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THESIS

ANALYSIS OF PROTECTION MEASURES FOR NAVAL VESSELS BERTHED AT HARBOR AGAINST TERRORIST ATTACKS

by

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June 2016

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13. ABSTRACT (maximum 200 words)

The defense of a naval ship berthed in a harbor is a complex task affected by many factors. These include the fishing vessel density close to the ship and the challenge of discriminating neutral vessels from threats. A naval vessel berthed at harbor is more susceptible to attack than a vessel in open seas. The chances of detecting and countering a terrorist boat vary widely depending on several factors, including early identification of the attack and weapons available.

This research uses modeling in Map Aware Non-uniform Automata (MANA) to analyze the protection measures adopted by naval vessels against terrorist boats. Design of experiments is used to efficiently generate data, which is then replicated using high-performance computing, to address a wide range of possibilities and outcomes. The data generated is analyzed using a variety of techniques. The study concludes that lethality of Blue weapons is the most important factor in determining Blue's ability to counter a Red suicide boat attack. Additionally, the tactic of firing a warning shot followed by disabling shots within the exclusion zone decreases Blue's success probability. Finally, an exclusion zone of at least 60 meters that is enforced with a patrol boat is recommended.

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**ANALYSIS OF PROTECTION MEASURES FOR NAVAL VESSELS BERTHED
AT HARBOR AGAINST TERRORIST ATTACKS**

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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

API	Armor Piercing Incendiary
AP	Armor Piercing
ATF	Alcohol, Tobacco, Firearms, and Explosives
DOE	Design of Experiments
HMG	Heavy Machine Gun
IRTC	Internationally Recommended Transit Corridor
LH	Latin Hypercubes
LMG	Light Machine Gun
MANA	Map Aware Non-Uniform Automata
NOLH	Nearly Orthogonal Latin Hypercube
POF	Pakistan Ordinance Factories
ROF	Rate of Fire
SEED	Simulation Experiments & Efficient Designs
SOPs	Standard Operating Procedures

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EXECUTIVE SUMMARY

The 12th of October 2000 is a day to be remembered by the whole world. On that day terrorists carried out a suicide boat attack on USS *Cole* while it was berthed in the Port of Aden. The attack was a major incident that generated many questions, including reconsidering tactics regarding ship protection. Since then, ship protection and force protection has been an important aspect for any warship—be it in harbor or at sea. Many defensive tactics are developed, tested, implemented, and are being improved upon each day.

When naval ships are berthed in a naval port, ship protection is often not a big concern for the ship's staff as there will be no or only controlled civilian vessels moving around the ship or in the harbor. However, when warships are berthed in a port that is under civilian control, or when the ship is on a goodwill or flag hoisting mission to another country, then the ships are berthed in a civilian port where there is a lot of nearby civilian vessel activity in the form of fishing vessels, cargo dhows, and recreational boats. When this occurs, ship protection is a real concern for the ship's staff. As per the threat level enforced, the ship maintains appropriate protection levels and posts armed sentries to thwart any untoward incident.

In order to analyze the action and protection measures adopted by a naval ship against terrorist boats, the following research objectives were identified to guide this research:

- Determine which weapons systems, how many of them, and what accompanying tactics are required to ensure successful defense of naval vessels berthed at harbor.

- Explore the probability of successful ship defense as a function of the number, type, and effectiveness of weapons used against different numbers and tactics of the threat.

To begin this research a baseline scenario was developed for a warship berthed at harbor with three sentries posted with weapons on board ship facing seaward. An exclusion zone around the ship on its seaward side is established. No boat is allowed in this area unless positively identified. An armed boat patrols the area at the fringes of the

exclusion zone. The task of this patrol boat is to ensure that no boat/vessel enters the exclusion zone. If the patrol finds a potentially threatening boat heading towards the exclusion zone, then it will intercept the threat and will direct that vessel to avoid the exclusion zone using non-lethal means, such as a whistle, bright light, or verbal warning. If an incoming boat is found to be non-compliant to the instructions, then the patrol boat will raise an alarm informing all sentries onboard the ship and patrol boat of the threat. The sentries are then allowed to fire disabling rounds as soon as the incoming boat enters the exclusion zone. The sentries have been ordered to ensure that no incoming boat is able to reach within five meters of the ship using whatever means they have to in order to stop the threat.

In this scenario Blue is able to achieve successful defense if all Red boats are destroyed before hitting the ship's side. If one or more Red boats are able to reach their target, then Red has achieved its mission and it's a failure for Blue. To explore the effectiveness of ship self-defense measures, a simulation of this tactical situation was developed using the agent-based modeling environment Map Aware Non-uniform Automata (MANA) (McIntosh, 2007). Many different scenarios were studied by efficiently varying inputs to the model in many possible combinations.

After the scenario was built, the next step was to apply design of experiments (DOE) to efficiently explore the model over a range of controllable and uncontrollable factors. Using different factor combinations, different scenarios were generated varying the number of Red boats, exclusion zone distance, number of sentries, probability of hit of Blue agents, speed of Red boats, and the number of shots taken by a Red boat before it sinks (i.e., its staying power). These factors were used in a Nearly Orthogonal Latin Hypercube (NOLH) design to obtain 257 space-filling design points. As the design points were obtained by a NOLH, the maximum absolute pairwise correlation between any two factors was 0.058. These 257 design points were crossed with eight levels of weapon combinations for Blue sentries and two-levels of the number of Blue patrol boats to obtain 4,112 unique design points. Using the cluster computers in the Simulation Experiments & Efficient Design (SEED) lab, each design point was replicated 100 times,

for a total of 411,200 simulated terrorist attacks on a warship berthed at harbor. The output was analyzed to obtain insight on the thesis research objectives above.

Different analysis techniques, such as regression models, partition trees, histograms, and ANOVA were used to analyze the data generated by the simulation experiments. The following important insights were obtained:

- The most important factor to defend a ship is the lethality of Blue weapons against the Red boat. In simple words, the type of weapons the sentries used is the most important factor in protecting the ship. There was a clear distinction among the results when the Red boat was able to sustain against Blue weapons and when it was not able to do so.

- Another important factor is the probability of hit by Blue sentries—i.e., their skill level.

- The presence of the Blue patrol boat and the speed of the Red boat also emerged as important factors. In almost all scenarios, the Blue patrol boat played an important part in ensuring a successful defense.

- The probability of successful defense is reduced when multiple Red boats attacked simultaneously, but it was not a major factor.

- Exclusion zone distance also played an important role in ensuring successful defense of the Blue ship. An exclusion zone of at least 60 meters is recommended to be maintained by the Blue force.

- It was also found that sentries should fire on the Red boat as soon as they enter the exclusion zone. Delivering a warning shot followed by a disabling shot will substantially reduce Blue's success probability.

References

McIntosh, G.C. (2007). *MANA version 4 user manual*. Auckland, New Zealand: Defence Technology Agency.

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I.   INTRODUCTION

A.   BACKGROUND

"On October 12, 2000, suicide terrorists exploded a small boat alongside the USS *Cole*, as it was refueling in the Yemeni port of Aden. The blast ripped a 40-foot-wide hole near the waterline of the *Cole*, killing 17 American sailors and injuring 39 others" (FBI, 2005). This suicide attack severely damaged the ship. It had to be towed to another location for necessary repairs in order to make it sea worthy again. Force Protection Plan Bravo was enforced onboard USS *Cole* at that time. This terrorist attack raised a series of questions regarding the efficacy and implementation of the force protection plan. Since that event, ship protection procedures have changed a lot. Navies around the globe have reviewed their protection plans and tactics, and tried to implement such plans in practice. Many changes were made in tactics and different standard operating procedures (SOPs) were devised. With every passing day improvements are being incorporated in these SOPs to ensure a reliable defense of naval vessels at sea and at harbor.

When a naval vessel is berthed at harbor within a home country, it is generally berthed at a naval harbor (that is, the harbor is controlled by the Navy). In a naval harbor, there is controlled movement of all vessels, and any vessel moving in close proximity of naval ships is well identified, so the chances of a terrorist suicide attack are low. However, when ships are berthed in a civilian controlled port or when warships pay goodwill or flag hoisting visits to other countries, then naval ships are generally berthed at a commercial jetty in a civilian port. Standard procedure is that an exclusion zone of 40 meters to 70 meters, depending on the space available, is established by the local host nation. No vessel is allowed to enter this exclusion zone, and an armed boat patrols this area to avoid a breach of this exclusion zone. It is the responsibility of this patrol boat to intercept any vessel moving towards the exclusion zone and direct them away from it, using non-lethal means, for example, whistles, bright lights, and radios. However, if any boat does not alter its course and continues to move towards the exclusion zone, then the vessel is believed to be hostile. In such a situation, the patrol boat alerts all sentries onboard the ship, and sentries are allowed to fire disabling shots on the boat entering the

exclusion zone. The number and type of weapons manned by the sentries depends on the threat level enforced at that time. Outside this exclusion zone, normal harbor traffic runs, including fishing boats, recreation boats, or cargo dhows. From this traffic, if there are one or more terrorist boats that alter their course to hit the side of the naval ship, then only sentries with small arms are available to defend against the attack. At that time, the probability of successful defense will mainly depend on the alertness of the sentries, the probability of hit by weapons carried by sentries, training of sentries, and the lethality of the weapons. To ensure an acceptable level of successful defense, the number and type of weapons by sentries, along with the width of exclusion zone, must be known by the ship's crew at all times.

B. OBJECTIVE

The goal of this thesis is to determine whether the standard procedures and weapons that are currently in place can ensure a successful defense of a naval vessel berthed at a civilian harbor. In addition, it explores which weapon systems and how many of them, as well as accompanying tactics, are required to ensure a successful defense of a naval vessel berthed at harbor. Here, "tactics" means the width of the exclusion zone, whether sentries should fire immediately on any vessel entering the exclusion zone, or whether they should first fire a warning shot and then disabling shots. This thesis also explores the probability of successful defense when the number and combinations of weapons is changed alongside the width of exclusion zone.

C. SCOPE OF THESIS AND RESEARCH QUESTIONS

This research focuses on tactical level scenarios in which a naval vessel is berthed at harbor. The threat level is high and it is believed that a suicide attack may be imminent. The ship is utilizing three sentries with weapons, and one armed patrol boat is maintaining an exclusion zone around ship. The objective of these defensive forces is to thwart any suicide attack in the form of suicide boats. The primary research question guiding this thesis research is:

- What type of and how many weapons are required to ensure the successful defense of a berthed ship against a terrorist suicide boat?

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Supporting questions are as follows:

- What should be the width of the exclusion zone with different weapon combinations?

- What accompanying tactics are required to ensure the defense of the ship?

- If the number of weapons, type of weapons, or width of the exclusion zone is changed, how does it impact the probability of successful defense by the Blue ship?

D.   THESIS OVERVIEW

The information about the capabilities of the Blue force, i.e., the weapons held by the sentries and their characteristics, is provided in Chapter II. A general literature review about important terms and methods used during this thesis are also explained in this chapter. Chapter III provides an overview of the methodology adapted for the research. In addition, this chapter also explains the agent-based modeling environment Map Aware Non-uniform Automata (MANA) that is used for simulating the scenario. Chapter IV describes the efficient design of experiments (DOE) techniques used to explore the model to answer the research questions. Chapter V presents an analysis of the data obtained from the simulation experiments and Chapter VI summarizes the conclusion drawn from the analysis.

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II. CAPABILITIES, SCENARIO DESCRIPTION, AND LITERATURE REVIEW

This chapter describes the capabilities and characteristics of different weapons held by Blue units. It also describes the operational setting used to calculate the measure of effectiveness (MOE), i.e., the probability of successful defense by Blue. In addition, this chapter discusses important concepts and methods used during this study.

A.   BLUE UNIT'S RESOURCES AND CAPABILITIES

Sentries onboard ships are posted as per the threat level enforced. The strength of these sentries and the weapons carried by them depends on the threat level. If the threat level is high, sentries are required to man big caliber guns and the number of sentries will increase. Threat level is issued via shore authorities and the ship has no control over it. A ship may take measures as per the threat level enforced, or if deemed appropriate by the commanding officer, as per one level above the level promulgated. The following are the type of guns carried/manned by sentries:

- 7.62mm G3/M16

- 7.62mm LMG

- 12.7mm Gun

1.   7.62mm G3 / 5.56mm M-16

Sentries armed with assault rifles are deployed if the threat level is low or it is considered that no attack will occur without adequate warning. The two types of assault rifles being considered here are the G3A3 and M16A4 (see Figure 1), respectively. Table 1 depicts the general characteristics of these assault rifles.

Table 1.   Assault Rifle General Characteristics. Adapted from "Automatic rifle G3A3 & G3P4" (n.d.), Powers (2016).

Rifle	Country	ROF	Magazine Capacity
7.62 mm G3A3	Pakistan	500–600 rpm	20 rounds
5.56 mm M16A4	U.S.	700–750 rpm	30 rounds

Figure 1.   Assault Rifles G3A3 and M16A4. Source: "Assault Rifle G3" (n.d.), "M16A4" (n.d.)

2.   7.62mm Light Machine Gun LMG MG1A3

Another potential weapon manned is the 7.62mm machine gun. "The MG3 (MG1A3) is an open, fully automatic weapon for sustained firing and firing in bursts. It is a 'recoil-operated weapon' in which the recoil forces are used to feed and load the cartridges and to extract and eject the spent cartridge cases" ("Machine Gun MG3 (MG1A3)", n.d.). It is a highly effective weapon in terms of its rate of fire (ROF) and ammunition capacity. Table 2 depicts general characteristics of a 7.62mm LMG.

Table 2.   Light Machine Gun Characteristics. Adapted from "Machine Gun MG3 (MG1A3)" (n.d.), "M240" (n.d.).

Weapon	Country	ROF	Magazine Capacity
7.62 mm MG1A3	Pakistan	1000–1300 rpm	250 rounds
7.62 mm Browning M240	U.S.	650–1000	200 rounds

The two different types of machine guns, whose characteristics are given in Table 2, are depicted in Figure 2.

Figure 2.   Browning M240 (U.S.) and LMG MG1A3 (Pakistan), Source: "Machine Gun MG3 (MG1A3)" (n.d.), "M240" (n.d.).

3.   12.7mm Gun

A 12.7 mm gun is an automatic weapon that employs 12.7 mm armor piercing (AP), armor piercing incendiary (API), and hard core ammunition. It is very effective against low flying aircraft and ground targets, especially armored vehicles ("Anti-Aircraft Machine Gun 12.7 MM TYPE 54," n.d.). Therefore, it can be considered the most effective weapon against incoming suicide boats, especially if the aim is to destroy and sink the boat. Table 3 depicts the general characteristics of two types of 12.7 mm guns.

Table 3.   12.7mm Machine Gun Characteristics. Adapted from "Anti-Aircraft Machine Gun 12.7 MM TYPE 54" (n.d.), "Browning M2" (n.d.).

Weapon	Country	ROF	Magazine Capacity	Armor Penetration
12.7mm gun	Pakistan	600 rpm	70 rounds	15mm at 500 m
12.7mm Browning M2 (HMG)	U.S.	500 rpm	110 rounds	15mm at 500 m

Figure 3 depicts the 12.7 mm machine guns used onboard ships by the Pakistan Navy and U.S. Navy.

Figure 3.   12.7mm Gun. Source: "Anti-Aircraft Machine Gun 12.7 MM
TYPE 54" (n.d.), "Browning 12.7mm" (n.d.).

B.   SCENARIO

A general depiction of the scenario we analyze is given in Figure 4.

