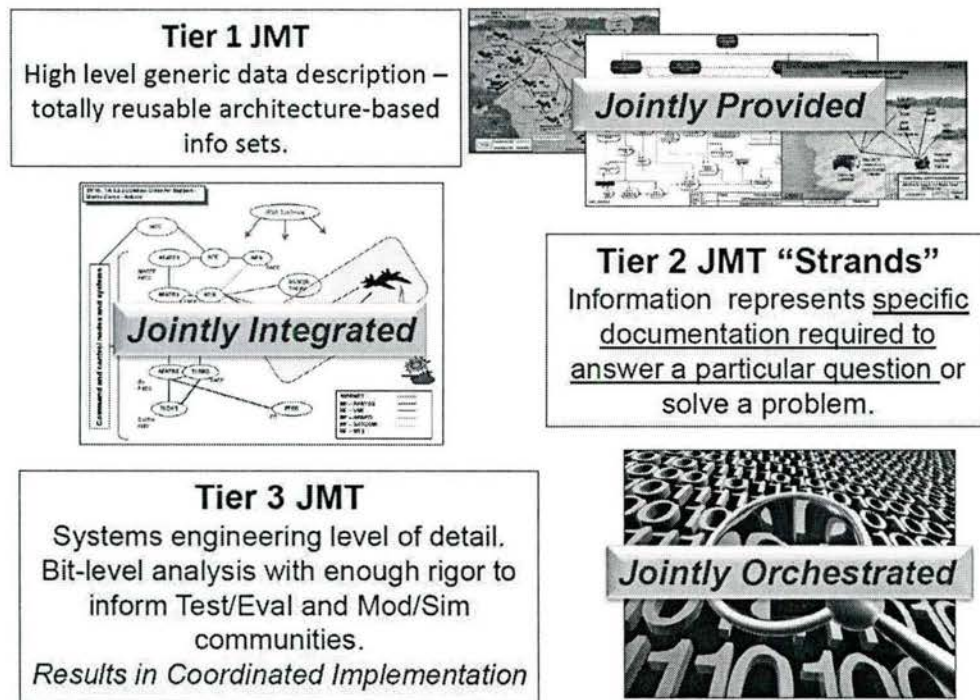


Figure 2. Joint Mission Thread Tiers

Specifically, Tier 2 data was obtained for the Joint Fire Support, Joint Close Air Support and Joint Personnel Recovery missions. This enabled the multi-thread analysis capability to become more fully developed. Below is a summary of some of the analysis questions pertaining to both single and multi-thread analyses.

- ❖ Single Mission Thread Analysis:
  - What processes/equipment supports the JMT best?
  - What DOTMLPF changes can be made to improve performance?
  - What is the bottleneck/vulnerability point of failure in the process?
  - What C2 construct enables the optimal JMT performance?
- ❖ Multiple Mission Thread Analysis:
  - What DOTMLPF commonality exists across all JMTs?

- What systems, functionality, etc. is unique across the threads?
- Where are the overlaps and redundancies? What is the effect of eliminating these?
- How do DOTMLPF changes in one thread affect the performance of others?

Simultaneously, more automated data ingestion methods were identified, making it easier to incorporate new mission threads in the future. This intersection also allows VC3ATS to be rolled out for analyst use and feedback via series of training sessions. These sessions were conducted and valuable feedback was obtained. The following list highlights a sampling of the feedback obtained from the user sessions:

- Provide ability to load baseline solutions for each JMT/Architecture to provide user with a starting point for comparisons
  - How is the JMT currently executed/what are the current systems in use or heavily relied upon?
- Additional system/program data would be useful for defining solutions:
  - Interoperability between systems is a major concern
  - Lifecycle data
  - Budget data
  - Additional metadata about systems, missions, etc.
  - System performance (test command data)?
- Access to authoritative data sources a top priority
- Refine target audience list – Action Item for J6
  - For e.g., how will Architects who generate data find this useful when VC3ATS needs all JMT data up front to ingest
- Comparison of model to model vs. data to data
  - Impact of change to one model has on other model may be lost/resident only in person who developed models
- Add a reset/clear option for solution history
- Add a 'Ctrl-Z' button to undo actions
- Add ability to view multiple OV-5 & SV-1 diagrams as separate windows (compare changes more easily)
- Auto-save function
- Provide catalog of user-selected displays
- Scrollable grid lines on System-Function Performance Overview (Bubble Plot)
- Provide ability to view more threads simultaneously
  - Speed up load time for many mission threads
  - Identify which displays are most vital to load initially, then load others as needed
- Refine system comparison list (functions unique/common to) and make clearer
- Clarify mission specific views vs. global views

