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Frigate defense effectiveness in asymmetrical green water engagements

Abel, Heiko

Monterey, California. Naval Postgraduate School

https://hdl.handle.net/10945/4655

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

FRIGATE DEFENSE EFFECTIVENESS IN ASYMMETRICAL GREEN WATER ENGAGEMENTS

by

Heiko Abel

September 2009

Thesis Advisor:	Paul J. Sanchez
Second Reader:	Jeffrey E. Kline

This thesis was done at the MOVES Institute

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13. ABSTRACT (maximum 200 words)

Asymmetric threats pose increasing challenges to combatant commanders in Stability, Security, Transition, and Reconstruction (SSTR) Operations. Threats once confined to littoral waters now extend out to the green water theater. Many NATO countries operate their post Falkland war built frigates in these missions, in which lightly armed small, agile and fast craft are often encountered.

This study uses freely available real-world data to build a simulation using an agent-based modeling platform called MANA. The simulation is exercised over a broad range of factor settings that are determined by an efficient experimental design. Using linear regression and partition trees, a robust analysis is performed on the resulting dataset to create statistical models.

Conclusions gained through these models suggest that a swarm of small craft, armed with handheld weapons, could attack and achieve a mission kill on a typical NATO FFH operating in a SSTR mission. It further implies that the FFH's mission survival is dependent on the sophistication of installed weapons, and that a mix of advanced, automated weapons is best suited for close-in defense against multiple small seaborne attackers. Therefore, it will benefit mission survivability to improve or replace existing body-aimed weapons of frigates serving on SSTR missions.

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FRIGATE DEFENSE EFFECTIVENESS IN ASYMMETRICAL GREEN WATER ENGAGEMENTS

Heiko Abel
Kapitänleutnant, German Navy

Submitted in partial fulfillment of the
requirements for the degree of

**MASTER OF SCIENCE IN
MODELING, VIRTUAL ENVIRONMENTS AND SIMULATION (MOVES)**

from the

**NAVAL POSTGRADUATE SCHOOL
September 2009**

Author: Heiko Abel

Approved by: Paul J. Sanchez
                      Thesis Advisor

                      Jeffrey E. Kline
                      Second Reader

                      Matthias Kölsch
                      Chair, Moves Academic Committee

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Acknowledgements

I would like to dedicate this thesis to my wife and my son. Stefanie, you were the supporting pillar during times of stocking progress, stress and doubt. You were my enabler, keeping the world at bay and my thoughts focused. You were my pusher, reminding me of my duties. Alexander, your innocence and general interest in the world helped me to notice life besides my work and that the sun actually does shine every day — you simply change my point of view.

I am obliged to thank the wonderful staff of NPS, and especially the MOVES Institute, to support me in the completion of this thesis. First and foremost my thanks go out to my advisor, Dr. Paul J. Sanchez, and my second reader, CAPT Jeffrey E. Kline, USN(ret.), for trusting me to finish this study. Dr. Sanchez aided me with his intricate knowledge in simulation modeling, statistical methods and design of experiments while CAPT Kline provided very important operational experience and made sure the setup and findings fit in the big picture.

Next I would like to thank Professor Quinn Kennedy, as she showed me that there is more to statistics than math, Professor Arnie Buss for his insights into simulation modeling techniques, Professor Chris Darken for harboring my interest in this study and Curtis Blais for insights into his area of research. I would also like to thank Hauptmann Dipl.Inf. Marco Draeger for his continuing support in matters concerning computer and information sciences generally and mathematical models specifically.

I am also very thankful for the resources provided by the Naval Postgraduate School's Simulation Experiments and Efficient Designs Center. The center provided me with research space, support and travel to both initially develop, mature and conclude my research. The SEED Center, especially Steven C. Upton, had a profound influence on the completion of my work.

In conclusion, this study is the culmination from the insight of many people, not the least of whom are my fellow MOVES section 081 students. Thank you for making my stay in the U.S. a rewarding one. Thank you for letting me participate in your dream.

Pebble Beach, autumn MMIX

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CHAPTER 1:
Introduction

According to the U.S. DoD Maritime Strategy (Carmel, Hughes, Pendley, Rubel, and Till, 2008) traditional and especially asymmetric threats continue to pose increasing challenges to any combatant commander in a notional Stability, Security, Transition, and Reconstruction (SSTR) Operation. Limited threats that were once confined to brown and littoral waters now extend out to the green water theater (U.S. Department of Defense, 2007). As building new frigates to specifically counter these threats is a very expensive and time consuming effort (Defense Industry Daily, 2008), it is necessary to investigate how well a typical North Atlantic Treaty Organization (NATO) operated Fast Frigate with Helicopter (FFH),[1] built between 1975 and 1990 and operating as a lone unit, would perform in a SSTR mission when attacked by small, agile fast craft armed with hand-held weapons.

A hypothetical defense against different sized swarms of small vessels at different speeds in differing environmental conditions is simulated. Different frigate defenses are modeled using a range of old and new armaments. The intent is to provide answers to the questions as enumerated in Chapter 1.1.

Figure 1.1: Köln Class Frigate Köln IV, F220 (From U.S. Defense Imagery, 1985).

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[1]In this study, Fast Frigates with Helicopter (FFH) and Fast Frigate, Guided Missile, with Helicopter (FFGH) are used as synonyms. The Guided missile does not influence proposed research. Please see Chapter 2 for further explanations.

1.1 Research Questions

1. Can a swarm of four to eight small agile boats armed with handheld weapons, attack and achieve a mission kill on a typical NATO FFH operating in a SSTR mission?

2. Is the FFH's mission survival dependent on the sophistication of installed weapons?

3. What type of weapon or weapons package is best suited for close-in defense against four to eight small seaborne attackers?

4. Would it benefit mission survivability to improve or replace existing weapons of frigates performing SSTR missions?

All testing for answering the research questions rests on the premise that the new or updated capabilities can at least theoretically be equipped on the average commissioned frigate while not, or only minimally, altering the ship's hull or its hull structure respectively.

1.2 Background and Motivation

The whole of the Mediterranean Sea, as well as the merchant routes between the Mediterranean Sea and the Persian Gulf, are strategic and economic assets for many NATO countries (Yost and Masala, 2005). Preserving the freedom of the seas, including the free passage of trade routes, and denying access to these resources for pirates and other asymmetrical threats is of vital importance (U.S. Department of Defense, 2008). NATO doctrine states that piracy and terrorism are partially interdependent (North Atlantic Treaty Organization, 2009). Therefore, task forces are stationed in both areas to demonstrate vigilance,[2] and at the same time control for those threats. Since the attack on the USS Cole on October 10, 2000, previously unrecognized or underestimated threats emerged for navy vessels engaged in SSTR operations.

Vessels in brown waters recognize the potential threat of small craft armed with handheld weapons or stacked with explosives, attacking from within the cover offered by other neutral vessels and using the element of surprise (News Navy.mil, 2009).

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[2]Both Operations Active Endeavor and Enduring Freedom evolved out of NATO's immediate response to the terrorist attacks against the United States of September 11, 2001. The Operation's goals are to monitor shipping and provide escorts to non-military vessels and to help detect, deter and protect against terrorist activity (NATO Operations, 2009).

In green water engagements, these threats can take the form of small, fast, relative lightly armed vessels in possibly large numbers, and disguising themselves as legitimate vessels prior to attack. Such attacks might be performed by terrorist organizations, as with the USS Cole, or as part of the increase in pirate activities currently observed in the Gulf of Aden and other comparatively unstable areas around the globe. The first in a continuing series of examples of this kind of activity is the sinking of a suspected pirate vessel by the USS Gonzalez on March 18, 2006, near Somalia territorial waters (Besheer, 2006).

Figure 1.2: Pirates off Somalia in a skiff, while closing in on a cruise liner in 2005 (From Associated Press, 2008).

The vicinity of the Gulf of Aden (GoA), while geographically compact, is crowded with commercial transport, recreational cruise ships, and a multitude of fishing vessels. Many of the local fishing vessels are in very poor condition. The same is true for the vessel's crews, whose sole survival is often dependent on whether they catch enough fish to eat and sell. The GoA also features calm seas, allowing for extensive use of small and fast vessels. Since this region also borders an unstable area, as well as a state hostile towards NATO, it is a prime candidate for an attack to occur (Figure 1.3) (Wright, 2007).

Commercial transport and recreational cruise vessels are easily identified by radar cross-section, speed and the mandated automatic identification System (AIS), but the local fisheries are not industrialized as in many western countries. The typical fishing vessel is built in the style of a dhow, made of wood, possibly equipped with a dated VHF transmitter, and more often with a Thuraya satellite phone than a radar system.

Some dhows are accompanied by small, agile and quite fast boats used to herd fish. These boats will further on be referred to as "small, agile fast craft" (SAFC). This name is chosen to differentiate these civilian craft from fast inshore attack craft, which in U.S. Navy terminology are specifically procured as military attack vessels, chosen with the specific intent to attack larger military[3] vessels in large numbers (Navy.mil, 2007). To identify these dhows and the accompanying SAFC, it is necessary to approach them and visibly read off the ship's name, as the physical differences between individual dhows are minute. Some of the speedboats accompanying the dhows are only detected by the wake they produce when at high speeds.

Many NATO countries participate in patrol missions, each sending different types of frigates, most of which were built between 1975 and 1990. Most of these frigates were designed for convoy protection and submarine hunting. As such, they have good surface radars, anti-ship missiles and anti-submarine capabilities but not a lot of close range defenses against small craft. They are either not or only minimally armored.
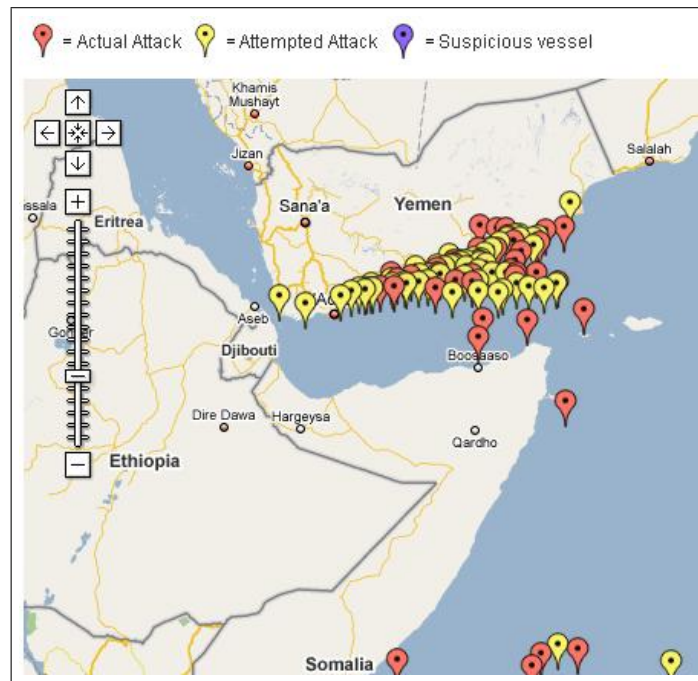
Figure 1.3: International Maritime Bureau Piracy Map for 2008 (From International Chamber of Commerce, 2008).

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[3]And also civilian vessels, for example during the tanker Wars with Iran (Navias and Hooton, 1996).

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When encountering SAFC in the GoA, most NATO Navy's standard operational proce-
dure is to advise the SAFC to steer clear of the frigate. Usually the SAFC will not react as they
have no means of communication[4] and will continue along their path towards the frigate. It is
then customary to avoid these vessels while still trying to assess the crews and determine their
intent. As long as the weather permits, many of those vessels are faster, some considerably, than
a frigate. It is nearly impossible to evade these craft even when they are not aiming to intercept
the frigate. Additionally, it is hard to evade the vessels and simultaneously identify the crew
or possible weapons. An adequate visual inspection requires approaching the vessels until they
are at most half a mile away. At this distance, assuming the small craft have an excess speed
of 10 knots in relation to their intended target, they will reach the frigate within at most three
minutes. Given the typical size of a NATO frigate, this is not a lot of time, and certainly not
enough to begin issuing combat stations and expect a stringent defense.

The motivation of the SAFC to attack a NATO frigate is thought to be the humiliation
and the subsequent retreat of that enemy. This might either be motivated by some political ide-
ology, or maybe the attacker's business model of generating ransoms for the release of captured
vessels is currently impeded by the frigate's presence in the area. The actual motivation is only
of interest insofar as the attack is not thought to be a suicide commando, but rather someone
who is interested in surviving the encounter.

The objective of SAFC during the attack then is maximum media coverage and the
disgrace of the stronger and technologically advanced enemy. As the attack occurs at sea, to
achieve and amplify the media effect[5] the attack must either be recorded or, for even better
results, the attacked ship needs to be able to return to port, with visible damage, exploiting full
media coverage. In this scenario, the frigate will therefore have lost a simulated encounter once
a mission kill is determined, allowing us to view the frigate as a single entity without the need
to model every and all compartments and machinery. Also, as similar in armament as most
NATO frigates are, some quite different building techniques are employed. Using the approach
discussed, all these different commissioned frigates can be reduced to one general design, with
varying numbers of hits admissible until the frigate is assumed to be a mission kill (for an
overview of former and current frigate designs, see Appendix B).

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[4]This fact is based on observation in 2006 only.

[5]A theory that relates how stories published in the media influence or amplify current trends (Bryant and
Thompson, 2001).

For the SAFC, up to four attackers per craft are assumed. The total number of occupants per craft might be higher, but four is thought to be a minimum for this type of exercise. One person will steer, one will fire a handheld weapon and up to two will fire rocket propelled grenade launchers, like the RPG-7 or a variant thereof.[6]

Further details of interest in this study are presented in Chapter 2.

1.3 Scope of the Thesis

This thesis describes an abstract model of a common NATO FFH type Frigate operating in a SSTR scenario, with the different scenarios being simulated using Agent Based Modeling (ABM). The small, agile fast craft will attack the frigate in different environment conditions, in different numbers and with the frigate employing defense systems of different kinds and varying sophistication, at the same time varying the hit probabilities of both attackers and defenders.

Armament, skill, speed, approach vectors and number of the SAFC will be varied. The attackers are positioned at random on the map during initialization. The survival and the performance of the SAFC are not issues to be researched; therefore, these factors are not accounted for. As such, advanced tactics, as for example luring the FFH into a trap and other such forms of attack or special formations are not studied.

The SAFC hit probabilities, as well as evasive maneuvers, are balanced assuming the best attack strategy is being employed. All engagements are assumed to occur during the day. To find and attack an enemy in green waters requires some sophistication. The SAFC need to have some general idea of the location of the frigate. This is represented in the model by them closing in from only two directions, but for the final approach they will need to have a visual reference. Even though low light and infrared equipment are getting cheaper, it is not assumed that the attackers have this equipment readily available. Therefore, they are denied the possibility of a night attack.

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[6]The Rocked Propelled Grenade launcher 7 and its variants are the most commonly used and easiest to acquire large caliber weapon available, and given its effectiveness, also the cheapest. A black market armor piercing grenade for this launcher costs about $15, whereas the launcher is an investment of about $600 if buying the original. Copies from countries other than Russia (except for those built under license in the U.S.) are thought to be even cheaper (Gebre-Wold and Masson, 2002).

The survival of the SAFC is not of interest as a measure of effectiveness (MOE), as regular NATO procedures are to defend, call for help, and tend to any casualties if necessary. However, the frigates would usually not try to pursue and kill enemy craft once those are retreating.

The frigate is assumed to try maneuvering in such a way as to achieve good weapons coverage on their opponents while simultaneously minimizing the cross-section they expose to the enemy's weapons fire. This will be achieved by varying the placement and speed of the frigate agents.

Deciding whether the approaching vessels present a threat or not is one of the problems assessed in this model. NATO operational procedure and Rules of Engagement (ROE) usually assume neutrality of contacts until proven otherwise. The ROE of the frigate are assumed to prohibit a preemptive strike on the approaching vessels. Nonetheless, it is assumed that the presence of the SAFC is not a surprise to the frigate, and the crew will thus be at battle stations when the actual attack of the SAFC occurs. Once the small vessels are proven hostile, a full response using reasonable but necessary force will be administered. The frigate will also react once an attacker crosses within the safe zone around it, which will be varied extensively in the simulations. A craft inside the safe zone is assumed to be hostile and will be attacked. For modeling purposes, this distance not only represents the different ROE each country operates within, but also represents the use of non-lethal weapons (NLW) to determine hostile intent. Most of these weapons are only effective over a short distance, and studies show that they do not deter a determined attacker from continuing with or starting an attack (Sickinger, 2006).

Adding to the problem when confronted with multiple closing SAFC is whether they all have the same intent, and may therefore be all classified as hostile. As this is a decision to be made by the commanding officer, both variants will be modeled. In one case, single vessels definitely classified as hostile will be attacked. In the other case, once one vessel is determined to be hostile, all nearby craft are valid targets. Due to the short range, an enemy being targeted by a NLW is possibly already within its admissible weapons range. The benefit of being able to discriminate friend and foe may therefore be range dependent, especially since some of the frigate's weapon systems have a minimum effective distance inside which they are not employable. To account for all these conditions, the frigate will either react when shot at, when

the SAFC are determined hostile or when they cross a minimum safe distance. Each of these conditions will be set in advance to control for their respective or combined effects.

All weapons that are modeled in each scenario are to be admissible weapons in accordance with ROE. ROE requirements allow a "necessary and reasonable response" to an encountered threat.

The study does not try to incorporate elements of advanced scouting, training issues or the effects of target selection.

All damage control, as well as target allocation, is assumed to be perfectly coordinated. It is also assumed that no magazines or other ammunition are hit. Effects of catastrophic hits, such as ordnance explosions, aboard the frigate or SAFC are not modeled. In reality these hits may well result in an instant mission/unit kill. Further, elements of exhaustion, fatigue, or any other human factors affecting the behavior of the frigate or the attacking SAFC, are not an issue in this study.

The frigate is not tested for armor effects, which may well be of significance in an attack involving small weapons fire. The incorporation of armor in an existing vessel's design is not trivial and would very probably necessitate an extensive redesign of the hull, a condition ruled out in the problem statement.

The use of a helicopter is studied. Most NATO shipboard helicopters are not designed for and are not effective in a surface interdiction and attack role. The U.S. Army, for example, is assigning ground interdiction and attack missions to fixed-wing aircraft because ground-attack helicopters have proved to be highly vulnerable to small-arms fire (Grant, 2006) in those roles. This does not apply to close air support (CAS) missions (Groenke, 2005). The only shipboard helicopter designed for ASuW missions is the recently introduced MH-60R Seahawk using the AGM-114N Hellfire II Missile (Figure 1.4). Using this weapon system, the stand-off distance and accuracy is such that it is thought to influence the frigate's survival. Many studies have shown a helicopter to be a valuable asset ((Efimba, 2003), and (Abbott, 2008)). Even if the helicopter has no weapon system comparable to the Hellfire System, and, therefore, is not as effective in the CAS role, it may draw some weapons fire away from the frigate and thus help the frigate survive. Shipboard helicopters in this model do not increase the defensive capability

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of a frigate by warning of an armed enemy approaching, as the frigate is assumed to be ready
to defend itself whenever the weapon exchange begins.

Figure 1.4: Lockheed Martin AGM-114N Hellfire II on display at ILA 2006.

The study will be able to give a plausible insight to the armaments beneficial to a frigate
that is expected to encounter a small boat non-suicide attack. The study will approach the ques-
tion of whether current frigates are adequately equipped to deal with the scenario they currently
face. It will not answer any question outside this very specific realm, and any changes to the
weapons mix that may be suggested by this study should be evaluated in the context of the many
other combat and support scenarios possible in the political environment we are living in today.
Also, as this study develops a distillation model of all NATO frigates built between 1975 and
1990, certain features that may have an impact on individual performance may be lost in the
study. Applying the results to any particular frigate would require further study explicit to its
particular design.

1.4   Methodology

The simulation is set up within an agent based modeling (ABM) environment called
the Map Aware Non-uniform Automata (MANA), version 4.04. This modeling environment
is capable of simulating the frigate, as well as different types of SAFC when they are pitted
against each other. The chosen ABM provides a data farm-able interface capable of being run
in batch mode. The input data for the model are assembled using spreadsheet techniques, and
are mainly based on sources such as Jane's Fighting Ships and Jane's Naval Weapons for tech-
nical data (Saunders, 2008). Open, publicly available literature such as manufacturer supplied
information, article reviews, and subject matter expert interviews are used for the determina-
tion and later calculation of hit probabilities. Both the subject matter experts, as well as the

manufacturer supplied spec sheets are understood to provide general guidance rather than precisely describing the true performance of any given system. The frigate design is abstract, and weapons performance varies with factors such as platform stability, weapon control, and sensor quality. When combined with the intention of exploring ranges of performance using robust experimental design techniques, these data sources are thought to be sufficient for the purpose of this thesis. Data on weapons for which neither an expert nor a technical data sheet can be found will be approximated by comparable designs and design ranges.

Exploring ranges of input values rather than discrete values will mitigate the effect of uncertainties in the input data and capture some of the stochastic effects of warfare. Different model starting conditions will be varied using a Nearly Orthogonal Latin Hypercube (NOLH) design (see Chapter 3), and each variant will be run on a computing cluster with sufficient replications to assess variability in the responses. Exploratory data analysis techniques will be used to characterize the impact of weapons packages and tactics on the FFH's performance.

1.5   Chapter Outline

Chapter 2 explores the set-up of the model inputs. A distillation of current frigate and SAFC designs is explored, and weapon systems, as well as hit probabilities explained. Included is a brief discussion of the real-life settings, conditions and constraints that are implicitly assumed for the model. After a brief overview of the model's capability, advantages and disadvantages of using MANA versus other modeling environments are discussed. The relative merits of using time stepped versus discrete event simulations are discussed and the measure of effectiveness is explained.

Chapter 3 contains the complete design of experiments. It describes how the frigate and SAFC real world representations are integrated within the modeling environment. It details what systems and capabilities are varied and by what amount. First the frigate's designs and its implementations are detailed, followed by the SAFC capabilities.

Chapter 4 contains an overview and explanation of the statistical methods used and the analysis of the data produced by the simulation.The analysis section is divided up in a section analysing data with and a section analysing data without a helicopter present within the simulation.

Chapter 5 concludes this thesis, summarizing the results and offering follow-on problems.

1.6   Benefits of the Study

The German Command for Transformation of the Armed Forces and those NATO countries contributing FF(G)H Frigates to SSTR operations will benefit from this study. This study identifies appropriate defense options for any maritime vessel facing "swarm" threats that are employing short to medium range weapons. There is also potential for identifying training needs unique to a SSTR mission. The New Zealand Defense Force, Defense Technology Agency (DTA), is interested in the results of this study. The DTA is currently simulating a frigate protecting a high value unit being attacked by multiple vessels employing red teaming.

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CHAPTER 2:
General Parameters

The primary objective of this research is to use modeling and simulation to determine whether current NATO operated FFH designs commissioned between 1975 and 1990 are suited for defending themselves against a swarm of 4–8 SAFC. This chapter describes how the different capabilities and characteristics of the distinct frigates, weapon systems and small craft were determined. It also shows how the frigate types and weapon systems fitting the selection criteria were distilled. Finally it describes the process of model environment selection, general model implementation considerations and explains the chosen Measure of Effectiveness (MoE).

Figure 2.1: FFH 56 SIMPSON, an Oliver-Hazard Perry Class Frigate.

2.1   Frigate Setup

Many NATO countries designed and commissioned new frigates between 1975 and 1990 (Figure 2.1). Findings made during the Falkland War in particular convinced some countries to remodel their existing fleet. In this subsection, all FFH designs as built between 1975 and 1990 and still in service of NATO countries at the time of writing are examined and distilled into a single frigate model to be used in the scenarios. The same is done for weapon systems capable of targeting SAFC. Finally, given SAFC as target for the different weapon distillations, to-hit probabilities are determined.

