SHIP SELF AIR DEFENSE ANALYSIS FOR DIFFERENT OPERATION CONDITIONS VIA SIMULATION

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To my wife Nurgül and my beloved daughter Betül;

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ABSTRACT

Rapid changes in defense technology have increased the importance of Anti-Air warfare for the naval battles. The increasing complexity of threats, such as anti-ship missiles, urges to develop new techniques and tactics against these threats.

This thesis developed simulation models with respect to different operational conditions so as to aid decision makers in ship air defense. We analyzed the effects of different combat systems with simulation models. Different firing policies in different situations were considered. In these situations, various SAM (Surface to air missile) types were used against particular types of threats.

The results of these simulation models indicate that use of these models provides good insight for the decision makers and leads them to appropriate decisions about selecting the best firing policy under varying operational conditions.

ÇEŞİTLİ HAREKAT ŞARTLARINDA GEMİ HAVA SAVUNMASININ SİMÜLASYONLA ANALİZİ

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Anahtar Kelimeler: Savunma, Gemi, Tehdit, Güdümlü Mermi, Simülasyon.

ÖZET

Son dönemlerde savunma teknolojisi hızla gelişmekte ve Hava Savunma Harbi gemiler için çok önemli bir hale gelmektedir. Gemilere karşı kullanılan güdümlü mermi gibi gelişen karmaşık tehditler, bu tehditlere karşı yeni teknik ve taktiklerin geliştirilmesine sevk etmiştir.

Bu tezin amacı farklı harekat şartlarına gore simulasyon modelleri geliştirmek, gemi hava savunmasında karar mercilerine yardımcı olmaktır. Simulasyon modellerinde farklı savaş sistemlerinin etkileri analiz edilmektedir. Farklı durumlarda farklı atış politikaları dikkate alınmaktadır. Bu koşullarda çeşitli SAM türleri kullanılmakta ve muhtelif tehditler gözönüne alınmaktadır.

Simulasyon modellerinin sonuçları, bu modellerin karar vericilerinin karar verme konusunda iyi bir şekilde yönlendirdiği ve farklı harekat şartlarında en iyi atış politikasını seçmeye yardımcı olduğunu göstermektedir.

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1. INTRODUCTION

1.1 Purpose

Nowadays, defense technology changes rapidly and Anti-Air warfare became crucial for naval platforms. Ship air defense modeling plays an important role in the development of modern maritime tactics [17]. The increasing complexity of threats, such as anti-ship missiles, urges analysts to develop new techniques and tactics against these threats. During naval operations main threat for the ships are anti-ship missiles. An anti-ship missile (ASM) is designed for use against surface ships. Most of the anti-ship missiles are sea-skimming (missiles fly at low altitude), subsonic (speed which is less than the speed of sound) or supersonic (speed over the speed of sound). Anti-ship missiles can be launched from different platforms such as;

- Warships
- Submarines
- Aircraft
- Helicopters
- Ground vehicles

ASMs have become a significant threat to modern warships in recent years and were used extensively during the 1982 Falklands War. In Falklands War, a British Navy frigate, HMS Sheffield, was hit also by Exocet missile fired by an Argentine Navy patrol aircraft. Since Exocet is a very destructive missile, HMS Sheffield sank. In 1987, a US Navy guided-missile frigate, the USS Stark, was hit by an Exocet missile fired by an Iraqi Mirage F-1 military aircraft and the USS Stark was damaged. In 1988, ASMs were fired by both US and Iranian forces in Operation Praying Mantis in the Persian Gulf. In 2006, Hezbollah forces fired a Chinese C-802 ASM at the Israeli corvette INS Hanit, and she suffered significantly from this attack [4].

These events show the importance of the Anti-air warfare (AAW). So, AAW is an important issue that is worth conducting research on. There are many articles and researches regarding AAW and ship air defense. Many of the previews studies about AAW and ship air defense did not focus on layered defense. The main difference of this thesis from the others is the implementation of layered defense system. Layered defense system consists of missiles Surface to Air Missile systems (SAM), gun systems, CIWS

(Close In Weapon System) systems. In the first step of layered defense system the ships engage to the incoming threat missile by missile, in the second layer by gun and at the last step by CIWS.

The objective of this thesis is to develop simulation models with respect to different operational conditions and to aid decision matters in ship air defense. In simulation models effects of different combat systems are analyzed. Different firing policies in different situations are also considered. In these situations, different SAM types are used and different types of threats are considered. For the simulation analysis some assumptions are made for the sake of simplicity and these assumptions are explained in chapter 3.

1.2 Background

Because of the high cost of live operational trials and limited budgets, it becomes very hard to make live exercises. Simulation is one of the most common used tools for the military analyses and training [5]. The importance of the simulation is now well recognized in most of military forces of countries. So big advances are being made in military simulation fields and these advances are mainly related with computer technologies.

Future naval operations are likely to be in littoral zones. This will lead ships operation close to enemy shore rather than to open sea. And this will urge warships to consider airborne and land-based ASM attacks together. There are many models to simulate ship defense system against missiles and aircrafts, but few of them provide insight on the layered defense system. Most of these models focused on only missile defense system. In this thesis, the layered defense system is simulated. When we consider the other models, we see that they provide good analyses but cannot be extended to handle a layered defense system.

In the models different types of measures of effectiveness (MOEs) are considered to evaluate the models' effectiveness. These MOEs are the percentage of leaker missiles (enemy missiles hit the ship); number of expended surface to air missiles (SAM) and SAM's kill range.

1.3 History of Anti Air Warfare

The development of Anti Air Warfare begins with the development of aircrafts. **AAW** or air defense is any method of engaging military aircraft or anti-ship missiles from the ship. Different types of gun systems have been used in anti air warfare since the first military aircraft were used in Trablusgarb war (1911). The military aircrafts were used in World War I to use chemical weapons. Since World War II guided missile used with the guns in AAW, specifically SAM, and today missiles, gun system and CIWS (Close In Weapon System) are used in combination in most roles.

The first anti-air warfare weapon was used in the Franco-Prussian War of 1870. After the disaster at Sedan, Paris was besieged and French troops outside the city started an attempt at resupply via balloon. Krupp (German family of steel and munitions manufacturers) quickly modified a 20 mm gun to be mounted on top of a horse-drawn carriage for the purpose of shooting down these balloons. In the late 1920s the 40-mm naval anti-aircraft gun is developed by Bofors Company. This gun was light, fast and reliable, and a mobile version on a four wheel carriage. It was known simply as the 40 mm; it was adopted by some 17 different nations just before World War II and is still in use today in some applications such as on coast guard frigates and attack boats.

Rocket powered missiles were used in World War II for shooting down aircraft. The British started with unguided missiles, fired in large numbers from *batteries*. By the end of the World War II, the British developed a guided surface-to-air missile, Stooge, which would be launched from Royal Navy ships against the Japanese Kamikaze attacks.

During World War II the Germans tried to develop various anti-aircraft missiles as well, but none of these was ready for service before the war ended. In particular, the Germans developed surface-to-air missile (Wasteful missile) during World War II but it never reached operational status and the project was cancelled in February 1945. After World War II, the anti air warfare missiles were developed rapidly.

Nowadays, all modern vessels contain anti-aircraft weapon systems. Smaller boats and ships typically have machine-guns or fast guns, which can often be deadly to low-flying aircraft if linked to a radar-directed fire-control system. Larger vessels (patrol boats, frigates, destroyers and cruisers) are typically equipped with surface-to-air missile systems, and in addition all of them carry radar-controlled guns for point defense. Aircraft carrier groups are especially well defended. There are many air defense armament ships in these groups and they are able to launch fighter jets for combat air patrol overhead to intercept incoming airborne threats [6].

2. LITERATURE REVIEW

2.1 Military Simulation

In this section we present a brief summary of the papers and conference proceedings published in the scientific literature and thesis. In this survey, we particularly focus on similarities and differences of the published works with this study.

Pace (1993) reviews verification, validation, and accreditation (VV&A) processes developed as interim policy guidance for Navy managed models and simulations. Relationships between the Navy interim policy guidance VV&A processes and other VV&A activities with in the Department of Defense (DoD) and elsewhere are discussed.

Polk, Mccants and Graberk (1994), develop a ship self-defense performance assessment methodology. With this methodology they provide data for the Office of the secretary of defense. In their work, hard kill elements, electronic warfare elements and integrated hard kill and soft kill elements are considered in performance prediction modeling. In addition they provide data to support programmatic decision. In the performance assessment methodology, the authors integrate hard kill weapons with soft kill capability; this part of work differs from this thesis, this work does not integrate.

Lee and Lo (1994)'s model is a good example of military simulation model. It is about optimal gun assignment in ship self defense. In this model, the ship is equipped with anti air weapons; there are no missiles on board. The objective is to minimize the number of targets striking at the ship and to maximize the ranges at which targets are destroyed. The ship motion is also simulated in this model. This is the main difference from this thesis. The radar detection range is not constant, it is random. The tracks are randomly generated like in this thesis. As a result of this simulation model, they concluded that the simulation using induction rules had better Measure of Effectiveness (MOE) in terms of minimizing the number of missiles striking at the ship and maximizing the ranges of target destroyed.

Dongen and Kos (1995) develop a computer simulation model for evaluating, analyzing and studying the performance of air defense systems aboard naval frigates. Their model integrates all the air defense systems on board a frigate. In this model Standard missile 1 (SM-1), NATO Seasparrow, Goalkeeper (close-in weapon system) are simulated. When this is compared with this thesis, it is observed that in this paper the gun system is not simulated and soft-kill measures are simulated. In their work radar detection probability is not constant, it changes with respect to target range, but in this thesis every object within the range of 200 km is detected by radar.

Smith (1998) identifies and explores the essential techniques necessary for modern military training simulations. His work provides a brief historical introduction followed by discussions of system architecture; simulation interoperability; event and time management; distributed simulation; and verification, validation, and accreditation. This is followed by fundamental principles of modeling in specific military modeling domains.

Townsend (1999) develops an analysis tool that is called anti ship defense model. It allows for analysis to be performed from an entire task force perspective, modeling the entire process by which ASMs select their targets and the methods by which the defending escorts assign defensive fire. This combat model is an analysis of Screen defense against anti ship missiles. The model can evaluate the threat posed by multi axis missile attacks, the impact of decoy, and other tactics. It can be used to plan missile attacks against enemy ship formations. Java programming language is used in the creation of this model. Townsend has used existing Java simulation components developed at the Naval Post Graduate School. Townsend constructs the Anti Ship Missile Defense model (ASMD) to determine the best screen arrangement for ships in a task force and determine the best firing policy.

Turan (1999) developed a Ship Self Air Defense (SSAD) system simulation model using discrete event simulation techniques and implemented it in Java programming language and Modkit. Modkit is a Java package developed by Major Arent Arntzen, Norwegian Air Force. The simulation is used to identify appropriate exploratory analysis capabilities including measures of effectiveness evaluation and parameter sensitivity analysis. His analysis techniques are used to evaluate two different SSAD systems and firing policies. These are Shoot-Shoot-Look (S-S-L) and Shoot-Look-Shoot (S-L-S) firing policies. This work considers only Surface to air missile (SAM) defense system. He did not use layered defense system.

Kulaç (1999) develops a model as an analysis tool to measure the effectiveness of radar and IR sensors in Ship Anti Air Warfare. A component-based simulation approach is adopted for this model using Java programming language to provide the necessary scalability and flexibility. To demonstrate the analysis capability of the model a comparative analysis was conducted for radar and IR sensors in Anti air warfare. He also designed Ship Self Defense Model to provide a simulation of one ship with its complement of weapons and sensors. The ship's mission is to defend herself and escorted ships against an attack of anti ship missiles. The purpose of the model is to assess the performance of active and passive sensors in different anti air warfare defense scenarios. This model is also developed using Java programming language.

Chapman and Kurt develop Ship Air Defense simulation model which is characterized by a complex interaction between the platform, detection systems, airborne threats, countermeasures and environment. Their model is described in the context of performance assessment of various system configurations with the objective of improving the probability of ship survival. Their model describes a Computer-based Ship Air Defense Model (SADM) developed by BAE SYSTEMS Australia, and used within BAE SYSTEMS Australia and the Electronic Warfare Division of DSTO. The model includes soft-kill modeling with active decoys, chaff, and jammers; hard-kill modeling with missiles, guns, and fire-control systems; and a Command and Control System to assign targets and coordinate soft-kill and hard-kill responses. SADM also models the interaction between the hard-kill and soft-kill systems deployed on the ship. Typical results are presented and it is shown how the model can be used to perform hard-kill/soft-kill tradeoffs during the ship design process.

Virlan (2001)'s model is a good example of ARENA based military simulation model. The model that he developed (Air Assault Operations Simulation Model) allows planners:(1) to build models of air assault operations early in the decision process and refine those models as their decision process evolve, (2) perform "*Bottleneck analysis*" of the preplanned operation using statistical procedures and take some precautions accordingly. (3) perform "*Risk management*" of the operation before conducting the real one. His model is created by using ARENA 3.0 simulation programming language. The outputs of the model are analyzed using experimental design procedures and the factors that are significant to the outputs are analyzed.

Kim (2003) develops an analytical model that describes defense for the Sea Base. Although models have been developed for defense of a carrier battle group (CVBG) with one High Value Unit (HVU) against air, surface and subsurface attacks, there are unique aspects of the Sea Base that are not specifically addressed in CVBG defense models. First, the defense of the sea base is different in that there are multiple HVUs expected in the Sea Base. In addition, there is a credible threat of being overwhelmed by High Density Threats (HDTs). This model specifically addresses the issue of defending multiple HVUs against HDTs. This model also gives a commander insight into the optimal placement of defenders with respect to parameters such as threat sector, minimum detection range, attacker and defender velocity, and defender weapon ranges. The model can also be used for Operational Requirements (ORs) development by Sea Base system designers. Kim uses Java programming language to simulate his model. By inputting parameters associated with certain scenarios, system developers can see how performance of a specific parameter, such as weapons range, probability of kill, and radar detection range, can affect the quality of Sea Base defense with respect to the effective area of defender coverage and the number of defenders required to achieve a certain level of protection.

Calfee and Rowe (2004) develop AEGIS Cruiser Air-Defense (ADC) Simulation. In their work they model the operations of Combat Information Center (CIC) watchstanders for a U.S. Navy battle group, using multi-agent system technology (Ferber, 1999). Conceived to assist training and doctrine formulation, the simulation provides insight into the factors (skills, experience, fatigue, aircraft numbers, weather, etc.) that influence performance, especially under intense or stressful situations. It simulates air tracks as well as the actions and mental processes of the watchstanders. All simulated events are logged to permit performance analysis and reconstruction for training. They have implemented their model in Java programming language.

Ozkan (2004)'s simulation is the Air Defense Laboratory (ADL) Simulation. It provides a simulation environment that allows users to create realistic air defense scenarios and examine automated reasoning about the tracks. It is written in Java and it uses multiagent system technology to model the components of reasoning. Agents include both track-generator agents that control aircraft activities based on the type of the aircraft, and track-predictor agents that receive data about the aircraft and generate predictions about their identity and possible intent.

3. SHIP AIR SELF DEFENSE SYSTEM

3.1 Single Ship Air Defense (SSAD) System

A naval ship can carry a limited amount of defensive missiles, so she has to efficiently use her missiles to accomplish her mission. The appropriate expenditure of these missiles will thus be an important part of this study. The main objectives of this study then are:

(1) To evaluate existing systems via simulation because of difficulties in executing real world systems due to impediments in creating real world conditions and also economic reasons.

(2) To detect the factors which have significant effects on the existing system.

(3) To foresee the possible problems of the existing system by studying the simulation model outputs using statistical methods.

3.2 Ship Air Self Defense

Complexity of ship air defense system processes depends on whether the air defense system consists of a single sensor and weapon or several sensors and weapons operating together [1]. For the purposes of this study only one ship's air defense system will be considered. Hence there will be one launcher and one or two trackers for air defense weapons. When we consider general area air defense, there may be land-based surface to air (SAM) battalion or guided missile frigates in a battle group.

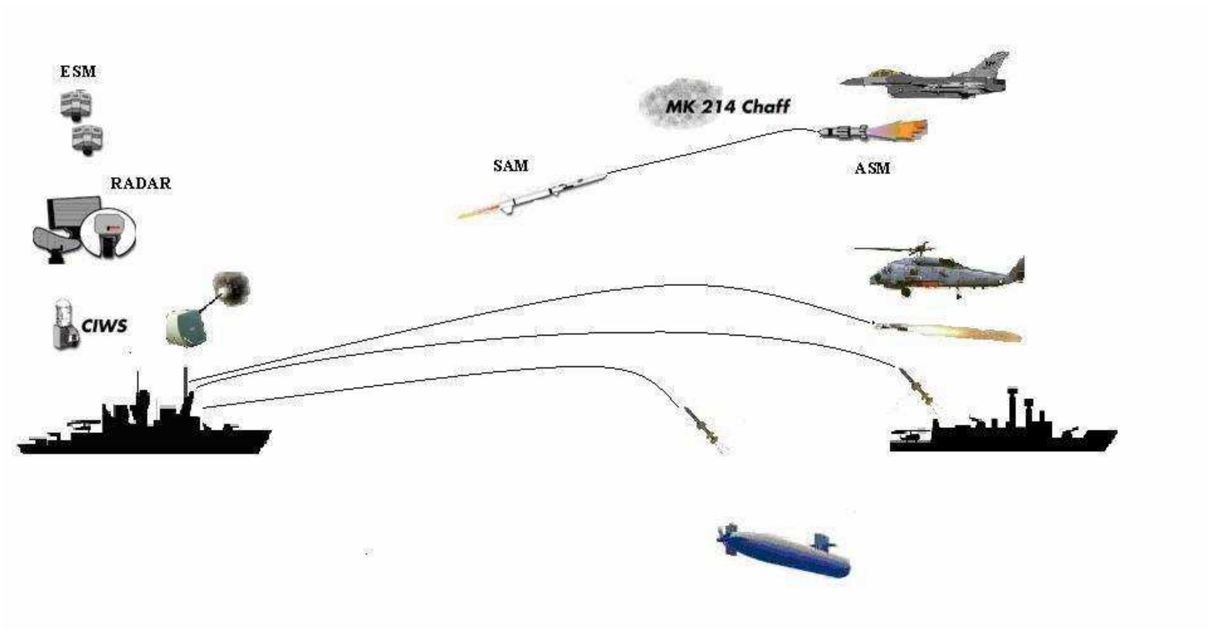


Figure 3.1 Targeting methods of ASMs

The main purpose of ship air defense (SAD) is to protect the ships against Anti-Surface Missiles (ASM). As we see from the figure 3.1, surface ships, attack aircrafts, bomber aircrafts, submarines, helicopters may attack ships by ASM. The other important threat for the ships is land based ASM and the figure 3.2 shows one of the land-based ASM's (Exocet MM-40) flight and attacking profile.

