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THESIS

COUNTER-PIRACY ESCORT OPERATIONS IN THE GULF OF ADEN

by

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June 2011

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Increased pirate activity in the Gulf of Aden (GOA) has gotten the attention of the international community, and many countries are engaged in counter-piracy operations to protect vulnerable shipping and provide humanitarian aid. In February 2009, the Internationally Recommended Transit Corridor (IRTC) was established in order to introduce safer and more organized passage for all merchant vessels transiting the GOA. This thesis uses simulation to identify the key factors involved in escorting vulnerable shipping through the Gulf of Aden (GOA). Specifically, a scenario in which a group of merchant ships travels under escort of a warship is modeled using an agent-based simulation environment. Using state-of-the-art experimental designs, over 300,000 counter-piracy escort missions are simulated and analyzed. The results indicate that convoys are most successful when they contain fewer than 14 merchant ships, travel at speeds greater than 18 knots, position the warship in front or on the flank of the convoy, and identify pirates at a range of no less than 4 kilometers. It is found that three or more pirate vessels are especially difficult to counter, as are pirates travelling at speeds greater than 39 knots.

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COUNTER-PIRACY ESCORT OPERATIONS IN THE GULF OF ADEN

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ABSTRACT

Increased pirate activity in the Gulf of Aden (GOA) has gotten the attention of the international community, and many countries are engaged in counter-piracy operations to protect vulnerable shipping and provide humanitarian aid. In February 2009, the Internationally Recommended Transit Corridor (IRTC) was established in order to introduce safer and more organized passage for all merchant vessels transiting the GOA. This thesis uses simulation to identify the key factors involved in escorting vulnerable shipping through the Gulf of Aden (GOA). Specifically, a scenario in which a group of merchant ships travels under escort of a warship is modeled using an agent-based simulation environment. Using state-of-the-art experimental designs, over 300,000 counter-piracy escort missions are simulated and analyzed. The results indicate that convoys are most successful when they contain fewer than 14 merchant ships, travel at speeds greater than 18 knots, position the warship in front or on the flank of the convoy, and identify pirates at a range of no less than 4 kilometers. It is found that three or more pirate vessels are especially difficult to counter, as are pirates travelling at speeds greater than 39 knots.

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THESIS DISCLAIMER

The reader is cautioned that the computer programs presented in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logical errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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LIST OF ACRONYMS AND ABBREVIATIONS

ABM	Agent-Based Model
AMISOM	African Union Military Mission in Somalia
BIC	Bayesian Information Criterion
CAEn	Close Action Environment
CART	Classification and Regression Trees
CTF	Combined Task Force
DP	Design Points
DOE	Design of Experiments
DTA	New Zealand Defense Technology Agency
EU	European Union
EUNAVFOR	European Union Naval Force
GOA	Gulf of Aden
GUI	Graphical User Interface
HPC	High Performance Computing
IRTC	Internationally Recommended Transit Corridor
JMSDF	Japanese Maritime Self Defence Force
LH	Latin Hypercube
MANA	Map-Aware, Non-Uniform Automata
MOE	Measure of Effectiveness
MSPA	Maritime Security Patrol Area
NATO	North Atlantic Treaty Organization
NOLH	Nearly Orthogonal Latin Hypercube
NONBMD	Nearly Orthogonal Nearly Balanced Mixed Designs
NMG	NATO Maritime Group
RPG	Rocket Propelled Grenades
RMSS	Russian Maritime Security Service
SEED	Simulation Experiments and Efficient Design
SHADE	Shared Awareness and DE-Confliction
SBR	Somali Basin Region
UAV	Unmanned Aerial Vehicle
UNCLOS	United Nations Convention on the Law of the Sea

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EXECUTIVE SUMMARY

Increased pirate activity in the Gulf of Aden (GOA) has gotten the attention of the international community, and many countries are engaged in counter-piracy operations to protect vulnerable shipping and provide humanitarian aid. The European Union Naval Force (EUNAVFOR) Somalia—Operation ATALANTA, is the European Union's first naval operation. In February 2009, the Internationally Recommended Transit Corridor (IRTC) was established in order to introduce safer and more organized passage for all merchant vessels transiting the GOA. The IRTC is a corridor between Somalia and Yemen within international waters, consisting of two lanes, each of five nautical miles (nm's) width, one eastbound and one westbound, with a space of two nm between them. The total length of the transit corridor is 480 nm, and a vessel maintaining 14 knots requires 34.5 hours to pass through it.

This thesis uses simulation to identify the key factors involved in escorting vulnerable shipping through the Gulf of Aden (GOA). Specifically, a scenario in which a group of merchant ships travels under escort of a warship is modeled using an agent-based simulation environment known as Map-Aware, Non-uniform Automata (MANA). The simulation is run to address the following questions:

- How does the number of merchant ships affect the ability of the frigate to defend them?
- How many pirates can a convoy adequately handle?
- What factors should be taken under consideration when we have an escorted convoy?

We provide insight into the critical factors and threshold values a decision maker should consider when deciding how many merchant ships a warship should escort and what tactics should be used.

The scenario simulated in MANA, shown in Figure 1, involves coalition force operations using a warship with a helicopter to protect a convoy of merchant ships transiting westbound in two columns along the IRTC. This area usually includes many fishing or other individual traveling vessels, and the pirates behave like one of them until they approach a potential target, attack it, and attempt to capture it.

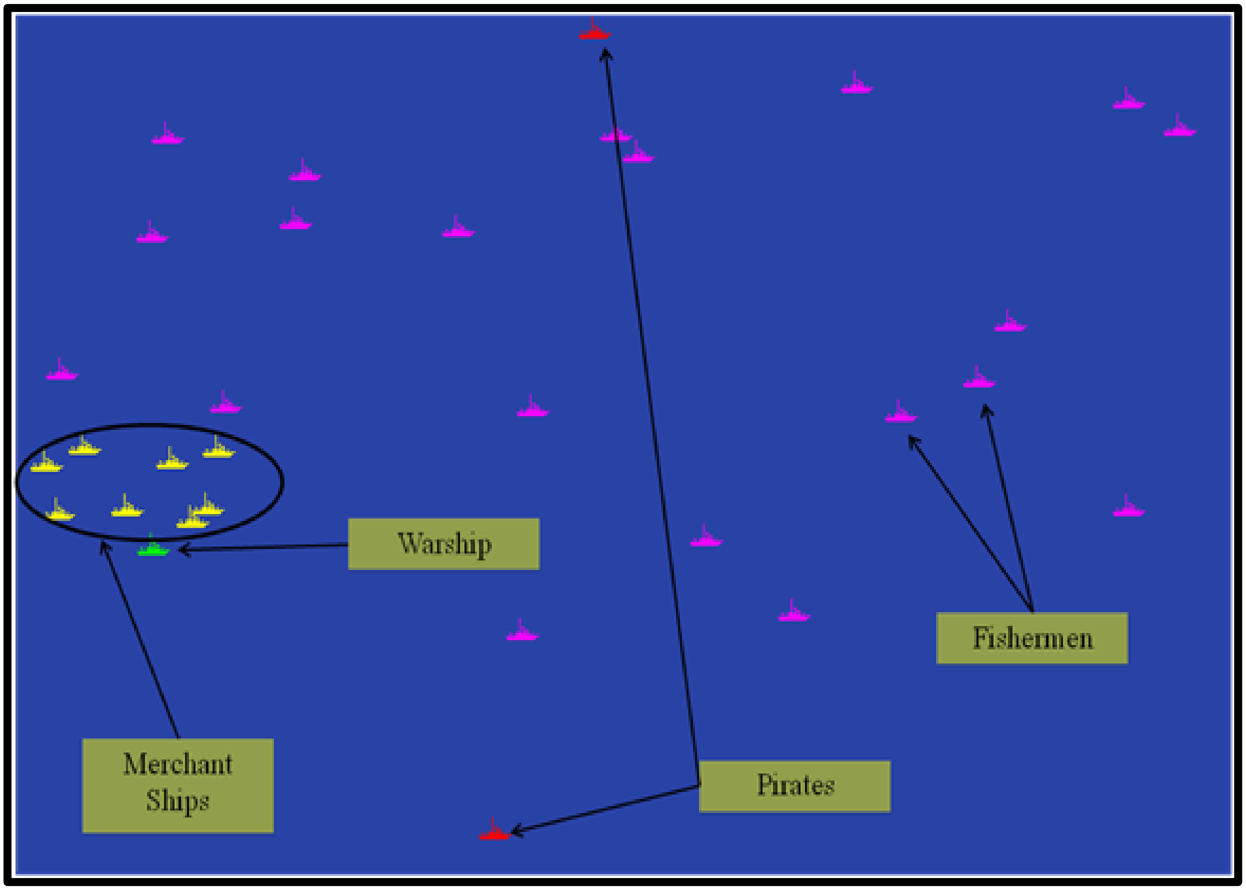

Figure 1. Map of the Scenario

Using state-of-the-art design of experiments (DOE), over 300,000 convoy operations are simulated. The DOE distinguishes between decision factors (i.e., those variables that we can control) and noise factors (those variables we cannot control), and varies the following:

- Decision factors: warship position, convoy speed, number of merchant ships, distance between merchant ships, and helicopter takeoff delay
- Noise factors: number of pirates, pirate speed, communication latency between merchant ships and warship, and distance from convoy at which pirates reveal identity

Three primary analysis techniques are used to quantify how mean merchant (blue) casualties are affected by the factors above: multiple-regression analysis, robust analysis, and classification and regression trees. The analysis finds that in the scenario modeled:

- The three most influential factors in the regression analysis are the number of pirates, pirate speed, and convoy speed,
- The most successful convoys have fewer than 14 merchant ships and travel at greater than 18 knots,
- The warship should patrol in front or on the flank of the convoy,
- It is important to be able to identify pirates at 4 kilometers from their target,
- More than three pirate vessels are especially difficult to counter, as are pirates that travel at more than 39 knots.

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I. INTRODUCTION

Everything should be made as simple as possible, but not simpler.

Albert Einstein

A. WHAT IS PIRACY?

The word pirate derives from the Greek “peirates” (πειρατής), the name of an ancient adventurer who attacked a ship (Johnson & Valencia, 2005). Most people think of pirates as belonging to a very long-distant era, from approximately 1500 to 1800, when the Barbary corsairs of North Africa made the Mediterranean Sea rampant with piracy (Berlatsky, 2010). In Southeast Asia, piracy has been present for approximately 2,000 years, but incidents have increased dramatically in the last two decades (Young, 2007). That augmented pirate activity has alarmed the international community, and many countries are engaged in counter-piracy operations to protect vulnerable shipping and humanitarian aid.

In 1982, the United Nations Convention on the Law of the Sea (UNCLOS) provided a framework for the repression of piracy under international law. In particular, Article 101 defines piracy as follows:

Article 101

Definition of piracy

Piracy consists of any of the following acts:

(a) any illegal acts of violence or detention, or any act of depredation, committed for private ends by the crew or the passengers of a private ship or a private aircraft, and directed:

(i) on the high seas, against another ship or aircraft, or against persons or property on board such ship or aircraft;

(ii) against a ship, aircraft, persons or property in a place outside the jurisdiction of any State;

(b) any act of voluntary participation in the operation of a ship or of an aircraft with knowledge of facts making it a pirate ship or aircraft;

(c) any act of inciting or of intentionally facilitating an act described in subparagraph (a) or (b) (Young, 2007).

B. LITERATURE REVIEW

The author found two related studies addressing maritime counter-piracy using agent-based simulations.

The first was in 2005, by Walton and others (Walton, Paulo, McCarthy, & Vaidyanathan, 2005). Their research was part of a larger study that examined maritime-domain protection in the Straits of Malacca. The scenario involved the attack of a small boat carrying explosives against a larger, high-value commercial ship, and was designed to demonstrate the quick reaction of the maritime-protection system. The scenario was developed in the simulation software MANA (Map Aware, Non-uniform Automata) and had either patrol crafts conducting a continuous patrol pattern in the straits or armed sea marshals aboard the commercial ship. The research examined ways to prevent the success of the small-boat attack when it exited from a fairly narrow portion of the straits that is usually congested.

The second study was in 2010, conducted by Decraene and others (Decraene, Anderson, & Yoke Hean Low, 2010). The scenario was a large commercial vessel transiting a wide expanse of water, when a pirate agent closes on it. The commercial ship employs evasive maneuvers and a non-lethal weapon. Decraene and Anderson's model was developed in MANA to investigate the requirements for a large commercial vessel using non-lethal deterrents to defend against hijacking.

Both scenarios are dealing with maritime vessel protection, the first is using either crafts patrolling congested straits or armed personnel aboard the vessels under protection, while the second is using self-defense deterrents. This thesis evaluates a scenario using an escort warship and a helicopter. All three of these theses used the MANA simulation environment.

C. RESEARCH QUESTIONS

The goal of this thesis is to simulate counter-piracy operations in the Gulf of Aden (GOA) and explore the benefits of escorting vulnerable shipping. This is done by simulating a scenario in which a group of merchant ships travels under escort of a warship. The simulation is run to address the following questions:

- How does the number of merchant ships impact the ability of the frigate to defend them?
- How many pirates can the convoy adequately handle?
- What factors should be taken under consideration when we have an escorted convoy?

D. BENEFITS OF THE STUDY

This study provides insight into critical factors and their threshold values for decision makers to take under consideration in determining how many merchant ships a warship can escort and what scheme should be followed.

E. METHODOLOGY

The scenario described is modeled using the MANA modeling environment.

The principles of robust design are used for the experiment. This research also makes use of the newest developments in Nearly Orthogonal Nearly Balanced Mixed designs (NONBMD).

Two Nearly Orthogonal, Nearly Balanced, Mixed designs, one for decision factors and one for noise factors, are generated and crossed to produce the overall experiment design.

The experiment is performed on the SEED Center's high-performance cluster, "Reaper." The xstudy, OldMcData, and Condor software packages are used to generate the required files and manage the execution of distributed jobs.

To analyze the output of the experiment, the following methods are used: statistical summaries, multiple regression, partition trees, plots/graphs, and robust analysis.

F. THESIS ORGANIZATION

Chapter II offers an outline of piracy in the GOA and a description of the Internationally Recommended Transit Corridor (IRTC). The chapter ends with a description of the European Union Naval Force mission in the GOA. Chapter III begins with an overview of the modeling tool MANA and the scenario description and closes with a detailed description of the model and the way it is built. Chapter IV includes a discussion of experiment design, a description of the variables used in the analysis, and an explanation of NONBMD. Chapter V describes the analytical methods used to interpret the results of the simulated tests and concludes with an explanation of the analytical results. Chapter VI is a discussion of the results and recommendations for follow-on research.

II. BACKGROUND

A. THE HORN OF AFRICA AND GULF OF ADEN

The Horn of Africa (Figure 2), a peninsula in East Africa, is a region comprising the countries of Eritrea, Djibouti, Ethiopia, and Somalia and is laved by the south part of the Red Sea and the GOA (Stock, 2004).

The Horn of Africa is one of the most strategically important international waterways. It carries almost the 95% of European Union (EU) trade (by volume) transported by sea and 20% of global trade (EUNAVFOR, 2010).

Piracy and absence of the rule of law in war-torn Somalia are directly linked. In the early 21st century, when the second phase of the Somali civil war began, piracy off the long coastline of Somalia began to be a threat to international shipping. The lack of a substantial government, the disintegration of the Somali armed forces, and the possibility of gaining quick wealth through ransom caused a rapid increase in pirate attacks and armed robbery in the GOA and the Somali Basin region (SBR) (UN Chronicle, n.d.).

Some observers also allege that illegal over-fishing of the Somalian waters by foreign poachers and the dumping of toxic waste have motivated some Somali groups engaged in piracy (Berlatsky, 2010). Big trawlers taking advantage of the lack of Somalian authority were illegally fishing vast amounts of sea life, estimated at $300 million's worth, leaving local fishermen with empty nets (Merchant, 2009). Also, it is hinted that a large amount of nuclear waste, including lead, cadmium, and mercury has been dumped in Somalian waters by other nations and individuals. This is allegedly contributing to the radical decrease in sea life (Hari, 2009). Early on, Somali fishermen started demanding that poachers pay fines, giving their groups names such as the National Volunteer Coast Guard of Somalia or Somali Marines. Later, they realized there was more money to be made from straightforward abductions for ransom (Berlatsky, 2010).

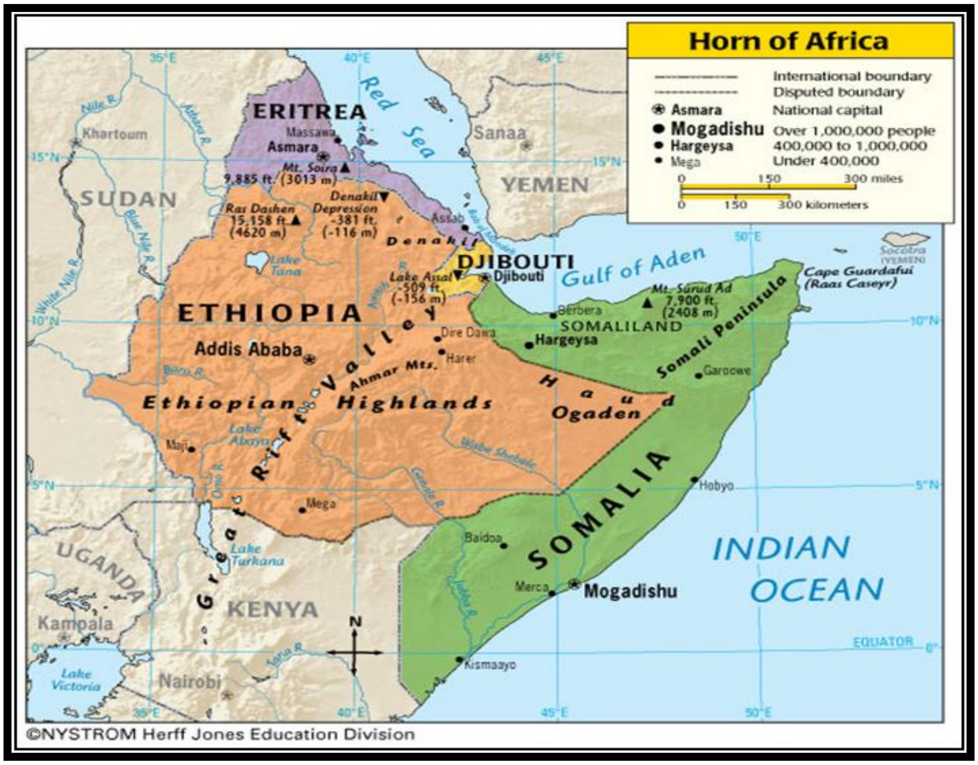

Figure 2. Horn of Africa and Gulf of Aden (From Herff Jones Nystrom, 2010)

B. PIRACY IN THE GULF OF ADEN

The augmented commercial traffic that passes through the straits is one of the main reasons for the increase in contemporary piracy. The low speed required for safe passage through these maritime choke points makes them vulnerable and easy targets (Chalk, 2008). The GOA is one of these choke points.

The GOA and area surrounding the Horn of Africa are the most dangerous areas for piracy in the world. The pirates are opportunity-driven individuals, divided into clans and based in mobile port towns, with varying patterns of operation and capabilities (Nelson, 2010). They are usually divided into groups of about ten people and use small, high-speed skiffs towed by a dhow, pretending to be fishermen. The skiffs are usually in very poor condition, old, made of wood or fiberglass, and powered by outboard motors; the GOA’s calm seas allow the use of such vessels. The pirates are equipped with drinking water, gasoline, grappling hooks, short ladders, and fishing lines and nets. They carry a large variety of handheld small arms, including AK-47 rifles and rocket-propelled grenades (RPGs) (Nelson, 2010) and (Kaplan, 2008). They venture out for a long period, usually three weeks, eating raw fish while waiting for their potential target. When they find it, they use ammunition firing to coerce the master of the vessel to either slow down or stop, and then climb aboard, making for the bridge to take control of the ship. After sailing to a safe harbor, they conduct negotiations for ransom while crew and cargo are held for weeks (Kaplan, 2008).

