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Assessment of the operational requirements for the transformable craft in Seabasing Missions

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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

ASSESSMENT OF THE OPERATIONAL REQUIREMENTS FOR THE TRANSFORMABLE CRAFT IN SEABASING MISSIONS

by

Sebastian Scheibe

June 2010

Thesis Advisor: Paul J. Sanchez
Second Reader: Eugene P. Paulo

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In 2005, the Broad Agency Announcement (BAA) #05-020 called for research and development efforts to design the Transformable Craft (T-Craft), a transport craft that will create a "game-changing" capability for the U.S. Navy's Seabasing concept. The T-Craft is intended to advance the concepts of Operational Maneuver from the Sea (OMFTS) and Ship-to-Objective Maneuver (STOM). In this thesis, we examine various T-Craft operational and performance requirements using discrete event simulation modeling, statistical design of experiments, and robust analysis techniques. The model is used to investigate the rates at which the T-Craft/Sea base system, as specified in BAA #05-020, can deliver materiel to shore. We use robust analysis to evaluate the impact of both operational and performance design choices for the T-Craft across a spectrum of conflict conditions. The result is a set of design and policy recommendations that are targeted toward achieving mission success in a broad variety of used scenarios.			
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ASSESSMENT OF THE OPERATIONAL REQUIREMENTS FOR THE TRANSFORMABLE CRAFT IN SEABASING MISSIONS

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Submitted in partial fulfillment of the
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ABSTRACT

In 2005, the Broad Agency Announcement (BAA) #05-020 called for research and development efforts to design the Transformable Craft (T-Craft), a transport craft that will create a "game-changing" capability for the U.S. Navy's Seabasing concept. The T-Craft is intended to advance the concepts of Operational Maneuver from the Sea (OMFTS) and Ship-to-Objective Maneuver (STOM). In this thesis, we examine various T-Craft operational and performance requirements using discrete event simulation modeling, statistical design of experiments, and robust analysis techniques. The model is used to investigate the rates at which the T-Craft/Sea base system, as specified in BAA #05-020, can deliver materiel to shore. We use robust analysis to evaluate the impact of both operational and performance design choices for the T-Craft across a spectrum of conflict conditions. The result is a set of design and policy recommendations that are targeted toward achieving mission success in a broad variety of used scenarios.

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EXECUTIVE SUMMARY

We assess the proposed capabilities of the Sea Base Connector Transformable Craft (T-Craft) listed in the Broad Agency Announcement #05-20 by the Office of Naval Research. The capabilities are evaluated using a combination of computer simulation and statistical design of experiments to determine what characteristics are necessary to achieve mission success in delivering personnel and materiel from the sea base to shore within a specified time frame.

The T-Craft is expected to fill a gap in the U.S. Navy's seabasing strategy by improving cargo transfer capabilities. In seabasing, forces arrive at the ships comprising the sea base and deploy from the sea base to objective areas ashore to conduct combat or relief operations. Seabasing requires a huge logistic system consisting of pre-positioned ships, high-speed sealift ships, high-speed connector vessels, the means to transfer troops, equipment, and stores between platforms in open ocean, and air and surface connectors for deploying and resupplying the forces.

We focus on the operational requirements of the high-speed connector vessels within the seabasing concept, the T-Craft. The T-Craft is expected to deploy in an unloaded condition from an intermediate support base to a sea base up to 2500 nm away, and then be used as a sea base connector to transport vehicles, personnel and cargo through the surf zone and onto the beach, feet dry.

In order to determine potential “game changing” capabilities, the desired capabilities of the T-Craft are tested based on a wide range of possible operational scenarios. These scenarios include various sea base structures, ranges to shore, number of shore spots, cargo loads, geographies, and situationally dependent challenges. The scenarios are implemented with the discrete-event simulation package Arena. The Arena-model that has been developed for this thesis simulates the whole process: arrival of the T-Craft at the sea base, loading troops, forming batches, traveling to the shore, converting from a surface effects ship to an air cushioned vehicle, unloading troops, converting back

to a surface effects ship, and traveling back to the sea base. The model explores the use of batching to minimize the threat of enemy attacks and the subsequent sinking or disabling of T-Craft.

Two different scenarios are investigated. The first scenario simulates the process of projecting troops from the sea base to shore without an enemy threat. In the second scenario, the presence of an enemy is considered. For the scenario without enemy threat, we investigated 22 different input parameters to determine the effect they had on the time to complete the mission. For the scenario with enemy threat, we studied the impact of 31 input parameters on three performance measures: mission completion time, proportion of materiel successfully delivered to shore, and proportion of T-Craft destroyed. The analyses were performed using "robust analysis," which has two advantages over more traditional analyses. First, robust analysis focuses on those factors that are actually controllable by the decision maker. Second, robust analysis captures both the quality and the consistency of the system's performance. In order to do the robust analysis, the input parameters are classified as decision factors or noise factors. For the purposes of this thesis, the decision factors are those associated with the performance of the T-Craft or those that can be influenced by the decision maker or mission planner. These include, for example, total load of the troops, distance between sea base and shore, cargo payload weight, deck size area, speed, load time, unload time, and the number of available T-Crafts. The noise factors are factors that are beyond the decision maker's control, such as the probability of the T-Craft being hit by enemy fire, the deck use efficiency that is achieved when the vessels are loaded, or the number of shore spots available at the beach.

For the scenario without enemy threat, we examine how the T-Crafts perform in peace-keeping missions or missions of humanitarian assistance. The experiment contains 2817 design points with 45 replications of each design point. The results of these 126,765 computational experiments show that the most important factors are the total load of troops, the number of T-Crafts that are available, the cargo payload weight, the distance between sea base and shore, and the time to load the T-Crafts. The number of T-Crafts should be at least 12 and the cargo payload weight should be at least 750 long tons.

For the scenario with enemy threat, we examine the impact of batching in order to minimize the threat of enemy attacks and sinking or disabling of T-Craft due to enemy hits. The experiment with 31 input parameters leads to 29,700 design points. With four replications for each design point, a total of 118,800 computational experiments were conducted. The presence of hostile forces in the landing area results in significant changes from the first scenario. The idea of grouping T-Craft into convoys was not discussed in previous papers, but the batch size has the highest impact on the proportion of cargo onshore. This is followed by the total load of the troops, the cargo payload weight, the number of available T-Crafts, and the unload time. The most significant factors for the proportion of destroyed T-Crafts are the total load of troops, the cargo payload weight, the number of available T-Crafts, the number of hits that the T-Craft can sustain before they require repair, the unload time, and the batch size.

Additional conclusions from the second experiment are that the batch size and sea spots should be at least eight. We recommend that the number of shore spots should have at least the same value. The T-Craft survivability is also an important factor in order to get a high proportion of cargo onshore. The T-Craft should be able to sustain multiple hits before repairs are needed. Furthermore the distance, the load time, and the unload time should be as small as possible. The speed of 40 knots proposed in the Broad Agency Announcement is sufficient.

Finally, we develop a predictor for time to complete mission in peacetime scenarios. The structure of the predictor shows that queuing effects are not an issue over the wide range of scenario settings we explored. The Arena model developed in this thesis can be used as a decision tool for planning future operations. The Arena model can also be used to assess the performance of the T-Craft prototypes when their capabilities are finalized.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACV	Air Cushioned Vehicle
BAA	Broad Agency Announcement
CONOPS	Concept of Operation
CONUS	Continental United States
FOD	Foreign Objective Detection
JFEO	Joint Forcible Entry Operation
JOA	Joint Operating Area
LCAC	Landing Craft Air Cushion
LCU	Landing Craft Unit
LHA	Landing Helicopter Assault
LHD	Landing Helicopter Dock
LMSR	Large Medium Speed Roll-on/Roll-off Ship
LT	Long Tons
MEB	Marine Expeditionary Brigade
MOE	Measure of Effectiveness
MLP	Mobile Landing Platform
MPF (F)	Maritime Prepositioned Force (Future)
nm	Nautical Miles
NSWCDD	Naval Surface Warfare Center Dahlgren Division
OCNO	Office of the Chief of Naval Operations
OMFTS	Operational Maneuver from the Sea
ONR	Office of Naval Research
SEED	Simulation Experiments & Efficient Design

SES	Surface Effects Ship
ST	Short Tons
STOM	Ship-To-Objective Maneuver
T-Craft	Sea Base Connector Transformable Craft

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The last months of working on this thesis have been a work-intensive and challenging time. First I would like to thank my fiancée Friederike for her unwavering support during this study. Without her patience and encouragement the work on this thesis would have been much harder and painful.

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I. INTRODUCTION

A. BACKGROUND

Since the fall of the "Berlin Wall" in 1989, the world has changed dramatically. In the last two decades, the old military doctrines have been modified and today it is expected that the military of the Western world can react to a military crisis or a humanitarian disaster within days. Recent examples of such rapidly mobilized operations are the war in Afghanistan and the earthquake relief efforts in Haiti in January 2010. The U.S. military needs a new capability to bring its armed forces to an arbitrary location in the world within days or weeks. The U.S. military is expected to have this capability even without host nation support in the Joint Operating Area (JOA). The National Security Strategy and the National Military Strategy both emphasize the need for military access to keep global freedom of action. Seabasing capabilities are vital to solve the problems that occur due to a lack of access to overseas bases, while enhancing the ability of U.S. forces to project power from the sea and conduct ship-to-objective logistics (Department of the Navy, 2006).

In Seabasing, forces arrive at the ships comprising the sea base, assemble with their equipment at sea, and deploy from the sea base to objective areas ashore to conduct combat or relief operations. Resupply of these forces also comes from the sea base. Seabasing requires a system of systems consisting of pre-positioned ships, high-speed sealift ships, high-speed connector vessels, the means to transfer troops, equipment, and stores between platforms in open ocean, and air and surface connectors for deploying and resupplying forces (Boensel & Schrady, 2004). This thesis focuses on the operational requirements of the high-speed connector vessels within the Seabasing concept. In the remainder of this thesis these high-speed connector vessels are called Sea Base Connector Transformable Craft (T-Craft).

In 2005, the Office of Naval Research (ONR) issued the Broad Agency Announcement (BAA) #05-020 for a prototype of the Sea Base Connector Transformable Craft (T-Craft). The T-Craft is expected to deploy in an unloaded condition from an intermediate support base to a sea base up to 2,500 nm away, and then be used as a sea base connector to transport vehicles, personnel, and cargo through the surf zone and onto the beach. The T-Craft is designed to fill a gap in the U.S. Navy's seabasing strategy by improving on the cargo capacity limitations of aircraft and Landing Craft Air Cushion (LCAC) vehicles, and the low speed of Landing Craft Units (LCU) although the T-Craft has a larger cargo load compared to the other vessels.

B. OBJECTIVES

The Naval Surface Warfare Center Dahlgren Division ([NSWCDD], 2009) addressed a variety of questions regarding the design characteristics of the T-Craft and its role of bringing forces and needed supplies to shore in a timely manner and without requiring a seaport. These included such issues as: What are the forces and what are their characteristics pertinent to being carried by a T-Craft? How much tonnage do they have? How quickly can the force roll on and roll off and transit to and from the beach? How long must a sortie take at what range?

This thesis extends the work of the NSWCDD. We build upon the prior work by addressing several new issues:

- How many T-Crafts are required to execute a mission within the mission time constraint?
- If there is an enemy threat capable of damaging or sinking the T-Crafts, how many additional T-Crafts are needed to accomplish the mission?
- How survivable does the T-Craft need to be?
- What are the tonnage capacity and deck size of a T-Craft that can successfully execute the spectrum of anticipated missions?
- How many spots are needed to load and unload the T-Crafts?
- How important are the speed, the load time, and the unload time of the T-Craft?
- How do fuel consumption and the frequency of refueling events impact operations?

We address these questions using a discrete event simulation model that captures the queuing behaviors of the process, in conjunction with statistical design of experiments, to study the system in a comprehensive fashion. We also provide recommendations for resource allocation. Additionally, the simulation model can be utilized in future analyses as a basis for studying particular scenarios.

C. SCOPE OF THE THESIS

This thesis provides numerical findings and qualitative information to help guide the Office of Naval Research in its plans to design and test the T-Craft to fulfill naval and joint operational requirements. The results of this thesis will help to build a concept of operation (CONOPS) capable of achieving the desired "game changing" capabilities in the areas of Seabasing, Operational Maneuvers from the Sea (OMFTS), and Ship-to-Objective Maneuver (STOM).

The main scope is to use a discrete event simulation model that incorporates the queuing issue to assess how the capabilities listed in ONR BAA #05-20 contribute to mission success. A robust statistical analysis of the T-Craft performance will assess its suitability for a broad variety of military and relief operation scenarios and will lead to a decision aid for using the T-Craft.

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II. SCENARIO DEVELOPMENT

A. INTRODUCTION

In order to provide military relevance to the analysis, plausible scenarios are explored. This thesis uses suitable scenarios for the T-Craft in order to conduct a robust analysis of the T-Craft performance. This chapter provides a brief introduction to seabasing, the T-Craft concept and possible scenarios. Following the scenario representation is a description of the ARENA simulation tool that is used to model and analyze the scenarios.

B. SEABASING

1. Seabasing Logistics Enabling Concept

In *Seabasing Logistics Enabling Concept*, the Office of the Chief of Naval Operations ([OCNO], 2006) defines Seabasing as:

> …the rapid deployment, assembly, command, projection, reconstitution, and re-employment of Joint combat power from the sea, while providing continuous support, sustainment, and force projection to select expeditionary Joint forces without reliance on land bases within the Joint Operating Area (JOA). Seabasing is a national capability for global force projection that exploits the sea as a maneuver space and enables the capabilities of Coalition and Joint Forces. It maximizes the effects of forward presence, reduces our dependence on vulnerable land bases, 'steps lightly' on allies and partners political concerns, and increases options. One of the key capabilities provided by the sea base is Seabasing Logistics which includes the ability to persistently sustain select Joint forces afloat and ashore. Seabasing provides sustainable logistics functions at-sea while reducing the footprint ashore and maximizing use of international waters.

The Seabasing Logistic Enabling Concept is forecast to be introduced in the U.S. Navy in the 2015–2025 timeframe.

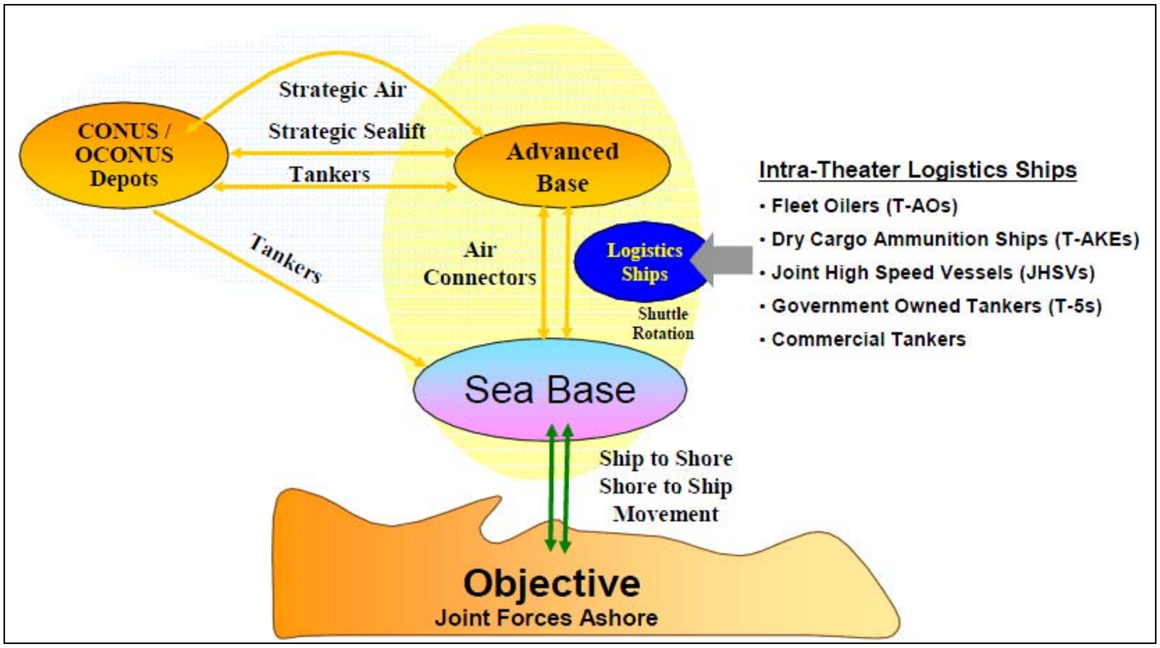

Figure 1. Seabasing Concept (From OCNO, 2006, p. 5)

Figure 1 gives an overview of the Seabasing Logistics architecture. The primary logistics nodes are Continental U.S. (CONUS) and the Advanced Base. Most of the sustainment for initial resupply for ground units is delivered from CONUS. The Advanced Base is important to the support of the sea base because it is the primary warehouse and transshipment point. The majority of supplies needed by the sea base will pass through the Advanced Base. The sea base is the primary demand node because it supports and sustains the Joint Forces ashore. The sea base must be able to operate at-sea in a JOA located up to 2,000 nautical miles from an Advanced Base. A network of logistics shuttle ships and aircraft connect the sea base with the Advanced Base and provide the transport capability in support of the expeditionary ground forces ashore. Adverse weather conditions, especially the sea state, directly impact the ability of logistics platforms to provide timely sustainment and throughput, i.e., transfer cargo, fuel, passengers, and other supplies to sea-based assets. Selected sea base platforms are required to have the capability to perform these operations in the open ocean in all weather, through Sea State 4 and potentially Sea State 5.

2. Required Performance Characteristics

According to the Dahlgren report (NSWCDD, 2009),

> …the sea base concept promises to enable a Joint Forcible Entry Operation (JFEO) from sea-based assets—an armed invasion against a hostile force—within 15 days of National Command Authority decision to perform such an operation and without the need to seize a port to deliver the Entry Force. The sea base is a set of joint/combined assets designed to meet a Combined Commanders tasking. It could include a Carrier Strike Group, an Expeditionary Strike Group, a Maritime Preposition Force, combat logistics force ships, and coalition forces. It could deploy to the theater of operation from thousands of miles away, from different ports, and assemble in the area of operation. Central to success of the sea base is the ability to project onto hostile held territory a sea based Marine Expeditionary Brigade (MEB) 2015 which comprises about 15,000 troops and hundreds of air and ground vehicles. Critical to the Joint Forcible Entry Operation from the sea base is delivery, to an unimproved beach, the Assault Wave of the Marine Assault Echelon within 8 to 10 hours (notionally under the cover of a single night). The ability to land this invasion force in this short specified time without the need of a sea port to any of a broad set of beaches from a position at sea over the horizon (at least 25 nautical miles from shore) provides great ambiguity and uncertainty to any adversary who must defend against such an invasion and provides great flexibility to the Joint Force Commander.

The Assault Echelon is the part of the Marine Expeditionary Brigade (MEB) 2015 which is carried on the amphibious warfare ships while the Sea Based Echelon is hosted on the other ships of the Maritime Prepositioning Force (Future) (MPF(F)). The amphibious assault vessels (LHA and LHD) are constructed to fight and survive in combat missions and are crewed by trained military personnel. The other MPF(F) ships are very lightly crewed with civilians who are qualified for sea-based logistics. During an assault, most parts of the sea base with the MPF(F) ships stand off from the shore between 100 to 200 miles or more. At that point the Assault Echelon warships would approach to a point of force debarkation 25 miles from shore. Figure 2 provides an overview about the planned Maritime Prepositioning Force of the Future. From the point of force debarkation the T-Crafts carry the assault forces ashore.

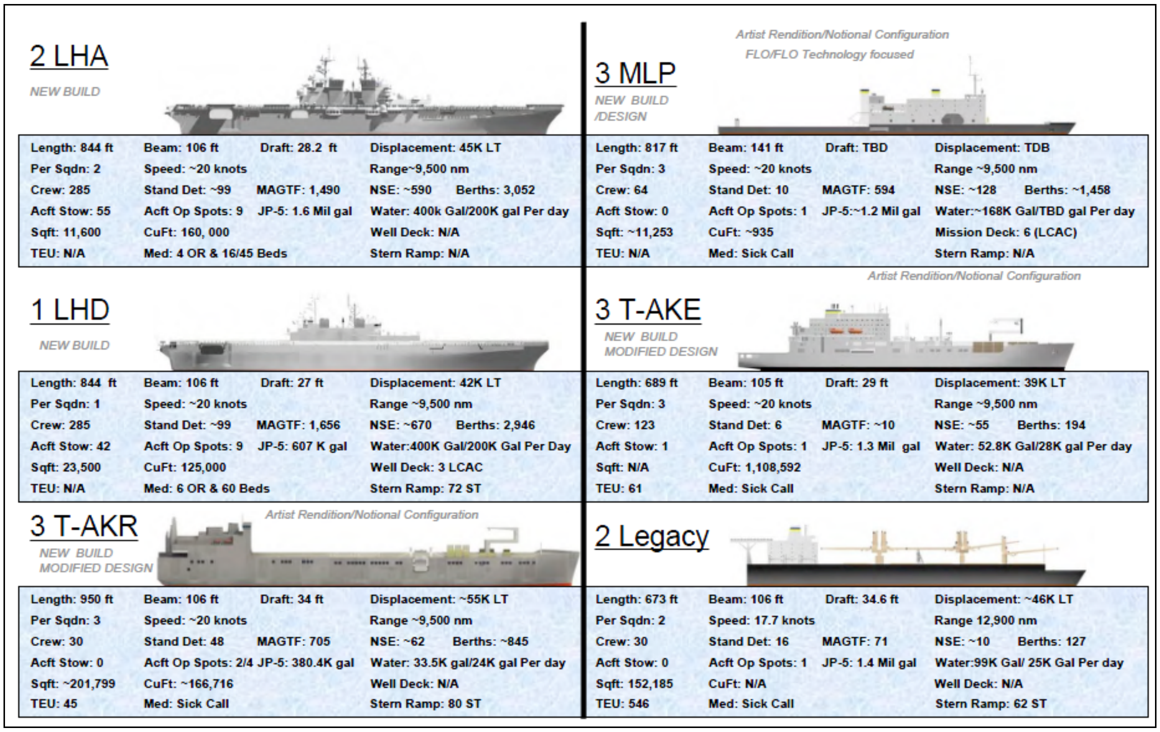

Figure 2. Maritime Prepositioning Force (Future) (From NSWCDD, 2009, p. 8)

The primary Measure of Effectiveness (MOE) for the T-Craft during an assault is its ability to transport the Assault Echelon Forces from the sea base to the shore within a time frame of 8 to 10 hours. The forces should reach the beach feet-dry, ready for immediate engagement with any hostile force and ready to proceed to the objective. The weight of the assault force totals up to 5,490 long tons and the footprint of the MEB 2015 totals to 73,759 square feet.

Table 1 shows the details on dimensions and weight for the Assault Wave components of the MEB 2015. Readers interested in a detailed description of the assault wave should consult the Dahlgren report (NSWCDD, 2009) *T-Craft: Critical Design and Operation Issues associated with the Sea-Basing Connector Role*. Additionally the report mentions that emerging plans over the past years suggest a new heavier Marine Corps Force for the future, the MEB 2024. The Assault Wave of the MEB 2024 covers approximately 88,080 square feet in footprint and weighs 32,559 long tons, which is much heavier than the MEB 2015 Assault Wave.

Besides that, the sea base must be able to sustain at least two brigades, according to Marine Corps/Navy plans.

Table 1. Surface Delivery MEB 2015 Assault Wave (From NSWCDD, 2009, p. 11)

Materiel/Unit Type	L feet	W feet	Weight lbs	H feet	# of Units	Deck Area Per Unit (Square Feet)	Square Feet (sqft) for Total MEB	Total Weight (short tons)
Personnel & Gear	2.44	2.44	250	7	1936.00	5.9536	11526.1696	242
HMMWVs	15	7.08	5900	6	124	106.2	13168.8	365.8
HMMWVs Armored	15	9.08	10000	6	41	136.2	5584.2	205
EFVs	35	12	76000	10.7	49	420	20580	1862
MTVRs (7 ton trucks)	32.25	8.2	30000	11.7	60	264.45	15867	900
M1A1 Tanks	32.04	12	135200	8	14	384.48	5382.72	946.4
LW 155 Howitzers	27.5	10	10000	9	6	275	1650	30
Assault Breach Vehicle	42	12	120000	8	2	504	1008	120
Assault CBT Excavator	27.9	8.2	26433	11.5	4	228.78	915.12	52.866
Armored Vehicle Launched Bridge	31	12	113200	10.5	1	372	372	56.6
LAV-22	20.96	8.2	28200	8.83	28	171.872	4812.416	394.8
Recovery Vehicle M88	29.38	11.5	123400	10.3	3	337.8125	1013.4375	185.1
MHE Rough Terrain Container Handler	55	12	115743	12	6	660	3960	347.229
HIMARS	23	7.9	24000	10.5	3	181.7	545.1	36
CBR Sys (Estimate)	30	8	12000	6	1	240	240	6
Logistics Vehicle System (Assume MK48/14)	38	8	40300	8.5	19	304	5776	382.85
Internal Transport Vehicle (ITV)	15	4.96	4000	5	8	74.4	595.2	16
Total ==>							73758.8896	6148.645

The availability of sea spots for the T-Craft is a vital issue in seabasing. Figure 2 gives an overview of the Maritime Prepositioning Force (Future) (MPF(F)). The ships within the MPF(F) vary concerning the available spots for loading the T-Crafts. Figure 3 shows that we currently anticipate nine available sea spots at the MPF(F). The number of available shore spots depends on the shape of the shore. Beaches are best suited for approaching the shore and should provide enough shore spots. However, since there are also rocky shores around the world, the possibility of limited numbers of shore spots has to be considered as well.

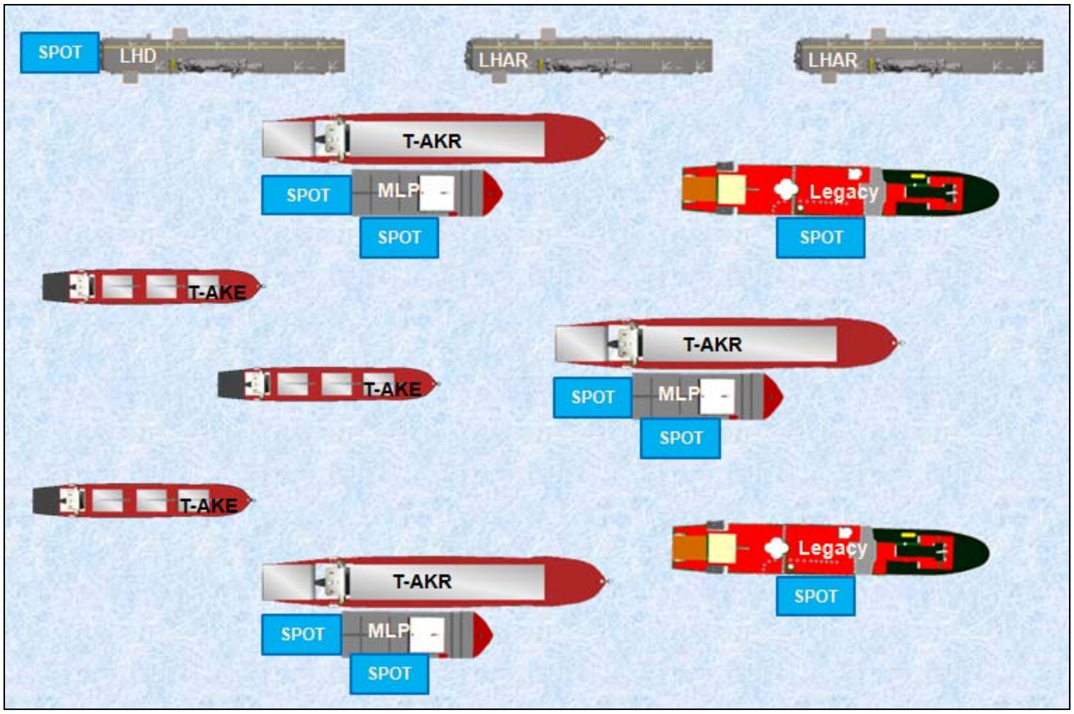

Figure 3. Available Sea Spots at the Sea Base

C. T-CRAFT CONCEPT

1. Desired Capabilities

As already mentioned in the introduction, the ONR issued the BAA #05-020 in 2005 for a T-Craft which can deploy in an unloaded condition (range of 2500 nm) from an intermediate support base to a sea base and then be used as a sea base connector, transporting wheeled and tracked vehicles, cargo, and personnel through the surf zone and onto the beach.