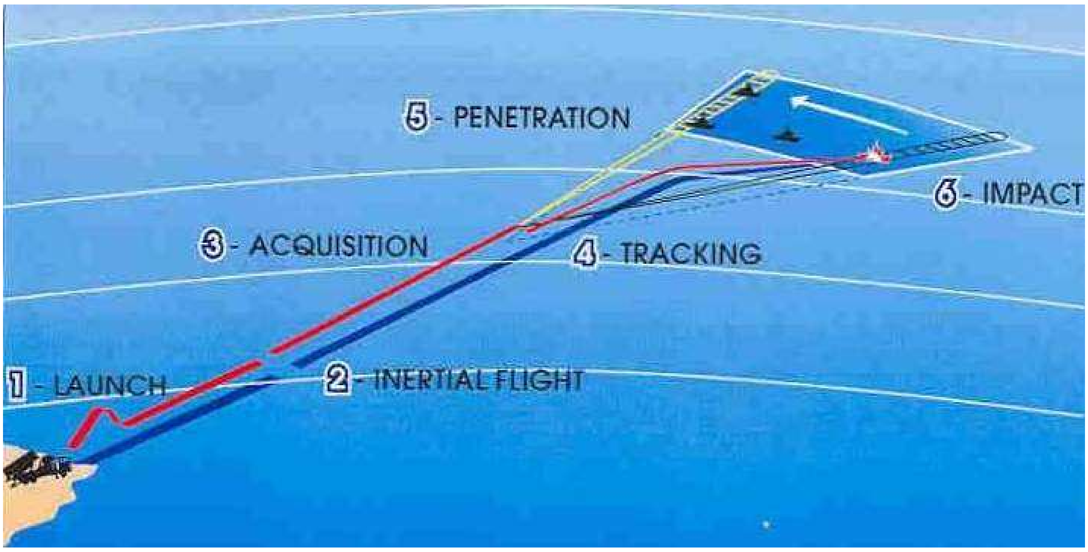


Figure 3.2 Flight and Attack profile of Exocet missile [29]

To protect the ships from these attacks, ships have missile launchers, guns, CIWS (Close In Weapon System) and chaff launchers. Ship air defense systems use

Hard-Kill and Soft-Kill Measures to protect the ship. Hard-Kill defense method is to destroy the incoming threats (missile or aircraft) by explosion. So Surface to Air Missiles (SAM), guns, CIWS are main Hard-Kill defense systems.

Soft-Kill defense method involves controlling and diverting the incoming threat missile away from the ship by confusing, distracting, or seduction. The integral part of soft kill defense method is decoys. Decoy is a self protect jammer. There are three types of decoys used for air defense: chaff, thermal decoys, and active radar decoys.

In ship air defense system the primary components are sensors. The first step of ship air defense system is detecting the incoming missiles or aircrafts. Especially detection of low altitude anti-ship missiles is very important for ships. In the first step the targets are detected by radars. Radar is an acronym for Radio Detection and Ranging. It uses radio transmissions to collect information. Radar can only identify whether there is a threat or not. Early detection of incoming missiles or aircraft determines the success of the ship air defense. Detection is a single event that provides limited information. Acquisition closely related to detection. It refers to the repeated detection of a new target during several scans. This allows the sensor system to make a decision that a new target has appeared and extract information concerning its position and velocity or its signal characteristics [1].

Identifying the target has been a vital issue in air defense system. In history, we can see the crucial results of misidentification of the aircrafts; one of them is *Iran Air Flight 655* disaster. In 1988, on patrol in the Persian Gulf, the USS *Vincennes* shot down an Iranian passenger jet that it had mistaken for a hostile Iranian fighter aircraft. The plane did not respond to seven warnings to identify itself, and the *Vincennes* picked up transmissions from the aircraft on the Mode 2 military frequency (IFF). As the plane came within 20 miles of the cruiser, radar indicated its descent from 9,000 feet and picked up altitude. (Data from other sources subsequently contradicted this.) When the aircraft was nine miles away, USS *Vincennes* fired two SM-2 surface-to-air missiles. The ship crew couldn’t understand whether the aircraft was civilian or not because the aircraft IFF (Identify Friend or Foe) systems did not respond the interrogations.

These IFF Systems are used on ships to electronically identify friendly aircraft. These systems have interrogators and transponders. They transmit an interrogation signal to which a transponder will respond to the interrogation. The failure of an aircraft responding to an interrogation does not mean it is hostile; its IFF system may be out of order. Only IFF response does not guarantee that an aircraft is hostile or friendly. After a target has been declared hostile and it is decided that the target will be engaged, a tracking sensor and a weapon must be assigned, the target must be designated to the tracking sensor and the tracker assigns a weapon system to the target.

Anti-Air warfare is top priority for navies in selecting most effective ship defense systems. The effectiveness of the sensors improves the defense capability of ships. The air defense of ship consists of finding and identifying threats, controlling sensors and weapons, and engaging threats. This engaging is known as “detect”,” control” and “engage”.

Air defense components of ships consist:

1. Surveillance sensors
    - Human eye
    - Radar
    - Laser
    - Infrared
    - Electronic Support Measures(ESM)
2. Fire control system
3. Hard-Kill weapons
    - Missiles
    - Guns
    - CIWS

4. Soft Kill systems
    - Decoys
    - Jammers [3]

3.3 Anti Ship Missile Threat

An anti-ship missile is a military missile designed for use against naval surface ships. There are different types of anti-ship missiles, most of them are sea-skimming, subsonic or supersonic [4]. Modern anti-ship missiles are of course serious threat to maritime assets. Since anti-ship missiles are small and attack quickly, naval war tactics have changed with respect to these properties of size and speed.

The Russian SS-N-2/P-15 Styx was the first missile to prove the anti-missile concept in actual combat area. In 1967, Egyptian Komar-class missile boats fired Styx missiles to the Israeli destroyer Eliat and sunk the ship. After this year the power of the anti-ship missiles was understood better and the most of the anti-ship missile types were developed after 1967.

In recent operations, aircrafts armed with anti-ship missiles have demonstrated operational advantages over ships, submarines and land-based systems since they allow greater employment flexibility and superior sensor range [7]. When we look at the last 40 years, we can see that most successful anti-ship missile attacks are made by aircrafts. During the past 40 years, nearly 20 warships and 200 civilian ships have been sunk or damaged by ASMs, one of them is Turkish warship TCG Muavenet is damaged by seasparrow missile launched from USS Saratoga.

Nowadays, the commonly used ASMs in NATO are Exocet, Harpoon, and Harm. These can be launched also from aircrafts. So in this work Exocet, Harpoon, Harm is considered as threats.

3.4 Elements of the Single Ship Air Defense (SSAD) System

The purpose of SSAD system is to defend ship against ASM (Anti surface missiles). The elements of SSAD system are as follows:

3.4.1 Radar:

Figure 3.3 Air Surveillance Radar [29]

RADAR is a system that uses radio waves to determine and map the location, direction, and/or speed of both moving and fixed objects such as aircraft, ships and missiles. In radar system a transmitter emits radio waves, which are reflected by the target and detected by a receiver, typically in the same location as the transmitter. Although the radio signal returned is usually very weak, radio signals can easily be amplified, so radar can detect objects at ranges where other emissions, such as visible light, would be too weak to detect [4]. Figure 3.3 represents an air surveillance radar.

3.4.2 IFF (Identify Friend or Foe):

IFF (Identify Friend or Foe) systems are used on ships to electronically identify friendly aircraft. These systems have interrogators and transponders. The interrogator transmits an interrogation signal and the transponder responds to the interrogation. The failure of an aircraft response to an interrogation does not mean it is hostile; if an aircraft does not respond, one cannot treat it as a hostile aircraft because the IFF system of aircraft may be out of order. However, an IFF response does not guarantee that an aircraft is hostile or friendly. After a target has been declared hostile and one decides to engage the target. A tracking sensor and a weapon must be assigned and the target must be designated to the tracking sensor. The tracker assigns a weapon system to the target.

3.4.3 ESM (Electronic support measures) System:

Figure 3.4 ESM System [29]

ESM system provides long-range threat detection, threat direction-finding, and accurate and positive identification of threat emitters. AN/SLQ-32 ESM system is one of the common ESM systems in the navies. ESM plays an important role in the targeting process. Information gained through ESM is also used to update data bases, provide information for the other systems like fire control systems, combat systems.

Electronic support measures (ESM) is the division of electronic warfare. It involves intercept, identify, and locate sources of radiated electromagnetic energy for the purpose of immediate threat recognition. Thus, electronic support measures (ESM) provide a source of information required for immediate decisions involving electronic counter-measures (ECM) (any sort of electrical or electronic device designed to fool radar, sonar, or other detection systems) [4]. Figure 3.4 shows an ESM system on frigates.

3.4.4 Chaff System:

Figure 3.5 Chaff Launcher Systems [29]

Chaff is a radar countermeasure in which aircraft or other targets spread short lengths of plastic or fiber with a conductive coating. Chaff is packed into containers that can be released by launchers on ships and aircrafts. Figure 3.5 shows one type of these launchers. Chaff is explosively discharged from the container into the atmosphere where it spreads out, moves with the wind. Chaff has little effect on incoming threat missiles.

3.4.5 Active Radar Decoys:

These decoys can be considered expendable jammers and they may be employed as a self protection measure by approaching threat. They are used by surface ships to break the fire control systems' tracks. And these devices can be designed to perform noise or deceptive jamming against surface-based search and track radar.

3.4.6 Thermal Decoys:

Thermal decoys provide background noise or false targets against infrared (IR) sensors [1]. It is mostly used against IR SAM in air defense system.

3.4.7 Fire Control System:

Figure 3.6 CAS Fire Control Radar [29]

The fire control system is very important in air defense model. A fire-control system consists of a computer designed to assist a weapon system in hitting its target. Fire-control systems are often interfaced with sensors (such as sonar, radar, infra-red search and track, laser range-finders, anemometers, wind vanes, thermometers, etc.) in order to cut down or eliminate the amount of information which has to be manually inputted to calculate an effective solution. The situation for naval fire control is more complex because of the need to control the firing of several missiles at once. In naval engagements both the firing missiles and target are moving, and the variables are compounded by the greater distances and times involved. Corrections are made for temperature, rate of change of range with additional modifications to the firing solution based upon the observation of preceding shots [4]. In this model we assume that the ship has a two unit fire control system and that their ranges are 100 km and 50 km respectively. The first fire control system tracks the target within the range of 100 km and the first missile is launched to meet the target at 45 km which is maximum effective range of SAM. The second fire control system takes over the threat within the range of 50 km, thus the first fire control system can track another threat. Figure 3.6 shows the second fire control system.

3.4.8 Launchers:

Figure 3.7 Mk-13 Launcher [29]

The task of the launcher is to carry and launch the missiles. The fire control system leads the launcher to fire. Most of the ships have two types of launcher. These are vertical launcher and deck mounted launcher. Vertical launchers have fewer moving part. A single set of vertical launch silos can provide hemispherical 360-degree coverage. Since they do not need to be slewed to face the target, they can launch rounds more quickly, while the elimination of manual or mechanical loading speeds up the firing of salvoes. Vertical launch systems can carry a much wider range of missile types than traditional launchers [8]. The deck mounted launchers must be controlled by a servo motor which receives engagement angles from the fire control system. Figure 3.7 shows one of the deck mounted launcher.

3.4.9 Surface to Air Missile Systems:

These systems are designed to be launched from ship to destroy anti-hip missiles and hostile aircrafts. Surface to Air Missiles (SAMs) are longest range ship self defense system. They are the main weapon in hard kill defense system. They can be launched from different types of launchers. Nowadays, all modern ships (frigates, cruisers, destroyers, aircraft carriers) are equipped with SAM systems.

3.4.10 Gun Systems:

Antiaircraft artillery system has terminal defense role in ship self defense system. It consists of a Gun System and Close in Weapon System (CIWS). Gun system is more effective at ranges of less than four kilometers against targets [1]. Many missiles are not effective at ranges of less than five kilometers, so the gun system is very important for ships in self defense. Almost every warship is equipped with a gun system. Guided missiles have adopted many roles in modern navies, but there is continued interest by ship operators in maintaining gun capability. Gun applications fall into three categories: ship defense; direct fire; and long-range indirect fire to support troops ashore. In these roles, guns are generally complementary to missiles. The advantage of guns is that the rounds fired are smaller and less expensive than missiles, so hundreds to thousands of rounds can be carried, compared with tens of the more expensive and larger missiles [9]. The SAMs are not very effective against low altitude targets, so ships can use gun system against low altitude targets.

3.4.11 CIWS (Close In Weapon Systems):

Figure 3.8 Phalanx Close-in Weapon Systems [29]

A Close-in Weapon System (CIWS) is an autonomous weapon system for detecting and destroying incoming anti-ship missiles and enemy aircraft at short range. It consists of a combination of radars, computers, and multiple rapid-fire medium-caliber guns placed on a rotating gun mount. It was originally designed to defend ships against low altitude anti ship missiles. Because of complexity of threats and its high firing rate, it is used against many types of missiles and aircrafts. All modern ships are equipped with a type of CIWS. Figure 3.8 shows one of the commonly used CIWS systems on ships.

3.5 Actual Systems Modeled In the Simulation Scenarious

The real systems in navy are modeled in this thesis. Since the exact values are confidential, the values for parameters have been obtained from open source. The threat missiles and SAMs are indicated as follows:

3.5.1 Exocet Anti-Ship Missile:

Exocet missile is a medium range anti-ship missile that was started in development in 1967 by the Aerospatiale Company. It is originally designed as the ship-launched variant MM 38 which entered service in 1975. The air-launched version, AM 39, was developed in 1974 and entered to service with the French Navy in 1979. The missile is designed to attack large warships.

The versions of Exocet are as follows:

- MM38 (surface-launched)
- AM39 (air-launched)
- SM39 (submarine-launched)
- MM40 (surface-launched)

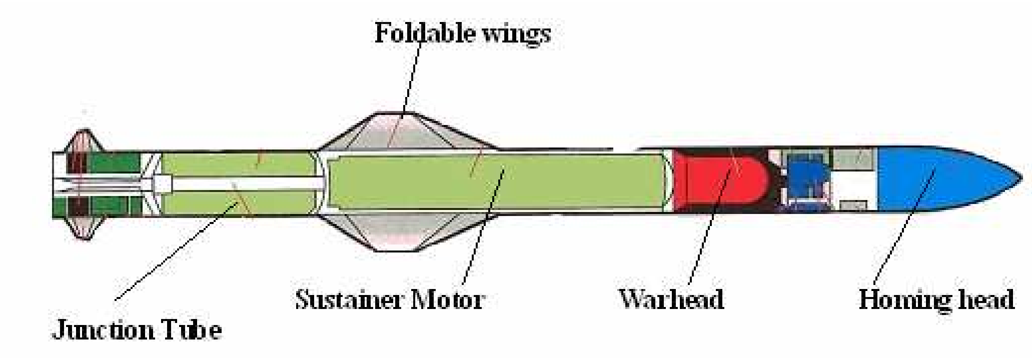


Figure 3.9 Parts of the Exocet MM-40[29]

Figure 3.9 shows the parts of the Exocet MM-40 missile.

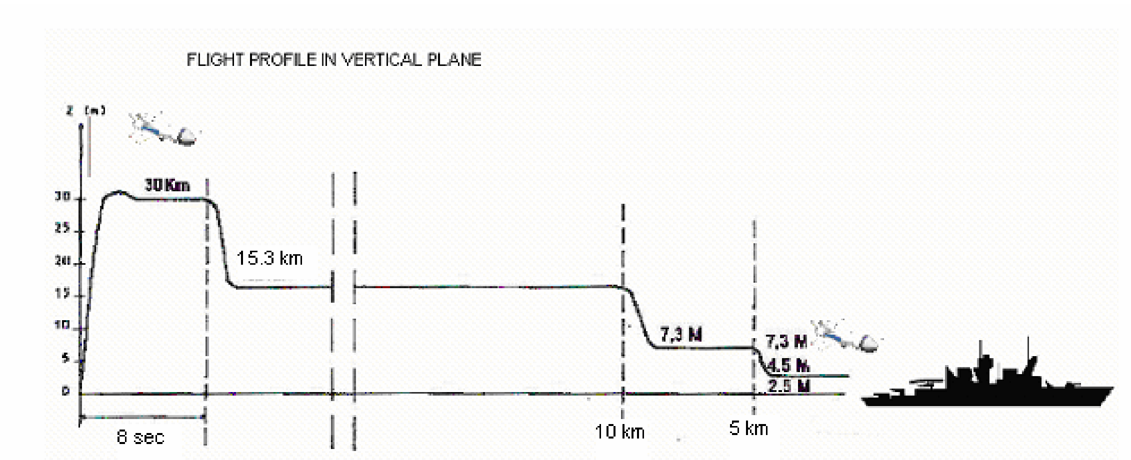


Figure 3.10 Flight Profile of Exocet Missile [29]

As it can be seen in figure 3.10, after the missile is launched, it flies at a 30 meter altitude; in 8 seconds it begins to fly a 10 meter altitude; and in terminal phase, altitude becomes between 2.5 and 7.3 meters. Table 3.1 represents the specifications of Exocet missile.

SPECIFICATIONS		
	MM 38	**MM40/AM 39**
Length	5.21 m	5.78 m
Diameter	0.35 m	0.35m
Weight	735 kg	855 kg
Speed	0.9 mach	0.9 mach
Range	2-22.5 nm	2-38 nm
Sea-Skimming Height	8 m	8 m

Table 3.1 Specifications of Exocet Missile [10]

3.5.2 Harpoon Anti-Ship Missile:

The Harpoon missile was developed in the early 1970s by the US Navy. Harpoon was designed for Navy's basic anti-ship missile. Its main purpose was to sink warships in open seas. With the recent developments, it can be launched from aircrafts, ships and submarines. Figure 3.12 shows these profiles. It has low level, sea-skimming cruise trajectory and active radar guidance. These parts can be seen from figure 3.11. It has high survivability and effectiveness against targets.

Since it has active radar guidance, once fired it flies to the target location without additional guidance from firing platform.

Submarines fire a capsule containing the Harpoon from their torpedo tubes. Table 3.2 presents the physical properties of Harpoon missile.

SPECIFICATIONS		
	Sea launched	**Air launched**
Length	4.55 m	3.79 m
Diameter	34.29 cm	34.29 cm
Weight	661.5 kg	515.25 kg
Speed	855 km/h	855 kg/h
Range	> 60 nm	> 60 nm

Table 3.2 Specifications of Harpoon [11]

Figure 3.11 Parts of the Harpoon Missile [12]

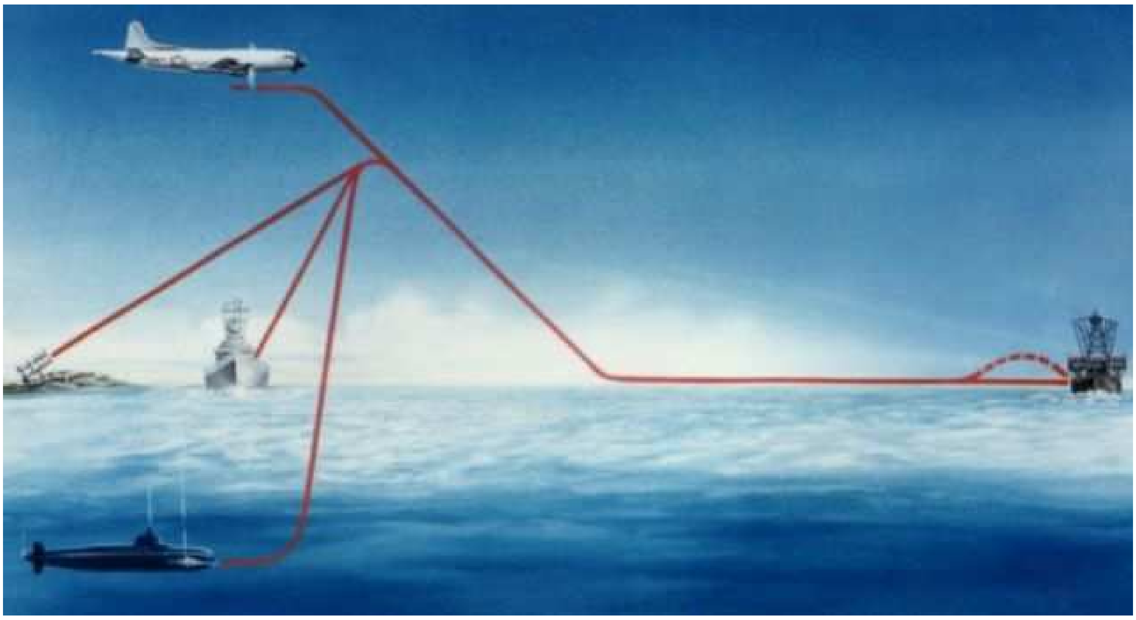


Figure 3.12 Harpoon Mission Profile [29]

3.5.3 HARM (High-speed antiradiation missile):

It is originally developed by US Navy and Raytheon [Texas Instruments] company. It was started to be used in 1982. Its first combat use was in Libya in 1986. During the Iraqi war more than 400 missiles eliminated the radar threat [13]. It is an air-to-surface missile designed to destroy enemy radar-equipped air defense systems. It is guided to radar signal. It is designed to be launched from aircrafts. Figure 3.13 shows parts of HARM missile. Table 3.3 represents Specifications of HARM missile.

