A QUANTITATIVE FRAMEWORK TO ASSESS CAPABILITY TRADEOFFS OF THE TRANSFORMABLE-CRAFT WITHIN THE SEABASING CONCEPT

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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 what capabilities are required of these new technologies and to quantify the impact of capability tradeoffs on the Seabasing concept in order for Seabasing to be considered a viable alternative to current force projection methods. This paper presents a quantitative framework to assess capability tradeoffs of systems on the overall system-of-systems. The proposed approach is applied to the Transformable-Craft (T-CRAFT) within a Seabasing context. An architecture-driven object-oriented approach is employed to develop a physics-based model of a Seabasing scenario. Surrogate models are employed to enable rapid capability tradeoffs to enable optimization of the T-CRAFT.

Keywords: capability-based tradeoff environment, probabilistic design space exploration, agent-based model, T-CRAFT

1. MOTIVATION

Seabasing has been identified as a critical future joint military capability for the United States (Howard and Pilling 2003). Seabasing is a sovereign, maneuverable capability for sustainable global force projection, exploiting the sea as a maneuver space 365 days a year. The current Seabasing concept involves a fourteen-ship Maritime Prepositioning Group (MPG) supporting a Marine Expeditionary Brigade (MEB)-sized force. Figure 1 depicts the different assets in an MPG and Figure 2 depicts the composition of a notional MEB. The Sea Base will also employ a Carrier Strike Group (CSG) to support air operations and an Expeditionary Strike Group (ESG) to support amphibious assault.

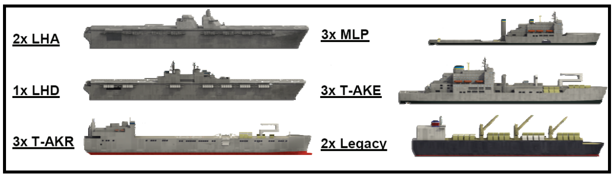

Figure 1: Fourteen-ship MPG (Conant 2005)

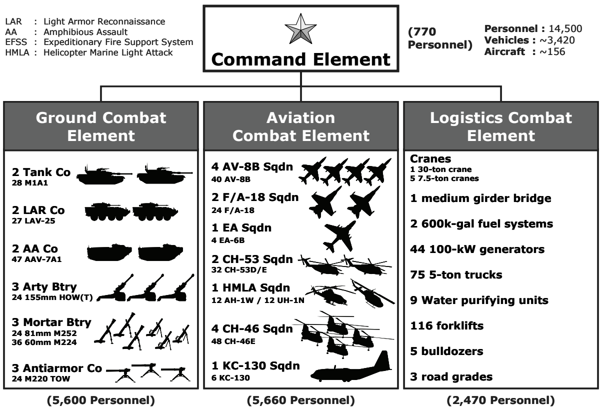

Figure 2: Notional MEB

The complexity of the Seabasing architecture, as depicted in Figure 3, requires a coordinated development effort to address identified issues and to create a joint Seabasing system-of-systems (SoS) (Howard and Pilling 2003). New technologies that provide updated capabilities are needed to make the Seabasing concept feasible. Five top-level threshold measures of performance have been identified in order to realize the Seabasing concept as a viable alternative to current systems (Seabasing Joint Integrated Concept 2005):

1. **Close** a MEB-sized force within 10 – 14 days
2. **Assemble** a MEB-sized force within 24 – 72 hours
3. **Employ** a minimum of one MEB via surface within 8 – 10 hours
4. **Sustain** selected joint forces and up to two MEBs operating up to 150 nautical miles (nm) inland with minimal logistics footprint ashore
5. **Reconstitute** forces for future operations within 30 days

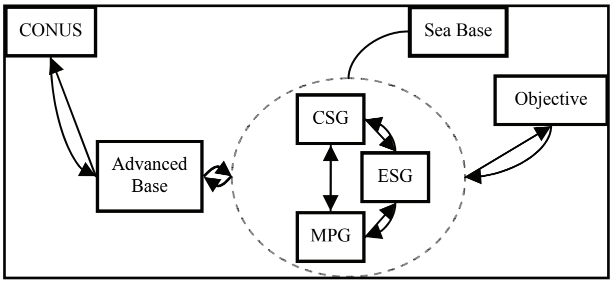

Figure 3. Seabasing architecture (based on Skinner 2004)

Independent studies have concluded that current assets do not meet the required capabilities to meet the threshold measures of performance, e.g., Bishop 2005, CBO 2007, Howard and Pilling 2003. One capability gap identified by the National Defense Industry Association for Seabasing is *Ships of Appropriate Design* (Bishop 2005). Emerging requirements by the Office of Naval Research (ONR) dictate that a 400%−1000% increase in payload capacity over the current Landing Craft, Air Cushion (LCAC) is required to make the Seabasing concept feasible. Thus, the ONR has solicited proposals for a new type of fully amphibious vessel known as the Transformable-Craft (T-CRAFT). The T-CRAFT is a variable hull form vessel that enables rapid, high capacity Sea Base-to-shore transfer of materiel and personnel, and is also self-deployable from an Advanced Base. Table 1 lists some of the new capabilities offered by the T-CRAFT as listed in ONR Broad Agency Announcement (BAA) 05-020 (2005). Figure 4 shows the primary mission profile for the T-CRAFT (BAA 2005).