ONR BAA #05-20 lists a series of desired capabilities, thresholds/objectives and other information relevant to the T-Craft prototype. The significant capabilities for this thesis are summarized in the following list:

1. To be used as an assault connector and a logistics connector ranging from a sea base to a shore objective.
2. Cargo Payload Weight Objective of 750 LT, threshold 300 LT.

3. Cargo Payload Area Objective of 5,500 sq. ft., threshold 2,200 sq. ft.

4. Crew Size Objective 2, threshold 3.

5. Maximum un-refueled range in High Speed/Shallow Water Mode ~500-600 nautical miles (40 knots, through Sea State 4) in loaded condition.

6. Maximum Speed, full load condition in High Speed, Shallow Water Mode of ~40 knots through top end of Sea State 4.

7. Un-refueled range, in a no-cargo condition, of 2,500 nautical miles in a Fuel Efficient/Good Sea Keeping Mode (20 knots, through Sea State 5)

8. Amphibious capability to traverse sand bars and mud flats, thereby providing a "feet dry on the beach" capability.

9. Ability to mitigate wave-induced motions in Sea State 4/5 to enable rapid vehicle transfer (loading/un-loading) between the T-CRAFT and a Maritime Prepositioning Force (Future)/Sealift ship.

2. Functional Flow Diagram

The T-Craft is a connector between the sea base and the shore. It must have the capability to deploy from an intermediate support base and conduct a 2,500 nautical mile transit to the sea base.

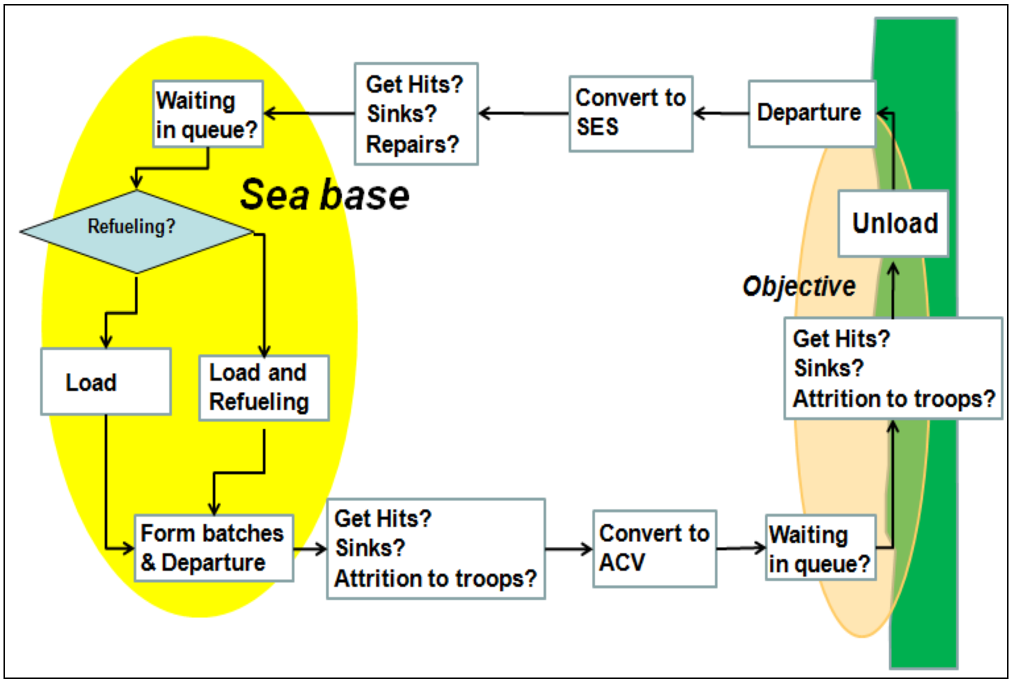

Figure 4. Functional Flow Diagram

Once in the operation area, it is used as a sea base connector, transporting cargo for the MPF(F). From the sea base, the T-Craft is used as a connector to the shore base and transits troops, wheeled, and tracked vehicles. Figure 4 illustrates this. Details are described in subsection 3.

3. Assumptions

The T-Craft is operating as an expeditionary and logistic connector. We made the following assumptions in building a model of operations.

a. Cargo Payload Weight vs. Cargo Payload Area

The number of sorties required depends upon the amount of total weight and the footprint of both the material and the troops that have to be projected to the shore. The Dahlgren report (NSWCDD, 2009) investigated different types of brigades and assumed different cargo payload weights and cargo payload areas for different versions of T-Craft. As a result the number of T-Craft sorties required depends upon both the cargo weight and the cargo footprint. Both the cargo deck footprint and tonnage capacity can be important and have to be considered. In some cases more sorties are needed when the number of sorties is based on the footprint, in other cases the tonnage is more important than cargo square feet. Furthermore, the Dahlgren report (NSWCDD, 2009) mentions that the Marines project 80 percent deck use efficiency. The 80 percent factor was derived from the cargo deck efficiency projected for the LCAC with a slight upgrade for T-Craft potential improvement. The model that was developed for this thesis considers different deck use efficiencies and different combinations for cargo payload weights and cargo deck areas in order to investigate the effects.

b. Loading and Unloading

The Dahlgren report (NSWCDD, 2009) identifies eight steps in a T-Craft sortie, in addition to the transit time, when connecting to a Large Medium Speed Roll-on/Roll-off (LMSR, also called Legacy) ship. These steps take a total of approximately 3.5 hours (Table 2).

Table 2. Steps of a T-Craft Sortie Excluding Transit Time (From NSWCDD, 2009, p. 7)

1. T-Craft connects to LMSR — 45 minutes
2. Load and gripe — 30 minutes
3. Disconnect from LMSR — 15 minutes (faster in an emergency)
4. Transform SES to ACV — 30 minutes
5. Approach beach — 15 minutes
6. Drop ramp, unload and ramp up — 30 minutes
7. Get off the beach—15 minutes
8. Transform ACV to SES—30 minutes.

When the T-Craft approaches the beach it transforms into an Air-Cushioned Vehicle (ACV) that can come ashore. It transforms back to a Surface Effects Ship (SES) to travel at high speed back to the sea base. Foreign Objective Detection

(FOD) removal and refueling are not included in the eight steps shown in Table 2. The report does not specify how the vehicles or cargo will be rolled on and rolled off to the T-Craft in only 30 minutes or how the gripe process will work. Our analysis accounts for the uncertainty by studying ranges of loading times, times to convert from SES to ACV and back to SES, and unloading times. We use the Dahlgren report to provide baseline figures for these values. Loading and unloading times were varied from 1 to 5 hours and from 1 to 4 hours, respectively.

The parameter unloading time in the model of this thesis does not consider the transition times. Transition times will be treated individually. We also analyze ranges of values for the transition distances to shore and speeds in the ACV mode.

c. Survivability and Batch Sizes

The most extensive and dangerous mission is to project an Assault Echelon of a MEB to the shore when the enemy is still present. In this case, we face the possibility that some T-Crafts will be destroyed or disabled during the mission.

A common strategy to decrease the number of ships lost in such a military operation is to beach the troops in echelons (also called batches). Batching decreases the probability of hits for each individual T-Craft when the troops are projected to the shore. In order to generalize the problem it makes sense to work with probabilities of hit for the batches. The probability of hit for an individual T-Craft can be computed based upon the size of batch. We assume that any troops onboard the T-Craft suffer attrition from the hits. The rate of attrition from each hit has to be one of the input parameters. Another question is how many hits an individual T-Craft can cope with before it sinks. We model this using a distribution where the probability of sinking depends upon the number of hits that the T-Craft has sustained during an operation. We assume that a T-Craft will sink with a certain probability after each hit. If a T-Craft has been damaged during a trip but not sunk, we assume it will be pulled from service for repairs and will be unavailable for the remainder of this mission.

d. *Probability of Failure*

We assume for our model that T-Craft with minor failures can be repaired within a short time frame. A T-Craft with minor failures will therefore remain available for additional trips.

e. *Fuel Consumption and Range*

The T-Craft must be able to deploy from the Advanced Base and travel up to 2,500 nautical miles at a speed of 20 knots in a no-cargo condition without any refuels. This is a huge distance compared with the maximum unrefueled range of 500 miles at a speed of 40 knots in cargo condition. The Dahlgren report (NSWCDD, 2009) specifies target values for the fuel consumption of the T-Craft at different speeds depending on cargo conditions. The numbers are provided in Table 3. The impact of the sea state on fuel consumption was not specified and is not considered in this thesis.

Table 3. T-Craft Rates of Fuel Consumption (From NSWCDD, 2009, p. 27)

In sea state 4 conditions the T-Craft designs currently being developed offer the following rates of fuel consumption:

Speed in knots	Fuel Consumption in Long Tons (2240 pounds)/hour
10	1.5
20	3.0
30	7.0
40	8.5

In the case of very long distances, when more fuel is needed for one turn than the tank capacity provides, a secondary or additional tank is needed that decreases the cargo payload weight of the T-Craft. The occurrence of this case has to be considered in the model. Based on the T-Craft rates of fuel consumption provided by the Dahlgren report, we conclude that the fuel capacity of the T-Craft should be at least 110 long tons without affecting the cargo payload weight. The Dahlgren report does not state whether the MPF(F) has the capability for concurrent fueling and cargo loading so both scenarios are considered in this thesis. If this capability exists, we assume that cargo loading would take more time than refueling. If not, then refueling and loading would be sequential operations and additional time is required for any refueling event. We estimate 120 tons/hour for non-concurrent fueling operations based on operational experience with the LCAC.

D. SCENARIO REPRESENTATION

1. Overview

Realistic scenarios are important when conducting simulation studies. In order to create a scenario we gained the basic outline for the scenario of this thesis from relevant publications. The first publication that we used was done in September 2009 by the Dahlgren report (NSWCDD, 2009), at the request of the ONR Program Manager for T-Craft, to describe the forces which potentially would be involved, especially the Marine Corps' envisioned MEB 2015 as well as the MEB 2024. The report also considered some very basic scenarios by using Excel spreadsheet models of how many T-Craft of a given design are required to accomplish the JFEO mission within the time constraints posed by the operational force strategy and tactics. The main assumptions and input parameters of the model used in this thesis are based on the results and conclusions of the Dahlgren report. The second important paper that influenced the range of the input factors is the BAA #05-020 by the ONR, which provides some desired capabilities, thresholds, and objectives of the T-Craft. The third paper that we used to develop the scenario outline is a Limited Systems Engineering Analysis study published by Hellard, Rowden, and Jimenez (2010) from the Naval Postgraduate School. The purpose of their project was to develop five very specific scenarios designed to flex the capabilities of the T-Craft and to create some simplistic models in order to discover important high-level issues. Since the five developed scenarios are too specific to conduct a robust analysis, we did not use these scenarios to design the experiments in this thesis. Instead, we used a very general scenario in order to measure the effectiveness and to find important threshold values. The following is a brief synopsis of the scenario that forms the basis of the simulation model.

2. General Situation

The general scenario established in this thesis is that the United States has become involved in a major military conflict and that a certain amount of force has to be projected from a sea base to the shore using T-Craft. The total weight and the footprint of these forces are important input parameters to compute the number of sorties that are needed to accomplish the mission.

a. Sea Base and Shore Characteristics

The number of available sea spots where the T-Craft are loaded can vary depending on the size and the structure of the sea base. Furthermore, the loading time at the sea base, transition times to ACV and back to SES, the unloading time at the shore, and the number of available shore spots on the shore base all affect the operational tempo. The T-Craft will also need refueling at the sea base. Because five of the six ships of the MPF(F) are still under development, there is currently no information about whether concurrent refueling and loading will be possible. The occurrence of both cases, concurrent and non-concurrent refueling and loading, is considered in the model.

b. T-Craft Characteristics

Because the performance parameters of the T-Craft are still unknown, several factors are studied by varying them over plausible ranges. Three of the most important performance parameters for the T-Craft are the cargo payload weight (in long tons), the cargo deck size (in square feet), and the deck use efficiency (in percent). The numbers of sorties that are required to project the forces to the shore depend on these values, as well as on the total weight and the footprint of the forces to be projected to shore. The number of sorties required can be computed based on these five parameters if no losses are sustained. Other T-Craft input performance parameters are the SES speed, the ACV speed, the fuel consumption in loaded and unloaded conditions, and the tank capacity of the T-Craft. The distance between sea base and the shore and the transition distance to shore also have an impact to the time of completion. Furthermore, the T-Craft should form batches after loading. We assume that a bigger batch size increases the probability of surviving for each individual T-Craft. Parameters, such as the probability of hit for a batch and the attrition rate of the troops that are onboard when a T-Craft is hit, affect survivability and the rate at which material can be transferred to the shore. When a T-Craft gets hit, the probability of sinking has to be handled. In this thesis it is assumed that an individual T-Craft can survive at most four hits, but there is a non-zero probability of sinking associated with every hit. With each additional hit, the probability of sinking increases; after five hits the probability of sinking is assumed to be one. Furthermore, there are three different situations when T-Craft can take hits: during transit from the sea base to shore with troops onboard, during unloading at shore, and during transit from the shore back to the sea base without troops onboard. Each of these situations has to be handled in a different way. Additionally, the possibility of minor failures and repairs of these failures has to be considered.

E. CHARACTERISTICS OF THE ARENA SIMULATION MODEL

This section describes the basic characteristics of the Arena modeling and simulation environment that was used to develop the T-Craft model and explains why Arena was chosen for building model. Arena supports entity-based, process-driven simulations. In Chapter III, the scenario implementation is described. Readers who want to know more about Arena can consult either the user's manual, which can be downloaded from the Rockwell Automation website at http://www.arenasimulation.com, or the textbook *Simulation with Arena* (4th edition) by Kelton, Sadowski, and Sturrock (2007).

1. Reasons for Choosing Arena

Arena is the simulation environment that we selected for developing the model of T-Craft operations. The Arena modeling and simulation environment was chosen because of its capability to model logistic problems, ease of handling, and its prevalence on the market. Arena was developed in the middle of the 1990s by Systems Modeling

Corporation and is a commercial product based on the SIMAN simulation language. In 2001, Rockwell Software purchased Systems Modeling. This company still develops and supports Arena.

Arena is very simple in design and very effective when analyzing processes or flows. Processes that can be described by means of a flowchart can also be simulated with Arena. It also provides 2-D model animation, which is very helpful in the debugging process and during demonstrations of the model. Visual support of process flow increases credibility and supports the understanding for decision makers.

Arena provides an intuitive discrete-event, entity-based simulation environment and is an effective modeling tool for analyzing complex large-scale processes involving warehousing, service, logistics, and distribution procedures. The ability of Arena to create custom templates for complex, repetitive logic, to simplify model development, and to reduce model development time is very useful for modeling processes. Arena models can use a spreadsheet for their inputs, which facilitates the use of data farming techniques.

2. Model Characteristics

This section describes our objectives in building the simulation model, followed by a conceptual overview of the model. Each component module in the model is then discussed in detail. A functional specification of the model is contained in the Appendix.

a. Goals and Measures of Effectiveness (MOEs)

The simulation models missions where the objective is to project a certain amount of troops and cargo to the shore. In general, the total load and footprint considered is equivalent to a MEB. The length of the simulation for an individual run cannot be adjusted directly—the simulation stops when the entire amount of troops and cargo is either unloaded onshore or destroyed. The simulation run-time depends on many input parameters to the model. These parameters are described in detail in Chapter III.D.

The most important input parameters are:

1. total load and footprint of the troops and cargo that have to be projected to the shore
2. cargo payload weight and the cargo deck size of the T-Craft
3. number of available T-Crafts
4. deck use efficiency
5. distance between sea base and shore
6. transition distance to shore
7. speed of the T-Crafts in SES and ACV mode
8. load and unload times
9. transition time from SES to ACV and ACV to SES
10. number of sea spots and shore spots
11. capability of concurrent loading and fueling
12. refueling rate
13. tank capacity and fuel consumption of the T-Craft
14. batch size of T-Crafts in case of enemy presence
15. probability of getting a hit, attrition rate of the troops onboard with each hit, and probability of sinking after getting hits of the T-Craft
16. number of hits until repair required
17. probability of failure and repair times

The ultimate goal of the simulation is determining the impact these input parameters have on the mission success. The primary MOEs that are used to assess mission success are:

1. time to complete a mission
2. proportion of troops and cargo successfully delivered onshore
3. proportion of T-Crafts destroyed

These MOEs directly relate to the combat effectiveness of the combatants because they affect the combat power after arriving onshore. Secondary measures of interest include, but are not limited to, the following: time in queues for T-Craft, number of sorties processed, the number of sorties that remain at the sea base (which happens if all T-Crafts are destroyed), and the number of refueling events. The use of data farming techniques allows analysis of these and other factors.

b. Conceptual Model

We have modeled T-Craft transport and delivery system as a discrete event-driven, entity-based inventory queuing model with multiple servers. Basic queuing models consist of customers who arrive for a service, servers who provide the service, and an inventory available to the servers. In this model, the customers are the T-Crafts. The service, required by all vessels, occurs in three steps. The first step is the loading without refueling at the sea spot, the second step is the unloading onshore, and the third step is (eventually) the loading with refueling at the sea spot based on a couple of input parameters that have to be considered. Successful service for a T-Craft is achieved by successful delivery of troops and cargo onshore which occurs in step two. This will increase the inventory level onshore—in this case, the amount of troops and cargo. The second successful service occurs in step one when the T-Craft receives its sortie at the sea base. In this case, the inventory level of the sea base will be decreased. The same happens in case of the loading with refueling service in step three.

c. Key Components of the Model

In this section, we describe some of the key components of the Arena simulation model. For more details, we recommend Chapter 2.3 of the textbook Simulation with Arena (4th edition) by Kelton, Sadowski, and Sturrock (2007).

1.) Entities. Entities are the dynamic objects in the simulation. They are built into the system with the Create module, move around through the model, wait in queues, change status and are affected by other entities, and then are disposed of when they leave the system. The entities are the parts in the simulation that are processed.

It is possible to have different kind of entities and each kind of entity can have many independent copies. For example, in this thesis the entities are T-Crafts. Because the number of T-Craft can vary, in different scenarios the number of entities will vary.

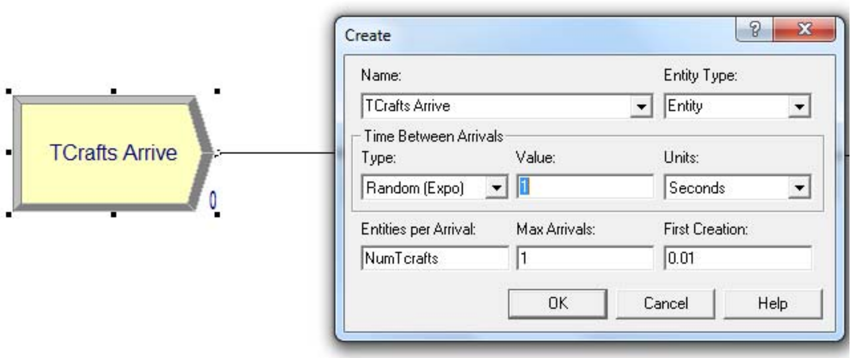

Figure 5. The Create Module and its GUI in Arena

2.) Attributes. The entities each have their own characteristics, referred to as attributes. The attributes individualize entities–the specific values of the attributes differ from one entity to another. An entity can have as many attributes as needed. Arena keeps track of some attributes automatically, but the user can define and change as many of his own attributes as are needed in the model by using the Assign module.

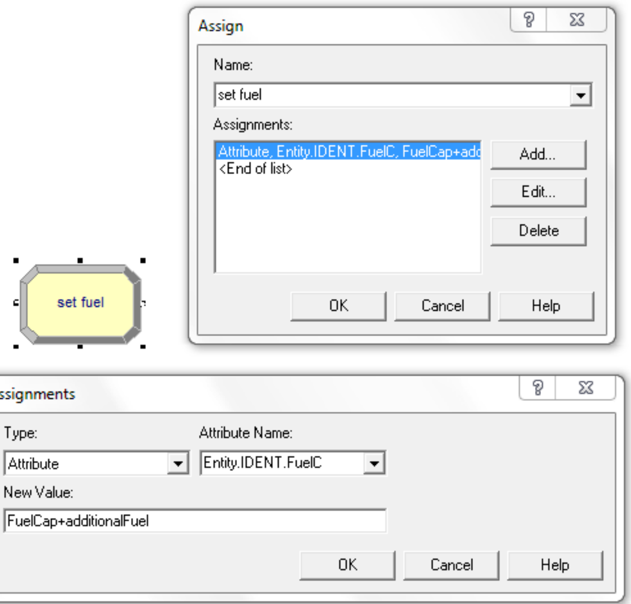

Figure 6. The Assign Module and its GUI in Arena

In the thesis model, all T-Crafts are assigned five user-defined attributes. These attributes are needed in the model as a part of the process logic. For example, Figure 6 illustrates setting the individual tank capacity for each T-Craft at the beginning of the simulation.

3.) Variables. Variables are used to reflect global characteristics of the whole system. The values of the variables are shared by entities—they don't store individual values for different entities, but their global values can be used or changed by individual entities as often as needed. There are two different types of variables. Within a model, the user can define many different unique variables. Additionally, Arena already provides built-in variables, such as number in queue, simulation clock time, number of busy servers, etc. Variables are defined and changed similarly to attributes, using the *Assign* module (Figure 6).

4.) Resources. Entities often compete with each other for service from resources. Resources are stationary elements like personnel, machines, or other kinds of equipment. They have a specified capacity at any point in time, which means that they are limited, and the capacity can change during the simulation run. A resource can represent a number of individual servers. The individual servers are units of the resource and have a set of states (usually idle or busy). In this thesis, resources are used to model the sea spots at the sea base and the shore spots at the coast. The entities (T-Crafts) queue for available resources, seize the resource (for example, the sea spot) when available, and release it when the service is finished. That resource then becomes available. If there are more entities than servers available, the entities wait in the associated queue of the resource. When the resource is available again, the next entity waiting will seize the resource. Any delays that occur due to resource unavailability lead to process delays. The information about resources is maintained in the resource table as seen in Table 4. In the resource table the type and capacity of any given resource can be defined. For the thesis model the available resources are the sea spots and the shore spots, each of them with a certain capacity, which is defined in the Excel-input file. An entity that seizes a resource is referred to as seizing a unit from its total capacity. Entities are authorized to seize and release multiple units of capacity. (Kelton, Sadowski & Sturrock, 2007)

Table 4. The Resource Data Table in Arena

Resource - Basic Process

	Name	Type	Capacity	Busy / Hour	Idle / Hour	Per Use	StateSet Name	Failures	Report Statistics
1	ShoreResource	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑
2	SeabaseResource	Fixed Capacity	1	0.0	0.0	0.0		0 rows	☑

Double-click here to add a new row.

5.) Queues. When an entity needs a place to wait because it needs to seize a unit of a resource that is tied up by another entity, the wait is spent in a queue. The entities enter the queue and are removed from it based on the change in state of the resource. Queues are generated at the *Process* module to indicate where an entity will wait for resources to complete the process if necessary.

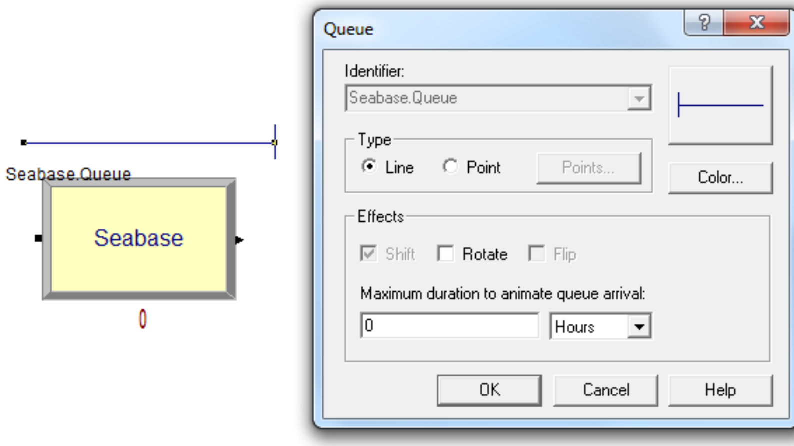

Figure 7. The Process Module and Associated Queue GUI in Arena

Arena provides two different types of queues. Individual queues have a specific capacity, a ranking rule, and a name. The entities in these queues can be animated and ranked using a ranking rule mechanism. Furthermore, it is possible to collect statistics on them and to collect them into batches. The second kind of queue is the internal queue. Internal queues just provide a first-in, first-out container for entities at a particular module. They do not provide animation, ranking, and statistics. An example of a queue in this thesis is the queue that rises at the sea base when entities are waiting for the next available sea spot. Figure 7 represents the *Sea base* module and its associated Queue GUI.

6.) Batches. Forming batches is a very useful feature. Batches allow the user to collect a certain number of entities by using a queue, form them into a unit, send the entire unit through some modules, and separate the unit into individual entities if needed. In the thesis, model T-Crafts form batches after loading at the sea base, travel as a unit to the shore, and are separated at the shore before unloading. Using this tactic increases the survivability of the individual T-Craft in the presence of an enemy. Figure 8 illustrates forming a Batch.

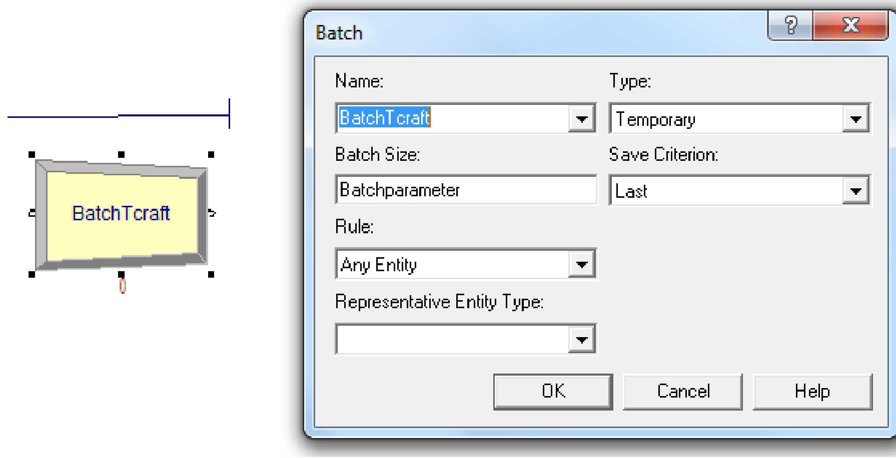

Figure 8. The Batch Module and its GUI in Arena

7.) Simulation time. Because Arena is a discrete-event simulation model, the simulation time does not flow continuously. Time advances only from the time of one event to the time of the next event scheduled to occur. For example, if a process needs a certain amount of time to complete mission, which implies a delay, the completion time will be added to a priority queue of pending events. The simulation clock will then advance to the time of next pending event, which may or may not be the completion event which was just scheduled. When nothing happens between two events, there is no need to waste computation time looking at simulated times that do not affect the simulation. Keeping track of the simulation clock is a critical aspect of simulation. Arena makes the simulated clock available via a read-only variable called TNOW.