Some weapon systems under consideration for development are not studied in this research. These include electromagnetic gun systems, otherwise known as "Gauss cannons" or "Railguns," as well as LASER based defense systems, such as LCIW.[7] Both systems are undergoing field tests, but both systems are very hard to integrate in one of the existing frigate designs, as they follow a different design paradigm — the all electric ship.

Following the 2002 intervention in Iraq, some new active defense systems have been released to the market. These systems may have a serious impact on RPG effectiveness, which, at least at the moment, seems to be the SAFC's most daunting weapon. Due to the short distance for engagement, in the current development stage these systems rely on an armored carrier. The carrier needs to be armored to protect itself from both the interceptor's and intercepted grenade's explosion and fragments. A frigate does not provide the kind of armor protection needed to employ this system. Additionally, these RPG defense systems are built to defend a single small land based vehicle, such as a Main Battle Tank or Armored Personnel Carrier, and not a large frigate (Defense Update, 2006).[8]

2.1.1 Distillation of Different NATO FFH Types

According to Jane's Fighting Ship, the following NATO FFH classes were commissioned between 1975 and 1990 and are still in operation by NATO countries (in alphabetical order):

- Bremen class (Type 122), Germany

- Broadsword class, Batch II (Type 22), UK

- Broadsword class, Batch III (Type 22), UK

- Duke class (Type 23), UK

---

[7]Laser Close In Weapon System. They will not be considered in this study as they 1) are not yet and for a few years will not be operational, and 2) require far higher amounts of electricity to operate than is usually available on a vintage design.

[8]Those systems use a fixed radar sensor, mounted on the protected platform, to detect potential threats, measure the distance and trajectory, and thus providing the fire control system with data for calculation of engagement plans. When a threat is identified, normally the muzzle flash in the case of an RPG, an explosive projectile or small missile interceptor is launched toward it. The interceptor either tries to hit the incoming projectile, or tries to destroy it using a fragmentation blast. Both the missile and the fragmentation blast may damage an unarmored carrier system in the process of defending against the incoming projectile. Compare (Defense Update, 2008) and (Defense Update, 2007).

- Elli class, Greece[9]

- Karel Doorman class, Belgium (ex Netherlands)

- Kortenaer class, Greece (ex Netherlands)

- Lupo class, Italy

- Maestrale class, Italy

- Nils Juel class, Denmark[10]

- Oliver Hazard Perry class, USA/Turkey/Spain

- Vasco da Gama class, Portugal

- Yavuz class, Turkey

Not considered is the Spanish Baleares class (Figure 2.2), based on the US Knox class design, as the last vessel is being retired at time of writing. Also not considered is the Danish Thetis class, as it is classified as an Ocean Patrol Frigate, and not comparable to the Fast Frigate Helicopter (FFH). The subset of the FFH, the FFGH[11] design, is considered in this study.

For frigates considered, minimum and maximum design parameters that are thought to be important are extracted. This is done in order to cover the complete range of capabilities for each frigate within the selection criteria. After this process, the following generic frigate set-up is determined:

- Maximum Speed using main propulsion: 21 – 34 kt

- Maximum Speed using economic propulsion: 14 – 26 kt

- Tonnage: 1320 – 4900

- Length: 84 – 149 meter

- Width: 10.3 – 16 meter

---

[9]A modified Kortenaer class, designed when this class was sold to Greece.

[10]In international comparison, mainly due to its small size and light weight, this type should be rated as a corvette. As it is registered as a frigate, it is included in this study.

[11]Fast Frigate Guided missile Helicopter.

Figure 2.2: FFH 71 BALEARES, a Spanish Knox type variation. Last of the class was decommissioned in December 2008.

- Main Gun(s): 1 x 76 mm – 1 x 127mm (2 x 76 mm)

- Auxiliary Guns: none – 4 x 30mm part automatic

- Small Guns: 2 x 7.62 mm MG's – 4 x 12.7 mm MG's

- CIWS[12] Gun: none – 30 mm full automatic

- CIWS Missile: none – 2 x 21 rounds automatic

- Surface to Air Missiles: none able to target small craft

- Surface to Surface Missiles: none able to target small craft

- Number of radar fire controls: 2 – 5 independent

- number of optronic fire controls: none – 2

- Helicopter firing AGM-114N Hellfire: none – 1

With this set-up, the next step is to determine the actual weapon types used within the model.[13]

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[12]Close In Weapon System, a last line of defense against low flying missiles. In recent upgrades, Helicopters, Small Boats and larger Vessels may be engaged. This is also true for the recent CIWS Missile systems.

[13]See the appendix for a full overview of individual frigate's capabilities.

2.1.2   Weapons Types Considered in the Model Set-Up

Even though there are thirteen different frigate designs determined to fit the selection criteria, it would be interesting to understand what weapons in what configuration would actually make a difference in a battle. Nonetheless, the ascertained design still needs to be realistic. In this subsection, all weapons considered for the model set-up will be briefly described.

Missiles

Most missile systems as installed aboard a FFH are employable against larger size targets only, as the missile will either not lock onto a target the size of a SAFC, or the preprogrammed detonation area is not at the height and depth of a SAFC.[14] Thus, anti-ship cruise missiles and anti-air missiles are not considered and not modeled for these runs.

Main Guns

A "Main Gun" is an artillery piece that is not clearly defined in size or purpose. Most of the frigate types investigated employ a 76 mm automatic cannon as the main artillery armament. The main gun on a frigate from the selected era is typically installed for air defense purposes, a feature that may be easily deduced by the placement of the 76mm gun aboard Oliver-Hazard Perry type frigates. This design places the main gun in the middle of the deck house, in between the main mast and the exhaust structure (see Figure 2.1 in combination with Figure 2.3).

Figure 2.3: USS Curtis' OTO Melara 76mm (Mk75) gun engaging.

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[14]Modern Missiles will try and detonate three to five meters within an enemies' hull, and penetrate about one to two meters above the water line. Therefore, most common missiles will pass any SAFC overhead and will not detonate, even if they had build-in multiple attack software (Gomar et al., 1996).

Item	min	max	measure
ammunition	5	90	ready Rounds
gun train	15	40	degrees/second
target acquisition	10	40	seconds
inter-firing time	0.5	3	seconds
firing arc	210	270	degrees
engagement distance	150 – 500	60000	yards

Table 2.1: Main Gun System characteristics

Even though this paradigm has changed and artillery is no longer specifically employed for air defense purposes, the guns of the selected era are specialized for AAW duty. Some countries have upgraded the main gun's soft- and hardware to enable firing on small vessels.[15] With legacy software, a hit with the main gun on SAFC type vessels is very hard to achieve, even in the best of circumstances.[16] The most prominent and widely used exponent of this class is the OTO Melara[17] 76 mm naval gun, also listed as the US MK 75 (Friedman, 2008).

On the other hand, more recent gun systems like the Bofors 57mm MK III (Figure 2.4), use an advanced ASuW mode employing advanced shells and digital gun control. This allows for different projectile behaviors, for example to detonate the projectiles directly above a target, dramatically increasing P(hit) especially for small targets. It is also worth mentioning that guns of higher caliber and short inter-firing times are often subject to jamming and/or misfires. Modern gun systems tend to have fewer of these reliability issues.[18] A direct or adjacent hit of any Main Gun projectile will achieve an instantaneous kill of a SAFC (Table 2.1).

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[15]Compare the most recent upgrade programs for Type 122 and Type 123 frigates of Germany, or the upgrade to hard- and software of US 5" guns now being able to fire a so-called shotgun shell, MK182 KE-ET (Steelman, 2005).

[16]Historically, these guns had two modes of operation, AAW and an ASuW . The ASuW mode was a backup and last resort to attack a larger hostile vessel. As such, the projectile is shot in a way to penetrate the target about 2 to 4 meters above the waterline, and detonate 3 to 5 meters after impact (Null and Wallace, 2003).

[17]After a merger this gun is also known as OTOBreda.

[18]Compare the problems the British Navy experienced during the Falkland War with the advanced MK8 gun system (Fischer, 2006).

Auxiliary Guns

Humans, especially when not constantly trained, are poor marksmen shooting medium-caliber auxiliary gun systems.[19] The guns themselves are usually quite accurate. Movement of the gunner, the gimbals, the ship and the target hamper good performance. Additionally, gun training is quite expensive, needs a huge free range, moving targets to produce effective training and is therefore time consuming. Whatever the reason, auxiliary gun training nowadays is not a common occurrence. In recent years, in light of the poor performance of human tracking, automatically tracking gun mounts have been introduced (Watkins, 2005). The human operator only needs to point the gun at the intended target, and the gun will acquire, follow and typically hit the intended target with great accuracy.

Figure 2.4: An air burst of a 57mm Bofors MK III projectile above its intended target.

Recent auxiliary gun designs further increase both lethality and kill probability by use of advanced projectiles. New designs either use the High Explosive (HE) timed round (Figure 2.4), the Frangible Armor Piercing Discarding Sabot[20] (FAPDS), or the Armour-Piercing Fin-Stabilized Discarding Sabot (APFSDS) (Figure 2.6).[21]

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[19]As an example, during World War II land based air raids an Anti-Aircraft Battery on average used between a few thousand and 18500 rounds of ammunition for hitting and destroying just one aircraft, at day and night respectively. These hit rates were for stationary guns — additionally the speed of aircraft was comparatively slow during that time period (Baldwin, 1999).

[20]This penetrator consists of a brittle tungsten alloy, designed to fragment after impacting a hard or soft target. The "round disintegrates into fragments, which then progressively break up into a cascade of ever-smaller particles. The result is a high-energy cloud of fragments" (Gander and Cutshaw, 2007).

[21]The Bofors 57mm MKIII gun employs this most recent development. Using an on-mount muzzle velocity radar, the rounds are programmed while traversing the muzzle to burst in air. Using this method, the rounds detonate within a 2–5 meter circle. This is especially useful for small boat defense (Watkins, 2005).

Item	min	max	measure
ammunition	6	100	bursts
gun train	10	45	degrees/second
target acquisition	2	25	seconds
inter-firing time	1	4	seconds
firing arc	120	210	degrees
engagement distance	50 - 200	4500	yards

Table 2.2: Auxiliary Gun characteristics

It may be important to point out that common frigate designs especially from the late seventies did not sport any auxiliary gun systems, since in the scenarios discussed in those times they were deemed incapable of aiding in the protection of convoy operations, ASW operations or the defense of the frigate itself (Table 2.2).[22]

Close In Weapon System (CIWS)

At the time of writing, two types of CIW systems are being deployed, missile based and gun based systems.
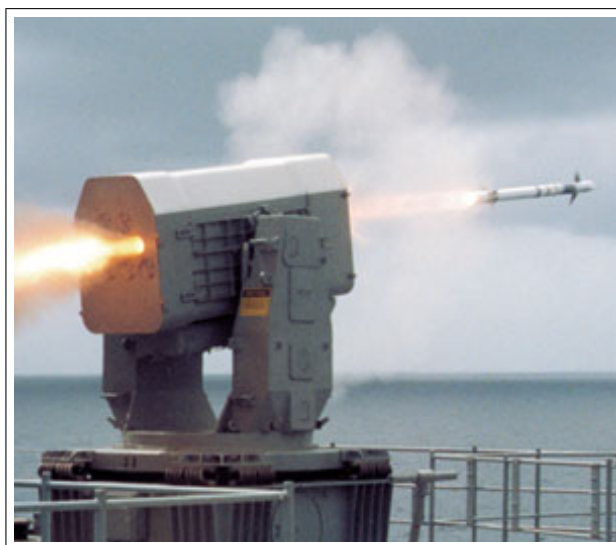
Figure 2.5: RAM launcher prior to HAS upgrade aboard a frigate.

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[22]The real threats were seen as guided missiles and missile equipped aircraft shooting from very long distances, therefore close in defense was secondary.

Item	min	max	measure
ammunition	8	14	bursts
gun train	30	60	degrees/second
target acquisition	5	15	seconds
inter-firing time	3	20	seconds
firing arc	180	360	degrees
engagement distance	150 – 300	4000	yards

Table 2.3: CIWS (Gun-based) characteristics

Gun based CIW systems fire a stream of projectiles to intercept an approaching enemy missile, with between 90 and 200+ projectiles per burst. Current gun designs have around 10–15 bursts until they need reloading. If possible, a complete at-sea reload takes anywhere from 15 to 60 minutes,[23] depending on how the gun was integrated and how much ammo is loaded. Both the GOALKEEPER and the Phalanx CIWS models have inherent tracking and interception capabilities for air targets. Recent versions also have a high hit probability for seaborne vessels of small to large sizes (Table 2.3) (Martin, 2000).

Missile based CIW systems fire one or more short range missiles at high speed at their intended target. They intend to either kill through kinetic force or through detonating a small charge and spraying the area with fragments. Of the many missile based CIWS[24] only RAM-HAS[25] BK I missiles are capable of tracking and intercepting waterborne targets. The probability to hit a target is in excess of P(hit) = 0.95 per missile (Table 2.6). Usually two missiles are shot at each target, and deliver a 25 pound blast-fragmentation warhead. The RAM system stores 21 missiles per launcher and usually two launchers are equipped on each ship. Therefore, it can attack 21 targets until it needs to reload (Diehl Defense, 2009). Even though technically possible, most vessels have no extra stock of RAM missiles in their magazines (see Table 2.4). To recap, of both gun and missile CIW systems only the newest generation can engage small, floating targets with high accuracy.[26]

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[23]Including the time to haul the ammo to the gun, reload, and clear the area afterwards.

[24]To name the most common: RAM (USA/Germany), Sea Wolf (UK), Sadral (France), Sea-Sprint (Canada), SA-N-11 (Russia), HQ-7 (China).

[25]HAS: Helicopter, Aircraft, Surface craft interception upgrade.

[26]Or, in case of missile CIWS, only the latest generation.
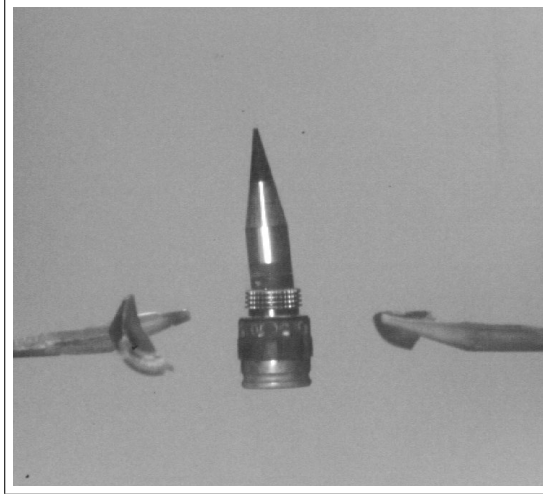
Figure 2.6: Phalanx MK149 Armour Piercing Discarding Sabot round discarding its sabot and petal (From DRS-Technologies, 2004).

Item	min	max	measure
ammunition	9	30	tandem missiles
launcher train	30	60	degrees/second
target acquisition	7	20	seconds
inter-firing time	3	20	seconds
firing arc	180	360	degrees
engagement distance	200 – 350	6000	yards

Table 2.4: CIWS (Missile-based) characteristics

As both systems are nearly identical, with the only exception being that gun based CIWS may be reloaded at sea, for this study they are modeled as a single system. The only true difference is in the cost per engagement, which is not a factor being investigated in this study.

2.1.3 Helicopters Equipped with AGM-114N Hellfire Missiles

Most NATO shipboard helicopters are not designed for and are not effective in a surface attack role. The U.S. Army is now assigning ground attack missions to fixed-wing aircraft because ground-attack helicopters have proved to be highly vulnerable to small-arms fire (Grant, 2006). The only shipboard helicopter designed for ASuW missions is the recently introduced MH-60R Seahawk using the AGM-114N and AGM-114M Hellfire II Missiles. In August of 2008, the first operational Naval Helicopter Squadron equipped with the new MH-60R Seahawk, accompanied by the AGM-114N Hellfire II missile, became combat operational. With

22

Item	min	max	measure
ammunition	2	8	Missiles
Helicopter Speed	0	195	Knots
target acquisition	5	15	seconds
inter-firing time	5	20	seconds
firing arc	180	360	degrees
engagement distance	250	10000	yards

Table 2.5: Helicopter with Hellfire Missile characteristics (From Norman Friedman, 2006)

this missile, precise, effective and lethal firepower may be projected at land and at sea based targets, from distances as far as five miles (Lockheed Martin, 2009).

To find its intended target, the Hellfire missile uses laser guidance. The missile's laser seeker acquires and locks-on to a coded laser's energy reflected from the target prior to launch. The seeker is designed to be resilient against dust, sea spray and light clouds. Once a Hellfire loses the laser designator, it will, with a high probability, not reacquire the designator and will then miss its target. Training data suggests a P(hit) of 0.3 to 0.7 depending on helicopter crew training, weather and target speed (Pike, 2007). If AGM-114M or AGM-114N missiles score a hit, there is a very high probability of killing the targeted SAFC.

Within the simulation there is either no or exactly one helicopter in a scenario. If there is a helicopter, it will be armed with two to eight AGM-114N Hellfire II missiles (Table 2.5). Zero helicopters in a scenario does not necessarily mean that the frigate has no helicopter complement aboard. This can also indicate that the frigate has a helicopter aboard, but has decided not to launch it, or that the frigate has a helicopter, but the helicopter is not armed with any reasonable air to ground capabilities. The launch of a helicopter during an attack is thought to be a very unlikely event and therefore is not modeled.[27]

2.1.4   Frigate Weapon Hit Probabilities

Current hit probabilities for military weapons systems are nearly always considered a national secret and therefore impossible to research and implement in a simulation using open

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[27]The launch of a helicopter while being attacked is unlikely considering the time to prepare and launch a helicopter, as well as the frigate's steering limitations during the actual launch of the helicopter, both according to a subject matter expert.

Weapon	P(hit) min	P(hit) max
Main Gun	0.05	0.85
Auxiliary Gun	0.01	0.95
Small Gun	0.01	0.98
CIWS	0.75	0.99
Hellfire	0.70	0.99

Table 2.6: Model used Frigate Single Engagement Hit Probabilities

sources. Fortunately, some data, originating both in studies on now outdated weapons and government backed research not deemed secret, is accessible to the general public. Therefore, it is possible to use this data within this thesis. Some publications such as Jane's Naval Weapon Systems (Hooten, 2008) or the Naval Institutes Guide to World Naval Weapons (Norman Friedman, 2006) publish hit probabilities. For these publications, it is unclear how the authors determined them. Companies trying to sell their weapon and targeting systems will often publish reference hit probabilities and are another source of information. Also, system builders[28] tend to publish hit probabilities. Both industrial information sources are usually exaggerated, either positively or negatively. Subject matter experts, where available, are a good source on some systems, but are often unreliable. Finally there are weapon systems for which no data exists at all. By using designed experiments, however, we span a range of settings which is selected as to include values that, to us, are unknown.

For this paper, all available open sources are used. Data input is further varied to allow for different systems performance and to fully explore the space of possibilities (Table 2.6). Factors such as wind, sea-state, crew training, weapon alignment and maneuvering are taken in account within the exploration of the model setting, yielding a robust structure for analyzing the model.

2.2 SAFC Setup

Fishermen in the Bab-El-Mandeb and Gulf of Aden region catch fish using small and mid-sized dhows. These dhows are often accompanied by small, agile and fast craft. These craft range from skiffs, flatbed boats to small inflatable dinghies. The preferred fishing method is either to trawl, or to hunt fish using the small craft. When using the fast craft, speed is im-

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[28]System builders usually do not produce weapons themselves, but buy and integrate different systems as a package and sell those.

portant to steer the swarm into the nets. Therefore, these craft usually get at least 15 knots, but modern variants can speed up to 45 knots.

Especially with the modern Somali buccaneers, a trend to upgrade, as well as to modernize, can be observed (NATO Operations, 2009). Those full time pirates not only invest their ransom money in good living (Arabian Business, 2007), but also in good equipment to get more money and, most importantly, in an improved business infrastructure. Early knowledge of targets is a valuable asset for the pirate business (Newton, 2008). With increased revenues, foreign criminal elements are trying to access these business infrastructures, providing additional logistics. These in turn allow the pirates to obtain a very recent operational picture, and are the basis of this study's assumption that the attack on the frigate is planned, not an accident (Tremlett, 2009).

Item	min	max	unit
Max Speed	15	45	Knots
Size	5	15	meters
RPG-7	1	2	ea
Handheld Weapon	0	2	ea

Table 2.7: Small Agile Fast Craft (SAFC) setup

2.2.1 Distillation of Different Small Agile Fast Craft Types

As with the frigates, the SAFC are a distillation of the multitude of vessels considered (Table 2.7). Based on observation and media coverage, almost any kind of floating small vessel will be used for fishing purposes, and as such for the occasional pirate activity. There are dinghies, inflatable dinghies, flatbed boats, skiffs and various other kinds of glass fabric, metal and wood open speedboats. There is not one influential or common type, normally not even within one fishing group. Therefore factors such as speed and stability (influencing hit probabilities) will need to be varied extensively.

2.2.2 Weapons Considered for the SAFC

Weapon types for the SAFC were chosen based on two assumptions: either because they are thought to be readily available on the black market, or because large quantities were sold to the area of interest, thus making them accessible to potential attackers. Both assumptions also

Item	min	max	measure
ammunition	5	15	bursts
target acquisition	2	5	seconds
inter-firing time	1	4	seconds
firing arc	120	360	degrees
engagement distance	0	1000	yards

Table 2.8: Hand-held Weapons characteristics

allow the attackers to acquire enough ammunition for the planned attack. Only medium and large caliber rifles and shoulder launched weapons are selected for inclusion in this study. Most weapons within one category do not differ much in relation to range, lethality and ammunition available. Therefore, it is not that important what specific kind of weapon the SAFC employ, only what category and how many. Anything smaller than an assault rifle is not considered relevant, as the effect on a frigate would be negligible.

Weapons considered in the "handheld weapon" role include the PK / RPK 7.62 mm, the Rheinmetall MG 3, the NSV 12.7 mm, the QJZ 89 (light version), the AK 47, AK 74, the H&K G3 and the FN FAL. The main weapon of choice for dealing damage to frigates is the well-known "RPG 7" rocket propelled Grenade launcher.[29] The RPG-7 was chosen for both market availability and price (Table 2.8 and Table 2.9).

2.2.3 Handheld Weapon Hit Probabilities

The hit probabilities for hand operated and aimed weapons, even more so than those of weapons mounted on a ship, depend on many factors. There are factors beyond the control of the attacker, like target size and speed. Factors under control of the attacker include the stability of the platform, speed at which the platform is moving, the weapon and aiming proficiency of the user and, only as a secondary measure, the accuracy of the weapon itself.[30]

Single shot and burst fire hit probabilities were collected from subject matter experts and, if open sources were accessible and still valid, from army and navy field experiment data.

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[29]Each of the listed weapons is produced by many countries, produced for at least 40 years, is officially adopted by at least 25 countries and has a very high number built, both licensed and copied (Jones and Cutshaw, 2005).

[30]Both LMG's and especially HMG's are not easily trained at targets, but usually have some kind of gun mount. In order not to shoot its own crew, and to keep the craft stable, in reality the firing arcs of both weapons are reduced. As all handheld weapons of the SAFC are distilled into one this reduced weapon arc is not modeled.

Item	min	max	measure
ammunition	4	8	rockets
target acquisition	2	5	seconds
inter-firing time	10	25	seconds
firing arc	90	180	degrees
engagement distance	50	950	yards

Table 2.9: RPG-7 characteristics (From U.S. Army Training & Doctrine Command, 1976)[31]

Weapon	P(hit) min	P(hit) max
RPG-7	0.20	0.90
Handheld Weapon	0.30	0.90

Table 2.10: Model used SAFC Single Engagement Hit Probabilities

Based on lengthy discussions, handheld weapon hit probabilities for a SAFC are thought to be between 1/4 and 1/10 of known hit probabilities, which were experimentally derived by firing these weapons at a dedicated range with a stable platform and weapon mounting (Table 2.10). Additionally, for series of shots that arrange themselves in chain-like patterns,[32] the simple formula $P = 1 - (1 - kp)^n$, where "p" is equal to the probability mass on target for a single shot, and "k" is the average fraction of the target area covered by shots, may be used to derive the probability of at least one hit out of a salvo of shots (Zahle, 1971). These probabilities are exponentially adversely influenced by sea state, from no influence at sea state 0, to a 35 percent decrease at sea state 1, 75 percent at sea state 2 and 95 percent at sea state 3. Small craft are not likely to operate beyond sea state 3 (Associated Press, 2009). These factors are included in the design of experiments. However, since they are outside the control of NATO Forces, they are only interesting insofar as they contribute to the uncertainty of the outcome in an encounter. As such, they are only modeled at two levels.