Blue agents on ship, with different
weapons configuration. Blue agents
are allowed to fire on boats entering
the exclusion zone

Blue boat with weapons patrolling in area 50-70 m from
the ship in order to keep all boats away from the ship

Boat Patrol Area

EXCLUSION ZONE (40-70 meters). Any boat
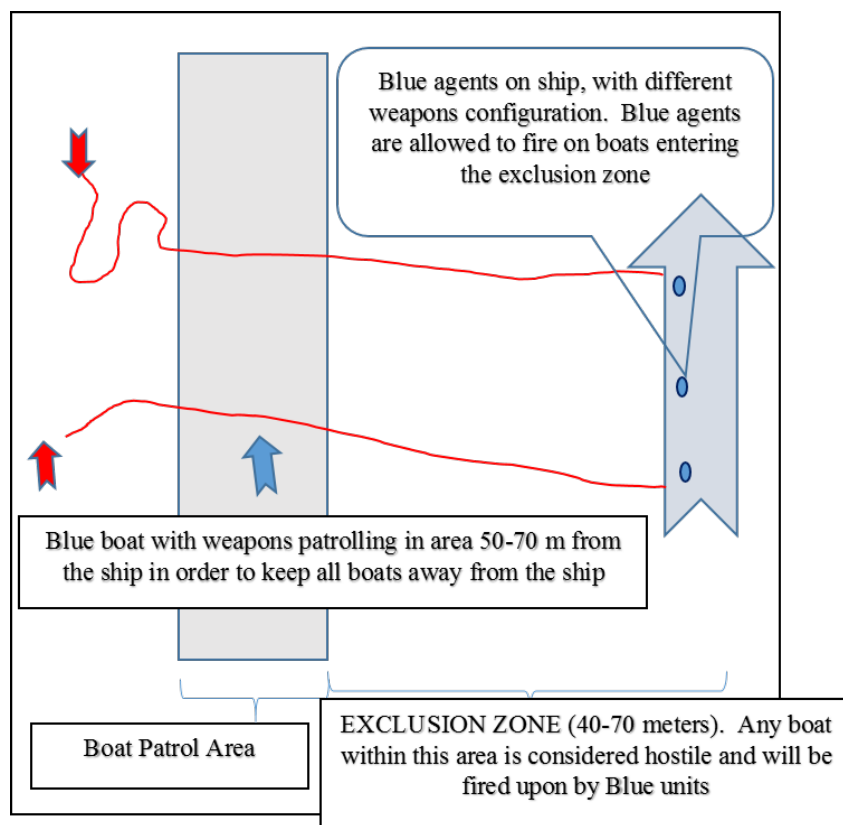within this area is considered hostile and will be
fired upon by Blue units

Figure 4.   General Depiction of Scenario.

Figure 4 shows a Blue ship berthed at a civilian harbor. The threat level is high, so three armed sentries are deployed onboard the ship. In addition to these sentries, one patrol boat is also patrolling in the area. The purpose of this boat is to ensure that no threat boat is able to reach the ship. To ensure this, an exclusion zone of 50 meters is established seaward side of the ship and no unidentified boat is allowed to enter in this area. If any boat tries to force her way towards the ship and enters the exclusion zone, then all sentries are allowed to fire on the threat boat until it is neutralized. Outside the exclusion zone, normal harbor traffic is allowed, including cargo dhows, recreational boats, and fishing vessels. The Red force consists of one or two Red explosive-laden suicide boats, which are not identified until these boats try to force their way towards the ship and enter the exclusion zone. It is assumed that as soon as any Red boat alters her course towards the ship, she will increase her speed to maximum and try to ram her boat into the side of the Blue ship. The Red boat is successful if any one or all of the Red boats are able to reach the ship's side (i.e., Red successfully rams boats into the Blue ship). The Blue force is successful if all Red boats are neutralized before they were able to reach their target.

C.   CIRCULATION MODEL

Defense of naval ships in harbor is best explained by the half leg of a circulation model. Defensive weapons on the ship and patrol boats are not the only available defensive arrangement for the ship; rather the ship's defense is a tiered operation, and sentries and patrol boats are the last tier of its defense. Another important tier is the "harbor protection organization." The purpose of this study is to analyze the last tier of the ship's defense. This last tier becomes particularly important when the ship is berthed in a foreign port where we do not control, have much information, or trust on other tiers. The circulation model is explained in ensuing paragraphs.

Let's say a terrorist leaves his base to attack a naval ship in harbor. After he gets into the water with an explosives-laden boat, he is expected to encounter two main tiers of defense. Each of the tiers has its own factors and players which will define the effectiveness of that tier in stopping the terrorist. These tiers will each have their own

probability of detection/hunting the terrorist and similarly the terrorist will have his survival probability from each tier. In this model we assume independence of these two tiers, although in reality they can be somewhat dependent depending on the coordination between harbor security and ship security. This concept is illustrated in Figure 5.
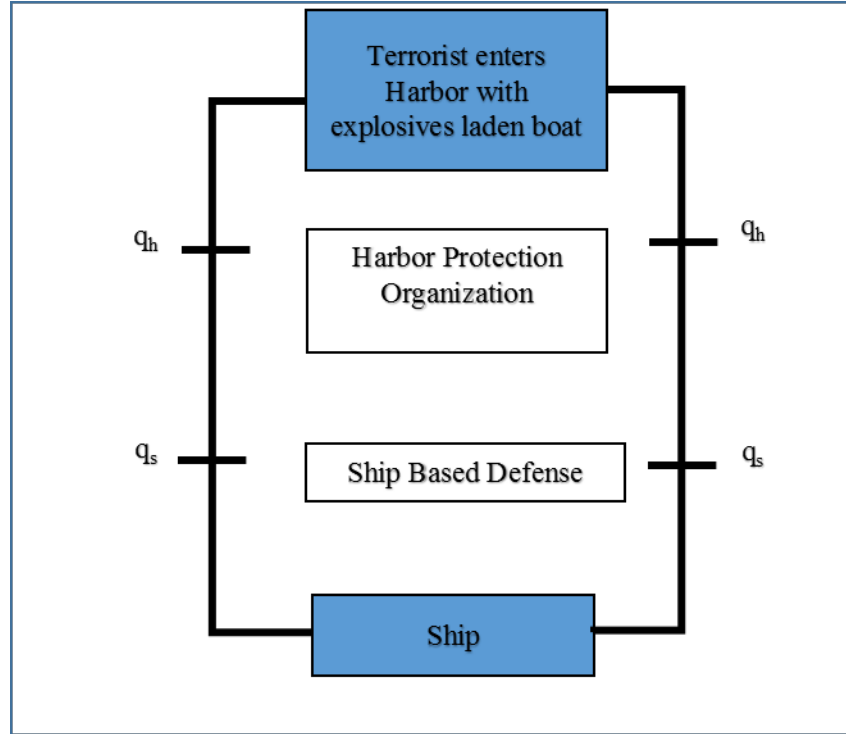
Figure 5.   Circulation Model for Terrorist Survival.

ph = probability (terrorist neutralized by harbor defense personnel).

ps = probability (terrorist is neutralized by ship based/patrol boat sentries).

qh = probability (terrorist is not neutralized by harbor patrol defense) = survival probability of terrorist from harbor defense personnel = $1 - ph$.

qs = probability (terrorist is not neutralized by ship based defense) = survival probability of terrorist against ship based defense = $1 - ps$.

The aggregate survival probability of a terrorist for a successful attack on the ship is q, which can be calculated as:

$$q = qh \times qs$$

So, q is one of two parts of the survival probability of the terrorist. As we are considering a suicide boat mission against the ship, the other part of the circulation model is not important, thereby the whole model can be viewed as a half circulation model, which simplifies to a Bernoulli distribution.

Let us suppose each tier has a probability of neutralizing the terrorist of 0.6; then, for a terrorist we have $qh = qs = (1 - 0.6) = 0.4$, which means that the terrorist has 40% chance of survival at each stage. Then, the cumulative probability that a terrorist can have a successful attack on a ship berthed at harbor can be calculated as:

$$q = qh \times qs = 0.4 \times 0.4 = 0.16,$$

which means that each terrorist has a 16% chance that he will be successful, assuming independence between all events. The probability of his success can be reduced by increasing the probability to neutralize the terrorist at any one or all of the stages. If the probability of intercepting the threat is increased by 0.1 at each stage, then the chances of success for a terrorist decreases drastically and it comes down to 9%. If ships are berthed at a home port, then ph is important. However, if the ship is in a foreign port, then ps (the probability of terrorist neutralization by the ship) becomes very important. At that time, it becomes very important for the ship's Commanding Officer to increase ps as much as possible to decrease the terrorist's probability of success.

D.   EXPLOSIVES USED IN SUICIDE BOATS

There are hundreds of types of explosives used by terrorists. The explosives may be stable and not explode even if someone shoots at it or even sets it on fire. In other cases, the explosive can be very sensitive to fire or a bullet hit. Although it may be true in rare cases that explosives are sensitive, generally it is not true. Explosives that terrorists generally use are inert and are not affected even if they are sprayed with bullets.

1.   Categories of Explosives

There are hundreds of formulas and compounds of explosive materials. Explosives can consist of a chemically pure compound, such as nitroglycerin, or a mixture of a catalyst fuel and oxidizer mixture, such as black powder (Peters, Tanner, & Kasper, 2010). The United States Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF) categorizes explosives into three types.

a.   Low Explosives

Low explosives deflagrate, meaning, they combust at much slower rates, thereby giving a reaction of a burst or flair of flame (Peters et al., 2010). Most fireworks fall into this category. These explosives are primarily used as a propellant to push an object. However, when low explosives are packed in a container, then natural forces of physics come in play and these explosives can be very dangerous and can detonate like high explosives.

b.   High Explosives

High explosives are those that are generally used for commercial applications like demolition, mining, and military uses (Peters et al., 2010). These explosives can be initiated using a blasting cap, which sends a shock wave into the explosive to cause it to burn. The burn rate of high explosives is very high. It causes more destruction as a shock wave is generated due to its high burn rate.

c.   Blasting Agents

Blasting agents are a mix of fuel and oxidizer that produce a high pressure shockwave when detonated (Peters et al., 2010). On their own they cannot be ignited or burned, as they require a more sensitive high explosive booster to set them off.

2.   Explosives Generally Used by Terrorists

When not in custody of gunpowder, terrorists often resort to improvisation to fulfill their evil deeds, by using improvised explosives. Generally available material, which is used as improvised explosives and is expected to be used by terrorists in urban

areas when gunpowder is not easily available, is inert and stable. The following is a list of generally used materials (there are many more as well) that can be used for making an improvised explosive device (IED) (Asthana & Nirmal, 2008):

- Chlorate Mixtures

- Flash Powders

- Bangor (Firecracker Powder)

- Permagnate Powder

- Ammonium Nitrate and Aluminum Powder

- Ammonium Nitrate Gel Explosives

These are the chemical names of the main substances used for making IEDs, according to the fact sheet by National Academies and Department of Homeland Security (Department of Homeland Security, 2008). The fact sheet further explains:

> Many commonly available materials, such as fertilizer, gunpowder, and hydrogen peroxide, can be used as explosive materials in IEDs. Explosives must contain a fuel and an oxidizer, which provides the oxygen needed to sustain the reaction. A common example is ANFO, a mixture of ammonium nitrate, which acts as the oxidizer, and fuel oil (the fuel source). Concern about the use of explosives created from liquid components that can be transported in a stable form and mixed at the site of attack is the reason that in 2006 the U.S. Department of Homeland Security restricted the amount of liquids that passengers can carry on commercial aircraft. (Department of Homeland Security, 2008)

E.   LITERATURE REVIEW

Various studies have addressed the defense of a naval ship against fast moving small boats; however, we mention three in particular that have used agent-based simulation to gain insight into tactical recommendations.

The first study was a thesis done in June, 2011, by Lt Cdr Thomas Tsilis of the Hellenic Navy, at the Naval Postgraduate School. The author explored the key factors involved in escorting merchantmen through the Internationally Recommended Transit Corridor (IRTC) in the Gulf of Aden, as a defense against small pirate boats. He used

MANA and design of experiments to conclude 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" (Tsilis, 2011).

The second study was conducted by Lisa R. Sickinger, Lieutenant, USN, in 2006. Her research was sponsored by the US Joint Non-Lethal Weapons Directorate. LT Sickinger considered a naval warship's defense against small boats while returning to a port and entering the harbor. The study's main research question was "What non-lethal capabilities are required in a maritime force protection environment in order to effectively determine intent and/or deter suspicious small vessels?" (Sickinger, 2006). During the course of study Sickinger used Multi Agent Simulation (MAS) alongside efficient design of experiments and data farming techniques to explore and answer her research question.

The third study, which is related to this thesis, was done by Felix Martinez Tiburcio, Lieutenant, Mexican Navy, in December 2005. Martinez analyzed the strategy developed by the Mexican Navy to prevent terrorist attacks on the strategic Campeche Sound (petroleum production area) in the Gulf of Mexico. Martinez used agent-based simulation, implemented in Map Aware Non-uniform Automata (MANA), and data farming to analyze and evaluate his research questions. From the study, Martinez concluded that "the most important threat factor in the scenarios is the speed of the enemy boats; and, with its broad surveillance and communication capabilities, the HAWKEYE is the most important Navy resource in the area" (Tiburcio, 2005).

All three studies dealt with naval ships against terrorist boats/fast patrol boats by using agent-based simulation, data farming, and design of experiments in different scenarios. Leveraging this methodology, this study deals with a scenario in which a naval ship is berthed at harbor and all major systems of the ship are switched off, and thus, the defense of the ship is entirely dependent on the vigilance, alertness, and abilities of the sentries posted.

III.   METHODOLOGY AND MODEL DESCRIPTION

A.   METHODOLOGY

To carry out this study, an agent-based modeling platform known as Map Aware Non-Uniform Automata (MANA) was used to model different scenarios. By using MANA, the technique of data farming was used to generate data for subsequent analysis. Data farming is the process of using simulation and efficient design of experiments to "grow" output data, which can then be analyzed using data analysis and visualization techniques (Lucas, Kelton, Sanchez, Sanchez, & Anderson, 2015). After choosing factors and the ranges of these factors to explore, an efficient design of experiments (DOE) and cluster computing is used to computationally generate output data. This data is analyzed in order to identify significant factors, important thresholds, and to see whether interactions exist between key variables. After data collection, JMP statistical software is used to analyze the effectiveness of different weapons and tactics in protecting ships berthed at harbor.

B.   CALCULATION OF PROBABILITY OF HIT

In order to analyze the protection measures of naval vessels berthed at harbor, it is important to calculate the probability of hit for all the weapons being carried by sentries. To calculate the probability of hit of a G3/12.7mm/7.62mm LMG, a small simulation using the 'R' language (https://www.r-project.org/) was run. To calculate the probability of hit (Phit) against a man-sized target, a target containing two rectangles, one on another, was considered. It is assumed that the driver of the boat is behind the wheel of the Red boat and a sentry has to hit the driver. It is also assumed that the driver's upper body is visible and his legs are behind some structure. So, two rectangles, one on top of other, are considered to depict a man from some distance. The lower rectangle is 1.5×2.5 feet and the upper rectangle is 1×1 feet. This is depicted in Figure 6.
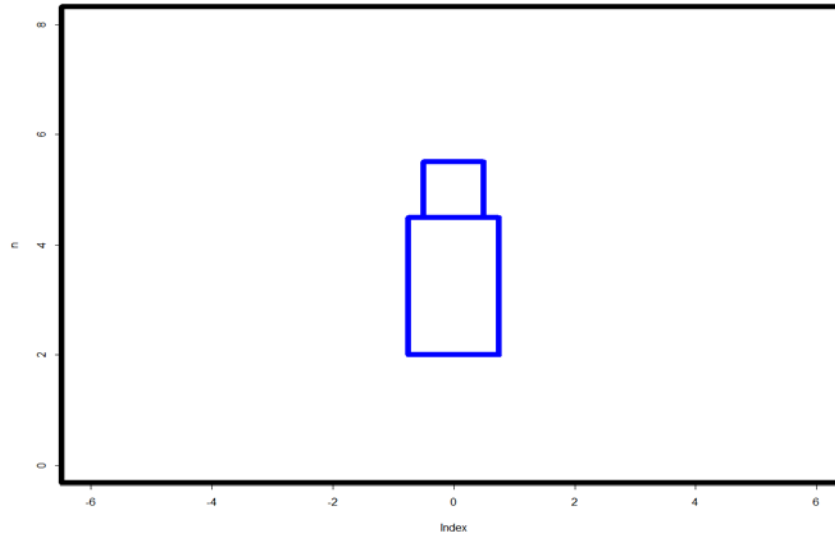
Figure 6.   Depiction of Driver in the Form of Two Rectangles.

