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A Quantitative Framework to Assess the Impacts of New Technologies and Systems on the Seabasing Concept

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14. ABSTRACT

Seabasing has been identified as a critical future joint military capability for the United States. The complexity of the Seabasing architecture requires a coordinated development effort to address identified issues and to create a joint Seabasing system-of-systems. New technologies that provide updated capabilities are needed to make the Seabasing concept feasible. It is essential to identify the capabilities required of these new technologies and to quantify the impact of capability tradeoffs on the Seabasing concept. This paper presents a quantitative framework to assess the impacts of new technologies and systems on the overall Seabasing system-of-systems. An architecture-driven approach is employed to develop a discrete event model of the Sea Base-to-Objective system. Surrogate models are constructed to enable rapid, probabilistic design for capability. Compared with previous methods, the proposed approach enables decision makers to make informed decisions during the requirements definition and conceptual phases and offers the potential to reduce the time and cost needed to develop a design that meets or exceeds customer requirements.

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Abstract

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This paper presents a quantitative framework to assess the impacts of new technologies and systems on the overall Seabasing system-of-systems. An architecture-driven approach is employed to develop a discrete event model of the Sea Base-to-Objective system. Surrogate models are constructed to enable rapid, probabilistic design for capability.

Compared with previous methods, the proposed approach enables decision makers to make informed decisions during the requirements definition and conceptual phases and offers the potential to reduce the time and cost needed to develop a design that meets or exceeds customer requirements.

Acknowledgements

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The team consisted of:

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1 Background

As outlined by Admiral Vern Clark, *Sea Power 21* is a strategic vision enacted by the United States Navy to navigate 21st century challenges by aligning, organizing, integrating and transforming its efforts to reach maximum combat power. In accomplishing these objectives, Sea Power 21 outlines capabilities that must be employed to counter the dangers of varied and deadly threats that pose challenges to national security and future war fighting. The capabilities that ultimately define *Sea Power 21* are *Sea Strike*, *Sea Shield* and *Seabasing*.

Sea Strike outlines a strategy for offensive power; *Sea Shield* outlines a strategy for global defensive assurance; as *Seabasing* outlines strategies for operational independence [1].

The Seabasing capability serves as a base and supports *Sea Shield* and *Sea Strike*. Seabasing will allow *"pre-positioned [war fighting] capabilities for immediate employment, enhanced joint support from a fully netted, dispersed naval force, strengthen international coalition building, increase joint force security and operational agility, and minimize operational reliance on shore infrastructure."* This concept enables the United States to augment force protection by reducing vulnerabilities [1].

A vulnerability gap, due the differences in the rate at which the initial landing force can be reinforced and the rate at which the enemy force can reinforce. This allows the possibility of the enemy projecting a greater force. Figure 1 clearly depicts how the vulnerability gap impacts the level of combat power over time.

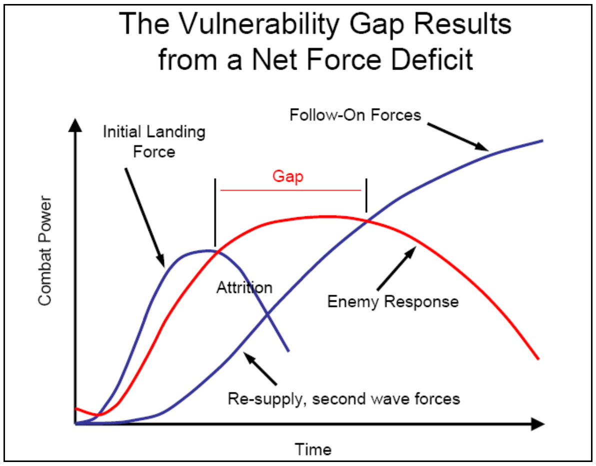

Figure 1: Vulnerability gap resulting from net force deficit [2]

Sea Base-Enhanced Projected Force amplifies combat power by sustaining troops over time and removes the transitory impact of the Initial Forces seen in Figure 1. Figure 2 depicts a reduction in the *Vulnerability Gap* with Seabasing and displays an improvement in the sustained level of combat power [2].

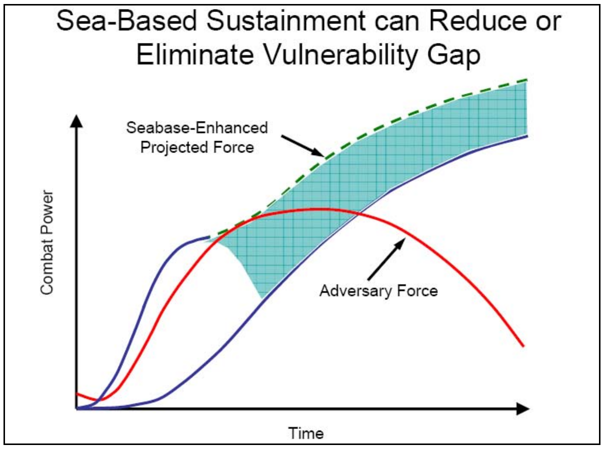

Figure 2: Reduction of vulnerability gap from Sea Based sustainment [2]

To achieve the desired Seabasing objectives and to reduce this Vulnerability Gap, a Concept of Operations (CONOPS) has been developed. Often referred to as CEASaR, the CONOPS for Seabasing is broken into five organizational phases: Close, Assemble, Employ, Sustain, and Reconstitute. These phases make the mobility of joint forces continuous and constant, over time – thus reducing the Vulnerability Gap.

In the Close phase, a Marine Expeditionary Brigade (MEB) sized force is brought to the Sea Base. This phase is defined by its ability to rapidly move joint forces to an area of crisis. Defined by its ability to safely allow the integration of the joint force, the Assemble phase provides a secure environment in preparation of troop employment. Through the support of the sea base, the Employ phase provides flexibility to the joint force by meeting changing requirements and mission objectives. This phase is defined by its ability to reduce the logistical footprint ashore and the force protection requirements. The Sustain phase provides a steady flow of support for ship and shore based joint forces. The Reconstitute phase allows joint forces to rapidly deploy joint forces again for subsequent operations [3].

This CONOPS has been further detailed with Measures of Performance (MOPs) and Measures of Effectiveness (MOEs) meeting Seabasing goals. MOPs are "*designed to correspond to accomplishment of mission objectives and achievement of desired effects"*. MOEs are "*designed to quantify the degree of perfection in accomplishing functions or tasks."* The MOPs for meeting Seabasing goals are as follows [3]:

> ***CLOSE*** *joint sea-based capabilities, including elements of [Joint Command and Control], to a [Joint Operations Area] to support major combat operations within 10-14 days of execution order.*

***ASSEMBLE** and integrate joint capabilities from the sea base to support major combat operations within 24-72 hours of arrival within the [Joint Operations Area].*

***EMPLOY** over-the-horizon from the sea base at least one (1) brigade for [Joint Forcible Entry Operations] within a period of darkness (8-10 hrs).*

***SUSTAIN** joint sea-based operations, including up to at least two (2) joint brigades operating ashore, for an indefinite period using secure advanced bases up to 2000 nm away; also support selected joint maintenance and provide level III medical within the sea base.*

***RECONSTITUTE** one (1) brigade from ashore to the sea base and reemploy within 10-14 days of execution order.*

Figure 3 shows an overarching view of Seabasing.

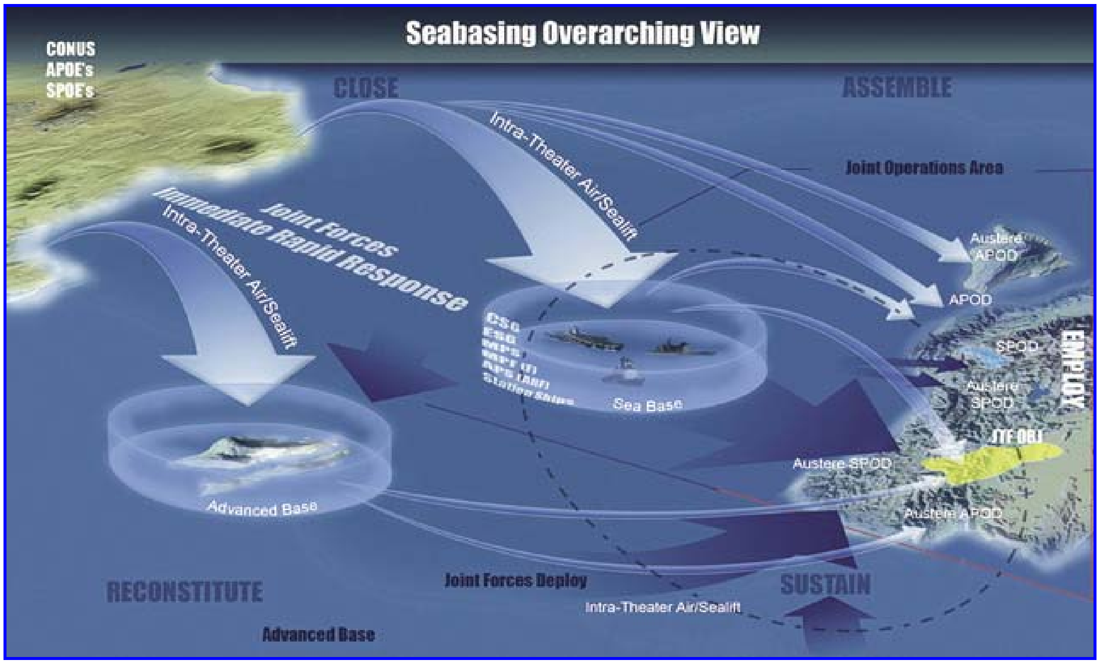

Figure 3: Seabasing overarching view (www.defenseindustrydaily.com)

Seabasing is a viable and attractive concept but for it to fully manifest, some points of action are: *"exploit the advantages of sea-based forces whenever possible; develop technologies to enhance on-station time and minimize maintenance requirements; experiment with innovative employment concepts and platforms; and, challenge every assumption that results in shore basing of Navy Capabilities"* [1].

It is not only imperative to assess the overall Seabasing Concept, but the assessment of new technology and systems becomes just as crucial. The possibilities offered by new technologies and systems require impact assessment for Seabasing to become a reality.