HARM was originally developed by US Navy and Raytheon [Texas Instruments] company. HARM is designed to be launched from aircrafts.The missile began to be used in 1982 with its first combat use in Libya in 1986. It is an air-to-surface missile designed to destroy enemy radar-equipped air defense systems. During the Iraqi war, more than 400 HARM Missiles eliminated the threat of radar [13]. Figure 3.13 shows parts of HARM missile. Table 3.3 represents Specifications of HARM missile

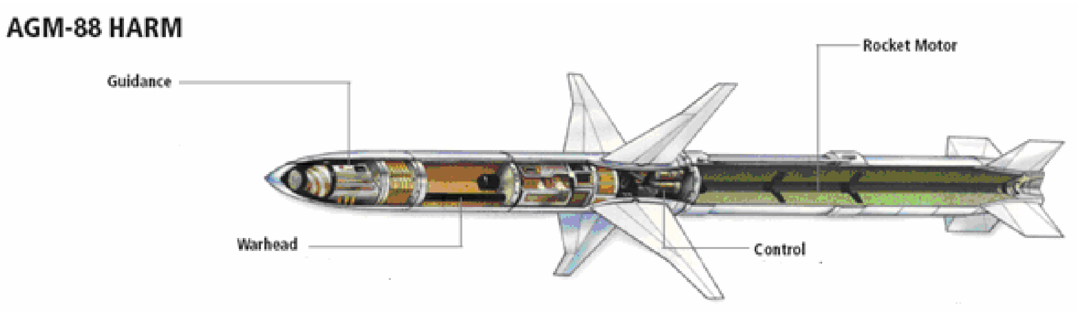


Figure 3.13 Parts of the HARM Missile [13]

SPECIFICATIONS	
Length	4.17 m
Diameter	25 cm
Weight	363 kg
Speed	2280 km/h
Range	> 48 km

Table 3.3 Specifications of HARM missile

3.5.4 Sea Sparrow Surface to Air Missile:

Figure 3.14 Sea Sparrow Missile [29]

This is a radar guided medium range surface to air missile. Originally it was developed by Sperry and the U.S. Navy; Sparrow's later versions were developed and produced by Raytheon Co. and General Dynamics. It was started to be developed in the mid-1950 as a lightweight "point defense" weapon. It is used against hostile aircrafts and anti-ship missiles. It is also used by aircrafts as self defense missile. The growing threats from the ASM's urge the development of the SAMs. So after 1968, the joint development effort was begun with NATO countries. Nowadays, many NATO countries and US Navy use Sea Sparrow as ship air defense missile. Figure 14 shows a launched Sea Sparrow missile from deck mounted launcher. Table 3.4 represents specifications of a Sea Sparrow missile.

SPECIFICATIONS	
Length	3.64 m
Diameter	20.325 cm
Weight	225 kg
Speed	4256 km/h
Range	6 nm

Table 3.4 Specifications of Sea Sparrow missile [11]

3.5.5 Standard Missile (SM-1):

Figure 3.15 SM-1 Missile [29]

The Standard Missile is the main surface to air missile for the many countries' Navies. The Standard Missile was begun to be produced in the 1970s. Since it is one of the most reliable SAM, it remains in operation with many international navies. Raytheon Company supports US Navy to develop SM-1 Missile. There are two major types; these are the SM-1 MR/SM-2 (medium range) and the SM-2 (extended range). Table 3.5 represents the specifications of medium range SM-1 missile. SM-1's primary function is to provide area defense against enemy aircraft and anti ship cruise missiles. Figure 3.15 shows a launched SM-1 missile from deck mounted launcher.

Specifications	
Length	4.48 m
Diameter	34.3 cm
Weight	616kg
Speed	>2500km/h
Range	46 km

Table 3.5 Specifications of SM-1 Missile [13]

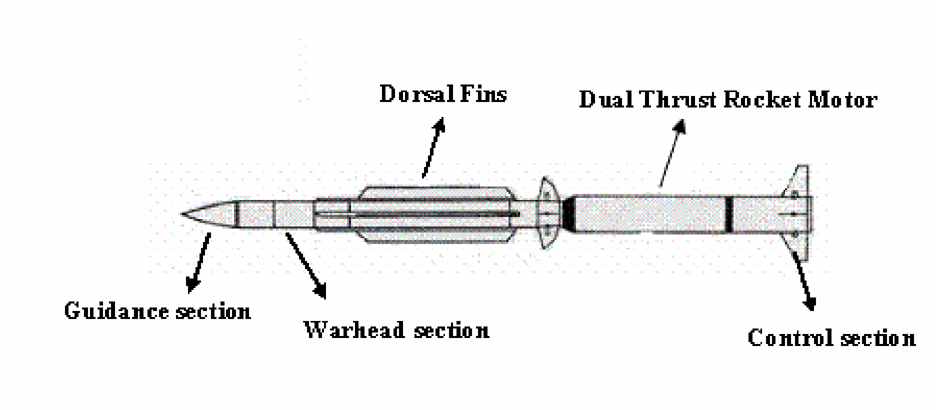


Figure 3.16 Parts of the SM-1 Missile [29]

4. SIMULATION MODELS

In our simulation models we have made some assumptions so as to elude the complexity of real environments conditions and system configurations.

4.1 Assumptions

1. Since operation periods are hundred hours, during operations the weather condition does not change significantly. Environmental conditions (Weather, sea condition, wind speed, etc.) are ignored during simulations.
2. Since there is no available data about operators' errors under different operational conditions, the operators' errors are not included in the models.
3. Only Hard Kill systems are modeled, Soft Kill counter measure system (chaff, decoys, radar jamming devices) are not considered. In real war conditions, the Soft Kill measures are used to distract the threat from very long range. In operation area many ships use soft kill measures to hide themselves from a very long range. Soft kill measures cannot be used for some type of missiles (like anti radiation missiles).
4. Since speed of the ship is very slow with respect to attacking missile, ship's movements are not taken into consideration during calculations.
5. Radar and ESM system are considered together while recognizing the threat. The radar can detect active homing threat missile earlier than ESM, on the other hand ESM can detect hostile aircraft earlier than radar.
6. Radar maximum detection range is assumed to be 200 km and it detects every threat within the range of 200 km. In real conditions the detecting ranges are not constant; they depend on type and power of a radar.
7. Most of the ships in the navies of today's can launch one type of SAM. So the ships in our simulation models can only fire one type of missile. During simulations SM-1 and Seasparrow missiles are simulated.
8. There is only one launcher on the ship, so the ship cannot launch more than one missile at the same time. There is loading delay between two subsequent firings. This delay differs with respect to the launcher type. In

this thesis, the loading delay is the same for all scenarios.

9. The SAM missiles and the threat missiles are assumed to move linearly. Acceleration and nonlinear movement are not considered.
10. Since only SM-1 and Seasparrow missiles (Semi-active homing missiles) are simulated, they need to be illuminated all the way of engagement.
11. There are two tracking sensors on board and they can only illuminate one threat at the same time. The SAMs maximum kill ranges are assumed to be 45 km and 15 km. Since the first tracker can illuminate the threats up to 100 km and the second tracker can illuminate the threats up to 50 km., the first SAM can hit the threat at 45 and 15 km with respect to SAM type. (Which are SM-1 and Seasparrow)
12. There are civilian aircrafts, hostile attacking aircrafts, and incoming anti-ship missiles in operation area. And these aircrafts and missiles have constant velocity during simulations. During the calculations, these constant velocities are considered.

4.2 Comparative Analysis

The analysis of ship air defense is not only simple numerical analysis and their comparison, because survivability of the ship also has to be considered in defense analysis. The effects of firing policies under different operational conditions are analyzed. In simulation models the following measure of effectiveness (MOE) will be used to compare the ship air defense systems. These MOEs will differ according to the scenarios. These MOEs are as follows:

- Number of expended SAMs (cost)
- The ranges at which targets are destroyed
- Number of leaker missiles(missiles that hit the ship)

These parameters are analyzed for different scenarios and each SAM missiles.

4.3 Parameters Used In SSAD Simulation Model

In this thesis the real threats are simulated. To simulate the threats and to determine the rate of tracks, we considered the aircrafts, the missiles, and the land based launchers in Aegean Sea. The other threats around Turkey are not considered. So a database is created to use in simulations. This database is unclassified. To create the database open sources like Jane's defense ship book, www.fas.org and the other related web pages are used.

1. **Threat missiles:**
   - **Harpoon:**

     - Speed: 0.8 mach

     - Frequency: 16670-16930

     - Range: 130 km

     - Guidance: Active homing

   - **Exocet**

     - Speed: 0.9 mach

     - Frequency: 8850-9600

     - Range: 70 km

     - Guidance: Active homing

   - **Harm**

     - Speed: 0.9 mach

     - Range: 148 km

     - Guidance: Anti-radiation missile

2. **Surveillance system:**

   - **Max detection range: 200 km**

3. **Firing policy:**

   - **Shoot-Shoot-Look (S-S-L) firing policy:** In this firing policy two missiles are fired one after another before a kill assessment is made. The time between two fired missiles depends on the type of missile launcher. The missiles may be expended unnecessary anyways, even if the second one hits.
   - **Shoot-Look-Shoot (S-L-S) firing policy:** In this firing policy, the second missile is not fired until the first fired missile reached its

destination. If the first missile cannot kill its target than the second missile is fired.

4. **SAM:**

- **SAM 1 (SM-1):**
  - **Max kill range: 45 km**
  - **Min kill range: 5 km**
  - **Speed: 2 mach**
  - **Guidance: semi active**

- **SAM 2 (Sea sparrow):**
  - **Max kill range: 15 km**
  - **Min kill range: 5 km**
  - **Speed: 2.5 mach**
  - **Guidance: semi active**

5. **Aircrafts:**

- **Military hostile aircrafts:**
  - **Speed: 1.2-2 mach**
  - **Radar frequency: 9700-10000 MHz**

- **Civilian aircrafts:**
  - **Speed: 0.6-0.7 mach**
  - **Altitude: 5000-10000 m**

4.4 General Situation in Scenarios

In all of the scenarios, we assume that a ship is patrolling an assigned area and performing ship self defense. There are air threats which may be missiles and aircrafts in operation area. Our mission is to defend the ship against these threats. To defend the ship against these threats, the ship has to have early warning systems and identifying systems like IFF. To identify the incoming track is to understand whether it is missile, friendly aircraft, civilian aircraft or hostile aircraft. To do this identification the ship has to use the systems that are on board. These systems are

- Radar
- IFF System
- ESM (Electronic support measures) System

In threat area the ship first tries to detect the threats by its radar. Early warning radars are very important for ship survivability, because they are long-range radar and their theoretical ranges may be up to 500 km. Theoretical range is a function of radars power output, pulse repetition frequency and assumed target cross-section. However, normally their effective ranges are not so long, because the weather conditions. The size of threat, and the performance of the radar affect the range of the radar. After the ship detects an object, she has to identify the object. IFF system and ESM system are used to identify the detected objects. By ESM system the ship can get signal from very long ranges and the ship can get ready for potential threat.

If detected object is a missile, layered defense system is implemented to shoot the missile. Layered defense system consists of missiles Surface to Air Missile systems (SAM), gun systems, CIWS (Close In Weapon System) systems. In these models SAM missiles are launched against incoming missiles within the SAM's range, if SAM can not shoot the missile within this SAM's range (usually SAMs' minimum kill range is 5 km) then gun is used to engage to the missile, at last step CIWS is used to engage to the very close incoming missiles.

If the detected object is an aircraft, we need to find out if it is a hostile or friendly aircraft. IFF system may be used to evaluate the detected aircraft's identity. If we assure that the detected aircraft is hostile, then we need to get ready to shoot the incoming aircraft. But the enemy aircrafts don't get within the ship's standoff ranges (the maximum range that the ship can shoot the threats with a SAM). In operation area, hostile aircrafts launch their missiles outside the standoff range. If a hostile aircraft launches its missile outside the ship's standoff range then the layered defense system is applied against this missile.

In this thesis, the actual systems are modeled. These systems are;

- AN/SPS-49 Air Surveillance Radar
- MK-13 Horizontal Launcher

} Ship systems

- SM-1 Surface to Air Missile
- Sea Sparrow Surface to Air Missile

} Defense missiles

- Exocet Anti Ship Missile
- Harpoon Anti Ship Missile
- Harm Anti Ship Missile

} Threat missiles

In this work, AN/SPS-49 Air Surveillance Radar's detection range is assumed to be 200 km. It is constant for all simulation models and parameters. AN/SPS-49 Air Surveillance Radar's theoretical range may be up to 500 km. But when the weather conditions, the size of threat, the performance of the radar are considered, 200 km is the effective range for detecting air objects with AN/SPS-49 Air Surveillance Radar. The detecting probability depends on the range, if an incoming object is within the range of 200 km, the sensor can detect it. That means every object within the 200 km is detected by the ship. Figure 4.1 shows the cover areas of the sensors of the ship that are modeled in this thesis.

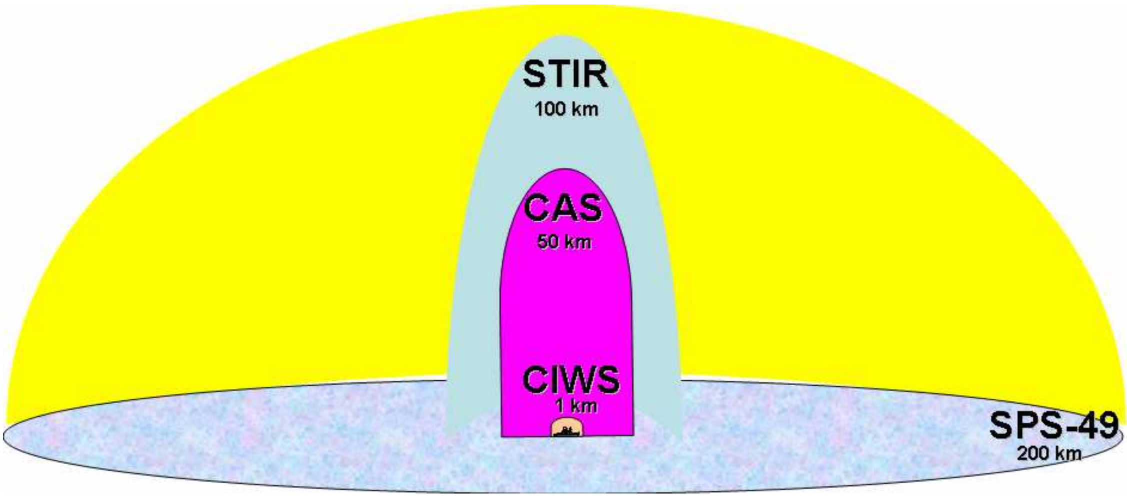


Figure 4.1 Sensor Coverage Areas [29]

When the sensor detects an object, the identity of the object is not known. To evaluate the incoming threats, several properties of the object are considered: range, speed, frequency, altitude. With respect to these properties, an object may be classified as a missile, civilian aircraft, hostile aircraft, or friendly aircraft.

If the incoming object is civilian aircraft the ship does not react to the aircraft with its defense system. If it is a hostile aircraft the ship is alerted and controls the aircraft.

The ships have defense zones, and in these zones, the layered defense system is applied. We divide the defense area in to three zones. The first zone is the outer defense zone, in this zone the incoming aircraft or missile is engaged by a SAM. In the middle defense zone the incoming aircraft or missile is engaged by a Gun. In the inner defense zone the incoming aircraft or missile is engaged by CIWS. Figure 4.2 illustrates these zones. Normally the aircrafts do not enter the inner and middle zone; they launch their missile out side of the middle zone. So we assume that the aircrafts launch their missiles from standoff range.

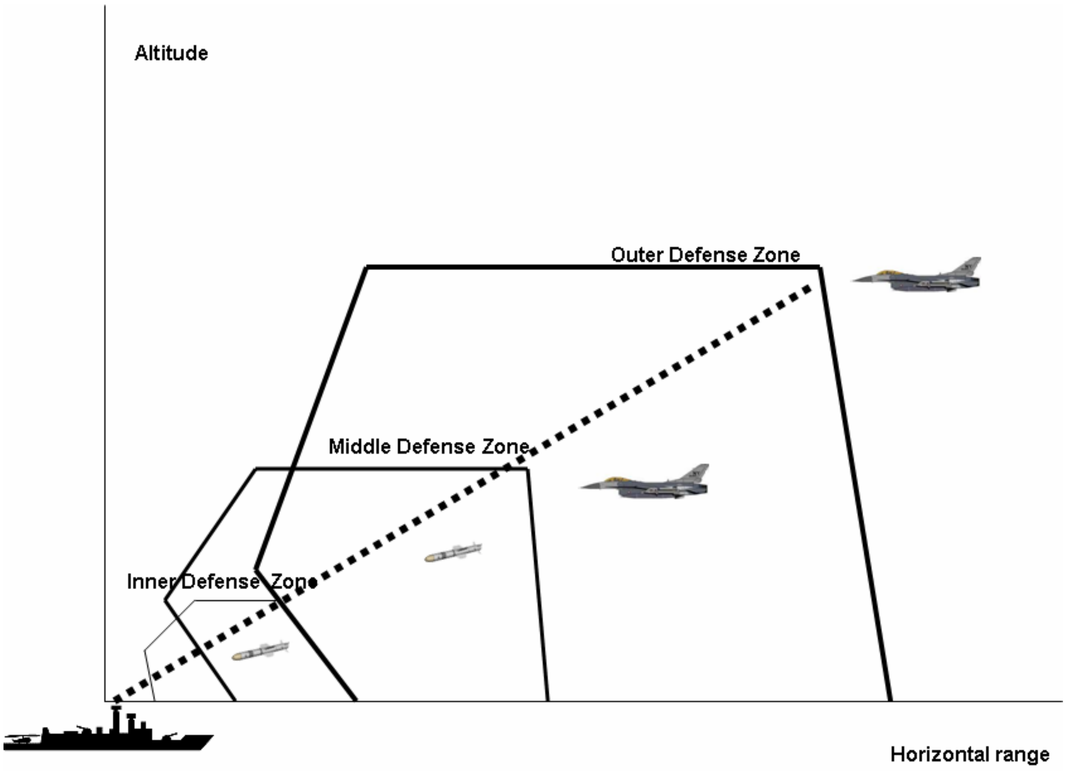


Figure 4.2 Defense Zones

These three defense systems have kill probabilities. These are single shot hit probabilities which are simulated in ARENA. Anti Surface Missiles do not have kill probabilities in our models. Target hit probability is determined only by the defense system hit probability.

4.5 Scenarios

In the scenarios the incoming objects are generated by create module. When we use exponential, uniform and triangular distribution to generate the tracks, the number of leaker missiles and number expended SAMs change significantly. Since we assume that we do not have any data about the frequency of the incoming tracks, the exponential distribution with the mean 30 minutes is used to generate the tracks.