2.2.4 Weapon Hit Probabilities versus Helicopter

No dedicated hit probabilities are designated for attacking the helicopter. As the frigate is the primary target, the helicopter is modeled so as to usually operate from out of reach of the SAFC, which is quite a realistic assumption. This way, the SAFC will focus its attack on the frigate, and only attack the helicopter if they happen to be near it by chance.

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[32]As for example with an automatic rifle/gun employing belted ammunition and a low inter-firing time.

Figure 2.7: A variety of SAFC weaponry (not to scale, clockwise from upper left): NSV 12.7, AK 47 II, H&K G3A5, Rheinmetall MG3A3, RPG-7.

2.3   Scenario and Modeling Environment

This section describes how the MANA modeling environment, Version 4.04, was utilized to develop a green water scenario of a frigate being attacked by multiple small, agile and fast craft. After a brief overview of the model's capability, the advantages and disadvantages of using MANA versus other modeling environments are discussed. The impact of using time stepped versus discrete event simulations is discussed. Finally, the model implementation and the chosen measures of effectiveness are explained.

It is important to remember that this study is interested only in whether the frigate survives an engagement or not. The survival rate of the SAFC and the survival of the helicopter if present in a scenario are not of interest.

2.3.1   Attacker Motivation

The motivation of SAFC is to achieve maximum media coverage of the incident and a disgrace of the stronger and technologically advanced enemy. The attackers hope for some form of retaliatory measure involving declared innocents, therefore gaining more followers or money to continue their aggressive behavior and expand their influence.

As the attack occurs at sea, for best effect the attack must either be recorded or the attacked ship needs to be able to return to port, exploiting full media coverage. This will be considered when determining the number of rounds each SAFC fires before it flees.

2.3.2   Area of Operations

The area of operations (AO) is set within a free stretch of water with no barriers or boundaries. The frigate is on an assumed typical intelligence gathering and observation mission. There are no other friendly forces but some assumed neutral traffic in the AO. There are no known hostile contacts in the AO, and no intelligence of planned hostile activities is known. The frigate operates under standard NATO ROE's. One noteworthy ROE is that the frigate may actively defend itself when being shot at or when the attackers cross into the frigates safety zone.

2.3.3   The Chosen Agent-based Modeling Environment: MANA

Many modeling environments were considered when planning this study. The MANA, Pythagoras and SimKit modeling environments were each considered to determine how well they were suited for the study.

A "model" as used in this study is defined "as a system used as a surrogate for another system (Schruben, 1992)." In a typical agent based modeling environment, a system of agents "substitutes for human subjects and military hardware in the experimentation process and are the sources of the data (Alberts, 2005)". An "agent" in context as used in this study is a network of interactive processes and elements (Holland and Miller, 1991). The environment is the software, spreadsheet or any other means within which the agent based simulation is executed. An Agent Based Simulation (ABM) is thus "a simulation made up of agents, objects or entities that behave autonomously. These agents are aware of (and interact with) their local environment through simple internal rules for decision-making, movement, and action (Cioppa et al., 2002)."

The first environment studied was SimKit. SimKit is a discrete event simulation application program interface (API) for creating models using Java. Building a model in SimKit starts by developing an event graph (Schruben, 1992) of the agent behavior to be modeled, and then implementing this event graph in SimKit (Buss, 2009). After development and initial implementation of the event graph (Appendix D), SimKit was not pursued any further. Even though

SimKit allows implementation of the model in great detail and exactly to specifications, the time to build a running model and to implement correct agent behavior was deemed too costly when compared to the time needed for actual analysis of data gathered by the model. The event graph was used for the implementation in the other modeling environments, as it is a great tool to visualize what is to be studied.

The next environment investigated was Pythagoras. Pythagoras is a time-stepped agent based simulation that was developed for the United States Marine Corps's Project Albert (Lawlor, 2005). Using Pythagoras it is possible to model soft decision rules, driving the agents by desires and distinguishing between different parties of the overall same side using a concept called "sidedness" (or affiliation). Pythagoras software has been released as open source (Stallman, 2002) and is designed to produce modeling results quickly and easily. Pythagoras was not chosen as the modeling environment for this study as it has no concept of agent orientation. Modeling port and starboard is an important concept for frigates. Frigate weapon systems are typically built symmetrically about the sagittal plane, resulting in complementary weapon arcs (Bitinas et al., 2005).

The model chosen was MANA, the Map-Aware Non-uniform Automata. MANA, currently at version 4.04, is actively developed by the New Zealand Defense Force. The developing agency is the Defense Technology Agency (DTA) (New Zealand Defense Force, 2009). At time of writing, version 5 of MANA is in beta testing, and is expected to be released around the beginning of 2010. MANA is a time stepped, agent based modeling environment designed with a graphic user interface. MANA was designed to be user friendly and to achieve fast run times. MANA is delivered as a pre-compiled executable for any Windows based environment. MANA has built-in data farming capability based on an XML input file, allowing one to implement a design of experiments quickly and efficiently once the XML syntax is well understood. Agent's desires are easily adjusted and state changes to their behavior are well implemented. By hosting and participating in International Data Farming Workshops, the NPS Simulation, Experimentation and Efficient Design (SEED) Center for Data Farming has direct ties with DTA (Horne, 2009). This allows for direct consultation and rapid problem resolution with DTA. MANA was chosen as it incorporates all aspects that were deemed necessary for a successful implementation of the model for this study.

2.4 Model Implementation in MANA

Whatever is necessary to answer the research question, a good vision of what needs to be implemented and measured is crucial in the process of building the simulation model. In case study, the behaviors and interactions were visualized using an event graph. Alas, as with most prefabricated modeling environments, it is not always possible to convert vision to model in a one-to-one fashion. Sometimes it is necessary to think around predefined edges, bending the model, and some things can not be implementable at all.

As is true with battle plans, a vision will not survive its first model runs unchanged.

2.4.1 Battlefield Map

The battlefield map represents open waters, with no natural movement constraints for any of the agents. The frigate agent's starting area is in the lower left corner. The frigate agent's goal is in the upper right corner.

Underlying the map is a grid of 600x600 pixels. Each grid is designed to represent a square with a side length of 50 yards. MANA is time stepped, and the fastest agent, the helicopter, has a maximum speed of 190 knots. A timestep is translated to represent 0.5 seconds, which prevents the helicopter from skipping over grid positions.[33] All agent movement and any actions taken therefore need to be scaled for compatibility with the selected timesteps.

2.4.2 Initial Settings of the Model

The scenario places the frigate on a straight track from the lower left to the upper right corner of the map. As described in Chapter 3, the track will be traversed at different speeds, allowing the frigate's contact with the SAFC to occur at different times, speeds and bearings.

The SAFC are randomly instantiated in the two yellow areas (Figure 2.8), whereas the frigate's instance (and the helicopter) will be randomly placed within the green area of the map. The frigate will initially follow the green track through the map (Figure 2.8).

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[33]Skipping grid positions is generally considered a bad thing, as it makes it possible to pass through barriers and teleport through agents occupying a given area without detecting and / or interacting with them.
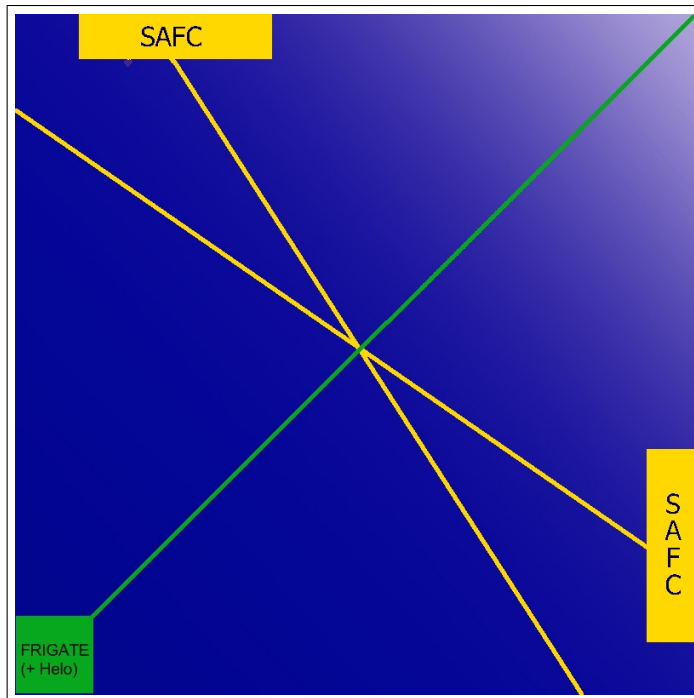
Figure 2.8: The basic setup of the battlefield map.

There will always be only one frigate, either with or without an accompanying heli-copter, and between four and eight SAFC. The SAFC will track and try to intercept the frigate, but will also attack the helicopter if offered the chance. The helicopter will either be available from the start of a scenario, or not at all.

2.4.3   Conditions of the Model

The frigate will be considered to have "lost" the scenario when it is hit as many times as it has allocated hit points. Using this method allows us to conceptualize the frigate as a single entity without the need to model every and all compartments, personnel and machinery.

The attackers are not evaluated regarding "lost" or "won" conditions. Attackers are designed to expend all ammo of their main weapon, trying to escape afterwards. An escaping SAFC is designed such as not to be a target of interest to the frigate.

2.4.4 Constraints of the Model

MANA is, essentially, designed and optimized for land combat modelling (McIntosh et al., 2007b). Therefore, many agent's behaviors are not modeled as would be expected from a naval perspective. The behavior lacking the most is weapons control and weapon assignment. Each agent can use up to six weapons, numbered one through six. Weapons are not fired truly simultaneously, even though they may be fired in the same timestep. MANA uses a simple algorithm for determining what weapon to use to attack a certain enemy agent. According to the MANA manual,

> Weapons in MANA are modeled using simple probabilities to decide if agents can been shot within a certain range.... (E)ach turn, each weapon with ammunition is fired. Firing is in order of weapon number. The user is advised to put their most effective weapon first (number 1) to avoid wasting ammunition from less effective weapons. (McIntosh et al., 2007a)

Thus the algorithm does not distinguish between hit probabilities (Figure 2.9). Extensive testing has also shown that an agent will within one timestep often not discharge more than one weapon at a distinct target. More interestingly, this behavior is observable over multiple timesteps, even if more than one weapon is within range and within the firing arc during all timesteps. This is caused by the probabilistic method to determine if a certain weapon is discharged during a certain time step. Most of the weapons shoot once every twenty turns, on average. Given this input, the probability that they will not discharge in a given round is 0.95. The chance that a certain weapon will not have discharged in 30 rounds is $(1 - P)^{30}$.

As it is not possible to influence the discharging algorithm, the hit probabilities per se have implications on modeling. The agents will shoot their weapons even when probabilities to hit are very low, for example at a long distance. An experienced or well trained human operator would probably not shoot and waste ammunition at those distances. Therefore, weapon ranges are reduced to avoid this undesired behavior. Weapon ranges are cut off at a predetermined maximum effective range. Similarily, the decision was made not to vary weapon position within the design panel. For the frigate, weapon numbers are as follows: 1 — Main Gun; 2 — Aux Gun Port; 3 — Aux Gun Starboard; 4 — Small Guns; 5 — CIWS. For the SAFC, weapon numbers are as follows: 1 — RPG-7; 2 — Handheld automatic weapon; 3 — RPG-7. The Helicopter only has one weapon system, the Hellfire missile, always at position one. The calculation of hit probabilities corresponding to the timestep is detailed in Chapter 3.

2.4.5 Constraints of Modeling

In order to intercept the frigate, the SAFC will always know the position of the frigate and never lose track, as may happen in reality. Also, the frigate will only employ up to six different weapons at one time, as the model only allows this many weapons to be equipped at once. Multiple identical weapons other than the auxiliary gun systems are modeled as one weapon with a higher $P(hit)$, as more shots are fired in the direction of the enemy than with a single weapon.

Two distinct behaviors of the frigate are modeled: with and without regard to ROE. Without ROE, once one SAFC is deemed hostile, all other approaching SAFC are also classified as being hostile. This may actually reflect the reaction of the frigate in a real engagement. In the heat of battle, most contacts closing in and somewhat similar to the hostile vessel would be assumed to be involved with the attack in progress.

When on the other hand the frigate is acting in accordance to ROE, it will only shoot at targets that either shoot at the frigate or get too close to the frigate. "Close" is a factor that is varied extensively, modeling different types of commanding officers. To prevent the frigate from shooting at fleeing targets, they will change to a different state, and be effectively neutral. The frigate will then at once cease firing upon the SAFC, even though in reality, more shots might be fired until the target is no longer deemed to be a threat.

Figure 2.9: MANA setup panel for a high explosive weapon.

2.4.6   Damage Model for the Frigate, Helicopter and SAFC

The frigate has a fixed number of initial hit points. After the frigate has sustained a number of hits corresponding to the number of hit points, it is considered to be killed, and the scenario is over. This kill represents a mission kill. The number of hit points allocated to the frigate is an abstraction and represents three different modeling aspects. First, it represents the structural integrity of the frigate, with all its components. Secondly, it represents the crew's training and aptitude to repair damage sustained. Third, it represents the size of the frigate. A frigate is comparatively large; it is very hard to actually hit it where real damage may be dealt.

The model developed does not allow for catastrophic failure on the part of the frigate. This decision is based on two assumptions: 1) the probability of a catastrophic hit on a frigate is not predictable (as there are few data available on hit probabilities, and there are no data on how fuel or explosives on board the frigate react to small arms fire) and 2) including catastrophic failures does not add to the analysis of this experiment. Even though the set of unit kills contains the mission kill, it might add undesirable interactions. For these two reasons, a catastrophic failure is not permitted.

Allowing SAFC to have hit points may seem awkward. When determining a hit on a SAFC by, for example, a frigate's 127mm main gun, it may seem wrong, or strange, to allow the SAFC to continue to operate. On the other hand, a hit on a SAFC is not necessarily a direct strike. When looking at it in this way, allowing the SAFC to have hit points makes sense. Contrary to the frigate, the SAFC hit points represent the inability of the frigate's weapon systems to accurately track and engage these small and fast vessels, especially in higher sea-states.

2.5   Measure of Effectiveness in MANA

A "measure of effectiveness" is a common measure in which vast amounts of data are distilled into relevant information related to a specific objective. As such in this study it is used as a performance indicator. The frigate is attacked by different numbers of varying types of small agile and fast craft. It was planned to measure the defender's effectiveness by the formula "damage obtained divided by attackers neutralized." This measure is not supported by MANA, as the software does not provide feedback on damage dealt or received.

Therefore, it was decided to use the number of frigates killed[34] as the measure of effectiveness. This binary response variable is then averaged over the iterations and over the noise factor settings, effectively converting the response from binary to continuous.

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[34]As only one frigate is modeled, this value obviously is either zero or one.

CHAPTER 3:
Design Of Experiments

3.1 Introduction

Design of Experiments (DoE) describes the setup of a simulation's variable parameter space. In reality this variability may or may not be under control of the designer (Fisher and Prance, 1974). Design of Experiments (DoE) follows a stringent methodology. DoE for simulations employs elements such as randomization, replication, orthogonality and experiments whose design consists of two or more parameters with discrete possible values each, known as "factorial designs" (NIST, 2009).

Within this thesis a fractional factorial design will be developed to answer the questions as discussed in Chapter 1. Following a brief discussion of definitions and formulas as used in the following sections, the variables varied in the frigate and SAFC design are detailed. Then it is explained how the experiment is set up. Finally insights that were discovered during the execution of preliminary model runs detailed.

3.2 Definitions and Formulas

3.2.1 Data Farming and Data Mining

In this thesis, a technique called "data farming" is employed. With this technique a simulation model is run over thousands or even millions of replications. At each replication, input variables are changed using a predefined, designed approach (Horne and Meyer, 2004). This data farming approach "allows a scenario's parameter space to be explored rapidly (McIntosh et al., 2007b)," and helps to identify regions containing interesting constellations (Cioppa et al., 2004). Using a specific experimental design ensures that the parameter space is searched in an efficient manner.

Data farming is not to be confused with data mining. Data mining is the science of analyzing large data sets or databases with many different algorithms and procedures to find some information previously unrecognized within all the available information (Hand et al., 2001). Thus, data mining will take any amount of data that is collected for varying purposes and extracts information, whereas in data farming through design of experiments resulting data seams

are modeled a way that information might be easily harvested by employing a predetermined procedure (O'Reilly, 2005). Using a data farming approach data mining may nonetheless be used to discover relations in the produced data stream that may otherwise be overlooked (Kusiak, 2006).

3.2.2   Robust Design and the Taguchi Method

Often, only parameters are admitted to a design of which the designer — sometimes with the help of some subject matter experts — believes are valid. They actively try to suppress any external variability when testing their design. Sometimes, this can result in assumptions that greatly underestimate the variance of certain events. To avoid this caveat a methodology called "robust design" will be used in this thesis (Taguchi, 2002). This method allows the experiments designer to determine which parameter values most affect the measure of effectiveness in a chain of experiments. This is achieved by both varying parameters that are influenceable by the design specifications, as well as those that are encountered under real conditions, and typically are not controllable. All these variations are then tested in a multitude of combinations, whether they might or might not occur in practice. This extensively regulated process is called the "Taguchi Method" (Taguchi, 1995). While in this thesis we will vary both controllable and uncontrollable parameters extensively, strict adherence to Taguchi's tactics are not required for a robust design. Therefore, Taguchi's strategy is followed, but not his tactics.

3.2.3   Controllable Factors and Noise Factors

Primary treatment variables or any input parameters and structural assumptions composing a model that could potentially be changed are called "factors" (Law, 2007). Factors are classified as controllable and uncontrollable factors. A controllable factor is one that may be influenced by the decision maker, e.g., the number of guns on a ship. Uncontrollable factors are those not controllable by the decision maker, e.g., the weather or an adversary's weapon systems (Kass, 2006). Uncontrollable factors may be treated as "noise factors". Even though it is accepted that it is not possible to influence their value, they might be relevant to the behavior of the system. Most often it is possible to predict a valid range in which they might be encountered, e.g., by assessing historic data. As all factors in the experiment are accessible to the experimenter, they may be varied and thus introduce natural variability to the model. In contrast to controllable factors, they are not treated as input parameters to the later analysis (Law, 2007).

3.2.4 Design Points

A factor may be static or have different levels during the run of an experiment. When constructing an experiment with multiple varying factor levels each factor will be combined with other factors. This is usually done in a manner such as to reduce correlation. These factor-level combinations are called design points (Banks et al., 2006).

3.2.5 Step Function, Concerning Hit Probabilities

In models not using physical representation,[35] a true (or more drastically, real) hit probability is nearly impossible to calculate due to the high level of abstraction. In contrast to approaches using highly complicated formulas to determine hit probabilities, it was decided to use a step-function to model this problem.

A step function results in hit probabilities that remain constant between a minimum distance[36] and a predefined maximum effective distance. This maximum distance is called maximum effective range (MER). MER is the "maximum distance at which a weapon may be expected to be accurate and achieve the desired result (Navias and Hooton, 2001)". It is assumed that a human controller proficient with a certain weapon would know about the rapidly declining accuracy and thus not shoot further than this distance.

3.2.6 Data Conversion for the Model Implementation

Conversion of speed, rounds per minute and inter firing times are calculated by formulas. Speed is the most complex formula, as distances are measured in basic grids of 50yds per timestep, and the corresponding timestep is half a second. The formula for converting MANA speed expressions to expression of speed in knots:[37]

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[35]By modeling atoms, molecules and their interactions.

[36]This is a physical constraint due to a gun's barrel position combined with its maximum elevations, and an explosive projectile's fuses arming only after some flight. Compare Joint Publication 1-02 (Navias and Hooton, 2001).

[37]This conversion is not quite correct, as one knot actually converts to approximately 2025.371 yards per hour. As the model of this study is based on quite a high level of abstraction, dropping about twenty six yards per knot per hour is deemed acceptable (Institute for Electrical and Electronics Engineers, 2007).

$$((\frac{(60*2)}{(1/(\frac{ManaSpeed}{100}))})*60*50)/2000.$$

MANA represents speed by the expression $P_{move} = (Grids/100)$ per turn, where Grids $\in \mathbb{N} < 1000$.

Rounds per minute, a measure often expressed in weapon system guides, are converted from MANA (and vice versa) as follows:

$$\frac{60*2}{(1/(\frac{InterFiringTime}{100}))}.$$

Another important measure to have a real world expression for is inter firing times. Inter-firing times are a measure for how long it takes between shots at a certain or two different targets. Inter-firing times are converted to and from MANA using the following formula :

$$\frac{1}{(\frac{2}{(1/(\frac{InterFiringTime}{100}))})}.$$

Inter firing times are represented in MANA by the Expression $P_{shoot} = (Shots/100)$ per turn.

3.2.7   Nearly Orthogonal Latin Hypercubes (NOLH)

NOLH History

NOLH experimental design techniques were researched and implemented by Lt.Col. T. Cioppa in 2002 and further refined by Joshua Ang Keng-Ern in 2006. Lt.Col. Cioppa began his work by relaxing Orthogonal Latin Hypercubes (OLH) design criteria. He coined the term NOLH and researched these Latin Hypercube subclasses to efficiently work with simulations that require a huge number of input factors. At the same time, NOLH designs require only a limited amount of prior assumptions (Cioppa, 2002).

The nearly orthogonal arrangement is designed in a way that a maximum pairwise correlation of 0.03 is observed. The nearly orthogonal quality of the design allow for addition or removal of terms without affecting the estimates, which in turn make the use of efficient analysis methods possible (Ang Keng-Ern, 2006). This property in contrast to traditional grid-based factorial design techniques, which either considered only high and low values for the factor lev-

els or had to constrain the number of input variables in order to complete the simulation study in a reasonable amount of time.

Desirable NOLH Characteristics

From a design of experiments point of view, the orthogonality as measured by the absolute maximum pairwise correlation ρ_{amp} and the condition number $cond(\mathbb{H}^T\mathbb{H})$ is very desirable. Another desirable characteristic of interest is the design's space filling characteristic ML_2 as measured by the formula (Hickernell, 1998):[38]

$$ML_2(\mathbb{X}) = \left(\frac{4}{3}\right)^k - \frac{2^{1-k}}{n}\sum_{d=1}^{n}\prod_{i=1}^{k}(3 - x_{di}^2) + \frac{1}{n^2}\sum_{d=1}^{n}\sum_{j=1}^{n}\prod_{i=1}^{k}[2 - \max(x_{di}, x_{ji})].$$

This measure is important, as it allows the fast exploration of huge factor ranges that otherwise would have to be explored by computing every possible factor-level combination. That kind of design is called a full factorial design. A full factorial design with up to five or six factors is computable in reasonable time.

NOLH used in this Study

NOLH designs will, due to their design characteristic, not explore the complete possibility space. This is best shown when comparing the scatterplot matrix of the frigate's factors (Figure 3.1). They will allow the analyst to explore — in finite and reasonable time — a larger and still very broad section of this input space as in comparison to traditional methods. To generate the NOLH design for this study, a spreadsheet coded by Professor Susan Sanchez, NPS Monterey, is used (Sanchez, 2005).