An example is the Office of Naval Research's development of a new Sea Base Connector Transformable-Craft (T-CRAFT). Currently under Phase II of development, T-CRAFT is a prototype demonstrator intended to be deployable from an advanced base to the Sea Base and used as a surface connector. The operational aspects of T-CRAFT surpass any current legacy platforms, and can be viewed in [4]. To validate its operational ability in meeting Seabasing goals, an assessment addressing how these operational capabilities perform must be conducted.

2 Literature Review

2.1 Assessing the Seabasing Concept

Seabasing has been identified as a critical joint forces capability allowing the United States to project forces more rapidly. The development of such a system requires a coordinated effort to ensure that it meet the needs of the joint forces [2]. Studies conducted to date, have been constrained to qualitative assessments. These evaluations shed light on Seabasing operations, but they don't specifically identify system performance in meeting Seabasing MOPs.

In 2007, the Congressional Budget Office conducted a study on deploying and sustaining troops in Seabasing operations. This study provided a guide to system capabilities and costs, sustainment requirements from a resulting force and detail of alternatives. Although there were well formed theories presented of how these alternatives would allow joint forces meet Seabasing goals, there is no evidence proving that these theories would meet the Seabasing MOPs [5].

2.2 The Need for Modeling & Simulation

The use of Modeling and Simulation has become increasingly important in understanding how complex systems behave. Modeling and Simulation gives decision makers the ability to identify manipulate systems and retrieve system behavior. The Department of Defense (DoD) has strongly advocated the use of Modeling and Simulation throughout the acquisition lifecycle [6].

In 1997, DoD formally adopted a vision for integrating modeling and simulation into the acquisition lifecycle [7]. Simulated Based Acquisition (SBA) reduces time, resources and risks associated with the acquisition process by integrating product and process development across the acquisition lifecycle [8]. This vision became a mandate in 2002 when DoD issued the directive 5000.01 requiring the integration of test and evaluation in the process of acquisition. The integration of test and evaluation allows the assessment of technical performance parameters and to determine the operational impacts of acquired systems. Under this directive, mandates of modeling and simulation are formalized in order to "*facilitate learning, assess technology maturity and interoperability, facilitate integration into fielded forces, and confirm performance against documented capability needs and adversary capabilities*" [9].

Recent studies have shown the feasibility and prowess of using Modeling and Simulation in the acquisition and development of complex systems. In 1996, the Director of Test, Systems Engineering and Evaluation in the Office of the Under Secretary of Defense for Acquisition, Logistics and Technology at the Department of Defense commissioned a study to access the use of Modeling and Simulation in the weapon systems acquisition process. This study found that cost, schedule, productivity, and quality/performance could be thoroughly analyzed through Modeling and Simulation and therefore aid decision makers in the systems acquisition process [10]. More recently, in 2004, the Naval Post Graduate School used Modeling and Simulation to define capability gaps in force projection while implementing Ship-To-Objective Maneuver via the Seabasing Concept. Through this study, various architectures (sensor, weapon, and force) were studied to meet force projection goals in Seabasing. The resulting findings include the best performing architecture and insight on how this architecture improves force projection. With over 60 students and 15 faculty members working on this project, the man-power to produce such a study is taxing [11].

Modeling and Simulation has been regarded for its effectiveness in allowing DoD decision makers ascertain the behavior of a system, but its ability to perform trade-offs of desired metrics is tedious, time consuming and restrictive. This research intends to build upon using Modeling and Simulation as a decision making tool by developing a quantitative and probabilistic capability based trade-off environment. The resulting framework created will give decision makers the ability to rapidly assess the impact different technologies and systems have on the Seabasing concept. Once established, this framework will allow validation of notional operational capabilities in new technologies and systems and their ability to meet Seabasing MOPs.

3 Proposed Approach

The proposed approach combines methods from Leite and Mensh [12] and Kirby [13]. Leite and Mensh develop a methodology for the generation of evaluation criteria for system acquisition modeling and simulation based on the underlying system requirements, and stipulate that *"all metrics must be traceable to requirements and all requirements must be associated with metrics."* Kirby outlines a methodology for technology identification, evaluation, and selection in conceptual and preliminary aircraft design. Kirby employs surrogate modeling techniques to rapidly evaluate aircraft performance under various technology combinations and to select the optimal technology combination that satisfies performance and economics requirements.

3.1 STEP 1 Problem Definition

The first step consists of three substeps: identification of the system of interest, identification of the capabilities to be modeled, and identification of the system metrics to be studied.

Identify System of Interest

The first substep in the development is to identify the system to be explored and to scope the problem to the desired level of detail. This may require decomposition and/or abstraction of the system to be studied.

Identify Capabilities of Interest

The second substep is to identify the system capabilities that will be modeled. This step bounds the model. In many cases, it is not possible to model all of the system's capabilities due to resource constraints. Furthermore, some systems may be too complex or undefined to be modeled in their entirety It is assumed that the system provides the capabilities that are not modeled for all cases to be studied. This is particularly true for new developments such as the Seabasing concept.

Identify System Metrics

The third substep is to develop the metrics for the capabilities being modeled. These metrics are defined for the operational system and are in the form of measures of performance, measures of effectiveness, and measures of force effectiveness.

3.2 STEP 2 Modeling and Simulation

Identify Systems Functionality

The first step in the model development is to identify the system functions that must be modeled to test the identified capabilities. Functions that are not related to the capabilities being modeled are assumed to perform correctly for all cases being studied and may be represented by nominal inputs.

Develop System Model

The next step is to develop a deterministic model that will quantify the impact of capability tradeoffs on the system. The level of the capabilities and metrics determine the scope of the modeling and simulation that is required. Before the model can be used as a representation of a system, it must be verified and validated. Verification involves tracing the model inputs through the system functions and ensuring that the model correctly implements the required system functions. The model must be validated against a set of inputs with known outputs. Model behavior must match that which is expected beforehand; when performance anomalies are encountered, developers must determine whether an anomaly is due to an incorrect representation in the model or whether the system itself is flawed.

3.3 STEP 3 Development of Tradeoff Environment

Development of the tradeoff environment entails sampling the model using Design of Experiments (DoE) in order to develop a surrogate model. The surrogate model is developed via regression of the DoE results. This enables the development of a rapid tradeoff environment that can be explored in real-time. If the model runs sufficiently quickly or the design space is small, the model may be executed directly. The surrogate model must be validated against the original model data and in general should not extrapolate to areas outside of the design parameter ranges.

3.4 STEP 4 Design Space Exploration

The final step is to use the tradeoff environment to explore the impact of capability tradeoffs on the system performance. A probabilistic assessment of achieving required system metrics is enabled by sampling the surrogate model using, Monte Carlo or Latin Hypercube sampling. Due to uncertainty in the design process, this step is probabilistic rather than deterministic in nature. Expressing the system metrics as probabilistic distributions has the additional advantage of allowing designers to determine if a change is statistically significant [14]. Sensitivities are studied to determine the robustness of selected designs. Design space exploration is iterative, as the initial design space may not capture a sufficient number of feasible solutions; in this case, the original model must be re-evaluated to determine the cause of failure.

4 Proof of Concept

The proposed approach is applied to study the Sea Base-to-Objective system of the Seabasing concept. The goal is to develop a quantitative capability-based tradeoff environment that can be used to explore the design space in real-time and offer insight into the probability of meeting required metrics.

4.1 STEP 1 Problem Definition

Identify System of Interest

The Seabasing architecture, depicted in Figure 4, is reduced to the Sea Base-to-Objective system depicted on the right-hand side of the same figure. Two vertical connectors (CH-53 and V-22), one conceptual surface connector (T-CRAFT), and one ground vehicle (MTVR) have been selected to be incorporated into this proof of concept involving sustainment operations from the Sea Base. The T-CRAFT is a fully amphibious vessel that enables rapid, high capacity Sea Base-to-Shore transfer of materiel and personnel, and is also self-deployable from an advance base [4]. The chosen vehicles operate on each of the three legs shown in the Sea Base-to-Objective system in Figure 4 and will illustrate capability tradeoffs involving a mix of legacy and conceptual vehicles. Each vehicle in the scenario provides troop and supply sustainment along its respective mission segment.

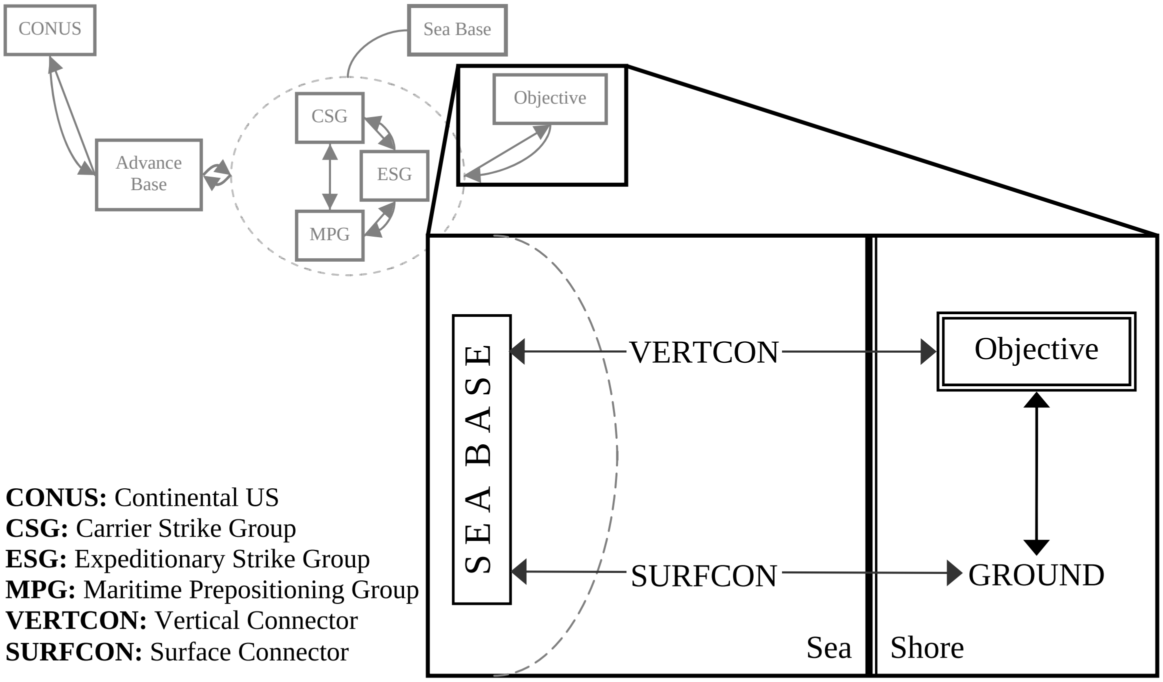

Figure 4: Sea Base-to-Objective system architecture based on [15]

Identify Capabilities of Interest

The capabilities identified in Table 1 are categorized into four sets of design parameters. The Combat Logistics Force (CLF), which delivers troops and supplies between an advance base and the Sea Base, is outside the scope of the identified system and is thus represented by nominal troop and supply arrival rates. Troops and supplies were discretized into JMICs[1] (1,000 lb. units) for the purpose of modeling based on weight capacity. This portion of the Seabasing concept is assumed to always perform correctly. The physical architecture of the Sea Base-to-Objective system is explored by varying the number of connectors on each mission segment. A T-CRAFT-like capability is incorporated into the study and is represented by dimensional parameters (DPs), i.e., physical properties of the T-CRAFT whose values determine system behavior and structure even when at rest [14]. Finally, mission-specific aspects of the Sea Base-to-Objective system are explored by varying the sea state, mission segment distances, and mission duration. The ranges for each of the parameters in Table 1 were derived from recent Seabasing literature, e.g., [2], [3], [4], [15], [16], [17], [18], [19], [20].