Figure 9 shows the Run Setup mode that provides the setting options for experiments to the user's specific model, such as project parameters, replication parameters, array sizes, run speed, run control, and reports.

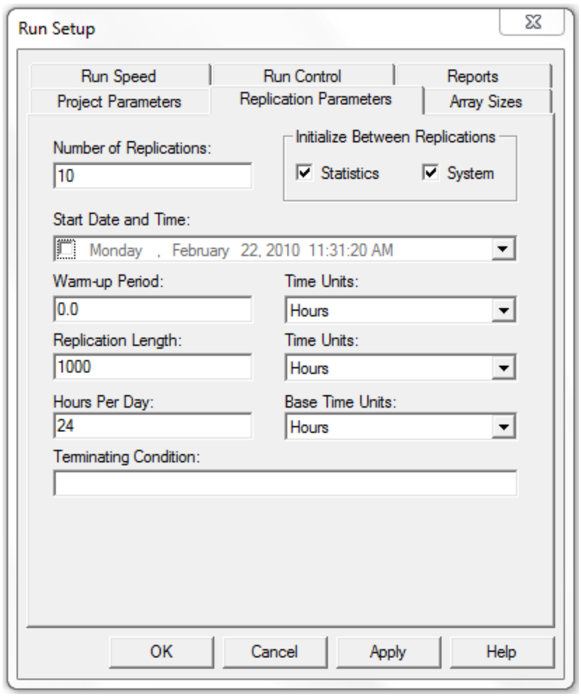

Figure 9. The Run Setup Menu in Arena

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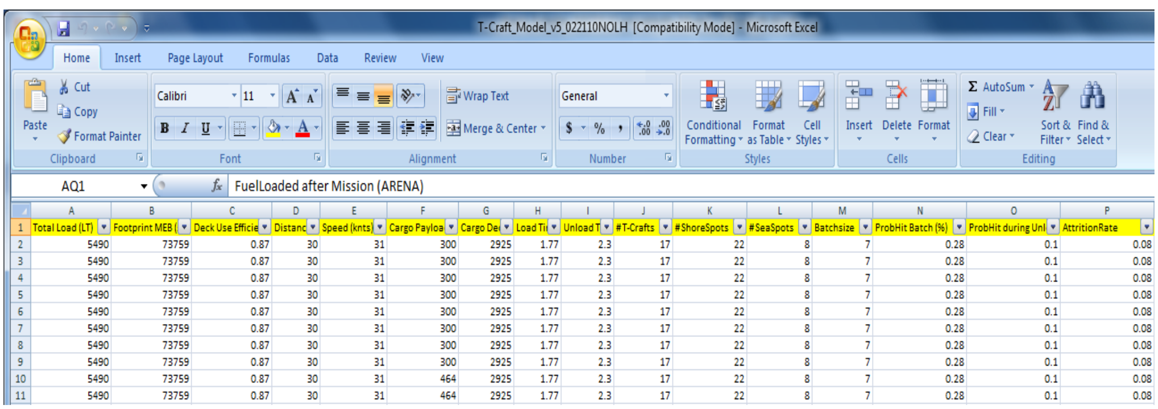
III. MODEL IMPLEMENTATION

A. INTRODUCTION

We use the technique of data farming that has been developed by the Simulation, Experiments, and Efficient Designs (SEED) Center at the Naval Postgraduate School. Data farming provides the analyst with methods to feed the model with inputs in an efficient manner and assess the corresponding results in the output. The technique allows running a simulation many times, while simultaneously changing the input parameters. In the Arena simulation software input parameters can be provided from an external Access data base or an Excel file. The latter is used in this thesis. In the Excel file, 31 input parameters have to be defined in the first 31 columns for every run. Each row in the file represents an individual run of the simulation model. When Arena finishes an individual run, the output parameters are written in another 20 columns of that row. Consequently, the Excel file provides 51 input and output values for every run. All input parameters and the three primary output variables will be described in section D of this chapter. Figure 10 shows a part of the Excel file with the first 16 input parameters.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	Total Load (LT)	Footprint MEB (	Deck Use Efficie	Distanc	Speed (knts)	Cargo Payloa	Cargo De	Load Ti	Unload T	#T-Crafts	#ShoreSpots	#SeaSpots	Batchsize	ProbHit Batch (%)	ProbHit during Unl	AttritionRate
2	5490	73759	0.87	30	31	300	2925	1.77	2.3	17	22	8	7	0.28	0.1	0.08
3	5490	73759	0.87	30	31	300	2925	1.77	2.3	17	22	8	7	0.28	0.1	0.08
4	5490	73759	0.87	30	31	300	2925	1.77	2.3	17	22	8	7	0.28	0.1	0.08
5	5490	73759	0.87	30	31	300	2925	1.77	2.3	17	22	8	7	0.28	0.1	0.08
6	5490	73759	0.87	30	31	300	2925	1.77	2.3	17	22	8	7	0.28	0.1	0.08
7	5490	73759	0.87	30	31	300	2925	1.77	2.3	17	22	8	7	0.28	0.1	0.08
8	5490	73759	0.87	30	31	300	2925	1.77	2.3	17	22	8	7	0.28	0.1	0.08
9	5490	73759	0.87	30	31	300	2925	1.77	2.3	17	22	8	7	0.28	0.1	0.08
10	5490	73759	0.87	30	31	464	2925	1.77	2.3	17	22	8	7	0.28	0.1	0.08
11	5490	73759	0.87	30	31	464	2925	1.77	2.3	17	22	8	7	0.28	0.1	0.08

Figure 10. Excel File with the First 16 Input Parameters

The concept of input and output factors in the Excel file is important to understand the model implementation in Arena. The following pages describe the main parts of the model. We start by outlining the resources of interest involved in the simulation followed by the description of the entities and their assigned attributes. Finally, we describe the parameters chosen as factors for the simulation experiment in this thesis.

B. RESOURCES

Resources are used to represent servers, equipment, or people that influence the entities in a system. The thesis model utilizes two resources. These are the sea spots and the shore spots that are available for loading and unloading. In Arena, the capacity of a resource is a constant that usually will not be changed during a running experiment.

1. Sea Base

The number of sea spots is one of the important factors. Figure 10 shows that the number of sea spots is provided in the Excel file in column L. Figure 3 shows that nine available sea spots at the MPF(F) are expected. But, the number and the kind of ships within the MPF (F) may vary; therefore, it should be possible to change the number of sea spots that are available. The Arena model reads the factors from the Excel file. Figure 11 shows how the individual runs are created and the resource “sea base” is defined based on the number of sea spots.

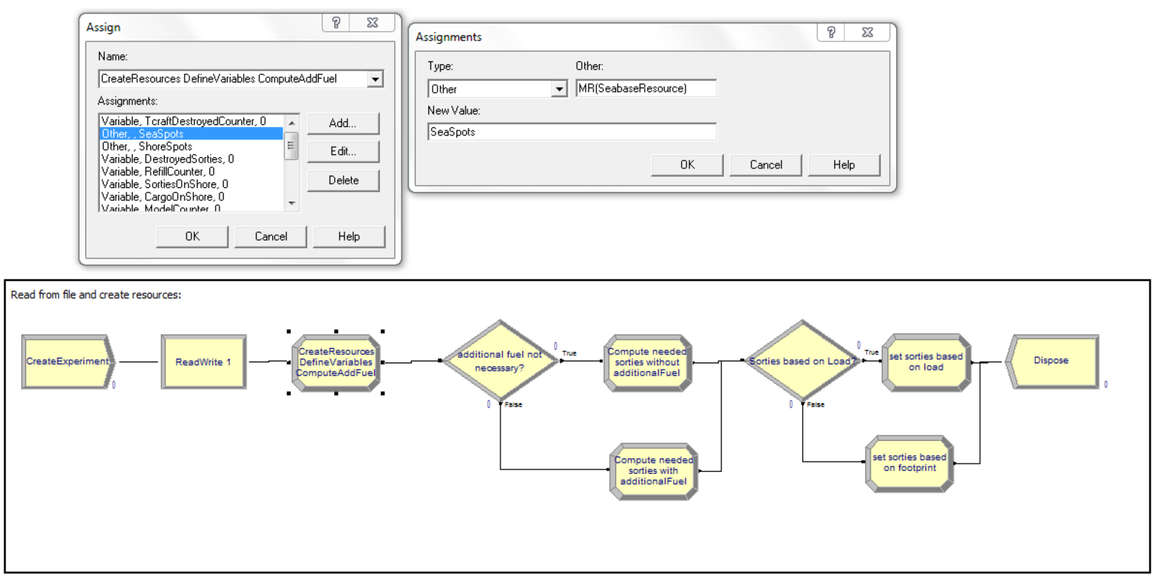


Figure 11. Defining the “SeaBaseResource”

The resource "sea base" is able to process the same number of T-Crafts as sea spots are available in the experiment.

2. Shore

The number of available shore spots can vary as well. This variable depends mainly on the nature of the shore. In an area of steep coast or other difficult terrain, it is imaginable that there are only a few places to beach T-Crafts despite their amphibious capability. Additionally, the nature of shore has to allow heavy vehicles to move into the interior of the country. Because an unloading time of one to four hours is expected for an individual T-Craft, the number of available shore spots is important and should be investigated as a factor. The Excel input file provides this capability in column K. Defining the resource "shore" is the same as defining the resource "sea base" shown in Figure 11. The resource "shore" is able to process the same number of T-Crafts as shore spots are available in the experiment.

C. ENTITIES AND ATTRIBUTES

Entities are the most important participants in an Arena simulation. Entities travel through the model, are influenced by processes, and utilize the resources. Entities get their unique identity from attributes—each entity can have as many attributes as needed. In the thesis model six different attributes are used. The attributes follow a naming convention—they begin with "Entity.IDENT.", followed by the attribute name. Two different kinds of entities are used in the thesis model—the minor entity and the major entity. We describe the two types and the attributes associated with each type.

1. Minor Entity

The minor entity type, which is called "Experiment" in the model, is defined as minor because its purpose is to initiate the "ReadWrite" process that reads the input parameters from the Excel file, create the resources "sea base" and "shore", and define values for some variables based on simple calculations. The logic associated with an "Experiment" entity is shown in Figure 12. Experiment entities have only those attributes that are defined by Arena automatically.

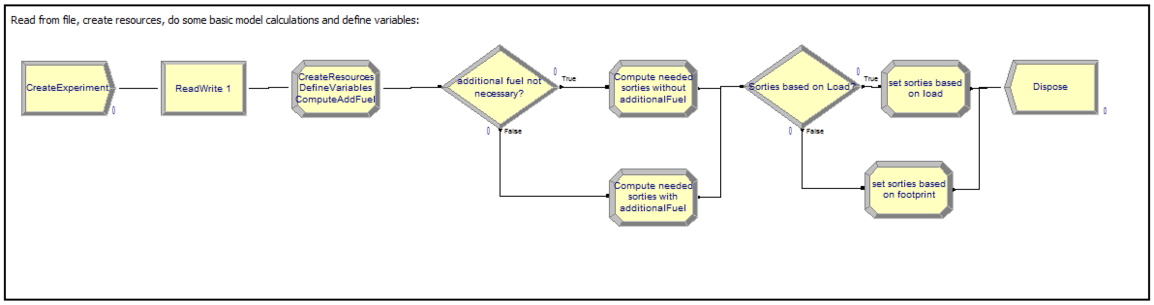


Figure 12. Initial Process and Logic of an "Experiment" Entity

2. Major Entity

The major entity type, which is called Entity in the thesis model, represents the T-Crafts that travel through the simulated process. The T-Craft entity is created at the beginning of the main process, shown in Figure 13.

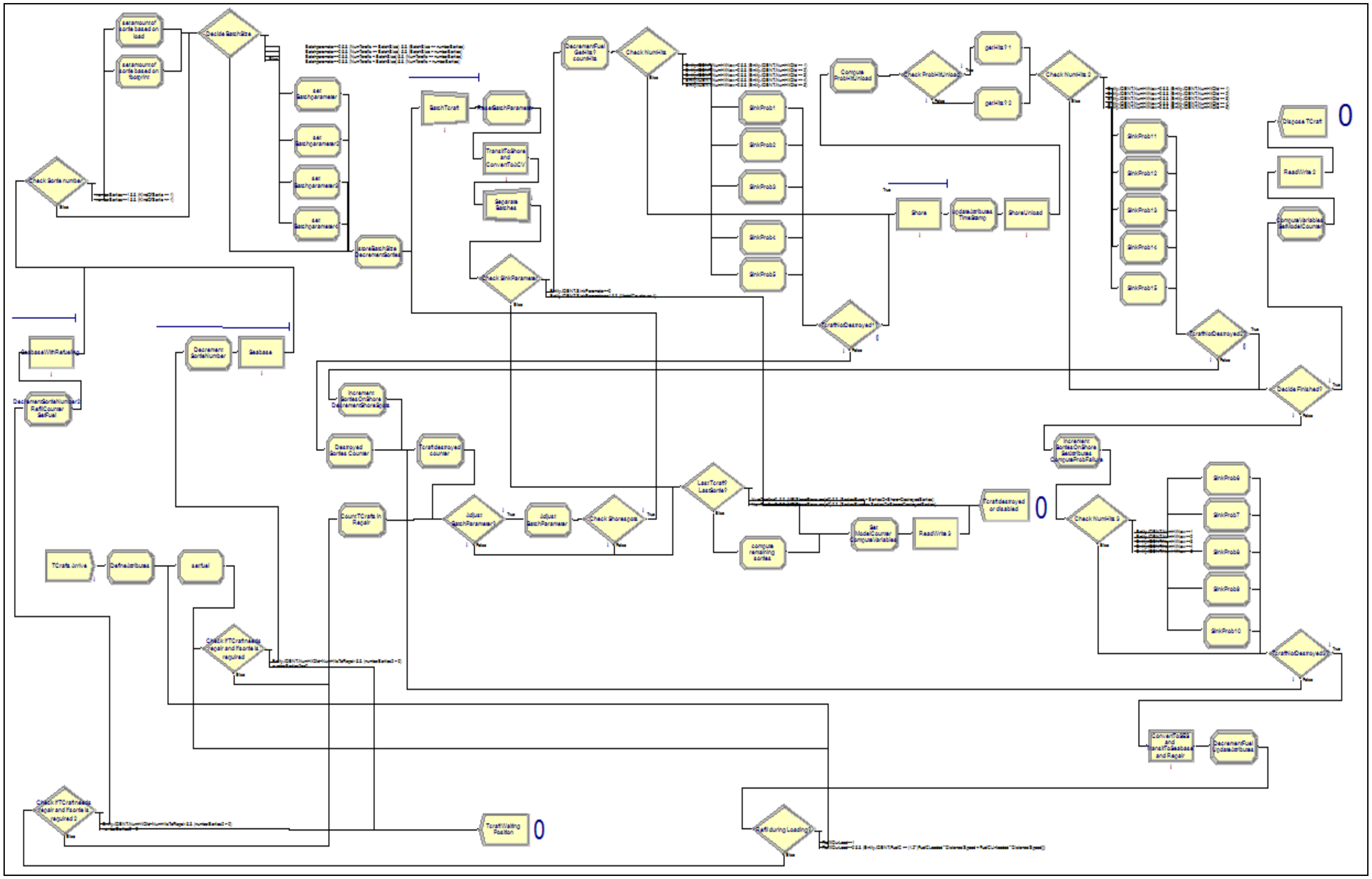


Figure 13. Main Process and Logic of a "T-Craft" Entity

The number of entities depends upon the input parameter "number of T-Crafts" that is provided by column J of the Excel file. Upon creation, the T-Craft entity is immediately assigned a set of eight attributes.

1. Amount of fuel capacity (Entity.IDENT.FuelC): This is the amount of fuel in long tons that is carried onboard by each individual T-Craft. The tank capacity is one of the input parameters and is provided by the Excel file in column W. The tank capacity is defined as the amount of fuel that the T-Craft can carry without decreasing the cargo payload weight. At the beginning of the simulation, the model determines if the tank capacity is sufficient to travel the distance from the sea base to the shore and back to the sea base. If this is the case, the amount of fuel will be determined by the tank capacity. Otherwise, the amount of additional fuel needed is calculated and the fuel capacity will be set to the sum of tank capacity and additional fuel. If this happens, the cargo payload weight will be reduced by the weight of the additional fuel. During traveling between sea base and shore, the T-Crafts consume fuel and the fuel level decreases until the T-Craft is refueled at the sea base.

2. Amount of loaded troops (Entity.IDENT.LoadedTroops): This is the amount of troops that are carried from the sea base to the shore during a single trip. The amount of troops can be measured as weight in long tons or as footprint in square feet depending on which yields the bigger number of sorties needed to transport the troops to the shore. When the T-Craft takes hits, the amount of loaded troops decreases based on to the attrition rate, which is provided by column P of the Excel file.

3. Size of batch (Entity.IDENT.BatchSize): This attribute stores the size of the batch in which groups of T-Craft travel to shore. The probability of hit for the entire batch is an input parameter that is provided by the Excel file, but the probability of hit for each individual T-Craft within the model still has to be computed. This probability depends upon the size of the batch, which may change during a mission. For example, the batch size may change when T-Crafts are destroyed or when there is not enough cargo to transport for the whole batch.

4. Number of new hits (Entity.IDENT.NumHitNew): This attributes stores the number of hits that an individual T-Craft has sustained during one of the three parts of a trip: during the transit from the sea base to the shore, during the unloading at shore, and during the transit from shore to the sea base. It is assumed that the T-Crafts are not vulnerable to enemy fire during loading and refueling at the sea base. The attrition of the troops onboard depends on the attrition rate per hit, which is given in column P of the Excel input file, and the number of hits that the T-Craft takes during transit and unloading. After this computation, the attribute will be updated

with the previous number of hits. Once updated, the attribute is used to calculate the probability of sinking. Sinking depends on the cumulative number of hits suffered by the T-Craft.

5. Number of old hits (Entity.IDENT.NumHitOld): This attribute is used to store the cumulative number of hits that a T-Craft has taken during a mission.

6. Sink parameter (Entity.IDENT.SinkParameter): This attribute is a binary value. If a T-Craft gets new hits, the model computes the sink parameter based on the probabilities of sinking. The parameter is set to one if the T-Craft sinks and zero if the T-Craft doesn't sink.

7. Time stamp (Entity.IDENT.TimeStamp): This attribute is used to give the T-Craft entities a time stamp. The time stamp is used to calculate the probability of hit during unloading. The Excel file provides a probability of hit per batch per hour during unloading. It is assumed that the individual probability of hit during unloading depends on the amount of time the T-Craft is onshore, excluding waiting time at sea, and including the size of the batch.

8. Probability of failure (Entity.IDENT.ProbFailure): This attribute is a binary value. The parameter is set to one if the T-Craft needs repair and zero if the T-Craft does not need repair.

D. VARIABLES OF INTEREST

This section describes the simulation factors and primary output variables that are used in the simulation model. Two different kinds of factors are distinguished. Decision factors can be controlled in the real world by the decision maker. Factors that are beyond the decision maker's control, such as weather influences or influences caused by the enemy, are referred as noise factors. In this thesis, the decision factors are the factors that have a direct effect on the operational requirements and the T-Craft performance or can be influenced by the decision maker. All other input factors are considered noise factors. The next two sections provide descriptions of the decision and noise factors. The third section describes the primary output variables that are generated by the simulation model.

1. Decision Factors

The following factors were chosen to explore the effect of competing system requirements for the T-Crafts. All factors are numbers that are provided by the Excel input file. The name of the variable within the model is presented in parentheses.

1. Cargo payload weight (Capacity): The Cargo Payload weight is the amount of weight in long tons that an individual T-Craft is able to project to shore. In the model, the Cargo payload weight decreases when the T-Craft needs to carry more fuel than the primary tank capacity permits.

2. Cargo deck size (DeckSize): The Cargo deck size is the area in square feet that the T-Craft provides for cargo.

3. Speed of the T-Craft in SES mode (Speed): This variable is defined as the speed of the T-Craft in knots in SES mode.

4. Speed of the T-Craft in ACV mode (SpeedACV): This variable is defined as the speed of the T-Craft in knots in ACV mode.

5. Load time (LoadTime): The load time is the time in hours that the T-Craft needs to load troops and cargo at the sea base.

6. Unload time (UnloadTime): The unload time is the time in hours that the T-Craft needs to unload troops and cargo at the shore.

7. Time to convert to ACV (ConvertTime1): The time to convert to ACV is the time that the T-Craft needs to convert from the SES to ACV mode before beaching.

8. Time to convert to SES (ConvertTime2): The time to convert to SES is the time that the T-Craft needs to convert from the ACV to SES mode before traveling from the shore to the sea base.

9. Number of T-Crafts (NumTcrafts): The number of T-Craft that are available to project the troops and the cargo from the sea base to the shore.

10. Number of sea spots (SeaSpots): The number of places that can be used to load the T-Crafts at the sea base. This number is dependent on the size and the type of ships that comprise the sea base.

11. Refueling during Loading (RefillDurLoad): This variable is binary. If the value is zero then refueling during loading is not possible. Otherwise, it is possible and refueling does not cause additional delays because it is assumed that loading takes longer than refueling.

12. Refueling Rate (RefuelingRate): The refueling rate defines how fast the fuel pumps that refuel the T-Craft work in the case of non-concurrent refueling and loading. The refueling rate is given in long tons/hour.

13. Primary tank capacity (FuelCap): The primary tank capacity defines the amount of fuel in long tons that can be loaded without decreasing the cargo payload weight. The primary tank capacity should be big enough to ensure that the T-Craft is able to travel 500 nm in loaded condition without refueling. For transits up to 2500 nm in unloaded condition, the secondary tank capacity has to be used. We assume that every ton of used secondary tank capacity will decrease the cargo payload weight of the T-Craft by the same amount. Furthermore, we assume that loaded fuel beyond the primary tank capacity has no impact on the deck size that is available for the T-Craft.

14. Fuel consumption in loaded condition (FuelCLoaded): This variable represents the fuel consumption in long tons per hour in loaded condition for an individual T-Craft.

15. Fuel consumption in unloaded condition (FuelCUnloaded): This variable represents the fuel consumption in long tons per hour in unloaded condition for an individual T-Craft.

16. Batch size (BatchSize): Once loaded, the T-Crafts form batches in order to increase the survivability. Forming batches increases the time to complete a mission but decreases the rate at which T-Craft are destroyed.

17. Probability of a failure (ProbFailure): The probability of a minor failure requiring repair during a single turn for an individual T-Craft.

18. Time to repair (RepairTime): The time that is needed to fix minor failures for an individual T-Craft.

19. Number of hits until repair required (NumHitsToRepair): Usually a vessel has to be repaired after it has taken a certain number of hits. This variable defines how many hits a T-Craft can take before it is in need of repair. Usually this value will be one or two. If it is more than four, repair events will not be scheduled. If a T-Craft needs repair due to hits, it will be removed.

20. Total load (Load): The total weight of the troops (assuming this is a Marine Expeditionary Brigade) that have to be projected to shore, measured in long tons.

21. Footprint of the Maritime Expeditionary Brigade (FootprintMEB): The total footprint of the Marine Expeditionary Brigade that has to be projected to shore, measured in square feet.

22. Distance between sea base and shore (Distance): The distance between the sea base and the shore in nautical miles (nm).

23. Transition distance (TransitionDistance): The distance from shore where the T-Craft convert between different modes, measured in nautical miles.

1. Noise Factors

The noise factors are used to ensure that the conclusions of this thesis reflect the broad range of potential requirements. These are factors that cannot be considered as design options but rather are expected to vary in a scenario-dependent way.

1. Deck use efficiency (DeckUseEff): The proportion of the deck size or the cargo payload weight utilized during transit. If the value is equal to one, then an efficiency of 100 percent is assumed.

2. Number of shore spots (ShoreSpots): The number of spots that are available to unload the T-Crafts on the shore. The number of shore spots is a noise factor because it depends upon the shape of the coast. We would expect the expeditionary force to seek a region of shore that can accommodate all available T-Crafts. However, because many shore regions do not have long beach's we have to consider the possibility that there may be a limited number of shore spots.

3. Probability of hit during transit (ProbHit): The probability of hit for a batch during transit from sea base to shore and back is a number between 0 and 1. We assume that this probability is independent of both the distance between the sea base and shore and the speed of the T-Craft.

4. Probability of hit during unloading (ProbHitUnload): The probability of hit per hour for a batch during unloading at the shore is a number between 0 and 1. We assume that the probability of hit during unloading increases with longer unloading times.

5. Attrition Rate (AttritionRate): The attrition rate is a number between 0 and 1 that defines how the troops onboard are reduced if the T-Craft takes a hit.

6. Probability of sinking (ProbSinkHit.1 to ProbSinkHit.4): These four variables define the conditional probability of sinking based on the number of hits the T-Crafts sustains. The probability of sinking increases when the T-Crafts take more hits. A T-Craft sinks with probability one after the fifth hit. When a T-Craft sinks, during transit all troops and cargo onboard will be destroyed; when a T-Craft sinks during unloading the troops onboard are reduced but survive.

2. Primary Output Variables

This section describes the primary output variables which are used as MOEs. The most important output variables are:

1. Time to complete a mission (TNOW at the end of mission): The time to complete a mission is measured in hours via time stamp just before the model terminates.

2. Proportion of cargo successfully delivered onshore (PropCargoOnShore): This variable represents the fraction of troops and cargo that reaches the shore compared with the overall amount of troops that had to be projected to the shore in the beginning of the mission.

3. Proportion of T-Crafts destroyed (PropTcraftDestroyed): The proportion of T-Crafts that not survive the mission.

E. PRIMARY PROCESSES

A process describes actions that entities take within the system. The processes are directly related to the resources described in section B of the chapter. An Arena Basic *Process* module can perform four different types of actions: Delay, Seize Delay, Seize Delay Release, and Delay Release. Figure 14 represents the GUI associated with an Arena Basic Process.