3.2.8 Factor Lockstepping

Due to the complexity of finding NOLH designs of high order, only models containing up to 29 factors may be modeled using the spreadsheet at this time. The final experimental model of this study contains 41 individual factors. To study these factors with the available designs, some factors were lockstepped. Lockstepping is the process of varying multiple measures

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[38] $ML_2(\mathbb{X})$ is a variant of the L_p-discrepancy where $\mathbb{X}$ denotes the matrix being measured. x_{di}, x_{ji} denote any two vectors of $\mathbb{X}$. n and k are width and depth of $\mathbb{X}$, and d is a counter.
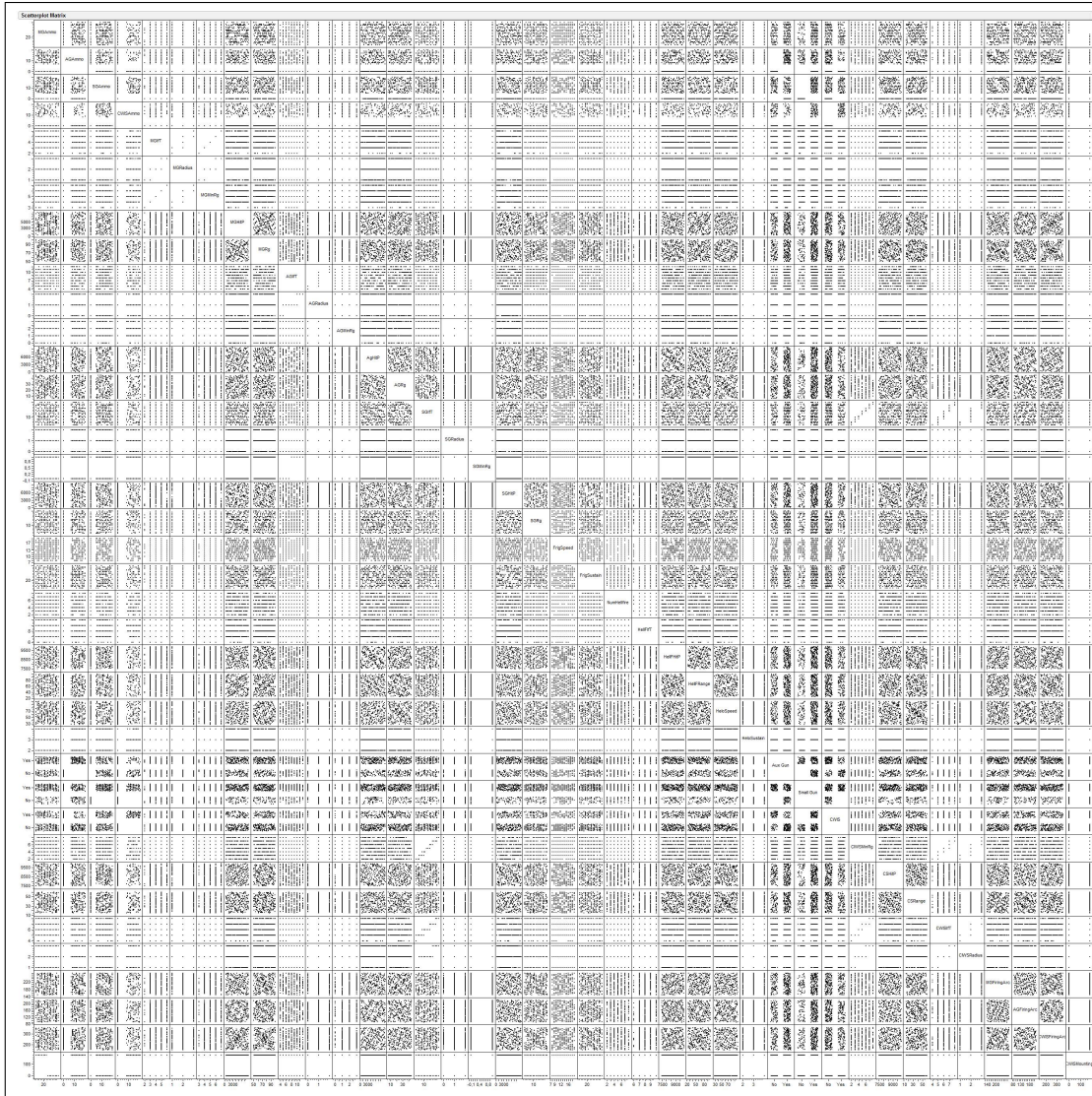
Figure 3.1: Scatter Plot Matrix of the frigate's variables to illustrate both the orthogonality and space filling properties of the NOLH used in this study. Names of the variables are in the diagonal.

using a single multiplier variable. Looking at Figure 3.1, rows 5,6 and 7 are easily recognized as being lockstepped.

The controllable factor matrix $\mathbb{C}$ is created by combining the non-lockstepped factors with the lockstepped factors calculated using the multiplication factors. The tables in the "Controllable Factors" (Chapter 3.3) section indicate the use of a NOLH or multiplication factor controlled variable.

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3.2.9 Hadamard Matrices

Hadamard matrices are named after the French mathematician Jacques Hadamard, invented in 1867. A "Hadamard matrix is a square matrix whose entries are either +1 or -1 and whose rows are mutually orthogonal (Mood, 1946)". A Hadamard matrix $\mathbb{H}$ of order n satisfies:[39]

$$\mathbb{H} \cdot \mathbb{H}^{\mathrm{T}} = nI_n$$

thus, consequently the determinant of $\mathbb{H}$ equals $\pm n^{n/2}$. Suppose that $\mathbb{M}$ is a complex matrix of order n, whose entries are bounded by $|\mathbb{M}_{ij}| \leq 1$, for each i, j between 1 and n. Then Hadamard's determinant bound states that

$$|\det(\mathbb{M})| \leq n^{n/2}.$$

Equality in this bound is attained for a real matrix $\mathbb{M}$ if and only if $\mathbb{M}$ is a Hadamard matrix.

The order of a Hadamard matrix is either 1, 2, or a multiple of 4. The Hadamard conjecture proposes that a Hadamard matrix of order $4k$ exists for every positive integer k (Cameron, 2006).

In this paper Hadamard matrices are used to induce factor variance with a two level noise factor design. The +1 entry is used for the high, and the -1 entry for the low level value. As Hadamard matrices are orthogonal, with a pure Hadamard design there is no correlation in between distinct factors.

3.2.10 Crossed Design

In a crossed design, each design point of one design matrix is concatenated to all rows of a second design matrix. For a robust design, a high-resolution design $\mathbb{C}$ such as the NOLH to study the controllable factors, and a low-resolution design $\mathbb{N}$ such as the Hadamard matrices to study the noise factors is used. This results in a run-file matrix $\mathbb{R}$. $\mathbb{R}$ is saved in the form of a comma separated values (CSV) file. CSV files are human-readable, standardized text-files.

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[39]Where I_n is the nn identity matrix and $\mathbb{H}^T$ is the transpose of $\mathbb{H}$.

3.3 Controllable Factors

In this section all controllable parameters are explained, whether they are factors directly controlled by a NOLH design, factors created by computation through lockstepping or fixed parameters.

3.3.1 Frigate Factors

Factors modeled for the frigate are its hit points, speed and the actual weapon mix employed by the frigate in each model run. Part of this weapon mix is the frigate's helicopter.

Frigate Hit Points

As shown in Chapter 2, a frigate is a complex system. For this study, most of the complexity is modeled by hit points. The hit points represent three major concepts. First, they represent the actual sustainable damage of the frigate's hull. Second, they represent how well the frigate's crew is able to control for any damage sustained. Finally, they are a measure of how probable a catastrophic hit is believed to be. As the frigate itself is a distillation of many different frigates, this value is varied extensively, and is implemented by an NOLH design. The minimum value of sustainable damage is 15 hits, and the maximum is 30 hits. Any damage sustained is not healed (repaired) during a run.

Frigate Speed

Once set, the frigate's speed is held constant during each run. This factor is varied by a NOLH design. The minimum speed modeled is 14.4 knots and the maximum speed modeled is 34.2 knots (Table 3.1). Speed is not represented in whole numbers as MANA input parameters are not entered as knots. One turn in MANA is defined as .5 seconds; therefore, the resulting real-world numbers are not whole.[40]

Frigate Weapon Mix

The weapons used by the frigate model are determined by a "weapon pack," varied via NOLH from 1 to 5. Each number is associated with a certain weapons pack; all packs equip a

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[40]Which, for the real world, is very real. It is actually very hard to exactly move at a certain speed — therefore, it is not deemed important that these numbers do not represent whole numbers.

Item	min	max	measure	varied by
Sustainable Damage	15	30	hits	NOLH
Maximum Speed	14.4	34.2	knots	NOLH

Table 3.1: Frigate factor design

main gun. Pack 1 adds a small gun; pack 2 consists of a small gun and a CIWS; pack 3 contains an auxiliary gun; pack 4 an auxiliary gun and a small gun; pack five adds an auxiliary gun, small gun and a CIWS. If a weapon is not enabled in a certain design point, its ammunition will also be reduced to 0 (Table 3.2).

Weapon Pack	Main Gun	Aux Gun	Small Gun	CIWS
Pack 1	1	0	1	0
Pack 2	1	0	1	1
Pack 3	1	1	0	0
Pack 4	1	1	1	0
Pack 5	1	1	1	1

Table 3.2: Frigate weapons packs — 0 denotes not present

3.3.2 Main Gun Factors

All frigates are modeled with having exactly one main gun. The main gun has six variable factors (Table 3.3). Factors modeled by a NOLH design are the main guns hit probability, ammunition, firing arc and its maximum effective range. Minimum range, inter-firing times and the round's impact probable lethal range (hit radius) are represented by dedicated scale factors modeled by NOLH. In multiple preliminary runs, these factors were shown not to be significant predicting damage to the frigate.

Main Gun Hit Probability

This factor describes the hit probability for the main gun's projectiles. It is held constant in between the main gun's minimum and maximum effective range. The hit probability is varied between 0.05 and 0.85.

Main Gun Ammunition

This factor describes the amount of ammunition for the main gun as carried by the frigate. The amount of ammunition is varied from 15 to 45 rounds.

Main Gun Inter Firing Time

The gun associated inter firing time. This factor subsumes such factors as reloading, target acquisition and aiming. The frigate's main gun is modeled shooting between 2.4 and 8 rounds per minute.

Main Gun Firing Arc

The firing arc of the main gun. This factor describes the physical and superstructure constraints of the weapons placement aboard the ship. The firing arc has its center at the bow of the frigate, and is divided in equal sections to both sides. The firing arc has a minimum value of $150°$ and a maximum value of $270°$.

Item	min	max	units	varied by
Hit probability			P(hit)	NOLH
Ammunition	15	45	bursts	NOLH
Inter firing time	2.4	8	rounds/minute	scale factor
Firing arc	180	360	degrees	NOLH
Lethal Radius	50	150	yards	scale factor
Maximum effective range	2500	5000	yards	NOLH
Minimum effective range	150	350	yards	scale factor

Table 3.3: Main Gun factor design

Main Gun Lethal Radius

The distance from point of impact around which lethal fragments are distributed. Many different sizes and types of rounds are used in naval warfare. Against SAFC, lethal radius is varied between 50 and 150 yards.

Main Gun Maximum Effective Range

The maximum range at which an efficient use of the expended round(s) is to be expected. Against SAFC, the MER is varied between 2500 and 5000 yards.

Main Gun Minimum Effective Range

The minimum range at which the frigate's main gun may shoot at. This factor subsumes two constraints. First, it is the physically constrained distance at which the main gun can fire from its mounting due to barrel minimum elevation. Secondly, it is the range at which a projectile will be armed and ready to engage. Minimum effective range is varied between 150 and 350 yards.

3.3.3 Auxiliary Gun Factors

All frigates modeled with an auxiliary gun have exactly two or four auxiliary guns. They are equally distributed on the port and starboard sides of the frigate model. The auxiliary gun has seven variable factors (Table 3.4). Factors modeled by a NOLH design are the auxiliary gun's hit probability, ammunition, firing arc and its maximum effective range. Minimum range, inter-firing times and the rounds impact probable lethal range (hit radius) are represented by dedicated scale factors modeled by NOLH. In multiple preliminary runs, these factors were shown not to be significant predicting damage to the frigate.

Auxiliary Gun Hit Probability

This factor describes the single engagement hit probability for a burst of the auxiliary gun's projectiles. It is held constant in between the auxiliary gun's minimum and maximum effective range. The hit probability is varied between 0.01 and 0.98.

Auxiliary Gun Ammunition

This factor describes the amount of ammunition for the auxiliary gun as carried by each weapon station. The amount of ammunition is varied from 7 to 20 bursts.

Auxiliary Gun Inter Firing Time

The gun associated inter firing time. This factor subsumes such factors as reloading, target acquisition and aiming. The frigate's auxiliary gun is modeled shooting between 4 and 12 aimed bursts per minute.

Auxiliary Guns Firing Arc

The firing arc of the auxiliary guns. This factor describes the physical and superstructure constraints of the weapons placement aboard the ship. The firing arc has its center on the port or starboard side of the frigate, and is divided in equal sections to both sides. Each firing arc has a minimum value of $90°$ and a maximum value of $220°$.

Auxiliary Gun Lethal Radius

The distance from point of impact around which a round is expected to inflict damage to a target. Many different sizes and types of rounds are used in naval warfare. Against SAFC, lethal radius is varied between 50 and 100 yards.

Auxiliary Gun Maximum Effective Range

The maximum range at which an efficient use of the expended round(s) is to be expected. Against SAFC, the MER is varied between 300 and 2250 yards.

Auxiliary Gun Minimum Effective Range

The minimum range at which the frigate's auxiliary guns may shoot. This factor subsumes two constraints. First, it is the physically constrained distance at which the auxiliary gun can fire from its mounting due to barrel minimum elevation. Secondly, it is the range at which a projectile, if active, will be armed and ready to engage. Minimum effective range is varied between 50 and 150 yards.

Item	min	max	units	varied by
Hit probability	0.01	0.98	P(hit)	NOLH
Ammunition	7	20	bursts	NOLH
Inter firing time	4	12	bursts/minute	scale factor
Firing arc	90	220	degrees	NOLH
Lethal Radius	50	100	yards	scale factor
Maximum effective range	300	2250	yards	NOLH
Minimum effective range	50	150	yards	scale factor

Table 3.4: Auxiliary Gun factor design

3.3.4   Small Guns Factors

If enabled, the frigate is modeled having multiple small guns. The small gun has five variable and two fixed factor (Table 3.5). Factors modeled by a NOLH design are the small gun's hit probability ammunition and its maximum effective range. Inter-firing times and the round's impact probable lethal error probable (projectile spray) are represented by dedicated scale factors modeled by NOLH. Small gun firing arc and minimum range factors are not varied. In multiple preliminary runs, these factors were shown not to be significant predicting damage to the frigate.

Small Gun Hit Probability

This factor describes the single engagement hit probability for a burst of the small gun's projectiles. It is held constant in between the small gun's minimum and maximum effective range. The hit probability is varied between 0.01 and 0.99.

Small Gun Ammunition

This factor describes the amount of ammunition for the small gun as carried at each weapon station. The amount of ammunition is varied from 6 to 20 bursts.

Small Gun Inter Firing Time

The small gun associated inter firing time. This factor subsumes such factors as reloading, target acquisition and aiming. The frigate's small guns are modeled shooting between 5 and 20 aimed bursts per minute.

Small Gun Firing Arc

The firing arc of the small guns. This factor describes the physical superstructure constraints of the weapons placement aboard the ship. The firing arc has its center at the bow of the frigate, and is covering $360°$ around the ship, without any variation.

Small Gun Lethal Radius

The distance from point of aim around which the bursts projectiles are distributed. A circular error probable is assumed for small guns. Against SAFC, lethal radius is varied between 50 and 100 yards.

Item	min	max	units	varied by
Hit probability	0.01	0.99	P(hit)	NOLH
Ammunition	6	20	bursts	NOLH
Inter firing time	5	20	bursts/minute	scale factor
Lethal Radius	50	100	yards	scale factor
Maximum effective range	200	1000	yards	NOLH

Table 3.5: Small Guns factor design

Small Gun Maximum Effective Range

The maximum range at which an efficient use of the expended round(s) is to be expected. Against SAFC, the MER is varied between 200 and 1000 yards.

Small Gun Minimum Effective Range

The minimum range at which the frigate's small guns may shoot at. This factor is fixed at 50 yards, the minimum distance allowable.

3.3.5 CIWS

If enabled, all frigates are modeled with having exactly one CIWS. The CIWS has eight variable factors (Table 3.6). Factors modeled by a NOLH design are the CIWS's hit probability, ammunition, firing arc, bow or aft placement and its maximum effective range.

Minimum range, inter-firing times and the round's impact probable lethal error probable (projectile spray) are represented by dedicated scale factors modeled by NOLH. In multiple preliminary runs, these factors were shown not to be significant predicting damage to the frigate.

CIWS Hit Probability

This factor describes a single engagement hit probability for a burst of CIWS projectiles. It is held constant in between the CIWS minimum and maximum effective range. The hit probability is varied between 0.75 and 0.99.

Item	min	max	units	varied by
Hit probability	0.75	0.99	P(hit)	NOLH
Ammunition	8	21	bursts	NOLH
Inter firing time	4	8	bursts/minute	scale factor
Firing arc	150	360	degrees	NOLH
Lethal Radius	50	150	yards	scale factor
Maximum effective range	750	3000	yards	NOLH
Minimum effective range	100	400	yards	scale factor
Placement	0	180	degree	NOLH

Table 3.6: CIWS factor design

CIWS Ammunition

This factor describes the number of bursts for the CIWS as carried by the frigate. The number of bursts is varied from 8 to 21.

CIWS Inter Firing Time

The CIWS associated inter firing time. This factor subsumes such factors as reloading, target acquisition and aiming, as well as projectile flight times. The frigate's CIWS is modeled shooting between 4 and 8 aimed bursts per minute.

CIWS Firing Arc

The firing arc of the CIWS. This factor describes the physical superstructure constraints of the weapons placement aboard the ship. The firing arc has its center according to the "CIWS placement" factor, and is divided in equal sections to both sides of the center. The firing arc has a minimum value of $150°$ and a maximum value of $360°$.

CIWS Lethal Radius

The distance from point of aim around which a burst's projectiles are distributed, or point of impact around which lethal fragments are distributed. Many different sizes and types of rounds are used in naval warfare. Against SAFC, lethal radius is varied between 50 and 150 yards.

CIWS Maximum Effective Range

The maximum range at which an efficient use of the expended round(s) is to be expected. Against SAFC, the MER is varied between 750 and 3000 yards.

CIWS Minimum Effective Range

The minimum range at which the frigate's CIWS may shoot at. This factor subsumes two constraints. First, it is the physically constrained distance at which the CIWS can fire from its mounting due to barrel minimum elevation. Secondly, it is the range at which a projectile, if active, will be armed and ready to engage. Minimum effective range is varied between 100 and 400 yards.

CIWS Placement

The placement of the single CIWS aboard the frigate. This factor influences where the center of the weapons arc is at. Modeled are either a bow ($0°$) or a stern ($180°$) placement of the weapon system.

3.3.6   Helicopter Factors

Helicopter Hit Points

As with the frigate, a helicopters complexity is modeled by hit points. The hit points represent two concepts. First, they represent the actual sustainable damage of the helicopter's hull. Second, they represent how good the helicopter's pilot is at evading incoming fire. The helicopter's hitpoints value is varied extensively, and is implemented by an NOLH design. The minimum value of sustainable damage is 2 hits, and the maximum is 4 hits. Any damage sustained is not healed (repaired) during a run.

Helicopter Speed

The helicopter's speed is held constant during each run. This factor is varied by a NOLH design. The minimum speed modeled is 50.3 knots and the maximum speed is modeled as 189.4 knots (Table 3.7).

Item	min	max	measure	varied by
Sustainable Damage	2	4	hits	NOLH
Maximum Speed	50.3	189.4	knots	NOLH

Table 3.7: Helicopter factor design

3.3.7 Air to Surface Missile AGM-114 Hellfire

If a helicopter is modeled, it is modeled using the AGM-114 Hellfire. The AGM-114 has three variable and three fixed factors (Table 3.8). Factors modeled by a NOLH design are the AGM-114's rounds of ammunition and its maximum effective range. The AGM-114's firing arc, lethal radius and minimum effective range are set at fixed values. The inter-firing time is calculated using a dedicated scale factor. In multiple preliminary runs, inter-firing times were shown not to be significant predicting damage to the frigate.

AGM-114 Hellfire Hit Probability

This factor describes the hit probability for the AGM-114 Hellfire missile. It is held constant between the minimum and maximum effective range. The hit probability is varied between 0.75 and 0.99.

AGM-114 Hellfire Ammunition

This factor describes the amount of AGM-114's carried by the helicopter. The amount of ammunition is varied from 2 to 8 rounds.

AGM-114 Hellfire Inter Firing Time

The Helicopter weapons operator's AGM-114 inter firing time. This factor subsumes such factors as target acquisition and missile impact time. The AGM-114 is modeled shooting between 4 and 12 rounds per minute.

AGM-114 Hellfire Firing Arc

The firing arc of the AGM-114 Hellfire. The hellfire may change its trajectory at any time, and the helicopter supplies a highly mobile launch platform. Thus, even though the Helicopter has to face its target straight forward at all times, the firing arc is fixed at $360°$.

Item	min	max	units	varied by
Hit probability	0.75	0.99	P(hit)	NOLH
Ammunition	2	8	rounds	NOLH
Inter firing time	4	12	rounds/minute	scale factor
Maximum effective range	2500	5000	yards	NOLH

Table 3.8: AGM-114 Hellfire factor design

AGM-114 Hellfire Maximum Effective Range

The maximum range at which an efficient use of the expended round(s) is to be expected. Against SAFC, the MER is varied between 2500 and 5000 yards.

AGM-114 Hellfire Lethal Radius

The maximum range at which an exploding round may inflict damage to a target. Many different sizes and types of rounds are used in naval warfare. Against SAFC, an AGM-114 lethal radius is set at 50 yards.

AGM-114 Hellfire Minimum Effective Range

The minimum range at which the AGM-114 may shoot at. This factor describes the range at which the AGM-114 will be armed and ready to engage. Minimum effective range is fixed at 550 yards.

3.4 Noise Factors

3.4.1 SAFC Setup

Factors modeled for the SAFC are their hit points, number of attackers and speed. All factors are varied using a Hadamard matrix, modeling the minimum and maximum of each factor.

SAFC Hit Points

The SAFC complexity is modeled by hit points. The hit points represent three concepts. First, they represent the actual sustainable damage of the SAFC's hull. Second, they represent how good the SAFC's pilot is at evading incoming fire. Finally, they represent factors such as SAFC size and wave height, influencing the probability to hit the SAFC. The SAFC's hitpoints

Item	min	max	units	varied by
Hit points	1	4	hits	min–max
Speed	20.1	44.8	knots	min–max
Attackers	4	8	amount	min–max

Table 3.9: SAFC noise factor design

value is varied. The minimum value of sustainable damage is 1 hit, and the maximum is 4 hits. Any damage sustained is not healed (repaired) during a run.

SAFC Speed

The SAFC speed is held constant during each run. The minimum speed modeled is 20.1 knots and the maximum speed is modeled as 44.8 knots (Table 3.9).

SAFC Numbers

The SAFC are attacking the frigate using different swarm sizes. The attack is modeled with either four or with eight craft attacking.

3.4.2 RPG-7

The SAFC are always equipped with at least one RPG-7 launcher. The RPG-7 launcher is modeled with six variable and two fixed factors (Table 3.10). Factors modeled by a Hadamard matrix design are the RPG-7's hit probability, number of rocket propelled grenades (RPG), inter firing time, minimum effective range, and the number of RPG-7 launchers used. The maximum effective range is varied by combining two Hadamard rows, iterating through four values. The firing arc and lethal radius are not varied.