Since we do not have any information about the distribution of the properties of incoming tracks and we know minimum and maximum value, we used uniform distribution in assigning properties.

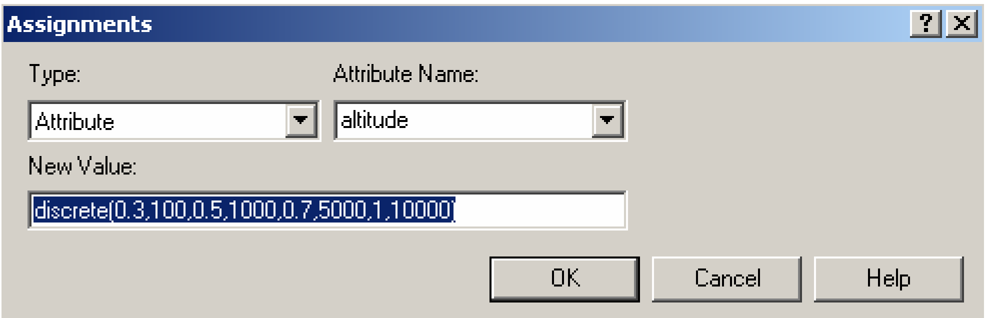
On average every 30 minutes one object (track) is created. To give identity every object, some properties are assigned (range, speed, altitude, frequency). The uniform distribution describes an outcome that is equally likely to fall anywhere between a minimum and a maximum value [22]. That is, there is an equal probability that all values of an outcome will fall between the minimum and maximum value. Furthermore, this distribution is used when the maximum and minimum values are fixed [23]. And also the uniform distribution can be used when an interarrival or service time is known to be random, but no information is immediately available about the distribution [21].

.

In determining the altitude of the incoming object, discrete probability distribution is used. Table 4.1 shows the configuration of the generated tracks. The track whose altitude is above 5000 m is considered as civilian aircraft in simulation models. The other tracks' altitudes are divided in three parts; these are 100 m, 1000 m and 5000 m. The sea skimming missiles are flying at very low altitude, so they are considered less than 100 m. The other missiles are assumed like flying between 100 and 1000 m. The hostile aircrafts are assumed like flying less than 5000 m. The altitude of the thirty percent of the threats are less than 100 m, twenty percent of the threats are between 100 m and 1000 m, twenty percent of the threats are between 1000 m and 5000 m, thirty percent of the threats are between 5000 m and 10000 m The real exercises results are considered to determine these proportions. These assumptions are implemented in the all scenarios.

Altitude	**Identity**	**Occurrence Probability**
Above 5000 m	Civilian aircraft	0.3
1000 m-5000 m	Aircrafts	0.2
100 m -1000 m	Missiles-aircrafts	0.2
0 m -100 m	Missiles	0.3

Table 4.1 Configuration of the Generated Tracks.



After an object has all its properties, it also has an identity. The max effective detection range of radar is 200 km, so the objects outside of 200 km range will be delayed until they will be within the range of 200 km. We assume that the radar detects every object within the range of 200 km.

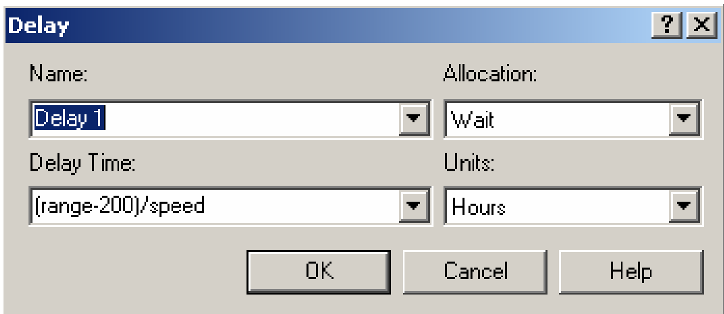


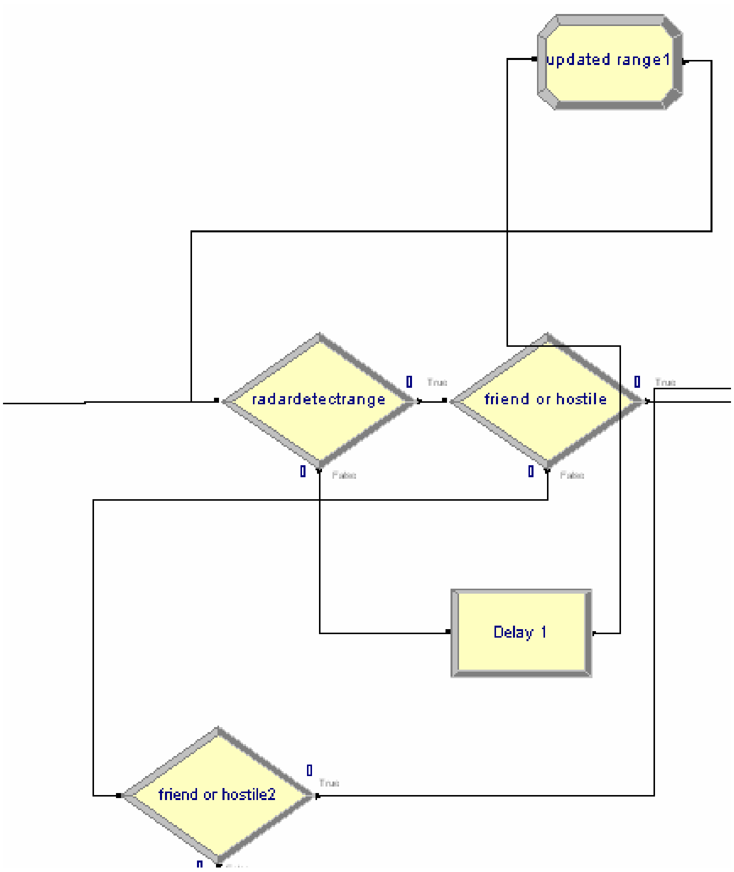
Table 4.2 shows the configurations of the scenarios.

	Firing Policy	**SAM type**	**Threats**	**SAM capacity**
Scenario 1	S-L-S	SM-1	Missiles	Unlimited
Scenario 2	S-L-S	Seasparrow	Missiles	Unlimited
Scenario 3	S-L-S	SM-1	Missiles	Limited
Scenario 4	S-L-S	Seasparrow	Missiles	Limited
Scenario 5	S-L-S	SM-1	Missiles-aircrafts	Unlimited
Scenario 6	S-L-S	Seasparrow	Missiles-aircrafts	Unlimited
Scenario 7	S-S-L	SM-1	Missiles	Unlimited
Scenario 8	S-S-L	Seasparrow	Missiles	Unlimited
Scenario 9	S-S-L	SM-1	Missiles	Limited
Scenario 10	S-S-L	Seasparrow	Missiles	Limited

Table 4.2 Configurations of the Scenarios

4.5.1 Scenario 1 (SM-1 SAM)

In this scenario, there are civilian aircrafts and threat missiles in the operation area and we do not consider the friendly military aircrafts and hostile military aircrafts. So after an object is detected, as it can be seen from the figure below (friend or hostile decide module), the speed is checked and if the speed is greater than 18 km/mn (which is about 1100 km/hr or 0.85 mach) than we can say that it is threat missile. Otherwise, the detected object may be civilian aircraft or threat missile. Because the civilian aircrafts' speed is between 0.6 and 0.7 mach and their altitude is over 5000 m. Then the altitude of track is checked (friend or hostile2 module). If the altitude is over 5000 m then we can say it is a civilian aircraft.



After the identity of the incoming object is determined, the engagement process is started. There are two trackers on board. One of them is Separate Track Illuminating Radar (STIR) whose tracking range is 100 km; the other one is Combined Antenna System (CAS) whose tracking range is 50 km. The incoming missile is tracked by STIR and since SAMs' range is 45 km, the first SAM is launched to shoot the incoming threat at 45 km. The engagement by SAM will continue between the ranges of 45-5 km. During these engagements, the S-L-S (Shoot-Look-Shoot) firing policy is used. Since SAM capacity is not limited in this scenario, one missile can be engaged by 3-4 SAM between these range intervals.

If SAM could not shoot the incoming missile between the ranges of 45-5 km, then the gun will engage to the missile between the ranges of 5-1 km. The firing rate of gun is about 60 rounds per minute and single shot probability is 0.05. During simulations, it is assumed that the gun will fire one round per second. If the gun can not shoot the missile, CIWS will fire with the kill probability of 0.25. The missiles which are not killed by CIWS become leaker missile (Missile that shoots the ship). Figure 4.3 illustrates a representative diagram of Scenario 1.

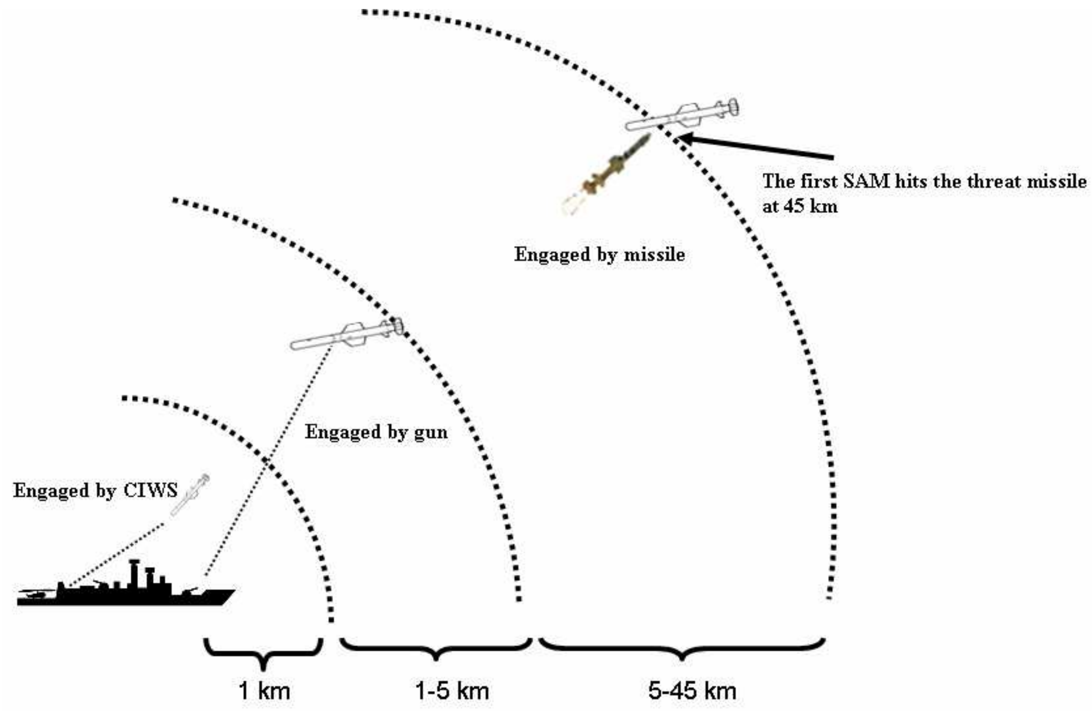


Figure 4.3 Representative Diagram of Scenario 1

4.5.2 Scenario 2 (Seasparrow SAM)

The difference of this scenario from scenario-1 is the type of SAM. In this scenario Seasparrow missile is used as SAM. Its maximum kill range is 15 km and its speed is 50 km per minute. Since the maximum kill range of Seasparrow is less than SM-1's maximum kill range, the ship can engage to the target by missile within the range of 15-5 km. The number of missiles that ship expends and cumulative kill probability of missiles decrease, so the number of leaker missiles increases when we compare with scenario-1. The higher speed of Seasparrow decreases the number of leaker missiles slightly.

4.5.3 Scenario 3 (Limited SM-1 SAM) – Scenario 4 (Limited Seasparrow SAM)

In real operation situation a naval ship can carry a limited number of missiles and with these missiles the ship has to defend herself and fulfill her tasks. Most of the ships can carry 30-40 SAMs. In scenarios 3 and 4 the number of SAMs is limited. It is assumed that the ship has only 30 missiles on board. So we revise our model as follows;

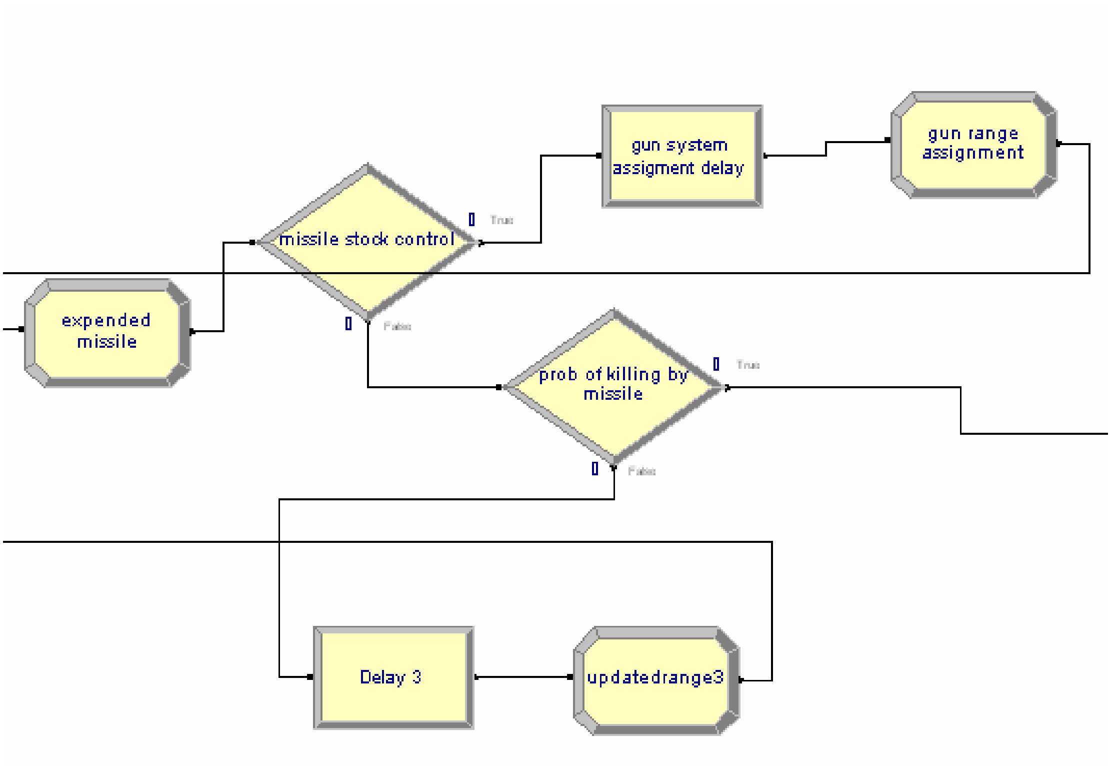
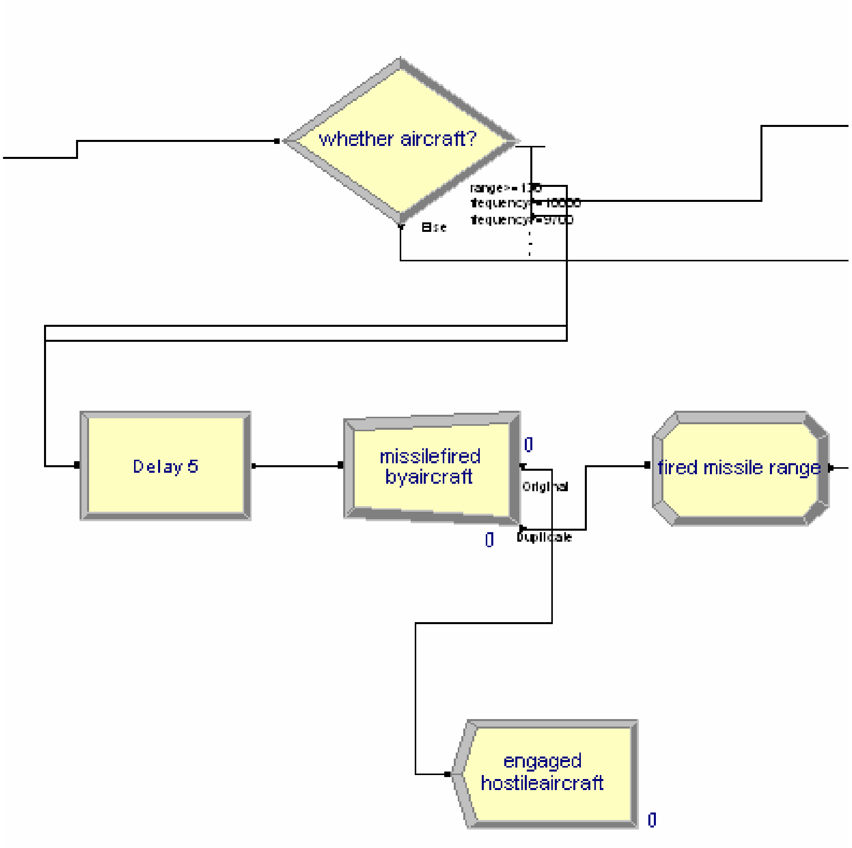


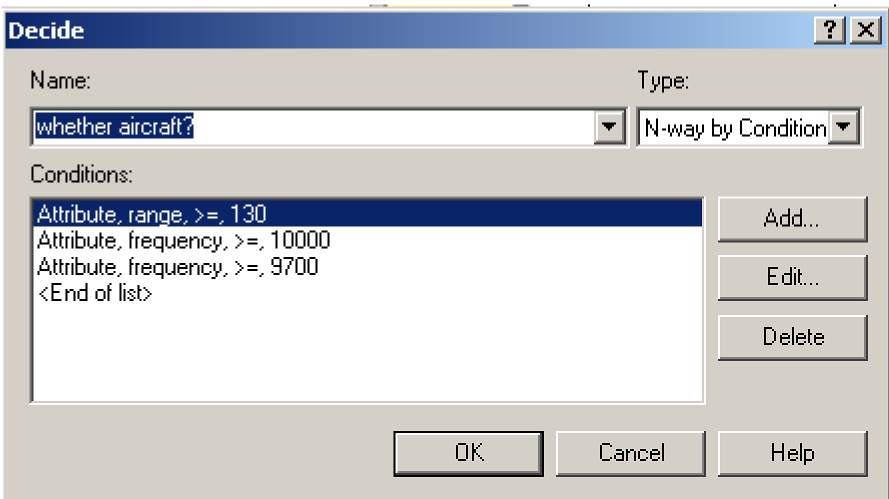
Figure above shows that another decide module (missile stock control) is added in the model, if the number of expended missiles is less than or equal to 30, the ship can engage to the threat with missile. Otherwise, the ship has to engage to the threat with gun system within the range of 5-1 km.

In these scenarios, the firing policy becomes more important. In scenario 3, SM-1 SAM is used and in scenario 4, Seasparrow SAM is used. In these models since the number of SAMs is limited, we observe that the number of leaker missiles increases. So the firing policy becomes more important. In chapter 4 the firing policies are analyzed and the best firing policy is determined for this operation condition.