To calculate the probability of hit of the weapons, this target was bombarded with 1,000 simulated rounds having specified standard deviations in the *x* and *y* axes to represent weapon error. The aim-point of the bombardment was always the center of mass, with no aim point bias error. Although the exact values of the standard deviations in the *x* and *y* axis are unknown, but based on practical experience, standard deviations were estimated as a function of range. The values used were $\sigma_x = 0.005 \times \text{range}$ and $\sigma_y = 0.005 \times \text{range}$ in meters. Then, the probability of hit, using the data from simulations run in "R," was calculated out to 100 meters. Two different situations were simulated. First, the upper body of the boat driver is visible to the firer and the firer aims at the center of mass. In the second condition, it is simulated that boat driver has a shelter in front of him and only the head is visible, so any fire that is away from the upper rectangle (head) is counted as a miss. Figure 7 depicts the graph of the probability of hit, obtained when the target was fired upon by a sentry at ranges varying between 0 and 100 meters.
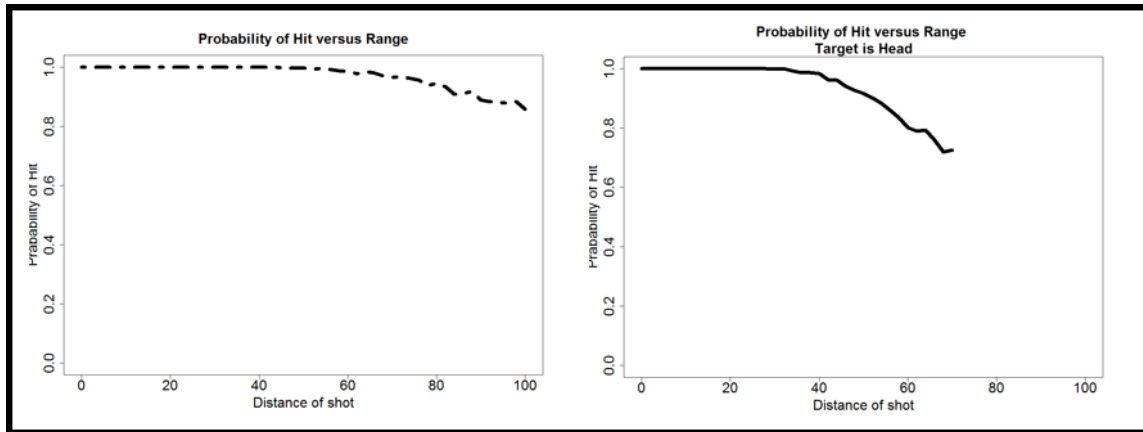
Figure 7.   Probability of Hit of Small Arms versus Range (Meters).

It is found that the probability of hit for all weapons is near one in both cases, if the weapon is to be fired at less than 60 meters (which is our main analysis area). However, this is the probability of hit by the weapon, not including the error induced by the shooter. The probability of hit by a shooter can be very different than the inherent probability of hit of the weapon. In an actual scenario, a lot of factors play a pivotal role in specifying the probability of hit, and these include, but are not limited to, the following:

- The armed sentry knows that the approaching boat is a suicide boat, so fear may play a very big role.

- Wind conditions at that time can cause inaccuracy of the shot.

- Only 8–10 seconds are available for a sentry to aim, fire, and neutralize the threat, as a 12 knot boat will take 8–10 seconds to cross the exclusion zone and hit the ship.

- The boat, and therefore the driver, is a moving target.

- The sea state may cause the boat as well as sentries to move up and down with the water, hence making it difficult for the sentries to shoot accurately.

All these factors and other conditions may be prevalent at that time, and could play a very important role in lowering the probability of hit of each weapon. Although no data is available to determine the probability of hit in such conditions, it is assumed that the probability of hit for individual rounds may decrease significantly.

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If we consider that the probability of an individual round hitting the target reduces to 0.3, then the following is the calculation for multiple independent shots:

- Probability of hit of an individual shot $= p = 0.3$.

- Number of shots fired $= n = 10$.

- Probability of at-least one successful shot $= 1 - (1 - p)^n = 0.9717$.

This calculation shows that even if an individual shot has a very low probability of hit, due to multiple shots being fired in burst mode by automatic weapons, the cumulative probability of hit increases very rapidly to one (assuming independence). We can see that within 10 rounds the probability of hit increases to near one. This means that in conditions such that the sentries are able to shoot several times, the terrorist will likely be neutralized. But, that's the case when only one shot is enough to neutralize the terrorist. However, in most of the cases, the objective of sentries is not to neutralize the terrorist, but to neutralize the suicide boat, which may take far more shots before it is disabled. Keeping this in mind, the single shot probability of hit for these weapons was taken as a factor in the design of experiments (DOE), and it was varied from 0.2 to 0.8.

C.   MANA

The modeling environment used to simulate the scenario is Map Aware Non-Uniform Automata (MANA). MANA is a time-stepped, stochastic, agent-based distillation model developed by the Defense Technology Agency (DTA) of New Zealand. As the name suggests, the individual entities (agents) in MANA are "map aware," which means that during the simulation individual entities' situational awareness includes both terrain information and battle space activities. MANA incorporates several features not appearing in some other (simpler) cellular automaton combat models; for example, "the MANA model uses a 'memory map' to provide shared situational awareness and guide entities about the battlefield" (McIntosh, 2007, p iii).

D. WHY WE USE AN AGENT-BASED MODEL

According to Grimm and Railsback, "Agent-based models" can be defined as:

> An agent-based model (ABM) is one of a class of computational models for simulating the actions and interactions of autonomous agents (both individual and collective entities such as organizations or groups) with a view to assessing their effects on the system as a whole. It combines elements of game theory, complex systems, emergence, computational sociology, multi-agent systems, and evolutionary programming. Monte Carlo methods are used to introduce randomness. ABMs are also called individual-based models (IBMs). (Grimm & Railsback, 2005, p. 485)

Agent-based models are the computational models of heterogeneous populations of agents and their interactions. It has always been a researcher's goal to describe any processes or event with the most simple model and method that can explain that process with an acceptable degree of accuracy.

The next question that comes to mind is: Why an agent-based model? In military applications, many different types of models are used to find the optimal solution of wide range of problems. It is best explained by Winston:

> Because of complexity, stochastic relations, and so on, not all real-word problems can be represented adequately in closed-formed models. Attempts to use analytical models for such systems usually require so many simplifying assumptions that the solutions are likely to be inferior or inadequate for implementation. Often, in such instances, the only alternative form of modeling and analysis available for the decision maker is simulation. (Winston, 2004)

Agent-based modeling adds a new aspect to simulations of combat systems. It allows direct representation of individual battlefield entities and their interactions. We all know that all individuals are different. Even though in the military, uniformity in actions and responses is imparted via training and SOPs, it is still true that different individuals behave differently under varying circumstances and pressure. The varying responses reflect stochasticity on the part of individual entities. By using agent-based models, the essence of individual behavior is captured and by running stochastic simulations, a range of results is produced, which can help provide insight on possible outcomes of combat scenarios.

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E.   MODEL IMPLEMENTATION IN MANA

After selecting MANA as the modeling environment and deciding on the details of the desired conceptual model, a base case scenario was developed. The following are some important aspects of MANA that were used to build the scenario.

1.   Battlefield

The first thing to be done in MANA is to define the battlefield, as MANA recognizes different types of terrain. It is important to select the terrain according to the scenario when building the model. The user defines the battlefield area for a given scenario (McIntosh, 2007). Although there are different types of terrains available, we use the "Billiard Table" terrain, which affords maximum mobility and no concealment or protection. In this case, we simulate movement of Blue and Red entities on the water where no physical barrier hampers the movement, so the Billiard Table terrain type is appropriate. The battlefield settings, including size of the battlefield, are illustrated in Figure 8.

Figure 8.   Edit Battlefield Tab.

2.   Squad

Groupings of homogeneous (same initial behavioral and physical properties) are called "squads" in MANA. "Conceptually, a squad is a group of agents of any size (between 1 and 1,000), as defined by user. Agents in a squad share the same properties and can switch into different states depending on their circumstances" (McIntosh, 2007, p. 7). A MANA squad should not be confused with an infantry squad. Agents in a squad are defined based on their properties with respect to their weapons, characteristics, and behaviors. For the purpose of this model, five different type of squads were defined; three blue squads, one red squad and one neutral squad. To add or edit squad properties in MANA, the "Edit Squad Properties" tab in the setup menu is used. Different tabs within "Edit Squad Properties" are further explained in the following sections.

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a.   General

On the *General* tab, several general properties of the squad are assigned, for example, the squad name, the number of agents in each squad, the initial orientation of the squad, and the fuel available to each member of the squad. *General* tab settings are illustrated in Figure 9.
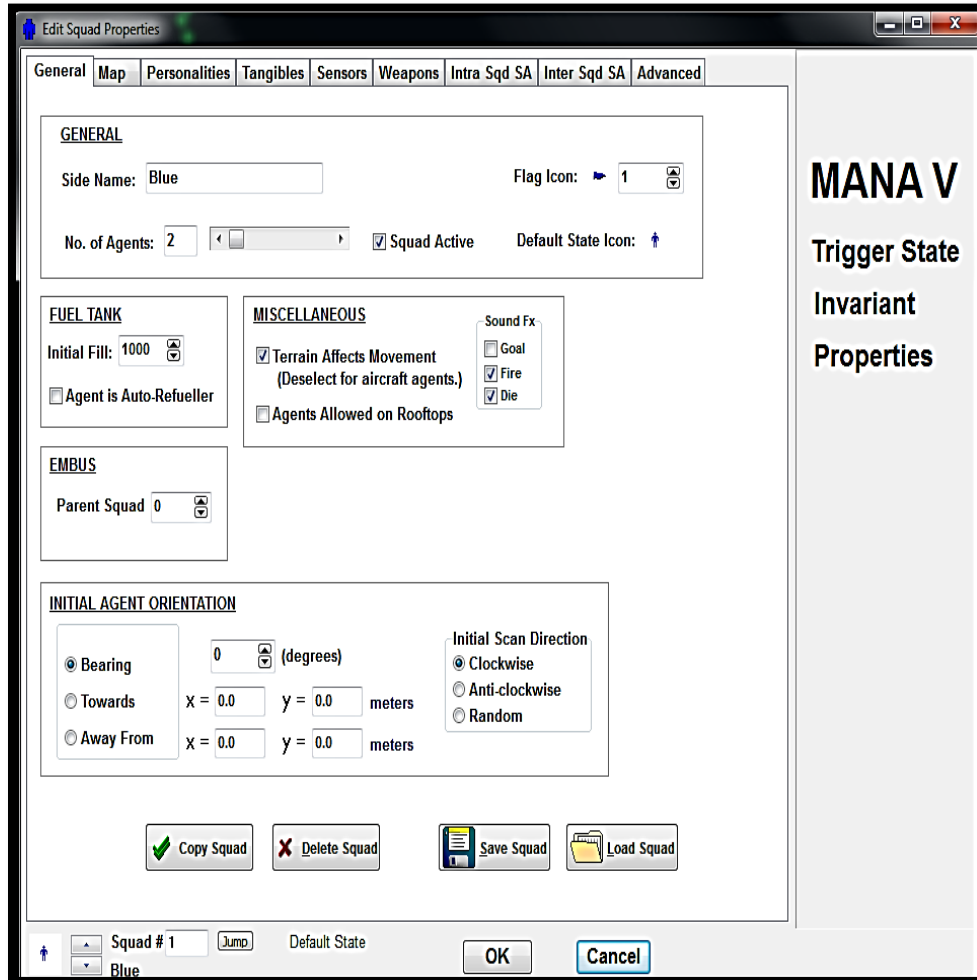

Figure 9.   General Properties for Each Squad.

b.   Map

Under the *Map* tab, the initial position for every squad is set by specifying their home boxes. All squads will start from their assigned home box when the simulation run starts. Similarly, way points and a final destination for each squad are also given using the same tab (McIntosh, 2007). An illustration of the "Map" tab is given in Figure 10.
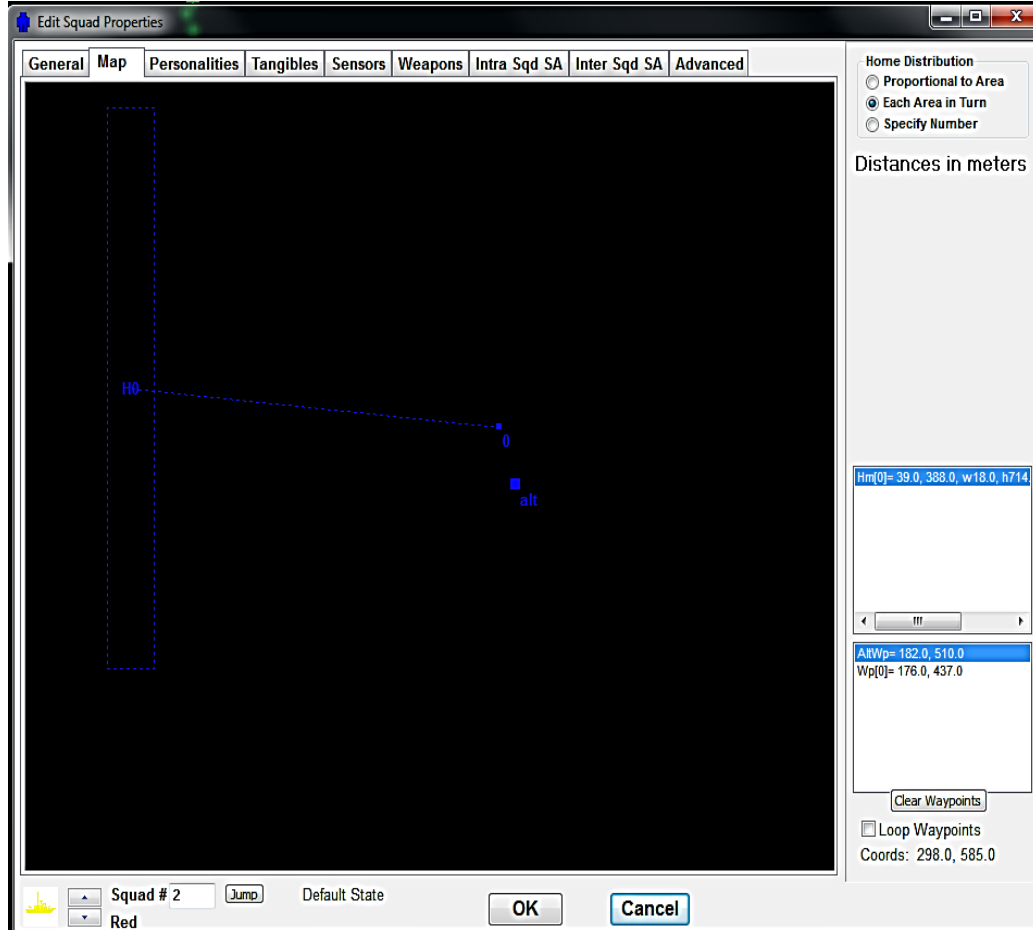

Figure 10.   Map Tab Used to Give Initial Start and Final Destination.