RPG-7 Hit Probability

This factor describes the hit probability for the RPG-7's rocket propelled grenades. It is held constant in between the minimum and maximum effective range. The hit probability is varied between 0.2 and 0.9.

RPG-7 Ammunition

This factor describes the amount of RPG's as carried by the SAFC. The amount of ammunition is varied between 2 and 8 rounds.

RPG-7 Inter Firing Time

The RPG-7 operator's inter firing time. This factor subsumes such factors as reloading, target acquisition and grenade flight time. The RPG-7 is modeled shooting between 2 and 6 rounds per minute.

RPG-7 Firing Arc

The firing arc of the RPG-7. The shooter must control the firing arc in order not to damage the boat or kill members of the crew. The firing arc is fixed at two $45°$ arcs on port and starboard per launcher.

RPG-7 Lethal Radius

The maximum range at which an exploding round may inflict damage to a target. Many different types of grenades may be shot with the RPG-7 launcher. Against a frigate and helicopter, the RPG-7 lethal radius is set at 50 yards.

RPG-7 Maximum Effective Range

The maximum range at which an efficient use and decent flight characteristics of the expended round(s) is to be expected. Against frigate and helicopter, the MER is varied between 400 and 800 yards.

RPG-7 Minimum Effective Range

The minimum range at which the RPG-7 may shoot at. This factor describes both the range at which the RPG-7 will be armed and ready to engage, as well as the minimum distance to which the SAFC will close in. Minimum effective range is varied between 50 and 100 yards.

RPG-7 Number of Launchers

The maximum number of launchers modeled aboard each single craft. All craft will have the same number of RPG-7 launchers. The number of available projectiles is multiplied by the number of launchers. Available launchers are varied between one and two launchers per craft.

Item	min	max	units	varied by
Hit probability	0.2	0.9	P(hit)	min–max
Ammunition	2	8	grenades	min–max
Inter firing time	2	6	grenades/minute	min–max
Maximum effective range	400	800	yards	four values
Minimum effective range	50	100	yards	min–max
RPG-7 launchers	1	2	amount	min–max

Table 3.10: RPG-7 noise factor design

3.4.3   Handheld Weapon

The SAFC are always equipped with some handheld weapons, represented as one single handheld weapon. The handheld weapon is modeled with four variable and three fixed factors (Table 3.10). Factors modeled by a Hadamard matrix design are the handheld weapon's hit probability, ammunition, and inter firing time. The maximum effective range is varied by combining two Hadamard rows, iterating through four values. The firing arc, lethal range, and minimum effective range are not varied.

Handheld Weapon Hit Probability

This factor describes the single engagement hit probability for a burst of a handheld weapon. It is held constant in between the minimum and maximum effective range. The hit probability is varied between 0.3 and 0.9.

Handheld Weapon Ammunition

This factor describes the amount of ammunition carried by the SAFC. The amount of ammunition is varied between 2 and 12 bursts.

Handheld Weapon Inter Firing Time

The handheld weapon operator's inter firing time. This factor subsumes such factors as reloading and target acquisition. The handheld weapon is modeled shooting between 5 and 15 bursts per minute.

Handheld Weapon Firing Arc

The firing arc of the handheld weapons. The shooter is basically free to fire in any direction. The firing arc is fixed at $360°$.

Handheld Weapon Lethal Radius

The circular error probable around the aim point of the handheld weapon. Against a frigate and helicopter, the handheld weapon's lethal radius is set at 50 yards.

Handheld Weapon Maximum Effective Range

The maximum range at which an efficient use of the expended round(s) is to be expected. Against frigate and helicopter, the MER is varied in 4 steps from 400 to 900 yards.

Handheld Weapon Minimum Effective Range

The minimum range at which the handheld weapon may shoot at. Minimum effective range for handheld weapons is set fixed at 50 yards.

Item	min	max	units	varied by
Hit probability	0.3	0.9	P(hit)	min–max
Ammunition	8	12	bursts	min–max
Inter firing time	5	15	bursts/minute	min–max
Maximum effective range	400	900	yards	four values

Table 3.11: Handheld Weapon noise factor design

3.5 Experiment Setup

In this section, the use of XML and the setup of the actual model runs is described. Then the lessons learned of the exploratory and preliminary design runs are described.

3.5.1 Cluster Runs

The files describing a complete setup of a single MANA model are called scenario files. MANA uses a XML based design for its scenario files setup. XML files are human-readable and editable using a standard text-editor. Variables within XML files are ordered in a hierarchical

fashion. Each hierarchy may contain zero or more elements and zero or more accompanying attributes. Each element or attribute is addressed by a one-to-one name. Elements and attributes can have values assigned to them. These values can be assigned externally using the corresponding element/attribute identifier.

The first step in designing the study is to complete a working MANA scenario file containing all behavior, state changes and fixed value parameters as described in the DoE. The design of the base case is not trivial, as some of the model's desired behaviors are not natively supported by MANA. Both were related to ROE's: Firing only at an attacking SAFC, and only firing at SAFC when they cross within a predefined distance.

Defending only against a single firing SAFC was modeled using the "Stealth" feature. By setting stealth to 100 the SAFC are not detectable by the frigate agent until they fire at the frigate. Using a state change stealth is set to 0 once they fire. Thus, the SAFC are detected by the frigate.

Attacking SAFC once they cross within the frigate agent's safe zone is modeled by using the "Refueling" feature. Once the SAFC cross this distance, they will change the frigate's state to "being refueled," triggering a defensive action by the frigate agent. This will also set stealth to 0, if applicable.

Next, a special XML file describing all factor's identifiers in the order of the columns of the $\mathbb{R}$ matrix is created. The software Old McData can read this XML file and, using a base case of the study setup with the $\mathbb{R}$ matrix, is used to control and create threads on the SEED Center's 38 core cluster. In addition to an ID and the study's author personal information, the Old McData XML file also contains the number of desired replications for each design point.

A typical run of the final model on one the SEED Center's cores takes 32^+_-4 seconds. The exploratory study's runtime was 58^+_-7 seconds. This improvement was achieved by amending a stop condition according to the number of agents present (according to the design point) to the Old McData file.[41]

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[41]For example, in a design point with 4 SAFC, a frigate and a helicopter, the stop condition was a) Frigate reaches goal (crossed the whole screen); b) 4 dead red (SAFC) agents; c) 2 dead blue (Frigate + Helicopter) agents.

3.5.2 Exploratory Design

The exploratory design was run as part of the International Data Farming Workshop (IDFW) 18 in Monterey, California. As runtime was not yet known, only two replications over the design space were performed. Two analyses were conducted. Results from these runs are described in (Abel et al., 2009).

During the design of the $\mathbb{C}$ matrix, a conversion error was made converting real world speed of the SAFC and frigate agents into MANA units. This error was discovered by visual analysis of both the original run's unabridged result data and visual replay of certain interesting runs within this design space. Speeds were four times faster than specified in the exploratory DoE. This mistake invalidates most of this model's results, and may be considered a Type III error (Sanchez, 2006). Mitroff and Featheringham (1976) describe a type III error as "the error [...] of having solved the wrong problem".

Insight was gained insofar as by using statistical analysis the helicopter was by far the most significant parameter, followed by frigate hitpoints and auxiliary hit probability. All two-way interactions also contained the helicopter. The generated model explains 86.4 percent of observed variability using five parameters and three interactions. Only hit probabilities and the frigate's damage sustainability were of interest. Mean frigates lost was very much higher than expected in these runs.

Since these runs were rendered invalid, the same DoE was used for the next setup, albeit correcting the conversion errors. Additionally, the scenario's maximum runtime was lengthened to 12000 time steps, as some runs were not finished after 8000 time steps.

Visual inspection was used to validate the overall design after the data transformation fix was applied. A total of 7 design points were run visually to deduce a realistic behavior as thought to be within an expected response surface. Some minor modifications were applied to the SAFC starting and target areas, such as to result in a higher probability of intercept of SAFC and frigate.
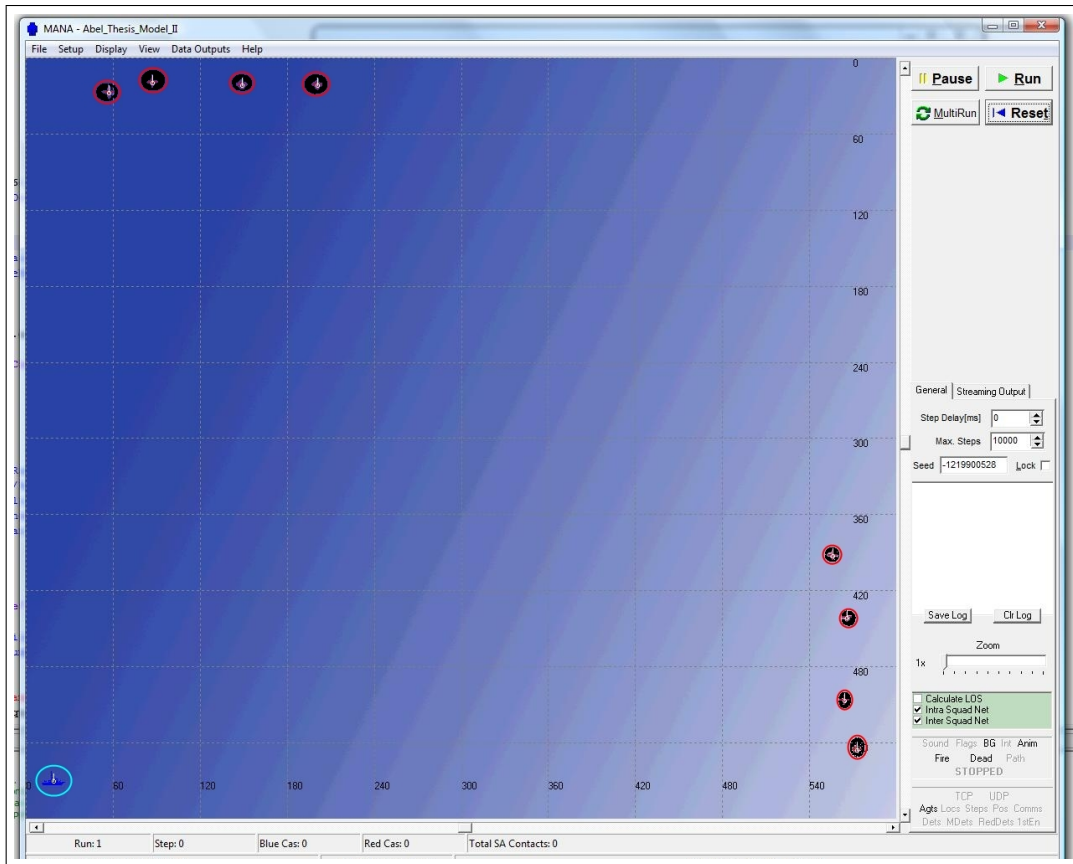
Figure 3.2: The final setup of the MANA simulation map, with 8 SAFC and a single frigate agent shown in their starting positions.

3.5.3 Preliminary Design

The preliminary design was run over 10 replications of 2580 design points. The average run length to simulate a single design point was $62.5^{+}_{-}5$ seconds, a slight increase over the exploratory design's runtime of $58^{+}_{-}7$ seconds. This increase was due to an increased runtime to 12000 time steps without adjusting the model's stop conditions.

A quick analysis of the data showed a huge percentage of runs with no red-blue interactions at all. Only 8000 out of the 25800 runs resulted in any units killed. Further statistical analysis yielded a model explaining 83 percent of observed variability with seven parameters and three interaction terms. The helicopter did not show up as significant within this analysis. Contrary to the predictions made when designing the DoE, some of the lockstepped factors were shown to be significant.

The preliminary design's analysis showed a very important factor when dealing with SAFC. If the frigate is at least 7 knots faster than the SAFC, these will not be able to intercept it without pre-arranged tactics. As this fact is established and this thesis focuses on the effectiveness of the frigate's defensive armament, there is no need for further research in this matter. As a result of these insights the minimum SAFC speed for the improved DoE is increased to 20.1 knots.

An interesting result was the presence of the "ROE engagement range" being very significant using statistical methods. Most important was a range ≥ 950 yards — the maximum range for the RPG 7. ROE range was varied between 200 and 2000 yards. The RPG 7 is the main weapon of the SAFC, and attacking them before they can use this weapon should prove to be significant. Therefore the ROE engagement range ≥ 950 yards being a significant parameter is a validation of the models behavior.

Further analysis generated a model that is partially relying on factors that are lockstepped. To understand which factors are actually responsible for the effect, these lockstepped factors need to be individually analyzed. For the preliminary model, two independent multiplication factors were used. The factors showing in the analysis were all part of one of these factors, varying the weapons ammunition, the auxiliary gun inter-firing time and the weapon's firing arcs. These factors will now be varied individually. This design decision necessitates the use of the 29 factor NOLH spreadsheet.

3.5.4   Final Design

The final design is run over 12 replications of 5140 design points. The model contains 72 factors, of which 56 are controlling parameters possibly significant on the runs result. Important changes to the last model are the additional independently NOLH varied factors in the DoE. Also, the SAFC have a much higher minimum speed in these runs. The placement of the CIWS is now randomized, to see whether there is a difference in between a bow and an aft placement. Finally the "ROE engagement range," the distance the frigate will begin shooting at approaching SAFC, is adjusted to 200–1000 yards, as the previous design was considered too far.

To reduce runtime, stop conditions were introduced to the model based on the number of blue and red agents killed. Using this method the average runtime was greatly reduced. In total the cluster worked 14 hours and 16 minutes for the computation of the 61680 runs.

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CHAPTER 4:
Data Analysis

The previous three chapters focused on explaining the initial idea, development and implementation of the simulation experimental design. With the final run finished, a large output file awaits analysis.

In this chapter, the output file and the programs and tools used for analysis are described briefly. This is followed by a thorough analysis in relation to the MoE, frigate's survival. Finally, the analysis is repeated for only those scenarios without helicopter presence.

4.1   Tools and Methods for Data Analysis

Before any analysis may be performed, the raw output data needs to be visually inspected and cleaned of non-runtime specific data. Non-numeric and indicator variables need to be translated, and design point iterations need to be summarized by producing estimates of loss, as described in the previous chapter.

4.1.1   Preparing the Data File

The resulting data stream generated by the models is a Comma Separated Values (CSV) file. It contains all input factor levels for each run, followed by that run's control and result values. For this thesis, the resulting file contains 94 columns and 65524 rows.

Data Inspection

First, a visual inspection of the output file is performed. It is important to do this analysis in order to assess whether information contained in the raw data might be lost when the data are summarized. For example, in this study it was discovered that at certain speed ratios, the frigate would simply outrun the SAFC, resulting in no frigates lost. This was an important finding that is not part of the summarized data. When it was clear that speed has this effect, the input speed ranges were reassessed and a new set of model runs were started.

A visual inspection also includes a quick graphical analysis of data rows, using for example distributions and 3D scatter-plots.

Data Adaptation

Translation is done so that statistics tools can correctly interpret the data. In this study MANA uses a binary variable to indicate whether weapons are enabled or disabled. This outcome must be translated to an indicator variable[42] for both summarizing and analysis. Additionally, all values dependent on the binary value are then copied in a new column and multiplied by the indicator value. Using this technique, the significance of the binary variables is retained.

Data Summary

Summarizing the iterations collapses each iteration of the noise factors and replications thereof over the signal space design point, producing an estimated mean and standard deviation. This significantly reduces the result set. A part of this activity is the stripping of any data not part of the engagement, such as for example data that was only needed to control the model.

4.1.2 Loss Function

It was decided to use a squared-error loss function where τ is the target value:[43]

$$\text{let}$$

$$
\begin{aligned}
l_i &= (X_i - \tau)^2 \\
&= ((X_i - \mu) - (\tau - \mu))^2 \\
&= (X_i - \mu)^2 + (\tau - \mu)^2 - 2(X_i - \mu)(\tau - \mu)
\end{aligned}
$$

$$\text{then}$$

$$
\begin{aligned}
E[l_i] &= E[(X_i - \mu)^2 + (\tau - \mu)^2 - 2(X_i - \mu)(\tau - \mu)] \\
&= E[(X_i - \mu)^2] + (\tau - \mu)^2 - 2(\tau - \mu)E[(X_i - \mu)] \\
&= \sigma^2 + (\tau - \mu)^2 - 2(\tau - \mu)0 \\
&= \sigma^2 + (\tau - \mu)^2 \\
&= \sigma^2 + \mu^2 \text{ (when } \tau = 0)
\end{aligned}
$$

---

[42] An indicator variable is one that can only be "0" or "1."

[43] Where the target value τ is 0 for X = frigates lost. l_i is the actual loss for state i, and $E[l_i]$ is the loss predicted for state i.

As the Values of σ^2 and μ^2 are not known, they are estimated with s^2 and $\bar{x}^2$. Thus the loss function is calculated by averaging each design point over the design point replications and noise factors while generating the sample mean ($\bar{x}$) and variance (s^2) for the number of frigates killed, resulting in the original signal design matrix. Using these statistics a loss function is calculated: $\bar{x}^2 + s^2$. The loss function has a target value of zero frigates lost, since zero frigates killed is optimal.

The combination of mean squared and variance penalizes being far off the target value τ of zero in expectation, having highly unstable results as determined by the variability σ^2, or both. A low loss using this formula is achieved by consistently being at or around zero frigates lost.

The benefit of using a loss function is that it captures the impact of factors outside of the experimenters control, while remaining focused on the impact of decisions which are under the experimenters control.

4.1.3   Regression Analysis

A regression analysis tries to estimate coefficients for some function of the input settings, X, so as to yield the "best" fit for the set of observed outcomes, Y (Goodnight and Sall, 2008). For a regression as used in this study, the resulting function is comprised of linear and non-linear terms.

Least Squares Regression

The fundamentals of least-squares analysis were developed by Carl Friedrich Gauss in 1795[44] to ease calculations for the movement of cosmic bodies (Dunnington et al., 2004).

Stepwise Regression

Stepwise regression uses regression models in which the selection of predictive variables for a least squares model is performed by an automatic procedure which seeks to maximize the increase in R^2, the proportion of explained variation in the model, at each stage.

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[44]Gauss was able to prove the statistical characteristics of the method in 1809, assuming normally distributed errors.

Due to the large number of factors that are explored, the number of potential terms in the model grows rapidly. Therefore only two-way interactions and polynomials up to degree 2 are examined.

The significance-thresholds to enter and leave the model are set at $P = 0.001$ and $P = 0.002$, respectively. The variables selected for inclusion are the input factors for least squares analysis.

Due to the large number of observations, a statistical significance level of less than $P = 0.0001$ is observed for many variables. To be able to differentiate in between statistical significance and the goal of gaining insight, the regression model is restricted to only those factors with an $|T| \geq 5$ (Figure 4.1).

4.1.4   Partition Tree

A partition tree finds a set of cuts or groupings of X values that best predict the observed Y value. It does this by exhaustively searching all possible cuts in the input data. These partitions of the data are done recursively, forming a tree of decision rules until the desired fit is reached (Goodnight and Sall, 2008).

In short, a partition tree is an exploratory model that is a visual tool to reveal structure within a data set (Goodnight and Sall, 2008). It is non-parametric in that it does not assume a particular functional relationship between inputs and outputs. It is very good at identifying abrupt transitions.

4.2   Overall Analysis

For the overall analysis, the aforementioned techniques are used to build models predicting the system's loss in relation to input factors. The analyzed data set contains 1028 rows of data with 68 independent input factors and one MoE each. The 1028 rows are a combination of the third preliminary and the final data run.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio		Prob>|t|
FrigateHP	-0.008977	0.000306	-29.30		<.0001*
SmallGunHitP	-1.322e-5	4.762e-7	-27.77		<.0001*
AuxGunhitProbability	-1.148e-5	5.028e-7	-22.83		<.0001*
HelicopterAirborne	-0.120274	0.005883	-20.45		<.0001*
MainGunHitProbability	-1.03e-5	6.024e-7	-17.10		<.0001*
(SmallGunHitP-5000.02)*(SmallGunEnable-0.75097)	-1.751e-5	1.32e-6	-13.27		<.0001*
SAFcStealth	0.0003377	2.555e-5	13.22		<.0001*
(AuxGunhitProbability-4950.01)*(AuxGunEnable-0.62646)	-1.318e-5	0.000001	-13.08		<.0001*
(SmallGunEnable-0.75097)*(AuxGunArc-155.004)	0.0010589	0.000084	12.61		<.0001*
AuxGunArc	-0.000468	3.719e-5	-12.57		<.0001*
(HelicopterAirborne-0.61089)*(SAFcStealth-50)	-0.000611	5.247e-5	-11.65		<.0001*
SmallGunAmmo	-0.007501	0.000675	-11.12		<.0001*
(FrigateHP-22.5019)*(HelicopterAirborne-0.61089)	0.0069869	0.000649	10.76		<.0001*
AuxGunEnable	-0.094092	0.008978	-10.48		<.0001*
(AuxGunProbableInterFiringTime-9.22763)*(AuxGunEnable-0.62646)	-0.00902	0.000924	-9.76		<.0001*
(MainGunHitProbability-4500.12)*(ROE_AutoFiringRange(RefuelRange)-12.0311)	-1.25e-6	1.304e-7	-9.58		<.0001*
AuxGunProbableInterFiringTime	-0.003846	0.000405	-9.49		<.0001*
ROE_AutoFiringRange(RefuelRange)	-0.002631	0.00029	-9.09		<.0001*
(SmallGunAmmo-9.36965)*(SmallGunAmmo-9.36965)	0.0008052	0.000092	8.75		<.0001*
(MainGunHitProbability-4500.12)*(FrigateHP-22.5019)	1.0511e-6	1.239e-7	8.48		<.0001*
(FrigateHP-22.5019)*(FrigateHP-22.5019)	0.0006913	8.279e-5	8.35		<.0001*
(AuxGunAmmo-8.35019)*(AuxGunMaxRg-25.5019)	-0.000133	1.619e-5	-8.22		<.0001*
(SmallGunAmmo-9.36965)*(AuxGunhitProbability-4950.01)	6.9478e-7	8.612e-8	8.07		<.0001*
(FrigateHP-22.5019)*(ROE_AutoFiringRange(RefuelRange)-12.0311)	0.0005977	0.000075	7.97		<.0001*
(CWISAmmo-5.55642)*(MainGunHitProbability-4500.12)	6.6734e-7	8.739e-8	7.64		<.0001*
(MainGunHitProbability-4500.12)*(AuxGunhitProbability-4950.01)	1.7433e-9	2.36e-10	7.39		<.0001*
SmallGunMaxRg	-0.002162	0.0003	-7.21		<.0001*
AuxGunMaxRg	-0.000848	0.00012	-7.10		<.0001*
(AuxGunAmmo-8.35019)*(CWISEnable-0.37743)	0.0033217	0.000476	6.97		<.0001*
(SmallGunMaxRg-12.0311)*(HelicopterAirborne-0.61089)	0.0042807	0.000621	6.90		<.0001*
(SmallGunMaxRg-12.0311)*(SmallGunEnable-0.75097)	-0.005658	0.000825	-6.86		<.0001*
(SmallGunHitP-5000.02)*(SAFcStealth-50)	-5.906e-8	9.002e-9	-6.56		<.0001*
(CWISAmmo-5.55642)*(SmallGunHitP-5000.02)	4.8887e-7	7.735e-8	6.32		<.0001*
(MGMaxRg-75.0039)*(AuxGunMaxRg-25.5019)	0.000052	8.509e-6	6.11		<.0001*
CWISEnable	-0.055393	0.009618	-5.76		<.0001*
HellFireProbableInterFiringTime	-0.007088	0.001249	-5.68		<.0001*
(HellFireAmmo-5.00389)*(HelicopterAirborne-0.61089)	-0.009195	0.001628	-5.65		<.0001*
(MainGunProbableKillRad-2.11284)*(CWISProbableInterFiringTime-6.2179)	0.0114547	0.002066	5.54		<.0001*
(AuxGunAmmo-8.35019)*(SmallGunEnable-0.75097)	0.0055191	0.001	5.52		<.0001*
(CWISAmmo-5.55642)*(MainGunProbableInterFiringTime-4.2179)	0.0009654	0.000176	5.48		<.0001*
(AuxGunhitProbability-4950.01)*(FrigateSpeed-13.5019)	8.2307e-7	1.513e-7	5.44		<.0001*
SmallGun ProbableKillRadius	0.0108878	0.00204	5.34		<.0001*

Figure 4.1: Model Parameter Estimates Overview.