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[1] Joint Modular Intermodal Container

Table 1: Design parameters and ranges

Category	Dimensional Parameter	Design Space Range	Units
CLF Sustainment to Sea Base	Food Supply	200 – 400	JMICs/arrival
	Water Supply	4000 – 8000	JMICs/arrival
	POL Supply	15000 – 20000	JMICs/arrival
	Ammunition Supply	600 – 3000	JMICs/arrival
	Other Supply	1500 – 2000	JMICs/arrival
	Troops Arriving	35 – 100	battalions[2]/arrival
	Arrival Interval	24 – 48	hours
Sea Base Physical Architecture	No. V-22	24 – 48	~
	No. CH-53	10 – 20	~
	No. T-CRAFT	4 – 10	~
	No. MTVR	120 – 240	~
Conceptual Vehicle Dimensional Parameters	T-CRAFT Speed	30 – 60	knots (kts)
	T-CRAFT Capacity	600 – 1400	JMICs
Mission Parameters	Sea State	0 – 4	NATO STANAG 4194 Sea State
	Distance To Shore	100 – 250	nautical miles (nm)
	Distance To Objective	25 – 75	nm
	Mission Duration	15 – 30	days

Identify System Metrics

The metrics were derived from literature to be relevant to the system being modeled [21] and are in the form of MOPs, i.e., measures of system behavior that are a consequence of specific configurations of physical elements [14]. They were separated into two categories: performance metrics and economics metrics. The metrics are summarized in Table 2 and discussed below.

For successful sustainment operations from the Sea Base, certain sustainment rates of supplies and troops must be met. A natural measure of performance for sustainment is the mission-averaged sustainment rate, defined in Equation (1).

$$\text{Sustainment Rate} = \frac{\text{Total Supplies or Troops Delivered}}{\text{Mission Duration}} \tag{1}$$

Connector and ground vehicle utilization is important in meeting readiness requirements; a system with a higher sortie generation rate exhibits a higher utilization and hence is more capable of meeting readiness requirements [22]. This MOP was considered in terms of the sorties per vehicle per day as shown in (2).

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[2] 1,000 troops

$$\text{SVD} = \frac{\text{Sorties}}{\text{No. Vehicles} \times \text{Mission Duration}} \tag{2}$$

Cost was considered in terms of fleet acquisition cost and operational cost. Fleet acquisition cost is based on the number of each type of vehicle and the reported acquisition cost per connector for existing connectors or the estimated prototype demonstrator cost for conceptual vehicles, i.e. T-CRAFT [4], [23], [24], [25]. The operational cost is defined as mission fuel consumption in metric tons (MT) normalized by the number JMICs delivered during the mission in order to derive the fuel-equivalent cost of delivering one JMIC. These metrics are defined in (3) and (4), respectively.

$$\text{Acquisition Cost: Acq \$} = \text{No. Connectors} \times \text{Unit Cost} \tag{3}$$

$$\text{Operating Cost: Oper \$} = \frac{\text{Mission Fuel Consumption}}{\text{JMICs Delivered}} \tag{4}$$

Table 2: System Metrics

Category	Metric	Nomenclature	Units
Performance			
Sea Base Sustainment to Shore	Food Sustainment	Food Sust.	JMICs/day
	Water Sustainment	Water Sust.	JMICs/day
	POL Sustainment	POL Sust.	JMICs/day
	Ammunition Sustainment	Ammo Sust.	JMICs/day
	Other Sustainment	Other Sust.	JMICs/day
	Troops Sustainment	Troop Sust.	battalions/arrival
Sortie Generation Rates	V-22 Sorties per vehicle per day	V-22 SVD	Sorties/No. V-22/day
	CH-53 Sorties per vehicle per day	CH-53 SVD	Sorties/No. CH-53/day
	T-CRAFT Sorties per vehicle per day	T-CRAFT SVD	Sorties/No. T-CRAFT/day
	MTVR Sorties per vehicle per day	MTVR SVD	Sorties/No. MTVR/day
Economics			
Operational Cost	V-22 operational cost	V-22 Oper $	MT fuel/JMIC
	CH-53 operational cost	CH-53 Oper $	MT fuel/JMIC
	T-CRAFT operational cost	T-CRAFT Oper $	MT fuel/JMIC
	MTVR operational cost	MTVR Oper $	MT fuel/JMIC
Acquisition Cost	Fleet acquisition cost	Fleet Acq $	FY08 $M

4.2 STEP 2 Modeling and Simulation

Identify Systems Functionality

Standard Department of Defense Architecture Framework (DoDAF) products were used to guide the modeling process by creating representative functional networks of the Sea Base-to-Objective system [26]. The DoD defines an architecture as *"the structure of components, their relationship, and the principles and guidelines governing their design and evolution over time."* It is evident that, given enough resources, all possible architectures could be examined over all functions, operational activities, and capabilities; for limited resources, the architectures determine the modeling fidelity that can be implemented based on the available resources and desired modeling detail [27]. The following DoDAF products based on the Universal Naval Task List [29] were modified from previous work [28]:

- **AV-1:** Overview and Summary Information
- **OV-1:** High Level Operational Concept Graphic
- **OV-5:** Operational Activity Model
- **SV-4a:** Systems Functionality Description
- **SV-5a:** Operational Activity to Systems Functionality Traceability Matrix

Figure 5 shows a graphical depiction of the *Operational Activity to Systems Functionality Traceability Matrix* (SV-5a), which maps the *Operational Activity Model* (OV-5) to the *Systems Functionality Description* (SV-4a). This mapping identifies the transformation of an operational need into a purposeful action performed by the system. SV-5a outlines the functions that need to be modeled in order to evaluate the capabilities that were identified in Table 1. The additional DoDAF products are located in "Annex A – DoDAF Products." Fueling/re-fueling is not present in the architectures due to the modeling decision to implement that part of the model as a stand-alone code.

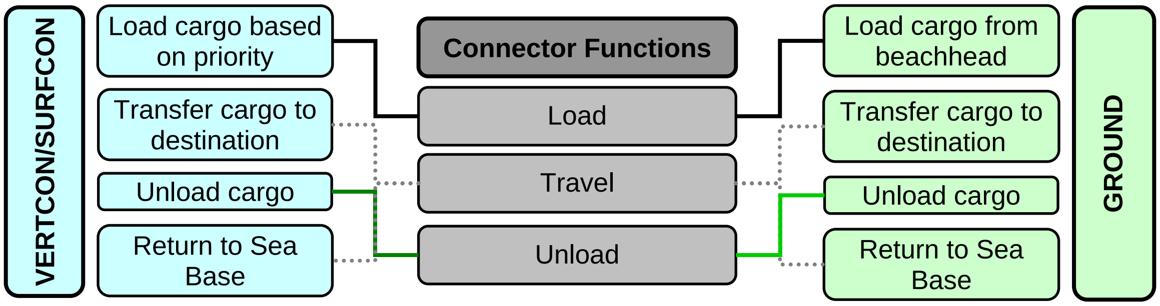

Figure 5: Operational Activity to Systems Functionality Traceability Matrix (SV-5a)

Model Development

A discrete event (DE) model was chosen to represent the system due its ability to model nonlinear, dynamic behavior and to represent hierarchies. The model was implemented and simulated in Extend® 6 [30], a modeling and simulation environment that provides the capability to directly implement architectures as models.

Verification

The Extend model was verified against the DoDAF products to ensure that the intended functionality was implemented. Boundary cases were used to test the model and inputs were traced through execution to ensure that there were no bugs in the logic or the underlying code.

Validation

In practice, the validation process is difficult for simulations of future concepts where there is no empirical evidence to validate against. This is a typical situation and the best practice for validation of this type of simulation is to independently assess each of the physics-based components to ensure that the physics are being modeled correctly. For logic-based components, the blocks must be tested under various conditions to ensure that they follow the correct execution paths. It is then usually inferred that the aggregated behavior is as correct as possible [27].

The only physics-based components of the model were the resistance and fuel fraction codes, which were used to predict fuel consumption and hence operational cost. The T-CRAFT was modeled as a surface effect ship; resistance was calculated using standard air-cushion vehicle powering calculations [31]. The resistance code was compared to experimental data obtained from scale model tests of the SES 100B [32]; the comparison is shown in Figure 6. The discrepancy in the resistance at higher Froude numbers is due to the assumption that the draft of the surface effect ship is constant with speed; in reality, the draft decreases with speed thus resulting in a decrease in resistance, as seen in the experimental data. The Breguet range equation was used to predict the empty weight fuel fraction for propeller-driven aircraft and rotorcraft [33]. The model was compared to existing vehicles and the results are presented in Figure 7. All logic-based components were found to perform correctly; validation results for the model logic are not presented here.