c.   Personalities

The *Personalities* tab is very important, as it is used to define the behavior of individual squad members. Here, how an agent should behave in response to enemy, friends, and neutrals is defined. For example, the desires to move towards or away from an enemy, friend, or destination points, are defined here. Agents are given simple rules to

move on the battlefield depending on the location of other agents and conditions on the battlefield (McIntosh, 2007). Using the sliding bar, personality weightings for different actions are defined by the user. Other options available within this tab are illustrated in Figure 11.
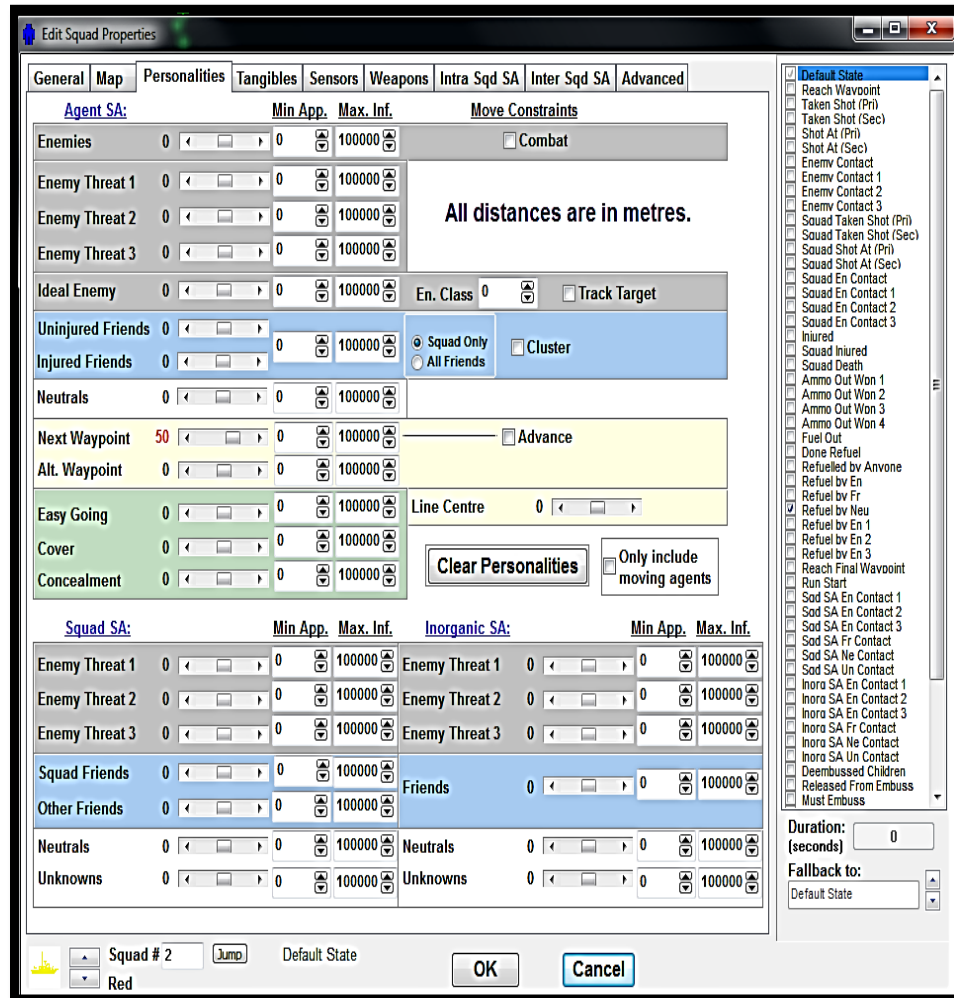

Figure 11.   Personality Tab Options.

d.   Tangibles

Beside personality weightings, there are a number of tangible aspects or physical properties that can be defined under this tab. These include:

- General properties such as allegiance, sensor height of agent, movement speed, and agent class

- Self-protection features, such as the number of hits to kill, concealment, and armor thickness

- Waypoint radius (how close an agent has to be to a waypoint to be considered to have arrived at it)

- Fuel consumption rate

- Embussing behavior (determines when a "child" agent is to be released from a "parent" agent)

This tab is depicted in Figure 12.

Figure 12.   Tangibles Tab for Describing Physical Properties of Squad.

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e.   *Sensors*

The sensor model in MANA is intuitive and incorporates simple probabilistic calculations within the sensor range of each agent (McIntosh, 2007). In the sensor tab, we can assign range-probability pairs for detection and classification. Detection is knowing that "something" is present and classification is knowing whether the detected agent is a friend, enemy, or neutral. One other important property is that the user can also specify which class(es) of agents can be detected or classified by that particular sensor. An illustration of *sensor* tab is given in Figure 13.
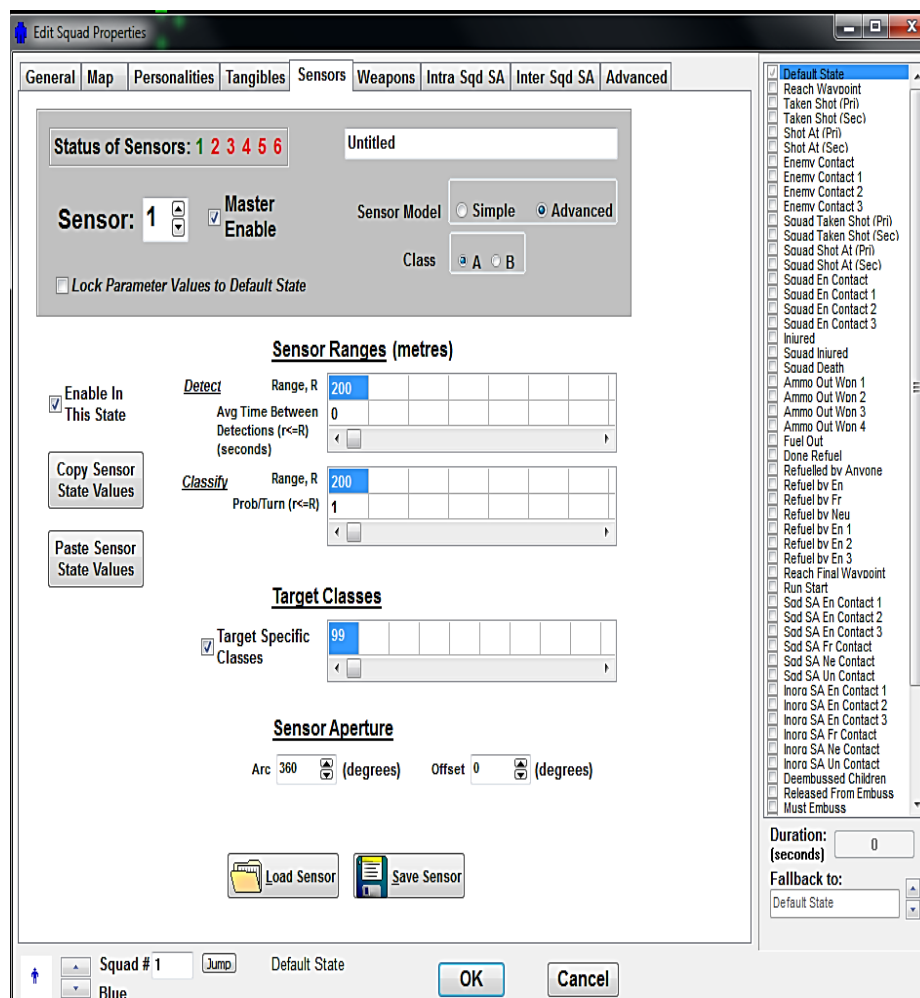
Figure 13.   Sensors Tab.

f.   Weapons

Like sensors, weapons in MANA are also based on probabilistic calculations (McIntosh, 2007). Here, the user can assign primary and secondary weapons (up to four classes of weapons can be assigned) to a squad and the user can specify probabilities of hit for each bullet at different ranges. Also, the weapons carried by the squad can be classified as kinetic energy or high explosive. A screen shot of the *Weapons* tab is depicted in Figure 14.
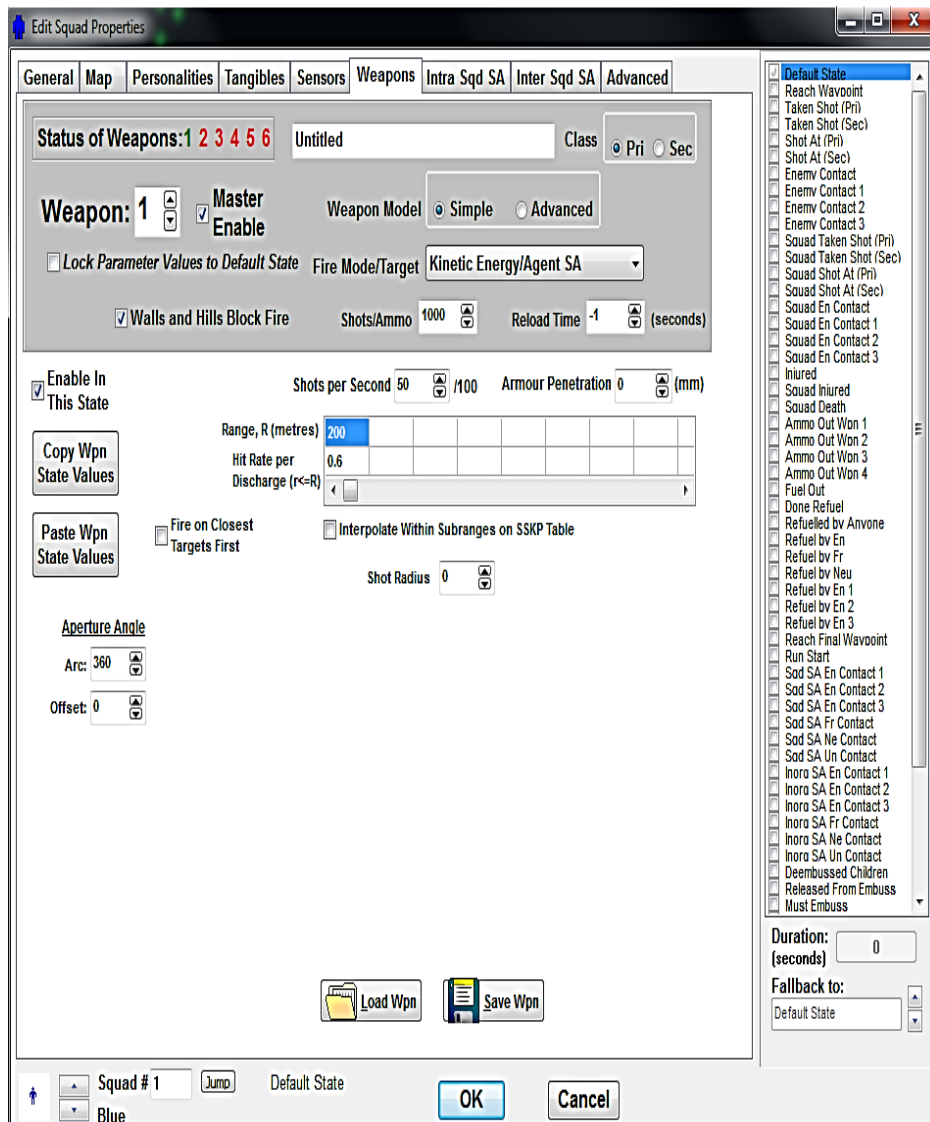
Figure 14.   Weapons Tab.

g.   *Trigger State*

For a base MANA scenario, all the characteristics and behavior of squad/agents are first defined for each squad's default state (McIntosh, 2007). For a simple scenario, this is all that may be required. But, for more complex scenarios, there may be a situation which warrants the behavior of an agent to change when certain conditions are fulfilled. For example, a squad may only be on a surveillance mission and is not allowed to fire on enemy agents until fired upon. In such situations, *trigger states* play a vital role. The user can also specify if an agent is forced into a *trigger state*, how long it will remain in the new state, and whether the agent will stay there, or return to its *default state* or any other new state. Figure 15 shows some of the *trigger states* available in MANA.
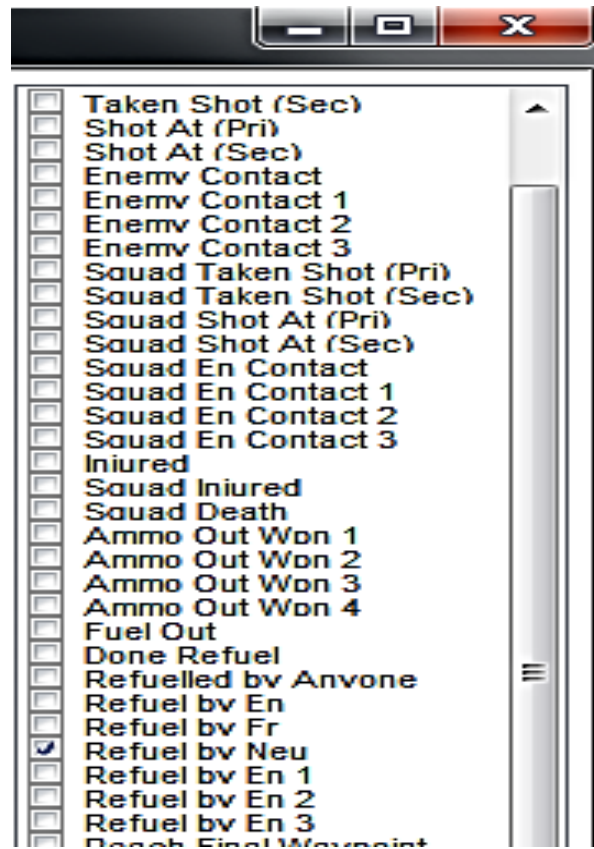
Figure 15.   A Portion of the *Trigger States* Available to Agents in MANA.

h.   *Inter Squad SA/Intra Squad SA*

There are two situational awareness (SA) tabs, which are used to define communication within the squad as well as between different squads. The *Intra Squad SA* controls the flow of the situational awareness within a squad and does not vary with the trigger states; all of the agents in the simulation retain their original parameters. *The Inter Squad SA* controls the flow of situational awareness between different squads (McIntosh, 2007).

i.   *Fuel*

Fuel capacity and consumption can be defined for each agent. Fuel can be used to represent a variety of quantities in study (food, batteries, endurance, etc.) and does not necessarily have to represent literal fuel. "Fuel" exchange can be used as a creative and symbolic interaction that might, for example, be used to trigger a state change. Examples of the creative use of fuel as given by the MANA manual are:

- Recording accumulation of some trait such as courage, fatigue or discontent

- Recording interactions with other agents, such as getting "close enough" to trigger a change

- Modeling the logistic supply for some commodity

F.   ASSUMPTIONS AND LIMITATION OF MODELING IN MANA

No software model can capture reality one hundred percent. Every model has its own unique limitations, and additionally, the user must also make certain assumptions while creating the scenario. The following are important limitations and assumptions with regard to the MANA model developed for this thesis:

- When the sentry weapon probability of hit was varied as an input factor for the design of experiments, the probability of hit for all sentry weapons were changed together (lock-stepped) for one simulation run. In reality, different sentries will have different probabilities of hit.

- In the MANA scenario, sentries are always alert and they start firing without any delay as soon as they become aware of a classified enemy. Also, as soon as a Red boat crosses the exclusion zone, sentries start firing

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simultaneously. In an actual scenario, there may be a delay of few seconds and that too will vary from sentry to sentry. Some may have a delay of one second and some may have a delay of three seconds or even more.

- In MANA weapons always fire. In reality, weapons may misfire.

- In MANA, sensors either make a detection, or a classification, or neither. It is not possible to make an incorrect classification (for example, incorrectly classifying an enemy as a neutral or friend).

- Battle damage assessment is instantaneous, and sentries never assess wrong. If Blue kills Red, he instantly knows it, and stops firing.

- There is no coordinated targeting amongst Blue sentries. Blue sentries independently decide to fire or not, and do not take into consideration who the other sentries are firing at. Thus, two or more sentries may fire upon the same Red boat at the same time. This may or may not be desirable. It is an option, however, for one squad to have the "fire on closest targets" property activated, while another does not.

- In this scenario, the fire rate, magazine size, and lethality of all weapons is the same. In reality, there may be variation in these.

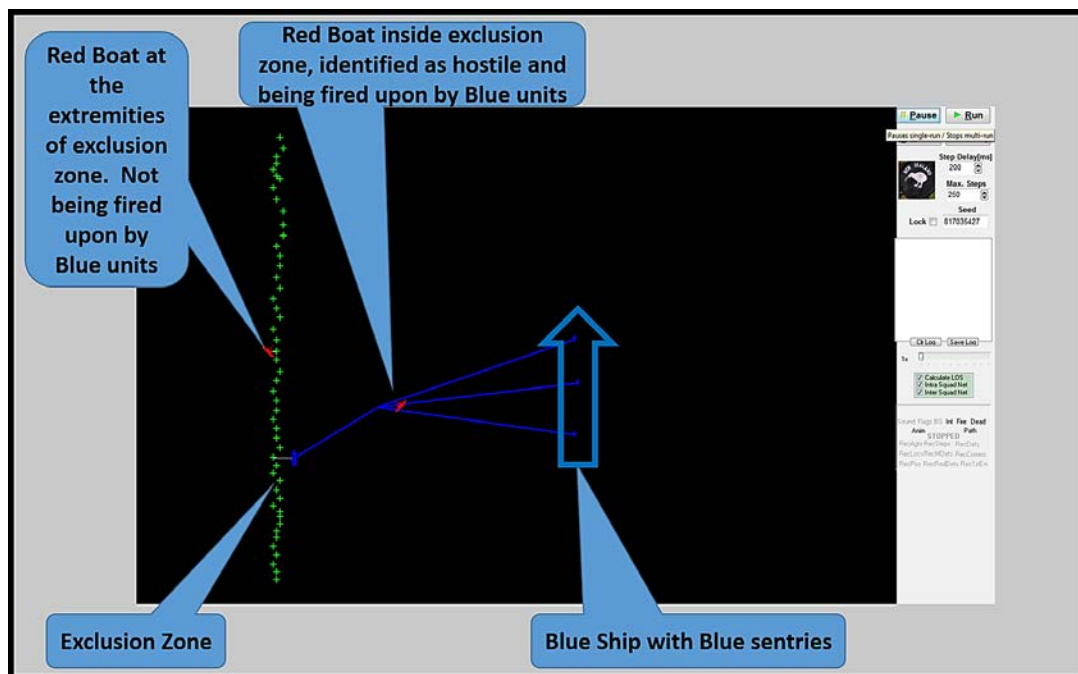An annotated picture of MANA scenario is depicted in Figure 16.