Table 1: Desired operational capabilities of the T-CRAFT prototype

Mission Segment	Desired Capability	
Open Ocean (un-refueled, no-cargo condition)	Range	2500 nm
	Speed	20 knots (kts) through NATO STANAG 4194 Sea State (SS) 5
	Seakeeping	Operation through SS 6 and survivable in SS 8
Intra-Sea Base	Seakeeping	Ability to mitigate wave induced motions in SS 4/5
High Speed Transit (un-refueled, full cargo condition)	Range	500nm – 600nm
	Speed	~40 kts through top end of SS 4
	Payload Capacity	300 long tons (lt) (threshold)/700 lt (objective)
Fully Amphibious	Beach Slope Climbing	0.5% (threshold)/2% (objective)
	Inland Range Requirement	No range requirements, but must provide "feet dry on the beach" capability
Other	~	Ability to convert between modes at sea without any external assistance

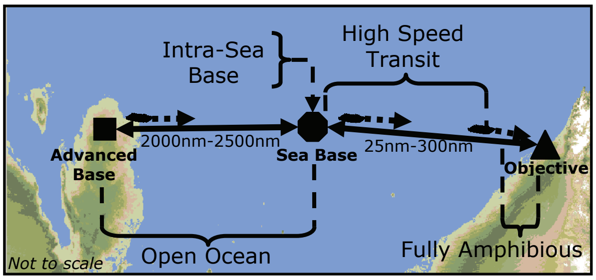

Figure 4: Primary mission profile for the T-CRAFT

Although Seabasing measures of performance have been defined, the Seabasing SoS is still being developed from the bottom-up, that is, in the same sense as forward design. Capabilities are defined deterministically, or at best intervals, for systems within the Seabasing SoS to obtain the resulting measures of performance. This process is inefficient, as it requires iteration at the systems level. The Seabasing concept has not been planned out in its entirety, thus the process of defining system capabilities requires a top-down approach, or inverse design. Inverse design allows for "design for capabilities" via surrogate modeling and probabilistics. Using this technique, it is possible to highlight a desired capability in relation to the SoS level metrics and identify potential designs at the systems level (Biltgen 2007). The Sea Base-to-shore system consists of a large number of entities governed by independent local rules, dimensional parameters, goals, and interactions. The combined effect of these properties produces emergent behaviors that are required to be understood in order to analyze and design the Seabasing SoS. However, these emergent behaviors are difficult to predict *a priori*, and require simulation.

One method to test how dimensional parameters affect the overall SoS is to simulate the T-CRAFT using an agent-based model. This work details the development of a probabilistic capability-based tradeoff environment for the T-CRAFT within the Seabasing concept; however, the methodology is equally applicable to similar systems of interest and can be used to identify critical capabilities and their effect on SoS performance.

2. PROPOSED APPROACH

The proposed approach combines methods from Leite and Mensh (1999), whose work develops a methodology for the generation of evaluation criteria for system acquisition modeling and simulation based on the underlying system requirements, and Kirby (2001), whose work outlines a methodology for technology identification, evaluation, and selection in conceptual and preliminary aircraft design.

2.1. Identify System

The first step in the development is to identify the system to be explored and to scope the problem to the desired level of detail. For this application, the focus is on the cargo delivery aspect of the T-CRAFT mission profile.

2.2. Identify Capabilities of Interest

The second step is to identify the system capabilities that will be modeled. This step bounds the model. It is assumed that the system provides the capabilities that are not modeled for all cases to be studied. 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. This is particularly true for new developments such as the T-CRAFT.

2.3. Identify System Metrics

The third step is to extract and/or 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 (MOPs), Measures of Effectiveness (MOEs), and Measures of Force Effectiveness (MOFEs).

2.4. Identify Systems Functionality

The fourth step 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.

2.5. Develop System Model

The fifth step is to develop a deterministic model that will quantify the impact of capability tradeoffs on the SoS. The level of the capabilities and metrics determine the scope of modeling and simulation that is required. Before the model can be used as a representation of a system, it must be shown to accurately represent the system at hand. This step is accomplished by model verification and validation. In general, verification involves tracing the model inputs through the system functions and ensuring that the model correctly implements the required system functions. If possible, 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.

2.6. Develop Tradeoff Environment

The sixth step is to sample the model using a 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 original model data and in general should not extrapolate solutions to areas outside the original design variable ranges.

2.7. Design Space Exploration

The seventh step is to use the tradeoff environment to explore the impact of capability tradeoffs on the SoS. A probabilistic assessment of achieving desired capabilities is enabled by sampling the surrogate model via, e.g., Monte Carlo sampling or Latin Hypercube sampling. Due to uncertainty in the design process, this step is probabilistic rather than deterministic in nature. 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 tradeoff environment must be re-evaluated to determine the cause of failure in meeting the desired capabilities.