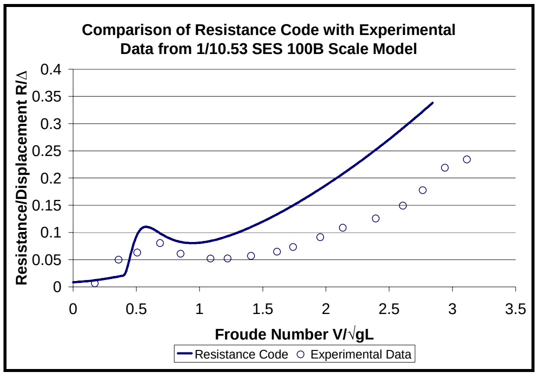

Figure 6: Comparison of resistance code with experimental data from [32]

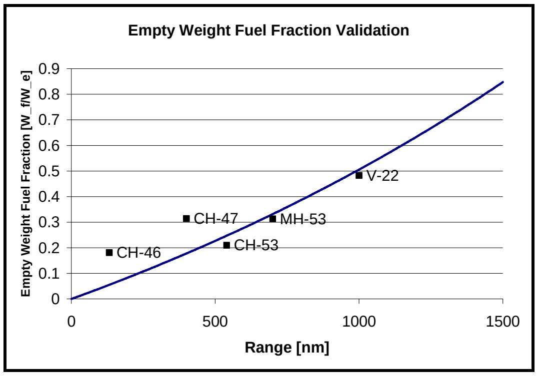

Figure 7: Aircraft and rotorcraft empty weight fuel fraction prediction

4.3 STEP 3 Development of Tradeoff Environment

Surrogate Model Development

To address the long run-times associated with DE simulations, surrogate models were constructed to enable rapid trade studies. The DE model was executed for up to 30 days of simulation time, which took on the order of one minute on a current desktop computer. The development of the surrogate models began with the creation of a DoE table. Due to the combination of continuous and discrete inputs, a custom DoE was created consisting of the following designs: (1) 256 full factorial type cases at 3 levels to capture the main effects of the model; (2) 32 Latin Hypercube cases to sample the interior design space of the model; (3) 32 random cases to evaluate the model representation error. The DoE table was constructed using SAS JMP® 7.1 [34], an interactive statistical analysis environment. Artificial Neural Networks (ANNs) were selected as the surrogate models in order to capture any potentially highly nonlinear and/or discrete behavior that would arise in the responses. Using Basic Regression Analysis of Integrated Neural Networks (BRAINN) 2.1 for MATLAB [35], ANNs were trained and their functional forms were passed into JMP.

BRAINN provides the means to validate the surrogate models against the original model data via five “goodness of fit” tests: R^2, actual by predicted plot, residual by predicted plot, model fit error, and model representation error. These tests are discussed in detail in [10] and [35]. In general, the surrogate models should predict the actual data points as closely as possible, residuals should be as small as possible and randomly distributed, and errors should approximate a standard normal distribution. Figure 8 shows the validation results for the ANN representing troop sustainment; additional results are presented in Annex B.

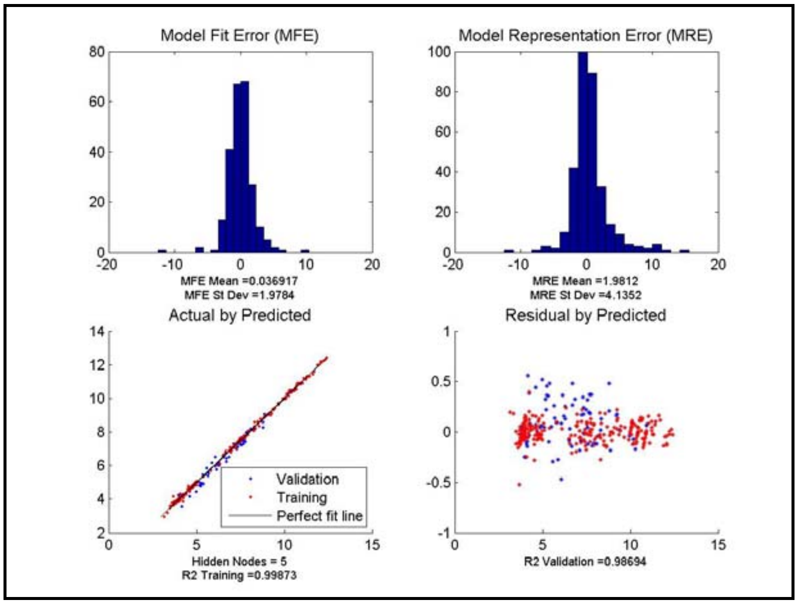

Figure 8: ANN validation tests for troop sustainment

With the goodness of fit tests accepted, the next step is to visualize the design space. JMP provides a suite of visualization tools that enable visual tradeoffs and probabilistic analyses to be performed. Figure 9 depicts the final modeling and simulation process employed for this study.

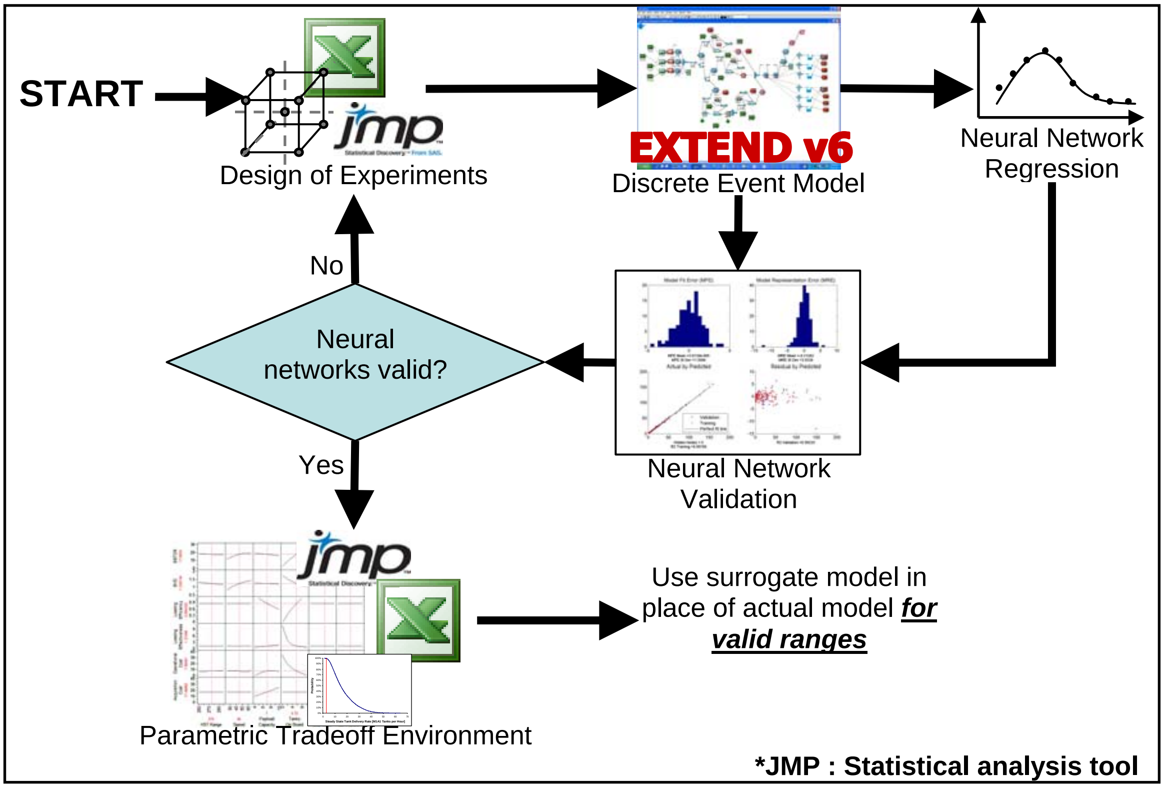

Figure 9: Modeling and simulation process

Visualization

The first tool used to visualize the tradeoff environment was the prediction profiler. JMP was used to produce an interactive prediction profiler as shown in Figure 10. Figure 10 only shows the portion of the profiler that relates to the T-CRAFT; the full prediction profiler is shown in Annex C. A prediction profiler is a matrix of bivariate plots that enables the designer to check the behavior of the model on a one-to-one basis with respect to the design parameters and MOPs, and to establish the sensitivities of each metric to those design parameters. Thus, the designer can validate the model from a physical standpoint and determine the main drivers for each measure of performance. For example, for the settings shown in Figure 10, the T-CRAFT operational cost increases with increasing distance to shore, which is correct from a physical standpoint based on (4). One can also note that troop sustainment is most sensitive to the troop arrival rate at the Sea Base. Figure 10 is a screenshot of the prediction profiler; in the actual program, the designer can move the crosshairs and instantaneously assess the impacts of new designs and capabilities. For this reason, the prediction profiler is useful in performing parametric design trades and optimization via desirability functions, e.g, [36], [37].

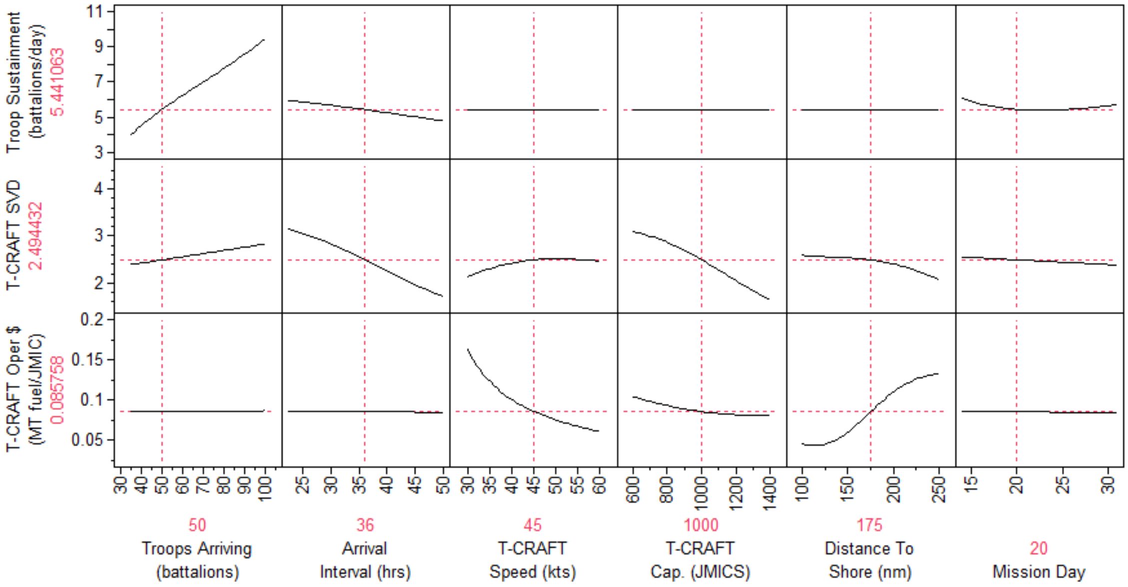

Figure 10: T-CRAFT performance prediction profiler

4.4 STEP 4 Design Space Exploration

The first step in the design space exploration is to develop requirements on the MOPs for the mission being studied. The required MOPs are derived from the top-level mission goals, in this case, the five top-level Seabasing MOPs. The Sea Base must be able to sustain up to two MEBs for an indefinite amount of time. For this application, MEB sustainment is treated as troops and POL per day. Notional MEB sustainment requirements of 1200 JMICs of POL per day and 10 battalions of troops per day will be used.