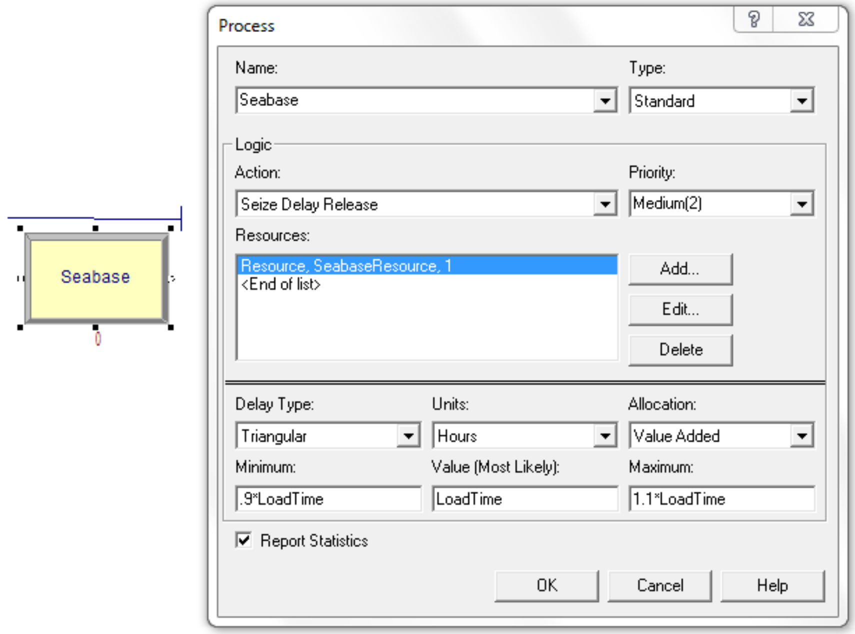


Figure 14. The Sea Base GUI of the Arena Process Module with a Triangular Distribution for the Delay

This section describes the major processes built into the thesis model. The primary processes are the sea base operations, the shore operations, and the sea base operations with refueling.

1. Sea base operations: At the sea base, the T-Crafts are loaded. The sea base provides as many sea spots as defined in the decision factor "number of sea spots." T-Craft entities experience a random delay with the specified mean load time. Triangular and shifted exponential distributions were utilized in the design of experiments to assess whether the degree of skewness in the distribution had an impact on the results. In Figure 14, the triangular distribution is shown. Changing the distribution to a shifted exponential distribution was done using a second model. The shifted exponential distribution is shown in Figure 15.

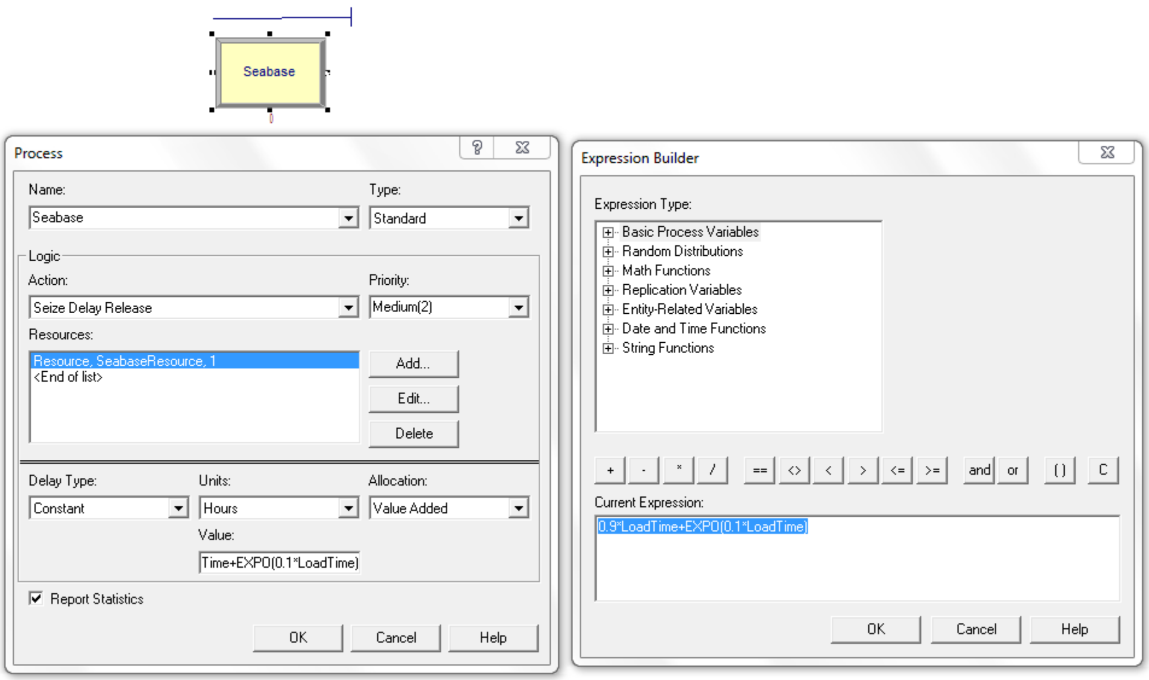


Figure 15. The Sea Base GUI of the Arena Process Module with a Shifted Exponential Distribution for the Delay

2. Shore operations: At the shore, the T-Crafts are unloaded. The shore provides as many shore spots as defined in the decision factor number of shore spots. T-Craft entities are delayed by the unload time. As in the sea base process, the unload time just represents the mean of the delay; the actual delay is a random variable. Triangular and shifted exponential distributions were used for the shore process similarly to the sea base process.

3. Sea base with refueling: This process includes the sea base process, but in addition the T-Craft entities are refueled as a separate process. This increases the delay for the entities. The refueling delay depends on the refueling rate and the amount of fuel required, which is based on the consumption in loaded and unloaded condition. All of these three factors are given by the Excel input file. Figure 16 shows the process using a shifted exponential distribution.

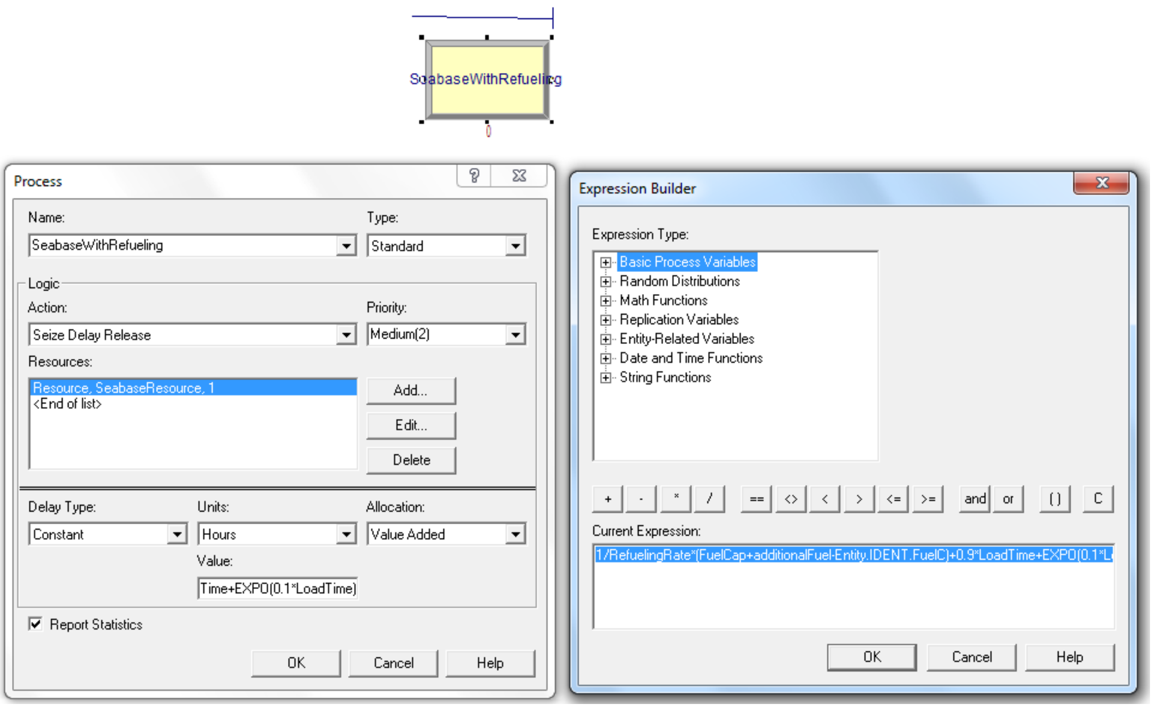


Figure 16. The Sea Base with Refueling GUI of the Arena Process Module with a Shifted Exponential Distribution for the Delay

IV. EXPERIMENTAL DESIGN

A. INTRODUCTION

Simulation models can be very complex and may need a large number of input variables. Some, but not all of these input parameters have a significant impact on the MOEs. Because the values of the input parameters are uncertain, the input parameters have to be sampled across their possible ranges. Additionally, the response surfaces may be nonlinear (Law & Kelton, 2000). In Chapter III section D, we described the variables that are used in the model. In this chapter, we explain the design that was used throughout the research and then describe the process of running the experiments.

B. EXPERIMENTAL DESIGN AND ANALYSIS PROCESS

Developing a simulation model and analyzing the data is an iterative process to ensure that the model works properly and that the output data are usable. At the beginning, the model developer starts with a small number of input parameters to become familiar with the experimental design and to identify bugs in the model. During the developing process, the size of the model and the amount of input parameters increases. This is also done with the model that has been developed for the purposes of this thesis. In the next step, for the full experiment, the ranges of the input parameters are defined as close to the expected ranges as possible in order to get results that are comparable to the real world scenario. After defining the ranges of the input parameters, the experiment is designed. Finally, the experiment is run and the final set of results for analysis is obtained.

1. Nearly Orthogonal Latin Hypercube (NOLH)

NOLH designs were developed by Thomas Cioppa (2002) for his Ph.D. dissertation *Efficient nearly orthogonal and space-filling experimental designs for high-dimensional complex models*. NOLH designs have good space filling and orthogonality properties, which means that the columns in the design matrix have correlations very near zero (Cioppa, 2002). This allows us to explore complex simulation models efficiently. Unlike two-level fractional factorial designs, which have only high and low settings and assume linearity of all factor terms in the model, the NOLH design makes it possible to detect nonlinearities that are prevalent in simulation models. Professor Susan M. Sanchez (2005) from the Naval Postgraduate School created an Excel NOLH generation tool (http://diana.cs.nps.navy.mil/SeedLab) that has been used to generate the NOLH designs for this thesis.

2. Design of Experiments

For the analysis of this thesis, two different scenarios were investigated. The first scenario simulates the process of projecting troops from the sea base to shore without an enemy threat; the second scenario considers the presence of an enemy. The design of each of these scenarios is described below.

a. Scenario Without Enemy Threat

The scenario without enemy threat requires a smaller set of input parameters than the model provides. In fact, 22 input parameters with 19 decision factors and 3 noise factors were used, which are listed in Table 5. The smallest NOLH which can accommodate 22 factors requires 129 design points. In order to improve the space filling 21 column rotations of the NOLH were added, yielding 2817 design points. The scatter plot matrix of the design points is shown in Figure 17. Note that, with the exception of the qualitative factors, the resulting design densely fills the space for all pair wise combinations of factors. For each design point 45 replications were made, resulting in a total of 126,765 runs.

Table 5. Summary of Factors for the Scenario Without Enemy Threat

S/N	Factor	MIN VALUE	MAX VALUE	
1	Cargo Payload Weight (LT)	300	1000	Decision Factors
2	Cargo Deck Size (sqft)	2200	10000	
3	Speed SES (knts)	35	55	
4	Speed ACV (knts)	4	10	
5	Load Time (hrs)	1	5	
6	Unload Time (hrs)	1	4	
7	Time to Convert to ACV (hrs)	0.25	1	
8	Time to Convert to SES (hrs)	0.25	1	
9	# T-Crafts	6	22	
10	# SeaSpots	5	13	
11	Refueling during loading? (1-yes, 0-no)	0	1	
12	Refueling rate (tons/hour)	80	160	
13	Tank capacity (LT)	110	150	
14	ProbFailure	0.01	0.1	
15	Time to repair (hrs)	1	3	
16	Total Load (LT)	5000	40000	
17	Footprint MEB (sqft)	50000	120000	
18	Distance (nm)	25	250	
19	TransitionDistance (nm)	0.5	5	
20	Deck Use Efficiency (between 0 and 1)	0.7	0.95	Noise Factors
21	# ShoreSpots	3	22	
22	Distribution (0-TRIA, 1-ShiftedEXPO)	0	1	

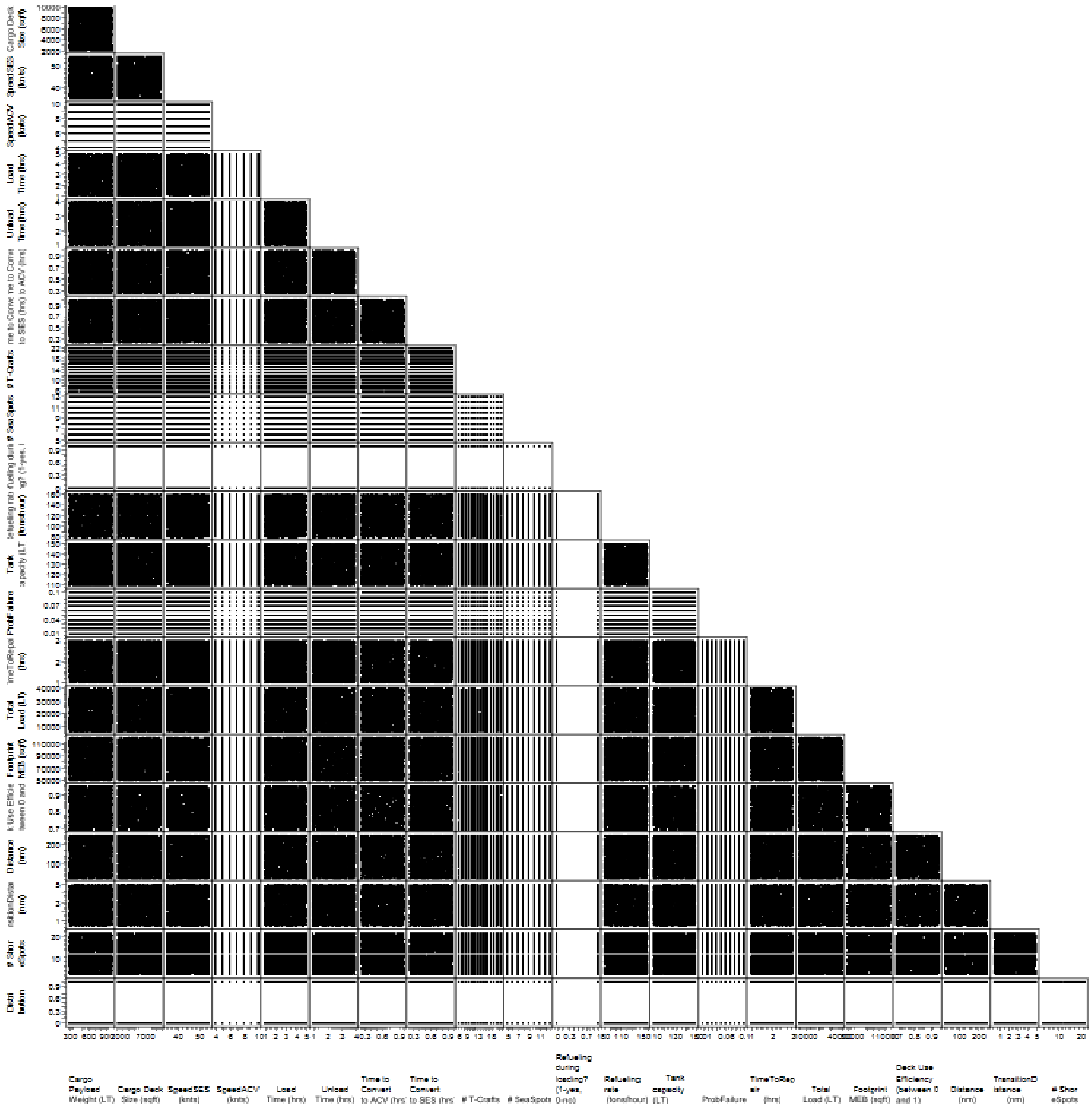


Figure 17. Scatterplot Matrix for the Scenario Without Enemy Threat

b. Scenario With Enemy Threat

The scenario with enemy threat requires the full set of model input parameters. The scenario has 31 input parameters with 21 decision factors and 10 noise factors; the parameters are listed in Table 6. Two of the 31 input parameters have binary values. For the other 29 decision factors, a NOLH with 257 design points is used. In order to improve the space filling, 28 column rotations of the NOLH were added, yielding 7425 design points. A Hadamard design matrix (Sanchez & Sanchez, 2005) was used for the 2 binary input parameters and crossed with the NOLH for a total of 29,700 design points. The scatter plot matrix of the design points is shown in Figure 18. As before, note that the resulting design densely fills the factor space for all pair wise combinations of quantitative factors. For each design point four replications were made, resulting in a total of 118,800 runs.

Table 6. Summary of Factors for the Scenario With Enemy Threat

S/N	Factor	MIN VALUE	MAX VALUE	
1	Cargo Payload Weight (LT)	300	1000	Decision Factors
2	Cargo Deck Size (sqft)	2200	10000	
3	Speed SES (knts)	35	55	
4	Speed ACV (knts)	4	10	
5	Load Time (hrs)	1	5	
6	Unload Time (hrs)	1	4	
7	Time to Convert to ACV (hrs)	0.25	1	
8	Time to Convert to SES (hrs)	0.25	1	
9	# T-Crafts	6	22	
10	# SeaSpots	5	13	
11	Refueling during loading? (1-yes, 0-no)	0	1	
12	Refueling rate (tons/hour)	80	160	
13	Tank capacity (LT)	110	150	
14	Batchsize	1	22	
15	ProbFailure	0.01	0.1	
16	Time to repair (hrs)	1	3	
17	# hits to repair	1	5	
18	Total Load (LT)	5000	40000	
19	Footprint MEB (sqft)	50000	120000	
20	Distance (nm)	25	250	
21	TransitionDistance (nm)	0.5	5	
22	Deck Use Efficiency (between 0 and 1)	0.7	0.95	Noise Factors
23	# ShoreSpots	3	22	
24	ProbHit Batch (%)	0.01	0.5	
25	ProbHit Batch during Unloading (per hour)	0.01	0.5	
26	AttritionRate Troops	0.01	0.5	
27	ProbSink (1 Hit)	0.01	0.3	
28	ProbSink (2 Hits)	0.31	0.5	
29	ProbSink (3 Hits)	0.51	0.75	
30	ProbSink (4 Hits)	0.76	0.99	
31	Distribution (0-TRIA, 1-ShiftedEXPO)	0	1	

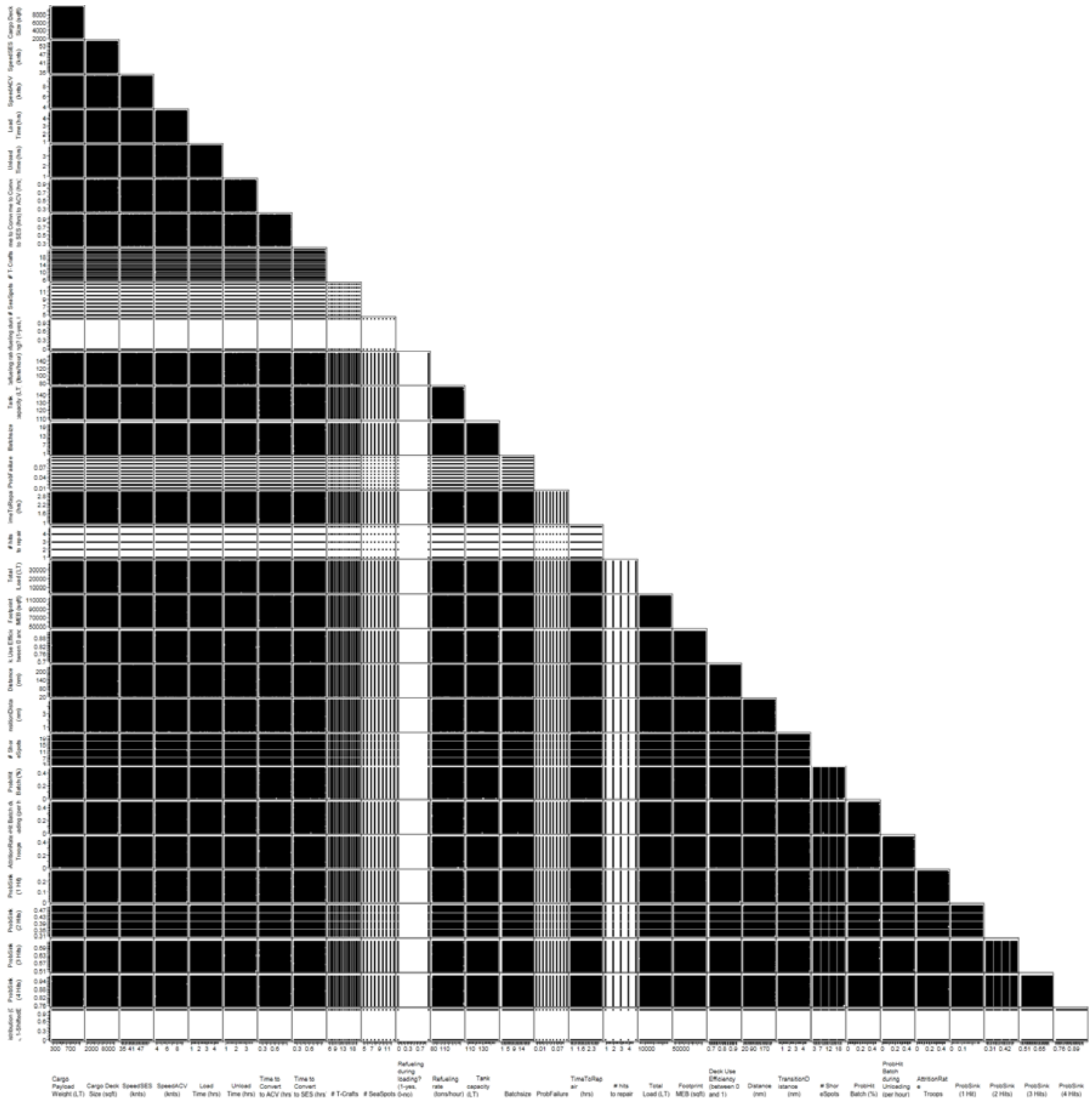


Figure 18. Scatterplot Matrix for the Scenario With Enemy Threat

C. RUNNING THE EXPERIMENT

Both scenario data sets require that the data are divided into two data sets. This is necessary to vary between the triangular and the shifted exponential distribution for the Loading and Unloading time. In order to implement the distribution in the experiment, two different simulation models were used. After designing the experiments, the data sets were divided. All runs that have a zero for the distribution input parameter were used for the model with the triangular distribution; all runs with a one for the distribution input parameter were used for the model with the shifted exponential distribution. The running of each of the two models in each of the scenario sets takes approximately eight to nine hours on an Intel Core Duo computer, which means that the running of one scenario set takes about 16 to 18 hours to complete. The amount of runs in each scenario provides adequate precision to resolve differences in statistically significant ways, while the computing time is still acceptable. The Arena random number generator ensures that the individual runs are independent from each other even if the same design point is used.

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V. DATA ANALYSIS

The scenario sets described in Chapter IV generate a large amount of data for analysis. We describe the collection and processing of the data. Following a detailed analysis of the MOEs of interest, we present the resulting insights.

A. DATA COLLECTION AND PROCESSING

Arena provides the opportunity to do data collection by the Process Analyzer. This tool provides statistical averages of replications in each run. Although this tool is useful for some applications, the run average data do not give an analyst enough insights about the outcomes. Working with the full output of the simulation gives us more information and more options for analysis. Response data from individual runs are written to the Excel spreadsheet input-output file which has been described in Chapter III. When an individual run terminates, the model writes the output of statistics created by the simulation to the specified Excel file. Figure 19 shows the *ReadWrite* module and its GUI that is used to write the output of statistics into the Excel file.

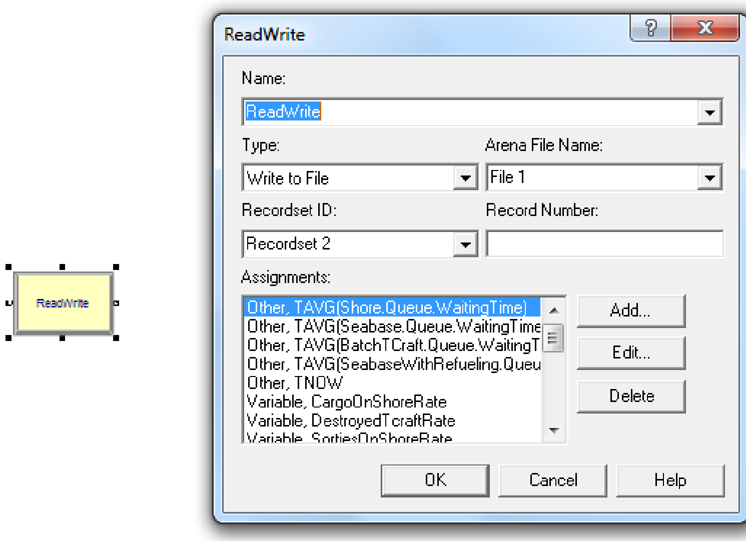


Figure 19. The ReadWrite Module and its GUI in Arena

The *ReadWrite* module is very flexible, so the analyst can define as many output statistics as needed for the analysis. The statistics can be provided by Arena or be defined by the analyst in the model.

The data that are written to the Excel file can immediately be post-processed by importing them into the statistical analysis software. We used JMP Statistical Discovery Software Version 8.0 for the analysis which follows.

B. INSIGHTS INTO RESEARCH QUESTIONS

Recall from Chapter I that we posed the following questions:

- How many T-Crafts are required to execute a mission within the mission time constraint?
- If there is an enemy threat capable of damaging or sinking the T-Crafts, how many additional T-Crafts are needed to accomplish the mission?
- How survivable does the T-Craft need to be?
- What are the tonnage capacity and deck size of a T-Craft that can successfully execute the spectrum of anticipated missions?
- How many spots are needed to load and unload the T-Crafts?
- How important are the speed, the load time, and the unload time of the T-Craft?
- How do fuel consumption and the frequency of refueling events impact operations?

The data analyses of the following section addresses directly these questions.

1. MOE Correlation Analysis

One question of immediate concern is whether all of the MOEs are really needed for the data analysis. In the scenario without enemy threat there is only one MOE. However, the scenario with enemy threat has multiple MOEs and it is worth investigating their correlation structure. The Correlation Multivariate Tool in JMP allows us to generate a matrix of correlation coefficients that shows the degree of linear relationship between the various MOEs. A high degree of correlation between two MOEs would indicate that one of them could be considered redundant. Figure 20 shows the scatter plot matrix and the correlation matrix for the scenario with enemy threat.

From Figure 20, it can be seen that the time to complete mission and the proportion of cargo onshore are only weakly correlated. The correlation between the time to complete mission and the proportion of T-Craft destroyed is moderate, which is not surprising because a high proportion of T-Crafts destroyed increases the time that is needed to finish a mission. Note that contrasting black versus white areas in the scatterplot matrix is misleading due to the huge volume of data—we recommend that the reader focus on the numerical correlation values of Figure 20 in considering whether the MOEs are co-linear.

Correlations

	TimeToComplete(Arena) (hrs)	PropCargoOnShore	PropTcraftDestroyed
TimeToComplete(Arena) (hrs)	1.0000	-0.1224	0.4679
PropCargoOnShore	-0.1224	1.0000	-0.6850
PropTcraftDestroyed	0.4679	-0.6850	1.0000

The correlations are estimated by Pairwise method.