4.5.4 Scenario 5 (SM-1 SAM and Hostile aircraft) – Scenario 6 (Seasparrow SAM and Hostile aircraft)

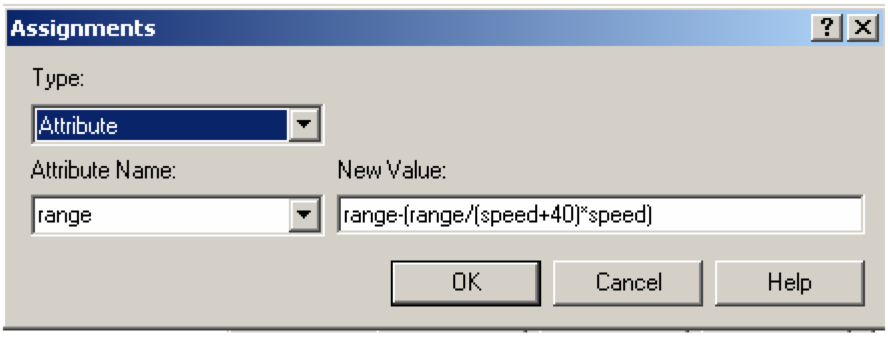
In scenario 5, there are threat missiles, civilian aircrafts and hostile aircrafts in the operation area. The engagement processes are similar to scenario-1. In scenario 1 there is only one threat evaluation, to determine if it is friend or hostile. After it is determined that the incoming object is hostile, we need to understand whether it is missile or aircraft. One way to do that is to check the range of the object. During simulations it is assumed that there are three types of Anti Ship Missiles (Exocet, Harpoon, Harm) in the operation area and it is assumed that their ranges are 70, 120, 130 km respectively. As it can be seen from the figure below, after we decide that the incoming track is a threat, if the range of the detected object is greater than 130 km, we can say that it is hostile aircraft. If the range of object is less than 130 km, we need to check its frequency to understand whether it is missile or aircraft. It is assumed that there are only two kinds of aircrafts which are F-16 and MIRAGE-2000 aircrafts, (their radar frequency is between 9700-10000 MHz), If the frequency of detected object is not between 9700-10000 MHz, it will be treated as missile. If it is an aircraft (whose frequency is between 9700-10000 MHz), then the aircraft will not engage to the ship until it comes to standoff border which is 45 km (for SM-1 SAM) from the ship. Because the ship cannot engage to the aircraft farther than 45 km, so the aircrafts usually attack from closest point that is possible this is 45 km in these models. Therefore, to react to the missiles which will launch from aircraft is harder than the other missile.





In the first scenario, there are only missiles as threats, so the defense system can follow the incoming missile and launch the first SAM to shot at 45 km. If the first SAM cannot shot the missile, it can launch 2-3 more SAM between the ranges of 45-5 km. But when there are hostile aircrafts, it is very hard to determine when the aircraft will launch the missile.

Normally the hostile aircrafts do not enter the standoff range. In this scenario the aircrafts launch their missiles 45 km from the ship. The distance that the first SAM will meet the missile is calculated as follows;



From the calculation above we can observe that the engagement range of first SAM decreases.

In scenario 6, Seasparrow is used as SAM. Its maximum kill range is 15 km and its speed is 50 km per minute. The distance that the first SAM will meet the missile will be calculated as follows;

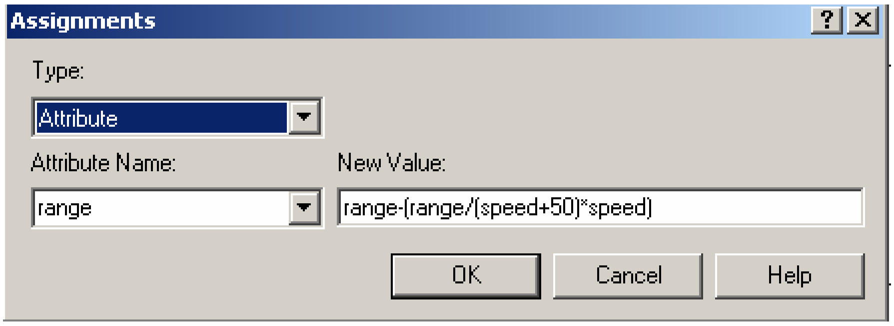


Figure 4.4 illustrates a representative diagram of Scenario 5.

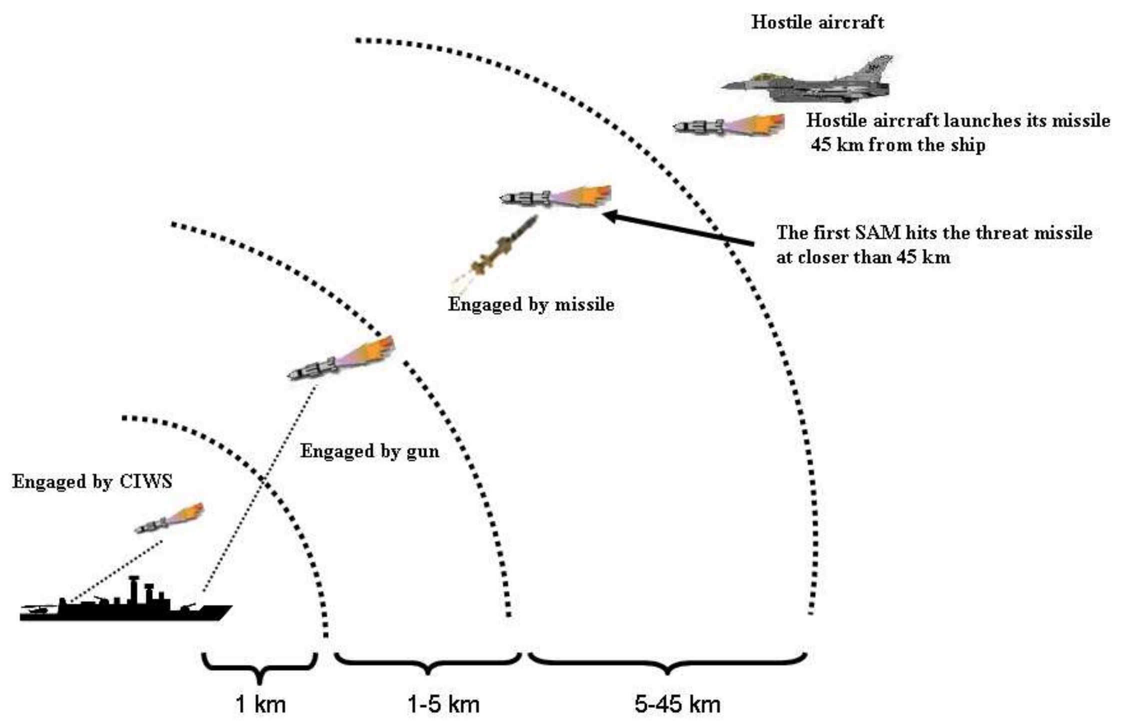
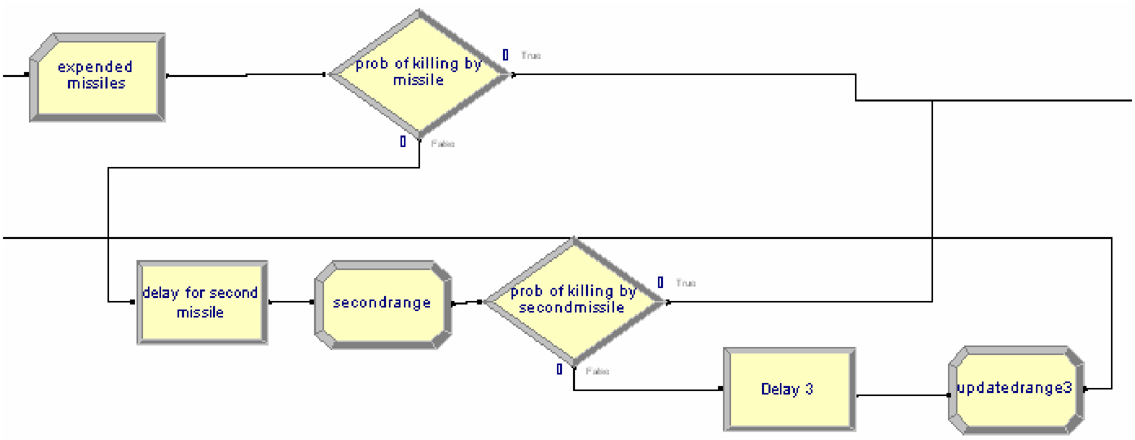


Figure 4.4 Representative Diagram of Scenario 5

4.5.5 Scenario 7 (SM-1 SAM and S-S-L firing policy) – Scenario 8 (Seasparrow SAM and S-S-L firing policy)

In these scenarios S-S-L (Shoot-Shoot-Look) firing policy is used. In the S-S-L firing policy, two missiles are fired to the incoming threat missile before a kill assessment is made. With this policy number of leaker missiles decreases. However, missiles may be expended unnecessarily using S-S-L policy if the target is destroyed by the first missile [1].

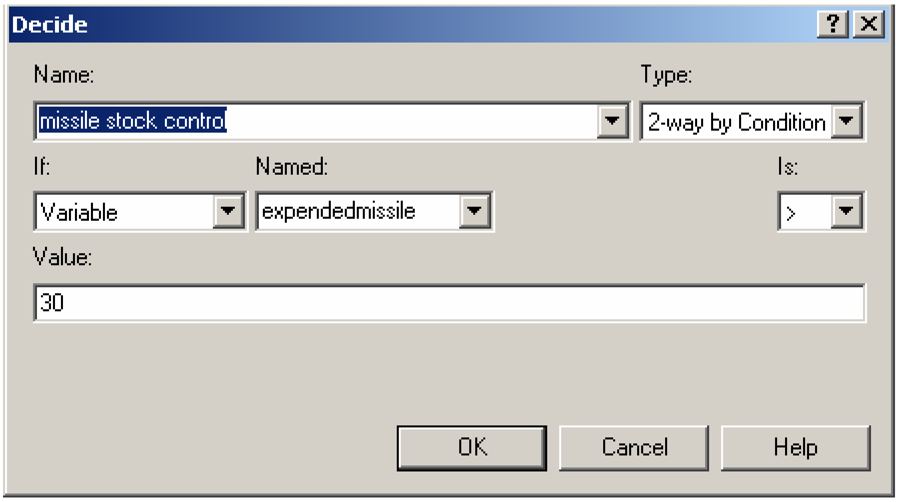
In this policy first a missile is fired, right after second missile is fired. The time between the fired missiles depends on launcher capability; in this thesis it is assumed that MK-13 Horizontal Launcher and Seasparrow launcher are used and the time between the two missile salvos is assumed to be 10 seconds. “Delay for second missile” entity in figure below is added to the model to give this delay. The number of expended missiles is more than the S-L-S system. In this model, first a missile is launched to kill the threat and after 10 seconds another missiles launches while the first missile has not yet reached its destination. If the first missile kills the threat then second missile will be wasted. In the first step model below, 2 missiles are expended for an incoming threat. If the incoming missile is killed by the first missile then the second missile is wasted. Otherwise after 10 seconds the second missile will try to kill the threat with the same kill probability.

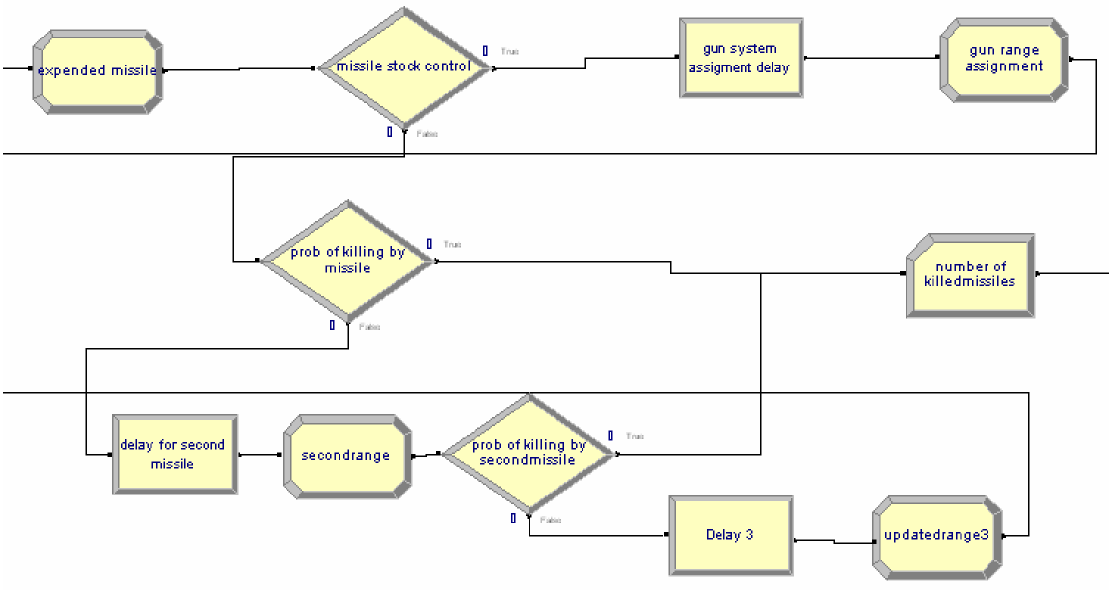


In these scenarios SM-1 (Scenario 7) and Seasparrow (Scenario 8) missiles are used. These missiles have the same kill probability as in the other scenarios.

4.5.6 Scenario 9 (Limited SM-1 SAM and S-S-L firing policy) – Scenario 10 (Limited Seasparrow SAM and S-S-L firing policy)

In these scenarios S-S-L (Shoot-Shoot-Look) firing policy is used. But, the number of SAMs is limited. The ship has only 30 missiles. In this model another decide module (expmissile) is added to the S-S-L firing policy model as follows;





In the model figure above, for an incoming threat two missiles are expended and the ship has only 30 missiles for an operation. So the firing policy becomes more important in these scenarios. In scenario 9, SM-1 SAM is used and in scenario 10, Seasparrow SAM is used.

5. COMPARATIVE ANALYSIS FOR MEASURE OF EFFECTIVENESS

In the tests below kill probability of SAM differs from 0.4 to 0.7. These kill probabilities change with respect to missile properties. The kill probabilities of recently improved missiles are higher than the other missiles. So we used different missile kill probabilities to show the differences between missile types.

As a result of these tests, we see that the systems which are equipped with missiles with higher kill probability reduce the number of leaker missiles. These differences show the importance of the missile kill probability and urge nations to develop new kind of SAMs against aircrafts and threat missiles.

In a simulation analysis, when estimating the number of simulation runs, if we wish the maximum error of our estimate to be (some given value) E with level of confidence 1-α, we should have set the number of runs for each simulation model to be at least

$$n=\left[\frac{Z_{\alpha/2}}{E}\right]^2 \frac{1}{4} \qquad [28]$$

When the number of replication is assumed 50 for scenario 1 *E=0.13* and number of leaker missiles becomes 6.82. On the other hand when it is assumed 96 *E=0.10* and number of leaker missiles becomes 6.72. Since in the models we want the maximum error of our estimate to be between 0.10 and 0.15, we took number of replication 50.

5.1 Comparative Analysis for Average Number of Expended Missiles and Average Number of Leaker Missiles for Different Scenarios.

Figure 5.1 illustrates average number of expended SAMs for different SAM kill probability for scenario 1 and 2.

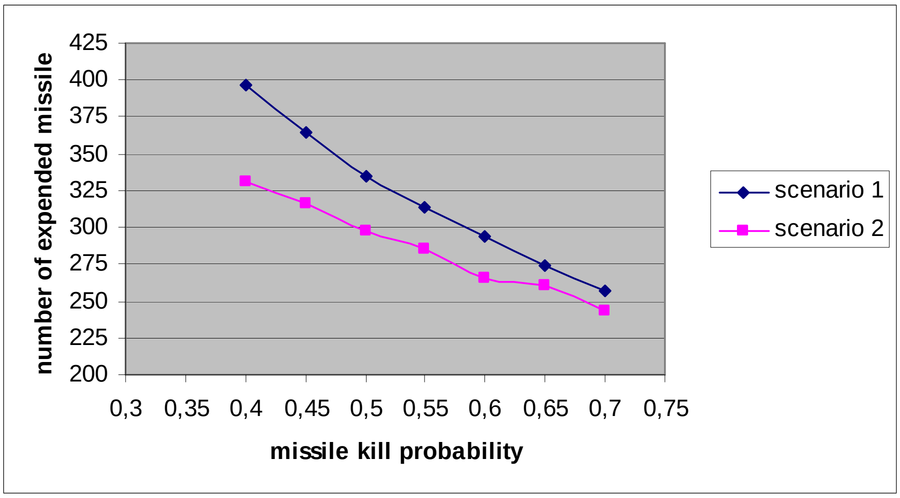


Figure 5.1 Average Numbers of Expended SAMs for Different SAM Kill Probabilities for Scenarios 1 and 2

In summary, for Scenario 1 and 2, when we increase the kill probability of SAMs, the number of expended missiles decreases. This is because we use fewer missile to shoot the incoming threat missiles. Since SM-1 kills threats at a longer range than the Seasparrow, the number of expended missiles in scenario 1 is more than the number of expended missiles in scenario 2 with the same kill probability of SAM. But the number of leaker missiles in scenario 1 is less than the number of missiles in scenario 2 with the same kill probability of SAM. Because in scenario 1, the ship begins to shoot the incoming threat at 45 km which is 15 km in scenario 2. So we can say that the ships which are equipped with long range missile can survive with higher probability.

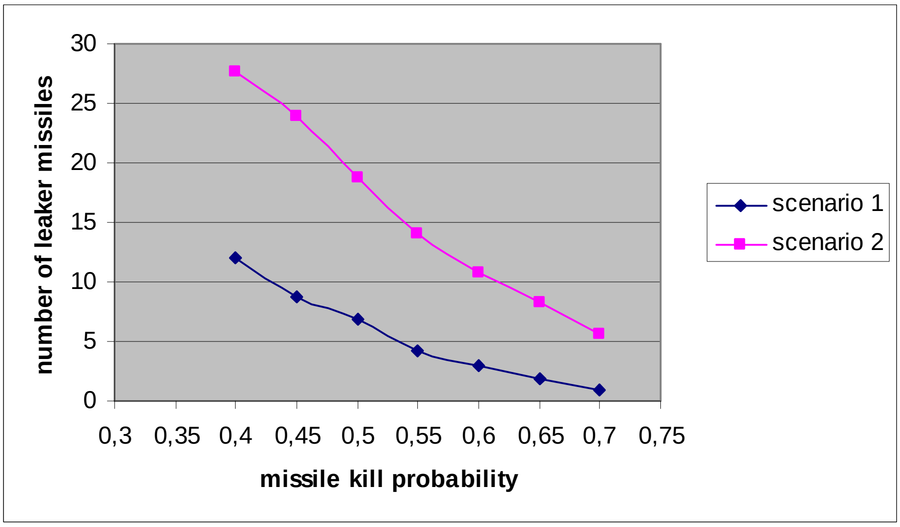


Figure 5.2 Average Numbers of Leaker Missiles for Different SAM Kill Probabilities For Scenario 1 and 2

Figure 5.2 illustrates average number of expended SAMs for different kill probabilities under for scenarios 1 and 7.