Capability tradeoffs are visualized using a scatterplot matrix, which shows correlations between selected MOPs via the red correlation ellipses. The scatterplot matrix for this application is shown in Figure 11. Only the MOPs relating to the T-CRAFT and the POL and troop sustainment are shown; the full scatterplot matrix can be found in *Annex C – Unabridged Tradeoff Environment*. The design points shown are the actual data points from the DoE; however, the surrogate models may be used to rapidly generate additional design points.

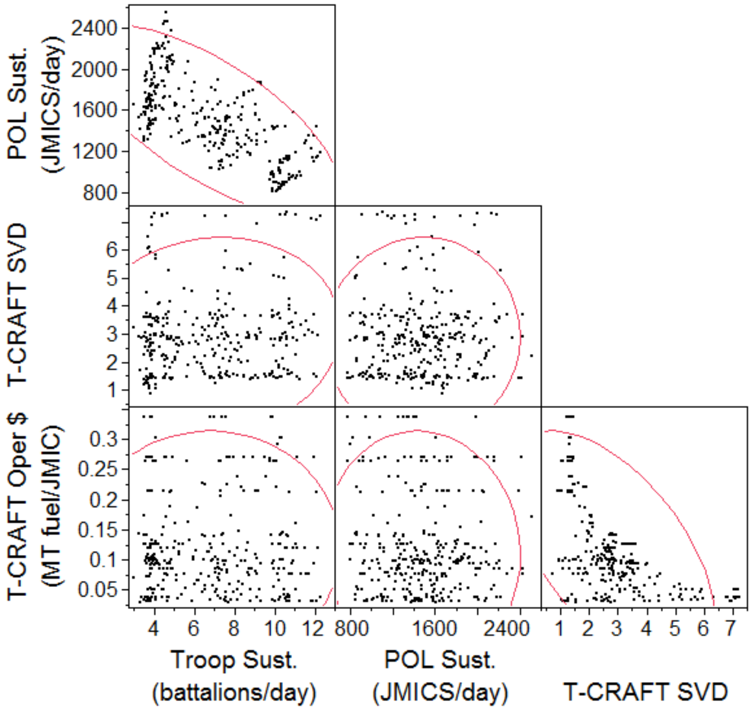

Figure 11: Scatterplot matrix

The next step is to impose the requirements on the design space. Once the requirements are imposed (Figure 12), the designs may be filtered to hide infeasible designs.

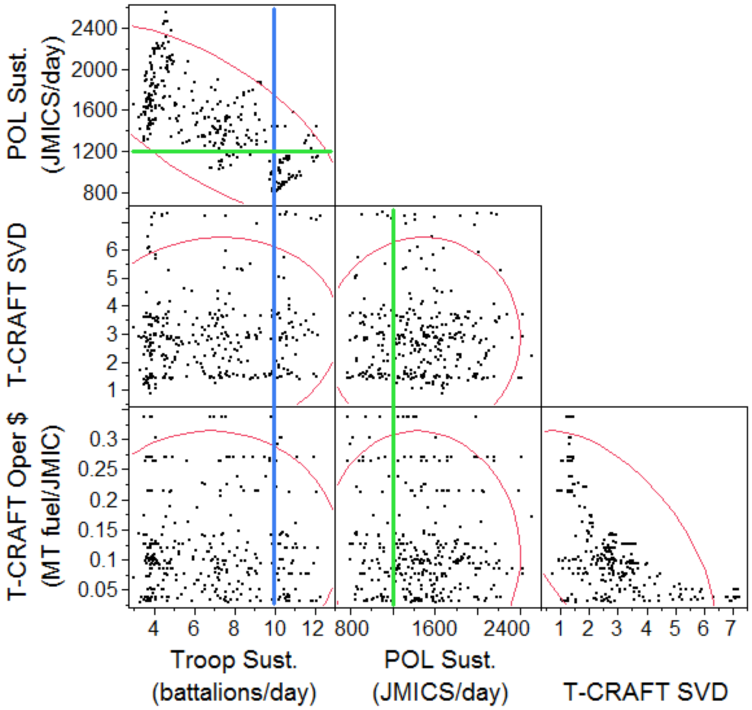

Figure 12: Scatterplot matrix with required MOPs superposed

This process of down selection results in Figure 13. Figure 13 shows that the majority of the designs do not meet the required MOPs. This is indicative that one or both of the requirements are constraining the design space.

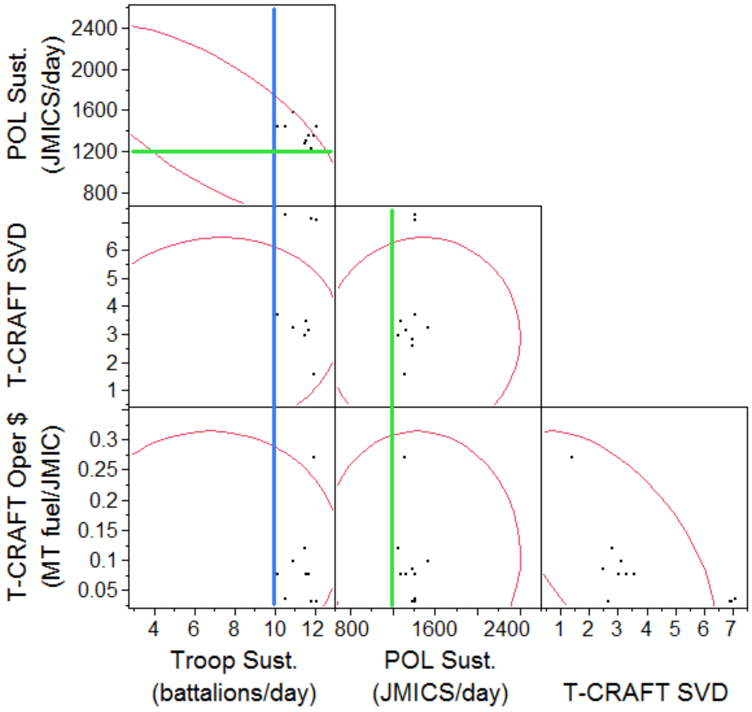

Figure 13: Down-selected scatterplot matrix

The utility of this approach becomes apparent when it is coupled with a Monte Carlo simulation (MCS) of the system. The purpose of MCS in this application is to quantify the probability of success, or confidence, of meeting the required MOPs with designs that are within the ranges of the design parameters. The design parameters are treated as uniform random variables to enable an unbiased exploration of the design space. In practice, MCS requires approximately 10,000 runs per input variable to produce dependable results. The MOPs are visualized using cumulative distribution functions (CDFs). A low confidence in meeting a required MOP implies that that requirement is constraining the system. This is indicative that one or more changes need to be implemented into the system in order to meet the required MOPs with a higher confidence. The system architectures and model must be revisited to determine the cause of failure. For the example presented here, it can be shown that the cause of failure in confidently meeting the troop sustainment requirement is due to the modeling assumption that only one connector of each type is loaded at a time. In reality, multiple connectors are loaded simultaneously; loading in queue is not a realistic representation of amphibious operations. Implementing this change in the system model and repeating Steps 3 and 4 may shift the distribution in Figure 15 to the right, resulting in a higher percentage of feasible designs. The designer has the added benefit of determining if such a change is statistically significant to the performance of the system through the use of this probabilistic approach.

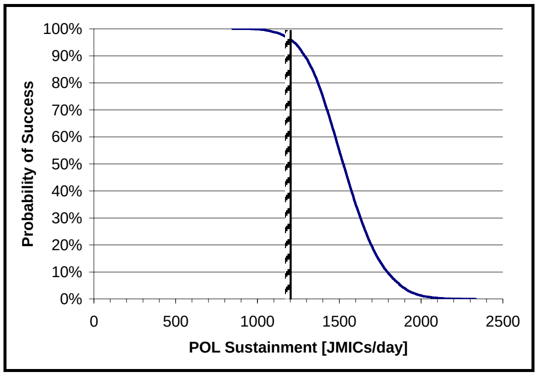

Figure 14: Probability of meeting required POL sustainment

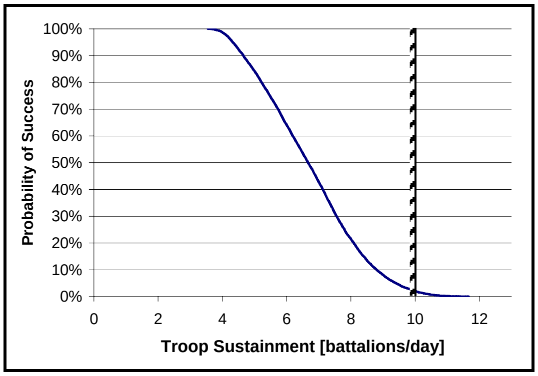

Figure 15: Probability of meeting required troop sustainment

5 Conclusions

A parametric and capability-based tradeoff environment is developed that enables rapid, probabilistic design space exploration via surrogate models. This quantitative framework can be used to assess the impacts of new technologies and systems on the system-of-systems. The proposed approach has been applied to the Sea Base-to-Objective system to determine the performance and economics impacts of a conceptual connector, i.e., T-CRAFT, as well as architectural changes on the system. The process enables designers to utilize a “design for capability” approach and to translate theater-level goals into specific asset and architectural requirements to accomplish those goals. The design space for the system is explored probabilistically to determine the feasibility in meeting required performance and economics metrics. This assessment indicates to designers which requirements are constraining the design and provides guidance to focus resources for the next design iteration. Compared with previous methods, the proposed approach enables decision makers to make informed decisions during the requirements definition and conceptual phases. It also offers the potential to reduce the time and cost needed to develop a design that meets or exceeds customer requirements.