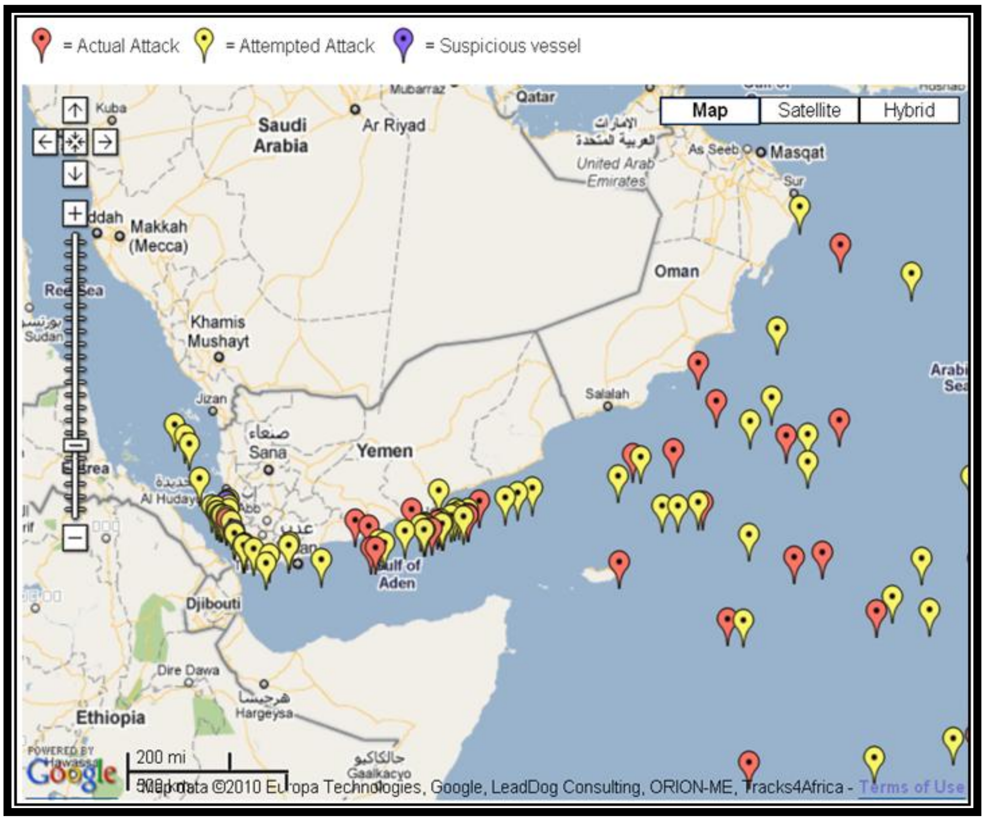

Figure 3. International Maritime Bureau Piracy Map for 2010 (From International Chamber of Commerce, 2010)

C. INTERNATIONALLY RECOMMENDED TRANSIT CORRIDOR

Shared Awareness and De-Confliction (SHADE) is a staff-level working group of officers from the various operational headquarters of all the alliances and individual countries conducting counter-piracy operations. One of the products of this group is the establishment of the IRTC (Nelson, 2010). In February 2009, the IRTC replaced the previous Maritime Security Patrol Area (MSPA) (Figure 4) in order to introduce safer and more organized passage for all merchant vessels transiting the GOA (Rietveld, 2009).

The IRTC is a corridor between Somalia and Yemen within international waters, consisting of two lanes, each of five nautical miles (nm's) width, one eastbound and one westbound, with a space of two nm between them. The total length of the transit corridor is 480 nm, and a vessel maintaining 14 knots requires 34.5 hours to pass through it. (North, 2010).

Vessels that intend to pass through the IRTC are grouped according to transit speed. Groups of 10, 12, 14, 16, 18, and 20 knots transit speed are formed at specific hours and dates, and traverse the IRTC under the coalition's escort/convoy services (North, 2010).

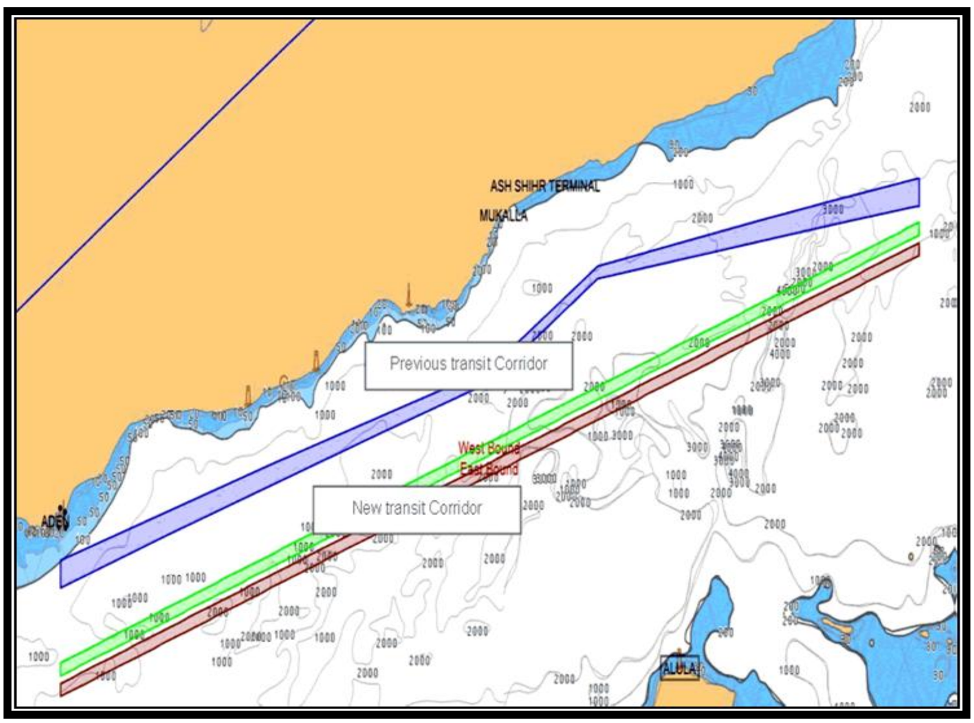

Figure 4. Internationally Recommended Transit Corridor (From http://www.eurocean.org/np4/file/863/Piracy_Gulf_of_Aden___Indian_Ocean.pdf, 2010)

D. EUROPEAN UNION NAVAL FORCE

Due to the importance of the GOA as a critical conduit for international trade, military counter-piracy operations are conducted by naval ships from the Combined Task Force 150 (CTF-150), NATO Maritime Group (NMG), Russia (Russian Maritime Security Service (RMSS)), China, Japan (Japanese Maritime Self Defense Force (JMSDF)), and India. Some of these forces operate within alliances such as NATO and EU, some as part of the CTF, and some independently represent their nation's interests. The European Union Naval Force Somalia (EUNAVFOR) – Operation ATALANTA, is the European Union's first naval operation, in support of resolutions 1814 (2008), 1816 (2008), 1838 (2008) and 1846 (2008) of the United Nations Security Council (EUNAVFOR, 2010).

The area of operations of EUNAVFOR consists of the south Red Sea, the Gulf of Aden, and part of the Indian Ocean. This now includes the Seychelles, which makes the area as large as the Mediterranean Sea.

The aim of operation ATALANTA is to contribute to:

- The protection of the vessels of the World Food Program, humanitarian aid, and the African Union Military Mission in Somalia (AMISOM),
- The protection of vulnerable shipping,
- The deterrence, prevention and repression of pirate activity and armed robbery, and
- The monitoring of fishing activities off the coast of Somalia.

In order to focus the scope of the operation, EUNAVFOR has been granted the authority to arrest, detain, and transfer persons who are suspected of, or who have committed, acts of piracy or armed robbery inside the area of operations. They can also seize the vessels of the pirates and the vessels hijacked by them, as well as the goods on board (EUNAVFOR, 2010).

Figure 5. An Escorted WFP Ship (From http://www.eunavfor.eu/about-us/mission/, 2010)

III. MODEL DEVELOPMENT

A. WHY MODELS ARE USEFUL

The main purpose of models is to collect information and gain insight about some aspect of the real world. A model mimics or describes the behavior of the system being modeled (Sanchez P. J., 2007). Pedgen (1995) describes the use of models in simulation as "[…] the purpose of understanding the behaviour of the system and/or evaluating various strategies for the operating system."

More specifically, models provide the ability to explore systems that cannot be disturbed because they are either sensitive or critical (Chung, 2004). Another benefit of the model is its ability to compress time. Systems that under normal conditions need a long time to be explored can effectively be shrunk. Also, in some cases, the cost of building a model is less expensive than experimenting directly with a real system (Sanchez P. J., 2007).

There are two different but very closely connected levels of modeling. The first level is the simulation model itself; it is the model that describes the phenomena of interest. The subsequent level is a statistical model that is built to describe the simulation's responses. The latter is a model of the model, and is often referred as a metamodel (Sanchez, Lucas, Sanchez, Nannini, & Wan, 2011, forthcoming).

B. MAP-AWARE, NONUNIFORM AUTOMATA (MANA)

1. Overview of MANA

Many complex systems can be studied through the use of agent-based models. This kind of model provides useful insights into how individual interactions give rise to emergent properties like structures and causality. Agent-based modeling is a useful tool in simulation because it can explore phenomena that deal with interactions between individual agents, for example, people in a football stadium or ants searching for food (Berryman, 2008).

The model chosen for this thesis is one such model: MANA, Version V. MANA is an agent-based, distillation-modeling environment, that is, it attempts to create models that capture only the important factors in a situation and avoids explicitly all physical details (Horne & Schwierz, Data farming around the world overview, 2008). MANA was developed by the New Zealand Defense Technology Agency (DTA) for use as a scenario-exploring model and is designed to address a broad range of problems. It resulted from the frustrations DTA faced in analyzing the output of physics-based models available at the time, basically CAEn (Close Action Environment) and Janus. Although these models are detailed, highly physics based, and can predetermine the behavioral outcomes of agents, they are quite limited in analysis, basically because it is difficult to get the entities to behave in unscripted ways (McIntosh, Galligan, Anderson, & Lauren, 2007).

In MANA, a realistic scenario can be taken and a rough model quickly built. That is because MANA is not intended to describe every aspect of a military operation. Once the skeleton of the model has been built, one can easily change agent parameters and states in order to create a reasonably accurate model of the desired interactions.

Two of MANA's limitations are that is has not been designed to examine careful formation fighting, and entities do not always behave in a sensible manner (McIntosh, Galligan, Anderson, & Lauren, 2007). This is also the major advantage of MANA, meaning that the lack of a central, predetermined, decision-making algorithm for controlling entity behavior results in the agents making their own decisions as they adapt to the environment (Walton, Paulo, McCarthy, & Vaidyanathan, 2005).

Finally, MANA is supplied with a built-in random-number generator using the Delphi function "random." The random-number generator has a cycle of 2^{32} and maintains a 32-bit seed. This means that the result can take on approximately 4.3×10^9 values before repeating the cycle.

2. Characteristics of MANA

MANA was adopted from the ISAAC model, developed by the Center for Naval Analyses, in order to explore key concepts that the ISAAC model was not able to handle (McIntosh, Galligan, Anderson, & Lauren, 2007). Those concepts are:

- **Situational awareness:** MANA provides two types of situational awareness maps: a squad map that holds direct squad contacts and an inorganic map that stores contacts provided by other squads through communication links.
- **Communications:** Allows squads to communicate with other squads in case of contact sightings.
- **Terrain map:** Contains terrain features such as roads that can be followed by agents and underbrush that can be used as concealment.
- **Waypoints:** Can define a set of waypoints, not merely the final goal.
- **Event-driven personality changes:** Different events such as contact of an enemy can change the behavior of an agent or whole squad. The new behavior lasts for a user-specified period.

MANA has a well-developed graphical user interface (GUI), and although it was originally developed to model land warfare, it can model alternative scenarios, such as sea based (McIntosh, Galligan, Anderson, & Lauren, 2007); see, for example, Abel (2009).

C. MODEL DEVELOPMENT

1. Scenario Description

As explained, the IRTC was established so that merchant or other vessels can assemble at specific points and transit as a group under the escort of coalition warships (Figure 6).

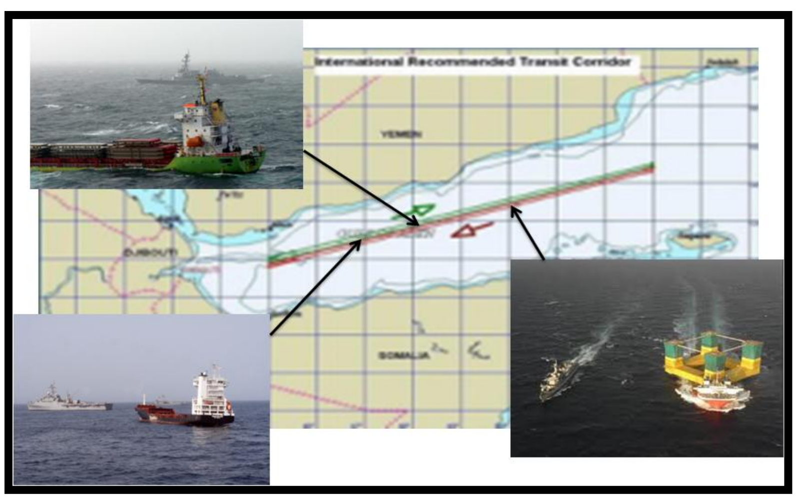

Figure 6. Warships Escorting Merchant Vessels in IRTC (After http://asianyachting.com/news/PirateCorridor.htm, 2011)

The scenario shown in Figure 7 takes place in the GOA and specifically in the IRTC. It simulates coalition operations to protect a convoy of merchant ships transiting westbound along the IRTC. Usually in the area there are also fishing or other individual traveling vessels, and the pirates behave like one of them until they approach a potential target. The scenario commences from the point that the pirates have reached high velocity heading towards the convoy. The pirates can be identified by one of the merchant ships or by the escorting warship.

The merchant ships are sailing in two-column formation. As soon as one realizes it is being approached by a quickly moving, suspicious vessel, it signals the fleet, increases speed, and begins evasive tactics while the entire convoy flees. The warship, which may be sailing beside, before, or behind the merchant formation, increases speed and heads towards the merchant under attack. At the same time, orders are given for a helicopter to take off, which heads towards the provocation.

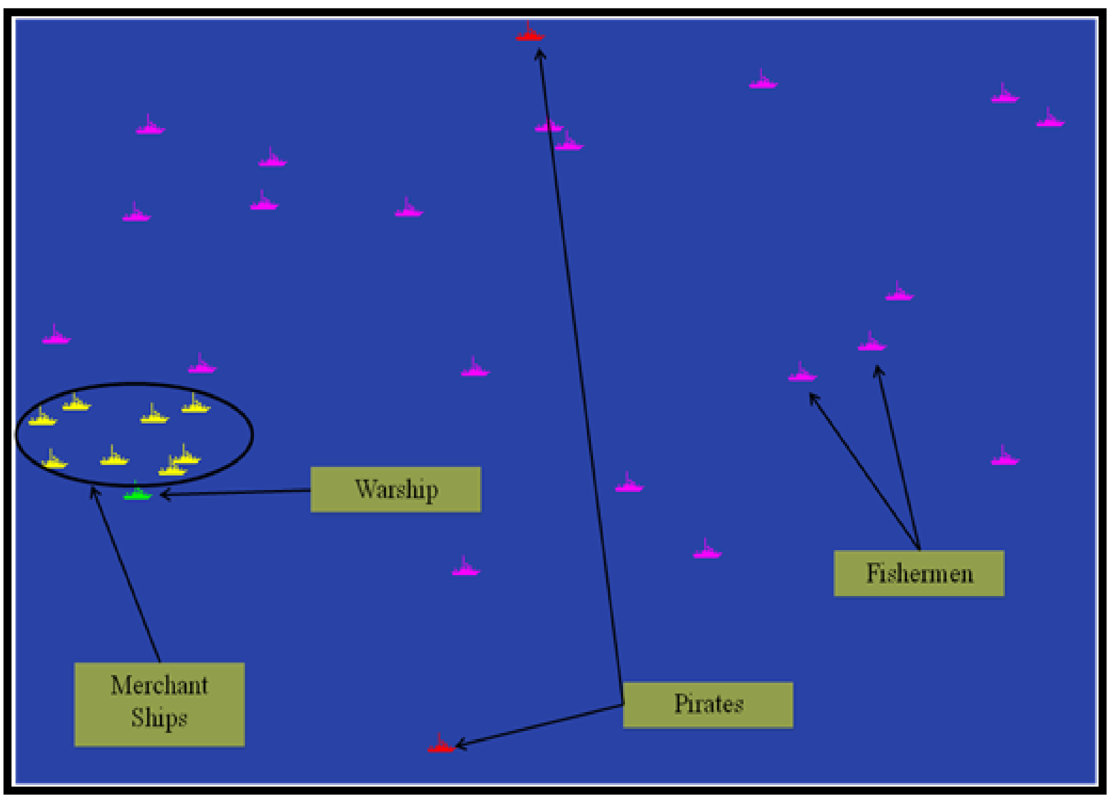

Figure 7. Map of the Scenario

2. Measure of Effectiveness

As a measure of effectiveness (MOE), the mean merchant (blue) casualties are computed. This is easily assessed using JMP by summarizing over the number of blue casualties for each design point of the experiment.

3. Scenario Assumptions

Any scenario must have some assumptions if it is to be framed in terms of time and space. For the purpose of this study, the key assumptions are:

- The pirate reveals his identity when he is close to the potential target. This proximity will always be within sensor range. Therefore, the quality of the sensors on the warship and the cargo ships has no impact on pirate detection.
- The helicopter and the warship cannot be attacked or fired on by the pirates.
- In the case of multiple pirates, either the helicopter or the warship will interdict the pirates by firing ammunition against them instead of trying to stop and arrest them. Thus, the helicopter or the warship can help in pursuing the other pirates.
- In representing the capture of a merchant ship, the range of the pirate weapon is limited to 75 meters and the merchant needs to be shot twice.
- The merchant ships are sailing in two-column formation.

4. Model Description

a. Battlefield

The battlefield is a 20 × 20 nm snapshot of the IRTC. There are no battlefield restrictions, as the area is open sea. One model time-step is set to equal ten seconds. To configure the settings of the battlefield, the option Edit Battlefield has been used in the setup option in MANA's menu bar. The battlefield settings of the scenario are shown in Figure 8. These settings are found on MANA's Setup menu on the Edit Battlefield screen. All other selections are at their default values.

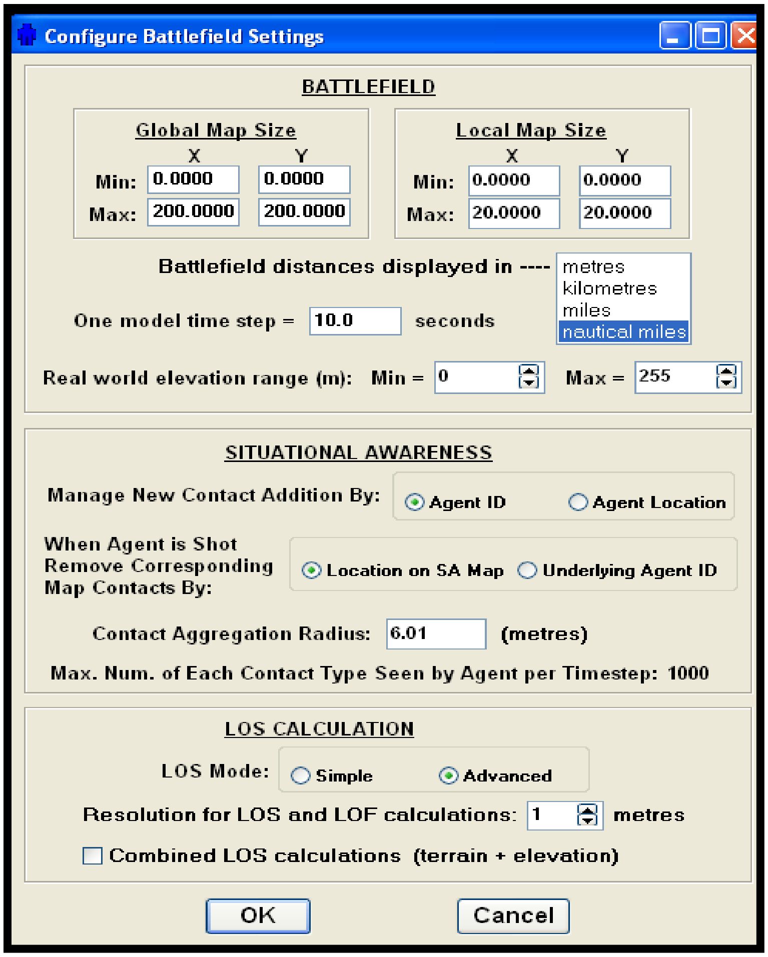

Figure 8. MANA Battlefield Settings

b. Squads

The squad is a key concept in MANA. A squad is a group of initially homogeneous agents given a size between 0 and 1000, as defined by the user. Table 1 shows the squads used in this study.