3. PROOF OF CONCEPT

The proposed approach is applied to study the T-CRAFT within a Seabasing context. The goal is to develop a quantitative capability-based tradeoff environment that can be used to explore the design space in real-time and can offer insight into the probability of meeting desired capabilities.

3.1. Identify System

The T-CRAFT was modeled in a payload delivery scenario in its High Speed Transit mode. The Seabasing architecture depicted in Figure 3 is reduced to the right-hand side of Figure 4, where the T-CRAFT will be operating between an MPG and a beachhead. Each vessel in the scenario continuously delivers fully-outfitted M1A1 tanks from the Ground Combat Element (GCE) of a MEB between an MPG and a beachhead.

3.2. Identify Capabilities of Interest

The desired capabilities defined in Table 1 are in the form of dimensional parameters (DPs), i.e., physical properties of the T-CRAFT whose values determine system behavior and structure even when at rest (Hootman 2003). The High Speed Transit DPs from Table 1 are range, speed (which includes sea state operations), and payload capacity. The range is the round-trip distance between the MPG and the beachhead, so half of the range will be used as the distance to objective. The upper value of 300 nm is used as a more stringent capability. The ships that form the Seabase would be vulnerable to weapons such as naval mines, submarines, strike aircraft, and antiship missiles. In recognition of those threats, DoD's plans call for such ships to remain at least 25 nm offshore (CBO 2007). Payload capacity was discretized into M1A1 tanks for the purpose of modeling loading and unloading delays under a single load plan; in the general case, payload capacity is a continuous variable with a large number of loading plans. Since the T-CRAFT is vulnerable to attrition when it is beached and to address the required rapid, sequential off-loading of vehicles during an assault, the number of tanks on board (which is between zero and the payload capacity) were also considered (CBO 2007). Finally, the physical architecture of the Sea Base was explored by varying the number of T-CRAFT operating in the scenario. Table 2 summarizes the identified capabilities of interest and their ranges in the design space. Where applicable, the ranges were taken from the BAA; in all other cases, a literature search on current amphibious operations served to bound the parameters (CBO 2007).

Table 2. Dimensional parameters and ranges

Dimensional Parameter	Design Space Range	Units
Distance to Objective	25 – 300	nm
HST Speed	30 – 60	kts
Payload Capacity	4 – 10	Number of M1A1s
Tanks On Board	1 – 10 (constrained by payload capacity)	Number of M1A1s
Sea State Operations	0 – 4	NATO STANAG 4194 Sea State
Number of T-CRAFT	1 – 4	~

3.3. Identify System Metrics

The metrics were derived from literature to be relevant to the system being modeled (Milton 2004). They were separated into two categories: performance metrics and economics metrics. Each metric was carefully selected to provide insight into the system. The metrics are summarized in Table 3 and discussed below.

Table 3. Quantitative system metrics

Metric	Nomenclature	Units
Performance		
Steady-state tank delivery rate	SSTDR	M1A1 tanks/day
Sorties per vessel per day	SVD	sorties/No. T-CRAFT/day
Loading efficiency	$\eta_{loading}$	%/100
Loading effectiveness	$e_{loading}$	minutes/minutes
Economics		
Fleet acquisition cost	Acq $	total tank capacity
Operational cost	Oper $	lt of fuel consumed (fleet)/tanks/No. T-CRAFT

For the Seabasing concept to be feasible, a certain number of tanks from the MEB must be delivered within a specified time period. A natural metric for this capability is the steady-state tank delivery rate, defined in Equation (1).

$$\text{SSTDR} = \frac{\text{Tanks Delivered}}{\text{Mission Duration (Days)}} \tag{1}$$

T-CRAFT utilization is important in meeting readiness requirements; a system with a higher sortie generation sortie rate exhibits a higher utilization and hence is more capable of meeting readiness requirements (NAVRIIP 2008). This measure of performance was considered in terms of sorties per vessel per day as shown in (2).

$$\text{SVD} = \frac{\text{Sorties}}{\text{No. T-CRAFT} \times \text{Mission Duration (Days)}} \tag{2}$$

The loading configuration was also investigated in terms of the loading efficiency $\eta_{loading}$ (how efficiently deck space is used) and the loading effectiveness $e_{loading}$ (how quickly the cargo is unloaded on shore relative to the full load condition). These metrics are defined in (3) and (4), respectively.

$$\eta_{loading} = \frac{\text{Tanks On Board}}{\text{Payload Capacity}} \tag{3}$$

$$\text{e}_{loading} = \frac{\text{Full-load Unload Time}}{\text{Unload Time}} \tag{4}$$

Finally, cost was considered in terms of fleet acquisition cost and operational cost. Fleet acquisition cost is based on number of T-CRAFT and payload capacity. It is assumed that the lightship displacement (and hence cost of the vessel) scales with its payload capacity. The operational cost is defined as mission fuel consumption normalized by number of T-CRAFT and total tanks delivered in order to derive the fuel-equivalent cost of delivering one tank. These metrics are defined in (5) and (6), respectively.