6 Recommendations

The proposed approach can be applied to different levels of modeling to include subsystems, systems, and systems-of-systems. The surrogate models that are developed for each level may be employed in higher level models for rapid capability-based tradeoffs. Using decomposition of the SoS and aggregation of the surrogate models, a high-fidelity Seabasing model may be developed to perform inverse design in order to identify what technologies, platforms, and MOPs are needed to meet the high-level MOEs. For instance, designers can perform a top-down decomposition of the goal *“Provide National Security”* to obtain the physical systems that are required to accomplish this goal. The proposed approach provides the level of abstraction and transparency that is necessary to enable decision makers to translate a Navy vision into engineering requirements via a unified tradeoff environment as illustrated in Figure 16.

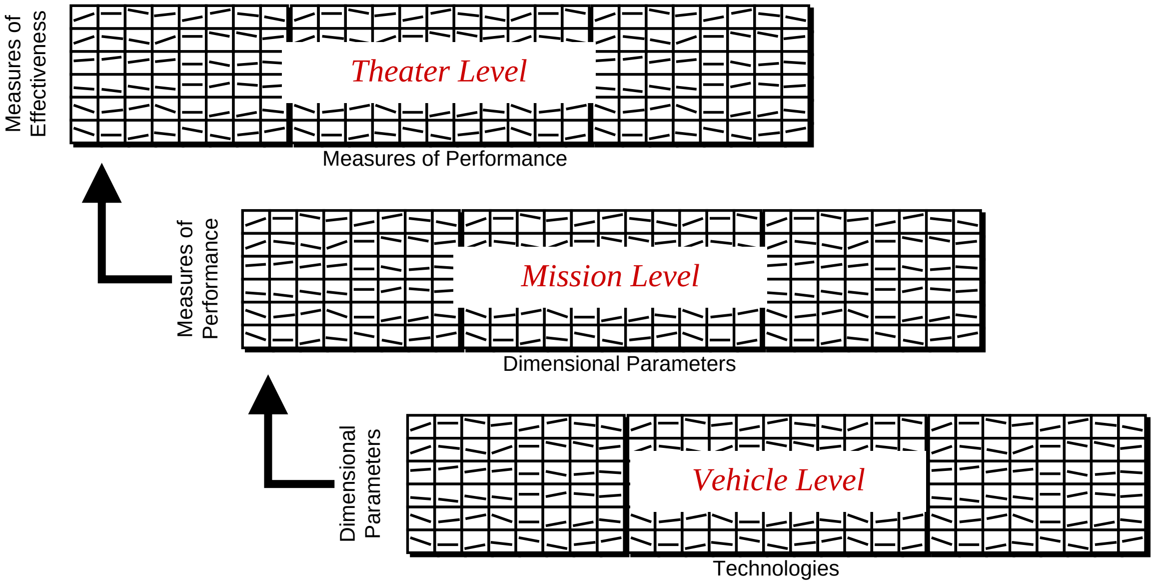

Figure 16: Unified tradeoff environment

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Annex A – DoDAF Products

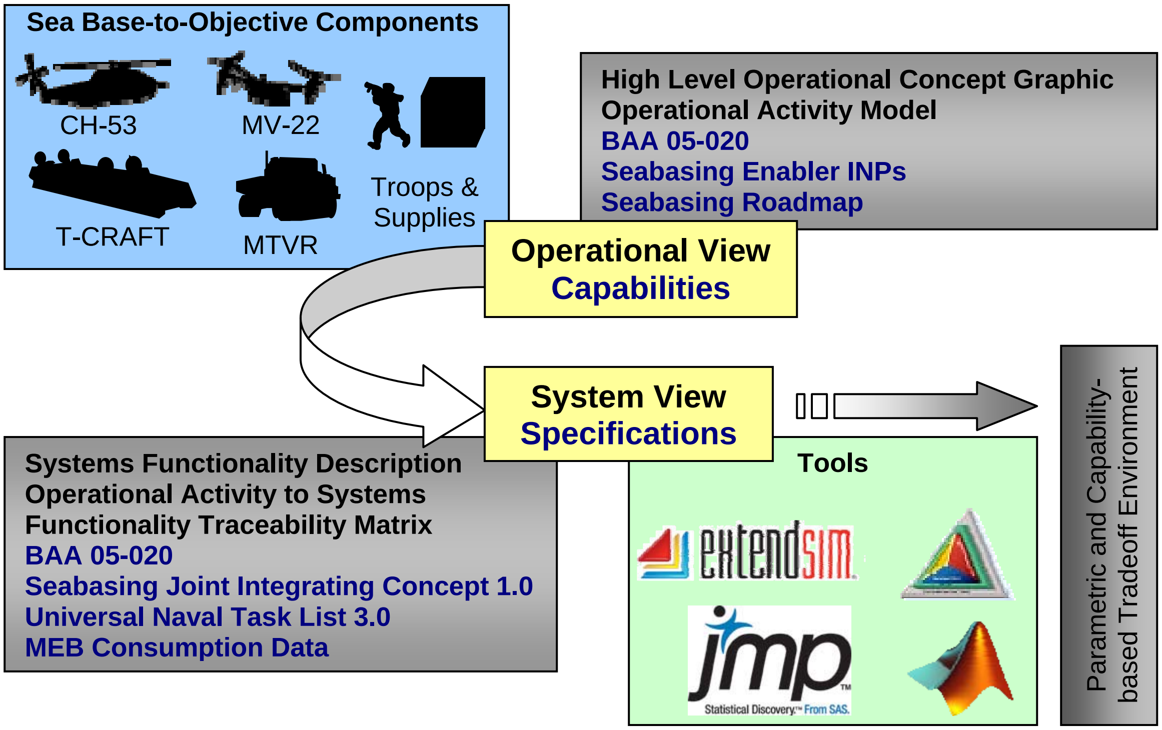


Figure 17: AV-1 Overview and Summary Information

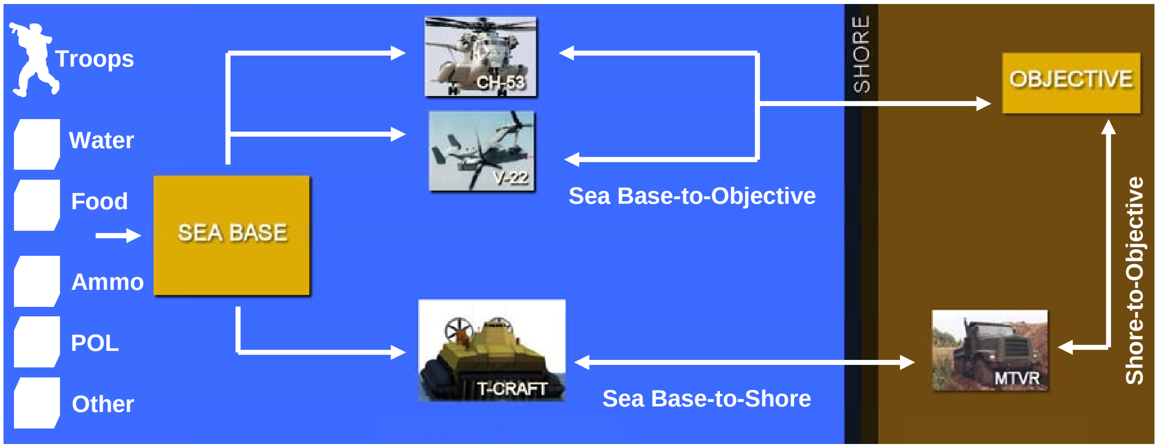
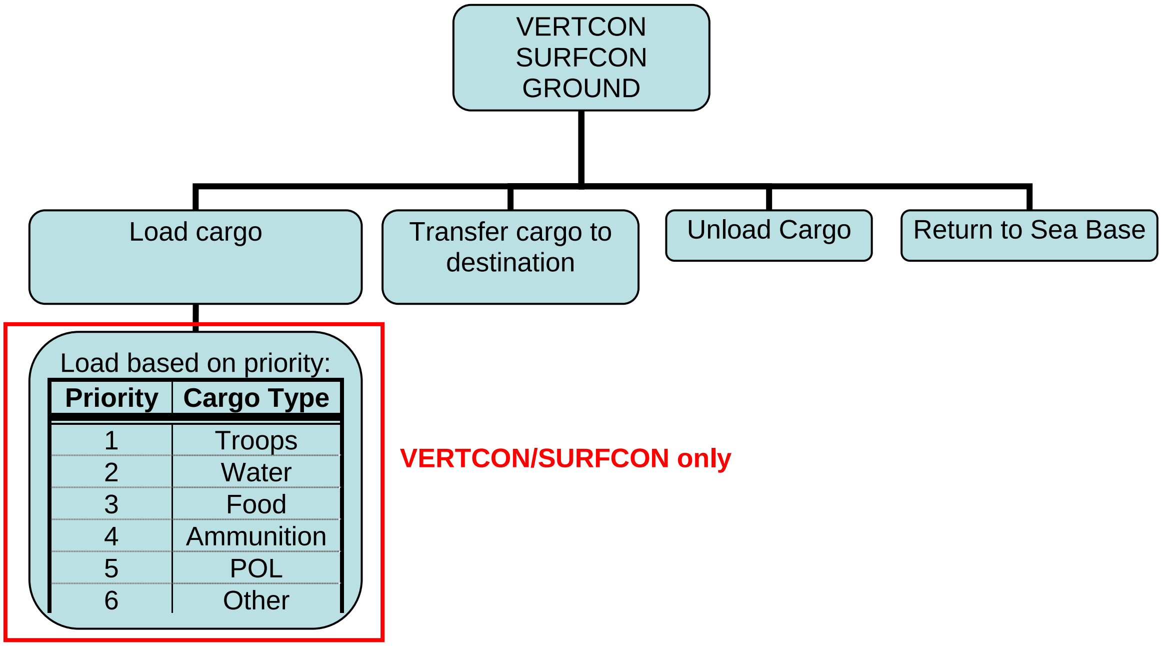