Squad #	Unit	Allegiance
1	Warship	1 (BLUE)
2	Merchant ships	1 (BLUE)
3	Pirates	2 (RED)
4	Helicopter	1 (BLUE)
5	Fishermen	0 (NEUTRAL)

Table 1. Model Squads

c. Warship

The warship squad consists of a single agent. The agent's personality weightings and different trigger states are shown in Figure 9. The personality weightings are defined using slide bars and may take on values from -100 to 100. A positive value indicates a positive propensity for the associated personality weighting, while a negative value indicates a negative propensity. Any propensity that has been changed from the default zero is shown in red. The warship, after contacting the pirates, has a propensity to move towards them (the Enemies weighting is set to 50). All other selections are at their default values.

States that are being used for the warship (other than the default state), are Enemy Contact, for behavior when the warship contacts the pirates using its own sensors, Inorganic SA Enemy Contact 2, when the warship is notified by the merchants using communication links, and Spare 1, for releasing the helicopter after enemy contact.

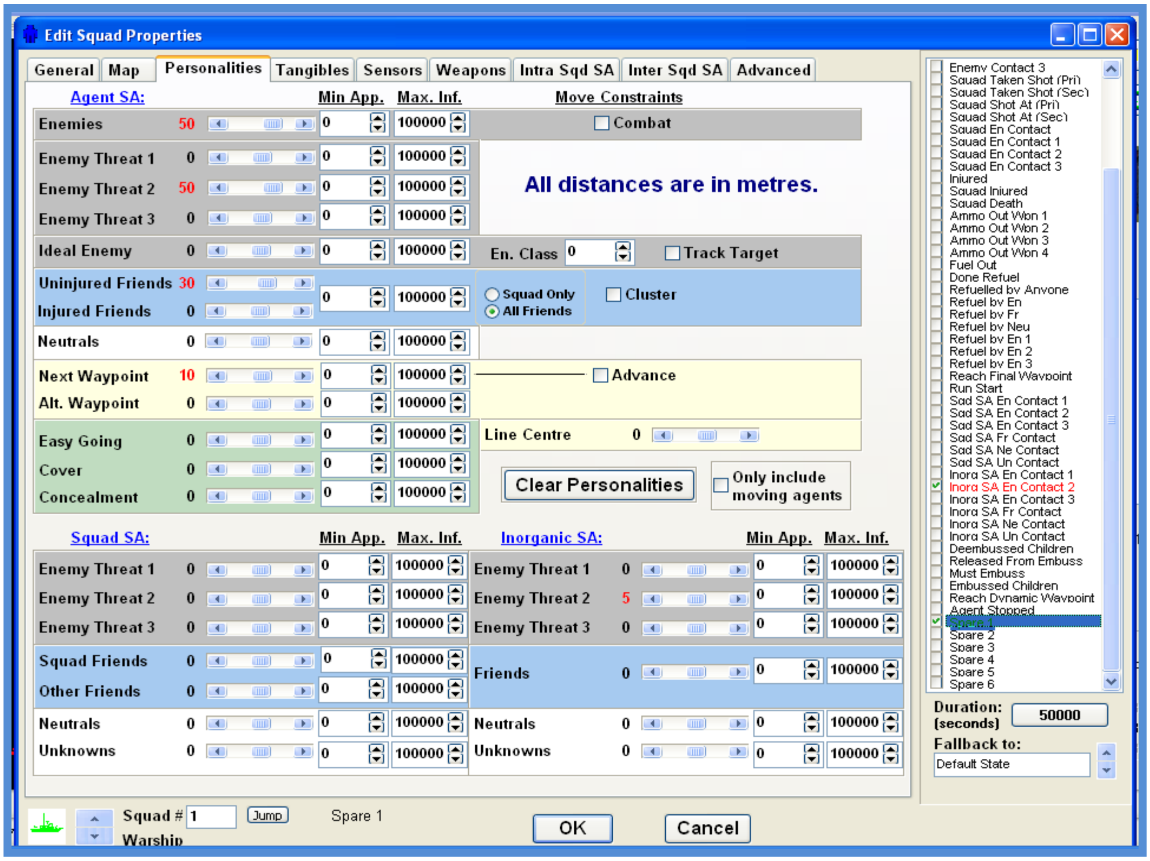

Figure 9. Warship Squad Properties

The Inorganic SA panel controls the flow of situational awareness among squads by using communication links as conduits of information. The parameters of this panel do not vary within the squad's different trigger states. The warship has communication links with the merchants and helicopter, as shown in Figure 10, Inorganic SA represents the actual communication between the warship, merchants, and helicopter.

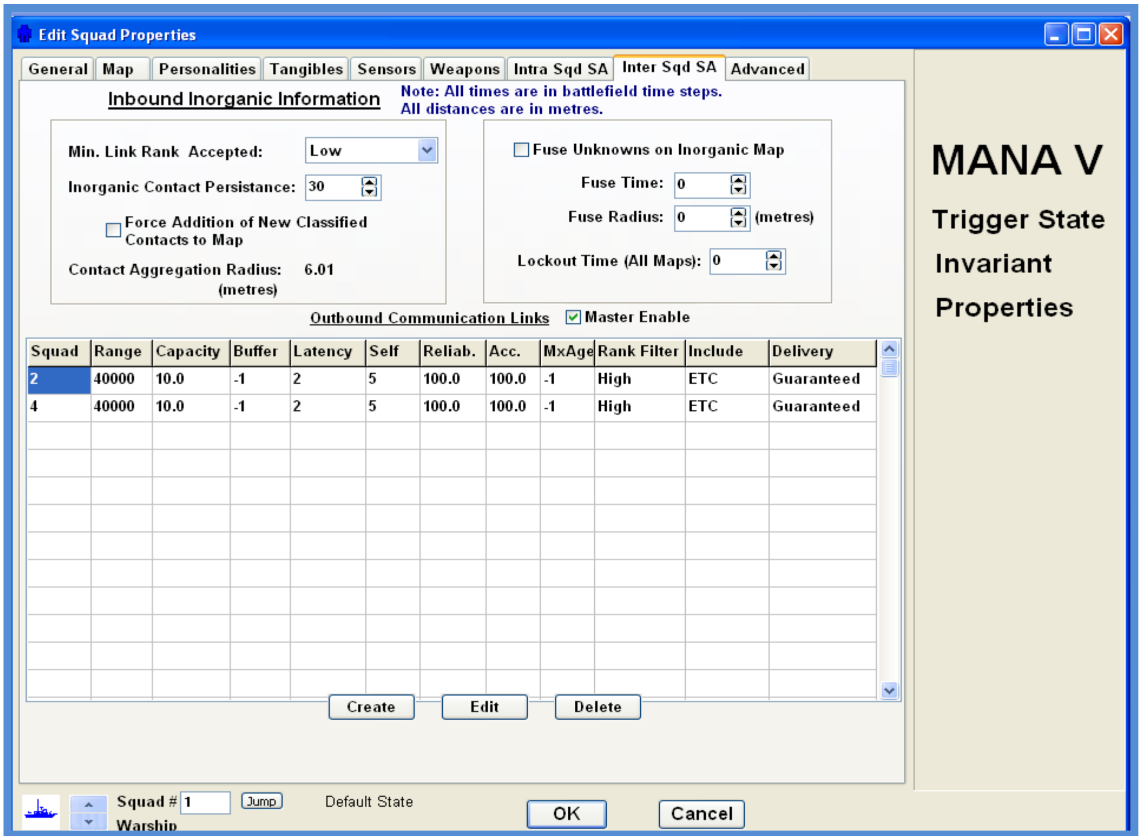

Figure 10. Warship Inorganic SA Communications

Each squad has up to four weapons available, and most of the parameters for the weapons are able to change within a trigger state. The warship has only one weapon, set to fire within a range of 250 meters and used to represent pirate deterrence. In the Protect Contact Type box, Self and Other Friends are selected to prevent the warship from firing against itself or the merchant ships. All other selections are at default values. The warship's weapon adjustments are shown in Figure 11.

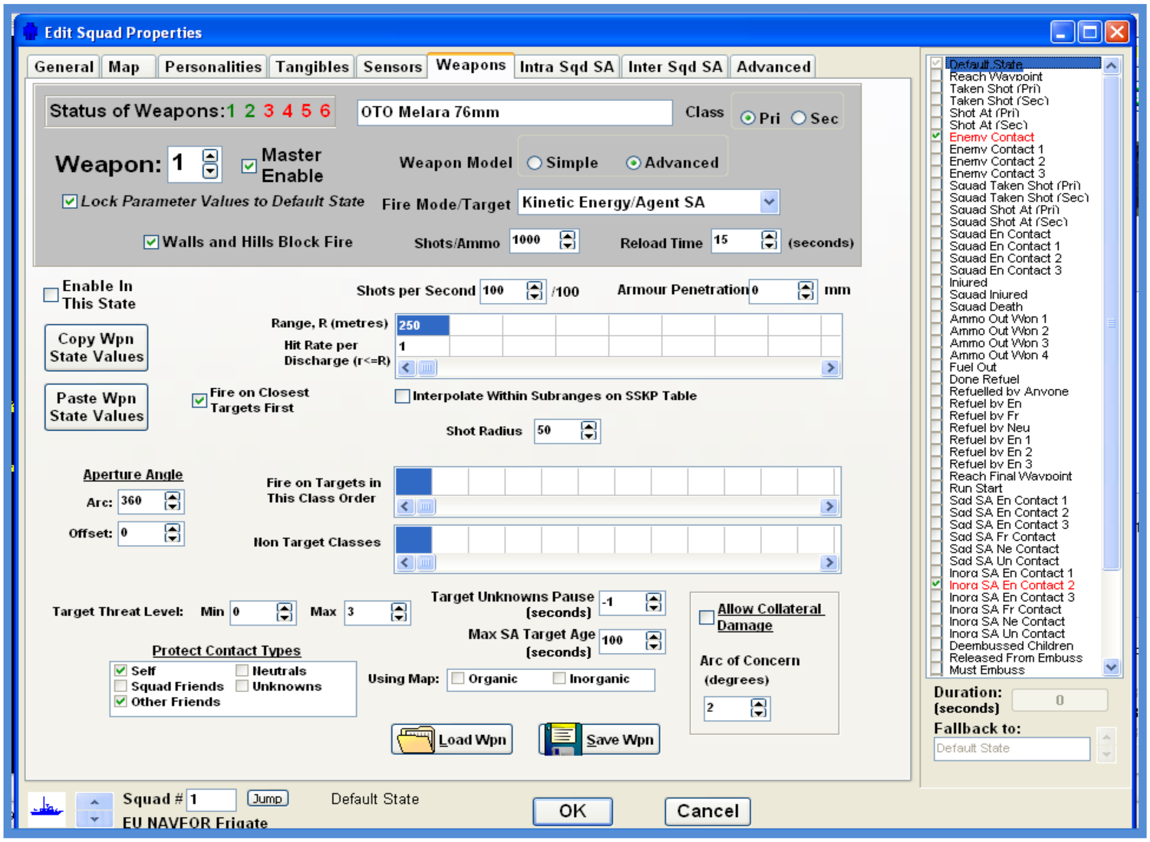

Figure 11. Warship Weapons

d. Merchant Ships

The merchant squad consists of eight agents. The agents' personality weightings and different trigger states are shown in Figure 12. The merchants, after contact with the pirates, have a propensity to move away from them (the Enemies weighting is set to -30). All other selections are at their default values.

The state used for the merchant ships, other than the default, is Enemy Contact, for behavior after contacting the pirates.

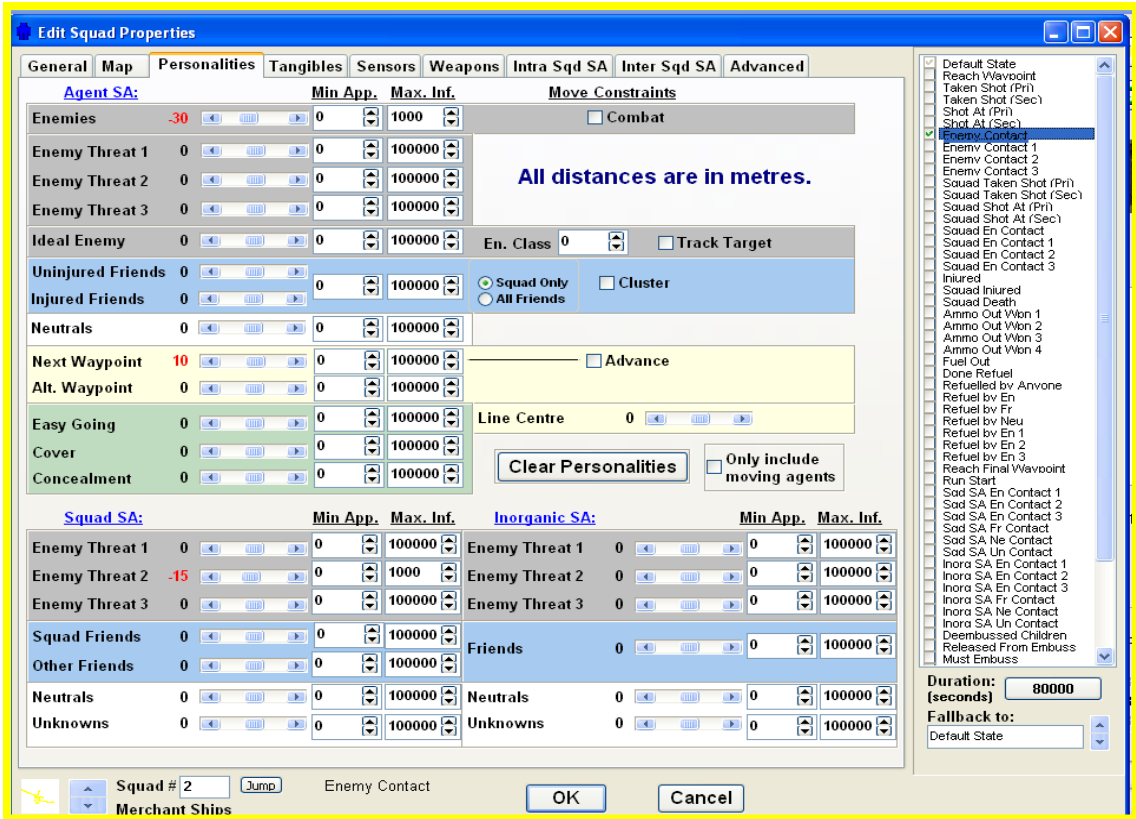

Figure 12. Merchant Ships Squad Properties

e. Pirates

The pirate squad consists of one or more agent. Agent personality weightings and different trigger states are shown in 13. The pirates, after contact with the convoy, have a propensity to move towards the merchants (Enemy Threat 3 and Ideal Enemy weighting are set to 100) while avoiding the warship and helicopter (Enemy Threat 1 weighting set to -100). All other selections are at their defaults.

Other than the default, the state used for the pirates is "Enemy Contact 3," for behavior after the pirates contact the convoy.

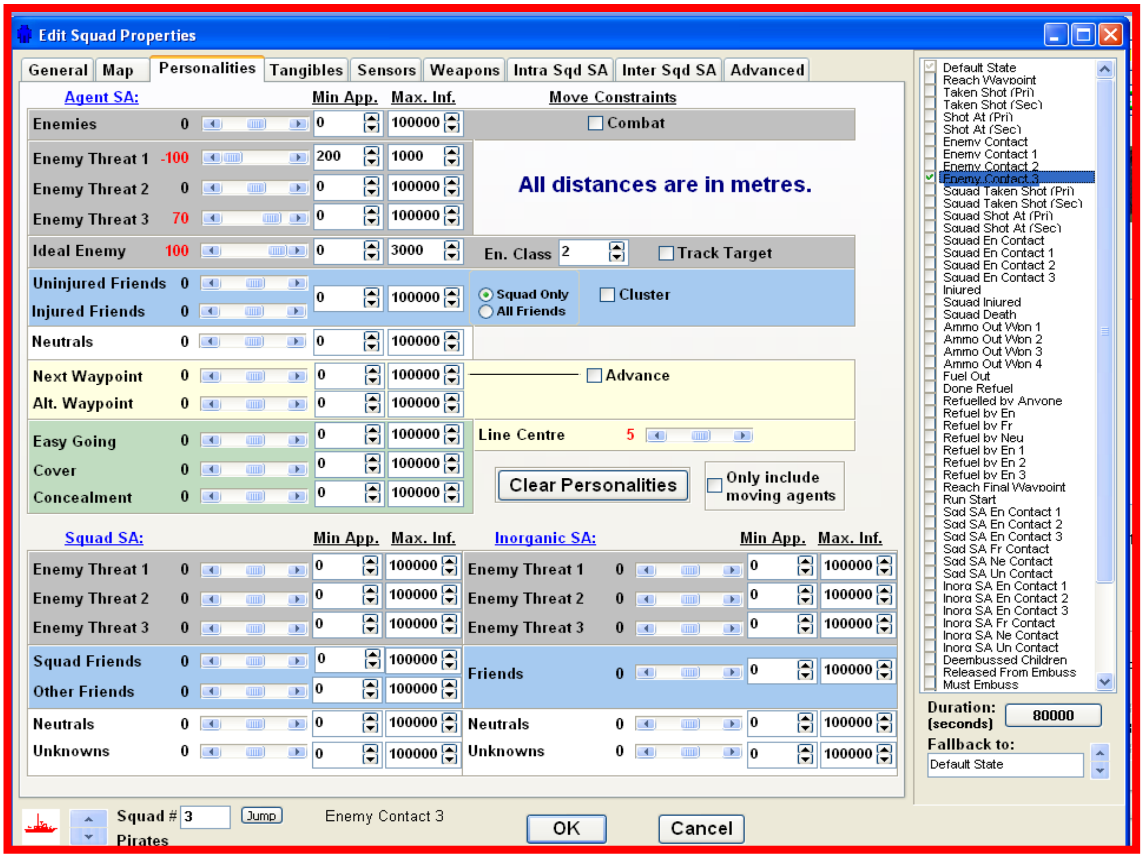

Figure 13. Pirates Squad Properties

The pirates, like the warship, have only one weapon. Their weapon is set to fire at a range of 75 meters, and is used to represent a merchant ship's capture. Using the Fire on Targets in This Class Order input box, the pirates are assigned to fire against the merchant ships only, while the use of Non Target Classes keeps them from firing against the warship and helicopter. All other selections are at their default values. The pirates' weapon adjustments are shown in Figure 14.