$$\text{Acq \$} = \text{No. T-CRAFT} \times \text{Payload Capacity} \tag{5}$$

$$\text{Oper \$} = \frac{\text{Mission Fuel Consumption}}{\text{Tanks Delivered} \times \text{No. T-CRAFT}} \tag{6}$$

3.4. Identify Systems Functionality

Standard Department of Defense Architecture (DoDAF) products were created to guide the modeling process by creating representative functional networks (DoD 2007). The DoD defines an architecture as *"the structure of components, their relationships, 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 (Biltgen 2007). The following DoDAF products were developed from literature search (UNTL 2007):

- **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 T-CRAFT *Operational*

Activity Model (OV-5) to the T-CRAFT *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 §3.2. Note that SV-5a in Figure 5 is for the complete T-CRAFT mission profile. Blocks A1.1 and A1.2 in Figure 5 correspond to the parts of the mission that are not modeled and are assumed to perform correctly for all cases being studied.

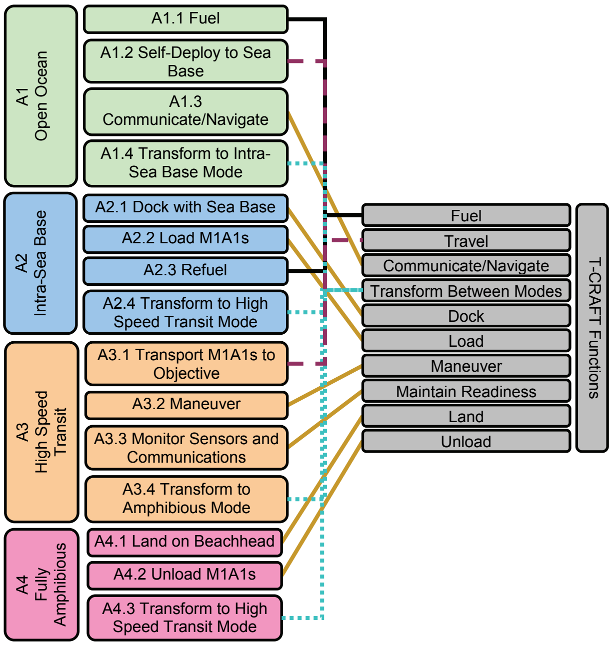

Figure 5: Operational Activity to Systems Functionality Traceability Matrix (SV-5a)

3.5. Develop System Model

3.5.1. Model development

DoDAF products were used in conjunction with Unified Modeling Language (UML) 2.0 to develop the system software architecture to the fidelity determined in §3.4. UML is a standardized visual specification language for object modeling that is being developed by DoD (2007). UML enables the rapid design, development, and sustainment of code via an object-oriented approach. In many cases, portions of the DoDAF products and UML diagrams were interchangeable. The following UML 2.0 diagrams were employed in the software development (Rational Software 1997):

- **Use Case Diagram:** How a user employs the system software
- **Component Diagram:** Dependencies amongst software components
- **Class Diagram:** Static structure diagram
- **Sequence Diagram:** Message exchange between objects

The units in the constructive simulation consisted of platforms whose motion was governed by physics-based rules and whose intelligence was governed by cognition models simulating human decision. Figure 6 shows the *Class Diagram*, which describes the structure of the platform and cognition classes, their attributes, methods, and relationships to other classes.

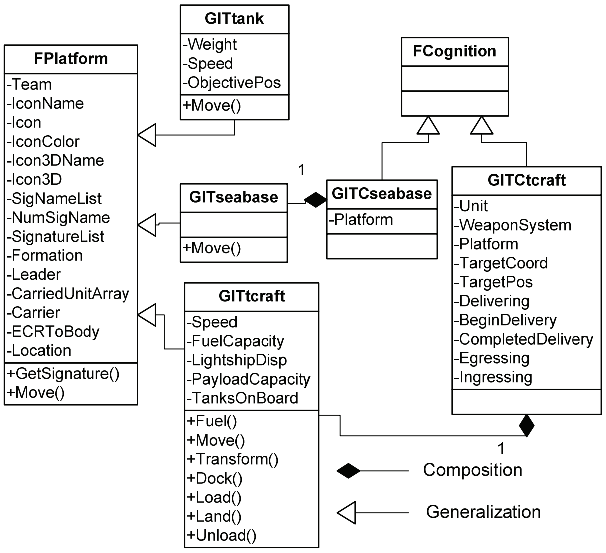

Figure 6. Class diagram showing platform/cognition composition and generalization

The code was compiled and linked with the Flexible Analysis, Modeling, and Exercise System® (FLAMES®) 6.1.1 (Ternion 2006) via Microsoft Visual Studio® 2005 (Microsoft 2005). FLAMES was integrated with Phoenix Integration ModelCenter® 7.1.2 (Phoenix 2007) to allow a DoE to be performed. Figure 7 shows the final, physics-based modeling and simulation environment developed for this study.