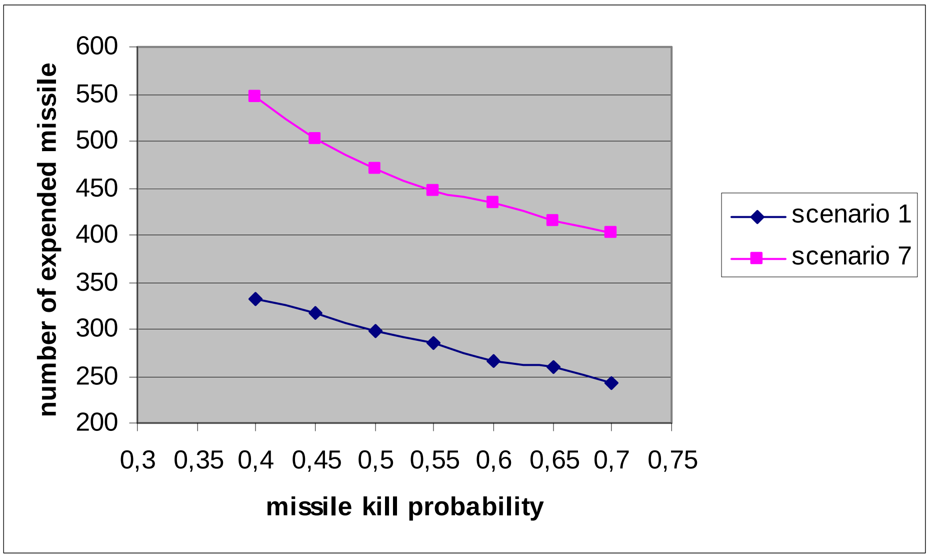


Figure 5.3 Average Numbers of Expended SAMs for Different SAM Killing Probabilities for Scenario 1 and 7

In the figure 5.3 the number of expended missile in scenario 7 is more than that of scenario 1. Because in scenario 7 Shoot-Shoot-Look (S-S-L) firing policy is used. In S-S-L firing policy the ships fire two missiles respectively for an incoming threat. This firing policy can be implemented by ships which have high SAM capacity. So when we consider a single ship in an operation area, it may not be possible to use S-S-L firing policy. Figure 5.4 below shows that the number of leaker missile is less in scenario 7.

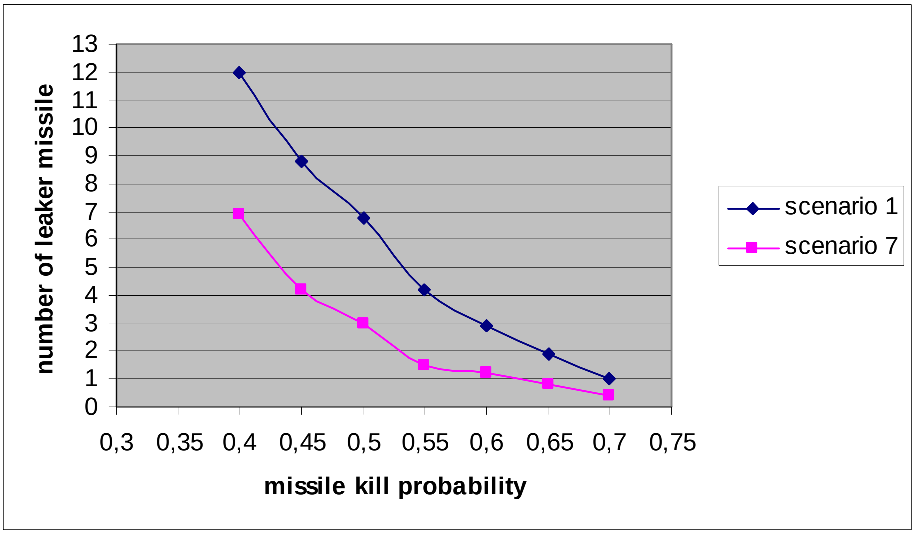


Figure 5.4 Average Numbers of Leaker Missiles for Different SAM Kill Probabilities for Scenario 1 and 7

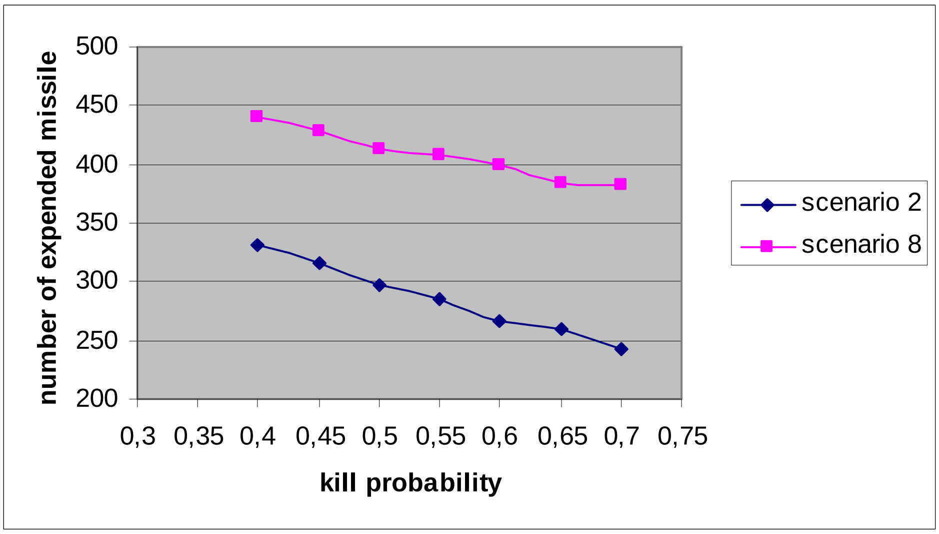


Figure 5.5 Average Numbers Of Expended SAMs for Different SAM Kill Probabilities for Scenario 2 and 8

Figure 5.5 shows a similar result the number of expended missile in scenario 8 is more than that of in scenario 2. Because in scenario 8 Shoot-Shoot-Look (SSL) firing policy is used. Figure 5.6 below shows that the number of leaker missile is less in scenario 8. Since missile engagement range is between 5 km and 15 km there is not a huge difference between these two policies.

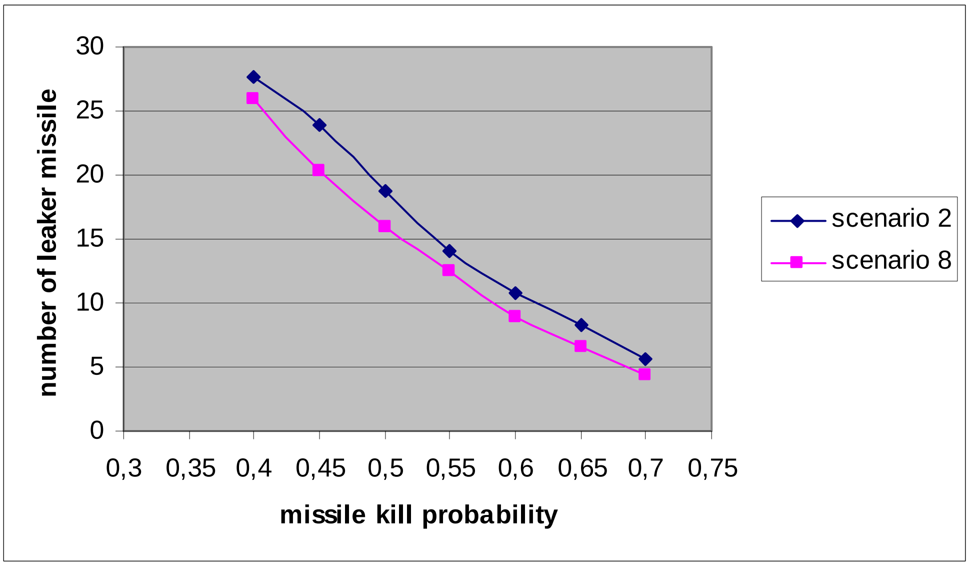


Figure 5.6 Average Numbers of Leaker Missiles for Different SAM Kill Probabilities for Scenario 2 and 8

When there are hostile aircrafts in the operation area, the number of expended missile does not change significantly for the same firing policy and missile kill probability, but the number of leaker missile increases. This is because the ship cannot react to an incoming aircraft far from its standoff range. Normally, the hostile aircrafts engage their missiles at ship’s standoff border and this delays the ship’s reaction. This delay increases the number of leaker missiles. The figures below show these configurations for SM-1 missile.

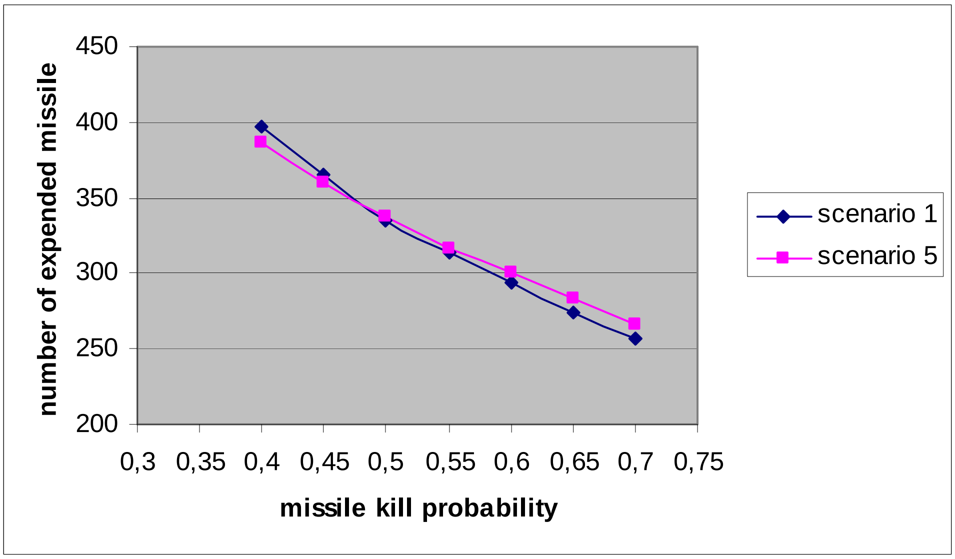


Figure 5.7 Average Numbers of Expended SAMs for Different SAM Kill Probabilities for Scenario 1 and 5

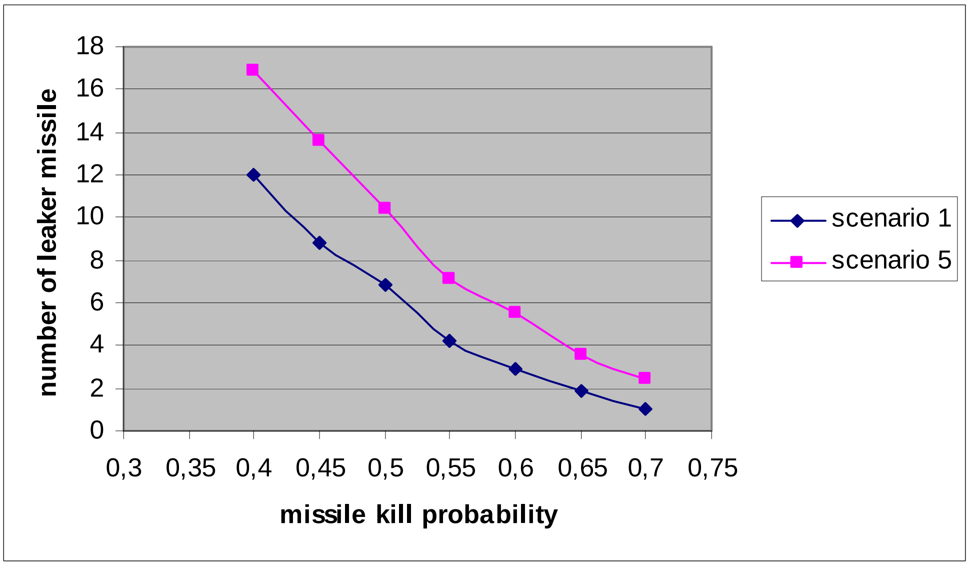


Figure 5.8 Average Numbers of Leaker Missiles for Different SAM Kill Probabilities for Scenario 1 and 5

Figure 5.9 and 5.10 is the same scenarios for Seasparrow SAM.

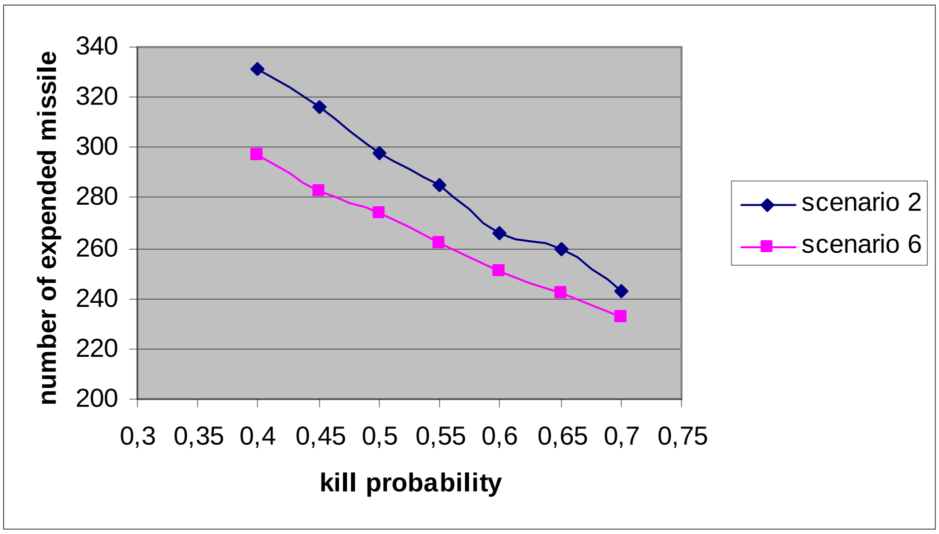


Figure 5.9 Average Numbers of Expended SAMs for Different SAM Kill Probabilities for Scenario 2 and 6

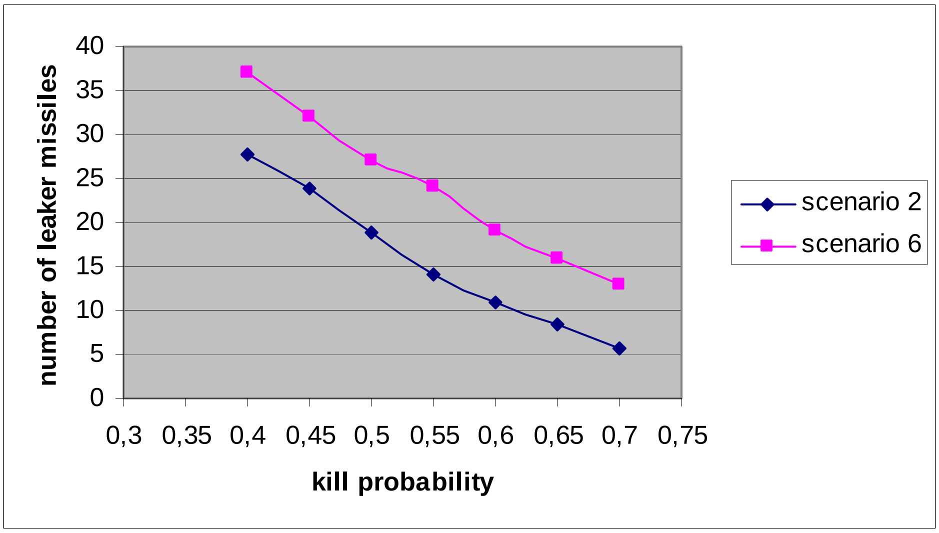


Figure 5.10 Average Number of Leaker Missiles for Different SAM Kill Probabilities for Scenario 2 and 6

Figure 5.11 and Figure 5.12 below shows the results of firing policy in real operation area. In scenario 9 and scenario 10 the ship has limited amount of SAM and it uses S-S-L firing policy. Since the ship expends its missiles in a short time, it cannot react to the incoming threats with SAM during whole operation. So in Scenario 9 the number of leaker missile is very high and it does not change significantly with respect to missile kill probability.

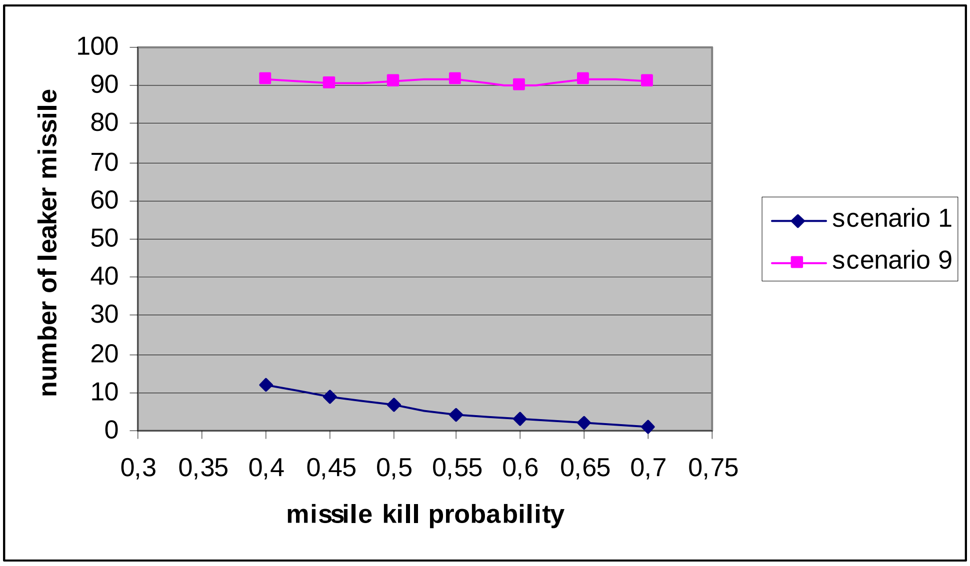


Figure 5.11 Average Numbers of Leaker Missiles for Different SAM Kill Probabilities for Scenario 1 and 9

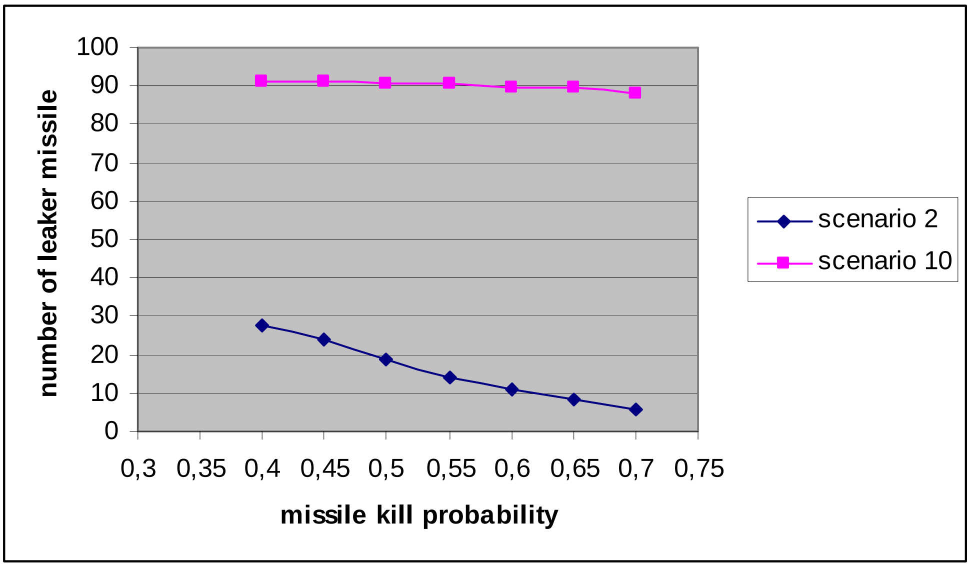


Figure 5.12 Average Number of Leaker Missiles for Different SAM Kill Probabilities for Scenario 2 and 10

5.2 Comparative Analysis for Kill Range of Threats for Different Scenarios

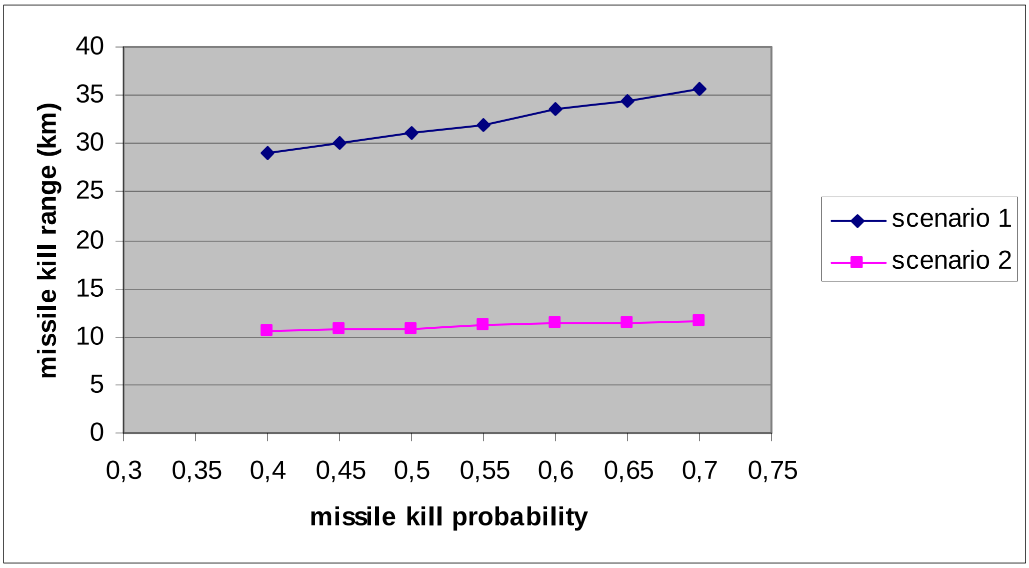


Figure 5.13 Kill Ranges for Different SAM Kill Probability for Scenario 1 and 2

In Figure 5.13 y axis represents where threat is destroyed. We see that the kill range of SM-1 is much more than the kill range of Seasparrow and this affects the number of leaker as mentioned above.