Figure 18: OV-1 High Level Operational Concept Graphic



Priority	Cargo Type
1	Troops
2	Water
3	Food
4	Ammunition
5	POL
6	Other

Figure 19: OV-5 Operational Activity Model

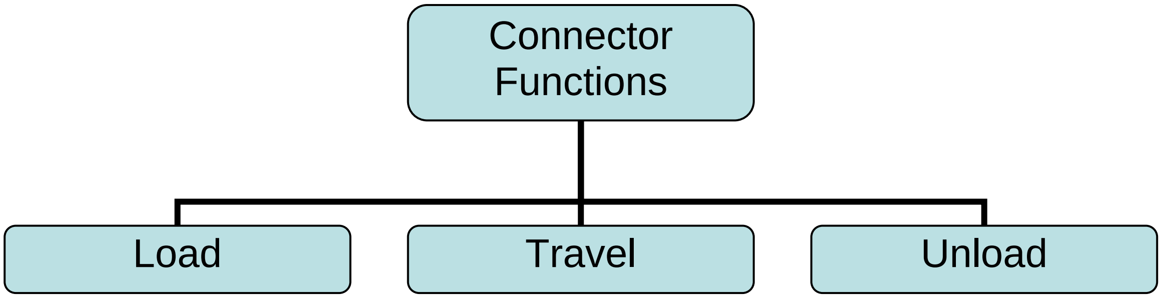


Figure 20: SV-4a Systems Functionality Description

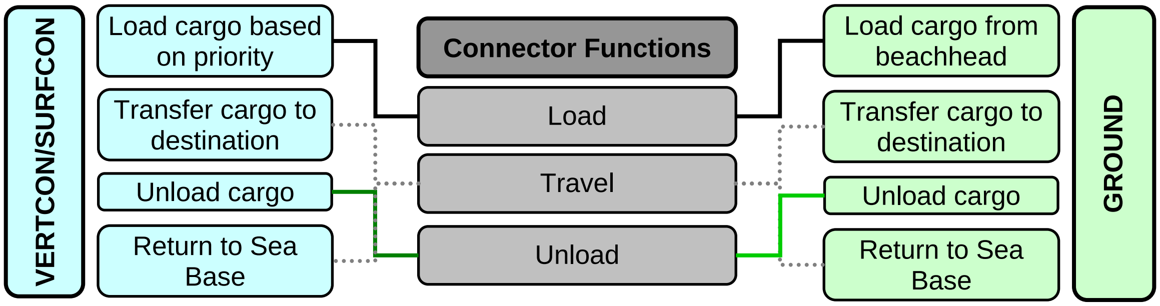


Figure 21: SV-5a Operational Activity to Systems Functionality Traceability Matrix