Figure 16.   Annotated Snapshot of the MANA Battle Scenario.

IV. DESIGN OF EXPERIMENTS

> The more accurate the map, the more it resembles the territory. The most accurate map possible would be the territory, and thus would be perfectly accurate and perfectly useless.
>
> —Neil Gaiman, *American Gods*

"One of the first things an experimenter or tester must do to design a good experiment is identify the experimental factors" (Sanchez & Wan, 2009, p. 61). In any process different factors may have a significant effect on that process and its output. These factors and their levels are used to determine the design for a particular experiment. A general way of exploring a process is to vary factors one at a time and observe how it affects the output of that process. However, it is not efficient or effective to vary factors one at a time. Factors may have an interaction between them, which means their effect on the output depends on the value of another factor, and without simultaneously varying the factors, their interactions can never be identified. Through design of experiments, the relationship between the input factors and output measure (response) can be explored in a systematic and effective way. According to Sanchez & Wan (2009), "if you are interested in exploring the behavior of a simulation model with more than a handful of input factors, efficient experimental designs are readily available—and much more powerful—than a petaflop supercomputer" (Sanchez & Wan, 2009, p. 73).

A. NEARLY ORTHOGONAL LATIN HYPERCUBE (NOLH)

A very efficient proven way to design experiments is through the use of the Latin Hypercube (LHs). According to Sanchez & Wan (2009), "Latin hypercube designs provide a flexible way of constructing efficient designs for many quantitative factors. LHs have the appealing space-filling properties of factorial designs with fine grids, but require orders of magnitude less sampling" (p. 68). LH designs are very effective because of their efficiency, space-filling properties, and analysis flexibility.

In comparison to gridded designs, Nearly Orthogonal Latin Hypercubes (NOLHs) are very effective and provide better coverage. Efficient NOLH designs were constructed by Lucas and Cioppa in 2007 (Lucas & Cioppa, 2007). For modest numbers of factors, efficient NOLH designs have excellent space-filling and orthogonality properties. Despite their usefulness, Latin hypercubes are sometimes plagued with unacceptable correlation among input variables. Hernandez, Lucas, and Carlyle (2012) expanded the set of readily available NOLHs. They developed a mixed integer programming algorithm capable of generating Latin hypercubes with little or no correlation, thereby overcoming the problem of correlation among input variables (Hernandez, Lucas, & Carlyle, 2012). Near orthogonality in Latin hypercubes guarantees that the factors are not confounded; and space-filling guarantees that there are no large gaps in the exploration. Just to give an example: if we want to explore a model with four factors and each factor has two levels, then there will be $2^4 = 16$ design points in a full factorial (all possible combinations) design. Alternatively, we can explore those four factors, each at more than two levels, using a catalogued NOLH design freely available via an Excel workbook that can be downloaded from https://harvest.nps.edu. The NOLH will give far better coverage and we can add up to three more factors without any additional sampling, and this can be accomplished with only 17 design points, only one more than the 16 design points required for the 2-level full factorial gridded design (see Figure 17 for a comparison).
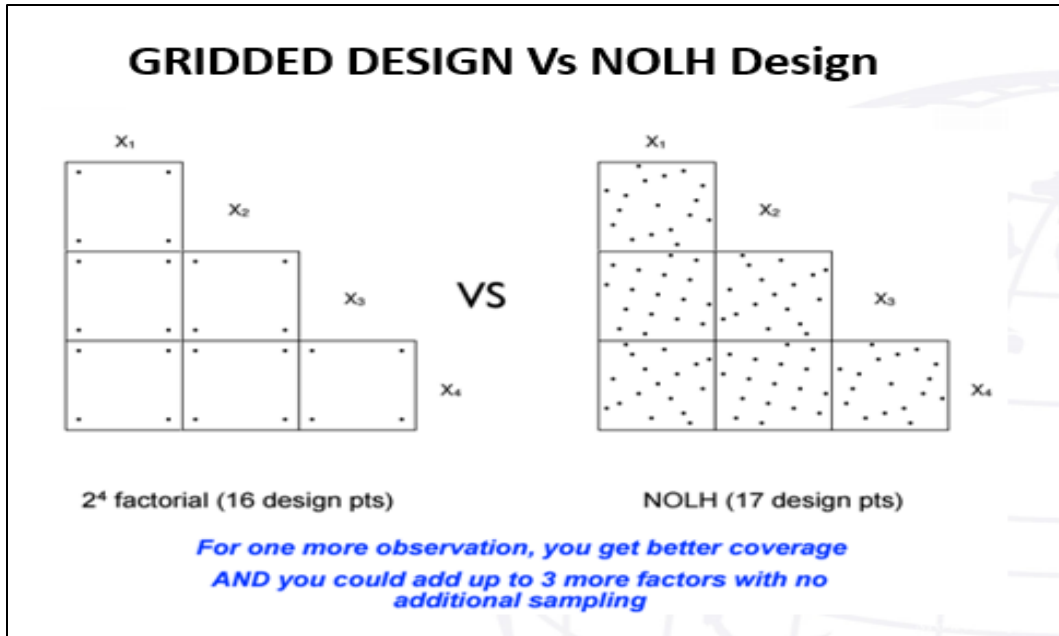
Adapted from class notes in OA-4333, Simulation Analysis.

Figure 17.   Comparison of Gridded Design and NOLH.

B.   EXPERIMENT FACTORS

Based on our knowledge of the scenario and analysis goals, we vary the following factors in the DOE:

- Probability of hit by Blue sentries

- Number of Blue sentries

- Number of Blue patrol boats

- Blue sentry weapons configuration

- Width of exclusion zone

- Number of Red boats

- Speed of Red boats after they enter the exclusion zone

- Number of shots Red boats takes before being neutralized

The ranges and levels for these factors are given in Tables 4, 5, and 6. Table 4 lists the three weapon options available for the Blue sentries.

Table 4.   Blue Sentry Weapon Options.

Weapon Type	ROF (Rounds per minute)	Magazine Capacity
W1 (7.62mm gun)	500	20
W2 (7.62mm Machine Gun)	1100	250
W3 (12.7mm)	600	70

Table 5 gives the set of eight cases (options) for how the three Blue sentries are equipped with weapons.

Table 5.   Possible Blue Sentry Weapons Configuration.

Sentry 1	Sentry 2	Sentry 3
W1	W2	W1
W1	W2	--- (no weapon)
W1	W3	--- (no weapon)
W1	W2	W2
W1	W3	W1
W1	W3	W3
W1	W2	W3
W3	W2	W3

Another important factor is the availability of a Blue patrol boat, so the two different levels for Blue patrol boat are zero and one, where one indicates that a boat is protecting the exclusion zone and zero indicates no Blue patrol boat. Besides the Weapon Configuration and Patrol Boat factors, the following six factors, in Table 6, were varied. These 6 total factors were explored using a 257 design point NOLH.

Table 6.   The Other Six Factors with Ranges.

No	Variable	Min Value	Max Value
1	Probability of hit	0.2	0.8
2	Number of sentries (on ship)	2	3
3	Number of Red boats	1	2
4	Speed of Red boat after it the enters exclusion zone	8	22
5	Exclusion zone width (in steps of 10)	40	90
6	Number of shots taken by Red boats before they are disabled	1	25

The 257 design points NOLH for the above six factors gave a maximum absolute pairwise correlation of 0.058, which is only slightly above the desired target of .05, due to rounding for discrete factors. Figure 18 displays the pairwise correlations and pairwise scatter plots for the six factors.

Figure 18.   Pairwise Correlation between 257 Design Points NOLH
for 6 Factors.

These 257 design points were then crossed with a full factorial for the eight levels of Blue sentry weapon configuration and the two levels for number of Blue patrol boats. This yielded a total of 4,112 final design points (8×2×257 = 4,112) for our experiment. These 4,112 design points represent 4,112 different simulated conditions of an attack on a ship when it is berthed at harbor. Since MANA is stochastic, each of the design points was

replicated 100 times. The experiment was run on the Simulation Experiments and Efficient Designs (SEED) high performance cluster. With 160 available processors, the 411,200 total runs were accomplished overnight. The SEED Center has also written a data postprocessor that gathers the MANA output data from the individual runs and places them into one file, together with the factor settings, facilitating easy loading and analysis into a statistical tool of choice, such as Excel or JMP.

V. ANALYSIS OF DATA

This chapter uses statistical methods to analyze the data generated from the experiment discussed in the previous chapter. For the analysis, the JMP statistical package was the primary tool used (see www.jmp.com). We begin with an initial assessment of the data and move to a more detailed analysis using a variety of statistical methods. The primary output metric, our measure of effectiveness, is the probability Red is able to achieve its goal of reaching the ship. The objective is to determine the relationship between the input factors and the probability of the Red force achieving its goal. To quantify this relationship, linear regression and partition tree techniques were applied. Histograms and other plots were also used to explore the probability that the Red force is able to achieve its goal as a function of the input conditions.

A. INITIAL ASSESSMENT OF DATA

After the completion of the simulation runs, the MANA output was obtained in the form of a csv file, which contained 30 output columns and 411,200 rows—with one row for each of the 411,200 simulated attacks on a Blue ship by one or two Red boats. A snapshot of a portion of the output file is shown in Figure 19

Identifier	ProbHit	RedBoatS	RedBtHits	WpnCase	NumBlue!	NumBluel	Exclusion	NumRedB	Run	Seed	Alleg1Cas	Alleg2Cas	Alleg0Cas	Blue Reac	Red Reach	Neutral R	Steps
I0E0	0.44	20	15	1	3	0	70	2	1	3.14E+08	0	0	0	No	Yes	No	49
I0E0	0.44	20	15	1	3	0	70	2	2	5.96E+08	0	0	0	No	Yes	No	34
I0E0	0.44	20	15	1	3	0	70	2	3	-1.1E+08	0	0	0	No	Yes	No	31
I0E0	0.44	20	15	1	3	0	70	2	4	1.63E+09	0	0	0	No	Yes	No	48
I0E0	0.44	20	15	1	3	0	70	2	5	64128166	0	0	0	No	Yes	No	55
I0E0	0.44	20	15	1	3	0	70	2	6	1.56E+09	0	0	0	No	Yes	No	57
I0E0	0.44	20	15	1	3	0	70	2	7	-5.7E+08	0	0	0	No	Yes	No	36
I0E0	0.44	20	15	1	3	0	70	2	8	5.87E+08	0	0	0	No	Yes	No	37

Figure 19.   Snapshot of Output File Obtained after Simulation Runs.

Out of these 30 MANA columns in the obtained csv file, only nine columns are of importance for our analysis. Eight of the columns are the input factors and one column is our response—a binary variable for whether or not Red achieved its goal. All of the rows of data for these nine columns were placed in a separate file for analysis. This file was

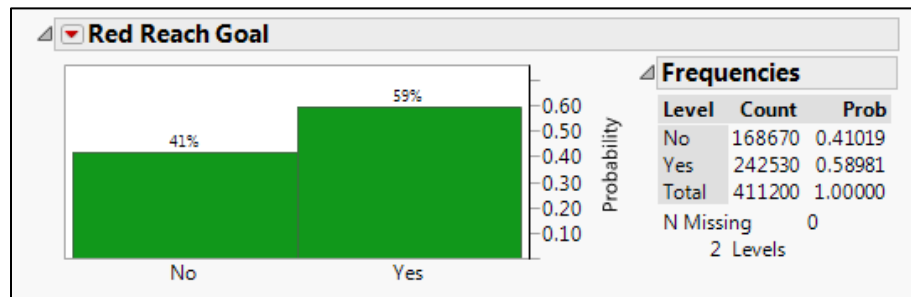then imported into JMP. A histogram of "Red Reach Goal" across all 411,200 runs is given in Figure 20.

Figure 20.   Overall Distribution of "Red Achieves its Goal."

The overall distribution of Red success indicates that Red forces were successful approximately 59% of the time and Blue was able to stop Red 41% of the time. The estimated standard error associated with 411,200 samples of independent Bernoulli random variables with a success probability of .59 is 0.00077. However, it should be noted that this histogram was obtained across all of simulated attacks and all of the input combinations. We can view this histogram by one or more factor combinations. In Figure 21 we examine the histogram by the number of Red boats, one on the left and two on the right.
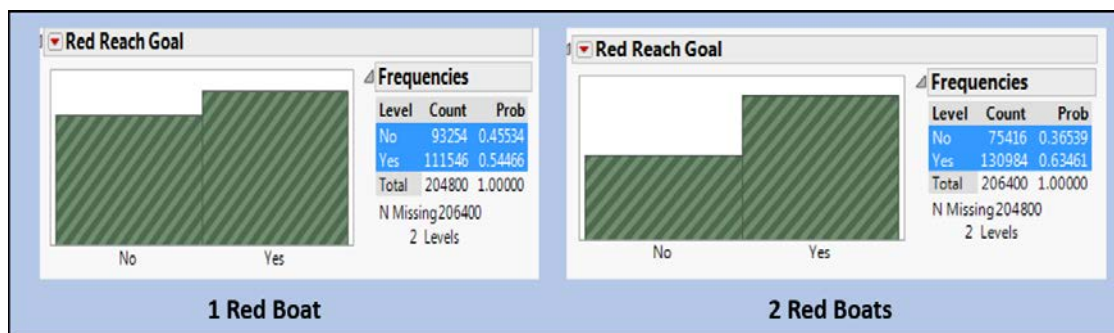

Figure 21.   Distribution of "Red Achieves its Goal" versus
Number of Red Boats.

From Figure 21, we can see that in the situations in which there were two Red boats, Red is able to achieve its goal 63% of time, as compared to 54% of time when the attack was carried out using one Red boat. The estimated standard error associated with samples of data when there is one red boat is 0.0011 and when there are two Red boats is 0.00105. That is, over all the input combinations, if Red attacks using two boats, then Blue has 9% less chance of being successful in stopping the terrorist attack. The bar chart in Figure 22 illustrates the comparison of success rate for Blue.
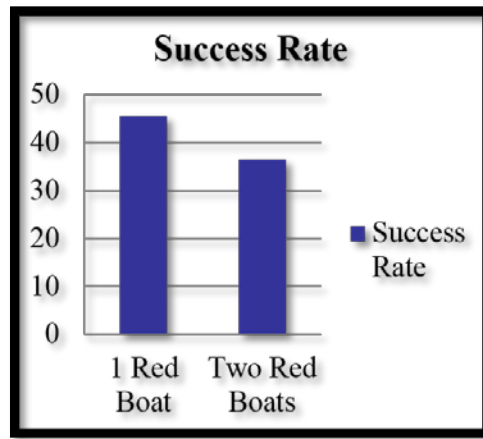

Figure 22.   Success Rate for Blue Sentries by Number of Red Boats.

B.   INFLUENTIAL FACTORS IN MODEL

One of our goals is to identify the most influential experiment factors, in order to gain some insight into improving the effectiveness of the Blue force against a terrorist boat attack. One method for exploring the relationship between the response and the experiment factors is the partition tree.