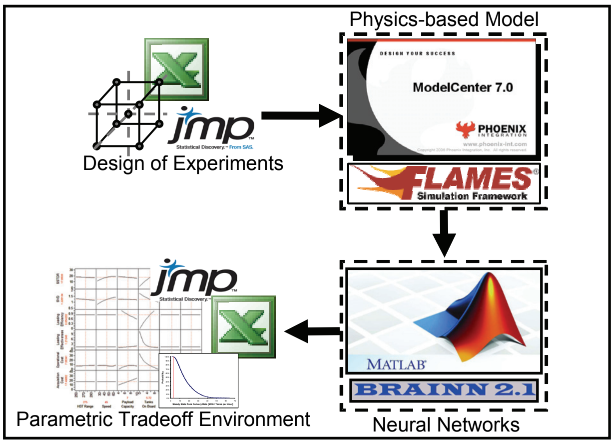

Figure 7: Modeling and simulation environment.

3.5.2. Verification

The T-CRAFT capabilities were successively decomposed into quantifiable, implementable solutions at three levels: high-level requirements, software requirements, and source code. Each level was verified and linked with the level above it. At the source code level, test cases were used and the inputs were traced through execution to ensure that there were no bugs in the code. Tracing was performed via incremental output files and animation. From a verification perspective, animation is a graphical form of tracing that provides information about the internal behavior and physics of the model (Etessami 2007). Figure 8 shows a screen capture of a fleet of four T-CRAFT leaving an MPG and headed towards shore.

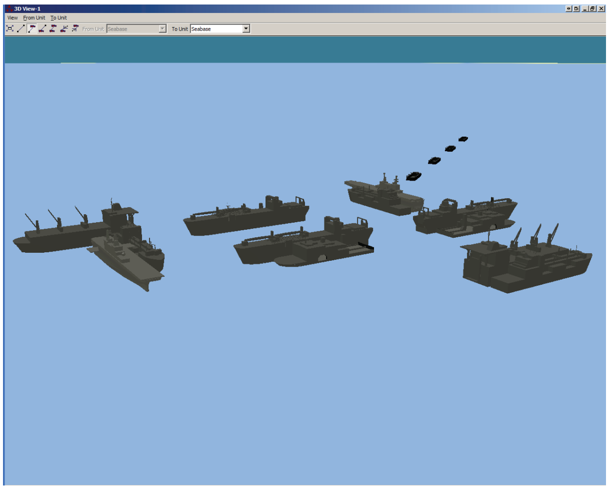

Figure 8. FLAMES animation screen capture of T-CRAFT fleet leaving MPG

3.5.3. Validation

In practice, the validation process is difficult for agent-based constructive 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 asses each of the physics-based models to ensure that the physics are being modeled correctly. For cognition models, the agents must be tested under various conditions to ensure that they follow the correct decision paths. It is then usually inferred that the aggregated behavior is as correct as possible (Biltgen 2007).

Unfortunately, critical measures of amphibious operations are unavailable, thus the scenario as a whole cannot be validate; however, following Biltgen's approach, the kinematics were validated against simpler relations, and powering was compared against experimental model data. Kinematics were validated via animation and application of the kinematical equation $s = v\Delta t$, which relates distance traveled to the product of a constant speed and a change in time. The time is given as an output of the animation and the speed and distance are inputs. Thus, the time was validated and was found to agree with the simulation results.

Resistance was calculated using standard powering calculations (Yun 2000). The resistance code was compared to experimental performance data obtained from a scale model of the SES 100B (Fridsma 1974). The comparison is shown in Figure 9. The discrepancy at higher Froude numbers is due to the assumption that the draft is constant with speed; in reality, the draft of a surface effect ship decreases with speed thus resulting in a decrease in resistance, as seen in the experimental data.

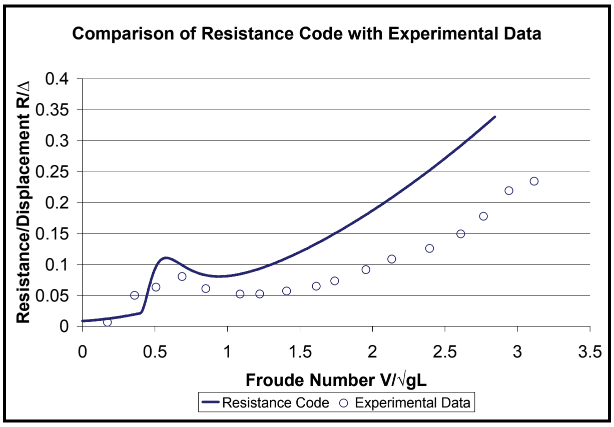

Figure 9. Comparison of resistance code with experimental data from Fridsma (1974)

3.6. Develop Tradeoff Environment

To address the long run-times associated with constructive simulations, surrogate models are implemented to enable rapid trade studies. The current model was executed for 60 hours of simulation time, which took approximately two minutes of actual time per run on a Windows XP Professional SP2 platform with a 2.0 GHz Pentium M Processor and 1 GB of RAM. The development of the surrogate models begins with creation of a DoE table. Due to the combination of continuous and discrete inputs, a custom orthogonal DoE of 80 cases was constructed using SAS JMP® 7.1 (SAS 2007). Neural networks were selected as the surrogate models in order to capture any highly nonlinear behavior that would arise in the responses. Using Basic Regression Analysis of Integrated Neural Networks (BRAINN) 2.1 developed at Aerospace Systems Design Laboratory (Johnson 2007), neural networks 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 four "goodness of fit" tests: R^2, actual by predicted plot, residual by predicted plot, and model error distribution. These tests are discussed in detail in Kirby (2001). In general, the surrogate model data points should be as close as possible to the actual data points, residuals should be randomly distributed, and error should be approximately distributed as a standard normal distribution. Figure 10 shows the results of these four tests for the SSTDR neural network.