4.3   Data Distribution

A first insight on the data was gained by graphing the distribution of loss with an observed number of $N = 1028$ data points.

On first sight, loss seems to be distributed exponentially, with most data showing no loss (Figure 4.2). Maximum loss is at 0.6. The distribution's mean, upper and lower quartiles are $0.155^+_-0.127$, 0.226 and 0.059, respectively. There is a tail of outliers, starting above a loss of 0.45, representing 2.5 percent of all data on loss.

69

Figure 4.2: Distribution of loss.

4.4 Significant Factors using Partition Trees

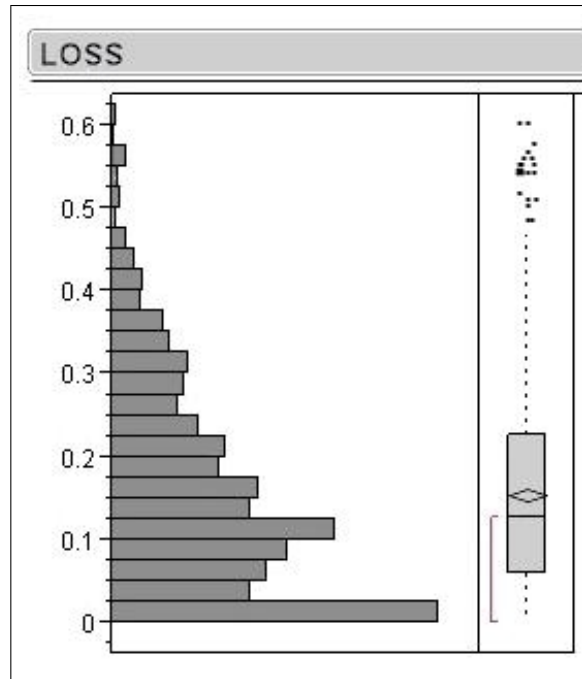Partition tree analysis on loss was not continued beyond ten splits as further splits did not contribute significantly to the models' predictive power. The resulting model explains 49.6 percent of variance (Figure 4.3).

Partitioning suggests that small gun inter-engagement time of at least 12 aimed bursts per minute contributes most significantly to a high mission survivability. Further important factors associated with low loss are the CIWS and the auxiliary guns being able to fire at least ten aimed bursts before needing to reload. The analysis also suggests the frigates being able to sustain at least 21 hits and a small gun hit probability ≥ 30 percent are important factors.

If the CIWS can shoot less than ten aimed bursts, an auxiliary gun's firing arc of at least $191°$ and a helicopter with at least six Hellfire missiles is significant. Therefore the Hellfire missile in combination with a very large auxiliary gun firing arc[45] at least partially substitute for low inter firing times.

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[45]Usually the maximum auxiliary gun firing arc is just below $180°$.
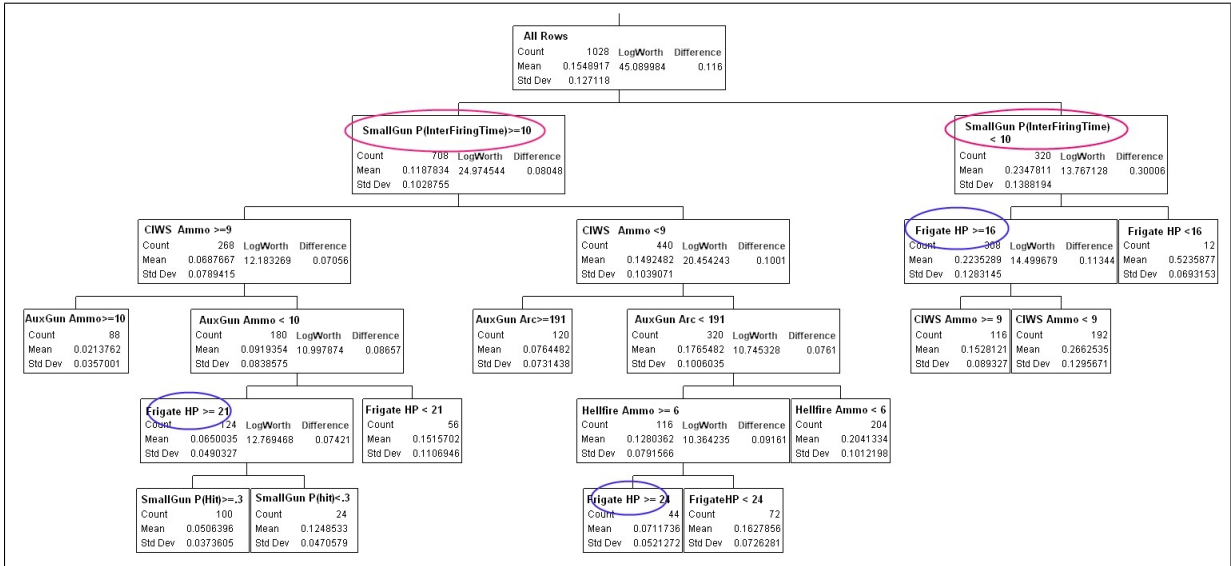
70

Figure 4.3: Partition tree displaying an R^2 of 49.6 percent using 10 splits. Notice the reoccurring factors for Frigate Survivability (FrigateHP, marked).

If the small gun inter-engagement time is less than 12 engagements per minute, the partition tree suggests that if the frigate is able to sustain the equivalent of 16 hits and has a CIWS magazine capacity of at least eight aimed bursts, loss is significantly lowered.

Besides the damage sustainability of the frigate, weapons that are precise or those that sport a low inter-engagement time show up as being significant using partition trees. These are the small-caliber weapons. The helicopter has only restricted power as it is only significant if other conditions do not apply. Also, the main gun seems not to be significant at all within this model.

4.5   Significant Factors using Least Squares Regression

In contrast to the partition tree, least squares regression can also take into account higher order terms such as interactions and polynomials. Due to memory constrains, for this analysis no terms higher than second order are modeled.

65 factors and factor interactions are identified by the regression model, explaining an adjusted 89.62 percent of the variance in loss within the model (Figure 4.4). In order to assess

Figure 4.4: Summary of Fit for the Least Squares Regression Analysis.

practical significance in relation to response variance, as a visual tool a prediction profiler is employed.

The actual by predicted plot shows a very good distribution of data points. There are no obvious outliers, and the shape is not abnormal (Figure 4.5).

4.5.1 Frigate Speed

The second preliminary study conducted showed the significance of the frigate's speed. If speed is high enough, the SAFC will have no chance to entangle the frigate in a fight. The frigate can thus outrun the engagement, which is the best solution in light of the research question.

4.5.2 Frigate Survivability

Statistically the frigate's survivability is an important measure (Figure 4.6). It showed up as the most important measure in the regression. When considering all factors, it is important to understand that within this study the frigate's capability to sustain damage showed diminishing returns. Being able to sustain more than 26 hits did not change the resulting survivability of the frigate in a significant way. As this was an interesting result, a total of 10 design points with a high survivability were conveniently chosen for visual inspection. Changing the simulation seed at random to alter the environment, a total of 100 observations were made. As was pre-
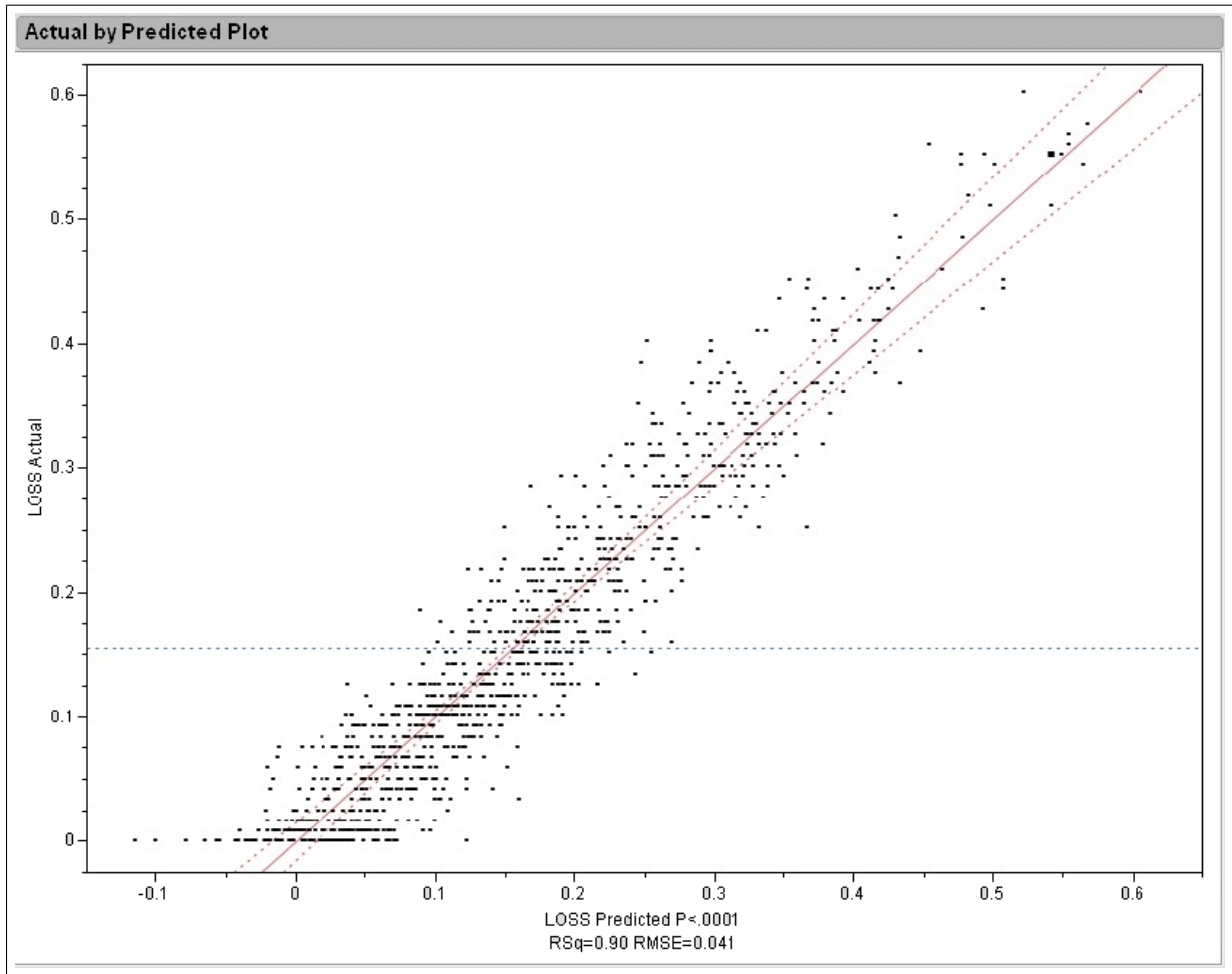
Figure 4.5: Actual by Predicted Plot using Least Squares Regression Analysis.

dicted by the partition tree, a frigate that can sustain more than about 25 hits will either destroy all attacking SAFC or simply sustain the SAFC attacks until those run out of ammunition. In either case, the result is a very low loss.

This result is also a confirmation and an insight of the model's predictive power. Hughes salvo equations (Hughes, 1995) indicate that the factor of "staying power" is one of the largest contributions to a ship's defense.

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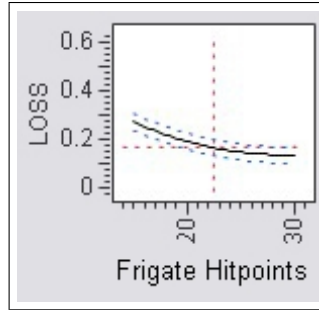
Figure 4.6: Prediction profiler for Frigate Survivability (FrigateHP).
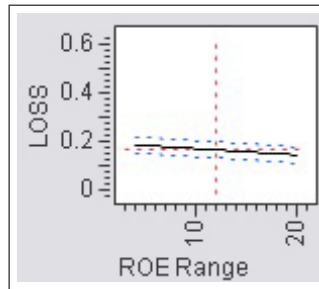
Figure 4.7: The range at which a contact is deemed hostile has low impact on predicted loss.

4.5.3 Tactics and Procedures

Firing range (beginning to shoot), as well as shooting at all small boats vs. shooting at only the attacker, are statistically significant in the regression. They do not make a visual difference in the prediction profiler, though (Figure 4.7). When considering the set-up of the simulation, this result is to be expected. The SAFC start off at random locations and with the same probability to move in a given turn. On average they will therefore have the same speed, and not reach the frigate at the same time. In the case of the frigate attacking only a single SAFC, all of the frigate's applicable weapons fire at that one target. This increases the chance of killing the SAFC within a short time, and will happen for each closing SAFC.

On the other hand, when the frigate attacks all targets at once, it has to distribute a limited amount of weapons on a potentially larger number of attackers. Thus, overall each of the attacking SAFC will be within its weapon range for a longer time and potentially inflict a higher amount of damage. But, as the MOE was not number of hits received, very often the frigate will simply survive these longer attacks and thus, even though the difference is significant, in this simulation it does not make a difference.

4.5.4 Main Gun

The main gun is the only weapon being modeled in all runs. Contrary to the first two preliminary run's results and the partition tree, using regression several of the main guns factors showed up as being statistically significant: ammunition, hit probability, inter-engagement time, range and firing arc. Out of these factors, using the prediction profiler, hit probability and the amount of ammunition available make a visible difference.
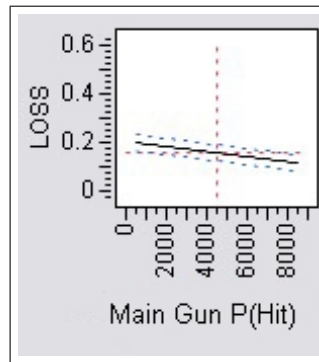
Figure 4.8: Prediction profiler for Main Gun Hit Probability.

4.5.5 Auxiliary Guns

Enabling auxiliary guns makes a significant difference in explaining model result variability, as does the gun's firing arc (Figure 4.9) and ammunition amount (Figure 4.10). Auxiliary gun hit probability is the third most important factor within the regression model.
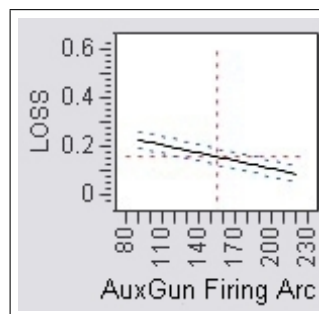
Figure 4.9: Prediction profiler for the auxiliary Gun firing arc width.
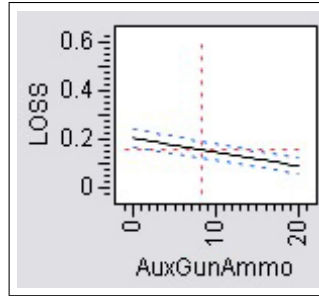
Figure 4.10: Prediction profiler for the amount of ammunition on the auxiliary gun.

In relation to explaining the model variability, the profiler shows that hit probability, the gun's maximum range and projectile dispersion (lethal radius) are not significant effects (Figure 4.11).

Within this simulation, maximum range was not expected to have an effect and could be seen as a "control" if the statistical tools over-fit. The engagements as determined by the restraints within the simulation's parameters are all well within each of the modeled weapon's maximum range. It is also interesting to note that the firing arc is so much more important than the hit probability. This seems to indicate that it is better to engage a SAFC even with a low hit probability than not to engage it at all.
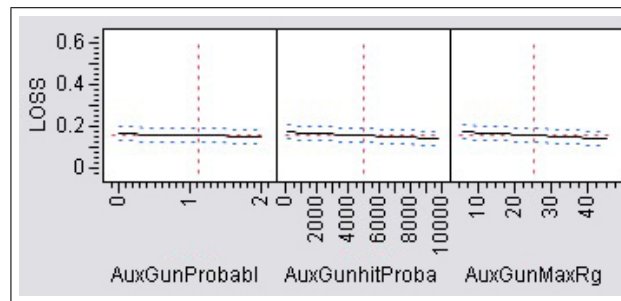
Figure 4.11: Prediction profiler shows no significant changes in survivability for auxiliary gun's hit probability, lethal radius or maximum range.

4.5.6 Small Guns

Small guns significantly influence the model's variability. Especially the amount of available ammunition (Figure 4.13) and inter firing times (Figure 4.12) have great influence on the variability of the model according to the prediction profiler.
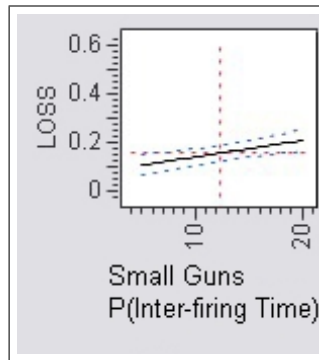
Figure 4.12: Profile of small guns inter firing times on model predicted loss.

Enabling the small gun showed some interesting results within the prediction profiler. The small guns presence or absence will both increase or decrease expected loss. If expected loss is low, enabling the small guns will increase loss, while the small guns will decrease overall loss if expected loss is high. A convenient sample of 10 design points that resulted in both high and low loss were selected and the simulation's raw result sets visually inspected. For half the samples the small gun was enabled, and for the other half disabled. Inspection indicates that activating small guns in low expected loss situations only minimally lowers mean missions lost while variance is much increased. In high loss situations, variance is not very much affected but mean missions lost is marginally lowered.

Increasing the number of aimed bursts fired per minute does increase expected loss. The expected result is that increasing the number of shots fired per minute, regardless of P(hit), results in more SAFC hit and thus in a lower loss. Visual inspection both of the simulation's runs, as well as raw data, did not help to explain this result. This is either suggesting volatility in the results, some kind of interaction that the employed statistical methods do not find, or it may be a modeling artifact.

The effect the amount of ammunition available to the small guns has on the model diminishes the more ammunition is supplied. This effect actually reverses at around 14 aimed bursts shot, increasing the loss. This effect is possibly related to the rise in loss that is observed when aimed shots per minute are increased. Alternatively, it may be because a quadratic fit is not the best choice to capture the non-linear response.
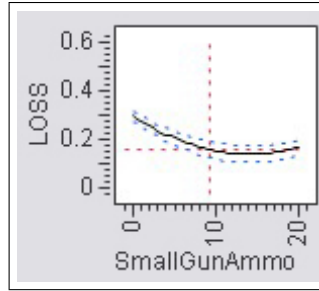
Figure 4.13: The prediction profiler shows diminishing returns on amounts of ammunition for small guns.

4.5.7   CIWS

In explaining the model, the CIWS do not make a significant impact. The profiler shows enabling CIWS having some influence on expected loss, but the factor is not part of the regression model. This does not indicate that the CIWS really has no effect, but shows that the CIWS' effect as set up in the simulation is not as significant relative to the other factors. The simulation models highly sophisticated weapon systems, on par with the CIWS on speed and hit probability. Therefore the CIWS not being highly significant is acceptable.

4.5.8   Helicopter

In the regression model, enabling the helicopter is the most significant factor following frigate survivability (Figure 4.14). Additionally, the helicopter has a significant influence explaining variability within the model. The number of hellfire missiles, or their hit probability, is rather insignificant.
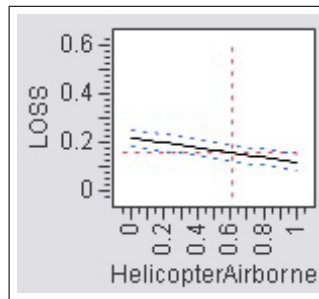
Figure 4.14: Having a helicopter airborne predicts lower loss.

4.6 Significant Factors – Effect Interactions

While it is important to understand which factors have an important influence on the outcome of a model, and thus give some insight to the system being modeled, it is not always possible to actually integrate all factors. It is of great interest to understand what factors allow trade offs or depend on one another. Therefore the analysis of interactions is very important when trying to understand a system.

The regression model determines that there are many proposed significant interactions in between factors. These are composed of merely technical interactions, due to the setup of the model, and interactions that allow some insight in the relationships between single factors.

Technical interactions are observed between the indicator variables of enabling the small guns, auxiliary guns and helicopter. For the gun systems, the interaction factor is hit probability, while for the helicopter it is amount of hellfire ammunition. These factors are dependent based on the design of the models run file.

The presentation of the interactions using a certain section header is for arrangement purposes only. Each interaction could also be presented using the other interaction term. The insights will also be true if they are reversed.

Interactions are included in the model only if their respective regression resulting F-ratio is greater than 30.

For each interaction, first the interactions are pictured. Then, each interactions insights are discussed.

4.6.1 Interactions Concerning Frigate Survivability

There is an interaction between the survivability of the frigate and having a helicopter, ROE engagement range and the main gun's hit probability.

The model suggests that survivability needs to be higher, if no helicopter is present. The helicopter both diverts and reduces the number of SAFC. It diverts the SAFC from the frigate

as the SAFC choose whether to attack the frigate or the helicopter. The simulation assigns the frigate a higher chance of aggregating SAFC then the helicopter. SAFC can either attack the frigate or the helicopter. Also, the helicopter fired Hellfire missiles have a high chance to reduce the number of attacking SAFC.

The lower the ROE engagement range, the higher the frigate's survivability needs to be for a low loss, as more SAFC will be able to discharge weapons before being neutralized. Hit probabilities are step functions, so distance only matters for being able to hit or not to hit. If the SAFC are close to the frigate, the frigates large– and medium caliber weapon systems have minimum effective ranges, thus reducing the number of weapon systems being able to target the SAFC. This increases the expected time before a single SAFC is neutralized, increasing the time it can fire on the frigate and thus increasing the number of hits the frigate will receive.

The same reasoning is true for a lower main gun hit probability necessitating a higher survivability for the frigate, as the SAFC have a higher probability to close in on the frigate before being neutralized. The longer a single SAFC survives, the longer the timespan to fire its weapon systems, resulting in a a higher number of expected hits on the frigate.

4.6.2 Interactions Concerning the Main Gun

There is an interaction between the main gun hit probability and ROE engagement range and CIWS amount of ammunition. There is an interaction between the main gun projectile kill radius and the CIWS inter-engagement time.

A high hit probability of the main gun offsets a reduced ROE engagement range as the main gun will reduce the number of SAFC in a shorter amount of time. This is only true while the minimum ROE engagement range is still farther than the main gun's minimum effective range, a subtlety that eludes this model. Similarly, a higher hit probability of the main gun allows a lower amount of ammunition on the CIWS with the same reasoning.

If the main gun has a larger projectile kill radius, a longer inter-engagement time for the CIWS will achieve the same predicted loss. A larger kill radius will inflict damage on a SAFC even if the projectile does not directly hit. This, for all practical purposes, significantly increases the hit probability of the main gun, such as this is a subset of the above interaction.

4.6.3 Interactions Concerning the Auxiliary Gun

There is an interaction between the auxiliary gun's hit probability and main gun hit probability, frigate speed and small gun's ammunition. There is an interaction between the amount of ammunition available to the auxiliary gun and enabling the CIWS, enabling small guns and overall range of the auxiliary guns. There is an interaction between the auxiliary gun's firing arcs and the tactic to attack only definitely hostile SAFC versus all approaching SAFC.

A higher auxiliary gun hit probability allows for a lower main gun hit probability as the same number of auxiliary gun engagements disable a higher number of SAFC. This is also the case for the amount of ammunition available to the small guns, which may be lower if the auxiliary gun hit probability is increased. A higher frigate speed allows for a lower hit probability for the auxiliary guns, as the engagement is prolonged before the SAFC can close in, allowing more auxiliary gun engagements.