Scatterplot Matrix

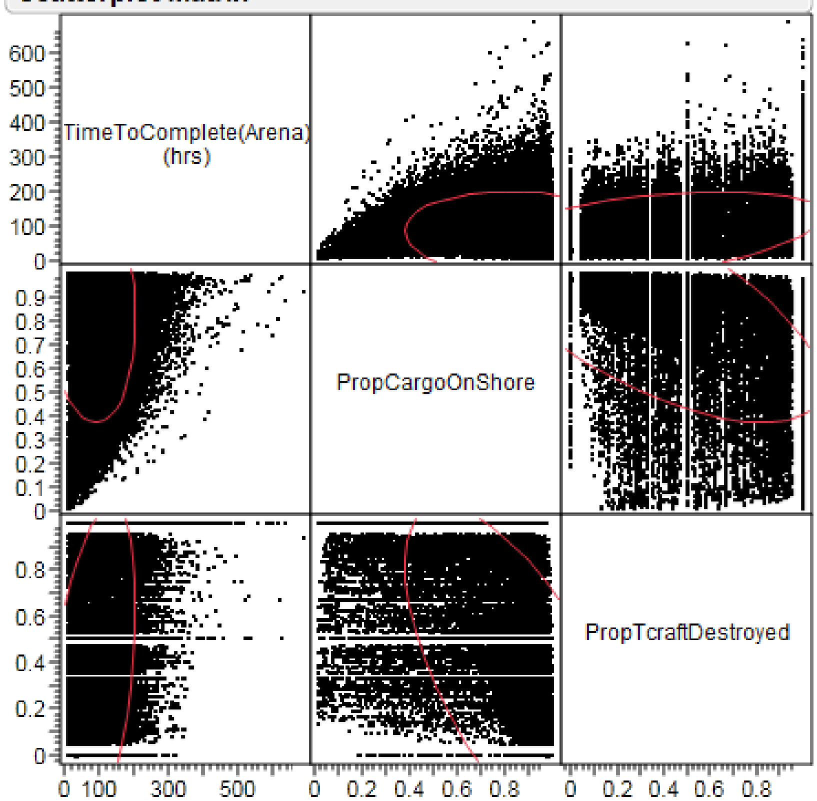


Figure 20. Correlation and Scatterplot Matrix for MOEs

The highest correlation is between the proportion of cargo onshore and proportion of T-Craft destroyed. These two MOEs show a moderate negative correlation (-0.685). This result is also not surprising—a higher proportion of T-Craft destroyed decreases the amount of troops that are projected to shore during a mission.

Because we have no strong correlation between the three MOEs, the analysis in this section uses all of them as separate measures of the influence of changing requirements and assessing parameter variability.

2. Analysis of the Scenario Without Enemy Threat

This section analyzes the data of the scenario without enemy threat. Figure 21 shows the distribution of all 126,765 runs of this scenario. This histogram illustrates that there is a broad range of possible outcomes across the scenarios.

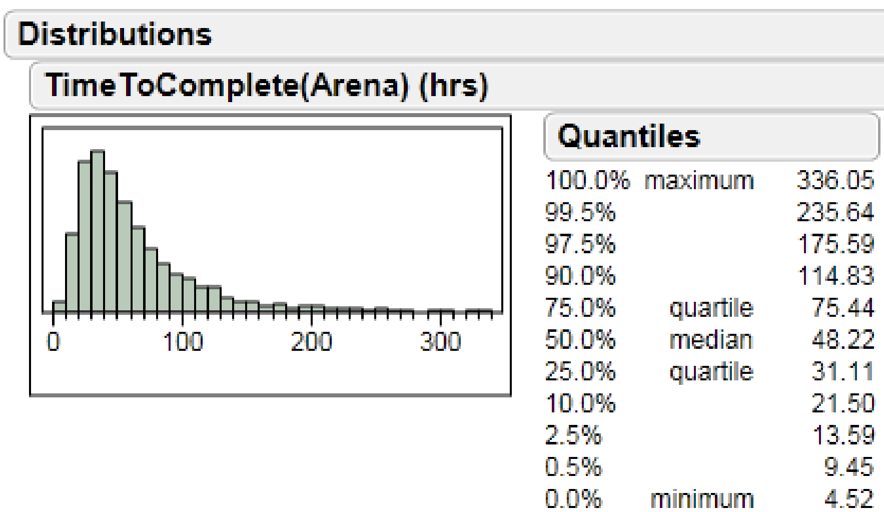
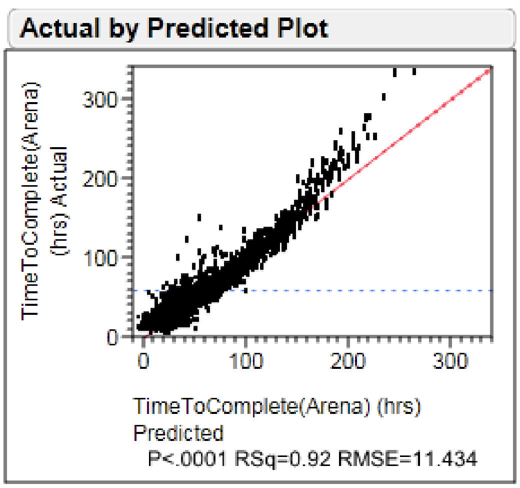


Figure 21. Scenario Without Enemy Threat: Distribution of Time to Complete Mission

The histogram shows that the distribution is unimodal and skewed right. Therefore, the percentiles of the distribution will give us a better understanding than a confidence interval about the mean would. The median of all outcomes is 48.22 hours. Notice that almost all outcomes are beyond the U.S. Navy's target value of 10 hours for time to complete mission. Only about 0.78 percent of the outcomes are within the 10-hour time frame.

a. Regression Analysis

In order to quantify the effects of different requirements to the system, we need to explore the factors in the model that are the most important. To identify these factors, we use regression analysis. As a first step, we are interested in which factors are the most important for the time to complete the mission, regardless of whether the factors are decision or noise factors. Our model is a linear regression with 2-way interaction and polynomial terms to degree four for all factors. For doing the analysis, we also have to consider practical versus statistical significance. In *Probability and Statistics* (7^{th} edition), Jay L. Devore (2008) points out that "a small p-value, which would ordinarily indicate statistical significance […], may be the result of a large sample size in combination with a departure from H_0 that has little practical significance." Devore also emphasizes that "in many experimental situations, only departures from H_0 of large magnitude would be worthy of detection, whereas a small departure from H_0 would have little practical significance." Since we have a sample size of 126,765 experiments we have to consider statistical versus practical significance very carefully. Otherwise, the models may suffer from overfitting. The results of the model we chose are displayed in Figures 22 and 23.



Summary of Fit

RSquare	0.924807
RSquare Adj	0.924791
Root Mean Square Error	11.43412
Mean of Response	59.71518
Observations (or Sum Wgts)	126765

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	27	203790041	7547779	57731.65
Error	126737	16569471	131	**Prob > F**
C. Total	126764	220359512		0.0000*

Figure 22. Regression Model with all Factors of the Scenario Without Enemy Threat

The R-Square for this model is 0.9248. The four most important factors are the total load of the troops, the distance between sea base and shore, the cargo payload weight of the T-Crafts, and the number of T-Crafts available. These four factors are followed by the speed in SES mode, the load time, the deck use efficiency, and the unload time. All other factors show no practical significance.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Total Load (LT)	0.0021048	3.146e-6	669.03	0.0000*
Distance (nm)	0.1780517	0.000489	363.88	0.0000*
(Cargo Payload Weight (LT)-650.016)*(Total Load (LT)-22500)	-4.533e-6	1.59e-8	-285.1	0.0000*
(# T-Crafts-14.0625)*(Total Load (LT)-22500)	-0.000157	6.92e-7	-226.2	0.0000*
(# T-Crafts-14.0625)*(# T-Crafts-14.0625)	0.3231188	0.001646	196.33	0.0000*
# T-Crafts	-3.163917	0.016846	-187.8	0.0000*
(Cargo Payload Weight (LT)-650.016)*(# T-Crafts-14.0625)	0.0062398	3.366e-5	185.37	0.0000*
Cargo Payload Weight (LT)	-0.066506	0.000394	-169.0	0.0000*
(Cargo Payload Weight (LT)-650.016)*(Cargo Payload Weight (LT)-650.016)	0.0001387	8.743e-7	158.66	0.0000*
(# T-Crafts-14.0625)*(Distance (nm)-137.5)	-0.014585	0.000105	-139.1	0.0000*
(Total Load (LT)-22500)*(Distance (nm)-137.5)	5.9923e-6	4.88e-8	122.79	0.0000*
(Cargo Payload Weight (LT)-650.016)*(Distance (nm)-137.5)	-0.000248	2.293e-6	-108.3	0.0000*
SpeedSES (knts)	-0.519899	0.005482	-94.84	0.0000*
Load Time (hrs)	4.6528929	0.068893	67.54	0.0000*
Deck Use Efficiency (between 0 and 1)	-63.68459	1.097222	-58.04	0.0000*
(# T-Crafts-14.0625)*(# T-Crafts-14.0625)*(# T-Crafts-14.0625)	-0.021975	0.000388	-56.59	0.0000*
Unload Time (hrs)	5.1278135	0.091764	55.88	0.0000*

Prediction Profiler

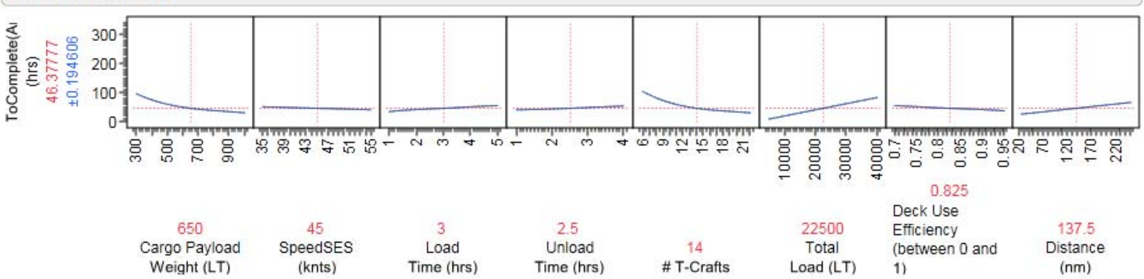


Figure 23. Most Important Parameter Estimates and Prediction Profiler of the Regression Model with all Factors of the Scenario Without Enemy Threat

One of the main results of this regression model is that almost all of the important factors are considered as decision factors. The only noise factor that appears to be significant is deck use efficiency.

We recommend that when deciding which of the T-Craft prototypes to procure, the Navy should focus on those factors that show high practical significance (see Figure 23). We were surprised to find that many of the factors we considered and implemented in the model show no practical significance. The first example is the deck size area and the footprint of troops. This shows that the Navy should focus on cargo payload weight when deciding for a particular prototype. For planning issues, the Military Commanders should focus on the total load of the troops that has to be projected to shore. The second example is speed in ACV mode, transition distance, and time spent converting between the modes. The whole process of converting between the modes and traveling in ACV mode shows no practical significance in the model. Similarly, the number of sea spots and shore spots that are available does not appear to be significant. Recall that we varied the number of sea spots between six and 13 and the number of shore spots between three and 22. It is surprising that these variations have no practical significance on time to complete mission over the broad range of scenarios that we explored. Additionally, all factors that are related to refueling appear to have no practical significance. Upon closer look, this result is not surprising because refueling is not necessary in many scenarios. Finally, we investigated the use of different distributions (triangular versus shifted exponential distribution) for loading and unloading times, but found no significant impact. This result is important to future modeling efforts, as it indicates that little or no modeling effort need be expended on this issue in the future.

b. Robust Analysis

A big disadvantage of classical regression models is that they predict mean performance. They do not contain any reflection of the potential variability in the response. That is the reason we use robust analysis to investigate T-Craft suitability to assess a variety of military scenarios. The paper Robust Design: Seeking the Best of all Possible Worlds by Susan M. Sanchez (2000) explains robust design in the following way: "In addition to exhibiting an acceptable mean performance, a 'good' system must be relatively insensitive to uncontrollable sources of variation present in the system's environment."

Robust design evaluates the performance of an MOE compared to a target value. In practice this is done by a loss function. For this thesis, we used a quadratic loss function, which squares the deviations between our MOEs (the Y in the loss function) and their associated target values τ. The quadratic loss function is therefore:

$$l = (Y - \tau)^2 \qquad (1)$$

The expected loss can thus be written as:

$$E[l] = E\left[(Y - \tau)^2\right] \qquad (2)$$

$$E[l] = E\left[\left(\left(Y - \mu_Y\right) - \left(\tau - \mu_Y\right)\right)^2\right] \quad (3)$$

$$E[l] = E\left[\left(Y - \mu_Y\right)^2 - \left(\tau - \mu_Y\right)^2 - 2(Y - \mu_Y)(\tau - \mu_Y)\right] \quad (4)$$

$$E[l] = E\left[\left(Y - \mu_Y\right)^2\right] + E\left[\left(\tau - \mu_Y\right)^2\right] - 2(\tau - \mu_Y)E\left[(Y - \mu_Y)\right] \quad (5)$$

$$E[l] = \mathrm{Var}(Y) + \left(\tau - \mu_Y\right)^2 - 2(\tau - \mu_Y)\left[E[Y] - \mu_Y\right] \quad (6)$$

$$E[l] = \mathrm{Var}(Y) + \left(\tau - \mu_Y\right)^2 \quad (7)$$

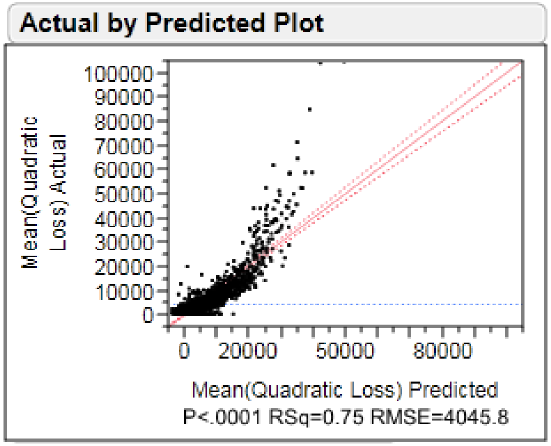
Equation 7 tells us that an ideal configuration has a mean for the MOE that is equal to the target value τ and has no variability. In other words, the ideal system always achieves its performance target with perfect consistency.

If the system has homogeneous variance, then robust analysis will yield identical results to classical regression. However, when variance is heterogeneous the results can be quite different. Because heterogeneous variance is the norm in simulation models, robust analysis is a better tool to use when analyzing simulation performance. In practice it is quite straightforward—we can estimate expected loss by calculating equation 1 for each run of the simulation and averaging the result over the noise factors of the model input parameters and the replications to estimate expected loss at each decision design point.

Recall from Chapter II section B.2. that the U.S. Navy's target value τ for projecting Assault Echelon Forces from the sea base to the shore is 10 hours. Y is the Arena outcome for time to complete mission. We use these values and get the following formula as the loss function for time to completion of mission:

$$\text{Loss} = (\text{TimeToComplete} - 10)^2 \quad (8)$$

Equation 8 is the basis for our robust analysis. Before we can build the regression model for the robust design, we have to average over the noise factors. The results for the regression model for the Mean (Quadratic Loss Time) are presented in Figure 24.



Summary of Fit

RSquare	0.750255
RSquare Adj	0.748738
Root Mean Square Error	4045.792
Mean of Response	4209.93
Observations (or Sum Wgts)	2817

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	17	1.3763e+11	8.0961e+9	494.6143
Error	2799	4.5815e+10	16368436	Prob > F
C. Total	2816	1.8345e+11		0.0000*

Figure 24. Regression Model for Mean(Quadratic Loss Time) of the Scenario Without Enemy Threat

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Total Load (LT)	0.2935866	0.007463	39.34	<.0001*
(Cargo Payload Weight (LT)-650.016)*(Total Load (LT)-22500)	-0.00107	3.77e-5	-28.39	<.0001*
(# T-Crafts-14.0625)*(Total Load (LT)-22500)	-0.043803	0.001641	-26.70	<.0001*
(Cargo Payload Weight (LT)-650.016)*(# T-Crafts-14.0625)	1.9036032	0.079507	23.94	<.0001*
Distance (nm)	27.002481	1.160797	23.26	<.0001*
(# T-Crafts-14.0625)*(# T-Crafts-14.0625)	72.191391	3.883721	18.59	<.0001*
(# T-Crafts-14.0625)*(Distance (nm)-137.5)	-4.087281	0.24878	-16.43	<.0001*
(Total Load (LT)-22500)*(Distance (nm)-137.5)	0.0017975	0.000116	15.56	<.0001*
(Cargo Payload Weight (LT)-650.016)*(Cargo Payload Weight (LT)-650.016)	0.0315693	0.002066	15.28	<.0001*
(Cargo Payload Weight (LT)-650.016)*(Distance (nm)-137.5)	-0.077884	0.005441	-14.31	<.0001*
# T-Crafts	-457.2041	39.83626	-11.48	<.0001*
Cargo Payload Weight (LT)	-10.35837	0.932523	-11.11	<.0001*
Load Time (hrs)	652.2218	65.27028	9.99	<.0001*
(Total Load (LT)-22500)*(Total Load (LT)-22500)	8.1841e-6	8.29e-7	9.87	<.0001*
(Load Time (hrs)-3.00062)*(Total Load (LT)-22500)	0.0480511	0.006753	7.12	<.0001*
(# T-Crafts-14.0625)*(# T-Crafts-14.0625)*(# T-Crafts-14.0625)	-4.328965	0.917386	-4.72	<.0001*

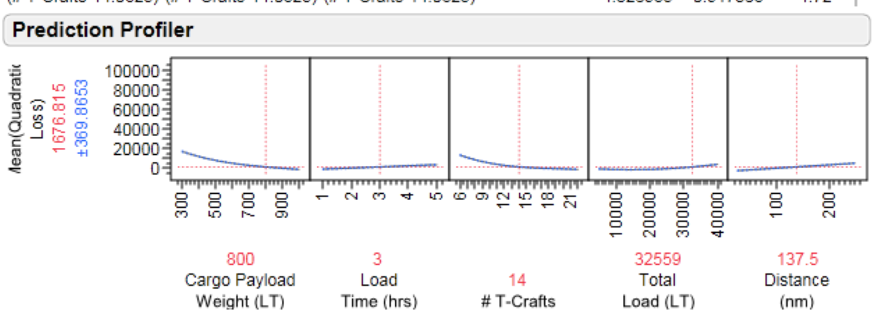


Figure 25. Sorted Parameter Estimates and Prediction Profiler for the Regression Model for Mean(Quadratic Loss Time) of the Scenario Without Enemy Threat

As before, we focus on factors of practical rather than statistical significance. The robust model we chose has an R-Square of 0.7502. The parameter estimates and the prediction profiler are shown in Figure 25 and the interaction profiles in Figure 26. When we have a closer look at the results of Figures 25 and 26, it turns out that the total load of troops is dominant. We have set the value for the total load to 32559 LT in the prediction profiler because this is the weight of the heaviest forces that are projected for the MEB 2024.

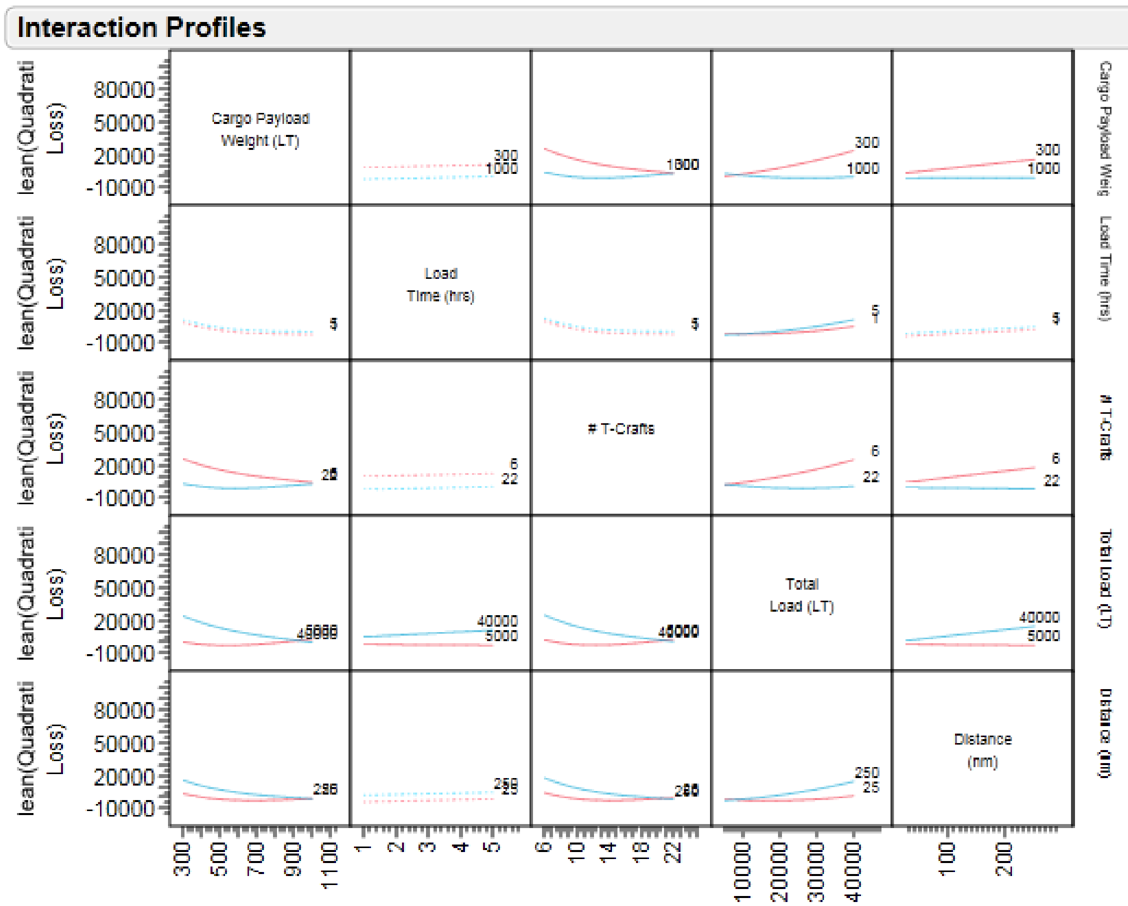


Figure 26. Interaction Profiles for the Regression Model of Mean (Quadratic Loss Time) of the Scenario Without Enemy Threat

There is an interaction between the total load and the number of T-Crafts available. Having a higher number of T-Crafts decreases the impact of the total load. There is also an interaction between the total load and the cargo payload weight of the T-Craft—if the cargo payload weight of the T-Craft is low then mission performance will be significantly degraded by large total load requirements. Having a high cargo payload weight reduces the loss significantly. From Figure 25 we, conclude that the cargo payload weight should meet or exceed 750 LT, which is mentioned in the BAA #05-20. Figure 26 also shows that the cargo payload weight has an interaction with the number of T-Crafts available. From the graphs, it appears that the number of T-Crafts available should be at least 14. For heavy load requirements, the number of T-Crafts available should be as large as possible to get robust results. Finally, load time and distance also have a significant impact on mission success. The design of the sea base should facilitate loading times to whatever extent possible, and the commander consider placing the sea base as close to the landing area as possible without subjecting it to undue risk.

We supplemented the regression analysis with a partition tree analysis, but did not gain any additional insights.

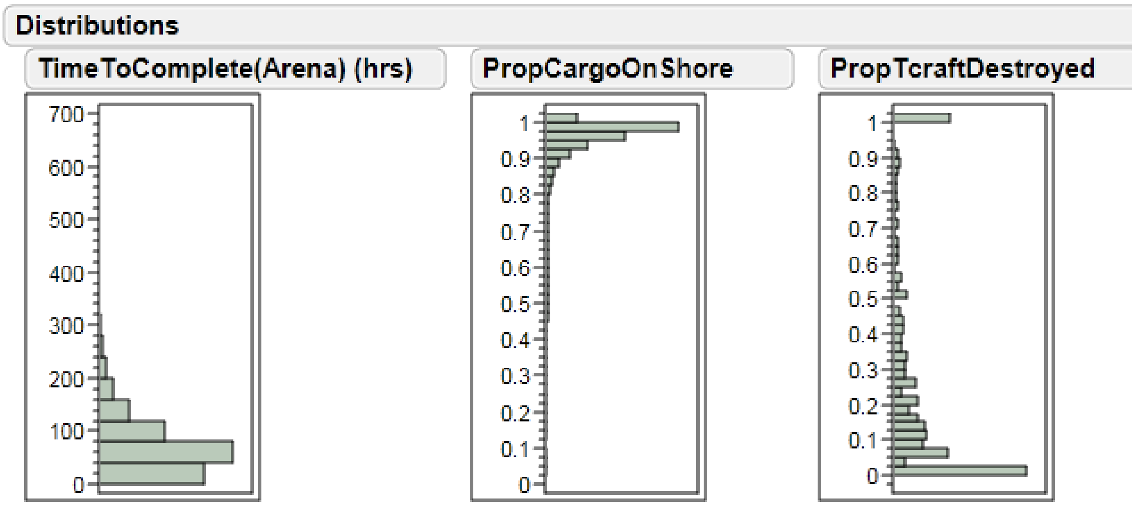
3. Analysis of the Scenario With Enemy Threat

We now proceed to an analysis of scenarios with enemy threat. Figure 27 shows the distribution of all 118,800 runs for the time to complete mission, the proportion of cargo successfully delivered onshore, and the proportion of T-Craft destroyed. As in the missions without enemy threat, there is a broad range of possible outcomes across the scenarios. All three of the distributions are skewed. Time to complete mission and proportion of cargo successfully delivered onshore are unimodal, while proportion of T-Craft destroyed shows two peaks at zero and one.

The median of all outcomes for time to complete mission is now 59.76 hours, which is more than 10 hours higher than the scenario without enemy threat. Again, almost all outcomes are beyond the U.S. Navy's target value of 10 hours for time to complete mission. Only about 0.47 percent of the outcomes are within the 10-hour time frame.

The median of the outcomes for proportion of cargo successfully delivered onshore is 0.96 while 75 percent of the outcomes show a proportion onshore rate of 0.89 or higher. Only 10 percent of the outcomes have a proportion of cargo successfully delivered onshore lower than 0.55.

The proportion of T-Craft destroyed has a median of 0.1667, 25 percent of the outcomes show a proportion of T-Craft destroyed lower than 0.0526 and 75 percent of the outcomes are lower than 0.44. Additionally, 10 percent of the outcomes show a proportion of T-Craft destroyed higher than 0.9.