With the goodness of fit tests accepted, the next step is to visualize the design space. JMP was used to visualize the results in the form of a tradeoff environment. JMP provides a suite of visualization tools that enable visual tradeoffs and probabilistic analyses to be performed. Note that the environment developed in this study is not unique; combinations of other commercial or in-house tools may be used.

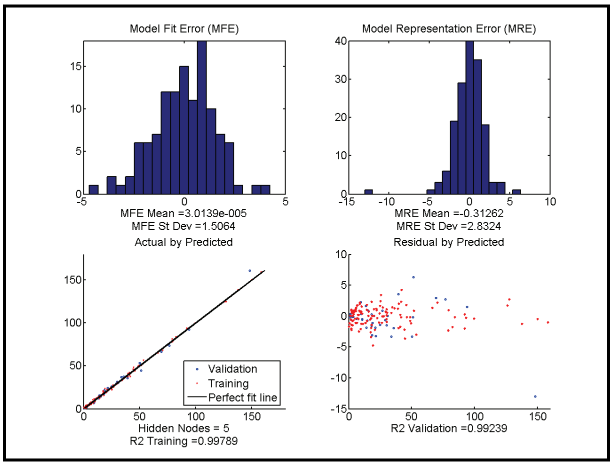

Figure 10. Neural network validation tests for SSTDR

JMP was used to produce an interactive prediction profiler as shown in Figure 11. This matrix of bivariate plots enables the designer to visually check the model for unexpected behavior and to establish the sensitivities of each metric to the input parameters. Thus the designer can determine the main drivers for each metric. For example, for the settings shown in Figure 11, the steady-state tank delivery rate is most sensitive to distance to objective.

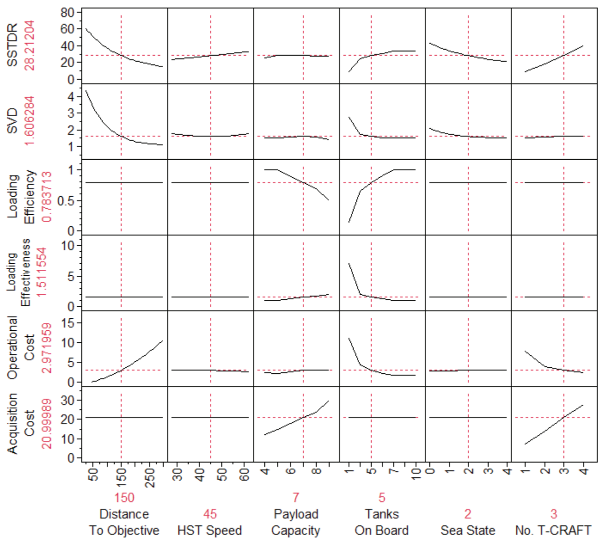

Figure 11. Prediction profiler

3.7. Design Space Exploration

The first step in the design space exploration is to establish a baseline vessel as a basis for comparison. A baseline configuration was established for an LCAC in amphibious assault and is shown in Table 4. The baseline will aid in the comparison of cost metrics, due to their relative rather than absolute measures, as well as the performance metrics. This in turn will aid in determining if the T-CRAFT is a viable alternative to the LCAC. The baseline metrics for the LCAC, shown in Table 5, are obtained from the original model because the dimensional parameters fall out of the ranges of validity of the neural networks.

Table 4. Baseline vessel dimensional parameters

Dimensional Parameter	**LCAC Baseline**	**Units**
Distance to Objective	45	nautical miles (nm)
HST Speed	25	knots (kts)
Payload Capacity	1	Number of M1A1s
Tanks On Board	1	Number of M1A1s
Sea State Operations	0	NATO STANAG 4194 Sea State
Number of T-CRAFT	1	~

Table 5. Baseline vessel metrics

Metric	**LCAC Baseline**	**Units**
Performance		
Steady-state tank delivery rate	5.87	M1A1tanks/hour
Sorties per vessel per day	5.87	sorties/No. T-CRAFT/day
Loading efficiency	1	%/100
Loading effectiveness	1	minutes/minutes
Economics		
Fleet acquisition cost	1	total tank capacity
Operational cost	7.17	lt of fuel consumed (fleet)/tanks/No. T-CRAFT