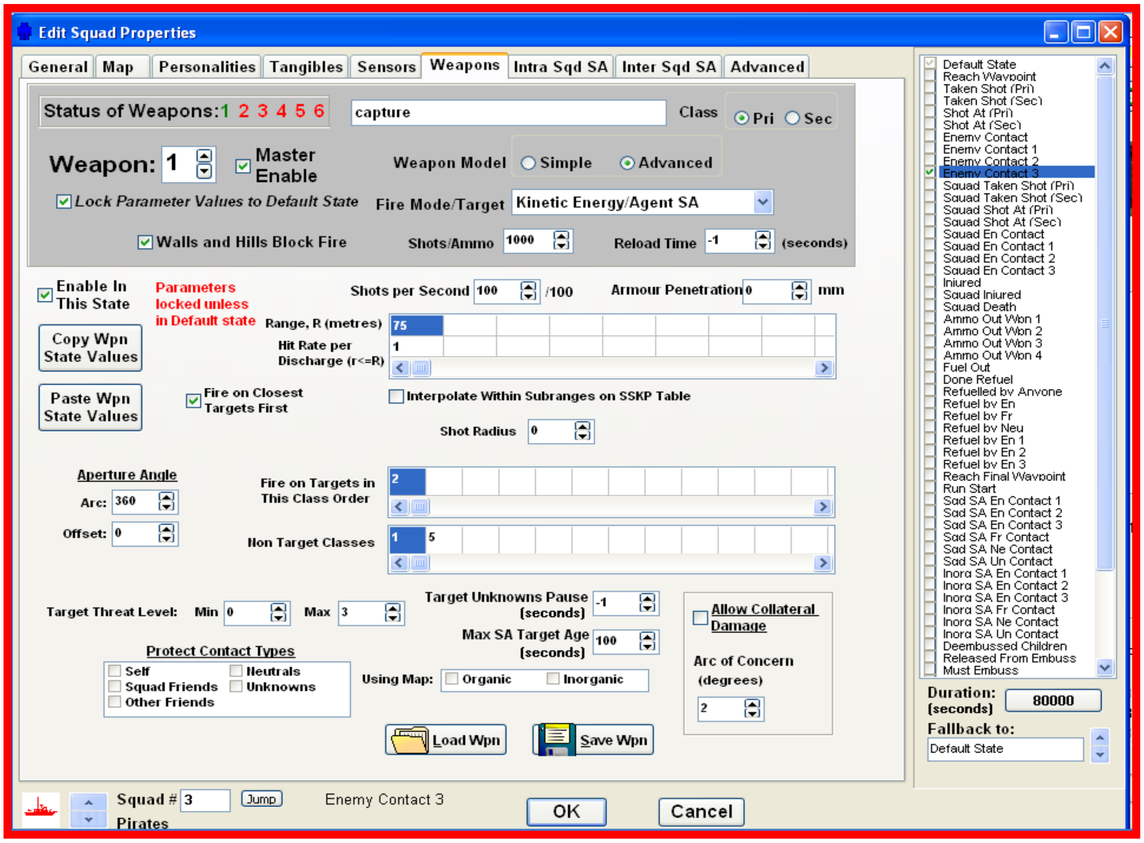

Figure 14. Pirates Weapons

f. Helicopter

The helicopter squad consists of one agent. The agent's personality weightings and different trigger states are shown in Figure 15. The helicopter, after release from the warship, has a propensity to move towards the pirates (the Enemies and Enemy Threat 2 weightings are set to 100 and 40, respectively). To ensure that the helicopter will not be hit by friendly or enemy fire, the Easy Going and Concealment weightings have been set to 100. All other selections are at default values.

The state that is used for the helicopter, other than the default, is Released From Embuss, for behavior after being released from the warship.

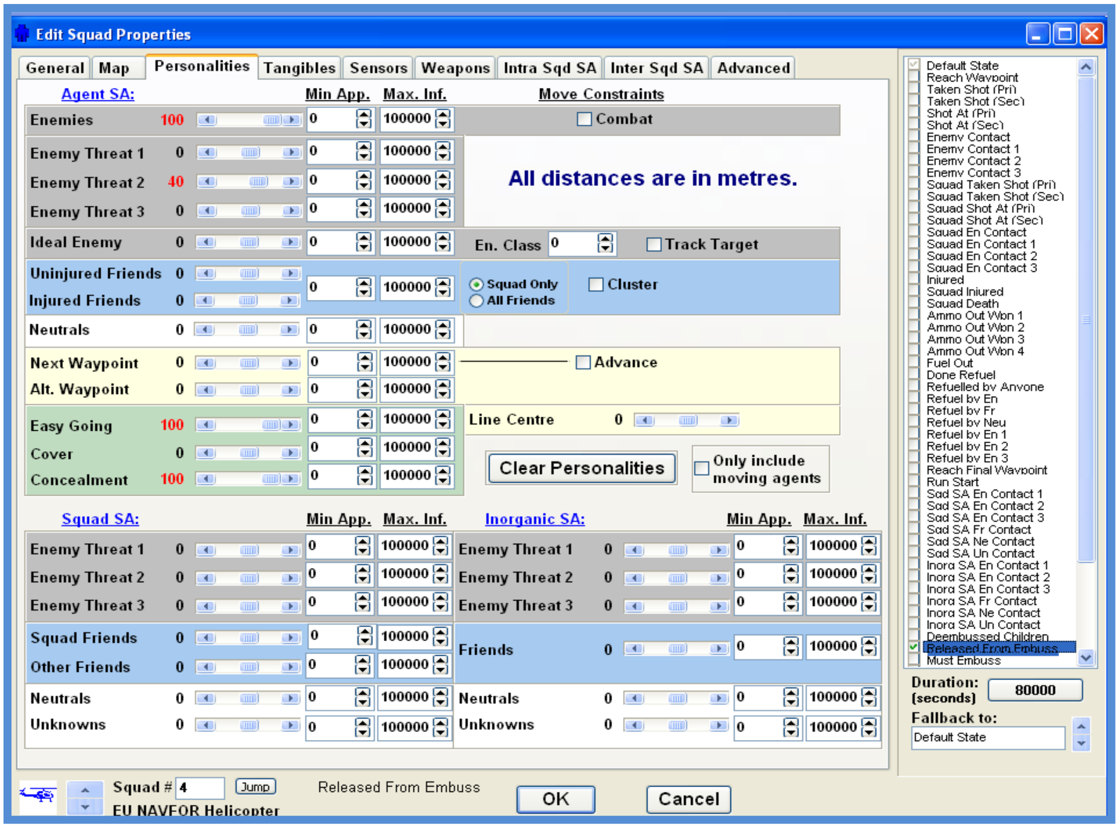

Figure 15. Helicopter Squad Properties

The helicopter has only one weapon. It is set to fire at a range of 250, 200, and 100 meters, with an assigned probability of 0.3, 0.5, and 1, respectively. It represents pirate deterrence. In the Protect Contact Type box, Self and Other Friends are selected to prevent the helicopter from firing against itself, the warship, or the merchant ships. All other selections are at their default values. The helicopter's weapon adjustments are shown in Figure 16.

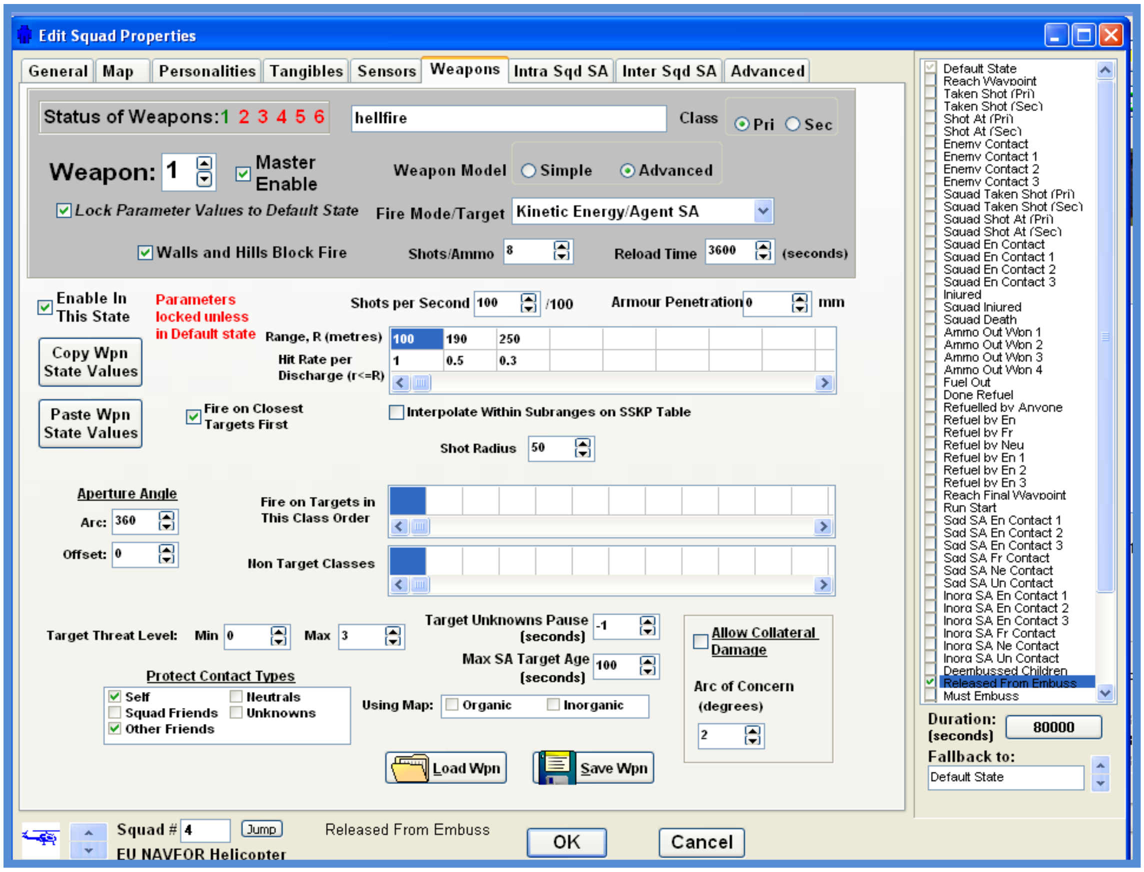

Figure 16. Helicopter Weapons

g. Fishermen

The fishermen squad motion does not influence the development of the scenario. The agent's personality weightings are shown in Figure 17. The Next Waypoint weighting is set to 20 to represent the traffic in the IRTC.

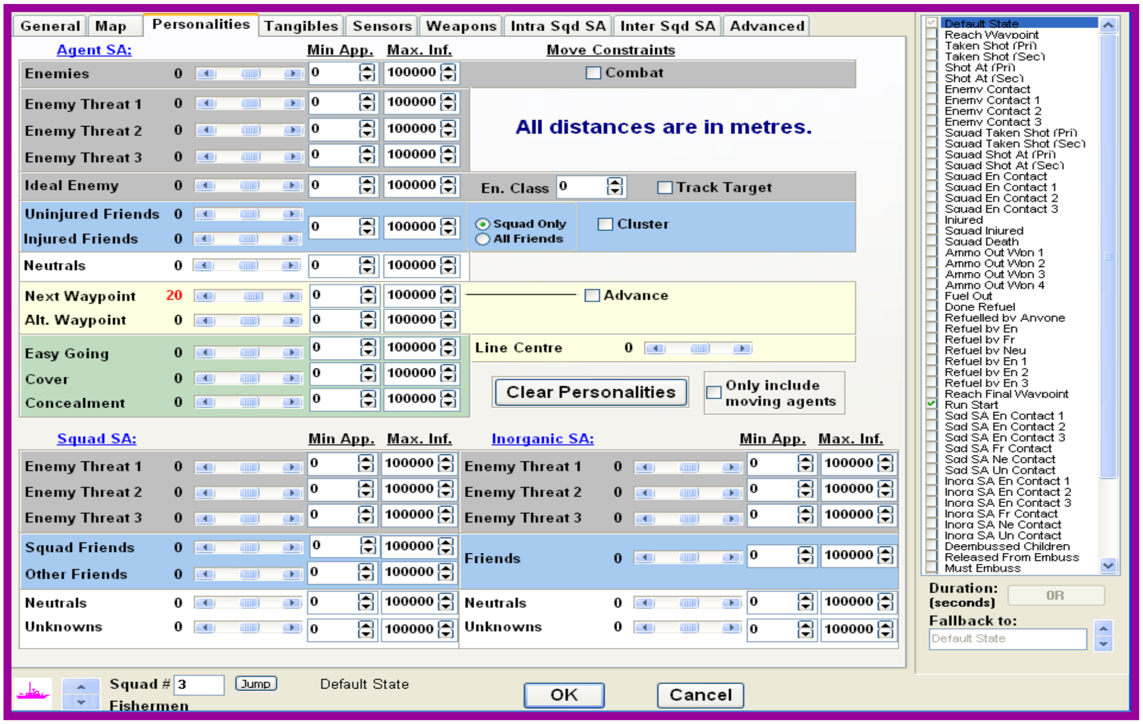

Figure 17. Fishermen Squad Properties

h. Stop Conditions

The Stop Conditions menu in MANA contains several ways to terminate a run, namely, having either agent reach his waypoints or specifying the number of losses sustained by one side, or both. These settings are found on MANA's pull-down Setup menu on the Stop Conditions screen. A scenario terminates, as shown in Figure 18, when the red or blue squads have one loss or when the merchant's ships (Squad 2) reach the waypoint. Where the number of pirates is greater than one, the stop conditions for the red losses are changing accordingly.

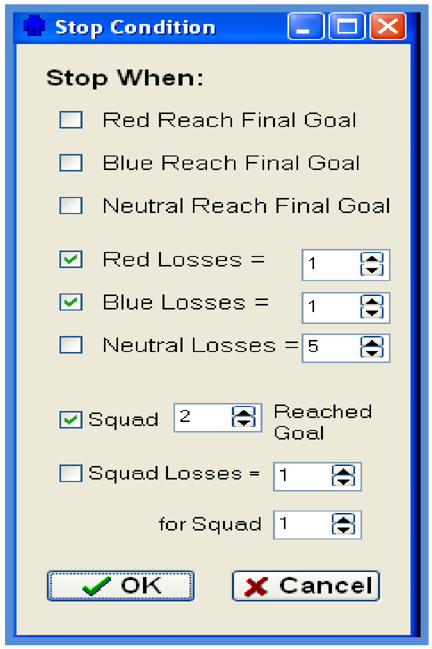

Figure 18. Scenario Stop Conditions

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IV. DESIGN OF EXPERIMENTS (DOE)

A. DATA FARMING

One tool used in this project is data farming. Data farming can be combined with the use of distillation models like MANA to explore a more complete landscape, i.e., more possible system outcomes, than merely trying to answer our problem (Horne & Schwierz, Data farming around the world overview, 2008).

Any model can be explored using data farming, but the use of distillations has the advantage that the model can be developed in a very short time, from a few minutes to hours or days. Once a model has been developed, high-performance computing (HPC), in combination with one of several existing DOE's, can be used, and a huge sample space can be efficiently and rapidly explored. Simulations are run thousands of times while the input parameters are varied across a wide value space.

The idea behind this technique is that it provides better insight into the question and reveals potential surprises, both positive and negative, that can lead to better-informed decisions (Horne & Meyer, Data farming: discovering surprise, 2004), (Horne & Schwierz, Data farming around the world overview, 2008).

B. DESIGN FACTORS

In a design, it is fundamental to identify all the factors that are expected to affect the system response. The factors involved here are classified as decision, noise, or artificial factors. Decision, or controllable, factors are those we can control in the real world, while noise, or uncontrollable, factors are those we cannot readily control in real life, or only at great expense. Finally, artificial factors are those that come from the simulation itself, e.g., the initial state of the system, the warm-up period, or terminal conditions (Sanchez S. M., Robust design: seeking the best of all possible worlds, 2000).

1. Decision Factors

The following factors have been chosen as controllable factors:

a. Warship Position

This is a categorical variable with three levels for the position of the warship in reference to the merchant ships: “behind” (indicated as 1), “on their sides/flanks” (indicated as 2), and “in front” (indicated as 3).

b. Convoy Speed

This is a continuous variable, sampled in discrete values, for the normal traveling speed of the convoy (warship and merchants). It is varied between 10 and 20 knots.

c. Number of Merchant Ships

This is a discrete variable for the number of merchant ships in the convoy. It is varied between 10 and 30.

d. Distance Between Merchant Ships

This is a continuous variable, sampled in discrete values, for the distance between merchant ships while in transit. It is varied between 50 and 500 meters.

e. Helo Take Off Delay

This is a continuous variable, sampled in discrete values, for the time it takes the helicopter to lift off after the warship becomes aware of the pirates, whether alerted by its own sensors or a merchant ship’s. It is varied between 15 and 60 minutes.

2. Noise Factors

The following factors have been chosen as uncontrollable factors:

a. Number of Pirates

This is a discrete variable for the number of the pirates that can attack the convoy. It is varied between 1 and 4.

b. Communication Latency Between Merchant Ships and Warship

This is a continuous variable, sampled in discrete values, for the latency in communication between the merchant ship under attack and the warship. It is varied between 1 and 10 minutes.

c. Pirates Speed

This is a continuous variable, sampled in discrete values, for the speed of pirate vessels. It is varied between 25 and 45 knots.

d. Distance from Convoy That Pirates Reveal Identity

This is a continuous variable, sampled in discrete values, for the distance from the merchant ships at which the pirates reveal their identity and increase speed. It is varied between 3000 and 5500 meters.

C. EXPERIMENTAL DESIGNS

The ultimate purpose of a simulation model is to gain insight into questions. With a well-designed experiment, the analyst is able to explore more factors than would otherwise have been possible by using DOE techniques developed specifically for analyzing high-dimensional computational models (Sanchez, Lucas, Sanchez, Nannini, & Wan, forthcoming).

Which DOE is suitable? Although many designs are available, the choice involves several issues, such as the complexity of the response, the time required for the simulation to run, and the ease of changing the parameter values (Kleijnen, Sanchez, Lucas, & Cioppa, 2005).

One possibility is the classical full-factorial (or gridded) design. Full-factorial designs are orthogonal designs in which the pairwise correlation between any two columns is zero. Though full-factorial designs examine all the possible combinations of factor levels, nevertheless, for studies involving a moderate or large number of factors, they are extremely large, and thus unmanageable. (Vieira, Sanchez, Kienitz, & Belderrain, 2011)

Another possible design is the fractional-factorial design, which can cover only two (2^k factorial design) or more (m^k factorial design) levels of each factor. They are also orthogonal designs and they let us examine more than one factor at a time. Additionally, for the later designs, the larger the value of *m*, the better space-filling it has. However, fractional-factorial designs are inefficient when *k* is large (Sanchez S. M., Better than a petaflop: the power of efficient experimental design, 2008).

A third option for experimental design is the Latin hypercube (LH). LHs have good space-filling properties, like m^k factorial designs, but require fewer samples. Unlike the 2^k factorial, they also provide information about what is happening in the center of the experimental region (Sanchez S. M., Better than a petaflop: the power of efficient experimental design, 2008).

Finally, Cioppa and Lucas (2007) introduced Nearly Orthogonal Latin Hypercube (NOLH) designs. These designs have nearly orthogonal properties (pairwise correlations less than 0.05), good space-filling, and can accommodate a large number of factors. A design that is nearly orthogonal will not suffer effects due to adverse/multicollineatity (Montgomery, Peck, and Vining, Introduction to linear regression analysis, 2006). NOLHs deal better with continuous factors; rounding in order to accommodate discrete factors has a result of increasing correlation and thus losing some of the nearly orthogonal properties (Sanchez S. M., Better than a petaflop: the power of efficient experimental design, 2008). Figure 19 shows the space-filling of selected designs.