## Refinement of VC3ATS Analysis Perspectives

Further development of the analysis framework resulted in the refinement of the analysis methodology to include both top-down and bottom-up perspectives. Sample use cases were developed and proved useful in the Joint Staff User Sessions. For the Top-down perspective, the following was assumed:

### Sample Use Case 1:

- Analyst very familiar with current C2 systems
- Asked to support analysis for a recommendation to trim down number of operational C2 systems
- Must recommend systems that should be phased out
- Must also be sure that loss of these systems will not result in loss of operational capability
- Accomplished by identifying common/redundant functions across systems and possible substitutes

Meanwhile, for the Bottom-down perspective, the following was assumed:

### Sample Use Case 2:

- A new commander is rotated in
- Needs to understand the current C2 systems in use by his organization/service component
- Must determine if other options exist that might better fill needs and close capability gaps
- However, may have limited knowledge of existing systems
- Therefore, needs to understand both the uses and performance of current and competing systems

## Identification of Phase 4 Objectives:

Funding for VC3ATS was discontinued prior to the completion of the next phase. The following objectives were identified for the subsequent phase of VC3ATS development, provided funding can be renewed at a future date:

- ❖ Enable DOTMLPF trades (Doctrine, Organization, Training, Materiel, Leadership, Personnel and Facilities) & improved traceability for acquisition decision makers
  - Expand across the entire DOTMLPF spectrum
  - E.g. Training vs. Force Structure Tradeoffs or Training vs. Technology Tradeoffs
- ❖ Continue transition to user & incorporate user feedback
  - Joint Staff User Workshops February 7, 2013
- ❖ Feasible Architecture Development

- Further development of system metrics and methodologies for developing and using those metrics
- Incorporation of completed Tier II JMT Data
- ❖ Complex SoS Architecture (Solution) Evaluation & Analysis
  - Further development of Business Process Model Executable Architecture Platform
    - Currently limited to JPR mission and older version of the BPM EA
    - New data available in the Tier II JMTs suggests potential to investigate expanding the EA for VC3ATS
    - Would like to consider both an expansion of the use of current Java-based BPM approach and other potential EA tools for phase 4

## Space Mission Architecture

The objective of this task is to demonstrate, train, and transfer Georgia Tech (GT) Advanced Design methodologies to the NASA/MSFC Advanced Concepts Office (ACO) in order to enhance NASA design practices and enable expanded trade study capabilities. This effort focuses on applications for in-space disciplinary analyses, Earth-to-orbit (ETO) modeling, and physics based engine modeling, enabling an encompassing look at a conceptual design for Mars exploration architecture. Opportunities associated with advanced manufacturing, materials, in-situ resource utilization (ISRU), and concepts of operation (CONOPS) will be evaluated utilizing advanced technology impact forecasting methods. The challenge of developing a fully reusable transportation architecture for manned Mars missions was selected in order to provide a demonstration problem of current relevance to NASA.

The technical objective of the architecting study is the identification of reusable architectures that support manned missions to Mars and its moons. Identified architectures should describe the functional and physical elements required to make them possible. The architecture design process must develop how the transportation architecture and supporting infrastructure evolve to advance from today's capabilities to an architecture where vehicles can operate for 20 or more years, with a stretch goal of achieving similar reusability and serviceability to what is experienced with aircraft today.

The architecting process employed in this task infuses object-oriented simulation, morphological analysis, and relational databases to assemble executable models. Components and technologies comprise vehicles, events and trajectory segments comprise missions, and vehicles closed to specific missions comprise architectures. Because the technology development evolution path and strategy are of key interest, an additional layer is added to the problem in which sequences of architectures employed over a period of years comprise a campaign. Figures 1 shows the general approach and current dashboard development strategy.