Increasing the auxiliary guns' ammunition significantly interacts with both enabling the CIWS and the small guns. While overall loss is lower for enabling both CIWS and small guns, a higher amount of ammunition allows more engagements, thus at least partially offsetting the higher loss expected by not having these additional assets. Loss is decreased by an interaction between high ammunition amounts and high maximum effective range. But these interactions are only possible when either increasing the ROE engagement distance, or when classifying all approaching SAFC as hostile upon first attack. This allows the auxiliary gun to engage single targets for a longer time while they are closing in, thus increasing the probability of neutralizing the approaching craft, which in turn reduces loss. The same explanation is true for the auxiliary gun's weapon arc, as a larger weapons arc allows for a higher probability to be able to engage approaching SAFC, but only if they are classified as being hostile.

4.6.4 Interactions Concerning the Helicopter

There is an interaction between employing a helicopter and attacking only definitely hostile SAFC versus all approaching SAFC and a CIWS being present.

If only SAFC shooting at the frigate or entering the ROE engagement distance are engaged, the model suggests the use of a helicopter may decrease loss. The helicopter employs a high probability of hit weapon, the Hellfire missile. Additionally, the helicopter is highly agile and is stationed where it might be able to attack otherwise inaccessible SAFC. The combination of all of these factors make it a great asset when only single, definitely hostile SAFC are engaged.

With the same reasoning, the use of an airborne helicopter is similar to employing a CIWS system. Both systems are high P(hit) systems, are agile but have a comparatively long inter-engagement time. Of course, a helicopter has the drawback of only limited availability.

4.7 Significant Factors when not Employing a Helicopter

As mentioned in both Chapter 1 and 2, the use of a helicopter during a given operation is limited. To determine the impact of not using a helicopter during an engagement, the analysis is repeated including the 400 design points in which the helicopter is not employed.

4.7.1 Influential Factors using a Partition Tree

Partition tree analysis on loss was not continued beyond seven splits as further splits did not contribute significantly to the models predictive power. The resulting model explains 52.2 percent of variance.

Partitioning suggests that small gun single engagement hit probability of above P$\geq$0.58 is most significant in predicting low loss configurations. The small gun is the only weapon capable of a $360°$ engagement arc in all design points, has a short minimum engagement range and a fairly low inter-engagement time. The combination of these factors allow the small gun, if combined with a high hit probability, to dominate as most significant factor.

If the small gun high P(hit) configuration is paired with the factor auxiliary gun single engagement hit probability of above P=0.64, loss is at a predicted minimum of about 0.07 in this model. The auxiliary gun also has a fairly large engagement arc and a low inter-engagement time. The minimum engagement distance is higher for some auxiliary gun design points, so if the SAFC close in on the frigate, the auxiliary gun ceases to be useful. But if the hit probability

of the auxiliary gun is high enough, the SAFC will not be able to close in fast enough to bridge the engagement zone before being neutralized, resulting in low loss.

If the auxiliary gun hit probability is below P=0.64, CIWS single engagement hit probability of above P=0.76 is introduced as an important factor to predict a loss of about 0.12. (Figure 4.15). The CIWS has a maximum firing arc of 260 degrees, far less than the aux and small guns. It has a higher inter-engagement time, but is also modeled with very much higher hit probabilities. Therefore both auxiliary and small guns dominate CIWS as a factor.
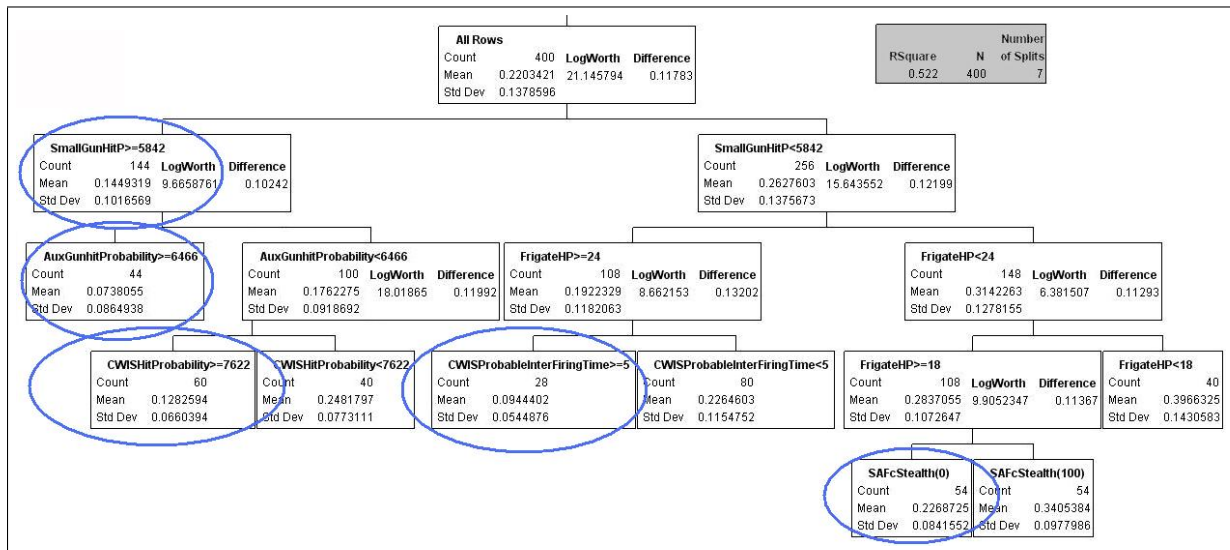
Figure 4.15: Partition matrix displaying an R^2 of 52.2 percent using 7 splits.

Should the small gun single engagement hit probability be below about P=0.58, a frigate's survivability level of above 24, in combination with a low CIWS inter-engagement time, is significant in predicting a loss of about 0.09. The frigate needs to be able to withstand more damage if the small guns have a lower hit probability. As the CIWS hit probability is set up to be high, a shorter inter engagement time results in more SAFC neutralized in the same amount of time, thus resulting in a low loss configuration.

As explained within the model with partial use of a helicopter, if the frigate has only moderate survivability levels, above 18 or below 24, the tactic of attacking all approaching SAFC without further identification is a significant factor to predict a loss of about 0.22.

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4.7.2   Influential Factors using Least Squares Regression

Summary of Fit	
RSquare	0.923583
RSquare Adj	0.915539
Root Mean Square Error	0.040065
Mean of Response	0.220342
Observations (or Sum Wgts)	400

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	38	7.0036246	0.184306	114.8184
Error	361	0.5794752	0.001605	Prob > F
C. Total	399	7.5830997		<.0001*

Figure 4.16: Summary of Fit for the Least Squares Regression Analysis of Loss Without Helicopter.

27 factors and factor interactions are identified by the regression model, explaining an adjusted 91.55 percent of the variance in loss within the model (Figure 4.16). The model shows fewer factors to be significant as the no-helicopter model determining input parameter list is $1/3^{rd}$ the length of the with-helicopter analysis. As with the with-helicopter evaluation, in order to assess practical significance in relation to response variance, a prediction profiler is employed as a visual tool.

The actual by predicted plot shows a very good distribution of data points. There are no obvious outliers, and the shape is not abnormal (Figure 4.17).

For frigate survivability, single engagement hit probabilities are much more significant when not employing a helicopter. The helicopter, if present, would employ a weapon with a high probability of kill, and a low variance in its results. While this weapon is not present, the other weapon systems need to make up for both the increased variance and the longer time it takes to neutralize the approaching SAFC. Decreasing the inter-engagement times would statistically increase the number of SAFC neutralized within a certain number of timesteps, but may also increase variance. Increasing hit probability will decrease variance and decrease the time it takes to neutralize the SAFC, thus, decreasing expected loss.
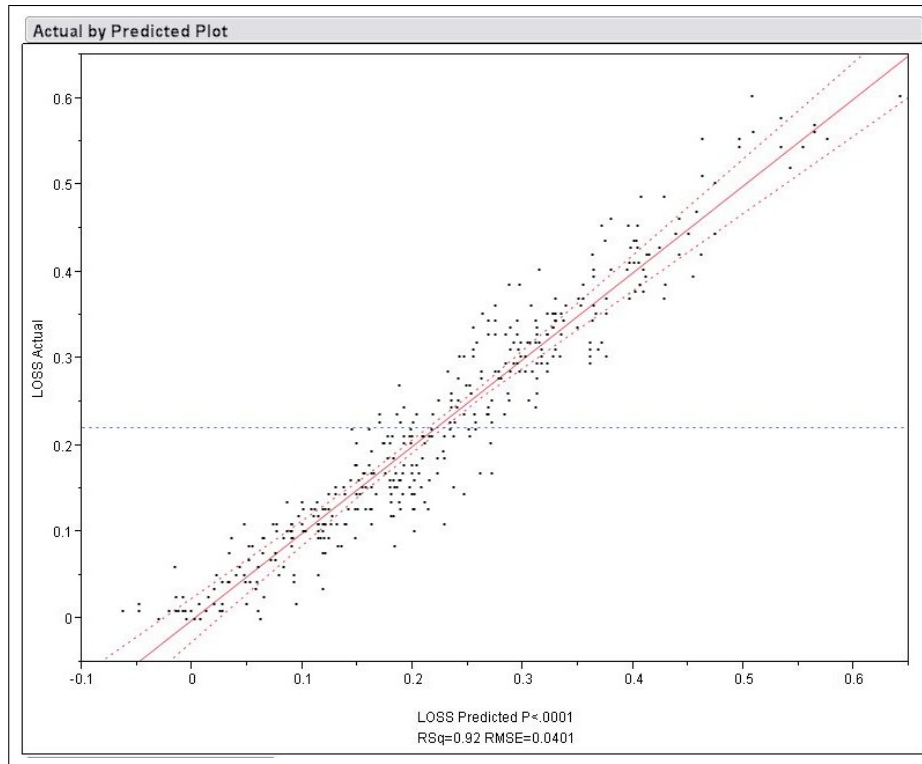
Figure 4.17: The Actual by Predicted Plot for Loss Without Helicopter.

Assuming all SAFC to be hostile once the first is determined to be hostile is significant when not employing a helicopter. The helicopter was shown to be a great asset when attacking the SAFC one at a time. Without the helicopter, it is now better to assume all hostile and thus gain the maximum utility from especially long-range weapons, such as the main gun, which also have a very long minimum engagement distance.

The prediction profiler shows there are six very influential factors that dominate the models predicted loss (Figure 4.19).

Both small gun ammunition and small gun single engagement hit probability are significant, as it allows the small guns to shoot longer and hit more often. Main gun single engagement hit probability is also adding a large effect. The main gun is modeled as an area effect weapon, so increasing hit probability multiplies the chance of the weapon actually damaging a SAFC, even if it does not hit its intended target. Increased survivability, another significant factor, has already been shown to decrease loss, as is predicted in this model. The CIWS maximum range

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Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio		Prob>|t|
FrigateHP	-0.014072	0.000509	-27.64		<.0001*
SAFcStealth[0]	-0.035977	0.002007	-17.93		<.0001*
MainGunHitProbability	-1.666e-5	9.879e-7	-16.86		<.0001*
AuxGunProbableInterFiringTime	-0.008258	0.000757	-10.91		<.0001*
CWISHitProbability	-1.413e-5	1.313e-6	-10.76		<.0001*
SmallGunHitP	-1.283e-5	1.224e-6	-10.49		<.0001*
AuxGunArc	-0.000997	9.561e-5	-10.42		<.0001*
AuxGunhitProbability	-2.926e-5	2.923e-6	-10.01		<.0001*
(CWISHitProbability-3226.25)*CWISFacingAt[0]	-1.129e-5	1.351e-6	-8.35		<.0001*
(AuxGunhitProbability-3145.15)*(AuxGunhitProbability-3145.15)	4.0525e-9	5.32e-10	7.62		<.0001*
SmallGunAmmo	-0.004784	0.000632	-7.57		<.0001*
(AuxGunAmmo-8.24)*(SmallGunMaxRg-8.65)	0.0004872	0.000066	7.38		<.0001*
CWISFacingAt[0]	-0.016562	0.002246	-7.38		<.0001*
(SmallGunHitP-4127.47)*SAFcStealth[0]	4.4599e-6	6.258e-7	7.13		<.0001*
AuxGunEnable[0]	-0.118724	0.016725	-7.10		<.0001*
SmallGunMaxRg	-0.004076	0.000584	-6.98		<.0001*
(SmallGunAmmo-9.39)*(SmallGunHitP-4127.47)	-1.288e-6	2.017e-7	-6.39		<.0001*
SmallGunProbableInterFiringTime	-0.008473	0.001479	-5.73		<.0001*
(CWISMaxRg-13.46)*CWISFacingAt[0]	0.0017435	0.000311	5.61		<.0001*
(SmallGunHitP-4127.47)*(AuxGunArc-94.96)	5.7224e-8	1.045e-8	5.48		<.0001*
(AuxGunArc-94.96)*SAFcStealth[0]	0.0002256	4.139e-5	5.45		<.0001*
(MainGunHitProbability-4500.11)*(MainGunArc-209.26)	-1.716e-7	3.332e-8	-5.15		<.0001*
AuxGunMaxRg	-0.001517	0.000299	-5.07		<.0001*
MGMaxRg	-0.000688	0.000147	-4.69		<.0001*
(AuxGunhitProbability-3145.15)*(MainGunArc-209.26)	8.965e-8	2.04e-8	4.39		<.0001*
CWISFacingAt[0]*SAFcStealth[0]	0.0087623	0.002016	4.35		<.0001*
(AuxGunMaxRg-15.73)*(SmallGunProbableInterFiringTime-5.68)	0.0002657	6.586e-5	4.03		<.0001*

Figure 4.18: Model Sorted Parameter Estimates.
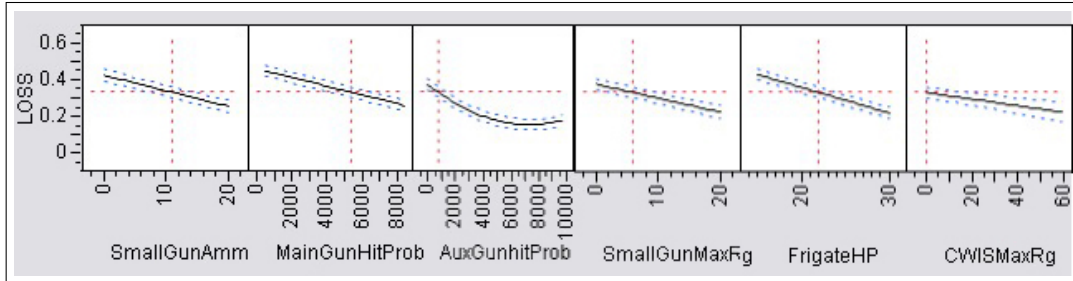
Figure 4.19: Model Sorted Parameter Estimates.

are predicted to reduce loss. The CIWS is a high P(hit) weapon, so the earlier it can engage a target, the more damage it can deal to the SAFC. This damage is also very consistent, as such reducing loss. Finally, the auxiliary gun's single engagement hit probability shows a high influence on predicted loss. Thus a high hit probability will generally reduce loss.

The auxiliary gun hit probability as determined by the prediction profiler shows diminishing returns and a leveling at a P(hit) of about 0.85. This prediction was expected. Increasing

a hit probability at a level of P=0.8 and above does not make as much a difference as increasing P(hit) from 0.2 (an expected hit in five shots) to 0.5 (an expected hit every two shots). But high hit probabilities not only reduce the number of SAFC more efficiently, but also reduce the number with a low variability in expected results. Inter-trial variability gets smaller the higher the P(hit). Thus with a loss function, predictions on P(hit) are expected to show diminishing returns.

Thus, overall an interesting change is that tactics have some influence on predicted loss. Without a helicopter, it is more important to determine all SAFC intentions early, or employ ROE that allow us to deduce intentions of a swarm of SAFC through the behavior of any of its members.

When comparing the model partially employing a helicopter to the model not employing a helicopter, a high overlap in the sets of factors determining loss is observed. Both factor weighting and the predicted factor profiles are unique to each model, but the factor effects are essentially the same for both scenarios.

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CHAPTER 5:
Conclusions And Recommendations

5.1 Research Summary

This study investigated how well a typical North Atlantic Treaty Organization (NATO) operated Fast Frigate with Helicopter (FFH), built between 1975 and 1990 and operating as a lone unit, would perform in a notional Security, Transition and Reconstruction (SSTR) mission when attacked by Small, Agile and Fast Craft (SAFC) armed with readily available hand-held weapons. A hypothetical defense against different sized swarms of small vessels at different speeds in differing environmental conditions was simulated, using the frigate's survivability as the measure of effectiveness. The goal was to determine if current frigate's survivability needs to be increased and if so, how this is to be achieved. The simulation study yielded some interesting insights about the influence of different factors on a frigates mission survivability.

5.2 Research Questions

In Chapter 1, the following research questions were posed:

1. Can a swarm of four to eight small agile fast boats armed with handheld weapons, attack and achieve a mission kill on a typical NATO FFH operating in a SSTR mission?

2. Is the FFH's mission survival dependent on the sophistication of installed weapons?

3. What type of weapon or weapons package is best suited for close-in defense against four to eight small seaborne attackers?

4. Would it benefit mission survivability to improve or replace existing weapons of frigates performing SSTR missions?

These questions were based on the premise that the new or updated capabilities could at least theoretically be equipped on the average commissioned frigate while not, or only minimally, altering the ship's hull or its hull structure, respectively.

It was found that currently employed NATO frigate's are vulnerable to an attacking swarm of four to eight SAFC. Even though predicted loss is only $0.155^{+}_{-}0.127$, this number is quite high considering the possible impact an actual mission kill might have.

It was further shown that the sophistication of the employed weapon mix is a significant factor in the survival of the frigates. Frigates using automatic, high-probability-of-hit weapon systems were significantly more likely to survive a hostile encounter than those using crew-served manual-aim weapon systems.

The observed interactions suggest that besides sophistication, a well balanced mix of weapons is key to a low rate of loss. No single sophisticated weapon dominates expected results. The model also suggests that expected loss is reduced by having enough ammunition on the weapons to allow for multiple engagements before a necessary reload. Loss is reduced further by using a helicopter employing stand-off, high probability of kill weaponry.

Based of these findings, recommendations to increase mission survivability include modernizing and replacing crew-served with automatic weapon systems, and update large-caliber and CIWS weapon systems to enable the engagement of SAFC type targets. Prior research suggests integration of modern, automatic and semiautomatic weapon systems in existing designs is technologically feasible. On the same note, increasing the number of small and medium caliber weapon systems while disregarding single engagement hit probabilities[46] has no significant effect on the frigate's survivability. Additionally, the model suggests that due to target allocation problems, simply adding random firepower may even decrease overall frigate survivability.

5.3   Further Insights

In addition to addressing the research questions posed in Chapter 1, some further insights have been gained through this research. This section discusses these insights and the impact these findings may have on the frigate's mission survivability.

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[46]Modeled by drastically increasing inter-firing times.

5.3.1 Frigate Speed

It was observed in the preliminary simulation runs that the higher the frigate's speed, the lower the probability of skirmishes happening. This in turn results in low loss, meaning high mission survivability. This concurs with current findings as presented in Chapter 1, that the slower a vessel, the higher the probability it will be intercepted by SAFC. Most FFH's included in this study do have high top speed, but high speeds result in very high fuel consumption. Also, most frigates have CODOG propulsion. Switching from diesel to gas turbine takes time, and switching often decreases turbine lifespan. Both high fuel consumption and turbine life reduction are undesirable and, thus, the influence of high frigate speed is good to know, but probably not very applicable to existing frigate designs.

5.3.2 SAFC Speed

It was observed during the preliminary simulation runs that the higher the SAFC speed, the more important the helicopter and small caliber, short range weapons are. This is due to the fact that the SAFC will swiftly cross the effective range of large caliber weapons, after which they may only be targeted by small caliber weapons. The helicopter is significant, as in the model there was no restriction on stand-off distance in relation to the frigate. In real life, a helicopter will in all probability not shoot at a SAFC alongside a frigate.[47] Nonetheless, if the helicopter is positioned well, it might take on a SAFC up to 50 yards off the frigates hull. This suggests that with very fast approaching unknown contacts, it is very important to determine intent early and swiftly take appropriate measures.

5.3.3 Helicopter Employment

It was observed during the simulation runs that employing a helicopter overall increases the probability of mission survival. The helicopter is not a dominating factor, though. When no helicopter is airborne it is important to determine hostile intentions early, or employ ROE that allow to deduce an approaching swarm's intentions through the action of any one of its members.

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[47]Even though the modeled Hellfire missile uses a laser designator, the missile may lose the rather small SAFC and lock-on to the frigate instead. According to subject matter experts, no Captain will allow Hellfire Missiles to be shot within about 500 yards of its vessel.

As observed weapon effects are essentially the same for both scenarios with and without helicopter, the model suggests not employing a helicopter may be compensated for by employing some other kind of sophisticated weapon system.

5.4   Recommendations

The insights gained do support the following observations and recommendations on frigate tactics, hull and effector design when dealing with small, agile and fast craft:

1. A frigate should be able to run at high speeds, outmaneuvering the attacker.

2. Weapons should achieve a high hit probability.

3. Highly trained human weapon operators achieve only very low P(hit).

4. Lower weapon's aimed inter-engagement times. A good example are modern CIWS.

5. Increase ammunition available on individual weapons, or reduce reloading times.

6. Employ a helicopter armed with a sophisticated maritime stand-off weapon whenever possible.

7. Large caliber ASW weapons are of no use in SAFC engagements.

All these suggestions are only valid in relation to a defense against up to eight small craft. This research does not suggest that these weapons are also effective against other types of threats. While they will probably not weaken power projection, they might not help.

It is also important to understand that even when all recommendations are put in practice, there is no guarantee that this will not result in a mission kill. As Clausewitz says,

> ... Absolute, so-called mathematical factors never find a firm basis in military calculations ... In the whole range of human activities, war most closely resembles a game of cards... The art of war deals with living and with moral forces. Consequently, it cannot attain the absolute, or certainty; it must always leave a margin for uncertainty, in the greatest things as much as in the smallest (Clausewitz and Schlieffen, 1905).

However, the major benefit of using robust analysis methodology is that they account for and mitigate the effects of uncertainty. Usage of these techniques is one of the contributions of this thesis.

5.5   Further Research

This study may well be expanded to include other MoE's, threats or higher level of detail. The following list surely is by no means comprehensive:

1. Employ suggested weapon mix in other scenarios and develop further insights.

2. Use of red teaming to find weaknesses in the improved defenses of the frigate.

3. Increase the attacking SAFC swarm size to determine limitations in the suggested setup.

4. Model catastrophic events such as hits in a magazine.

5. Model effector and system deterioration with damage received.

6. Model the effect of armoring on survivability.

7. Include a model of the frigate in sections, reducing the level of abstraction.

8. Model curves for weapon hit probabilities, sea states and greater variability of attackers capabilities.

9. Develop a set of mathematical equations describing interactions between frigate and SAFC.

10. Modeling partial or full integration of new automatic weapons in a certain frigate's C2 system, run a cost-benefit analysis, considering both the probability of attack and the cost of a mission kill of a frigate.[48]

5.6   Impact of Time

While this study was in the process of being written, some of this study's recommendations began being implemented. Defense news magazines, e.g., Jane's Defense Weekly (Janes Defense Weekly, 2009) and Naval Technology (Naval Technology, 2009), report that some

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[48]Considering political issues, evaluate cost of follow-on missions and cost of human/system losses.

navies are in the process of upgrading some of their weapon systems to use new targeting software, automated targeting and tracking modules, and computer-controlled turrets.

It is reassuring that the recommendations made within this study coincide with the decisions taken by the defense sector.

Naval Weapon Data Overview

This section covers the technical details, as far as they are known, of the weapons that were evaluated when determining the input data for the models run. The sections include Main Guns, Auxiliary Guns, Close In Weapon Systems, Small Guns and Handheld Weapons.