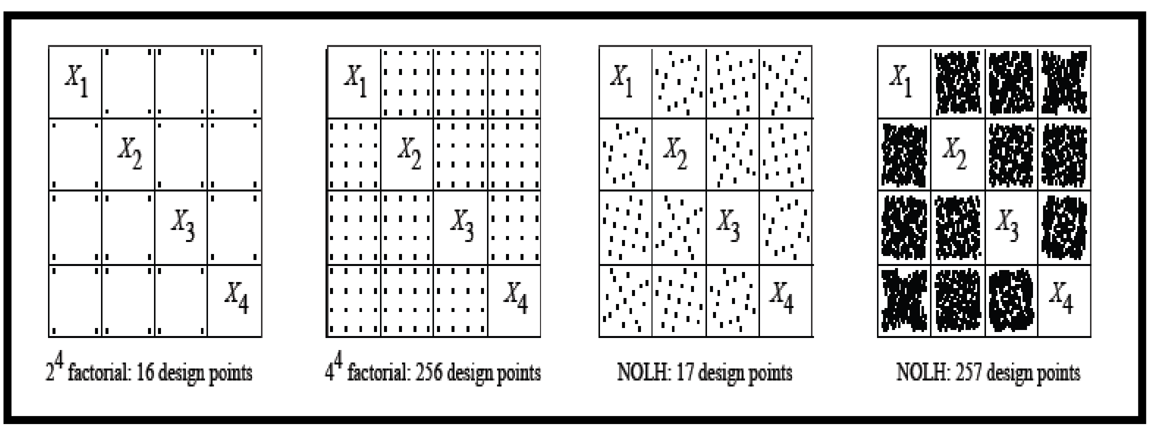


Figure 19. Scatterplot Matrices for Selected Factorial and NOHL Designs. (From Sanchez, 2008)

D. NEARLY ORTHOGONAL NEARLY BALANCED MIXED DESIGN

For this study, the NONBMD is used. NONBMD developed by Hélcio Vieira (2010) for his PhD (Figure 20), are designs suitable for dealing with a combination of continuous, categorical, and discrete factors. The design is “nearly orthogonal” and “nearly balanced,” which means that the absolute value of the maximum pairwise correlation is less than 0.05, and that it samples factors with different numbers of levels in a balanced manner (Vieira, Sanchez, Kienitz, & Belderrain, 2011).

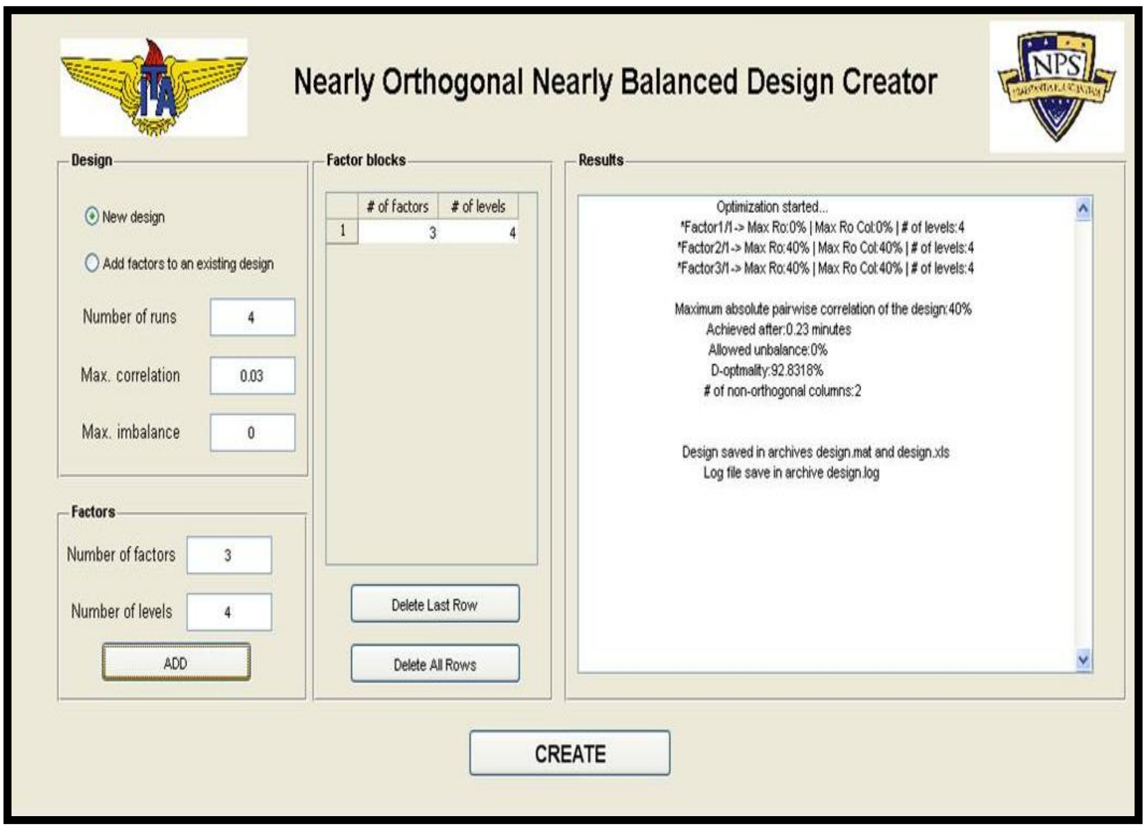


Figure 20. Snapshot of the Nearly Orthogonal, Nearly Balanced, Design Creator

For this analysis, two separate designs were created, one for decision factors and one for noise. The first design provides 51 design points (DP), while the second provides forty-two (Figure 21). A design point is a unique combination of input factors.

	D	D	D	D	D	N	N	N	
	CAT	D	D	D	D	D	D	D	D
	warshipPosition	convoy speed	# of merchants	distance between merchants	helo take off delay	# of pirates	com latency between warship-merchants	pirate speed	distance
	Ahead-back-side	10-20 (discrete)	10 - 30 (discrete)	50-500 (cont)	15-60 (cont)	1-4 (discrete)	1-10 (discrete)	25-45 (discrete)	3500-5500 (discrete)
HIGHER	3	20	30	500	60	4	10	45	5500
LOWER	1	10	10	50	15	1	1	25	3500
UNITS	1	2	1	10	1	1	1	1	500
# LEVELS	3	6	21	46	46	4	10	21	4

DECISION DESIGN MAX PAIRWISE CORRELATION = 0.16%					NOISE DESIGN ORTHOGONAL			
warshipPosition	convoy speed	# of merchants	distance between merchants	helo take off delay	# of pirates	com latency between warship-merchants	pirate speed	Distance
3	20	28	130	23	1	7	26	5500
3	16	16	210	31	3	5	26	5000
3	20	30	120	22	2	10	27	5000
1	18	15	340	35	4	10	27	5500
3	20	19	420	21	3	3	28	4500
1	12	16	300	33	2	5	28	4500
2	16	15	270	36	4	9	29	4500
3	10	26	110	48	2	2	29	4500
1	12	27	200	30	3	9	30	4000
2	18	14	330	59	2	3	30	4000
1	18	14	100	53	2	4	31	4500
2	18	29	320	42	3	3	31	4000
2	20	20	230	47	4	10	32	4000
2	20	26	370	38	1	8	32	4000
1	20	13	80	55	1	7	33	4000
2	18	13	70	18	3	6	33	3500
3	16	17	80	32	4	2	34	4000
3	12	25	470	50	1	2	34	5000
1	12	29	190	49	3	6	35	3500
2	10	13	350	17	2	6	35	5500

Figure 21. Screen Shots of the Separate Designs for Decision and Noise Factors. The display shows the decision factors, the noise factors, ranges, levels, and factor classification.

Both the decision and noises factors, as shown in Figure 22, have good space-filling properties while the maximum pairwise correlations are 0.0016 and zero, respectively.

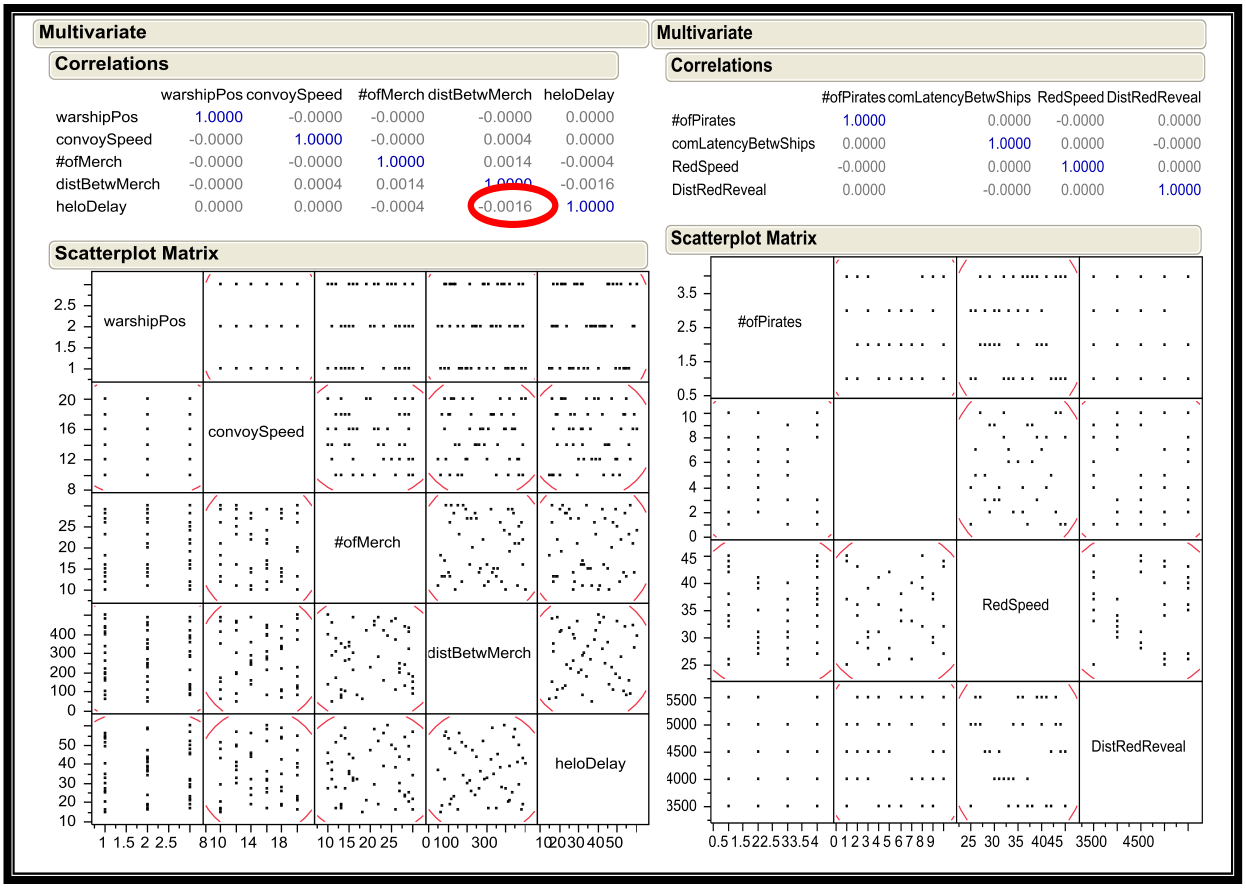
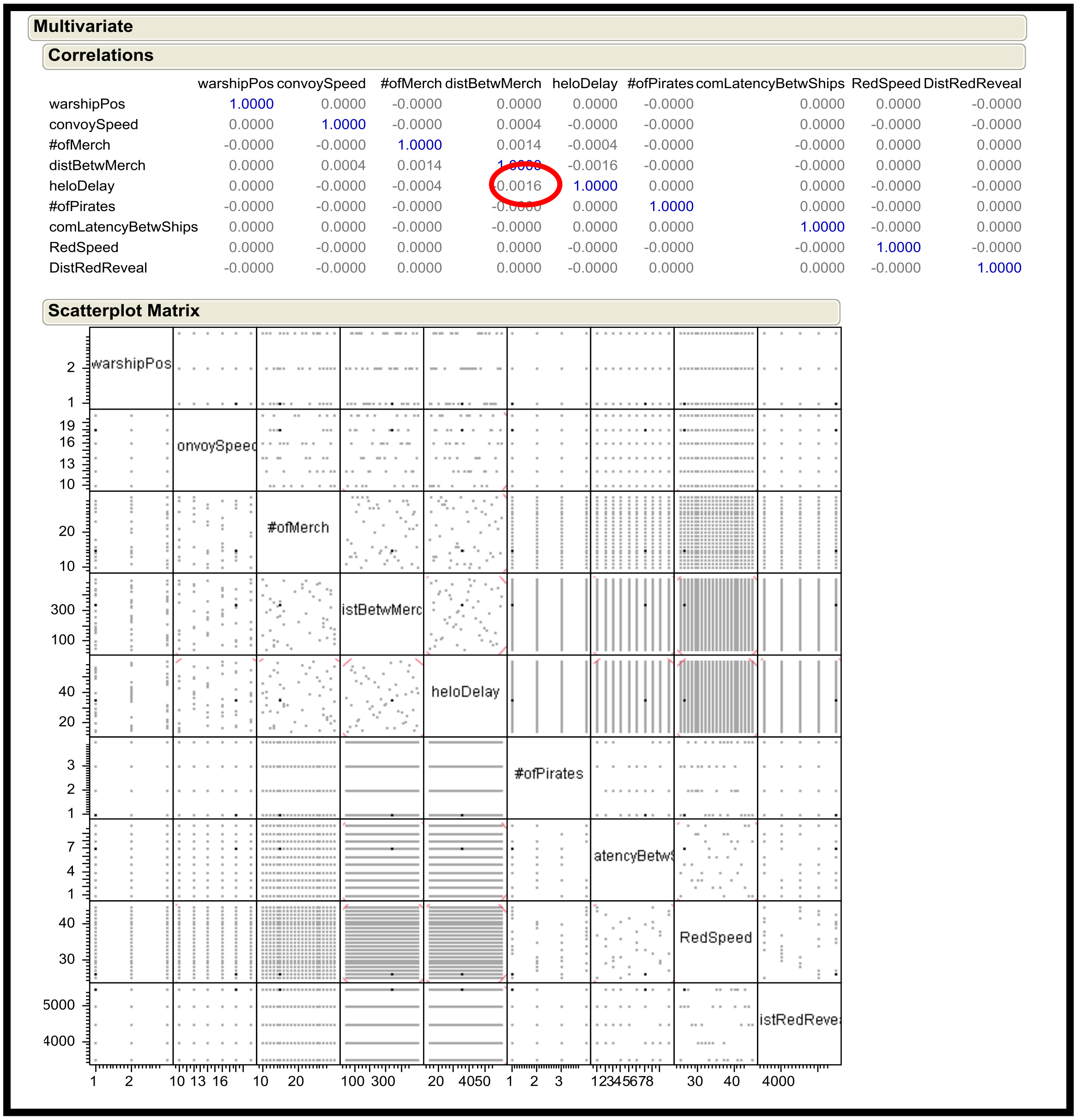


Figure 22. Pairwise Correlation Matrix for Decision Factors (left) and Noise Factors (right).

Next, the two separate designs are crossed using a ruby program, creating a total of 2142 DP (51 x 42). The crossed design has also maximum correlation 0.0016 and good space-filling, as shown in Figure 23.



Multivariate

Correlations

	warshipPos	convoySpeed	#ofMerch	distBetwMerch	heloDelay	#ofPirates	comLatencyBetwShips	RedSpeed	DistRedReveal
warshipPos	1.0000	0.0000	-0.0000	0.0000	0.0000	-0.0000	0.0000	0.0000	-0.0000
convoySpeed	0.0000	1.0000	-0.0000	0.0004	-0.0000	-0.0000	0.0000	-0.0000	-0.0000
#ofMerch	-0.0000	-0.0000	1.0000	0.0014	-0.0004	-0.0000	-0.0000	0.0000	0.0000
distBetwMerch	0.0000	0.0004	0.0014	1.0000	-0.0016	-0.0000	-0.0000	0.0000	0.0000
heloDelay	0.0000	-0.0000	-0.0004	-0.0016	1.0000	0.0000	0.0000	-0.0000	-0.0000
#ofPirates	-0.0000	-0.0000	-0.0000	-0.0000	0.0000	1.0000	0.0000	-0.0000	0.0000
comLatencyBetwShips	0.0000	0.0000	-0.0000	-0.0000	0.0000	0.0000	1.0000	-0.0000	0.0000
RedSpeed	0.0000	-0.0000	0.0000	0.0000	-0.0000	-0.0000	-0.0000	1.0000	-0.0000
DistRedReveal	-0.0000	-0.0000	0.0000	0.0000	-0.0000	0.0000	0.0000	-0.0000	1.0000

Figure 23. Pairwise Correlation Matrix for the Crossed Design.

Finally, the experiment was executed on the Simulation Experiments and Efficient Design (SEED) Center's high-performance cluster, "Reaper." A hundred and fifty replications of each DP were performed for data farming, yielding a total number of 321,300 simulated convoy operations. The xstudy, OldMcData, and Condor software packages were used to generate the required files and manage the execution of the distributed jobs (see http://harvest.nps.edu). Since each replication completed very quickly (in seconds), this experimental design took only a little more than five hours to complete, much less time than it would take to run the same scenario in traditional full-factorial design or 2^m design (Figure 24).

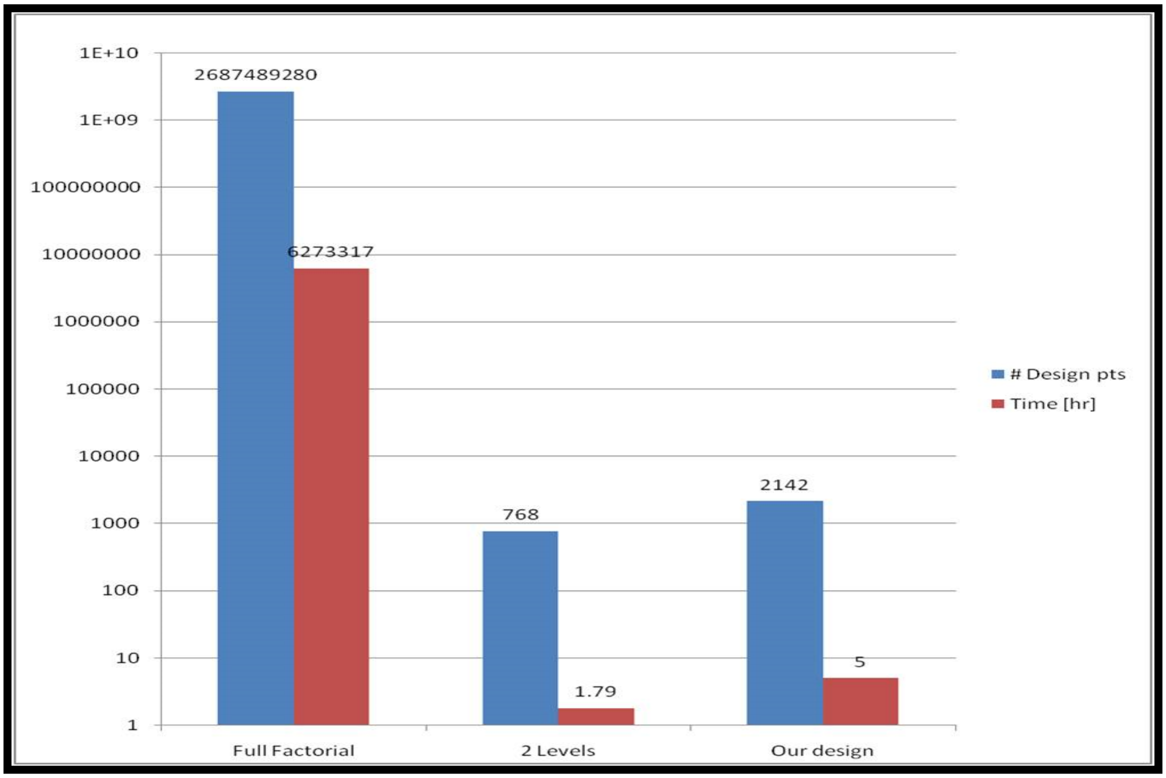


Figure 24. Comparison Plot for the Time Acquired for the Experiment to Run

E. ROBUST DESIGN

Robust design is a technique that combines Taguchi's philosophy and strategy on improving product performance (1980) and response-surface metamodeling. The use of robust designs and analysis may lead to decisions based not only on a mean system's performance, but also on the variance of its performance. Specifically, the system's performance must be acceptable and relatively insensitive to uncontrollable sources that may increase its variance (Sanchez S. M., Robust design: seeking the best of all possible worlds, 2000).

As mentioned, classifying design factors into decision or noise is fundamental. In robust design, this classification is important for the analyst to identify design points that yield a good performance of a system across the range of all noise factors (Sanchez S. M., Better than a petaflop: the power of efficient experimental design, 2008).