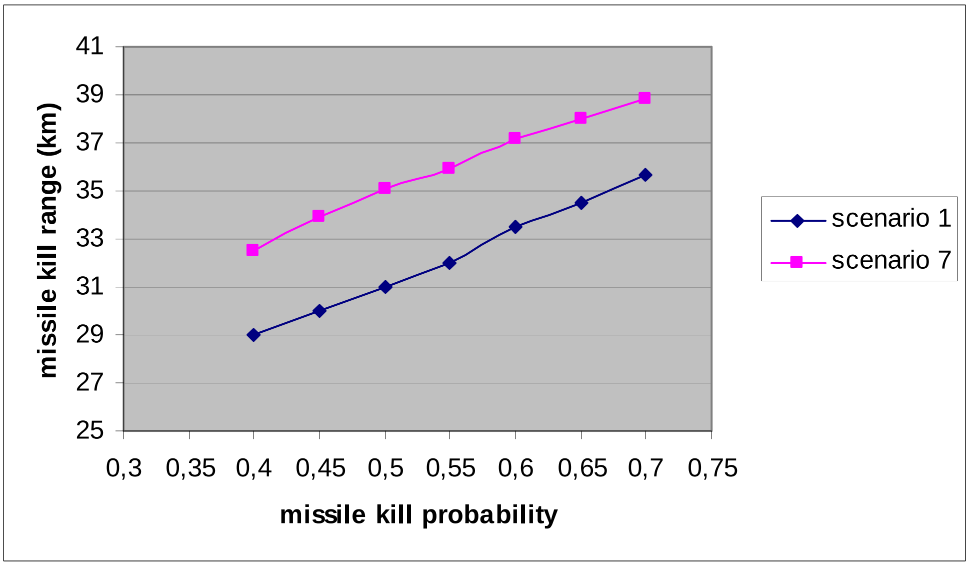


Figure 5.14 Kill Ranges for Different SAM Kill Probability for Scenario 1 and 7

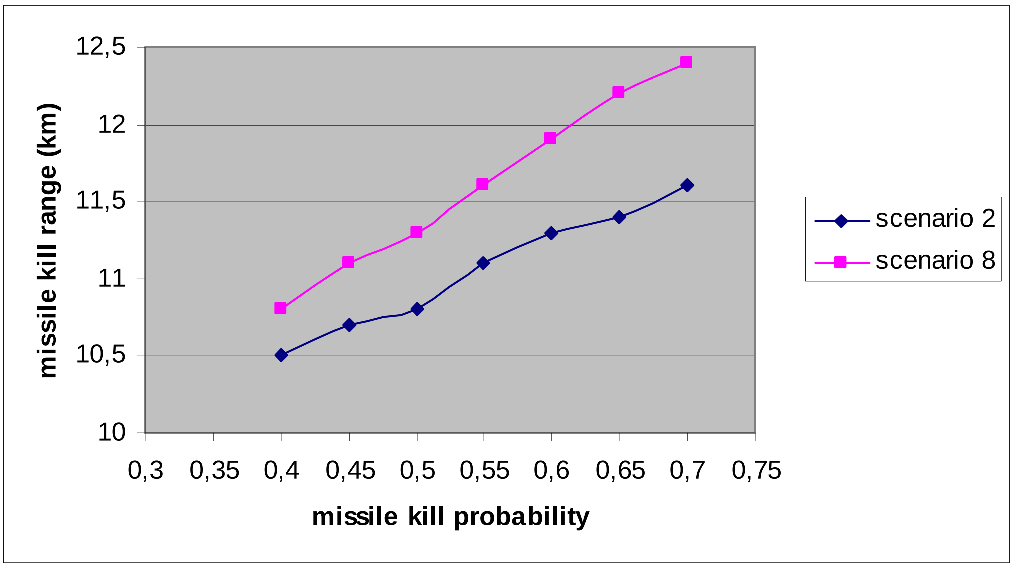


Figure 5.15 Kill Ranges for Different SAM Kill Probability for Scenario 1 and 7

Figure 5.14 and Figure 5.15 shows that S-S-L firing policy increases the missile kill range. Because when the ship shoots the incoming threat with two SAM respectively, the incoming threat is killed earlier than S-L-S firing policy.

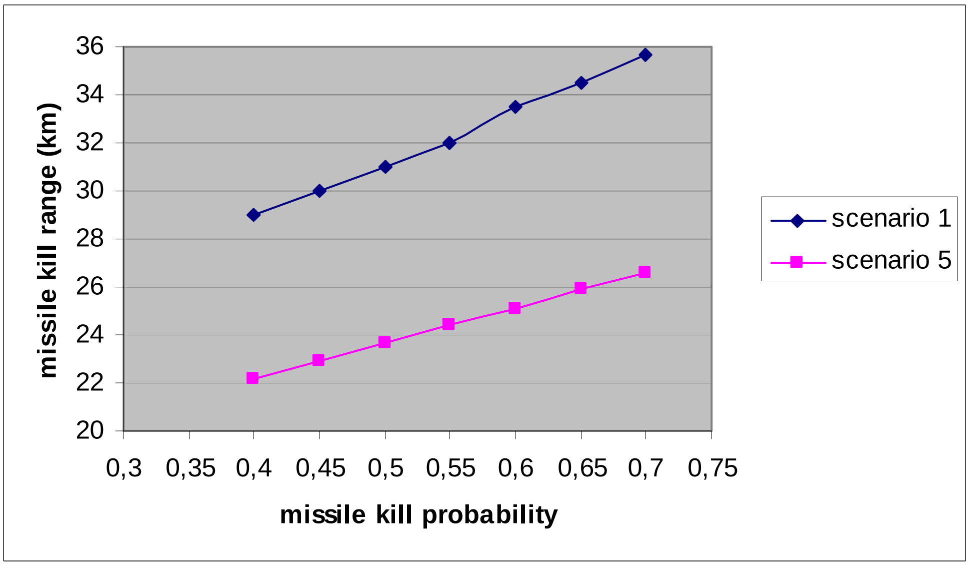


Figure 5.16 Kill Ranges for Different SAM Kill Probability for Scenario 1 and 5

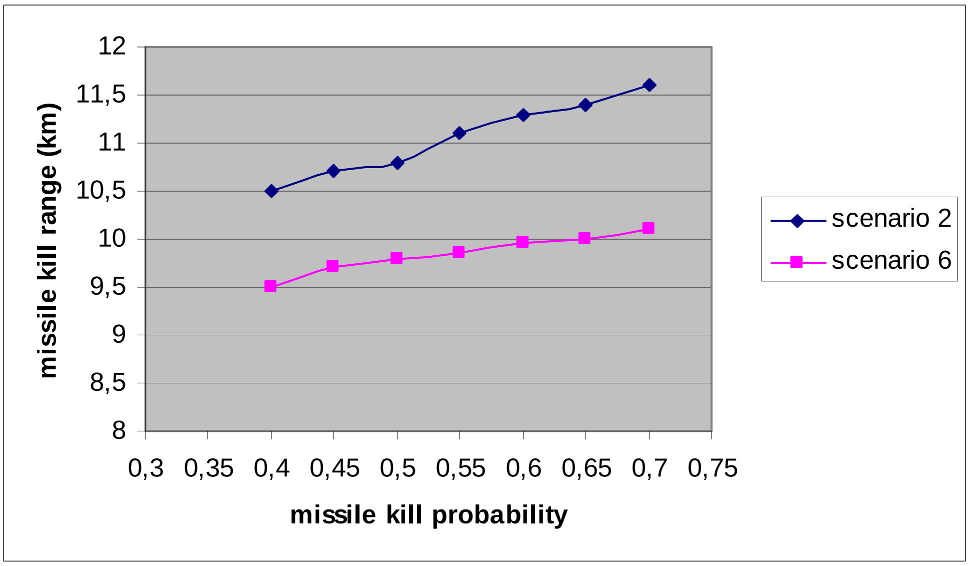


Figure 5.17 Kill Ranges for Different SAM Kill Probability for Scenario 2 and 6

Figure 5.16 and 5.17 shows that when there are hostile aircrafts in the operation area, the kill range decreases significantly for the same firing policy and missile kill probability. Normally, the hostile aircrafts engage their missiles at ship's standoff border and this delays the ship's reaction and decreases the missile kill range.

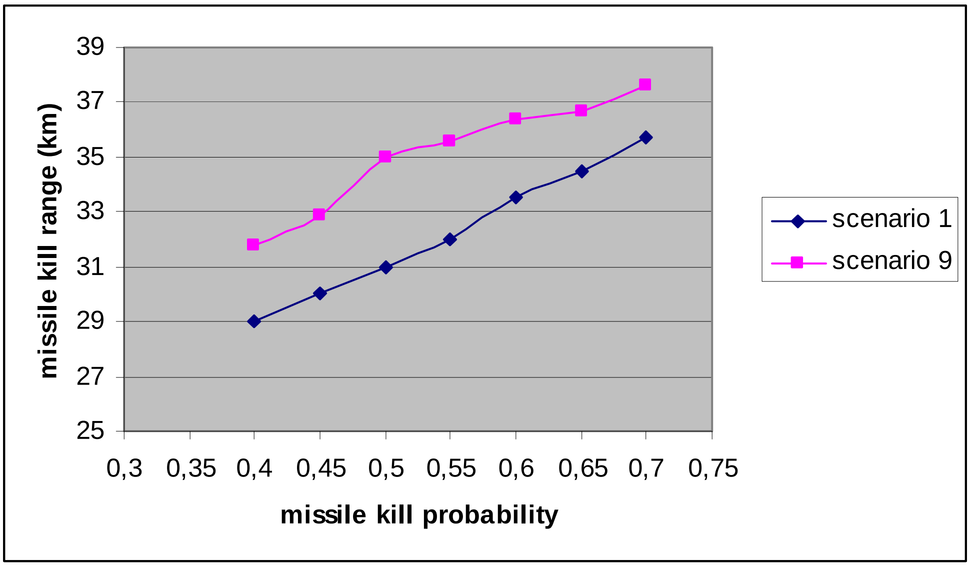


Figure 5.18 Kill Ranges for Different SAM Kill Probabilities for Scenario 1 and 9

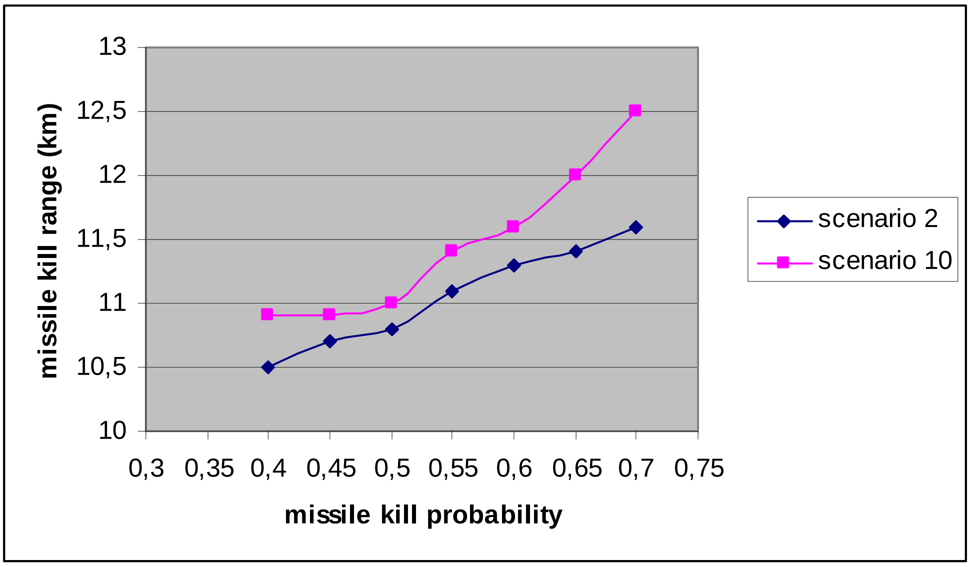


Figure 5.19 Kill Ranges for Different SAM Kill Probabilities for Scenario 2 and 10

Figure 5.18 and 5.19 shows that the S-S-L firing policy kills the threat missiles at longer distance than the S-L-S firing policy. But when we compare the number of leakers of both firing policies, it is observed that S-S-L firing policy is not convenient firing policy for ship survivability.

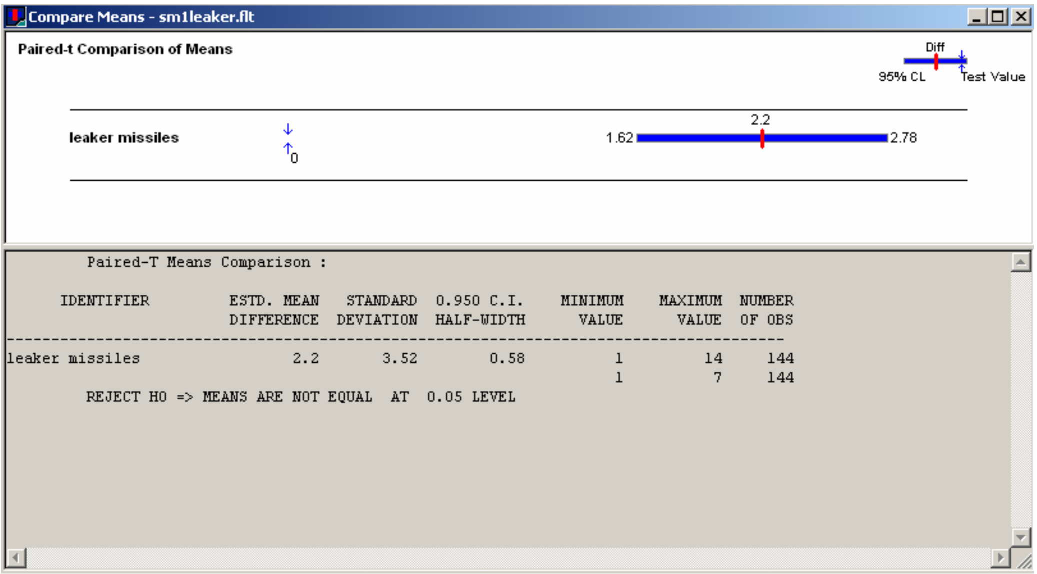
5.3 Comparative Analysis for the Effects of Kill Probability Improvements in Combat System Types

In these tests we try to determine which combat system is more vital for ship survivability. For these tests, the SM-1 kill probability in scenario 1 is changed from 0.50 to 0.60 and the average number of leaker missile is compared with output analyzer as follows;

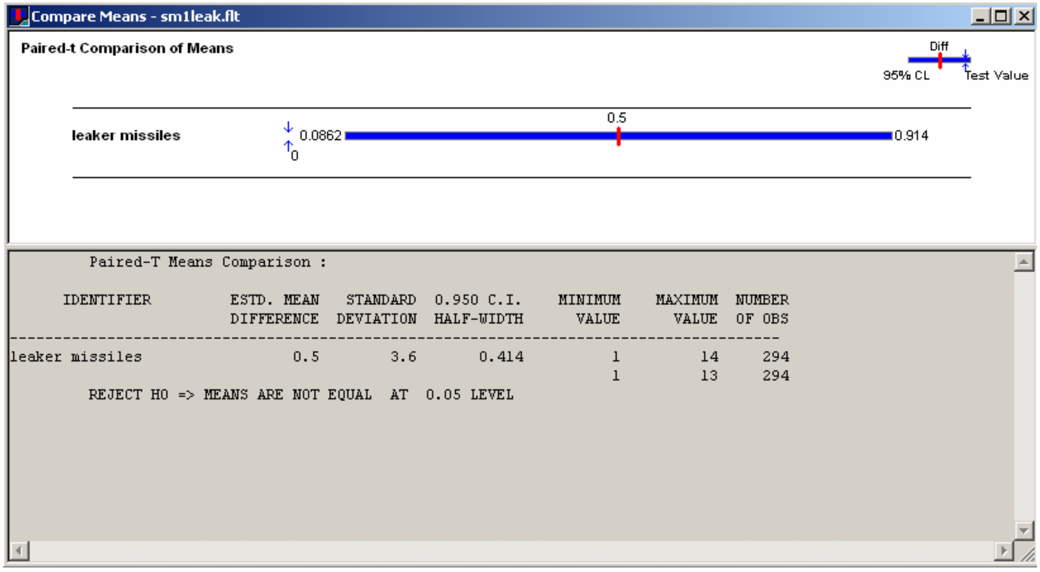
Given two paired sets X_i and Y_i of *n* measured values, the paired *t*-test determines whether they differ from each other in a significant way under the assumptions that the paired differences are independent and identically normally distributed [27]. Since we want to determine whether the means of leaker missiles differ from each other significantly with different kill probability, we use paired t test.

H_0= At the selected confidence level, there is no difference between the means of the number of leaker missiles provided by S-L-S firing policy and with SM-1 SAM.

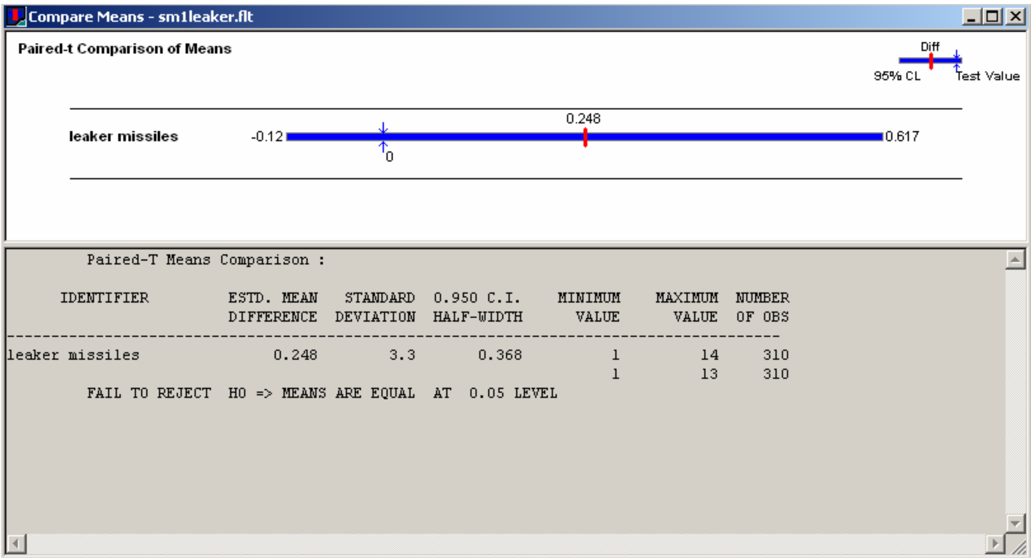
H_1= At the selected confidence level, there is difference between the means of the number of leaker missiles provided by S-L-S firing policy and with SM-1 SAM.