Main Guns

OTO Melara 76 mm gun (traditional/compatto/rapid)

- Effective range: 19000 meters

- Min range: 300 meters

- Caliber: 76 mm (3 inch)

- Rate of Fire: 35 - 120 rds/min

- Magazine Capacity: 80 rounds

- Traverse: 35 degrees / second

- Alias: U.S Mark 75

Bofors 57/70 mm MKII / MKIII

- Effective range: 14500 meters

- Min range: 250 meters

- Caliber: 57 mm

- Rate of Fire: 60 - 140 rds/min

- Magazine Capacity: no limit

- Traverse: 65 degrees / second

CADAM Turret / Loire 100mm / MK55 Mod 68

- Effective range: 12000 meters

- Min range: 300 meters

- Caliber: 100 mm

- Rate of Fire: 30 - 90 rds/min

- Magazine Capacity: 60

- Traverse: 40 degrees / second

OTO Breda 127/54

- Effective range: 24000 meters

- Min range: 300 - 800 meters

- Caliber: 127 mm (5 inch)

- Rate of Fire: 40 rds/min

- Magazine Capacity: 22 x 3 (66)

- Traverse: 40 degrees / second

OTO Melara 127/64

- Effective range: 50000 meters

- Min range: 500 - 800 meters

- Caliber: 127 mm (5 inch)

- Rate of Fire: 35 rds/min

- Magazine Capacity: 22 x 3

- Traverse: 35 degrees / second

114mm Mark 8 Mod 0 / Mod 1 (4.5 inch)(Fischer, 2006)

- Effective range: 220000 meters

- Min range: unknown

- Caliber: 114 mm (4.5 inch)

- Rate of Fire: 25 rds/min

- Magazine Capacity: 1 or 18 (Mod 0 / Mod 1)

- Traverse: 42 degrees / second

Giat CADAM Turret

- Caliber: 100 mm

- Rate of Fire: 25 rds/min

Auxiliary Guns

OTO Breda 40/L70 twin

- Effective range: 125000 meters

- Min range: 50 meters

- Caliber: 40 mm

- Rate of Fire: 300 rds/min

- Magazine Capacity: 444

- Alias: Type 64 / FastFourty

Mauser EADS MLG 30/27 mm

- Effective range: 3000 / 3500 meters

- Min range: 25 meters

- Caliber: 25 / 30 mm

- Rate of Fire: 800 rds/min

- Magazine Capacity: 90 to 105 rounds

- Alias: Marineleichtgeschuetz

Rheinmetall GDM-08 with MSP 500

- Effective range: 5500 meters

- Min range: unknown

- Caliber: 35 mm

- Rate of Fire: 1000 rds/min

- Magazine Capacity: 1200 rounds

- Alias: Millennium NGS

Oerlikon Gam/BO 1

- Effective range: 2000 meters

- Min range: unknown

- Caliber: 20 mm

- Rate of Fire: 1000 rds/min

- Magazine Capacity: 200 rounds

Allied Telesyn DS 30M Automated Small Calibre Gun System

- Effective range: 2000 meters

- Min range: unknown

- Caliber: 20 mm

- Rate of Fire: 200 rds/min

- Magazine Capacity: 150 rounds

Rheinmetall RH 202

- Effective range: 2500 meters

- Min range: 25 meters

- Caliber: 20 mm

- Rate of Fire: 880 - 1000 rds/min

- Magazine Capacity: 30 - 120 rounds

Close In Weapon Systems

Mauser Oerlikon MeRoKa

- Effective range: 3000 meters

- Min range: 150 meters

- Caliber: 20 mm

- Rate of Fire: 1440 rds/min

- Magazine Capacity: 2160 rounds

Signaal GAU-8/A

- Effective range: 1500 meters

- Min range: 100 meters

- Caliber: 30 mm

- Rate of Fire: 4200 rds/min

- Magazine Capacity: 14 * 90 rounds

- Alias: Goalkeeper, GE-30

GE / GDC MK 15 Mod 2

- Effective range: 2500 meters

- Min range: unknown

- Caliber: 20 mm

- Rate of Fire: 4500 rds/min

- Magazine Capacity: 1250 rounds

- Alias: Phalanx

Raytheon / Diehl RIM 116 Block 1 HAS

- Effective range: 7500 meters

- Min range: 250 meters

- Caliber: 127 mm (5 inch)

- Rate of Fire: 30 rds/min

- Magazine Capacity: 21 / 11 rounds

- Alias: Rolling Airframe Missile (RAM), Mk 44

Small Arms

Browning M3M

- Effective range: 2000 meters

- Min range: 0 to 25 meters

- Caliber: 12.7 mm (0.5 inch)

- Rate of Fire: 500 - 1200 rds/min

- Magazine Capacity: 50 - 200 rounds

- Alias: Ma Deuce, .50 Browning

GE M 134 GAU-2B

- Effective range: 750 meters

- Min range: 0 meter

- Caliber: 7.62 mm (0.308 inch)

- Rate of Fire: up to 6000 rds/min

- Magazine Capacity: up to 1500 rounds

- Alias: Minigun

OTO Melara 12.7mm HITROLE NT

- Effective range: 2500 meters

- Min range: 5 to 25 meters

- Caliber: 12.7 mm (0.308 inch)

- Rate of Fire: 500 - 1200 rds/min

- Magazine Capacity: 110 to 400 rounds

Handheld Weapons

RPG - 7 40mm w/ HEAT grenade

- Max effective range: 350 m

- Max absolute range: 940 m (4.5 sec flight)

- Weight loaded: 12 kg

- Rounds per minute: 2-4

- Country of origin: USSR

- Number Produced: 9000000

RPK 7.62 mm light machine gun

- Max effective range: 800 m

- Weight loaded: 6 kg

- Rounds per minute: 600-660

- Country of origin: USSR

- Number Produced: 1000000

PK 7.62 mm light machine gun

- Max effective range: 850 m

- Weight loaded: 8 kg

- Rounds per minute: 650 800

- Country of origin: USSR

- Number Produced: 1000000

Rheinmetall MG 3 7.62 mm LMG

- Max effective range: 1200 m

- Weight loaded: 12 kg

- Rounds per minute: 1000 1300

- Country of origin: Germany

- Number Produced: 1000000

NSV 12.7 mm HMG "Utjos"

- Max effective range: 2000 m

- Weight loaded: 40 + kg

- Rounds per minute: 700 800

- Country of origin: USSR

- Number Produced: ?

QJZ 89 12.7 mm HMG light

- Max effective range: 1500 m

- Weight loaded: 28 kg

- Rounds per minute: 540 660

- Country of origin: China

- Number Produced: ?

AK 47 7.62 mm Asault Rifle

- Max effective range: 250 - 300 m

- Weight loaded: 4 kg

- Rounds per minute: 600 +- 50

- Country of origin: USSR

- Number Produced: 30000000-50000000

HK G3 7.62 mm Assault Rifle

- Max effective range: 400 m

- Weight loaded: 5 kg

- Rounds per minute: 600-660

- Country of origin: Germany

- Number Produced: 9000000

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Included Frigate Classes

This section covers the technical details, as far as they are known, of the frigates that were evaluated when determining the input data for the models run. The frigates are listed by name of class. If the same class has different details for individual nations, or if the same class has been significantly updated over the course of time, more than one setup is included in this section.

F122 "Bremen"

- Country : Germany

- Max Speed: 30

- Economic Speed : 21

- Tonnage : 3680 tons

- Lenght : 131 m

- Width : 14.5 m

- Draft : 5 m

- Main Guns : 1 x OTO Melara Compact/62

- Aux Guns : 2 x 20 mm Rheinmetall

- Small Guns : 2 x 7.62 mm MG

- Missiles : 8 x Harpoon Bk 1C

- CIWS Missile : 0

- CIWS Gun : 0

- AAW Missile : 16 Sea Sparrow RIM-7P

- Nav Radar : 1 x Raytheon

- Air/surf radar : 1 ea DA08 / WM25

- Fire control : 1x WM25 / 1x Signaal STIR

F122 "Bremen" Mod

- Country : Germany

- Max Speed: 30

- Economic Speed : 21

- Tonnage : 3710 tons

- Lenght : 131 m

- Width : 14.5 m

- Draft : 5 m

- Main Guns : 1 x OTO Breda Rapid/62

- Aux Guns : 2 x 27 mm Mauser

- Small Guns : 3 x .50 Browning w/ digi sight

- Missiles : 8 x Harpoon Bk 1G

- CIWS Missile : 42 x Rim 114 RAM Blk I HAS mode

- CIWS Gun : 0

- AAW Missile : 16 Sea Sparrow RIM-7P

- Nav Radar : 1 ea

- Air/surf radar : 1 ea TRS3D / WM25

- Fire control : 1x WM25 / 1x Signaal STIR / Optronic

TYPE 22 "BROADSWORD" Batch II

- Country : United Kingdom

- Max Speed: 30

- Economic Speed : 22

- Tonnage : 4800 tons

- Lenght : 146.5 m

- Width : 14.8 m

- Draft : 6.4 m

- Main Guns : 1 x Vickers 4.5 In MK 8

- Aux Guns : 4 x Oerlikon GCM/A03 30mm

- Small Guns : 2 x Oerlikon Gam/BO1 20mm

- Missiles : 4 x MM38

- CIWS Missile : 32 x Sea Wolf Mod 3

- CIWS Gun : 0

- AAW Missile : 0

- Nav Radar : 1 ea

- Air/surf radar : 1 x Marconi 968

- Fire control : 2 x Marconi Type 911

TYPE 22 "Broadsword" Batch III

- Country : United Kingdom

- Max Speed: 30

- Economic Speed : 22

- Tonnage : 4900 tons

- Lenght : 149 m

- Width : 14.8 m

- Draft : 6.4 m

- Main Guns : 1 x Vickers 4.5 In MK 8 Mod 1

- Aux Guns : 2 x Oerlikon Gam/BO1 20mm

- Small Guns : 2 x M 323 Mk44 7.62 mm Minigun

- Missiles : 8 x Harpoon Bk 1C

- CIWS Missile : 32 x Sea Wolf Mod 3

- CIWS Gun : 1 SGE-30 B Goalkeeper

- AAW Missile : 0

- Nav Radar : 1 ea

- Air/surf radar : 1 x Marconi 967 / 968

- Fire control : 2 x Marconi Type 911

TYPE 23 "Duke"

- Country : United Kingdom

- Max Speed: 28

- Economic Speed : 18

- Tonnage : 4200 tons

- Lenght : 133 m

- Width : 16 m

- Draft : 5.5 m

- Main Guns : 1 x Vickers 4.5 In MK 8 Mod 1

- Aux Guns : 2 x DES/MSI DS 30B 30mm

- Small Guns : 2 x M 323 Mk44 7.62 mm Minigun

- Missiles : 8 x Harpoon Bk 1C

- CIWS Missile : 32 x Sea Wolf VLS Mod 1 Blk I

- CIWS Gun : 0

- AAW Missile : 0

- Nav Radar : 1 ea

- Air/surf radar : 1 ea Plessey Type 996(I) / Deca Type 1008

- Fire control : 2 x Marconi Type 911

"Elli" (Kortenaer Mod)

- Country : Greece

- Max Speed: 30

- Economic Speed : 21

- Tonnage : 3630 tons

- Lenght : 130.5 m

- Width : 14.6 m

- Draft : 6.2 m

- Main Guns : 2 x OTO Melara Compact/62

- Aux Guns : 2 x Oelikon 20mm

- Small Guns : 0

- Missiles : 8 x Harpoon Bk 1C

- CIWS Missile : 0

- CIWS Gun : 2 x MK-15 Bk 1 Phalanx

- AAW Missile : 24 x Sea Sparrow RIM-7P

- Nav Radar : 2 ea

- Air/surf radar : 1 ea WM 25/ ZW06

- Fire control : 1 ea WM 25 / Signaal STIR

"Karel Doormann"

- Country : Netherlands

- Max Speed: 30

- Economic Speed : ?

- Tonnage : 3320 tons

- Lenght : 122.5 m

- Width : 14.5 m

- Draft : 4.5 m

- Main Guns : 1 x OTO Melara Compact/62

- Aux Guns : 2 x Oelikon 20mm

- Small Guns : 2 x 12.7mm MG's

- Missiles : 8 x Harpoon Bk 1C

- CIWS Missile : 0

- CIWS Gun : 1 x SGE-30 Goalkeeper

- AAW Missile : 16 x Sea Sparrow RIM-7P

- Nav Radar : 1 ea

- Air/surf radar : 1 ea Signaal SMART/ LW-08

- Fire control : 2 x Signaal STIR

"Kortenaer"

- Country : Netherlands

- Max Speed: 30

- Economic Speed : ?

- Tonnage : 3630 tons

- Lenght : 130.5 m

- Width : 14.6 m

- Draft : 6.2 m

- Main Guns : 1 x OTO Melara Compact/62

- Aux Guns : 2 x Oelikon 20mm

- Small Guns : 0

- Missiles : 8 x Harpoon Bk 1C

- CIWS Missile : 0

- CIWS Gun : 1 x SGE-30 Goalkeeper

- AAW Missile : 24 x Sea Sparrow RIM-7P

- Nav Radar : 1 ea

- Air/surf radar : 1 ea WM 25/ ZW06

- Fire control : 1 ea WM 25 / Signaal STIR

"Lupo"

- Country : Italy

- Max Speed: 35

- Economic Speed : ?

- Tonnage : 2525 tons

- Lenght : 114 m

- Width : 11.3 m

- Draft : 3.7 m

- Main Guns : 1 OTO Merlara 127/54

- Aux Guns : 4 x Breda 40mm / 70 twin compact

- Small Guns : 2 x Oerlikon 20mm

- Missiles : 16 x OTO Melara Teseo Mk 2

- CIWS Missile : 0

- CIWS Gun : 0

- AAW Missile : 16 x Sea Sparrow RIM-7P

- Nav Radar : 1 ea

- Air/surf radar : 1 ea Selenia SPS-774/ SPQ-2F

- Fire control : 2 x SPG 70/ 2 x SPG 74 / 1 x MK 95 Mod 1

"Maestrale"

- Country : Italy

- Max Speed: 32

- Economic Speed : 21

- Tonnage : 3200 tons

- Lenght : 122.7 m

- Width : 12.9 m

- Draft : 4.6 m

- Main Guns : 1 OTO Merlara 127/54

- Aux Guns : 4 x Breda 40mm / 70 twin compact

- Small Guns : 2 x Oerlikon 20mm

- Missiles : 4 x OTO Melara Teseo Mk 2

- CIWS Missile : 0

- CIWS Gun : 0

- AAW Missile : 16 x Selenia Albatros Aspide

- Nav Radar : 2 ea

- Air/surf radar : 1 ea Selenia SPS 774 / SPS 702

- Fire control : 1 x SPG 75 / 2 x SPG 74

"Niels Juel"

- Country : Denmark

- Max Speed: 28

- Economic Speed : 18

- Tonnage : 1320 tons

- Lenght : 84 m

- Width : 10.3 m

- Draft : 3.1 m

- Main Guns : 1 x OTO Melara Compact/62

- Aux Guns : 0

- Small Guns : 4 x 12.7 mm MG's

- Missiles : 8 x Harpoon Bk 1C

- CIWS Missile : 4 x Stinger AAM

- CIWS Gun : 0

- AAW Missile : 12 x SeaSparrow RIM 7M, Mk 48 Mod 3

- Nav Radar : 1 ea

- Air/surf radar : 1 x DASA TRS-3D

- Fire control : 2 x MK 95 / Philipps 9LV 200 MK 1

"Oliver Hazard Perry"

- Country : United States, Turkey, Spain

- Max Speed: 29

- Economic Speed : ?

- Tonnage : 4100 tons

- Lenght : 138 m

- Width : 13.7 m

- Draft : 7.5 m

- Main Guns : 1 x OTO Melara Compact/62

- Aux Guns : 2 x Boing 25mm MK 38

- Small Guns : 4 x 12.7 mm MG's

- Missiles : 4 x Harpoon Bk 1C

- CIWS Missile : 0

- CIWS Gun : 1 x MK 15 Bk 1B Phalanx

- AAW Missile : 36 x SM-1MR

- Nav Radar : 1 ea

- Air/surf radar : 1 ea SPS-49V4 / Cardion SPS-55

- Fire control : 1 x Signaal WM28

"Oliver Hazard Perry" Mod

- Country : United States

- Max Speed: 29

- Economic Speed : ?

- Tonnage : 4065 tons

- Lenght : 138 m

- Width : 13.7 m

- Draft : 7.5 m

- Main Guns : 1 x OTO Melara Compact/62

- Aux Guns : 2 x Boing 25mm MK 38

- Small Guns : 4 x 12.7 mm MG's

- Missiles : 0

- CIWS Missile : 0

- CIWS Gun : 1 x MK 15 Bk 1B Phalanx

- AAW Missile : 0

- Nav Radar : 1 ea

- Air/surf radar : 1 ea SPS-49V4 / Cardion SPS-55

- Fire control : 1 x Signaal WM28

MEKO 200 PN "Vasco Da Gama"

- Country : Portugal

- Max Speed: 32

- Economic Speed : 21

- Tonnage : 3300 tons

- Lenght : 115.9 m

- Width : 14.9 m

- Draft : 6.1 m

- Main Guns : 1 x Creusot-Loire 100mm/55 Mod 68 CADAM

- Aux Guns : 2 x Oerlikon 20mm (turret)

- Small Guns : 2 x Oerlikon 20 mm

- Missiles : 8 x Harpoon Bk 1C

- CIWS Missile : 0

- CIWS Gun : 1 x MK 15 Bk 1B Phalanx

- AAW Missile : 16 x SeaSparrow RIM 7M, MK 29

- Nav Radar : 1 ea

- Air/surf radar : 1 x Signaal WM 25

- Fire control : 2 x Raytheon SPG-51C

MEKO 200 TN "Yavuz"

- Country : Turkey

- Max Speed: 27

- Economic Speed : 15

- Tonnage : 3030 tons

- Lenght : 110.5 m

- Width : 13.3 m

- Draft : 4 m

- Main Guns : 1 x Oto Breda 127/54

- Aux Guns : 0

- Small Guns : 2 x 12.7 mm MG's

- Missiles : 8 x Harpoon Bk 1G

- CIWS Missile : 0

- CIWS Gun : 3 x Oerlikon Contraves Sea Zenith

- AAW Missile : 16 x SeaSparrow Rim 7P, MK 29

- Nav Radar : 1 ea

- Air/surf radar : 1 ea AWS6 / DA-08

- Fire control : 1 x Signaal STIR 124

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Code

This section includes the code used to interweave the NOLH and Hadamard varied designs. It is written in JAVA, version 6.2.

```java
package extendcvs;

import java.io.BufferedReader;
import java.io.BufferedWriter;
import java.util.ArrayList;
import java.io.FileReader;
import java.io.FileWriter;
import java.io.IOException;
import java.util.logging.Level;
import java.util.logging.Logger;
/**
*
* @author heiko abel
*/
public class Main {
public static void main(String[] args) {
        System.out.println(args[0]);
        readFile(args[0], args[1], args[2]);
    }
    public static void readFile(String filenameOne, String
      filenameTwo, String outfile){
        BufferedReader in = null;
        ArrayList<String> fileOneData = new ArrayList<String>();
        BufferedReader inSAFC = null;
        try {
            in = new BufferedReader(new FileReader(filenameOne));
            inSAFC = new BufferedReader
(new FileReader(filenameTwo));
            String nextlineone = in.readLine();
```

```java
        String nextlineTwo = inSAFC.readLine();



        BufferedWriter out = new BufferedWriter(new
                FileWriter(outfile));
        StringBuffer buf = new StringBuffer();
        //out.write("cpi_number,response\n");

        buf.append(nextlineone);
        buf.append(",");
        buf.append(nextlineTwo);
        buf.append("\n");

        while ((nextlineTwo = inSAFC.readLine())!= null) {
            fileOneData.add(nextlineTwo);
        }
        while((nextlineone = in.readLine()) != null) {

            for (String s : fileOneData){
                buf.append(nextlineone);
                buf.append(",");
                buf.append(s);
                buf.append("\n");
            }
        }



        in.close();
        inSAFC.close();
        out.write(buf.toString());
        out.close();
    } catch (IOException ex) {
        Logger.getLogger(Main.class.getName())
                .log(Level.SEVERE, null, ex);
```

```java
        } finally {
            try {
                in.close();
            } catch (IOException ex) {
                Logger.getLogger(Main.class.getName())
                        .log(Level.SEVERE, null, ex);
            }
        }
    }

}
```
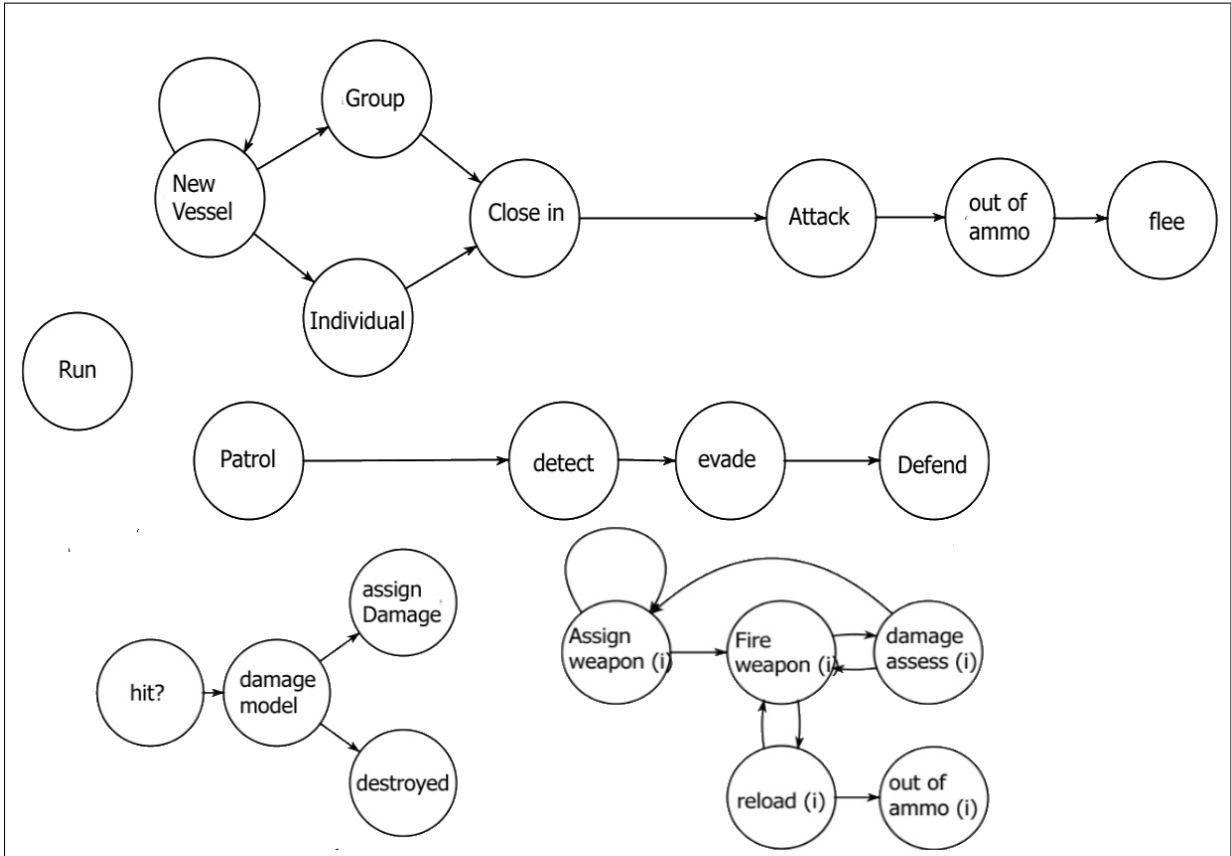
Event Graph

Figure 1: Event Graph as developed for the SimKit implementation visualizing the basic concept of the frigate – SAFC encounter.

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