The analyst specifies a target value τ and evaluates the performance of an MOE compared to that value. This is achieved by the use of a loss function such as a quadratic, inverted normal, or truncated quadratic. In this thesis, a quadratic loss function is evaluated to minimize blue-squad casualties. The benefits of the quadratic loss function are that it is easy to manipulate mathematically and that it is a kind of loss function used in many other statistical applications, like regression.

Evaluating a robust design may yield beneficial results for the system performance under examination. First, the system may perform well across a range of all noise factors, resulting in fewer surprises when moving from simulation to real life implementation. Another benefit is improved communication between analyst and client by the use of the expected loss. Finally, robust designs facilitate continuous improvement and lead to better decisions (Sanchez S. M., Robust design: seeking the best of all possible worlds, 2000).

Having crossed the decision design with the noise design, we have created a design that serves well the purpose of robust analysis and we focus our attention on blue casualties (blueCas), with the goal of minimizing them.

First, we introduced the raw data from 321,300 runs of MANA in JMP. We have specified the target value τ equal to zero blue casualties, and then created a new column for the loss, making use of the quadratic loss function: $\ell\ (\text{blueCas}) = (\text{blueCas} - \tau)^{2}$. Finally, we summarized over the noise factors, calculating the mean loss and the mean and standard deviation of the response blueCas.

V. DATA ANALYSIS

A. MULTIPLE REGRESSION ANALYSIS / INTERACTION PLOTS: ALL FACTORS

Multiple-regression analysis is a common statistical technique for exploring and modeling the relationships between various factors, called predictor or regressor variables, and a response variable (Montgomery, Peck, & Vining, 2006). Various statistical packages are available to facilitate regression analysis. JMP Statistical Discovery Software version 9.0.0 is used for this work.

The coefficient of determination, R-squared, is a popular way to assess the overall adequacy of a model. R-squared shows the proportion of the total variation of the response variable that is explained by the model. It takes values between zero and one, with the higher R-squared values (closer to one) being more desirable. However, R-squared never decreases, even when an independent variable is statistically insignificant. Therefore, an analyst must always be aware that using R-squared may result in an over-fitted model.

To avoid over-fitting, a better statistic for the overall adequacy of a model is the adjusted R-squared. The difference between R-squared and adjusted R-squared is that the former can go down if statistically insignificant predictors are entered into a model (Montgomery, Peck, & Vining, 2006).

Once the regression model is created, an adequacy check should be performed. The four major assumptions made about the residuals/errors are the following:

- They have mean zero.
- They have constant variance.
- All errors are independent.
- All errors are normally distributed.

The above assumptions can be abbreviated as $\varepsilon \sim NID(0, \sigma^2)$ (Montgomery, Design and analysis of experiments, 2009). If any of these assumptions are violated, the analyst has a variety of tools for resolving the issue. For example, transformations or other advanced techniques can be used if normality assumptions are violated. (Montgomery, Peck, & Vining, Introduction to linear regression analysis, 2006)

The plots and models were generated using JMP. We first imported 321,300 rows of raw data, indicated in the previous chapter, in JMP. Next, we created a summary data table with all independent variables by averaging responses of the two MOEs, mean blue casualties and mean red casualties, across the 150 runs of each DP. This new data table contained 2,142 rows.

Analyzing the distribution for the mean blue casualties we see that the majority of the output is zero casualties with a mean of 0.175 and standard deviation of 0.18, with maximum casualties of 0.78, as shown in Figure 25.

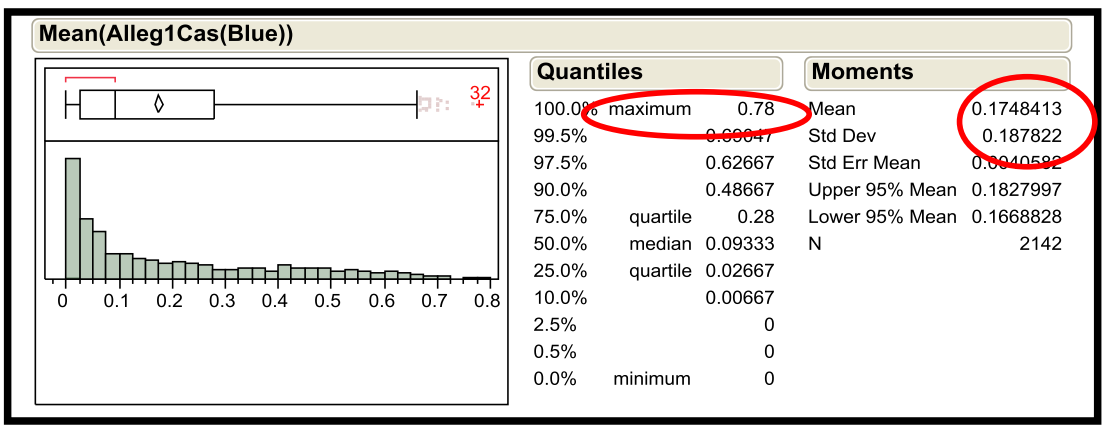


Figure 25. Distribution for the Mean Blue Casualties

The process for creating the regression model consisted of a forward Bayesian information-criterion (BIC) stepwise technique. We allowed main effects, two-way interactions, and second-order polynomial terms into the model. We examined the stepwise-regression step history in order to see the “knee in the curve” of R-squared as new terms were added to the model. We used this information to guide us in final selection of our regression model. As Figure 26 indicates, we quickly reach a point where adding statistically significant terms has essentially no practical impact on the fit of the model.

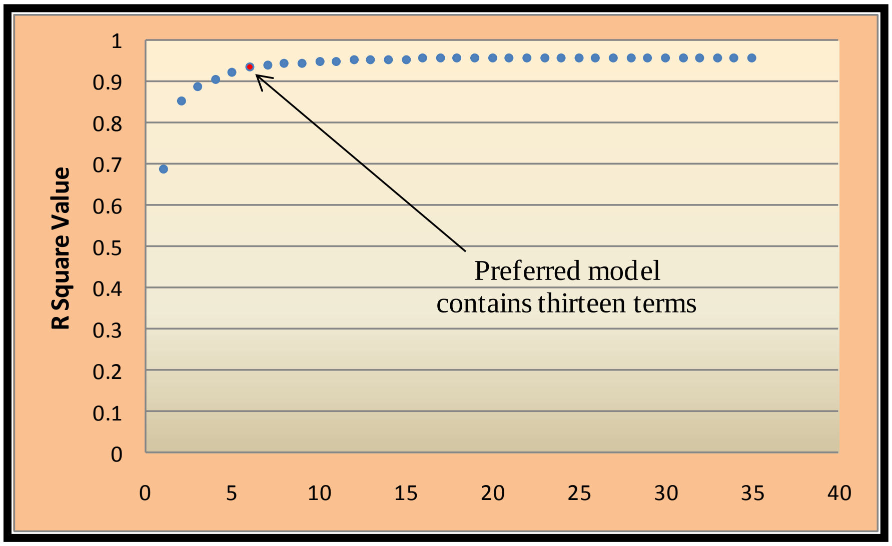


Figure 26. R-Squared Values of the Fitted Model for Mean Blue Casualties

Figure 27 displays the actual value by predicted plot and summary data for the final model. This model, consisting of 13 terms, including the intercept, explains almost 94% of the variance within the model. For that model, the adjusted R-squared is 0.93596.

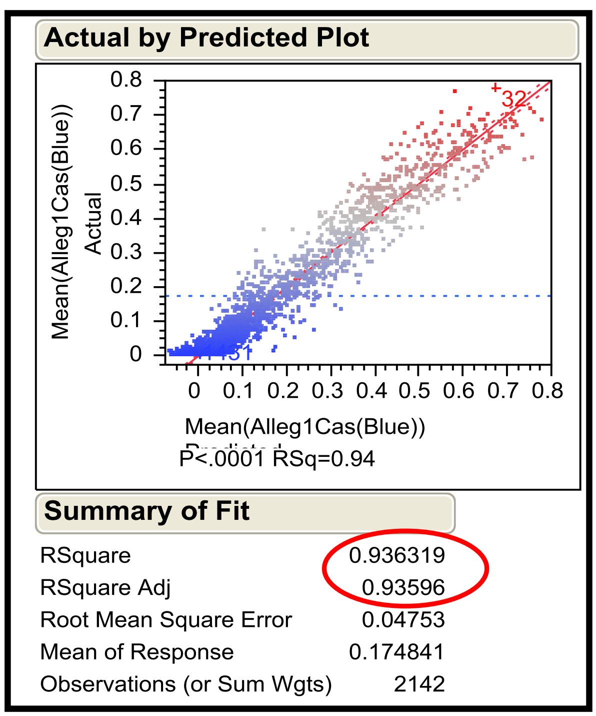


Figure 27. Fitted Model for Mean Blue Casualties

To check the adequacy of the model, we examined whether the four assumptions for the residuals hold. First, the independence assumption holds because we used different random-number seeds. The mean zero and constant variance assumptions are also satisfied, as shown in Figure 28.

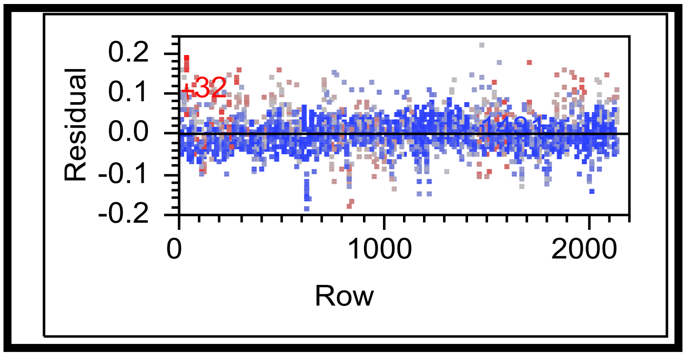


Figure 28. Residual by Row Plot

The only assumption that is not met is the normality of the errors, as indicated in Figure 29. The histogram looks fine, but the normal quantile plot and the goodness of fit test justify the rejection of normality. One reason for this rejection is that we are dealing with proportions and are limited to more zeros than ones. Asymptotically, we expect our distribution to be closer to normal.

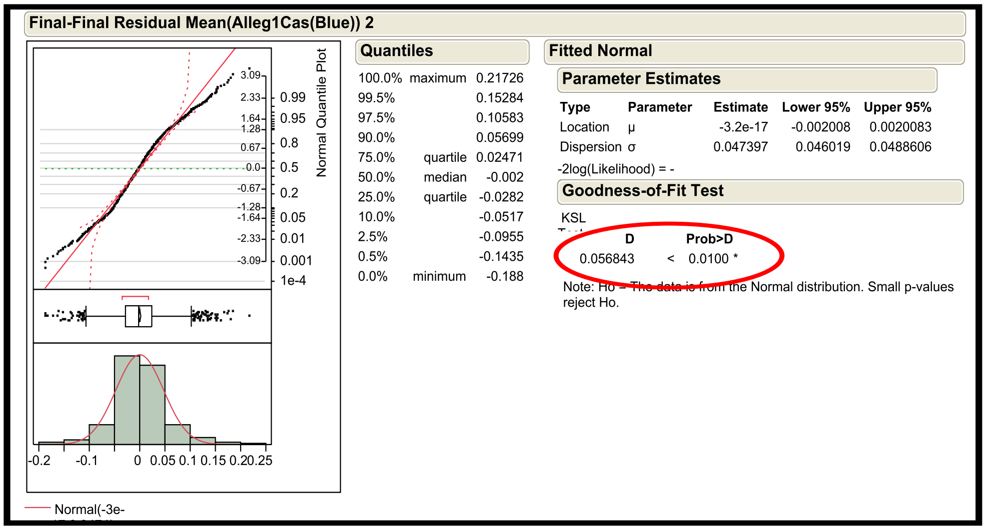


Figure 29. Distribution of the Residuals for the Fitted Model

To address the violation of the normality assumption, different data transformations, including log, logit, exponential, and Box-Cox were used. None was successful, because normality tests are sensitive to outliers, and also because we are dealing with bounded values (0,1) and a majority of our data is zero (no casualties). Nevertheless, the histogram and the normal quantile plot of exponential transformation looked quite normal (Figure 30).

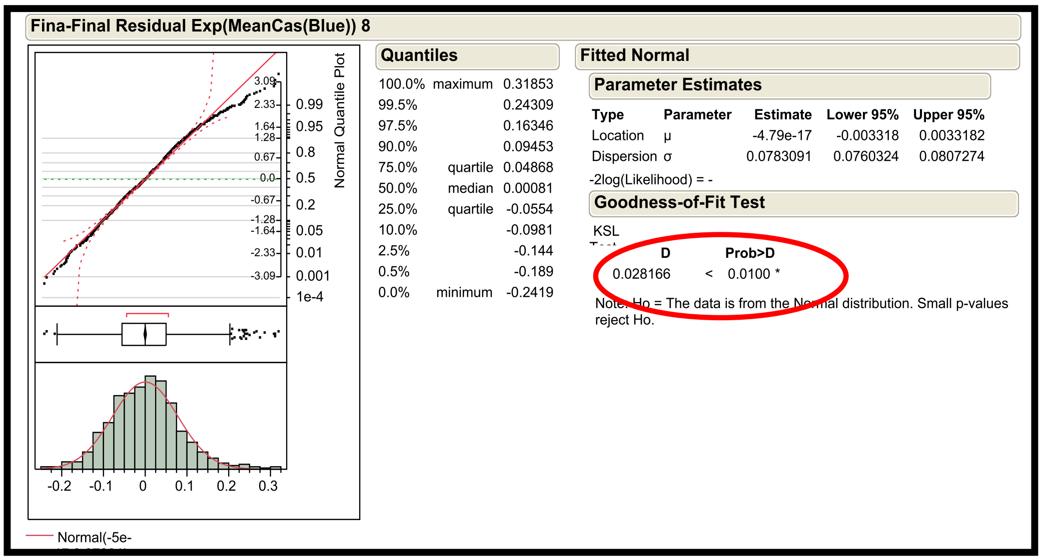


Figure 30. Distribution of the Residuals for the Exponential Transformed Fitted Model

Again, our process for creating the regression model consisted of a forward BIC stepwise technique followed by standard least-squares regression. Into the model we allowed main effects and two-way interactions. We examined the stepwise-regression step history to see the knee in the curve of R-squared as new terms were added to the model. We used this information to guide us in final selection of a regression model. As Figure 31 indicates, we reach a point where adding statistically significant terms has essentially no practical impact on the model of fit.

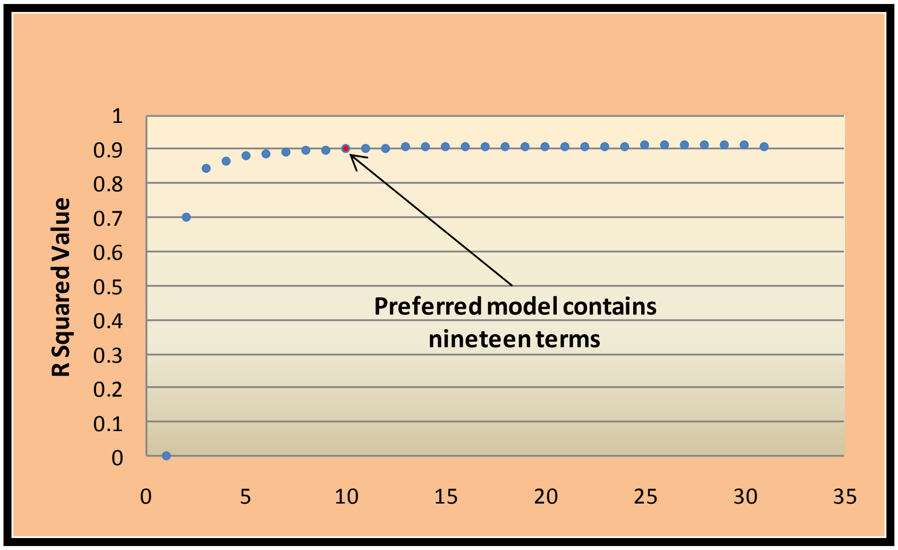
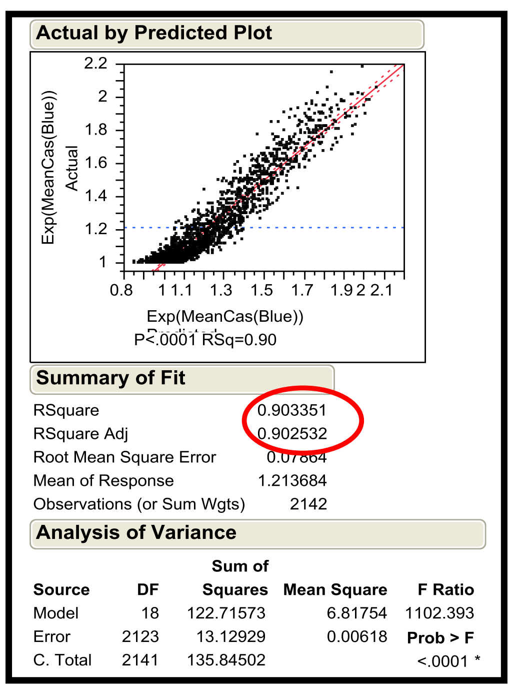


Figure 31. R-Squared Values of the Exponential Transformed Fitted Model for Mean Blue Casualties

Figure 32 displays the actual by predicted plot and summary data for the final model. This model consists of 19 terms, including the intercept, and explains more than 90% of the variance within the model. For this model, the adjusted R-squared is 0.902532.



Summary of Fit

RSquare	0.903351
RSquare Adj	0.902532
Root Mean Square Error	0.07864
Mean of Response	1.213684
Observations (or Sum Wgts)	2142

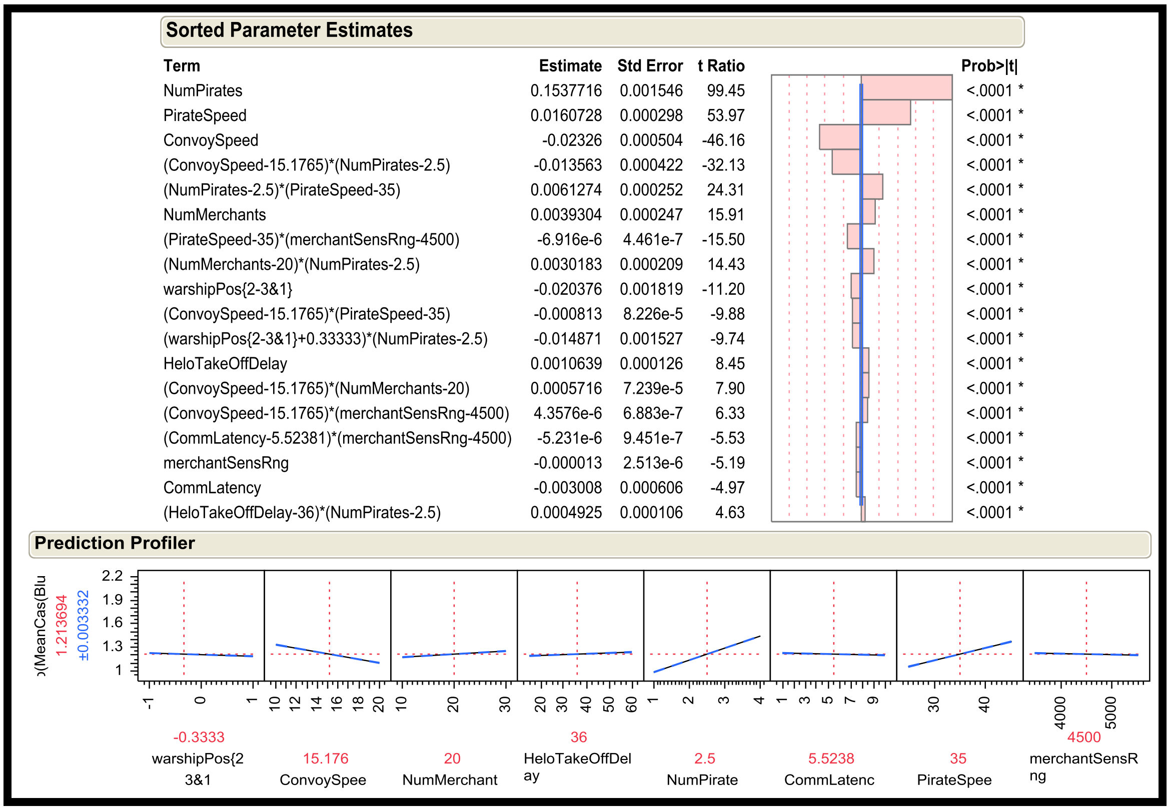
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	18	122.71573	6.81754	1102.393
Error	2123	13.12929	0.00618	Prob > F
C. Total	2141	135.84502		<.0001 *

Figure 32. Fitted Model for Mean Blue Casualties

Figure 33 displays the set of parameter estimates and prediction profiler. The top two influential factors are number of pirates and pirate speed. Both estimates are positive, indicating that they yield greater blue casualties. On the other hand, the third most important regressor is convoy speed, which is negative. Thus, increasing convoy speed results in fewer blue casualties.