The next step is to extract the capabilities that are required to make Seabasing feasible. Recall from Figure 2 and the five top-level Seabasing measures of performance that 28 M1A1 tanks must be delivered in an 8 – 10 hour period. The additional equipment in the GCE will not be considered. The T-CRAFT is capable of transporting these vehicles; however, this model is only valid for tank payload. For 8 hours, the steady state-tank delivery rate is 84 tanks per day; for 10 hours, the rate is less stringent at 63 tanks per day. No requirement currently exists for the operational and acquisition cost other than that cost should be "reasonable and realistic" (BAA 2005). For this problem, cost will be minimized. The LCAC operational cost in Table 5 shall serve as a basis for comparison to existing systems and methods. $e_{loading}$ is to be maximized in order to effect rapid off-loading, and $\eta_{loading}$ is left unconstrained. Finally, in order to maximize T-CRAFT utilization, the sorties per vessel per day are maximized. Table 6 summarizes the targets for the system metrics

Table 6. Targets for system metrics

Metric	**Target**	**Units**
Performance		
Steady-state tank delivery rate	≥ 63 (T), ≥ 84 (O)	M1A1tanks/day
Sorties per vessel per day	maximize	sorties/No. T-CRAFT/day
Loading efficiency	~	%/100
Loading effectiveness	maximize	minutes/minutes
Economics		
Fleet acquisition cost	minimize	total tank capacity
Operational cost	minimize	lt of fuel consumed (fleet)/tanks/No. T-CRAFT

The last step is to explore the design space via Monte Carlo simulation. The inputs to the system are treated as random variables with uniform distributions within the ranges of validity of the neural networks. The resulting outputs are presented as cumulative distribution functions (CDFs). The goal of this approach is to determine the percent feasibility of the design space with respect to the metric targets. If a metric has a high probability (or confidence) of achieving a desired target, the design space available for optimization is considered plentiful and robust. A low probability of success implies that the design space is not sufficiently wide for optimization, and the design variable ranges should be increased to capture potentially feasible solutions.

From the reverse cumulative distribution function (CDF) in Figure 12, the probability of achieving the threshold tank delivery rate is 5.1%. This means that 5.1% of the designs in the design space meet the delivery rate for the 10-hour employment time; 1.6% of the designs meet the delivery rate for the 8-hour employment time. Figure 12 shows one aspect of why the Seabasing concept is difficult to implement: even with new assets there is still a high probability of failure if the Seabasing SoS is not planned correctly. The design space is not robust and optimization is not recommended. At this stage, there are three options: (a) relax the constraints or requirements; (b) expand the design space ranges and repeat 3.6; or, (c) infuse new technologies into the baseline vessel. (a) is not an option at this time since the requirements are set and the approach for (c) has not been developed in this work but is outlined in Kirby (2001). (b) is the recommended option, and would entail increasing the number of T-CRAFT in the mission. For illustrative purposes, optimization will continue with the current design space.

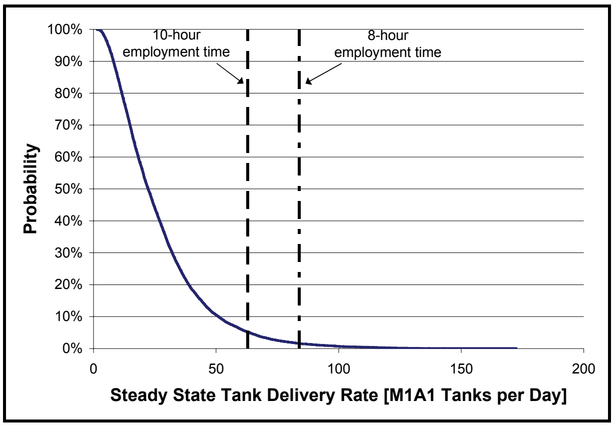

Figure 12. Probability of success in meeting the required steady-state tank delivery rate

Optimization in the JMP® prediction profiler is enabled via desirability functions (Rèthy 2004, Engineering Statistics Handbook 2003). Desirability functions convert a multidimensional objective function into a one-dimensional objective function. The optimization results are shown in Figure 13. Table 7 compares the results from the neural networks to the results from the actual model. This indicates the error in neural networks and also obtains actual values for the optimal point.

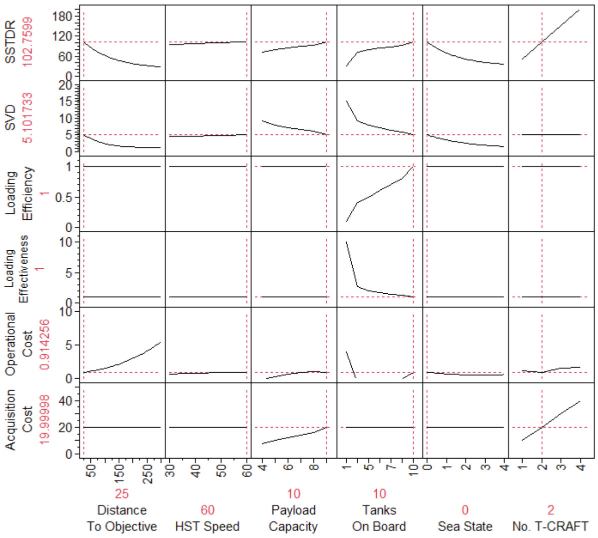

Figure 13. Optimization results

Table 7. T-CRAFT optimization results

Metric	Optimized Value (Surrogate Model)	Optimized Value (Actual Model)	Units
Performance			
Steady-state tank delivery rate	103	102	M1A1tanks/hour
Sorties per vessel per day	5	5	sorties/No. T-CRAFT/day
Loading efficiency	1	1	%/100
Loading effectiveness	1	1	minutes/minutes
Economics			
Fleet acquisition cost	20	20	total tank capacity
Operational cost	0.91	0.49	lt of fuel consumed (fleet)/tanks/No. T-CRAFT