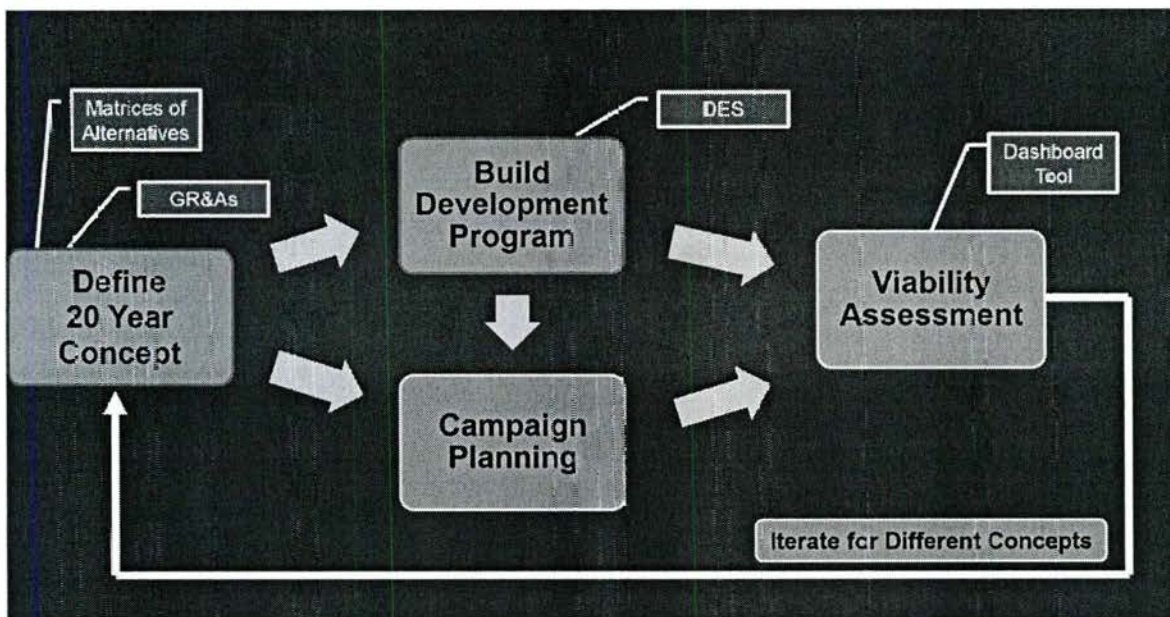


Figure 1. General Approach to Creating Viable Campaigns

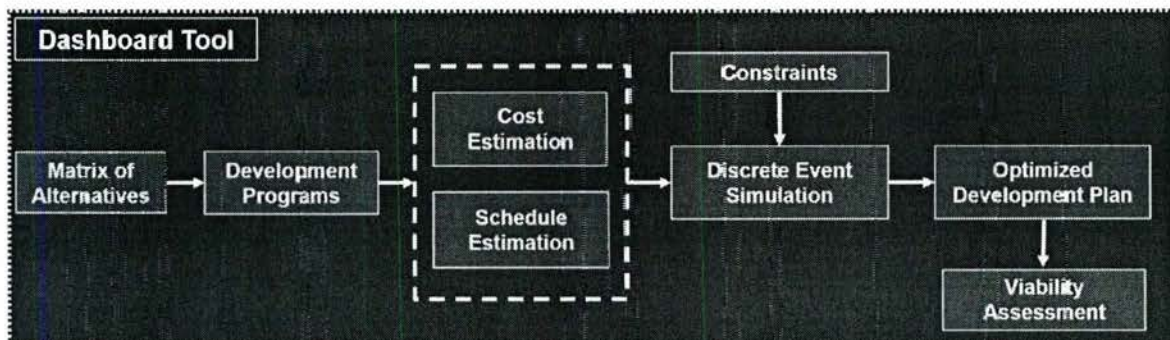


Figure 2. Dashboard Tool Outline

Various challenges are incorporated into the overall setup and analysis of the problem. In-space assets should have minimal dependence on Earth for resupply except for provision of food and crew supplies. Except for the launch and crew Earth entry vehicles, elements are not returned to Earth surface for refurbishment. Refurbishment and resupply of Mars-vicinity vehicles may be provided in orbit or on the Mars surface. The emplacement of any resources and infrastructure used in the architecture must be accounted for, and may include a combination of government and commercial capabilities. Identify capabilities that need to be developed and provide a roadmap of how those capabilities will be introduced over time to evolve the architecture.

To date, progress has been made on a number of fronts, including architecture trade space definition, architecture evolution modeling, and space transportation system sizing. The architecture trade space has been defined via a novel dynamic matrix of alternatives (DYMOA), which was necessary for concisely capturing all of the possible alternatives in a system-of-systems problem. Architecture evolution, interpreted as a time varying problem that traces the path of development program investments, has been modeled using a discrete event simulation (DES). An integer programming routine has been wrapped around the DES in order to optimize technology and system development program investment strategies in order to ensure budget and schedule constraints are met. Finally, a space transportation system sizing environment is under development that will provide a technical feasibility assessment to complement the viability assessment performed by the architecture evolution modeling.