Quantiles (TimeToComplete(Arena) (hrs))

100.0%	maximum	691.43
99.5%		285.89
97.5%		211.74
90.0%		142.76
75.0%	quartile	96.94
50.0%	median	59.76
25.0%	quartile	36.20
10.0%		23.81
2.5%		13.88
0.5%		10.11
0.0%	minimum	5.78

Quantiles (PropCargoOnShore)

100.0%	maximum	1.0000
99.5%		1.0000
97.5%		1.0000
90.0%		0.9973
75.0%	quartile	0.9870
50.0%	median	0.9619
25.0%	quartile	0.8932
10.0%		0.5518
2.5%		0.2339
0.5%		0.0657
0.0%	minimum	0.0033

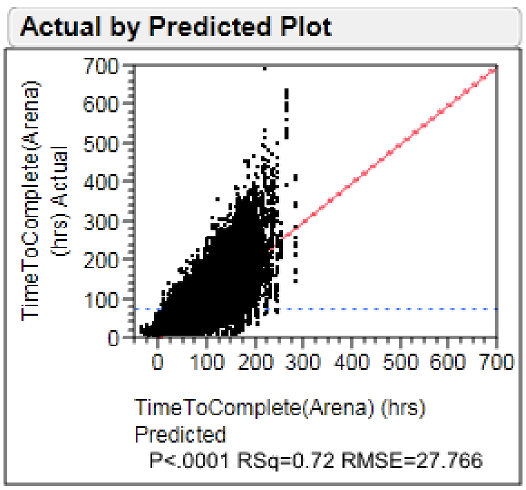
Quantiles (PropTcraftDestroyed)

100.0%	maximum	1.0000
99.5%		1.0000
97.5%		1.0000
90.0%		0.9000
75.0%	quartile	0.4444
50.0%	median	0.1667
25.0%	quartile	0.0526
10.0%		0.0000
2.5%		0.0000
0.5%		0.0000
0.0%	minimum	0.0000

Figure 27. Distribution of Time to Complete Mission, Proportion of Cargo Successfully Delivered Onshore and Proportion of T-Craft Destroyed of the Scenario With Enemy Threat

a. Regression Analysis

As in the scenario without enemy threat, we first explore the factors that have the highest practical importance. We are interested in which factors are the most important for all MOEs regardless of whether the factors are decision or noise factors. For this reason, we created regression models for our three MOEs with 2-way interaction and polynomial terms to degree four for all factors. The first MOE that we consider is time to complete mission. The results are shown in Figure 28. The R-Square for this model is 0.721. Having a closer look at the parameter estimates (Table 7), we conclude that the six most important factors are the total load, the number of T-Crafts available, the distance, the load time, the cargo payload weight of the T-Crafts, and the deck use efficiency. These six factors are followed by the batch size, unload time, speed in SES mode and cargo deck size. The result is fairly comparable with the results observed in the scenario without enemy threat. There are two new factors: the batch size and the cargo deck size. Because the batch size is always one in the scenario without enemy threat, the absence in that scenario is not surprising. Only one noise factor appears to be significant: the deck use efficiency. All other factors show no practical significance. Overall, the results from this scenario are consistent with the scenario without enemy threat for time to complete mission.



Summary of Fit

RSquare	0.720966
RSquare Adj	0.72091
Root Mean Square Error	27.76593
Mean of Response	73.97071
Observations (or Sum Wgts)	118800

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	24	236596237	9858177	12787.11
Error	118775	91569195	771	**Prob > F**
C. Total	118799	328165432		0.0000*

Figure 28. Regression Model for the Time to Complete Mission with all Factors of the Scenario With Enemy Threat

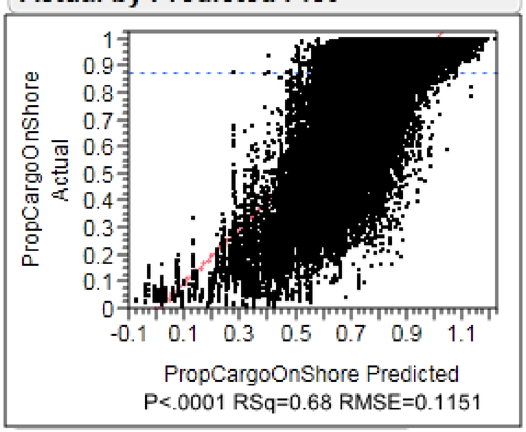
Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Total Load (LT)	0.0026753	7.928e-6	337.47	0.0000*
# T-Crafts	-3.591615	0.017278	-207.9	0.0000*
Distance (nm)	0.2052984	0.001233	166.44	0.0000*
(Cargo Payload Weight (LT)-650.008)*(Total Load (LT)-22500)	-4.524e-6	3.977e-8	-113.7	0.0000*
Load Time (hrs)	6.4959412	0.069367	93.65	0.0000*
Cargo Payload Weight (LT)	-0.075715	0.000992	-76.30	0.0000*
Deck Use Efficiency (between 0 and 1)	-75.73295	1.106947	-68.42	0.0000*
(Total Load (LT)-22500)*(Distance (nm)-137.5)	7.6342e-6	1.207e-7	63.27	0.0000*
(# T-Crafts-14.0312)*(ProbHit Batch during Unloading (per hour)-0.255)	6.6086455	0.121228	54.51	0.0000*
(Batchsize-11.5001)*(Batchsize-11.5001)*(Batchsize-11.5001)	0.0229304	0.000438	52.38	0.0000*
(# T-Crafts-14.0312)*(Distance (nm)-137.5)	-0.01339	0.000268	-49.95	0.0000*
Unload Time (hrs)	4.3466687	0.092533	46.97	0.0000*
SpeedSES (knts)	-0.621699	0.013873	-44.81	0.0000*
(Cargo Deck Size (sqft)-6100.02)*(Total Load (LT)-22500)	1.5404e-7	3.49e-9	44.14	0.0000*
ProbHit Batch during Unloading (per hour)	-21.53346	0.566165	-38.03	<.0001*
(Batchsize-11.5001)*(Batchsize-11.5001)*(Batchsize-11.5001)*(Batchsize-11.5001)	-0.003043	8.023e-5	-37.94	<.0001*
Batchsize	-1.217063	0.032389	-37.58	<.0001*
Cargo Deck Size (sqft)	-0.001249	3.558e-5	-35.10	<.0001*

Table 7. Most Important Parameter Estimates of the Regression Model of the Time to Complete Mission with all Factors of the Scenario With Enemy Threat

Next, the impact of all factors on the proportion of cargo successfully delivered onshore is considered. The results are shown in Figure 29 and Table 8. The R-Square for the model is 0.681.

Actual by Predicted Plot



Summary of Fit

RSquare	0.681015
RSquare Adj	0.680939
Root Mean Square Error	0.115097
Mean of Response	0.875735
Observations (or Sum Wgts)	118800

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	28	3359.0904	119.968	9056.033
Error	118771	1573.3889	0.013	Prob > F
C. Total	118799	4932.4794		0.0000*

Figure 29. Regression Model for the Proportion of Cargo Successfully Delivered Onshore with all Factors of the Scenario With Enemy Threat

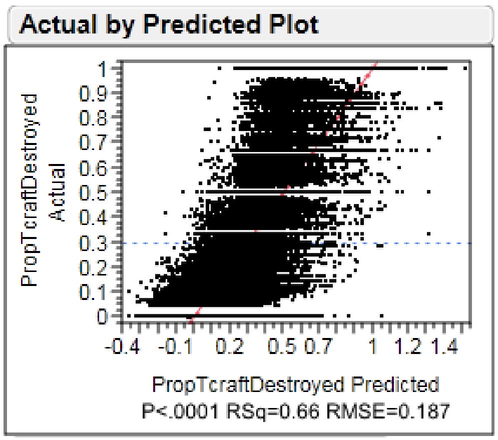
Table 8. Most Important Parameter Estimates of the Regression Model for the Proportion of Cargo Successfully Delivered Onshore with all Factors of the Scenario With Enemy Threat

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
ProbHit Batch during Unloading (per hour)	-0.349755	0.002349	-148.9	0.0000*
Total Load (LT)	-4.442e-6	3.286e-8	-135.2	0.0000*
(Batchsize-11.5001)*(Batchsize-11.5001)*(Batchsize-11.5001)	0.0002377	1.816e-6	130.88	0.0000*
(# T-Crafts-14.0312)*(# T-Crafts-14.0312)	-0.001791	1.713e-5	-104.5	0.0000*
(# T-Crafts-14.0312)*(Total Load (LT)-22500)	6.6519e-7	7.166e-9	92.83	0.0000*
Unload Time (hrs)	-0.033815	0.000384	-88.12	0.0000*
(Batchsize-11.5001)*(Batchsize-11.5001)*(Batchsize-11.5001)*(Batchsize-11.5001)	-2.632e-5	3.33e-7	-79.04	0.0000*
(Batchsize-11.5001)*(ProbHit Batch during Unloading (per hour)-0.255)	0.0294519	0.00039	75.49	0.0000*
(Cargo Payload Weight (LT)-650.008)*(# T-Crafts-14.0312)	-0.000026	3.583e-7	-72.67	0.0000*
(# T-Crafts-14.0312)*(ProbHit Batch during Unloading (per hour)-0.255)	0.0336511	0.000503	66.92	0.0000*
(Cargo Payload Weight (LT)-650.008)*(Total Load (LT)-22500)	9.818e-9	1.65e-10	59.55	0.0000*
(Batchsize-11.5001)*(Total Load (LT)-22500)	3.1312e-7	5.463e-9	57.32	0.0000*
(Total Load (LT)-22500)*(ProbHit Batch during Unloading (per hour)-0.255)	-1.068e-5	2.313e-7	-46.18	0.0000*
(# T-Crafts-14.0312)*(# T-Crafts-14.0312)*(# T-Crafts-14.0312)	0.0001812	4.058e-6	44.66	0.0000*
Cargo Payload Weight (LT)	0.0001582	4.113e-6	38.45	<.0001*
# T-Crafts	0.006577	0.000175	37.56	<.0001*
ProbHit Batch (%)	-0.204877	0.005861	-34.96	<.0001*
Batchsize	-0.004262	0.000134	-31.72	<.0001*
(Batchsize-11.5001)*(Batchsize-11.5001)	0.0007885	0.000034	23.18	<.0001*
AttritionRate Troops	-0.128804	0.005861	-21.98	<.0001*
(Cargo Payload Weight (LT)-650.008)*(Cargo Payload Weight (LT)-650.008)	-3.915e-7	3.184e-8	-12.30	<.0001*
(ProbHit Batch (%)-0.255)*(ProbHit Batch (%)-0.255)	0.7550251	0.064683	11.67	<.0001*

For the proportion of cargo successfully delivered onshore, the six most significant factors are the probability of hit for the batch during unloading, the total load of the troops, the batch size, the number of T-Crafts available, the unload time, and the cargo payload weight. These factors are followed by the probability of hit during transit and the attrition rate of troops. From the sorted parameter estimates, we observe that the total load of troops is an important factor, but is not a matter of choice within a given scenario. The number of T-Crafts, and the batch size have to be considered very carefully to achieve high-delivery proportions. The impact of the batch size is not surprising because this factor decreases the probability of sustaining enemy hits dramatically. Based on the observation that probability of hit during transit and unloading, the unload time and the attrition rate are all among the significant factors, we conclude that the delivery of material onshore would benefit if T-Crafts are protected during the whole process of projecting troops to the shore.

Finally, we look at which factors influence the proportion of T-Craft destroyed. Figure 30 shows that we get an R-Square of 0.6606 for the model. From Table 9, we infer that the total load, the probability of hit during unloading, the cargo payload weight, the probability of hit during transit, the unload time, the number of T-Crafts available, the batch size, the probability of sinking after the first hit, and the number of hits that a T-Craft can take before it needs repair are the factors with practical significance. The last two factors are observed for the first time in one of our models. Both factors are related to T-Craft survivability. This shows that it is important that the T-Craft is able to survive at least one hit. The T-Craft developer should establish a design that makes the T-Craft as solid against enemy hits as possible.



Summary of Fit

RSquare	0.660628
RSquare Adj	0.660559
Root Mean Square Error	0.186978
Mean of Response	0.295552
Observations (or Sum Wgts)	118800

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	24	8083.264	336.803	9633.733
Error	118775	4152.465	0.035	Prob > F
C. Total	118799	12235.729		0.0000*

Figure 30. Regression Model for the Proportion of T-Craft Destroyed with all Factors of the Scenario With Enemy Threat

Table 9. Most Important Parameter Estimates of the Regression Model for the Proportion of T-Craft Destroyed with all Factors of the Scenario With Enemy Threat

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Total Load (LT)	9.8283e-6	5.344e-8	183.92	0.0000*
ProbHit Batch during Unloading (per hour)	0.549738	0.003813	144.17	0.0000*
Cargo Payload Weight (LT)	-0.00035	2.669e-6	-131.2	0.0000*
ProbHit Batch (%)	0.3380557	0.003813	88.65	0.0000*
Unload Time (hrs)	0.0531379	0.000623	85.26	0.0000*
# T-Crafts	-0.022916	0.000285	-80.53	0.0000*
(# T-Crafts-14.0312)*(Total Load (LT)-22500)	-7.254e-7	1.164e-8	-62.34	0.0000*
(Batchsize-11.5001)*(Batchsize-11.5001)*(Batchsize-11.5001)	-0.000169	2.946e-6	-57.45	0.0000*
(# T-Crafts-14.0312)*(ProbHit Batch during Unloading (per hour)-0.255)	-0.040074	0.000816	-49.13	0.0000*
(Unload Time (hrs)-2.50008)*(ProbHit Batch during Unloading (per hour)-0.255)	0.1656728	0.004443	37.29	<.0001*
ProbSink (1 Hit)	0.5674431	0.015951	35.57	<.0001*
(# T-Crafts-14.0312)*(# T-Crafts-14.0312)	0.0021932	9.358e-5	23.44	<.0001*
Batchsize	-0.005077	0.000218	-23.28	<.0001*
(# T-Crafts-14.0312)*(# T-Crafts-14.0312)*(# T-Crafts-14.0312)	-0.000153	6.598e-6	-23.26	<.0001*
(Batchsize-11.5001)*(Batchsize-11.5001)*(Batchsize-11.5001)*(Batchsize-11.5001)	1.2041e-5	5.4e-7	22.30	<.0001*
(# hits to repair-3.00781)*(# hits to repair-3.00781)*(# hits to repair-3.00781)	0.0059315	0.000313	18.94	<.0001*
(Batchsize-11.5001)*(Batchsize-11.5001)	0.0007986	5.516e-5	14.48	<.0001*

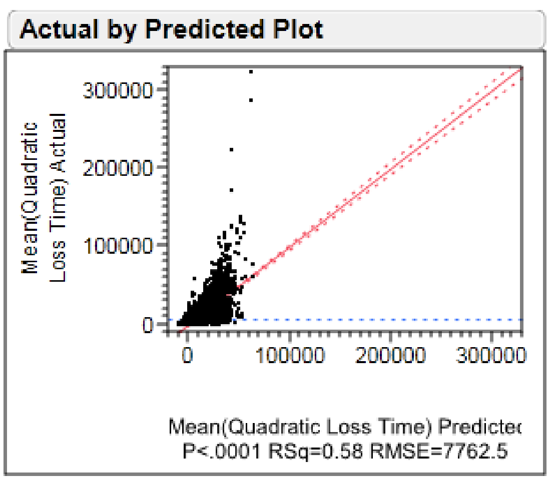
As already discussed in the scenario without enemy threat, all factors that are related to converting between modes, traveling in ACV mode, number of sea and shores spots and to refueling T-Craft show no practical significance in the models.

b. Robust Analysis

This section explains the results of the robust analysis for all three MOEs of the scenario with enemy threat. The first MOE that we consider is time to complete mission. The loss function is the same one that we used for the scenario without enemy threat:

$$\text{Loss} = (\text{TimeToComplete} - 10)^2 . \quad (9)$$

Before we build the regression model for the robust analysis, we average again over the noise factors. The results for the regression model for the Mean (Quadratic Loss Time to complete) are presented in Figure 31. The regression model has an R-Square of 0.5812. The parameters and the prediction profiler are shown in Figure 32 and the interaction profiles in Figure 33.



Summary of Fit

RSquare	0.581193
RSquare Adj	0.580572
Root Mean Square Error	7762.509
Mean of Response	6854.588
Observations (or Sum Wgts)	14850

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	22	1.2398e+12	5.636e+10	935.2708
Error	14827	8.9342e+11	60256553	**Prob > F**
C. Total	14849	2.1333e+12		0.0000*

Figure 31. Regression Model for Mean(Quadratic Loss Time) of the Scenario Without EnemyThreat

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Total Load (LT)	0.4633137	0.006269	73.91	0.0000*
# T-Crafts	-641.3105	13.66244	-46.94	0.0000*
(Cargo Payload Weight (LT)-650.008)*(Total Load (LT)-22500)	-0.001397	3.144e-5	-44.42	0.0000*
Distance (nm)	40.154415	0.975337	41.17	0.0000*
(Total Load (LT)-22500)*(Distance (nm)-137.5)	0.0025859	9.542e-5	27.10	<.0001*
(Cargo Payload Weight (LT)-650.008)*(Distance (nm)-137.5)	-0.115327	0.00491	-23.49	<.0001*
(# T-Crafts-14.0312)*(Total Load (LT)-22500)	-0.031384	0.001366	-22.98	<.0001*
Load Time (hrs)	1234.2164	54.85141	22.50	<.0001*
(# T-Crafts-14.0312)*(Distance (nm)-137.5)	-4.452984	0.211978	-21.01	<.0001*
(Cargo Payload Weight (LT)-650.008)*(# T-Crafts-14.0312)	1.1981253	0.06835	17.53	<.0001*
(Load Time (hrs)-3.00031)*(Total Load (LT)-22500)	0.0940039	0.00537	17.51	<.0001*
(Cargo Payload Weight (LT)-650.008)*(Load Time (hrs)-3.00031)	-4.157732	0.274489	-15.15	<.0001*
Cargo Payload Weight (LT)	-11.60498	0.784278	-14.80	<.0001*
SpeedSES (knts)	-142.7997	10.97015	-13.02	<.0001*
(Batchsize-11.5001)*(Batchsize-11.5001)*(Batchsize-11.5001)	4.3112779	0.346098	12.46	<.0001*
(Cargo Payload Weight (LT)-650.008)*(Cargo Payload Weight (LT)-650.008)*(Cargo Payload Weight (LT)	-0.000118	9.703e-6	-12.14	<.0001*
Batchsize	-270.1191	25.60555	-10.55	<.0001*
(SpeedSES (knts)-45.0016)*(Total Load (LT)-22500)	-0.011296	0.001077	-10.49	<.0001*
(Batchsize-11.5001)*(Batchsize-11.5001)*(Batchsize-11.5001)*(Batchsize-11.5001)	-0.483777	0.06348	-7.62	<.0001*

Prediction Profiler

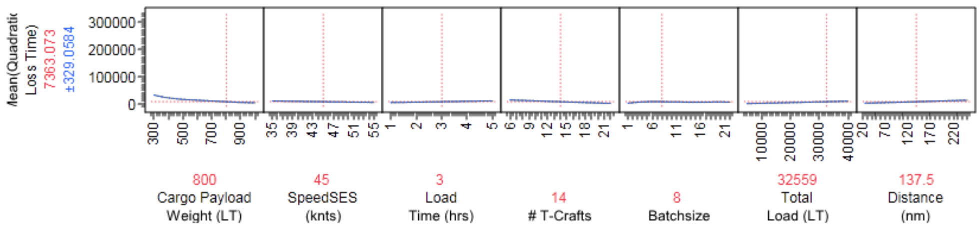


Figure 32. Sorted Parameter Estimates and Prediction Profiler for the Regression Model for Mean(Quadratic Loss Time) of the Scenario With Enemy Threat

When we compare the results in Figures 32 and 33 to the scenario without enemy threat, we note that five of the seven factors are common to both models. The interactions of these five factors are similar to those observed in the scenario with enemy threat, but are not as strong as in the scenario without enemy threat. Two new factors manifest in the scenario with enemy threat: the speed in SES mode and the batch size. The seven additional noise factors noted in part (a) act to reduce the consistency of the model in the robust analysis. Even though the speed in SES mode and the batch size show practical significance, their impact is not as strong as of the other five factors we already found in the scenario without enemy threat.

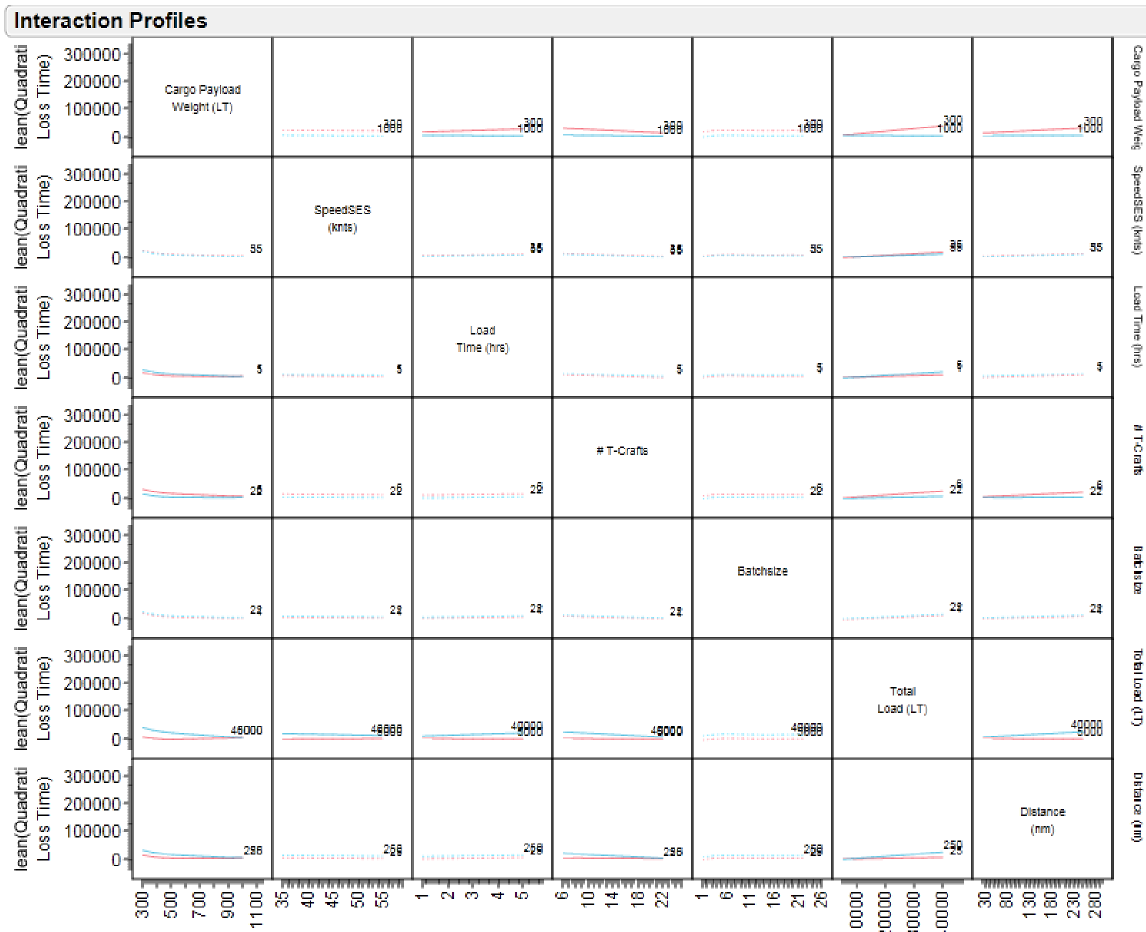
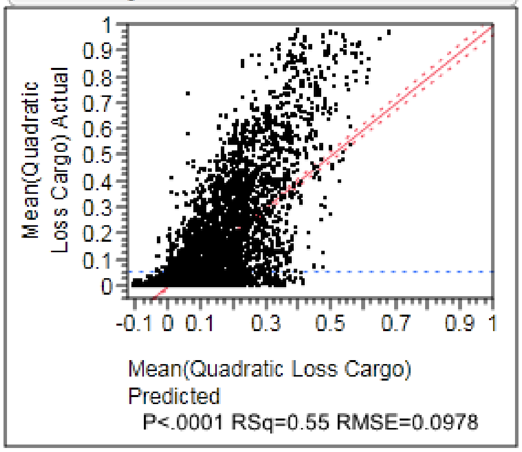


Figure 33. Interaction Profiles for the Regression Model of Mean (Quadratic Loss Time) of the Scenario With Enemy Threat

The second MOE that we consider for robust analysis is the proportion of cargo successfully delivered onshore. Since the target value for the proportion cargo on shore is 100 percent the quadratic loss function is:

$$\text{Loss} = (\text{ProportionCargoOnshore} - 1)^2 \tag{10}$$

The results for the regression model for the Mean (Quadratic Loss Cargo) are presented in Figures 34, 35, and 36.