1.   Partition Tree

A partition tree is a useful, nonparametric technique used to explore the effect of multiple factors on an output measure. The output can be categorical or continuous. Partition trees, being nonparametric, do not make any assumptions about the distributions of the underlying data. They additionally have the nice features of being able to easily handle large data sets, as well as provide a result that is deemed by many non-technically

trained decision makers as both intuitive and interpretable. JMP statistical discovery software defines partition trees as:

> The partition platform recursively partitions data according to a relationship between the *X* and *Y* values, creating a tree of partitions. It finds a set of cuts or groupings of *X* values that best predict a *Y* value. It does this by exhaustively searching all possible cuts or groupings. These splits (or partitions) of the data are done recursively forming a tree of decision rules until the desired fit is reached. This is a powerful platform, because it chooses the optimum splits from a large number of possible splits. ("Partition Models," n.d.)

The result of applying the partition tree technique to our data is given in Figure 23. The response is Red's ability to achieve its goal.
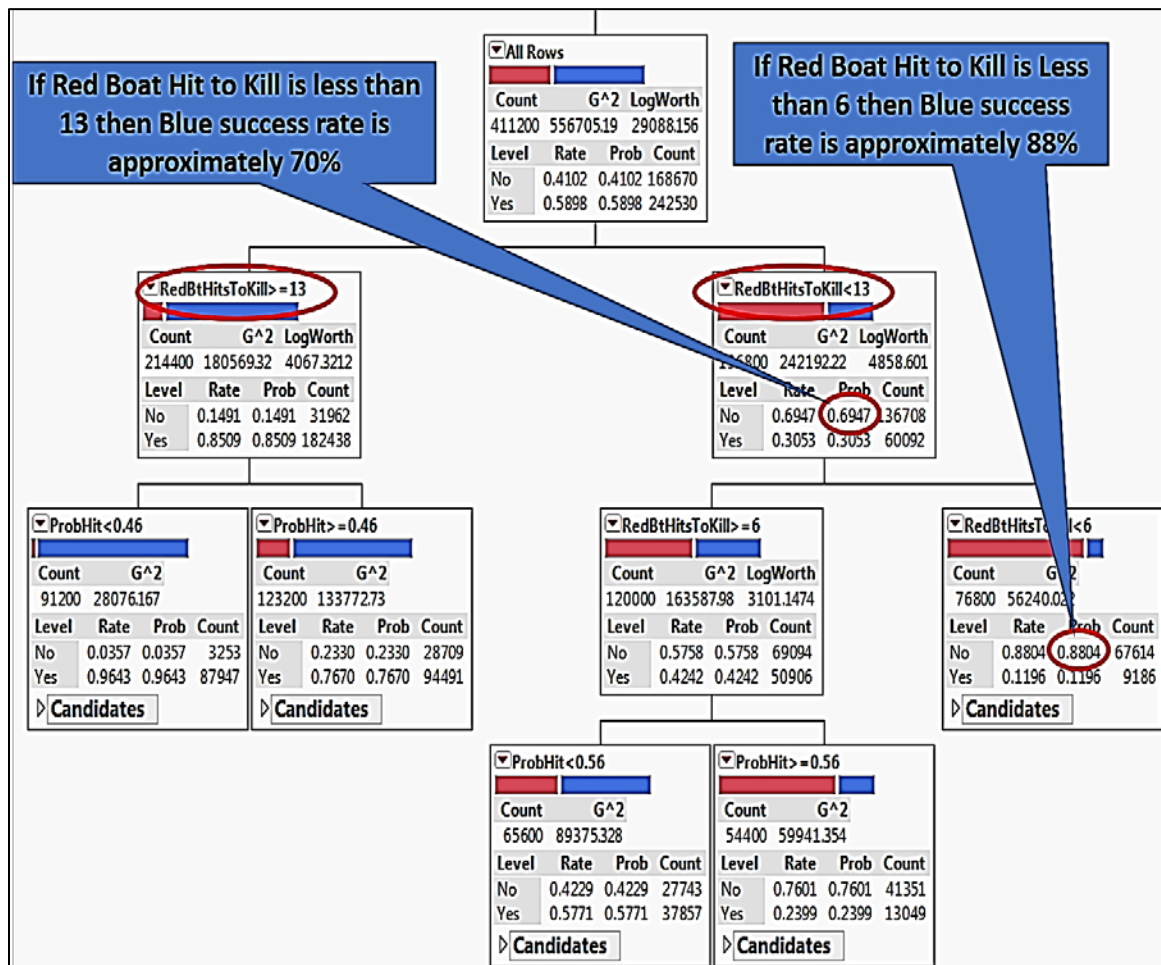

Figure 23.   Partition Tree Indicating Critical Factors of the Model.

The response variable selected for partition is "Red achieves its Goal," and all input factors were fed to the model. The goal of the analysis is to determine which factors have the maximum impact on the response variable. We see that the first split occurs on number of hits on Red boat to kill, which makes it an important factor. Red boats hits to kill are defined as the number of shots fired by Blue agents to neutralize Red boat. This depends on the lethality of Blue weapons and the staying power of Red. Since Blue cannot control the staying power of Red, Blue weapon lethality has the most significant effect of the controllable factors on the ability to stop a terrorist attack. The next split, in each group, further defines the next most important factor in each respective group. In the split performed on the "Red Hits to Kill < 13" category on the right, we see again that we split on Red boat hits to kill. This suggests a nonlinear relationship between the probability of Red success and number of shots fired by Blue to neutralize Red boats—and that this single factor dominates. In subsequent splits, the probability of hit by Blue sentries plays an important factor. Probability of hit is the probability that Blue sentries will hit the Red boat per shot. So we can conclude that lethality followed by probability of hit of Blue weapons (i.e., accuracy) are the two most critical factors in defeating Red suicide boat attacks.

2.   Analysis of Summarized Data

An alternative to analyzing the full data set with 411,200 rows, is to summarize each of the 4,112 designs points by their mean and standard deviation. We then look to fit metamodels to the means of the design points, in order to achieve higher *R*-square values. For this approach, two new binary columns were created. The "Red Reaches Goal" column was originally in the form of "Yes" and "No," and this was converted to binary numerical form, where one indicates "Yes" and zero indicates "No." The complement of this column is "Blue success," which was also converted to a numerical binary form. A snapshot of the new data file obtained is depicted in Figure 24.

Figure 24.   Data Sheet Generated after Creation of Two New Columns in Binary Form.

For each of the 4,112 design points, the sample mean and standard deviation of Red success and Blue success were calculated. This gives us 4,112 estimates of the probability of Red and Blue success, an estimate for each of the design's input combinations. A snapshot of the new data file generated is shown in Figure 25.

Figure 25.   Data Sheet Created after Collapsing (Summarizing) Data.

Histograms and summary statistics for Mean(Red Success) and Mean(Blue Success) are given in Figure 26. Note that the histograms are reflections of each other. That is, if Red is successful, then Blue is not. It is worth noting that Red's empirical probability of success ranges from zero to one over the 4,112 design points. So, we have induced a good deal of variability with our experiment, useful for evaluating the impact of the factors.

Mean(Red Success)		
Quantiles		
100.0% maximum	1	
99.5%	1	
97.5%	1	
90.0%	1	
75.0% quartile	0.99	
50.0% median	0.72	
25.0% quartile	0.14	
10.0%	0.03	
2.5%	0.01	
0.5%	0	
0.0% minimum	0	

Summary Statistics	
Mean	0.5898103
Std Dev	0.3937203
Std Err Mean	0.0061399
Upper 95% Mean	0.6018478
Lower 95% Mean	0.5777728
N	4112

Mean(Blue Success)		
Quantiles		
100.0% maximum	1	
99.5%	1	
97.5%	0.99	
90.0%	0.97	
75.0% quartile	0.86	
50.0% median	0.28	
25.0% quartile	0.01	
10.0%	0	
2.5%	0	
0.5%	0	
0.0% minimum	0	

Summary Statistics	
Mean	0.4101897
Std Dev	0.3937203
Std Err Mean	0.0061399
Upper 95% Mean	0.4222272
Lower 95% Mean	0.3981522
N	4112

Figure 26.   Histograms and Summary Statistics for Mean Blue and Red Success.

We can see that after collapsing the data, we obtain a partition tree very similar to the one produced using the full data set. The insights as to the critical factors and breaks are nearly identical. Figure 27 depicts the partition tree generated from the collapsed data.
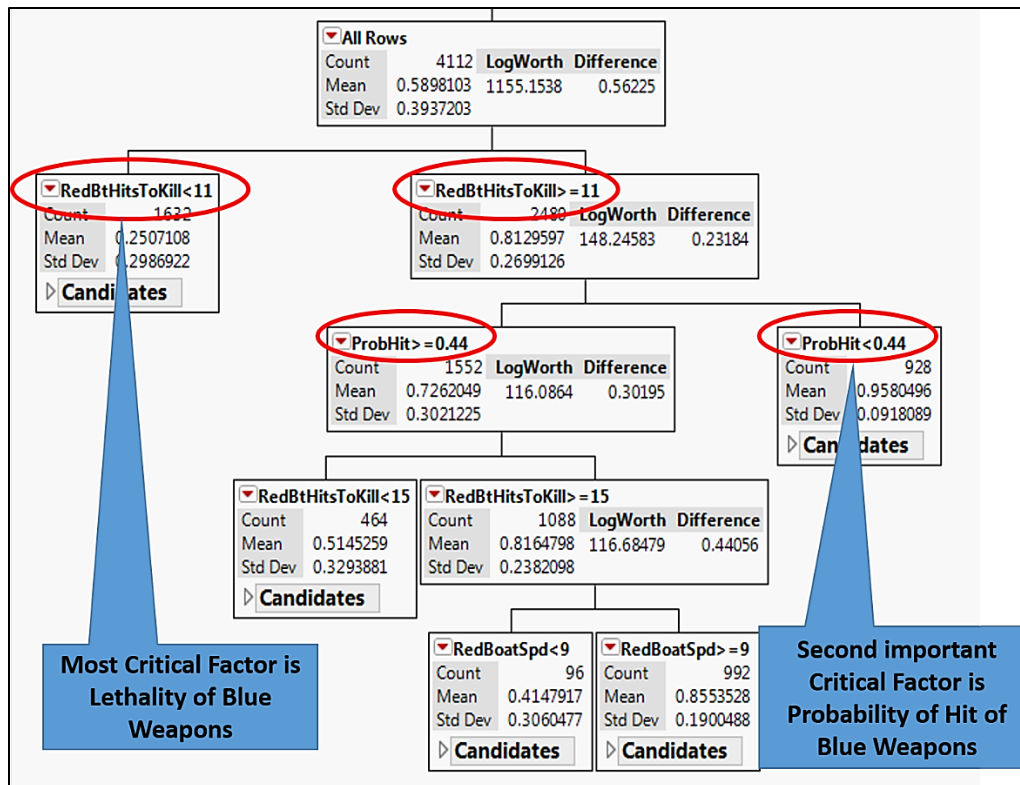
Figure 27.   Partition Tree of Collapsed Data for Red Success.

The partition tree indicates that Red boat hits to kill (i.e., Blue lethality and Red staying power) is again the most important factor. While the most critical factor obtained by the partition tree after collapsing the data against design points was the same, the "Red boats hit to kill" split is now reduced from 13 to 11—and we get a much better R square value, i.e., 0.651 after 5 splits against 0.355 in the previous case. It is also worth noting that the Red boat speed appears in this partition tree—with faster boats more successful, as expected.

C. LOGISTIC FIT OF DATA

In order to check the individual effects of input factors on the probability of Red success, a logistic regression fit for all input factors, one at a time, was carried out. Since this approach does not consider interactions between the input factors, we complement this technique with use of stepwise regression in the next section. Figure 28 shows the logistic fit of the different input factors against the response.
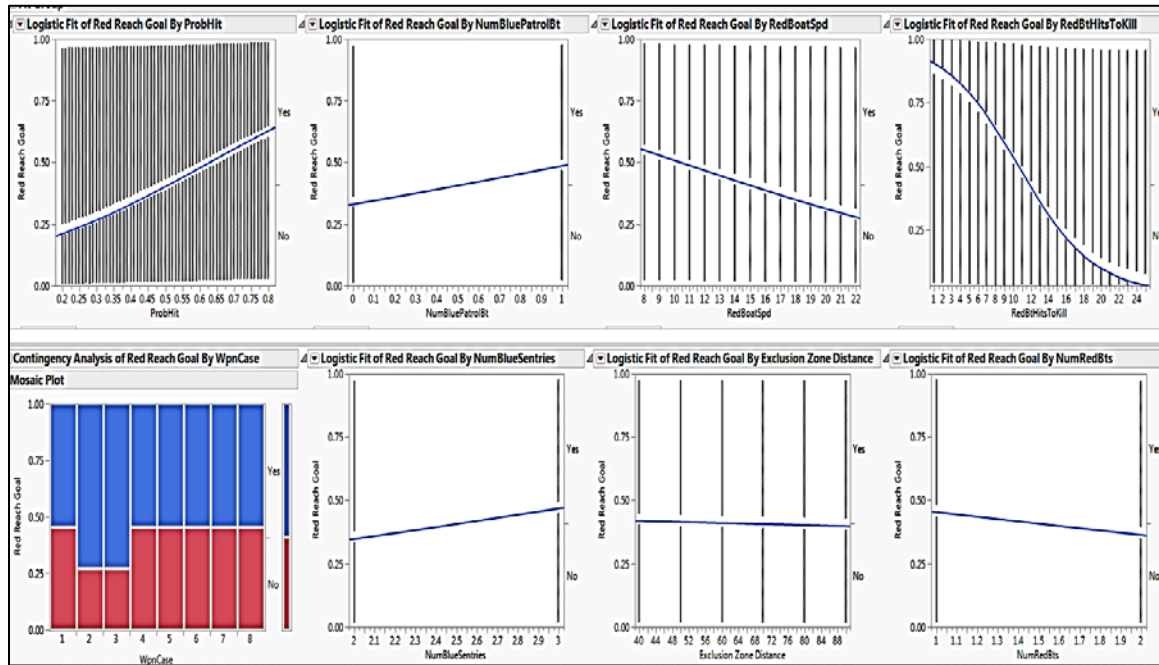
Figure 28.   Logistic Fit of the Response against Different Input Variables.

Here we can see that most variation comes from "Red boats hit to kill" or number of shots fired by Blue to kill Red boat and probability of hit by Blue weapons. While not as significant, we also see that Blue does better with more sentries and a patrol boat. Red does better with two boats and greater attack speed. Weapon cases two and three were associated with higher Red success, as compared to the other weapon cases. Although, some labels in Figure 28 are not clearly visible, they appear clear in subsequent figures. Figure 29 gives the whole model test for a logistic fit of Red Reaches Goal by probability of hit of Blue weapons and number of Blue patrol boats.
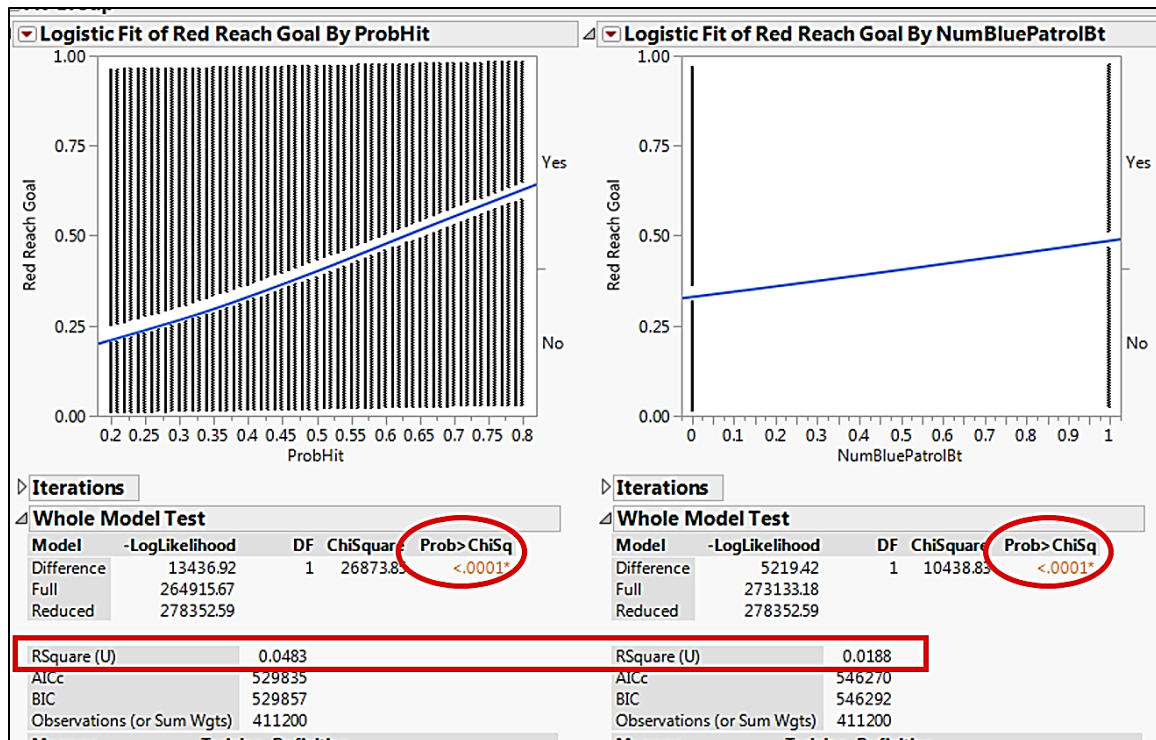
Figure 29.   Logistic Fit of Red Success by Probability of Hit and Number
of Blue Patrol Boats.