We also note that a lesser, but still significant, factor is the number of merchant ships. Increasing the number of merchants leads to an increase in blue casualties.



Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
NumPirates	0.1537716	0.001546	99.45	<.0001 *
PirateSpeed	0.0160728	0.000298	53.97	<.0001 *
ConvoySpeed	-0.02326	0.000504	-46.16	<.0001 *
(ConvoySpeed-15.1765)*(NumPirates-2.5)	-0.013563	0.000422	-32.13	<.0001 *
(NumPirates-2.5)*(PirateSpeed-35)	0.0061274	0.000252	24.31	<.0001 *
NumMerchants	0.0039304	0.000247	15.91	<.0001 *
(PirateSpeed-35)*(merchantSensRng-4500)	-6.916e-6	4.461e-7	-15.50	<.0001 *
(NumMerchants-20)*(NumPirates-2.5)	0.0030183	0.000209	14.43	<.0001 *
warshipPos{2-3&1}	-0.020376	0.001819	-11.20	<.0001 *
(ConvoySpeed-15.1765)*(PirateSpeed-35)	-0.000813	8.226e-5	-9.88	<.0001 *
(warshipPos{2-3&1}+0.33333)*(NumPirates-2.5)	-0.014871	0.001527	-9.74	<.0001 *
HeloTakeOffDelay	0.0010639	0.000126	8.45	<.0001 *
(ConvoySpeed-15.1765)*(NumMerchants-20)	0.0005716	7.239e-5	7.90	<.0001 *
(ConvoySpeed-15.1765)*(merchantSensRng-4500)	4.3576e-6	6.883e-7	6.33	<.0001 *
(CommLatency-5.52381)*(merchantSensRng-4500)	-5.231e-6	9.451e-7	-5.53	<.0001 *
merchantSensRng	-0.000013	2.513e-6	-5.19	<.0001 *
CommLatency	-0.003008	0.000606	-4.97	<.0001 *
(HeloTakeOffDelay-36)*(NumPirates-2.5)	0.0004925	0.000106	4.63	<.0001 *

Figure 33. Parameter Estimates and Prediction Profiler for Final Fitted Model

Figure 34 displays the interaction profiler generated by JMP. In this plot, the y-axis represents the mean blue-casualties value. Strong interactions are seen as highly nonparallel lines in interaction plots. Here, the strongest interaction occurs between the convoy speed and number of pirates. In this case, increasing the number of pirates has great effect on increasing blue casualties when the convoy speed is low. We can also note that the warship can adequately handle the case where there is only one pirate, independent of convoy speed.

Finally, a significant interaction occurs between the number of pirates and the number of merchant ships. When the number of pirates increases, the blue casualties are greater with an increasing number of merchant ships. Again, it is important to note that in the case of one pirate, the blue casualties are independent from the number of merchants.

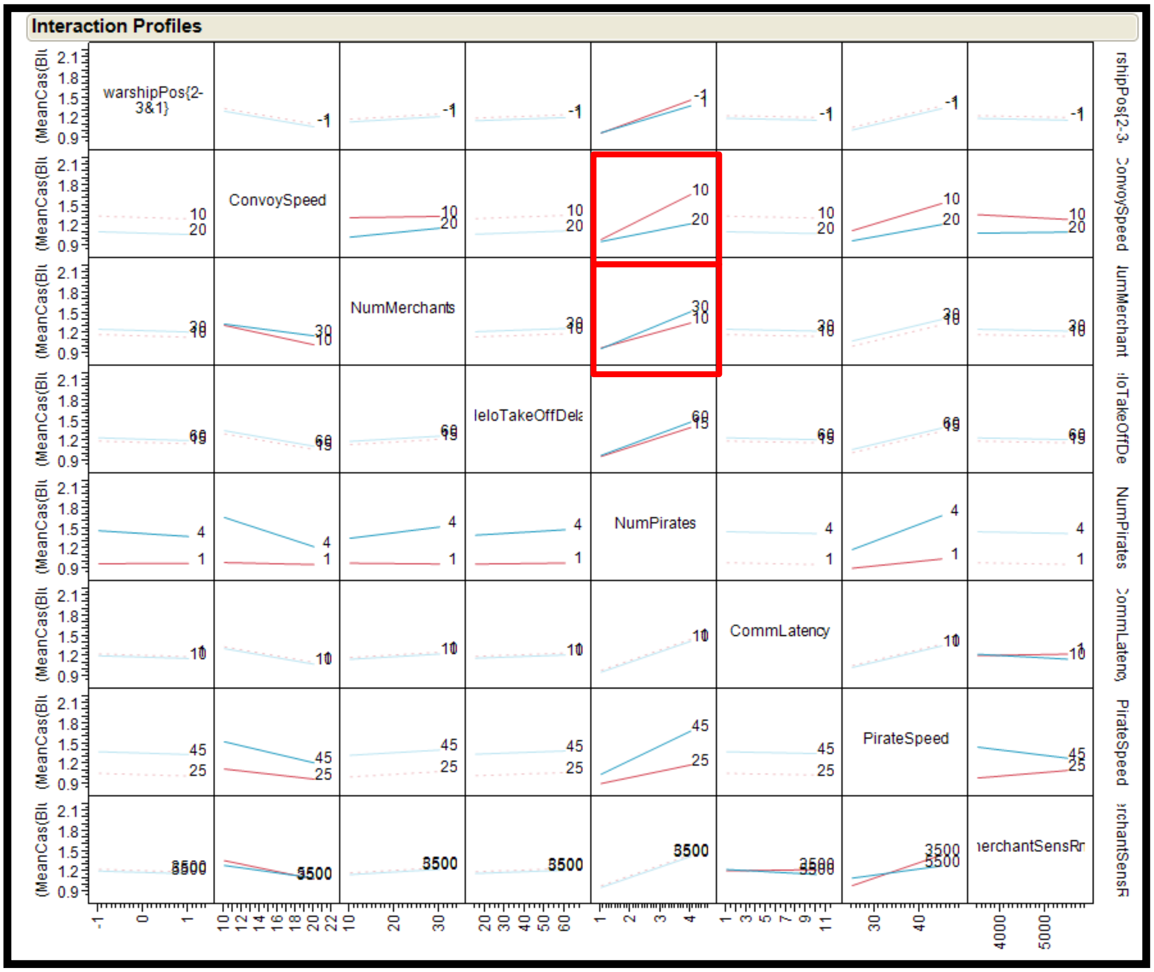


Figure 34. Interaction Profiler for Final Fitted Model of Mean Blue Casualties

B. CLASSIFICATION AND REGRESSION TREES

The use of classification and regression (or partition) trees (CART) is an easy way to quickly look at the data and gather the important relationships between factors and responses. We call the procedure “classification” when the response variable is discrete and “regression” when the response variable is continuous. CART is a partitioning of the data that occurs consecutively according to the optimal splitting value determined from all possible values of each variable. The pictorial representation of the CART is an upside-down tree with the root at the top, with branches and leaves below (Montgomery, Peck, & Vining, 2006).

Figure 35 displays a recursive split of mean blue casualties over all decision and noise factors. As partitioning of the data proceeds, the most significant factors and split values produce the leaves of the tree. The splitting point for each factor may suggest a lower or upper limit. Each box includes the number of data points in the split, as well as the mean and the standard deviation of the blue casualties. In this particular tree, we chose to stop at nine splits, yielding a partition tree model that explains almost 85% of observed variability.

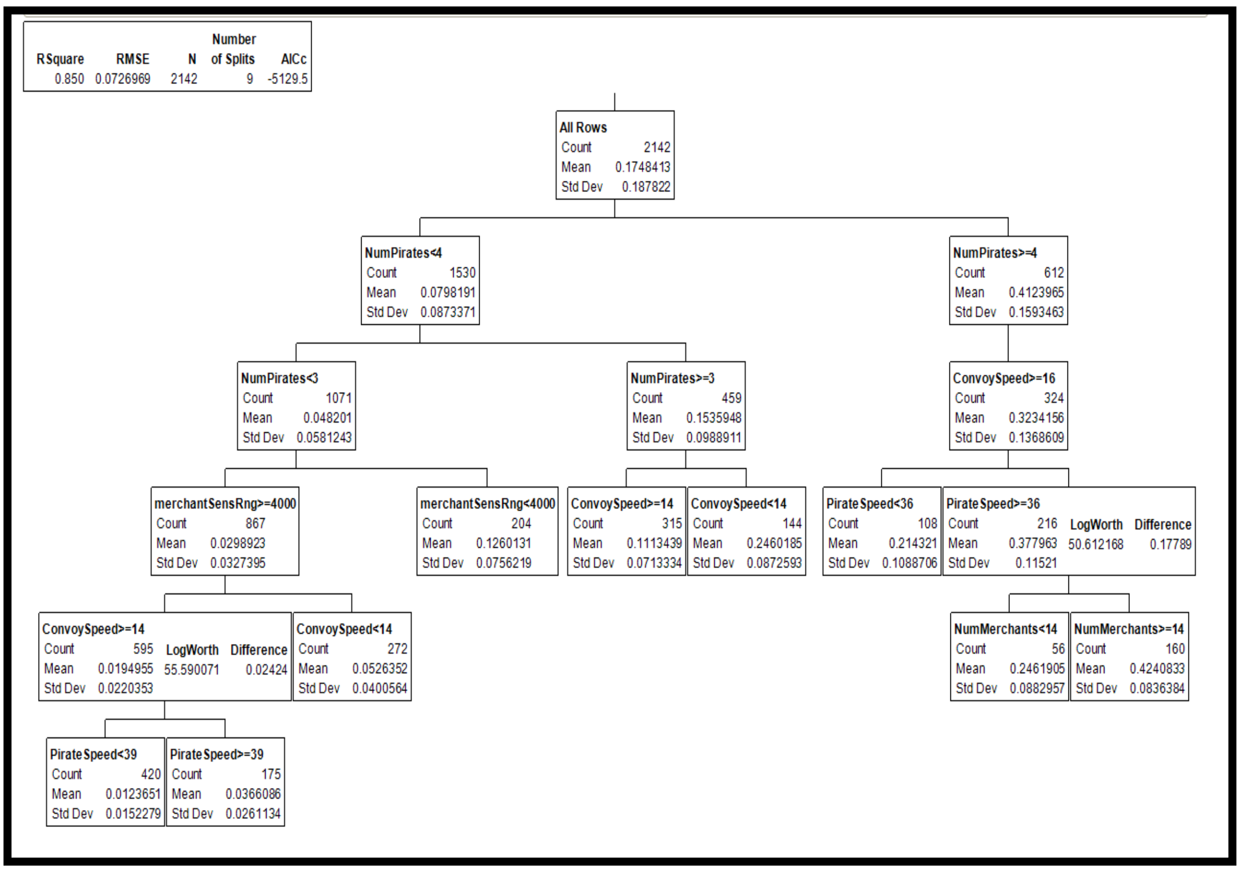


Figure 35. Partition Tree for Mean Blue Casualties

The first split is made on the number of pirates. This is the most significant factor in the scenario. The optimal split point is at the value of three pirates and any number smaller than that can be expected to result in significantly fewer blue casualties. The next split is in the merchant-sensor range, which is the second most significant factor. A merchant-sensor range equal or greater to 4,000 m results in fewer blue casualties. The third split occurs in convoy speed, where a speed greater or equal to 14 knots results in fewer blue casualties. The fourth split is pirate speed. A speed less than 39 knots results in fewer blue casualties. We finally note that when the number of pirates in the scenario is greater or equal to four, then a number of merchant ships less or equal to 14 provides better protection.

C. ROBUST ANALYSIS

We first defined our target value τ to be equal to zero blue casualties. We then created a new column for the loss, making use of the quadratic loss function: ℓ (blueCas) $=$ (blueCas – τ)^2. Finally, we summarized over the noise factors, calculating the mean loss and mean and standard deviation of the response blueCas. This new data table contained fifty-one rows.

We first examine the partition tree over the mean loss, displayed in Figure 36.

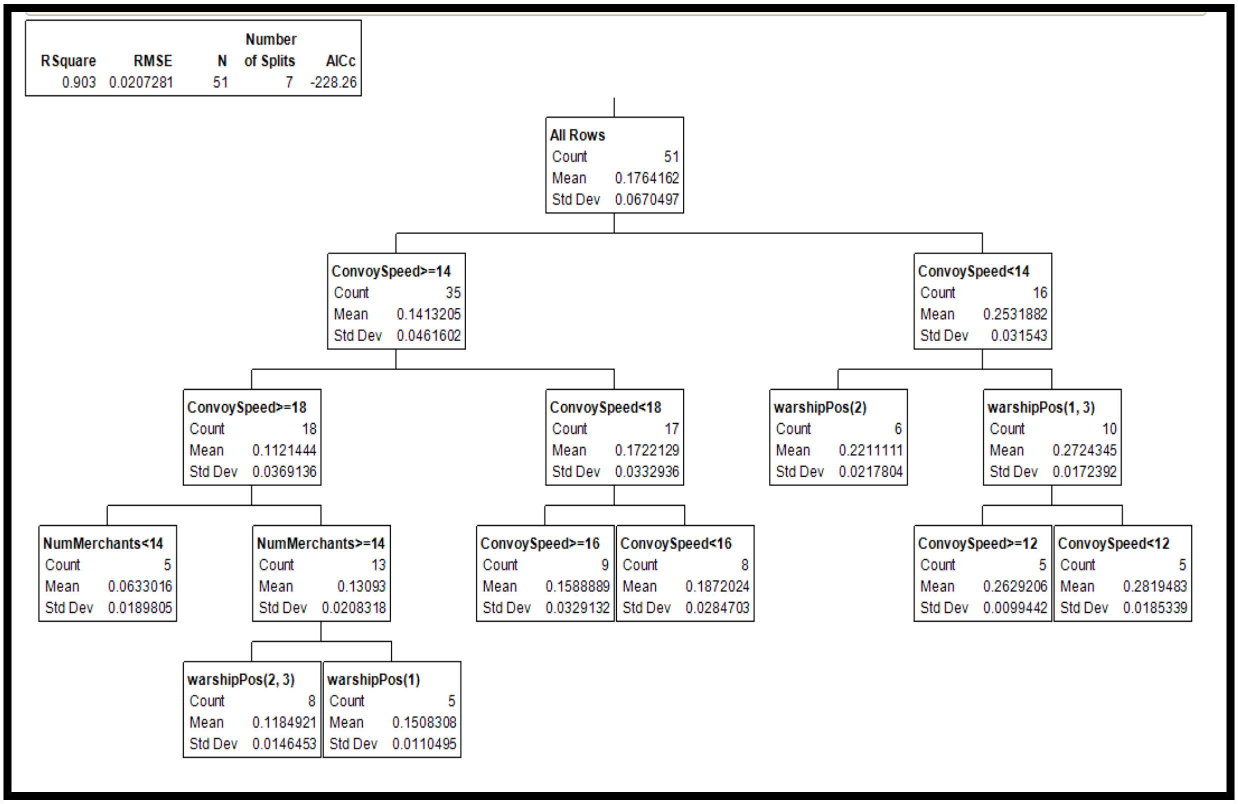


Figure 36. Partition Tree for the Mean Loss

The first split of the data occurs in the convoy speed, where convoy speed greater or equal to 18 knots yields better results in the protection of the merchant ships. The second most significant factor is the number of merchant ships in the convoy. Fewer than 14 merchant ships results in a lower number of blue casualties than if the number of merchants is greater than or equal to 14. The third split is made on warship position, which is the third most important factor for the robust analysis. A position on the flanks or in front of the convoy results in fewer blue casualties; sailing behind the convoy results in greater blue casualties.

Analyzing the data for the mean loss, we see that the distribution is quite normal with a mean of 0.176 and standard deviation of 0.067, with maximum loss of 0.31, as shown in Figure 37.

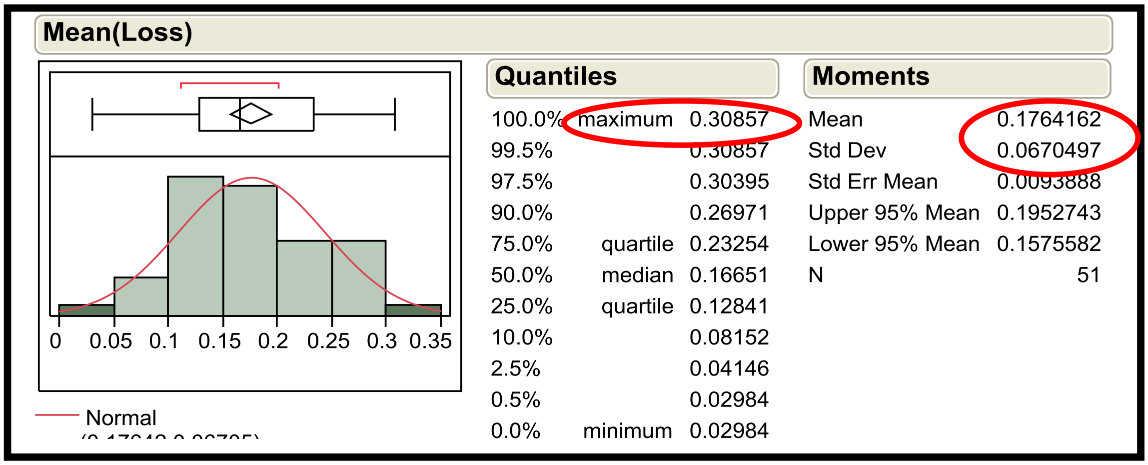


Figure 37. Distribution for the Mean Loss

For the robust analysis, a regression model was created. The process for creating the regression model consisted of a forward BIC stepwise technique followed by standard least-squares regression. Into the model we allowed main effects, two-way interactions, and second-order polynomial terms. We examined the stepwise-regression step history in order to see the knee in the curve of R-squared as new terms were added to the model. (Figure 38)

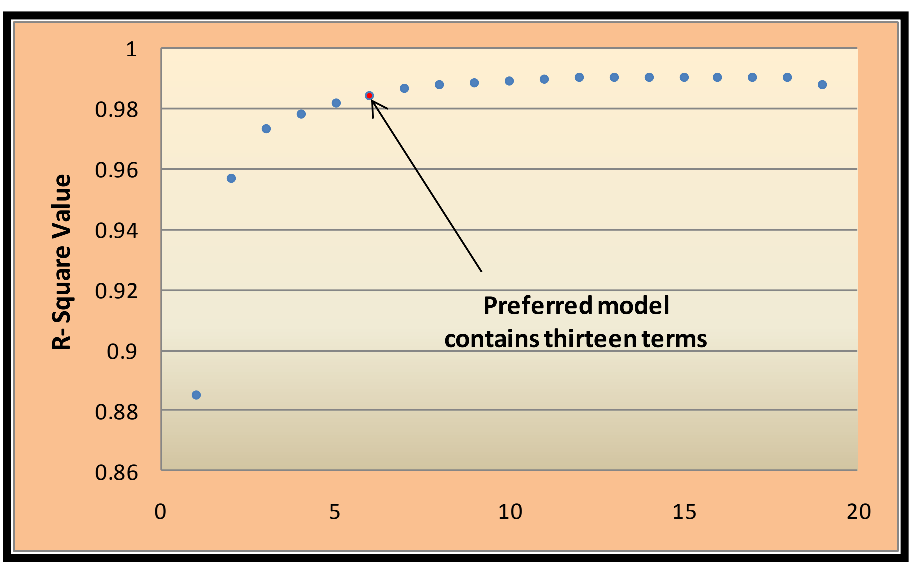


Figure 38. R-Square Values of the Fitted Model for Mean Loss

In contrast to what we saw above in the analysis of the residuals for the whole model, the analysis of the residuals here indicates that all four assumptions are satisfied. As shown in Figure 39, the residuals pass the normality test.