Summary of Fit

RSquare	0.546039
RSquare Adj	0.54558
Root Mean Square Error	0.097788
Mean of Response	0.056961
Observations (or Sum Wgts)	14850

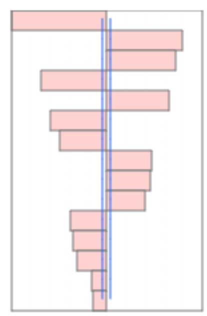
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	15	170.62010	11.3747	1189.521
Error	14834	141.84863	0.0096	**Prob > F**
C. Total	14849	312.46874		0.0000*

Figure 34. Regression Model for Mean(Quadratic Loss Cargo) of the Scenario With Enemy Threat

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
(Batchsize-11.5001)*(Batchsize-11.5001)*(Batchsize-11.5001)	-0.000203	4.357e-6	-46.48	0.0000*
Total Load (LT)	2.9175e-6	7.897e-8	36.95	<.0001*
(Batchsize-11.5001)*(Batchsize-11.5001)*(Batchsize-11.5001)*(Batchsize-11.5001)	2.7024e-5	7.992e-7	33.81	<.0001*
Cargo Payload Weight (LT)	-0.000127	3.948e-6	-32.05	<.0001*
(# T-Crafts-14.0312)*(# T-Crafts-14.0312)	0.0012486	0.000041	30.44	<.0001*
(# T-Crafts-14.0312)*(Total Load (LT)-22500)	-4.702e-7	1.72e-8	-27.33	<.0001*
(Batchsize-11.5001)*(Total Load (LT)-22500)	-2.965e-7	1.311e-8	-22.61	<.0001*
Unload Time (hrs)	0.0203634	0.000922	22.09	<.0001*
(Cargo Payload Weight (LT)-650.008)*(# T-Crafts-14.0312)	1.8625e-5	8.607e-7	21.64	<.0001*
Batchsize	0.0060712	0.000322	18.83	<.0001*
(Cargo Payload Weight (LT)-650.008)*(Total Load (LT)-22500)	-6.963e-9	3.96e-10	-17.57	<.0001*
(Batchsize-11.5001)*(Batchsize-11.5001)	-0.001303	8.163e-5	-15.96	<.0001*
(# T-Crafts-14.0312)*(# T-Crafts-14.0312)*(# T-Crafts-14.0312)	-0.00014	9.749e-6	-14.34	<.0001*
(Cargo Payload Weight (LT)-650.008)*(Unload Time (hrs)-2.50008)	-0.000034	4.565e-6	-7.44	<.0001*
# T-Crafts	-0.002624	0.000421	-6.24	<.0001*



Prediction Profiler

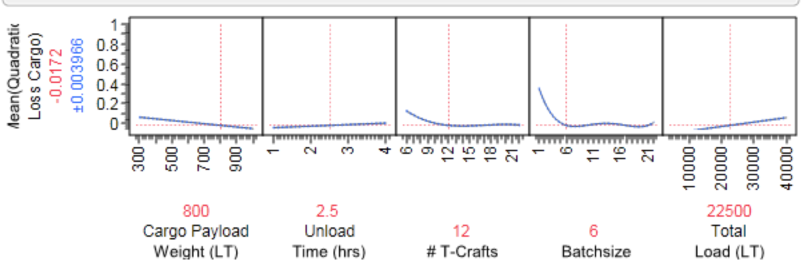


Figure 35. Sorted Parameter Estimates and Prediction Profiler for the Regression Model for Mean(Quadratic Loss Cargo) of the Scenario With Enemy Threat

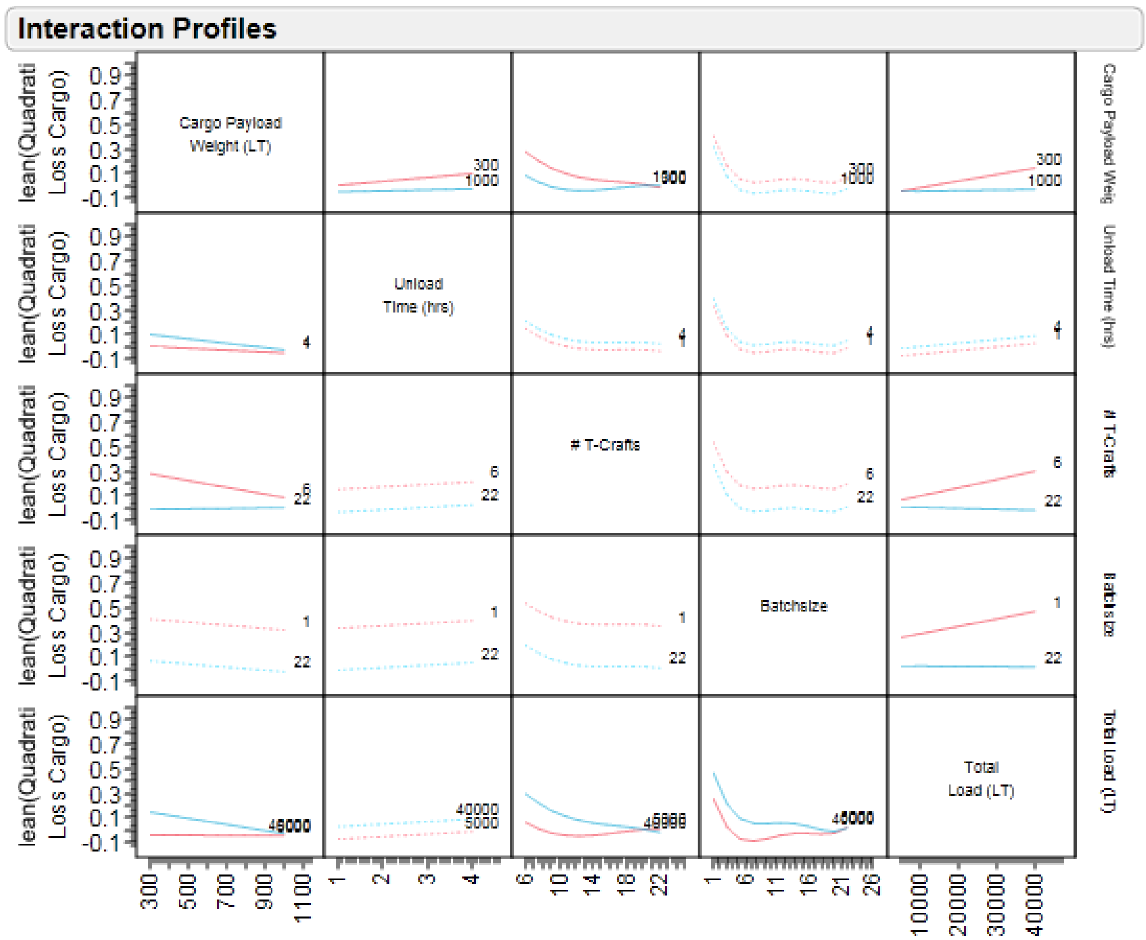


Figure 36. Interaction Profiles for the Regression Model of Mean (Quadratic Loss Cargo) of the Scenario With Enemy Threat

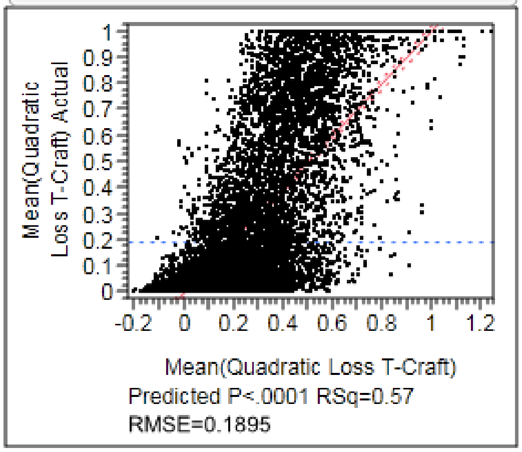
The model has an R-Square of 0.546. The sorted parameter estimates of Figure 35 show that the factor with the greatest impact is the batch size. This model behavior is not surprising because forming batches drastically decreases the probability of hits. Figures 35 and 36 also show that the batch size has a threshold value. Robustness improves drastically as we increase batch size up to a value of six, and then levels off. This behavior can be seen in all interaction profiles that are related to the batch size. The total load of troops and the cargo payload weight are both significant and show a high interaction. Large cargos will require large payload capacities or large numbers of T-Craft to achieve mission success. We conclude again that the cargo payload weight should meet or exceed 750 LT, as the stated objective in BAA #05-20. The cargo payload weight shows also an interaction to the number of T-Crafts available. From analyzing the prediction profiler (Figure 35) we observe a threshold value of 12 T-Craft. The interaction profiles of Figure 36 confirm this result. The number of T-Crafts available shows interactions to all other factors and all profiles support the threshold of 12 T-Crafts. We conclude that 12 or more T-Crafts are needed to achieve high delivery rates. The last significant factor is the unload time. This result is not surprising because a shorter unload time decreases the probability of hit for the individual T-Craft and increases the T-Craft survivability. As a consequence the proportion of cargo onshore also rises.

The last MOE we evaluate is the proportion of T-Craft destroyed. The target proportion of T-Craft destroyed is zero percent, so the quadratic loss function becomes:

$$\text{Loss} = (\text{ProportionTcraftDestroyed} - 0)^2 . \qquad (11)$$

Before we can build the regression model for the robust design, we average over the noise factors. The results for the regression model for the Mean (Quadratic Loss T-Craft) are presented in Figure 37. The model has an R-Square of 0.5744. The prediction profiler of Figure 38 once more confirms that the total load of troops is very important in achieving mission success. Because of this, the cargo payload weight should be sufficiently large to reduce the number of trips required for a large landing force. The number of T-Crafts available will have a similar impact on loss. The interaction profiles of Figure 38 show that for low and medium numbers of total load a threshold value of 14 T-Crafts exists. This threshold terminates when the total load of troops increases. For heavy armored forces like the MEB 2024, as many T-Craft as possible are needed to achieve a low proportion of T-Craft destroyed. The number of hits before the T-Craft needs repair also has a huge impact. This factor should be as small as possible to get robust results. These results are unsurprising because the probability of sinking for T-Craft increases with every hit T-Craft takes. What is surprising is that this factor showed no practical significance in the robust analysis of proportion of cargo successfully delivered onshore. The occurrence of the next factor, the unload time, is logical because a longer unload time increases the probability of the T-Craft taking hits.

Actual by Predicted Plot



Summary of Fit

RSquare	0.574429
RSquare Adj	0.574027
Root Mean Square Error	0.189487
Mean of Response	0.190345
Observations (or Sum Wgts)	14850

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	14	718.9715	51.3551	1430.289
Error	14835	532.6566	0.0359	**Prob > F**
C. Total	14849	1251.6281		0.0000*

Figure 37. Regression Model for Mean(Quadratic Loss T-Craft) of the Scenario With Enemy Threat

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Total Load (LT)	8.3918e-6	1.53e-7	54.84	0.0000*
Cargo Payload Weight (LT)	-0.000312	7.651e-6	-40.72	0.0000*
(# T-Crafts-14.0312)*(# T-Crafts-14.0312)	0.0027154	7.949e-5	34.16	<.0001*
(# T-Crafts-14.0312)*(Total Load (LT)-22500)	-9.356e-7	3.333e-8	-28.07	<.0001*
# hits to repair	0.0332714	0.001263	26.33	<.0001*
Unload Time (hrs)	0.0441899	0.001786	24.74	<.0001*
# T-Crafts	-0.018586	0.000815	-22.80	<.0001*
(Batchsize-11.5001)*(Batchsize-11.5001)*(Batchsize-11.5001)	-0.000186	8.444e-6	-22.03	<.0001*
(# T-Crafts-14.0312)*(# hits to repair-3.00781)	-0.005338	0.00027	-19.75	<.0001*
(Cargo Payload Weight (LT)-650.008)*(Total Load (LT)-22500)	-1.298e-8	7.68e-10	-16.91	<.0001*
(# T-Crafts-14.0312)*(# T-Crafts-14.0312)*(# T-Crafts-14.0312)	-0.00021	1.89e-5	-11.11	<.0001*
(Batchsize-11.5001)*(Batchsize-11.5001)*(Batchsize-11.5001)*(Batchsize	1.466e-5	1.548e-6	9.47	<.0001*
(Batchsize-11.5001)*(Batchsize-11.5001)	0.0003867	0.000158	2.45	0.0145*
Batchsize	-0.001103	0.000625	-1.76	0.0777

Prediction Profiler

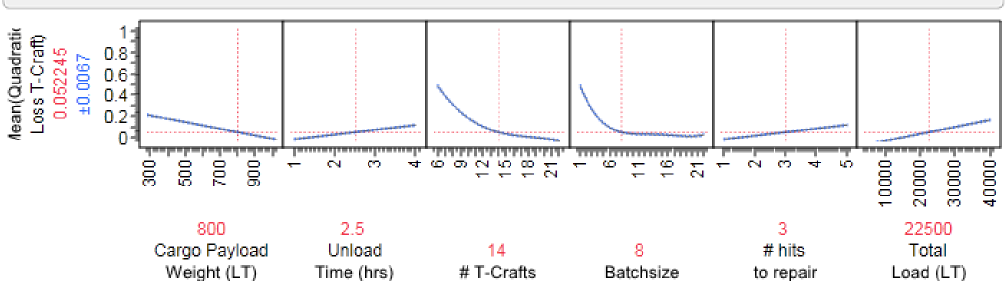


Figure 38. Sorted Parameter Estimates and Prediction Profiler for the Regression Model for Mean(Quadratic Loss T-Craft) of the Scenario With Enemy Threat

The batch size is the last factor of practical significance. For the proportion of T-Craft destroyed, we observe a threshold of eight T-Crafts or more to achieve robust results. The interaction profiles of Figure 39 confirm that this threshold holds for all possible scenarios.

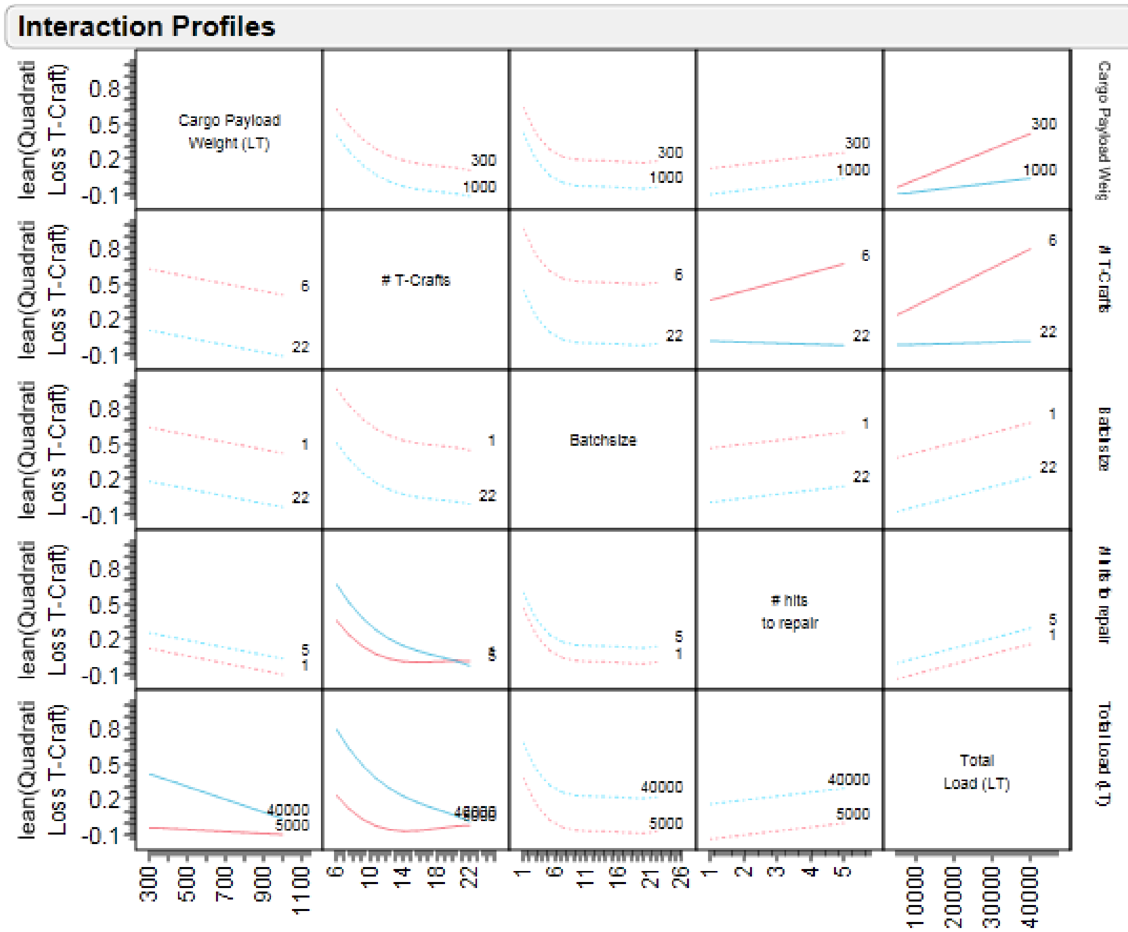


Figure 39. Interaction Profiles for the Regression Model of Mean (Quadratic Loss T-Craft) of the Scenario With Enemy Threat

We also analyzed the loss functions for all MOEs using partition trees, but these analyses did not provide any additional insights.

4. Decision Aid Tools

For operational planning, it is always useful to have decision aid tools that help the decision maker to predict the amount of assets needed to finish a mission successfully. In order to do this, two different devices are usually considered: spreadsheet models or the use of simulation. The beauty of spreadsheet models is that they are very easy to develop and to use, while simulation is usually more complicated, more time intensive, and requires a fair amount of specialized training to use properly. Therefore, we have tried to find a spreadsheet predictor for time to complete mission for the two different scenarios. The other two MOEs are not predictable without using simulation. We describe the results in the following section.

a. Scenario Without Enemy Threat

The scenario without enemy threat is the easier of the two scenarios. Because our objective is to find a predictor that can be implemented in a spreadsheet, we started by considering the regression model developed for the analysis in section 2a of this chapter. That model has an R-Square of 0.9248, which may not be precise enough to be used as a predictor for time to complete mission.

We found that a different approach yields excellent results. We compute the number of T-Craft sorties that are needed to project all troops to shore. We then divide the number of trip cycles by the number of T-Craft available to determine the number of trip cycles that have to be finished, i.e., the number of trips that a T-Craft has to complete before all troops have reached the shore successfully. Finally, we multiply this by the duration of a cycle to obtain the predictor for time to complete mission:

$$\#\text{Sorties} = Max(\left\lceil \text{Footprint}/\left(\text{DeckUseEff} * \text{CargoDeckSize}\right)\right\rceil, \quad (12)$$

$$\left\lceil \text{TotalLoad}/(\text{DeckUseEff} * \text{CargoPayloadWeight})\right\rceil)$$

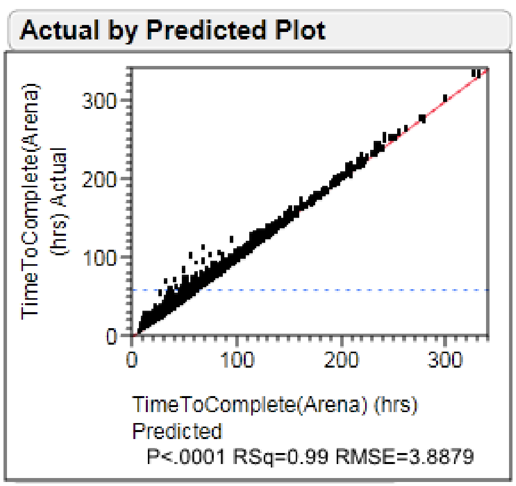
$$\#\text{TripCycles} = \left\lceil \#\text{Sorties}/\#\text{T-Crafts}\right\rceil \quad (13)$$

$$\hat{t} = \#\text{TripCycles} * \begin{bmatrix} 2*(\text{Distance-TransitionDistance})/\text{SpeedSES} \\ +2*\text{TransitionDistance}/\text{SpeedACV} \\ +\text{ConvertTimeToACV} \\ +\text{ConvertTime ToSES} \\ +\text{LoadTime} \\ +\text{UnloadTime} \end{bmatrix} \quad (14)$$

$$-.5*\begin{bmatrix} (\text{Distance-TransitionDistance})/\text{SpeedSES} \\ +\text{TransitionDistance}/\text{SpeedACV} \\ +\text{ConvertTimeToSES} \end{bmatrix}.$$

The final term is an adjustment to correct for the fact that the final return trip to the sea base does not count against delivery time.

Equations 12 to 14 are a set of nonlinear equations that represent projecting the troops to shore. Figure 41 shows the result of fitting a regression model of the outcomes from the Arena model versus the predictive equation results.



Summary of Fit

RSquare	0.991305
RSquare Adj	0.991305
Root Mean Square Error	3.887865
Mean of Response	59.71518
Observations (or Sum Wgts)	126765

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	1.3247717	0.018846	70.30	0.0000*
Tau Mission Time	0.9761513	0.000257	3801.5	0.0000*

Figure 40. Regression Model of the Predictor of Time to Complete Mission versus the Arena Outcome of Time to Complete Mission for the Scenario Without Enemy Threat

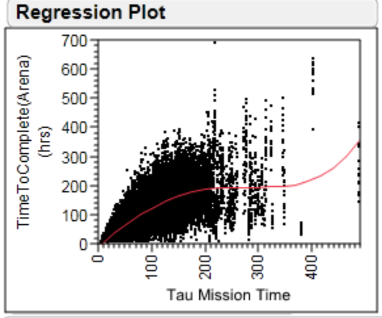
The regression model has an R-Square of 0.9913, which is a surprisingly good result. We conclude from this that queuing effects are not an issue over wide ranges of peace time scenarios.

If the decision maker wants more detailed results, the Arena model that has been developed for this thesis can be used as well. In the second part of the next section, we describe the procedure for generating predictions using Arena.

b. Scenario With Enemy Threat

The predictor for time to complete mission that we used for the scenario without enemy threat does not work as well for the scenario with enemy threat. The R-Square of 0.69 that we achieve with a regression model by using the predictor with polynomial to degree four, shown in Figure 42, is the best value we are able to achieve. This result is even worse than the result of the regression model in section 3a of this chapter, where we had a R-Square of 0.721. We conclude that the queuing effects of forming batches are an important issue over wide ranges of scenarios with enemy threat.

Regression Plot



Summary of Fit

RSquare	0.690162
RSquare Adj	0.690151
Root Mean Square Error	29.25599
Mean of Response	73.97071
Observations (or Sum Wgts)	118800

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	3.5888098	0.186487	19.24	<.0001*
Tau Mission Time	1.2953378	0.002985	433.94	0.0000*
(Tau Mission Time-59.3347)*(Tau Mission Time-59.3347)	-0.003575	7.631e-5	-46.86	0.0000*
(Tau Mission Time-59.3347)*(Tau Mission Time-59.3347)*(Tau Mission Time-59.3347)	-4.339e-6	5.986e-7	-7.25	<.0001*
(Tau Mission Time-59.3347)*(Tau Mission Time-59.3347)*(Tau Mission Time-59.3347)*(Tau Mission Time-59.3347)	2.1323e-8	1.137e-9	18.76	<.0001*

Figure 41. Regression Model of the Predictor of Time to Complete Mission versus the Arena Outcome of Time to Complete Mission for the Scenario With Enemy Threat

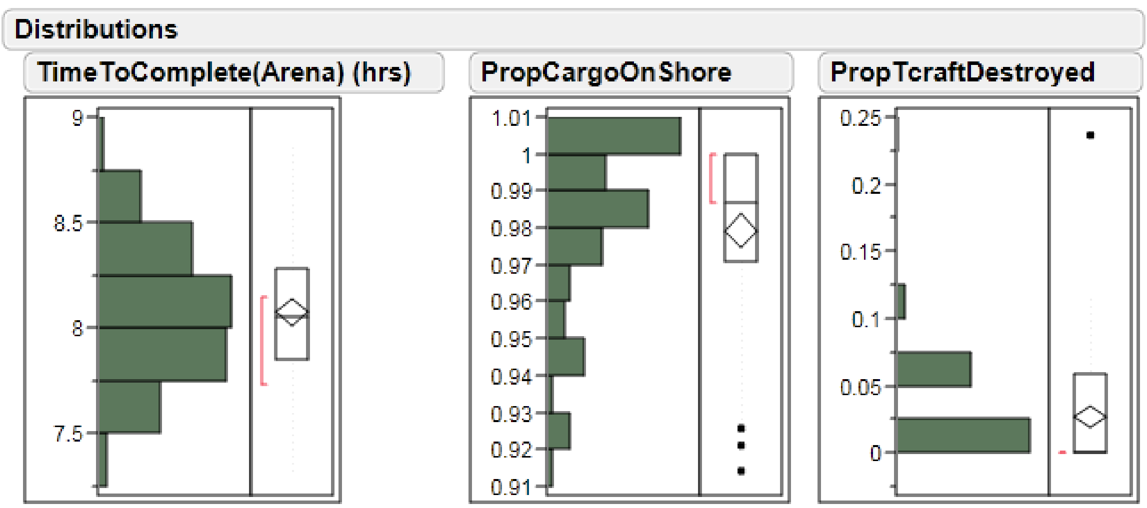
Therefore, we recommend using simulation to predict the outcomes in war scenarios. The Arena model that has been developed for this thesis can easily generate predictions. To illustrate this, we investigate a scenario where a MEB 2015 has to be projected to shore over a distance of 50 nm within 10 hours. We wish to determine the number of T-Crafts that are needed to bring the MEB 2015 to shore within this time constraint. The presumed cargo payload weight of the T-Craft is 700 LT. The factor settings needed to fulfill the mission within the time constraint of 10 hours are displayed in Table 9.

We replicated the scenario 100 times. The outcomes of time to complete mission, proportion of cargo successfully delivered onshore and proportion of T-Craft destroyed are shown in Figure 43.

Table 10. Assumed Factors to Estimate the Outcomes for a Certain Mission

S/N	Factor	VALUE
1	Cargo Payload Weight (LT)	700
2	Cargo Deck Size (sqft)	5500
3	Speed SES (knts)	40
4	Speed ACV (knts)	5
5	Load Time (hrs)	2
6	Unload Time (hrs)	1.5
7	Time to Convert to ACV (hrs)	0.5
8	Time to Convert to SES (hrs)	0.5
9	# T-Crafts	17
10	# SeaSpots	9
11	Refueling during loading? (1-yes, 0-no)	0
12	Refueling rate (tons/hour)	120
13	Tank capacity (LT)	110
14	Batchsize	9
15	ProbFailure	0.1
16	Time to repair (hrs)	2
17	# hits to repair	2
18	Total Load (LT)	5490
19	Footprint MEB (sqft)	73759
20	Distance (nm)	50
21	TransitionDistance (nm)	1
22	Deck Use Efficiency (between 0 and 1)	0.8
23	# ShoreSpots	12
24	ProbHit Batch (%)	0.255
25	ProbHit Batch during Unloading (per hour)	0.255
26	AttritionRate Troops	0.255
27	ProbSink (1 Hit)	0.145
28	ProbSink (2 Hits)	0.405
29	ProbSink (3 Hits)	0.63
30	ProbSink (4 Hits)	0.875
31	Distribution (0-TRIA, 1-ShiftedEXPO)	1

The results indicate that we need 17 T-Crafts to execute the mission in less than 10 hours. With 16 T-Crafts we exceed the required time frame. With 100 replications of the scenario in the Arena model, none of the completion times exceeds nine hours and the model predicts a mean time to complete mission of 8.05 hours. We also observe a proportion of cargo successfully delivered onshore in excess of 0.91 and a proportion of T-Craft destroyed below six percent in more than 90 percent of the replications.



Quantiles

	TimeToComplete(Arena) (hrs)	PropCargoOnShore	PropTcraftDestroyed
100.0% maximum	8.8825	1.0000	0.23529
99.5%	8.8825	1.0000	0.23529
97.5%	8.6737	1.0000	0.11765
90.0%	8.4978	1.0000	0.05882
75.0% quartile	8.2815	1.0000	0.05882
50.0% median	8.0545	0.9870	0.00000
25.0% quartile	7.8496	0.9707	0.00000
10.0%	7.6736	0.9403	0.00000
2.5%	7.4125	0.9231	0.00000
0.5%	7.3065	0.9138	0.00000
0.0% minimum	7.3065	0.9138	0.00000

Moments

	TimeToComplete(Arena) (hrs)	PropCargoOnShore	PropTcraftDestroyed
Mean	8.0765018	0.9791772	0.0270588
Std Dev	0.3158676	0.0229563	0.0395882
Std Err Mean	0.0315868	0.0022956	0.0039588
Upper 95% Mean	8.1391768	0.9837322	0.034914
Lower 95% Mean	8.0138268	0.9746222	0.0192037
N	100	100	100

Figure 42. Distribution of the MOEs for the Example of Figure 41

Although it takes some time with simulation to determine the number of T-Crafts that are needed to undercut the 10 hour time constraint, we believe that the results are more reliable and informative than the predictions obtained from a regression/spreadsheet model.

VI. CONCLUSIONS

A. THESIS SUMMARY

We set out to assess the desired capabilities of the T-Craft defined in the BAA #05-20. Through the combination of previous studies, the development of an Arena-based discrete-event simulation model, comprehensive experimental design, and robust analysis we have developed insights into the required T-Craft capabilities and the operational needs of major seabasing operations. By studying broad ranges of the simulation's input parameters we have determined both minimum design characteristics and operational recommendations needed for the T-Craft to achieve its mission objectives. The techniques used in this thesis can also be used for future study regarding the performance assessment of T-Craft prototypes.

B. THESIS QUESTIONS

In Chapter I, the following research questions were defined:

- How many T-Crafts are required to execute a mission within the mission time constraint?
- If there is an enemy threat capable of damaging or sinking the T-Crafts, how many additional T-Crafts are needed to accomplish the mission?
- How survivable does the T-Craft need to be?
- What are the tonnage capacity and deck size of a T-Craft that can successfully execute the spectrum of anticipated missions?
- How many spots are needed to load and unload the T-Crafts?
- How important are the speed, the load time, and the unload time of the T-Craft?
- How do fuel consumption and the frequency of refueling events impact operations?

This section summarizes the answers to these questions as far as we were able to find answers to the research questions.