Here we can see that the probability of hit and number of Blue patrol boats are both significant factors as indicated by their respective *p*-values. The observation is consistent with our previous findings. The logistic fit graphs show that probability of hit is more impactful on the outcome than number of blue boats. This finding is also evident from the *R*-square values, where bigger *R*-square values imply that the corresponding factor explains more of the variability in the outcome. From Figure 29, we observe that *R*-square values are low, but we have to keep in mind that these are one factor at a time fits (while the other factors are changing in the "background"). The whole model test of logistic fit for Red success against Red boat speed and shots required by Blue to neutralize Red boats is given in Figure 30.
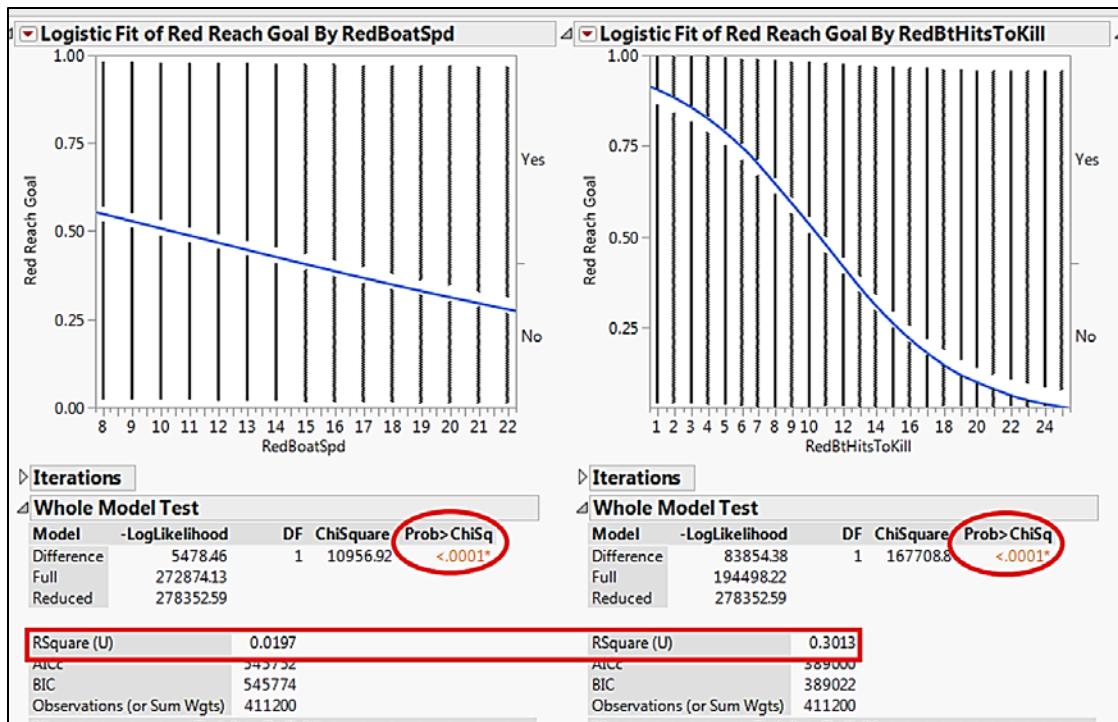
Figure 30.   Logistic Fit of Red Success by Red Boat Speed and Red Boat
Hits to Kill.

Here we can clearly see that most prominent factor, which has the biggest effect on output, is Red boats hit to kill, i.e., the lethality of Blue weapons against the target—as it causes the biggest change. The p-value also indicates its significance, and we can also see that it has an R-square value of 0.3013, far bigger than other input factors. The other factor, Red boats speed is also significant, as indicated by the p-value, but it has a low R-square value, indicating that it has a lower effect on Red success as compared to lethality of Blue weapons. The logistic fit for weapon configuration case and number of Blue sentries is given in Figure 31.

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Figure 31.   Logistic Fit of Red Success by Weapon Case and Number of
Blue Sentries.

The *p*-values of both factors indicate these are significant factors. In the case of logistic fit of Red success by number of Blue sentries, we do not observe much change. In the weapon case, we see that all weapon cases have approximately the same effect on Red success except for weapon cases two and three. Weapon cases two and three have two weapons only, as compared to th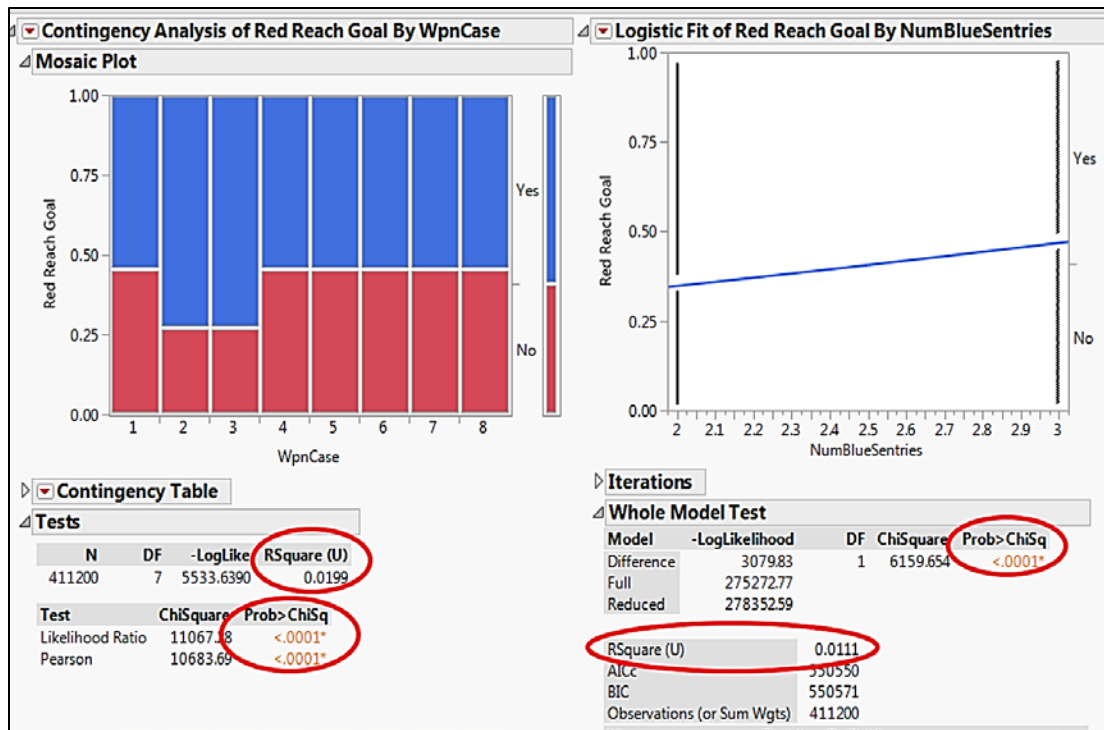ree weapons by Blue sentries in all other cases, so this result makes sense. Two weapons reduces the number of shots received by Red, hence increasing the probability of Red success. Now the question is, why do all other weapons have the same effect on Red success, despite these weapons cases corresponds to different weapons combination with Blue sentries? After further analysis it was revealed that this is a limitation of our model. In an actual scenario, the type of weapons of Blue sentries determines the number of shots Red takes before it sinks, but in our model we have defined hits to kill as a separate input factor. In MANA we cannot directly define that when a sentry is using a particular type of weapon, then the Red boat will have a particular staying power. Therefore, weapon case is not significant in defining

the staying power of Red boat, but it is important for determining the combined rate of fire (ROF) by Blue sentries. The logistic fit of Red success for exclusion zone distance and number of attacking Red boats is given in Figure 32.
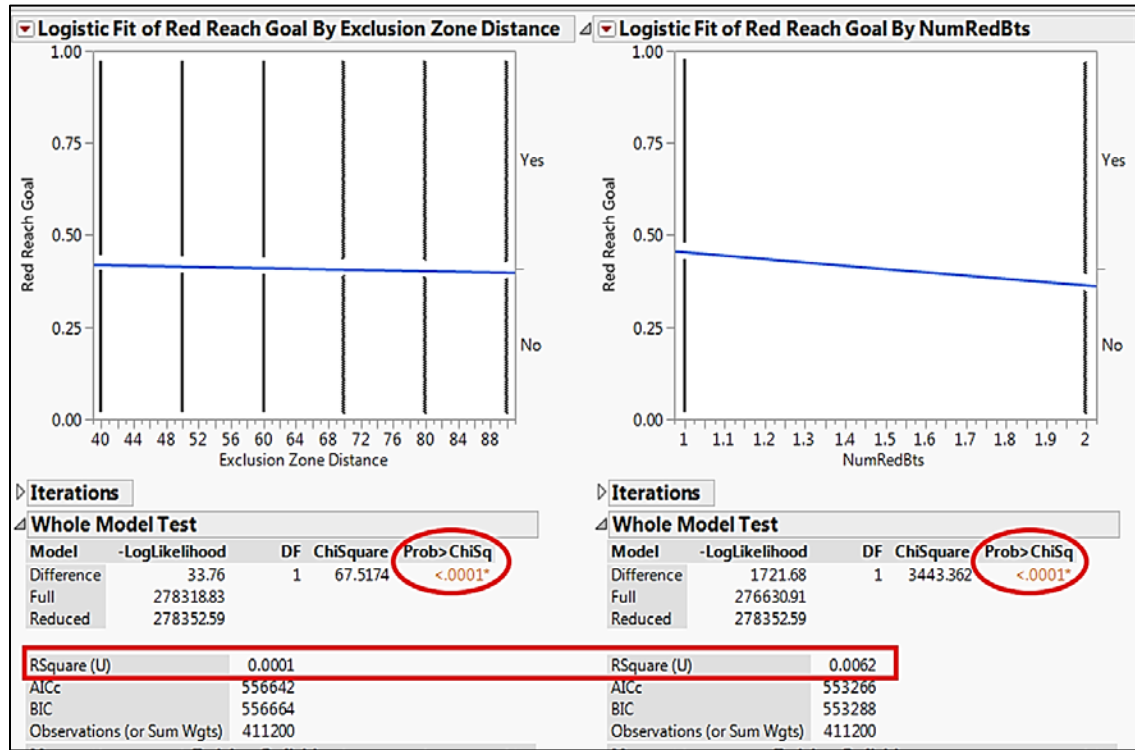
Figure 32.   Logistic Fit of Red Success by Exclusion Zone Distance and Number of Red Boats.

We see that both factors have very low *p-values*, thereby indicating that these are significant factors. The number of Red boats has an intuitive effect on the outcome, although not very pronounced. Out of these factors, we see that the exclusion zone distance also has minimal effect, which is counter intuitive, so this aspect was further explored by keeping all other factors as constant and running the MANA simulation for different exclusion zone distances.

D. EXPLORING THE EFFECT OF EXCLUSION ZONE DISTANCE ON RED SUCCESS

Sometimes during an exploration of complicated simulations with many variables, the effects of one or more factors are masked by other dominant factors. In order to explore whether exclusion zone distance was dominated by other factors, we did a one factor experiment on our scenario while keeping all the other factors constant. In the basic scenario file of MANA, all input factors were fixed except the factor, "Exclusion Zone Distance," as shown in Table 7.

Table 7.   Factors Used in Scenario for Exploring the Effect of Exclusion Zone Distance on Red Success.

No	Input Factor	Fixed Value in Scenario
1.	Probability of Hit	0.4
2.	Red Boat Speed	15
3.	Weapon Case	8
4.	Number of Blue Sentries	3
5.	Number of Red Boats	2
6.	Number of Blue Patrol Boat	1
7.	Red Boat Hit to Kill (Staying Power)	25
8.	Exclusion Zone Distance	Varied for Exploration

After fixing the input factors as per Table 7, hundred simulations were run for each scenario and the data was obtained. The output result of each simulation was placed in Table 8.

Table 8.   Mean Probability of Red Success against Exclusion Zone Distance
while Keeping Other Inputs Constant.

Serial Number	Exclusion Zone Distance	Mean Probability (Red Success)	Estimated Standard Errors
1	40	0.31	0.046249
2	50	0.13	0.03363
3	60	0.05	0.021794
4	70	0.03	0.017059
5	80	0.02	0.014
6	90	0.01	0.00995

Table 8 is displayed graphically in Figure 33.
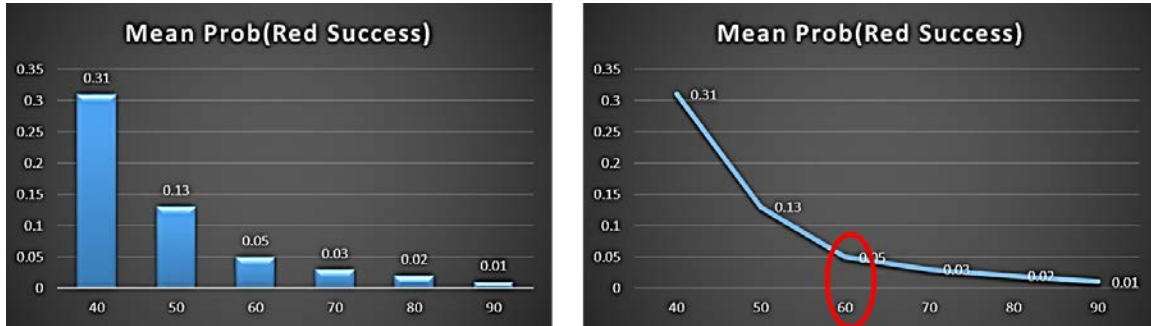
Figure 33.   Probability of Red Success against Varying
Exclusion Zone Distance.

It can be seen that, as exclusion zone distance increases from 40 to 60 meters the probability of Red success decreases sharply, but after 60 meters there is not much difference. The knee of curve lies at about 60 meters, indicating that a 60 meter exclusion zone may be taken as an acceptable distance to protect the Blue ship.

E.   REGRESSION ANALYSIS

Out of many important applications of statistics, one is regression analysis. It is the process of estimating (predicting) the mean value of a response variable y, based on knowledge of related independent variables x (Mendenhall & Sincich, 2007). When we perform regression analysis, there may be a large number of potentially important independent variables, with associated main effects and interactions. A popular objective

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method of building a parsimonious model with only the most important independent variables and building a model is called **stepwise regression analysis** (Mendenhall & Sincich, 2007).

It is important to note that with binary responses the basic assumptions for linear regression are not met. Specifically, the errors will not be normally distributed with a constant variance. Moreover, the response must be restricted to between zero and one, while the regression equation may make predictions outside of this region at the extremes. However, we are using the regression for descriptive purposes, i.e., to provide insight into the relationship between the input factors and our response (Kleijnen et al. 2005). Ideally, we will produce readily interpretable relationships between the input variables and the response. As noted by Hellevik (2009), "the intuitively meaningful interpretation [of linear regression] makes it easier to communicate research results [than logistic regression]." Of course, since the errors are not normally distributed, or even continuous, the p-values do not have a precise interpretation. Nonetheless, the p-values are functions of the sums of squares explained by the variables, and smaller p-values indicate more significance for the terms.

While not optimal in terms of power, the regression coefficient estimates are unbiased. Furthermore, given our large sample and high R-square value, optimal power is not a critical issue. For more discussion on this common practice, see Hellevik (2009).