Annex B – Neural Network Validation Results

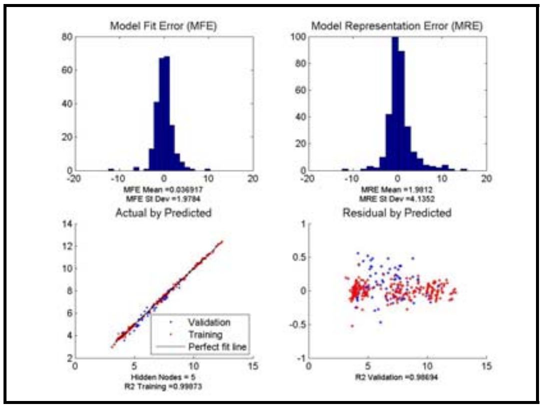


Figure 22: Troop sustainment

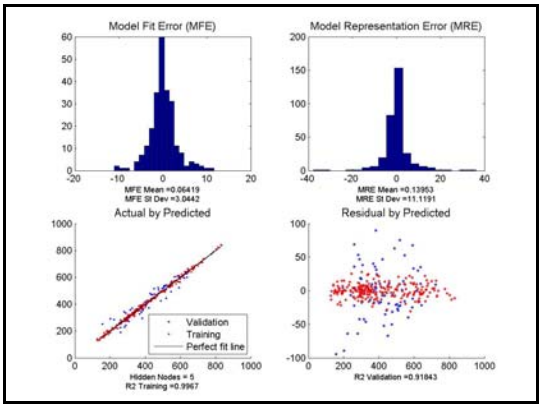


Figure 23: Water sustainment

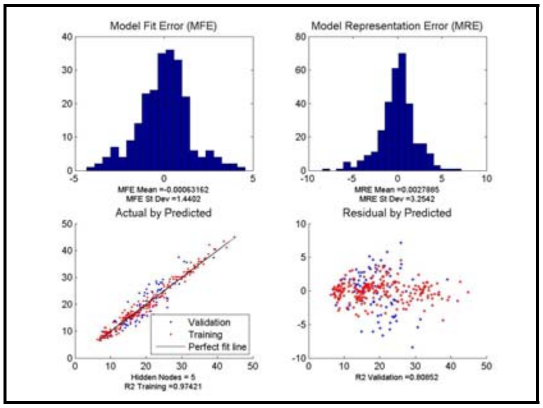


Figure 24: Food sustainment

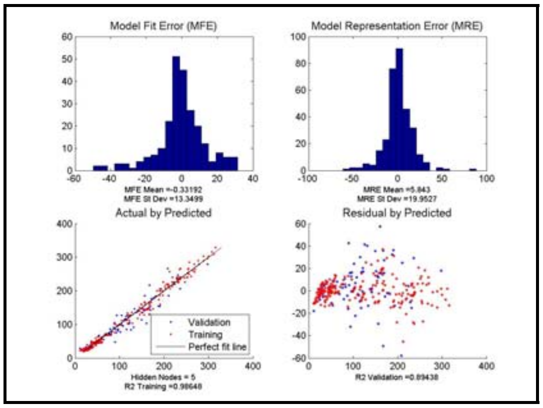


Figure 25: Ammunition sustainment

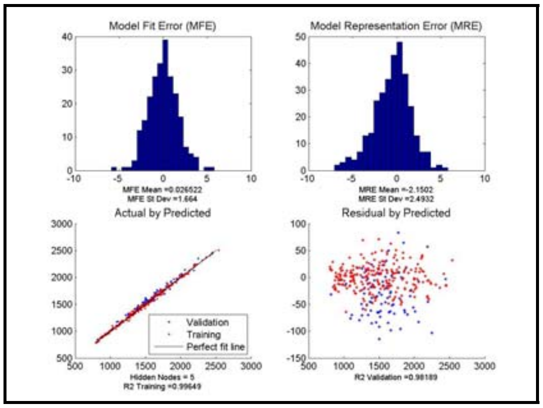


Figure 26: POL sustainment

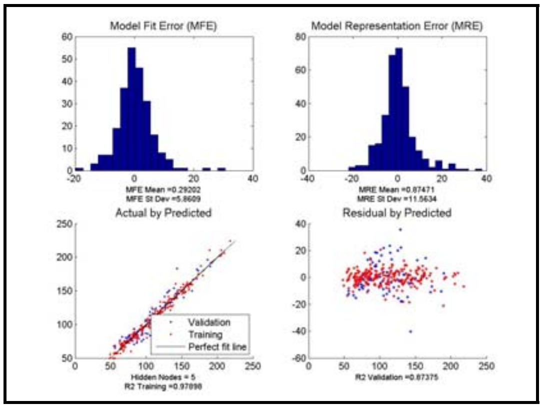


Figure 27: Other sustainment

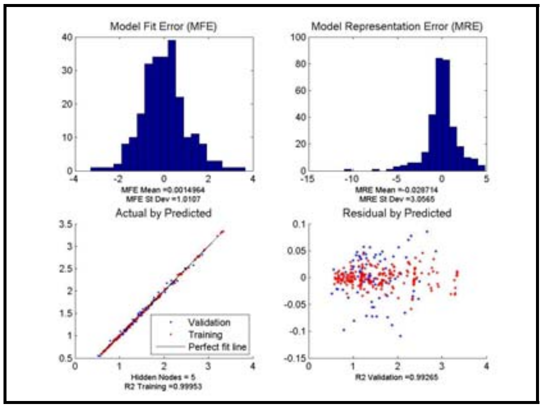


Figure 28: V-22 SVD

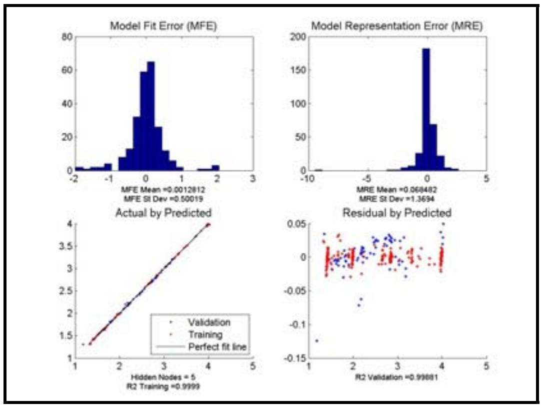


Figure 29: CH-53 SVD

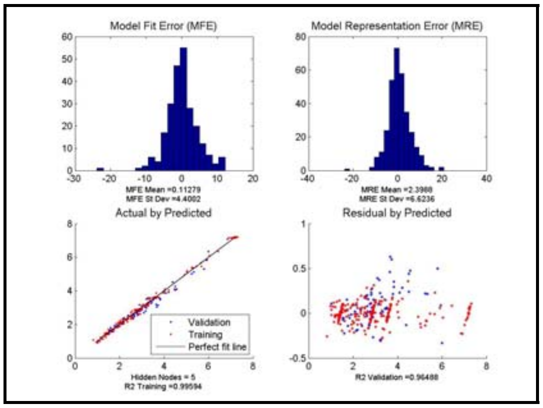


Figure 30: T-CRAFT SVD

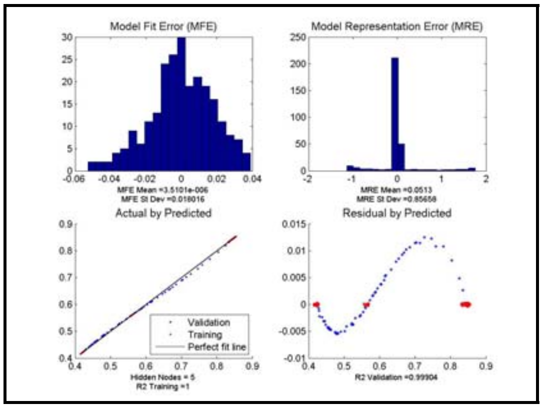


Figure 31: MTVR SVD

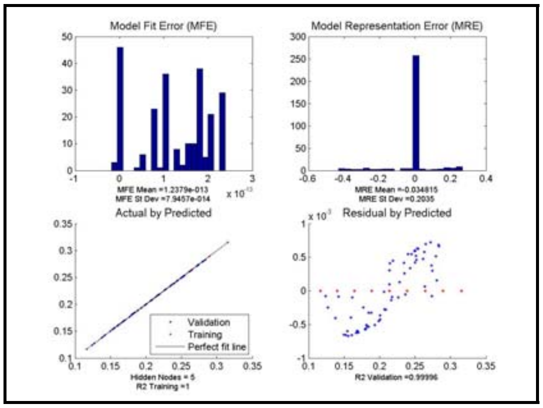


Figure 32: V-22 operational cost

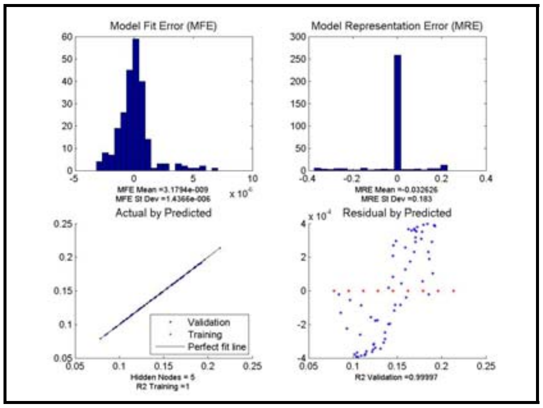


Figure 33: CH-53 operational cost

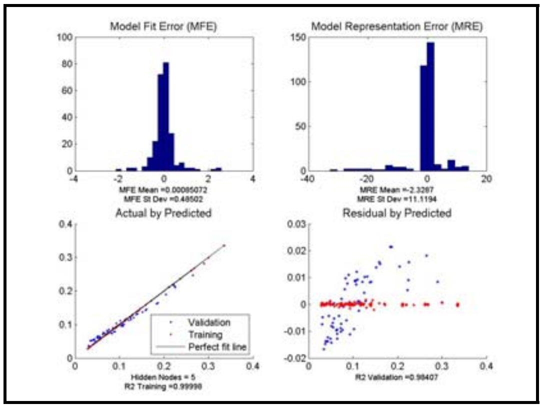


Figure 34: T-CRAFT operational cost

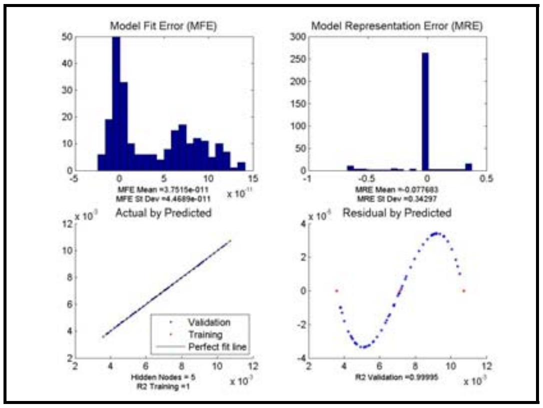


Figure 35: MTVR operational cost

Annex C – Unabridged Tradeoff Environment

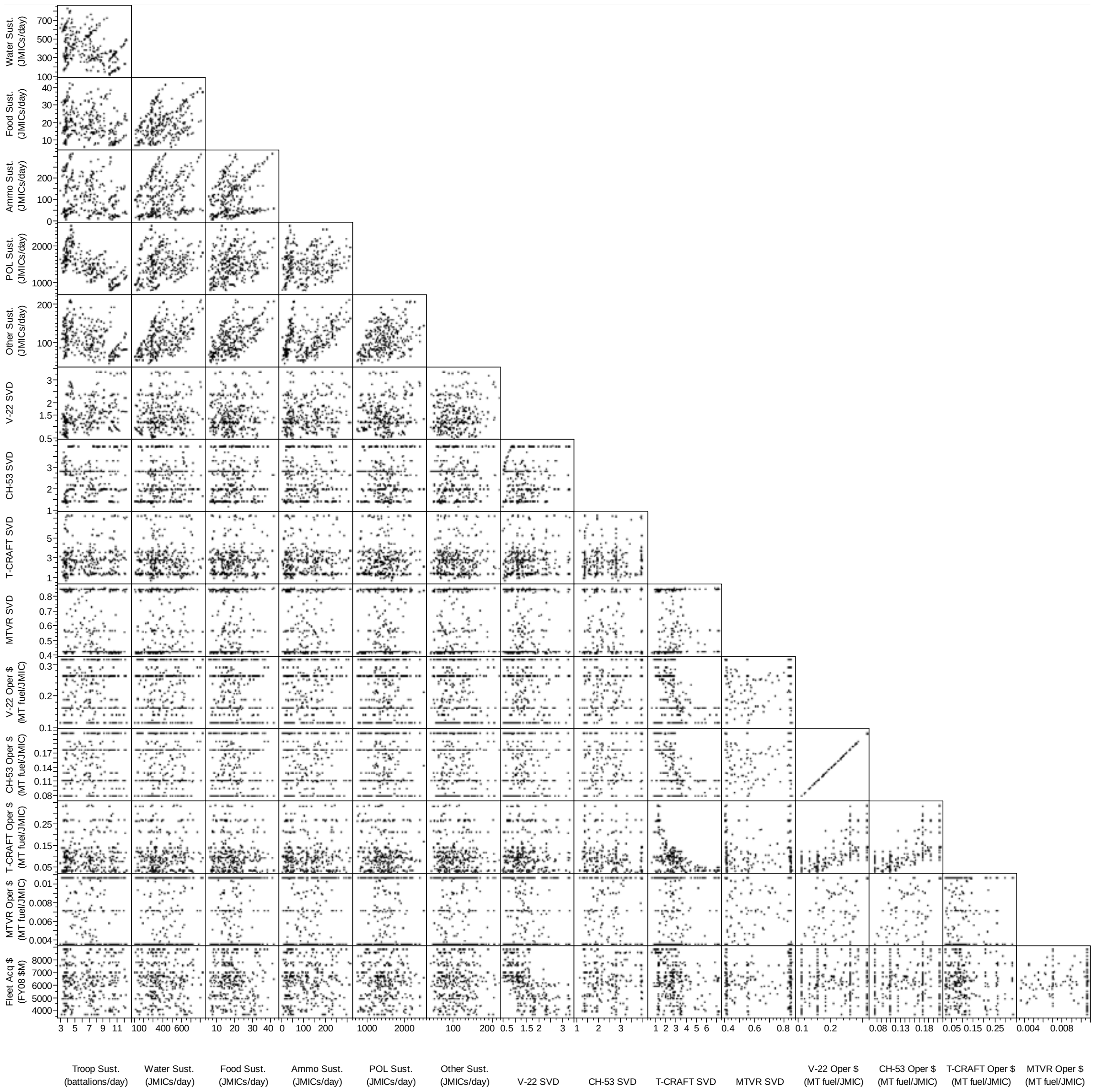


Figure 36: Scatterplot matrix

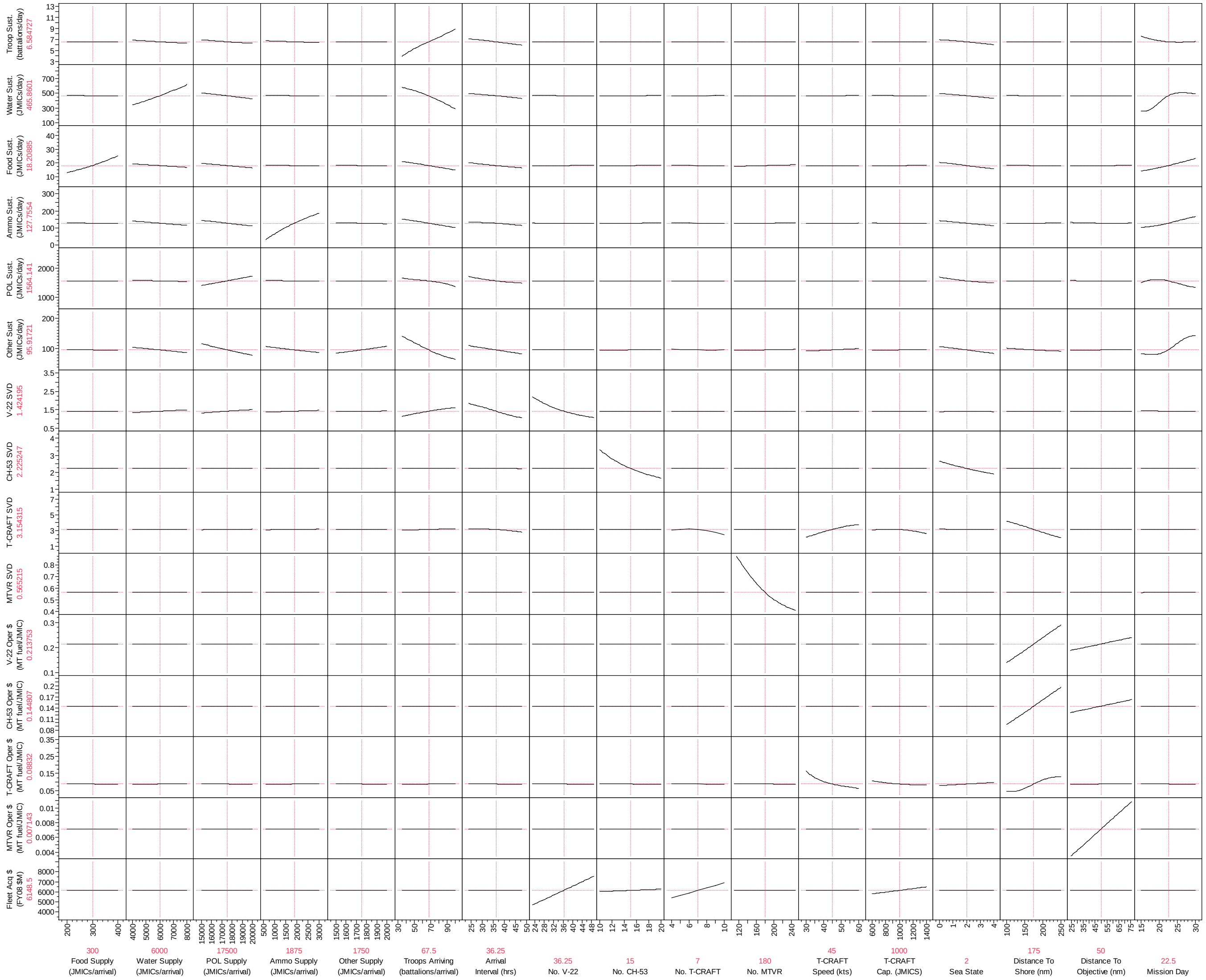


Figure 37: Prediction profile