In this example, the operational cost is highly constraining on the resulting design. Relaxing this constraint yields designs that may operate beyond 150 nm from shore and still meet the required delivery rates. The optimization process presented above is useful for determining system parameters that meet desired capabilities for a single design and for interpolating between design points for more solutions; however, it is inefficient for obtaining a *family* of solutions that provide the desired capabilities. A scatterplot matrix, an example of which is shown in Figure 14, visualizes correlations between selected capabilities and metrics. The points shown may be obtained from the actual model or from the surrogate models. Figure 14 implements the surrogate models so that more design points may be included without re-running the actual model. In this example, the metrics along with distance to objective are shown. This plot allows the designer to implement constraints and to down-select a family of feasible solutions. Constraints for an 8-hour employment time and distance to objective of 100 nm are implemented as an example. The down-selected scatterplot is show in Figure 15; only feasible design points are shown.

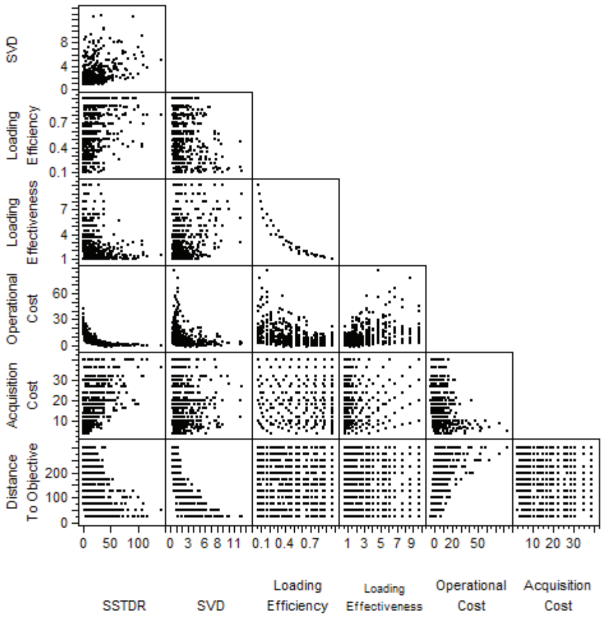

Figure 14. Scatterplot matrix

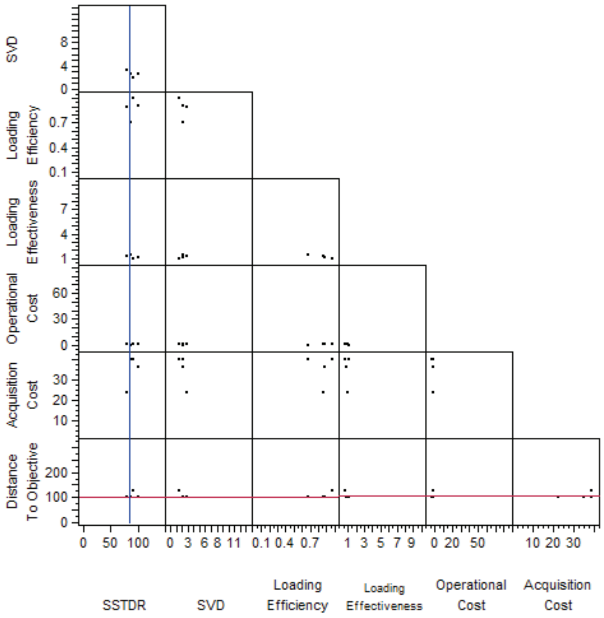

Figure 15. Down-selected scatterplot

4. CONCLUSIONS

A parametric tradeoff environment is developed that enables rapid, probabilistic design space exploration. This quantitative framework can be used to assess capability tradeoffs of the T-CRAFT within the Seabasing concept and is expandable to accommodate additional entities and variable-fidelity physics or cognition models. The design space can be explored probabilistically in order to determine the feasibility in meeting certain goals. Furthermore, if desired capabilities of the T-CRAFT are defined, a probabilistic simulation can be performed on the neural networks to produce cumulative distributions of the probability of meeting these capabilities under uncertainty.

The neural networks that are developed may be employed in higher level models that depict more than one system for rapid capability-based tradeoffs. This large-scale, multi-aspect system of models is currently being developed by the Aerospace Systems Design Laboratory at Georgia Institute of Technology under funding from the ONR. Using decomposition of the SoS and aggregation of the surrogate models, a high-fidelity Seabasing model may be developed to perform inverse design and capability analysis.

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