Stepwise regression was performed on the data collapsed across design points to explore the relationships between different input factors on the probability of Red success. The response variable is the probability of Red boat survival. The purpose of regression is to find a mathematical model that estimates the success rate of Blue or Red forces based on different input factors. Figure 34 displays the final regression model that was obtained.
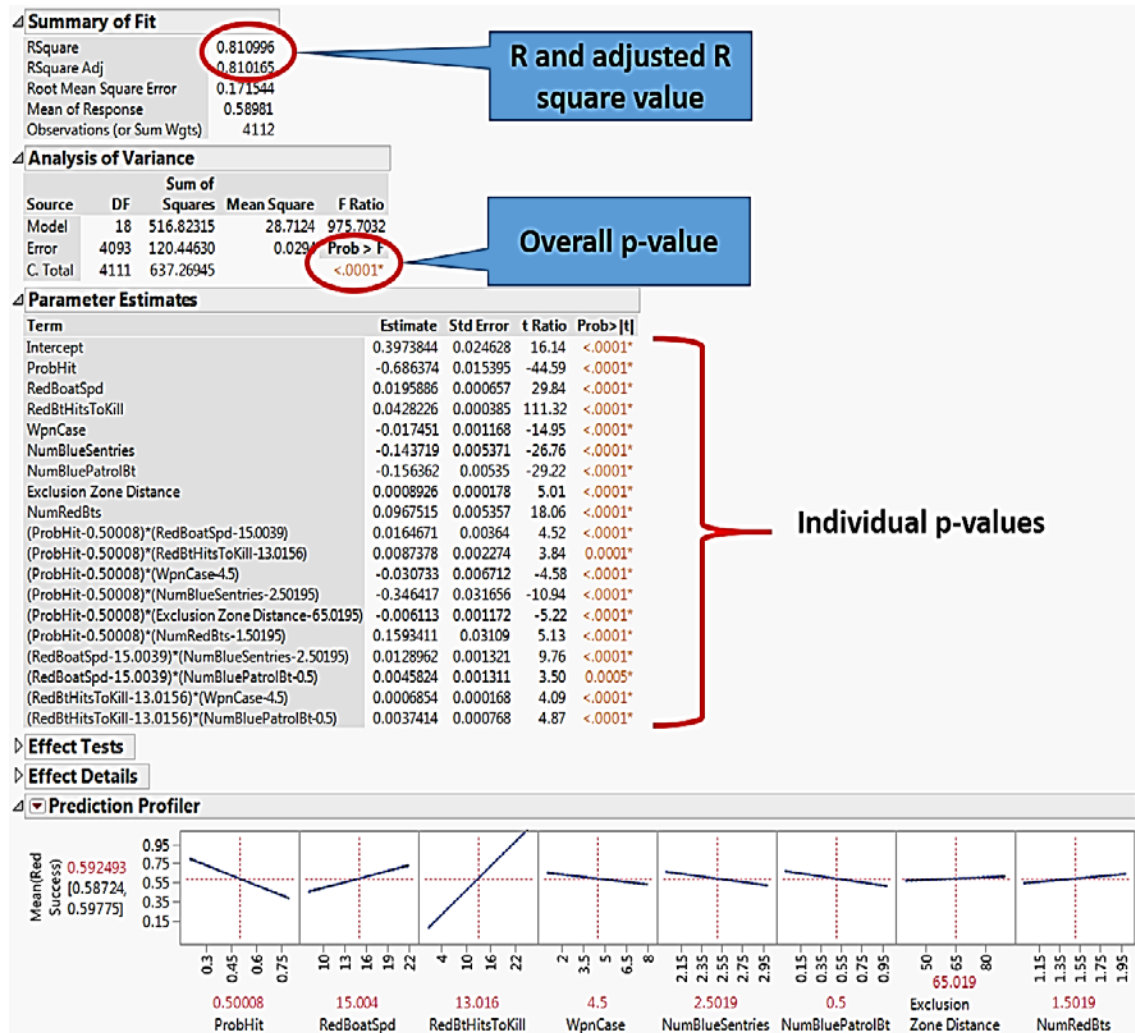
Figure 34.   Regression Model with All Input Factors.

The *R square* and adjusted *R square* values are very high, indicating that the regression model is capturing over 80% of the variability of the simulation model. The maximum value of *t ratio* is 111.32, for hits to kill Red boats. A large *t-ratio* indicates the significance of the corresponding factor—though the lack of normality of the residuals means that these values should not be intercepted in the usual sense. Our regression confirms our earlier finding that shots required to neutralize Red boats is the most important factor. From the regression model above, we can also see the consistency of the second most important factor being the probability of hit (with a −44.59 *t ratio*). The negative sign associated with *t ratio* indicates that there is a negative correlation between

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that factor and the output response. That is, as the probability of hit increases, the probability of Red success decreases. The prediction profiler plots show the marginal effects of each factor on the probability of Red success. It is worth noting that the main effects are more significant than the interactions.

Figure 35 displays the actual by predicted plot. It can be seen that predicted values are generally consistent with actual values, indicating the effectiveness of the model. It should be noted that the residuals are not normal, thus the *p-values* are not precise.
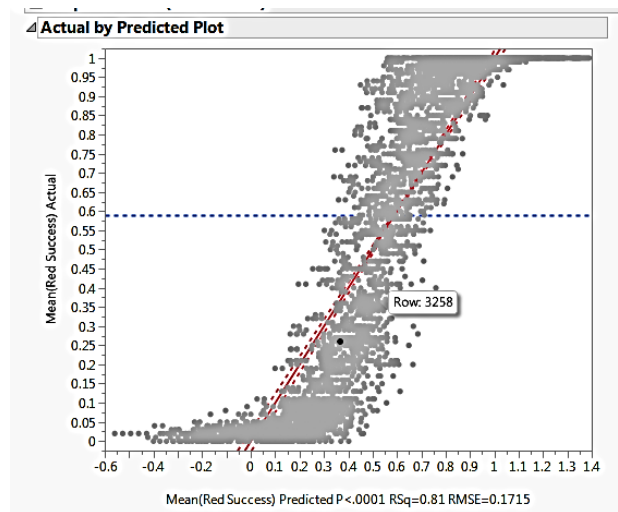

Figure 35.   Actual by Predicted Plot of Mean (Red Success).

F.   SIGNIFICANT INTERACTIONS

An interaction measures the change in response (Red reaches goal) caused by varying one input factor that is dependent on the value of another input factor. In this model, there are eight different inputs and all may potentially have interactions between them. In order to examine the interactions between different factors, an interaction profile plot was generated and examined to look for significant interactions between input factors. The interaction plot in Figure 36 shows the high and low levels of all pairs of factors, and the effect on the response. By observing the near parallel lines in the graphs, we see that the interactions are not that strong. Some interesting interactions are (1) the

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probability of Red success drops faster with probability of Blue shots hitting Red, when the exclusion zone is greater and (2) the probability of Red success drops faster with probability of Blue shots hitting Red, when there are three sentries as opposed to two.

Figure 36.   Interaction Profiler.
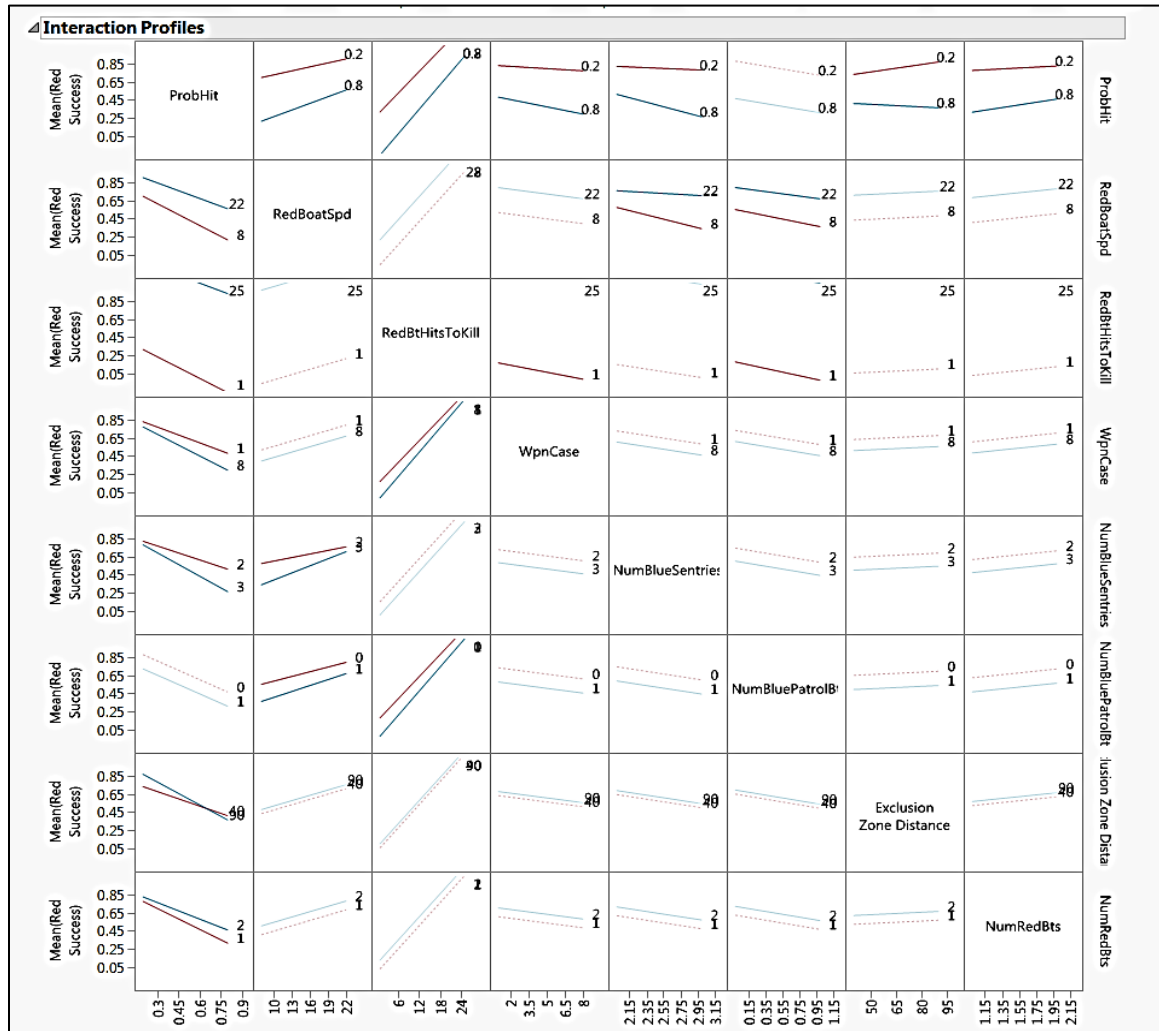
G.   TACTICS WITHIN EXCLUSION ZONE

If sentries see an incoming boat heading towards a ship inside the exclusion zone, should the sentries fire a warning shot and then disabling shots, or they should directly fire disabling shots? A ship's crew is always concerned about what to do in this situation. Although we did not carry out simulation for this scenario, the situation was analyzed

using the results of previous simulation runs (with an exclusion zone distance of 60 meters) and simple mathematics calculations involving time and distance. We have found in our analysis that, with the given parameters, 60 meters is an adequate exclusion zone distance, which must be maintained to have an acceptable level of defense by the Blue ship. A boat traveling at 15 knots will cover 7.5 meters each second. If a sentry fires a warning shot, observes its effect on the incoming boat and then fires disabling shots, it may take six to eight seconds and at best it will take three to four seconds. A boat moving at 15 knots will take only eight seconds to cross the exclusion zone and hit the ship's side. If sentries are very alert and good at observing the effect of a warning shot, even then there will be only about five seconds available for the sentries to disable the attacking boat. It will be the same as if exclusion zone is now established at 38 to 40 meters. After incorporating the delay of three to four seconds in opening up disabling fire, the overall distribution of Red achieves its goal is depicted in Figure 33.

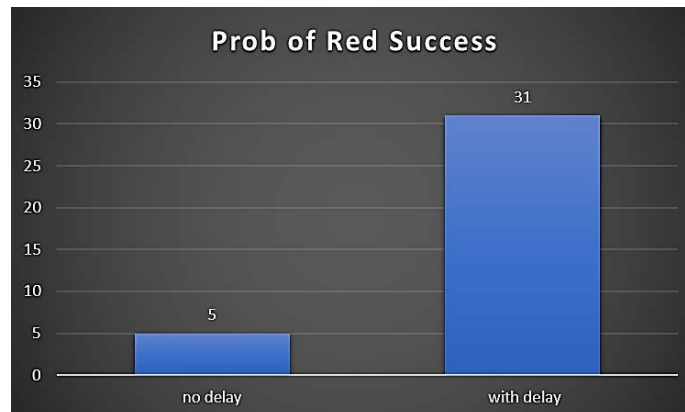Figure 37.   Distribution of Red Success after Incorporating a Three- to Four-Second Delay.

We can see that incorporating a delay of three to four seconds results in the probability of Red success increasing from 6% to 32%, indicating that a warning shot may not be a good idea if the exclusion zone is of only 60 meters or less in width. Thus, the Blue patrol boat should be tasked with implementing the exclusion zone effectively.

VI.   CONCLUSION

The main purpose of this study was to analyze the protection measures that might be employed by a ship's crew against a suicide terrorist boat. To that end, 4,112 design points were generated for simulation. Each design point represents a set of input factors that generates the output, i.e., whether Red achieves its goal or not. Each design point was replicated 100 times in order to explore a range of possible results from the stochastic model. This study analyzes the data obtained by performing 411,200 simulated attacks on a Blue ship by Red boats. Analysis techniques used to explore the resultant data include histograms, partition trees, logistic fits of Red success against all input factors, and stepwise regression. In order to further explore the exclusion zone distance effect on Red success, a one factor experiment was also performed.

A.   CRITICAL FACTORS IN MODEL

After analyzing the data, the following important insights were discovered:

- The most important factor is the number of Blue shots needed to kill the Red boat (neutralize)—that is, the lethality of Blue weapons against the threat. Further, an important threshold value for this factor was 11. In other words, there was a clear difference in the estimate of Red success when hits required to neutralize Red boat were less than eleven or more than eleven. All analysis techniques recommended that lethality of Blue weapons is the most critical factor. This is because, in such a situation, time is very important. Sentries will have 6-12 seconds, depending on the speed of the Red boat and the exclusion zone distance. So, the more lethal the Blue weapons are, the greater the chances are of stopping a Red boat attack.

- Another important factor is the probability of hit by Blue Sentries. In such situations, probability of hit by Blue sentries will largely depend on their weapons, environmental factors, confidence, fear factor and their resolve to stop the attack. Out of these factors, confidence, control of fear, and resolve of sentries to stop a Red boat, can be improved by better training of Blue sentries.

- Exclusion zone distance also plays an important role. At least a 60 meter exclusion zone is recommended, but it will depend on input factors, especially hits required to neutralize Red boat. It is very important to

know how many rounds of a particular weapon are required to neutralize the attacking boat.

- The presence of a Blue patrol boat also reduces the chances of Red success, but is not a dominant factor. However, a Blue patrol boat is vital for implementing the exclusion zone.

- At whatever distance the exclusion zone is established, it must be implemented effectively by a Blue patrol boat. There will be a manifold increase in the probability of Red success if the tactic of firing a warning shot followed by disabling shot is adopted.

B. FOLLOW-ON WORK

We recommend the following potential areas for future research:

- The standard deviations of weapons in the *x* and *y axis* was not available, so for the purpose of this study, values for standard deviation were assumed, based on experience. Theoretical probability of hit of all weapons can be calculated by using actual standard deviations based on live fire tests. Additionally, in-field calculation of probability of hit by Blue sentries can be carried out in near actual conditions.

- No data was available on the actual effectiveness of particular types of weapons in terms of how many rounds are required to neutralize an attacking Red boat. Collection of this data would therefore be useful to refine the scenario.

- A useful scenario variant to consider is if a Red boat also starts firing on the Blue ship, while attacking. In our scenario, this was not the case.

- It would also be useful to study the case of a Blue ship coming under attack from the sea as well as from the land—what tactics and protection measures are required?

- Allow friendly boats to also enter the exclusion zone.

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