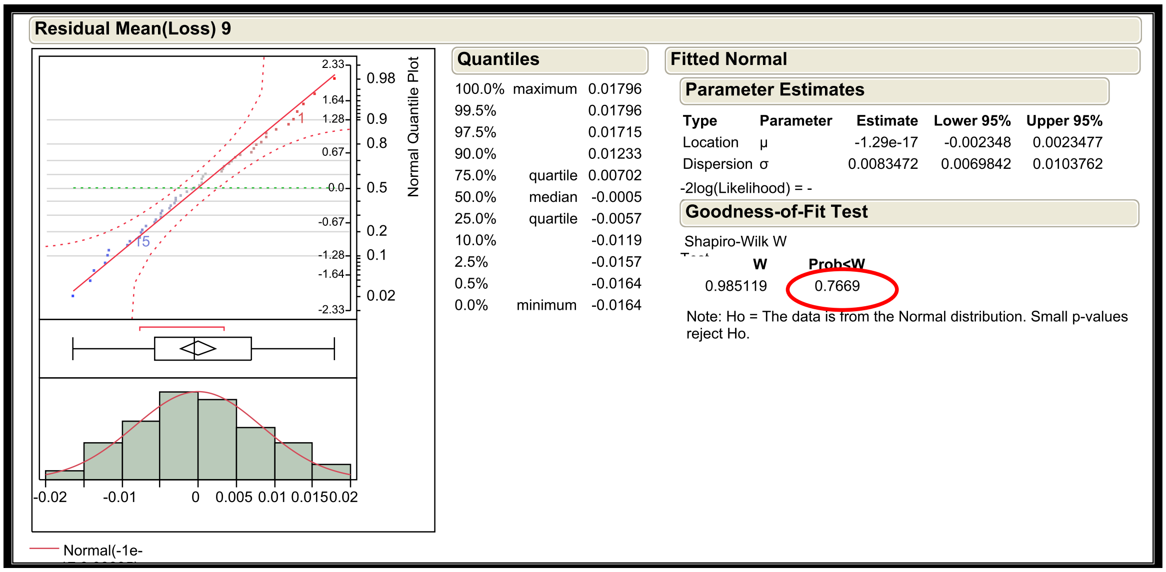


Figure 39. Distribution of the Residuals for the Mean Loss

Figure 40 displays the actual value by predicted plot and summary data for the final model. This model, consisting of 13 terms, including the intercept, explains more than 98% of the variance within the model. For that model, the adjusted R-squared is 0.9845.

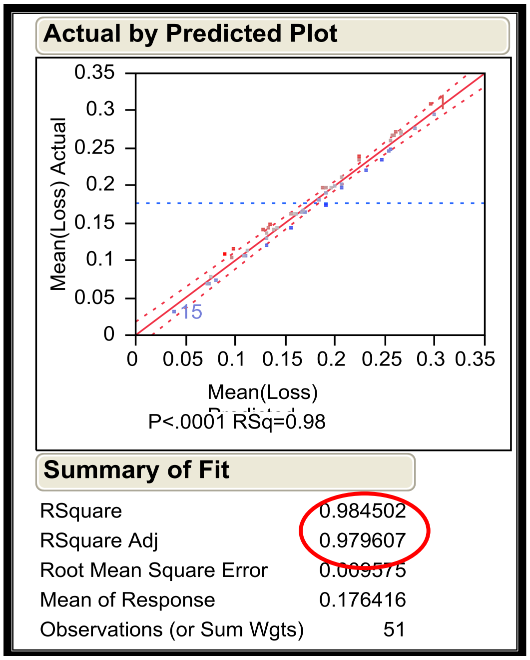


Figure 40. Fitted Model for Mean Loss

Figure 41 displays the set of parameter estimates and the prediction profiler. The top two influential factors are convoy speed and number of merchants. The convoy speed parameter is negative, indicating that it yields lower mean loss, while the number of merchants is positive, indicating greater mean loss.

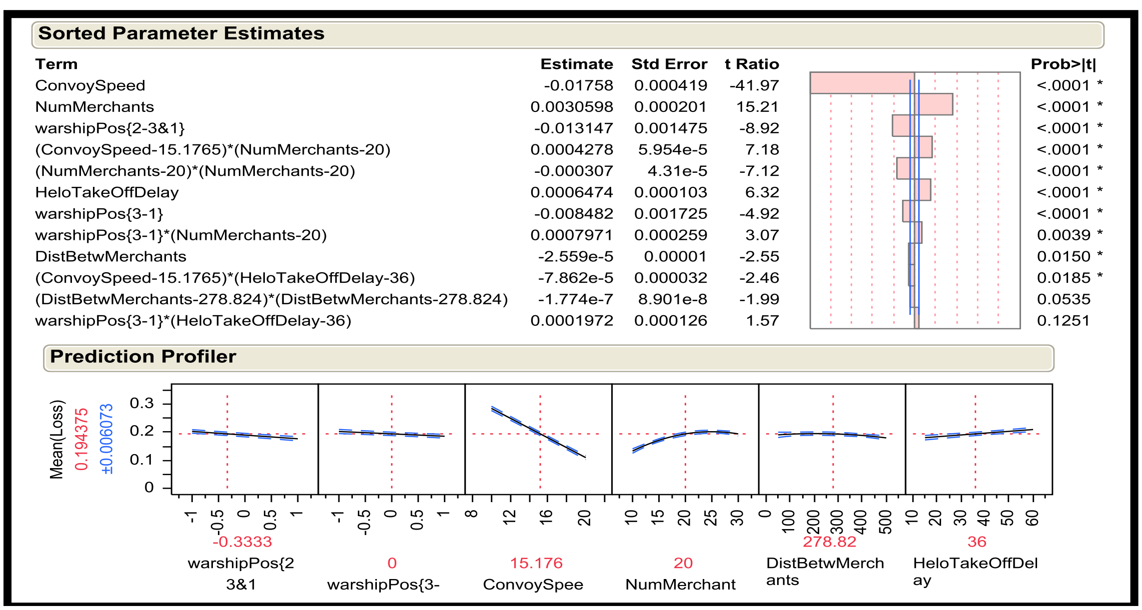


Figure 41. Parameter Estimates and Prediction Profiler for Final Fitted Model

Figure 42 displays the interaction profiler generated by JMP. In this plot, the y-axis represents the mean loss value. Here, the strongest interaction occurs between convoy speed and the number of merchant ships. In this case, increasing the number of merchants has great effect on increasing the mean loss when the convoy speed is high.

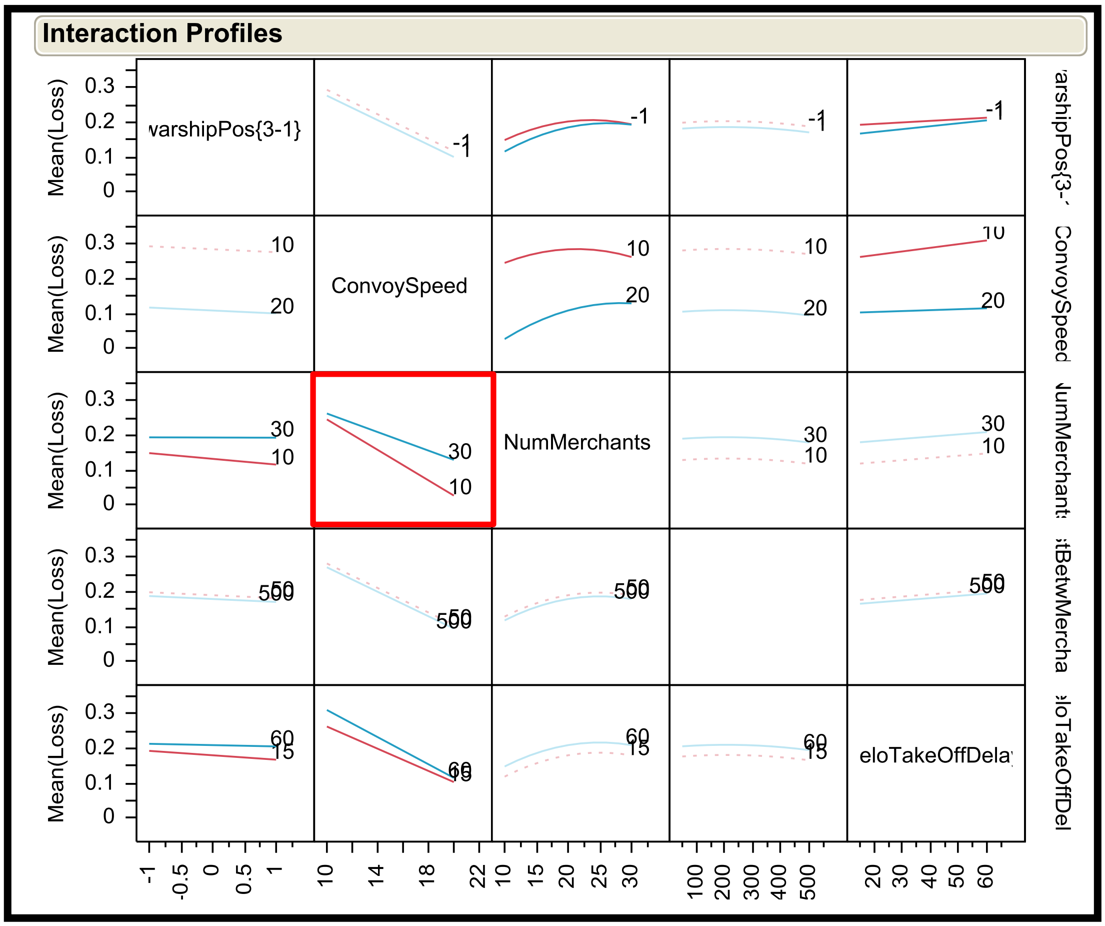


Figure 42. Interaction Profiler for Final Fitted Model of Mean Blue Casualties

D. PARALLEL PLOTS

Parallel plots provide a visual representation of the interaction between the variables. In Figure 43, 2,142 lines connect the response variable with 2,142 DPs. Traces associated with the higher- and lower mean blue casualties are highlighted with red and blue solid lines, respectively. Translating the insights of the parallel plot in the context of the scenario, positioning the warship in front of the convoy results in the lowest mean blue casualties, whereas placing it behind of the convoy results in the highest mean blue casualties. As stated earlier in the regression analysis, however, the position of the ship is not a significant factor of the model. This result is reinforced with the parallel plot, since the position of the warship in front of the convoy results in some of the highest mean blue casualties as well. Moreover, the position of the warship behind the convoy yields some of the lowest mean blue casualties.

An important takeaway from the parallel plot, which reinforces the results from the regression analysis, is that the number of pirates is a significant factor. The higher the number of pirates, the higher the mean blue casualties is.

Finally, pirate speed is another significant factor of the model, since high pirate speed results in high blue casualties and low pirate speed results in low blue casualties.

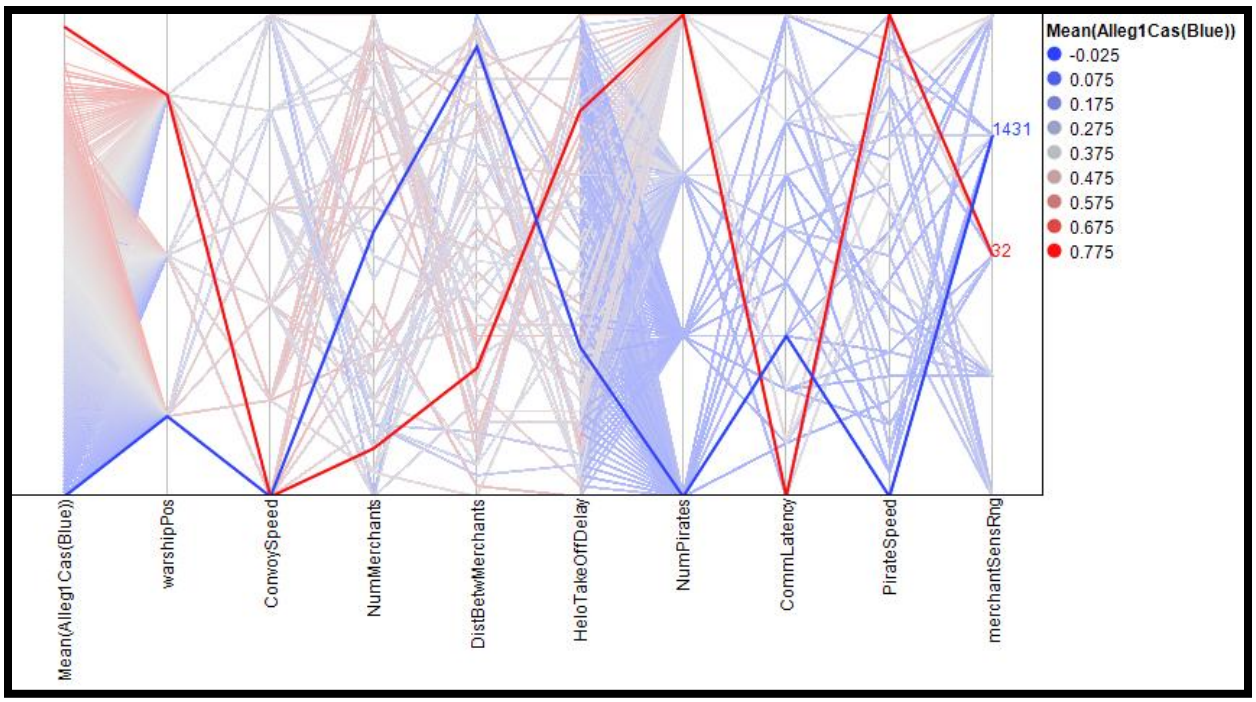


Figure 43. Parallel Plot for Mean Blue Casualties

For the robust analysis, 51 lines representing the 51 design points are shown in Figure 44. The plot indicates that high convoy speed yields low mean loss, while low convoy speed results in high mean loss.

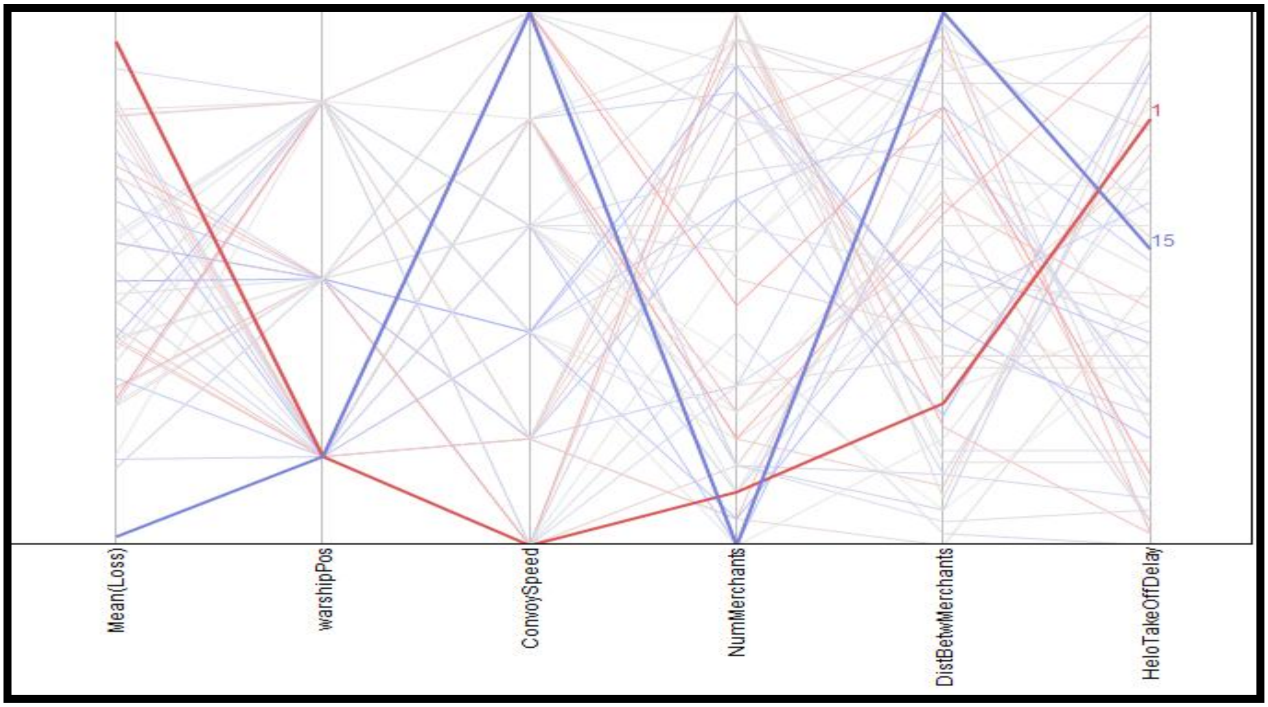


Figure 44. Parallel Plot for the Mean Loss

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VI. CONCLUSIONS

A. ANALYSIS SUMMARY

This research set out to determine how well an escorting warship can protect a convoy of merchant ships while handling pirate attacks. In addition, we tried to answer how many merchant ships a warship can adequately protect and what formation (speed, distance, position of the warship) the convoy should follow to safely travel through the IRTC.

This study mainly uses three analysis techniques to look at the mean merchant (blue) casualties: multiple-regression analysis, robust analysis, and classification and regression trees based on over 300,000 simulated convoy missions.

The three analyses complement each other. Each analysis identifies similar factors of greatest importance and key interactions and provides similar insights. Moreover, the regression analysis yields a formula for predicting mean merchant casualties and insight into the significant factors of the scenario. The three most influential factors are the number of pirates, pirate speed, and convoy speed. Additionally, the regression analysis reveals some interesting interactions between the important factors. Increasing the number of pirates has great effect on increasing blue casualties when the convoy speed is low. Another significant interaction occurs between the number of pirates and the number of merchant ships. When the number of pirates increases, blue casualties are greater for increasing numbers of merchant ships. Finally, the regression notes that the warship can adequately handle the case where there is only one pirate, independent of convoy speed, and that increasing the number of merchants leads to an increase in blue casualties.

For the robust analysis, a regression model was also created, providing a prediction formula based on the decision factors of the scenario only. The two most influential factors are convoy speed and number of merchant ships. The interaction that occurs between the convoy speed and the number of merchant ships indicates that increasing the number of merchants has great effect on increasing the mean loss when the convoy speed is high.

Two separate classification and regression trees were conducted: one for the robust analysis over decision factors and one over the whole number of scenario factors. The first CART indicates that a convoy speed greater than or equal to 18 knots and a number of merchant ships in the convoy less than 14 yields better results in the protection of the convoy. Also, positioning the warship on the flanks or in front of the convoy results in fewer merchant casualties, whereas a position behind the convoy results in greater merchant casualties. The second CART indicates that the most significant factor of the scenario is the number of pirates. Three pirates or fewer can be expected to result in significantly fewer merchant casualties. Two other important takeaways from the later CART are the merchant sensor range and convoy speed, where values equal to or greater than 4,000 m and 14 knots, respectively, result in fewer merchant casualties. Finally, a pirate speed of less than 39 knots results in fewer merchant casualties than a pirate speed greater or equal to 39 knots.

B. FOLLOW-ON WORK

This thesis provides many opportunities for follow-on research:

- The scenario may be expanded using more than one escort warship or Unmanned, Aerial Vehicles (UAVs) to patrol over the convoy for the whole or part of the trip.
- The scenario may also include other MOEs, such as the time it takes for the warship to interdict the pirates.
- Finally, the scenario may be expanded to a higher level of detail. It may include the time it takes the warship or helicopter to stop and arrest the pirates or the actual self-protection measures the merchants may take to deter or delay the attack, like razor-wire barriers or water, spray, and foam monitors.

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