1. Number of T-Crafts

The analysis of Chapter V showed that the number of T-Crafts that are available during a mission is one of the key factors that determine whether a mission is successfully completed within a certain time constraint. However, in order to compute the number of T-Crafts that are needed to execute a mission within the mission time constraint, the capabilities of the T-Craft and the mission parameters are needed. The Arena model can be used to compute the expected time to complete mission, the proportion of cargo successfully delivered onshore, and the proportion of T-Craft destroyed. The robust analysis also showed that the number of T-Crafts when enemy forces are opposing the landing should be at least 12–14 to achieve high proportion cargo successfully delivered onshore and low proportion of T-Craft destroyed. If the final T-Craft design has low capacity, the mission has a total load at the high end of the range we investigated, or the sea base is stationed far off shore, then increasing the number of T-Craft further will help achieve the 10-hour time constraint.

2. Mission Accomplishment With Enemy Threat

The presence of an enemy may increase the number of T-Crafts needed to accomplish the mission within a 10-hour time frame. In some scenarios, even though fewer troops reach the shore the time to complete mission does not increase necessarily. Using batches significantly improves the amount of troops that reach the shore. The batch size is the most significant factor in order to ensure a high proportion of cargo successfully delivered onshore. This factor is also a key factor for achieving a low proportion of T-Craft destroyed. One of the main conclusions from the analysis is that when enemy forces are present the batch size should be eight or higher in order to get a high proportion of cargo successfully delivered onshore and a low proportion of T-Craft destroyed. If the sea base has at least that many sea spots available the wait times for forming batches are short. To avoid wait times and exposure to enemy fire at the shore, the batch size should also not be greater than the number of shore spots that are available.

3. T-Craft Survivability

The insights from the robust analysis show that the proportion of T-Craft destroyed is reduced if the number of hits that a T-Craft can sustain before it requires repair is low. Additionally the regression analysis shows that a high probability of sinking after the first hit increases the proportion of T-Craft destroyed. That means that a high survivability is important and should be evaluated on the T-Craft prototypes.

4. Tonnage Capacity and Deck Size

The results of the analysis of Chapter V show that the Cargo Payload Weight should be at least 750 LT. A Cargo Payload Weight of 750 LT, specified as the objective in BAA #05-20, should be enough to project a MEB 2015 force to shore within a 10-hour time constraint. Values larger than 750 LT for the cargo payload weight will further reduce the time to complete mission. This is particularly important when we consider heavy troops such as the MEB 2024. The impact of the deck size is not as significant as the cargo payload weight. From the analysis, we conclude that a larger deck size does not in practice lead to shorter mission times. As such, the objective of 5500 sq. ft. for the deck size of the T-Craft should be sufficient.

5. Sea Spots and Shore Spots

According to the analysis, the number of available sea spots and shore spots show no practical significance for any of the MOEs. These two factors did not have anywhere near the impact on mission success that we expected. Over the broad range of scenarios, we explored the number of sea spots and shore spots were completely dominated by other factors. The nine sea spots that are currently planned for the sea base appear to be sufficient. Since we recommend that the batch size should be at least eight in presence of an enemy, the number of sea spots and shore spots should also have at least this value to deliver a high proportion of cargo onshore, low proportion of T-Craft destroyed, and to avoid delays in forming batches. When T-Crafts may be destroyed during unloading, blocking some of the shore spots, we recommend a minimum of 10 shore spots for an average mission. However, we observed that queuing effects are not an issue over wide ranges of peacetime scenarios.

6. Importance of Speed, Load Time, Unload Time and Transition Times

The unload time is a key factor in proportion of cargo delivered onshore and proportion of T-Craft destroyed. The impact is caused by the fact that a longer unload time increases the probability of a hit during unloading. The load time at the sea base is also very important in order to achieve short mission durations. The selection criteria for selecting the final T-Craft design should take both loading and unloading times into account.

Speed in SES mode is of lesser importance in determining the time to complete the mission, while speed in ACV mode shows no practical significance. Especially when we consider that the distance between sea base and shore will be not more than 50 miles in most scenarios, we find that the speed objective of 40 knots in SES mode is sufficient. The SES speed is only important when projecting troops over long distances to shore. Transition times between SES and ACV mode also show no practical significance.

7. Fuel Consumption and the Frequency of Refueling

The fuel consumption and refueling procedures show no practical significance in any of the analyses. At first glance, this is surprising but a closer inspection of the model outputs shows that refueling is necessary only for a minority of missions. That is the reason why the data analysis shows no significance for the factors refueling rate, tank capacity, and refueling during loading. Refueling events are necessary only for missions with long distances between sea base and shore. Even so, it is recommended that the T-Craft have the capability of concurrent refueling and loading. However, the variations in tank capacity and refueling rate that we studied played no significant role in determining mission success over the range of scenarios we explored.

C. SUMMARY OF RECOMMENDATIONS

We make the following recommendations based on the conclusions of this thesis.

1. Factors Related to T-Craft Performance

1. Cargo payload weight of 750 LT and deck size area of 5500 sq. ft. as specified in BAA #05-20 are sufficient for success of the most missions. Increasing the cargo payload weight even further will improve mission performance at the extremes of distance and/or payload.

2. Increasing the number of T-Crafts reduces mission durations. To achieve a high proportion of cargo successfully delivered onshore and low proportion of T-Craft destroyed, we recommend a minimum number of 12 T-Crafts.

3. The T-Craft survivability is an important factor in order to achieve a low proportion of T-Craft destroyed. The T-Craft should be able to sustain multiple hits before repairs are needed.

4. Unload time should be as small as possible to increase T-Craft survivability.

5. Load Time should be small to achieve short mission durations.

6. A speed of 40 knots in SES mode is sufficient; speed in ACV mode and transition times between the modes show no practical significance.

7. Fuel consumption and all other factors that are related to refueling are not significant.

8. Probabilities of failure and repair times show no practical significance.

2. Factors Related to Decision Maker

1. Total Load of troops is the factor that shows the highest significance of all factors for time to complete mission. Decision makers should balance pros and cons very carefully when they decide about the force structure that has to be projected to shore. For example, using infantry rather than heavy armored troops will yield shorter durations for the landing phase of the mission.

2. Footprint of troops shows no practical significance.

3. In presence of an enemy, the batch size should be at least eight; in this case the number of available sea and shore spots should not be smaller than the batch size to provide a high proportion of cargo delivered onshore and a low proportion of T-Craft destroyed. When T-Crafts may be destroyed during unloading, blocking one or more of the shore spots, choosing a beachhead that is not constrained for shore spots is recommended.

4. Having nine sea spots at the sea base appears to be sufficient. The number of sea spots had little impact over the range that has been analyzed. Nine sea spots provide ample turnaround capability in conjunction with the recommended batch size of eight.

5. The distance between sea base and shore should be as small as possible, consistent with the safety of the sea base, to achieve robust outcomes. The transition distance shows no practical significance.

D. FOLLOW-ON WORK

Based on the work that has been done in this thesis, we recommend two different avenues for future research:

1. Once the capabilities of the different T-Craft prototypes are finalized, the analyses should be repeated to assess which prototype provides the highest performance.

2. The Arena model can be extended to incorporate other kinds of vessels such as LCUs and LCACs. This will provide the Commanding Officer an improved decision tool in order to plan seabasing operations.

APPENDIX: DESCRIPTION OF MODEL COMPONENTS

A. INTRODUCTION

In this appendix, we explain the implementation of the simulation model in detail to facilitate use of the model as a decision aid in future sea basing operations. The model components and process modules are described in detail.

The Arena model is developed in the Microsoft Windows operating system environment. According to the install notes, the minimum software and hardware requirements necessary to run the model are:

- Arena version 12.0 or higher;
- Windows 2000 Professional (SP4 or later), Windows 2000 Server (SP4 or later) , Windows XP Professional (SP2 or later), Windows XP Home (SP2 or later), Windows 2003 Server (SP1 or later);
- Hard drive with 75-250MB free disk space (depending on operating system and options installed;
- 64MB RAM (recommended 128MB RAM or higher, depending on operating system);
- Pentium processor 300 MHz or higher. The Arena software can be run on single processor, dual processor, and dual-core processor computers; however, only one instance of Arena can be run at a time.

B. MODEL DESCRIPTION

The following section explains the model runtime and all components and modules used in the model. Requests for additional information about the model can be directed to the author or the SEED Center at the Naval Postgraduate School.

1. Model Runtime

The model runtime depends on the input parameters. The base unit of time used in the model is one hour. A simulation experiment ends when the last sortie is either projected to shore or destroyed, when all T-Crafts are destroyed, or when the last shore spot is blocked with a destroyed T-Craft.

2. Model Components

Figures 44 and 45 give an overview of the entire model.

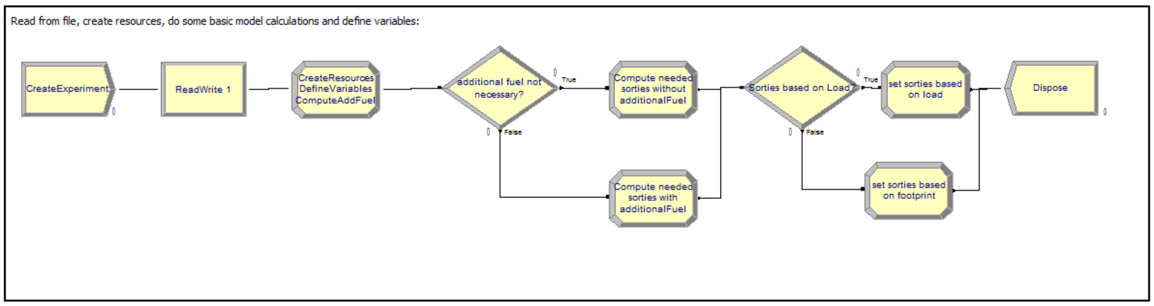


Figure 43. Initial Process and Logic of an "Experiment" Entity

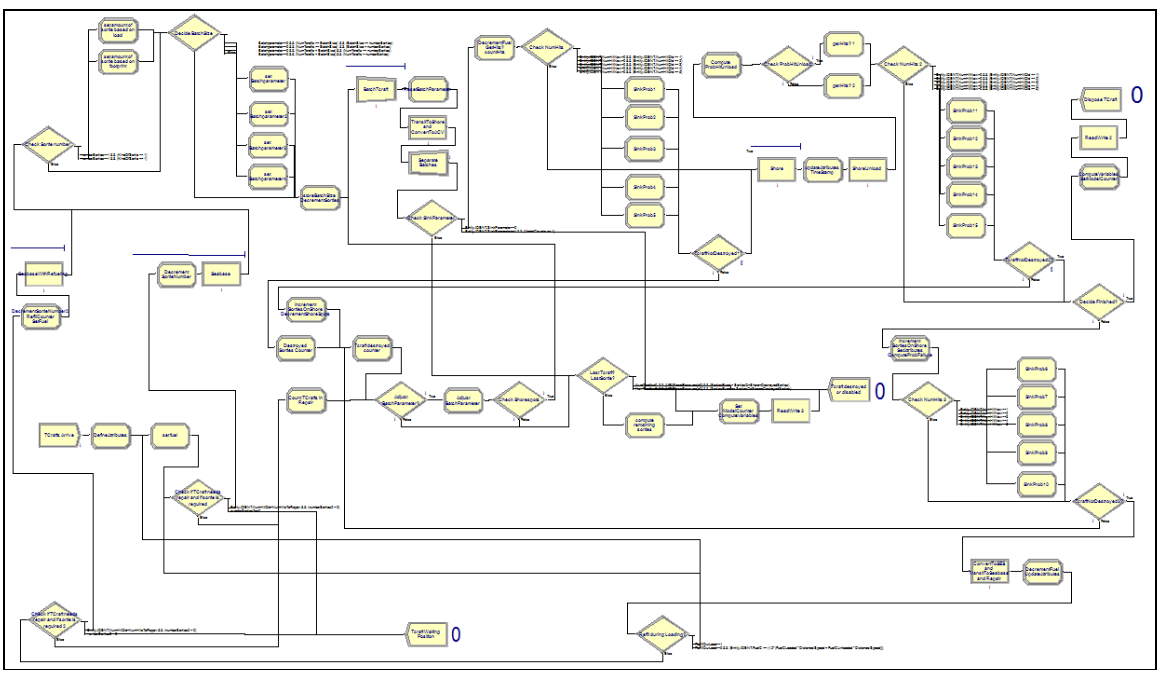


Figure 44. Main Process and Logic of a "T-Craft" Entity

The following table explains all model components and modules used in this thesis. The modules are described in the order they appear in the process tab.

Basic Processes:

Create Modules	**Description**
Create Experiment	This one-time entity is created at the beginning of the simulation and enables the model to read the input parameters and to compute several basic variables that are used during the simulation run.
T-Crafts arrive	A T-Craft is first created at 0.01 sec. Subsequent T-Crafts are created randomly according to an exponential distribution. The number of T-Crafts that are created is defined by the input parameter Number of T-Crafts.
Dispose Modules	**Description**
Dispose ExperimentEntity	This module disposes Experiment entities when they complete the initial process in the system.
Dispose T-Craft	This module disposes T-Craft entities when the last sortie is projected to shore.
T-Craft destroyed or disabled	This module disposes T-Craft entities when T-Craft are destroyed or need repair.
T-Craft Waiting Position	This module disposes T-Craft entities when T-Crafts are not needed any longer to bring sorties to shore before the last sortie reached the shore.
Process Modules	**Description**
Seabase	This process performs a Seize Delay Release action on T-Craft entities for a delay period of either TRIA(0.9*LoadTime, LoadTime, 1.1*LoadTime) or 0.9*LoadTime+EXPO(0.1*LoadTime) hours depending on whether the Triangular or the shifted Exponential distribution is desired.
TransitToShore and ConvertToACV	This process performs a Delay action on T-Craft entities for a delay period of TRIA(TransitionDistance/speedACV+ConvertTime1+(Distance-TransitionDistance)/Speed, 0.9, 1.1) hours.
Shore	This process performs a Seize Delay Release action on T-Craft entities for a delay period of 0.0 sec.
Shore Unload	This process performs a Delay Release action on T-Craft entities for a delay period of either TRIA(0.9*UnloadTime, UnloadTime, 1.1*UnloadTime) or 0.9*UnloadTime+EXPO(0.1*UnloadTime) hours depending on whether the Triangular or the shifted Exponential distribution is desired.
ConvertToSES and TransitToSeabase and Repair	This process performs a Delay action on T-Craft entities for a delay period of TRIA(TransitionDistance/speedACV+ConvertTime2+(Distance-TransitionDistance)/Speed), 0.9, 1.1) + TRIA(RepairTime*Entity.IDENT.ProbFailure, 0.9, 1.1) hours.
SeabaseWithRefueling	This process performs a Seize Delay Release action on T-Craft entities for a delay period of (1/RefuelingRate*(FuelCap+additionalFuel-Entity.IDENT.FuelC)+TRIA(0.9*LoadTime, LoadTime,1.1*LoadTime)) hours.
Decide Modules	**Description**
additional fuel not necessary? (2-Way)	This is a 2-way by Condition decision module which decides the entity path by checking the variable additional fuel. For additionalFuel >= 0, then TRUE; Else FALSE

Sorties based on Load? (2-Way)	This is a 2-way by Condition decision module which decides the entity path by checking if the number of sorties that are required is based on the load or the footprint of the troops. For SortiesBasedLoad >= SortiesBasedFootprint, then TRUE; Else FALSE
Check if TCraft needs repair and if sortie is required (N-Way)	This is a N-way by Condition decision module which decides the entity path by checking attributes and variables: For Entity.IDENT.NumHitOld<NumHitsToRepair && (numberSorties2 > 0), then Way 1; for numberSorties2<=0, then Way 2; Else Way 3
Check if TCraft needs repair and if sortie is required 2 (N-Way)	This is a N-way by Condition decision module which decides the entity path by checking attributes and variables: For Entity.IDENT.NumHitOld<NumHitsToRepair && (numberSorties2 > 0), then Way 1; for numberSorties2<=0, then Way 2; Else Way 3
Check Sortie Number (N-Way)	This is a N-way by Condition decision module which decides the entity path by checking sortie number and kind of sorties: For numberSorties == 1 && (KindOfSortie == 1), then Way 1; For numberSorties == 1 && (KindOfSortie <> 1), then Way 2; Else Way 3
Decide BatchSize (N-Way)	This is a N-Way by Condition decision module which decides the entity path by checking Number of T-Crafts, Batchparameter, Batch size input parameter and number of sorties that still have to be projected to shore. For Batchparameter == 0 && (NumTcrafts >= BatchSize) && (BatchSize <= numberSorties), then Way 1; For Batchparameter == 0 && (NumTcrafts >= BatchSize) && (BatchSize > numberSorties), then Way 2; For Batchparameter == 0 && (NumTcrafts < BatchSize) && (NumTcrafts <= numberSorties), then Way 3; For Batchparameter == 0 && (NumTcrafts < BatchSize) && (NumTcrafts > numberSorties), then Way 4; Else Way 5
Check Sinkparameter (N-Way)	This is a N-Way by Condition decision module which decides the entity path by checking Sinkparameter and ModelCounter. For Entity.IDENT.SinkParameter == 0, then Way 1; For Entity.IDENT.SinkParameter == 1 && (ModelCounter == 1), then Way 2; Else Way 3
Check NumHits (N-Way)	This is a N-Way by Condition decision module which decides the entity path by checking number of new and total hits of a T-Craft. For Entity.IDENT.NumHitNew > 0 && (Entity.IDENT.NumHitOld == 1), then Way 1; For Entity.IDENT.NumHitNew > 0 && (Entity.IDENT.NumHitOld == 2), then Way 2; For Entity.IDENT.NumHitNew > 0 && (Entity.IDENT.NumHitOld == 3), then Way 3; For Entity.IDENT.NumHitNew > 0 && (Entity.IDENT.NumHitOld == 4), then Way 4; For Entity.IDENT.NumHitNew > 0 && (Entity.IDENT.NumHitOld == 5), then Way 5; Else Way 6
TcraftNotDestroyed1? (2-Way)	This is a 2-Way by Condition decision module which decides the entity path by checking the attribute Sinkparameter. For Entity.IDENT.SinkParameter == 0, then TRUE; Else FALSE
Check ProbHitUnload (2-Way)	This is a 2-Way by Condition decision module which decides the entity path by checking the probability of a hit during unloading. For ProbHitUnload2 <= 1, the TRUE; Else FALSE

<table>
<tr><td>Check NumHits 2 (N-Way)</td><td>This is a N-Way by Condition decision module which decides the entity path by checking number of new and total hits of a T-Craft.
For Entity.IDENT.NumHitNew > 0 && (Entity.IDENT.NumHitOld == 1), then Way 1;
For Entity.IDENT.NumHitNew > 0 && (Entity.IDENT.NumHitOld == 2), then Way 2;
For Entity.IDENT.NumHitNew > 0 && (Entity.IDENT.NumHitOld == 3), then Way 3;
For Entity.IDENT.NumHitNew > 0 && (Entity.IDENT.NumHitOld == 4), then Way 4;
For Entity.IDENT.NumHitNew > 0 && (Entity.IDENT.NumHitOld == 5), then Way 5; Else Way 6</td></tr>
<tr><td>TcraftNotDestroyed2? (2-Way)</td><td>This is a 2-Way by Condition decision module which decides the entity path by checking the attribute Sinkparameter.
For Entity.IDENT.SinkParameter == 0, then TRUE; Else FALSE</td></tr>
<tr><td>Decide Finished? (2-Way)</td><td>This is a 2-Way by Condition decision module which decides the entity path by comparing sorties at the beginning with the sum of sorties onshore and number of destroyed sorties.
For SortiesFixed <= SortiesOnShore+DestroyedSorties+1, then TRUE; Else FALSE</td></tr>
<tr><td>Check NumHits 3 (N-Way)</td><td>This is a N-Way by Condition decision module which decides the entity path by checking number of total hits of a T-Craft.
For Entity.IDENT.NumHitNew == 1, then Way 1;
For Entity.IDENT.NumHitNew == 2), then Way 2;
For Entity.IDENT.NumHitNew == 3), then Way 3;
For Entity.IDENT.NumHitNew == 4), then Way 4;
For Entity.IDENT.NumHitNew == 5), then Way 5; Else Way 6</td></tr>
<tr><td>TcraftNotDestroyed3? (2-Way)</td><td>This is a 2-Way by Condition decision module which decides the entity path by checking the attribute Sinkparameter.
For Entity.IDENT.SinkParameter == 0, then TRUE; Else FALSE</td></tr>
<tr><td>Adjust BatchParameter? (2-Way)</td><td>This is a 2-Way by Condition decision module which decides the entity path by checking the variables batchparamter, batchparameter2 and number of T-Crafts.
For Batchparameter == (NumTCrafts+1) || (Batchparameter2 == NumTCrafts+1), then TRUE; Else FALSE</td></tr>
<tr><td>Check Shorespots (2-Way)</td><td>This is a 2-Way by Condition decision module which decides the entity path by checking the attribute Sinkparameter and the number of shore spots.
For Entity.IDENT.SinkParameter == 1 && (MR(ShoreResource)>0), then TRUE, Else FALSE</td></tr>
<tr><td>Last Tcraft? LastSortie? (N-Way)</td><td>This is a N-Way by Condition decision module which decides the entity path by checking number of T-Crafts, number of shore spots and number of sorties that still have to be projected to shore.
For NumTcrafts > 0 && (MR(ShoreResource)>0) && (SortiesFixed > SortiesOnShore+DestroyedSorties), then Way 1;
For NumTcrafts > 0 && (MR(ShoreResource)>0) && (SortiesFixed <= SortiesOnShore+DestroyedSorties), then Way 2; Elses Way 3</td></tr>
<tr><td>Refill during Loading? (N-Way)</td><td>This is a N-Way by Condition decision module which decides the entity path by checking the variable RefillDurLoad and whether there is still enough fuel in the tank for the next turn.
For RefillDurLoad == 1, then Way 1;
For RefillDurLoad == 0 && (Entity.IDENT.FuelC >= (1.2*(FuelCLoaded *Distance/Speed + FuelCUnloaded *Distance/Speed))), then Way 2;
Else, Way 3</td></tr>
</table>

Check if TCraft needs repair and if sortie is required 2 (N-Way)	This is a N-way by Condition decision module which decides the entity path by checking attributes and variables: For Entity.IDENT.NumHitOld<NumHitsToRepair && (numberSorties2 > 0), then Way 1; for numberSorties2<=0, then Way 2; Else, Way 3
Assign Modules	**Description**
CreateResources DefineVariables ComputeAddFuel	This module creates the resources, defines all variables that are needed during the simulation and computes if additional fuel in the second tank is needed.
Compute needed sorties without additionalFuel	This module computes the number of sorties that are needed based on footprint and on weight of the troops without the need of additional fuel.
Compute needed sorties with additionalFuel	This module computes the number of sorties that are needed based on footprint and on weight of the troops with additional fuel.
set sorties based on load	This module sets variables that are needed in the case when the number of sorties is based on load.
set sorties based on footprint	This module sets variables that are needed in the case when the number of sorties is based on footprint.
DefineAttributes	This module defines all attributes of the entities at the beginning of the main process.
set fuel	This module sets the fuel attribute of the T-Craft entities.
Decrement SortieNumber	This module decrements the number of sorties due to loading a T-Craft.
set amount of sortie based on load	This module sets the amount of load in LT for the very last sortie.
set amount of sortie based on footprint	This module sets the amount of load in sq. ft. for the very last sortie.
set Batchparameter	This module sets the batchparameter based on the input parameter batch size.
set Batchparameter2	This module sets the batchparameter based on the number of sorties that are left. (necessary when number of sorties becomes smaller than the batch size)
set Batchparameter3	This module sets the batchparameter based on the number of T-Crafts that are available. (necessary when the number of T-Crafts is smaller than the batch size)
set Batchparameter4	This module sets the batchparameter based on the number of sorties that are left. (necessary when the number of sorties becomes smaller than the number of T-Crafts)
storeBatchSize DecrementSorties	This module stores the batch size as an attribute to each T-Craft entity and decrements the number of sorties.
ResetBatchParameter	This module resets the variable Batchparameter to zero after a batch left the sea base.
DecrementFuel GetHits? countHits	This module decrements the fuel for the transit to shore, computes the hits that the T-Craft entities get during transit, and counts the total number of hits with troops aboard.
SinkProb1	This module computes the probability of sinking after one hit during transit and the attrition that the troops suffer from this hit.
SinkProb2	This module computes the probability of sinking after two hits during transit and the attrition that the troops suffer from these hits.
SinkProb3	This module computes the probability of sinking after three hits during transit and the attrition that the troops suffer from these hits.
SinkProb4	This module computes the probability of sinking after four hits during transit and the attrition that the troops suffer from these hits.

SinkProb5	This module computes the probability of sinking after five hits during transit and the attrition that the troops suffer from these hits.
updateAttributes TimeStamp	This module resets attributes and sets a time stamp to the T-Craft entity in order to measure the time that is needed for unloading.
get Hits? 1	This module computes how many hits a T-Craft takes during unloading.
get Hits? 2	This module computes how many hits a T-Craft takes during unloading.
SinkProb11	This module computes the probability of sinking after one hit during unloading and the attrition that the troops suffer from this hit.
SinkProb12	This module computes the probability of sinking after two hits during unloading and the attrition that the troops suffer from these hits.
SinkProb13	This module computes the probability of sinking after three hits during unloading and the attrition that the troops suffer from these hits.
SinkProb14	This module computes the probability of sinking after four hits during unloading and the attrition that the troops suffer from these hits.
SinkProb15	This module computes the probability of sinking after five hits during unloading and the attrition that the troops suffer from these hits.
ComputeVariables SetModelCounter	This module computes output variables and sets the ModelCounter.
Increment SortiesOnShore SetAttributes ComputeProbFailure	This module increments the number of sorties onshore, resets attributes and computes the probability of a minor failure for the T-Craft entity.
SinkProb6	This module computes the probability of sinking after one hit during transit back to the sea base.
SinkProb7	This module computes the probability of sinking after two hits during transit back to the sea base.
SinkProb8	This module computes the probability of sinking after three hits during transit back to the sea base.
SinkProb9	This module computes the probability of sinking after four hits during transit back to the sea base.
SinkProb10	This module computes the probability of sinking after five hits during transit back to the sea base.
DecrementFuel UpdateAttributes	This module decrements the fuel for the transit to sea base and updates the attributes of the T-Craft entity.
Destroyed Sorties Counter	This module counts how many sorties are destroyed during a mission.
Increment SortiesOnShore DecrementShoreSpots	This module decrements the number of shore spots that are available and increments the number of sorties that have reached the shore.
Tcraft destroyed counter	This module counts how many T-Crafts are destroyed during a mission
Count TCrafts in Repair	This module counts the number of T-Crafts that need repair due to enemy hits.
Adjust BatchParameter	This module adjusts the Batchparameter.
compute remaining sorties	This module computes the remaining sorties on the sea base when the last T-Craft is destroyed.
Set ModelCounter ComputeVariables	This module computes output variables and sets the ModelCounter.
DecrementSortieNumber2 RefillCounter SetFuel	This module decrements the number of sorties that remain at sea base, counts the number of refills and sets the fuel.

Batch Modules	Description
BatchTcraft	This module creates batches according to the batchparameter.
Seperate Modules	**Description**
Separate Batches	This module separates the batches.

Advanced Processes:

ReadWrite Modules	Description
ReadWrite 1	This module reads all input parameters from the Excel input file.
ReadWrite 2	This module writes all output parameters in the Excel file.
ReadWrite 3	This module writes all output parameters in the Excel file.

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