The cumulative gun hit probability in scenario 1 is changed from 0.25 to 0.35 and the average number of leaker missile is compared with output analyzer as follows;



The cumulative CIWS hit probability in scenario 1 is changed from 0.25 to 0.35 and the average number of leaker missile is compared with output analyzer as follows;

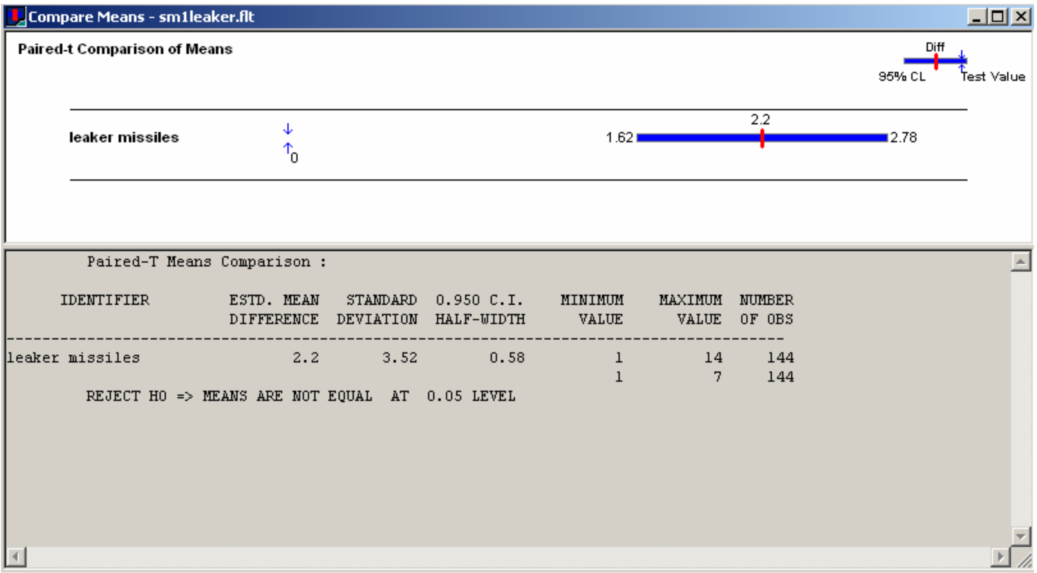


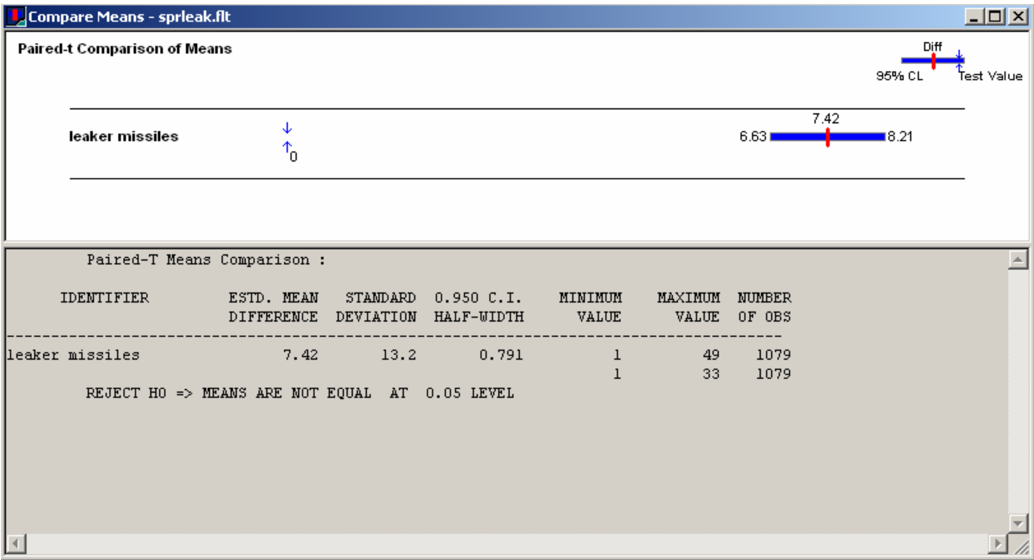
In these tests we compare how improvements in hit probability affect the number of leaker missiles. When we increase the kill probability of combat systems at the same rate, it is observed that the SAM system is more effective system for ship survivability. In the first test when we increase the hit probability of SAM from %50 to %60 the number of leaker missiles decreases about 2.2 in average. In the second test, when we increase the hit probability of gun from 5% to 7% (in cumulative probability it is %25 to %35) the number of leaker missiles decreases about 0.248 in average. In the third test, when we increase the hit probability of CIWS from 25% to 35% the number of leaker missiles decreases about 0.5 in average. So we conclude that to improve the hit probability of missiles increases the ship survivability more than the other combat systems. These results lead the nations to make improvement in missile design and constructions.

The Seasparrow kill probability in scenario 2 is changed from 0.50 to 0.60 and the average number of leaker missile is compared with output analyzer as follows:

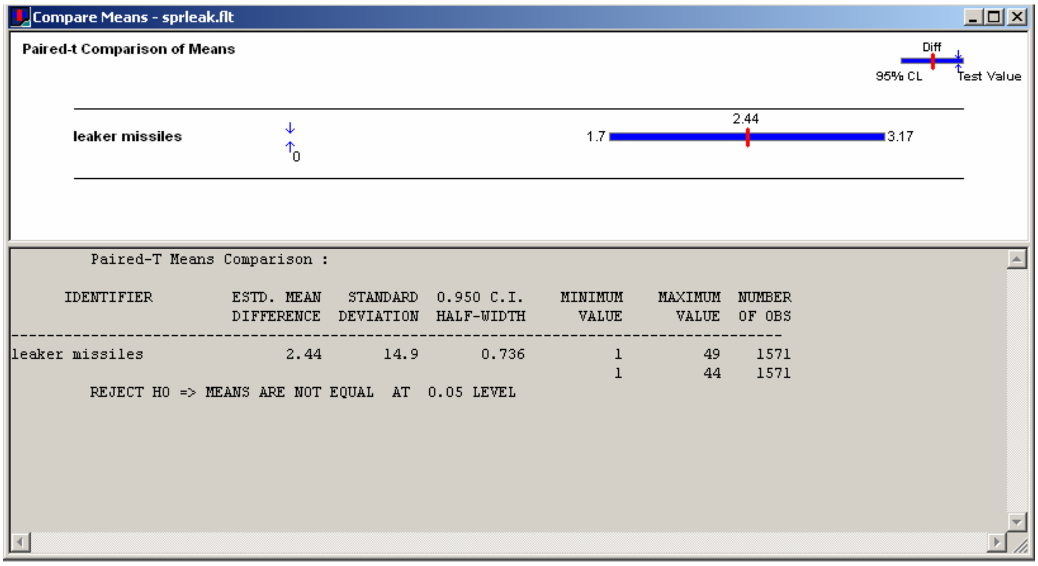
H_0 = At the selected confidence level, there is no difference between the means of the number of leaker missiles provided by S-L-S firing policy and with Seasparrow SAM.

H_1 = At the selected confidence level, there is difference between the means of the number of leaker missiles provided by S-L-S firing policy and with Seasparrow SAM.

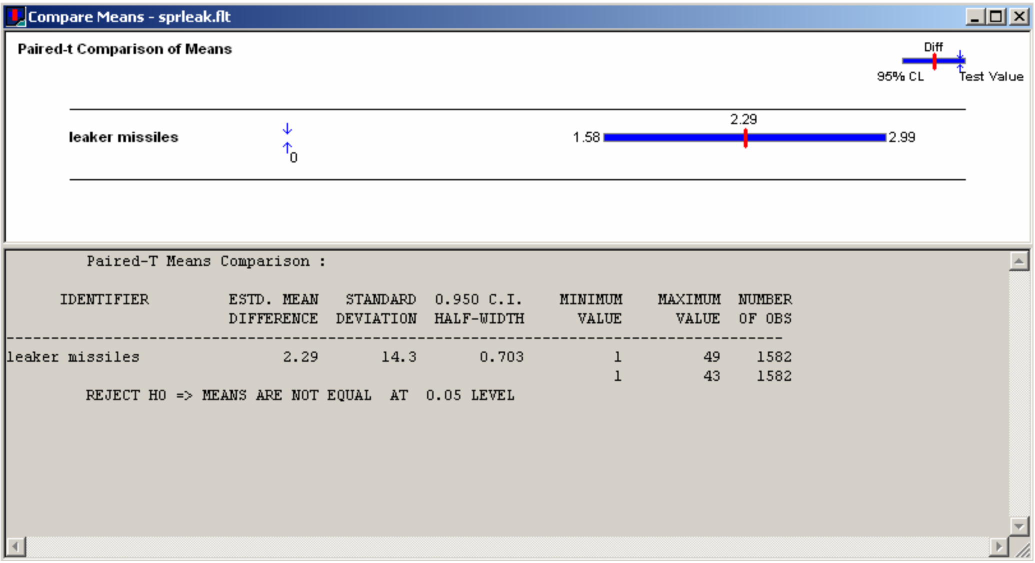




The cumulative gun hit probability in scenario 2 is changed from 0.25 to 0.35 and the average number of leaker missile is compared with output analyzer as follows:



The cumulative CIWS hit probability in scenario 2 is changed from 0.25 to 0.35 and the average number of leaker missile is compared with output analyzer as follows:



We conclude that as a result of these tests, increasing the hit probability of missiles decreases the number of leaker rather than the gun system and CIWS system.

5.4 Comparative Analysis for the Effects of Maximum Kill Range Improvements in Combat System Types

Kill range improvements affect the number of leakers and ship survivability. So determining to improve which combat system is very critical for decision makers. The analyses below show these decisions.

H_0 = At the selected confidence level, there is no difference between the means of the number of leaker missiles provided by SAM kill range 60 km and 45 km.

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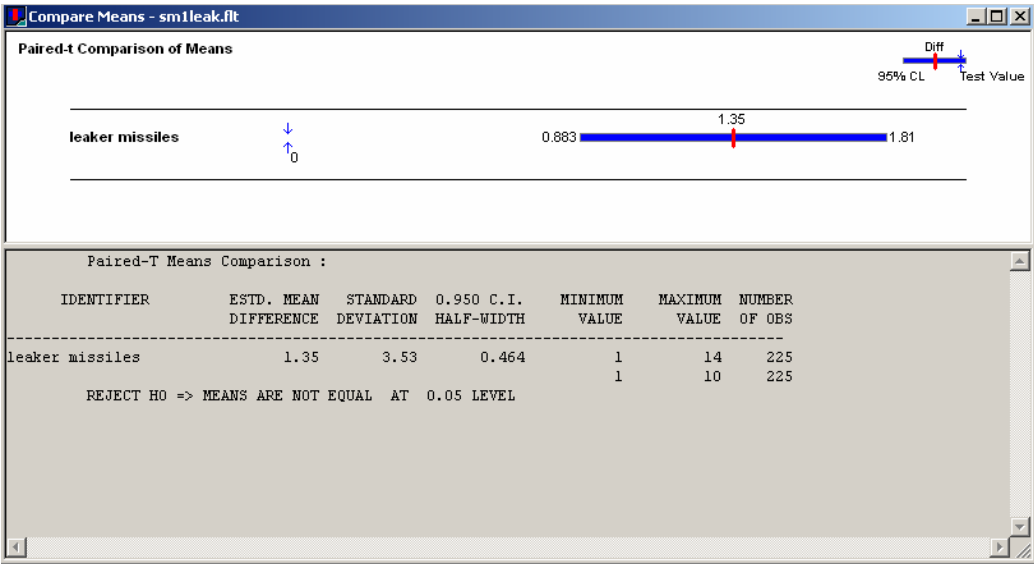
H_1 = At the selected confidence level, there is no difference between the means of the number of leaker missiles provided by SAM kill range 60 km and 45 km.



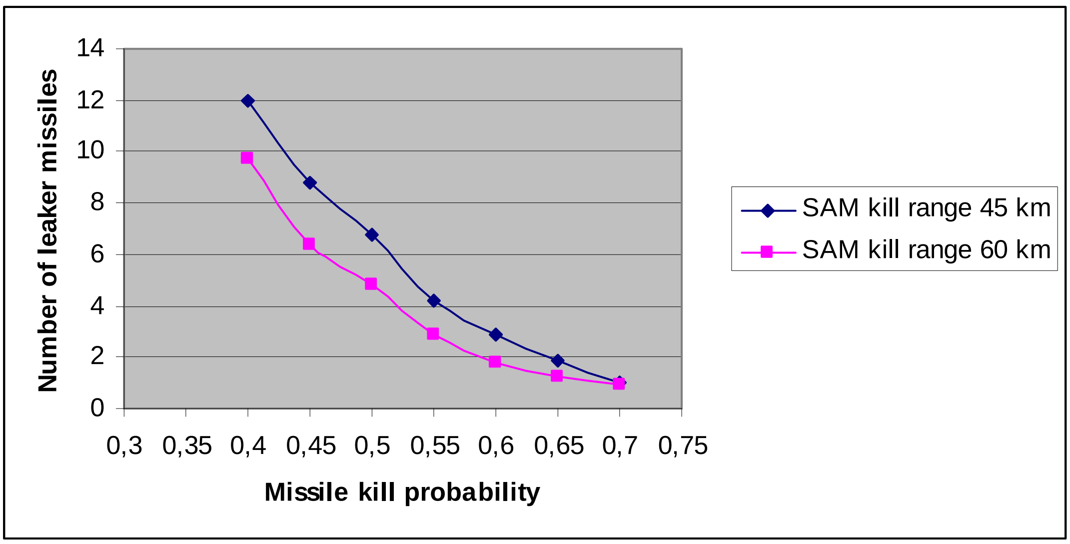


Figure 5.20 Number of Leaker Missiles for Different SAM Kill Ranges and Kill Probabilities.

When SAM range is extended from 45 km to 60 km, the improvements in ship survivability and number of leaker can be seen from figure 4.20.When maximum gun kill range is extended from 5 km to. 20 km, the improvements in ship survivability and number of leaker can be seen from figure 4.21.

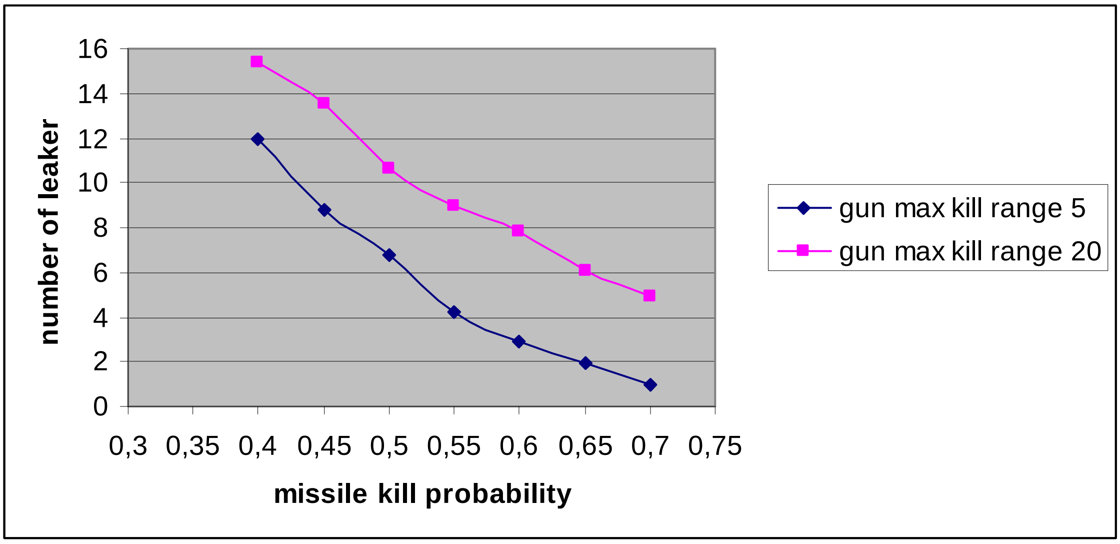


Figure 5.21 Number of Leaker Missiles for Different Gun Kill Ranges and Kill Probabilities.

The figure above illustrates the importance of the missile. In this test we increase the gun kill range from 5 km to 20 km and limit the missile kill range between 20 and 45 km. The maximum kill range of the combat system in this scenario is the same as in scenario 1 which is 45 km. As a result of this test, when the ships engage to the incoming threats with missile within the range of 20 and 45 km, the number of leaker increases. Because the engagement range of missile decreases from 40 km to 25 km, this affects the number of leakers negatively.

When we analyze the CIWS kill range, it is observed that to improve the kill range of CIWS from 1 km to 5 or to 10 km is very hard. So it won't be very realistic to make the range improvement analysis for CIWS.

To increase the maximum kill range of SAM decreases the number of leaker missiles more than the other system. This urges the Navies to get the missiles with longer range and to protect the ship from further sides.

6. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDIES

6.1 Conclusions

This thesis has developed a discrete event Ship Self Air Defense (SSAD) simulation model to simulate Ship Self Air Defense. This model is modular and expandable and develops a model as an analysis tool to measure the effectiveness of SAM system, gun system and different firing policies. As results of the tests following results are observed;

- SM-1 kills threats at a longer range than the Seasparrow, so the number of expended missiles in scenarios with SM-1 and the number of leaker missiles in scenarios with SM-1 is less than the number of missiles in scenarios with Seasparrow.
- The systems which are equipped with missiles with higher kill probability reduce the number of leaker missiles more. This difference shows the importance of the missile kill probability and urges nations to develop new kind of SAMs against aircrafts and threat missiles.
- When there are hostile aircrafts in the operation area, the number of expended missile does not change significantly for the same firing policy and missile kill probability, but the number of leaker missile increases. This is because the ship cannot react to an incoming aircraft far from its standoff range. Normally, the hostile aircrafts engage their missiles at ship's standoff border and this delays the ship's reaction. This delay increases the number of leaker missiles.
- S-S-L firing policy increases the missile kill range. Because when the ship shoots the incoming threat with two SAM respectively, the incoming threat is killed earlier than S-L-S firing policy.
- When there are hostile aircrafts in the operation area, the kill range decreases significantly for the same firing policy and missile kill probability. Normally, the hostile aircrafts engage their missiles at ship's standoff border and this delays the ship's reaction and decreases the missile kill range.
- The S-S-L firing policy kills the threat missiles at longer distance than the S-L-S firing policy. But when we compare the number of leakers of both firing

policies, it is observed that S-S-L firing policy is not convenient firing policy for ship survivability.

- To improve the hit probability of missiles increases the ship survivability more than the other combat systems. These results lead the nations to make improvement in missile design and constructions.
- To increase the maximum kill range of SAM decreases the number of leaker missiles more than the other system. This urges the Navies to get the missiles with longer range and to protect the ship from further sides.

The analyses in this thesis showed that this model:

- Can be efficiently used to determine the best SSAD system among the alternative systems.
- Can be efficiently used to determine the best firing policy with respect to different war conditions.
- Can be efficiently used for sensitivity analysis of SAM and the combat systems parameters.
- May provide useful insight to evaluate suitable tactics for different operation area and conditions.
- Provide training opportunity for decision maker.

Results were analyzed by naval officers and they are compared with the real data from the naval operations**.** The results of the simulation models showed that this work provides an insight for decision makers.

6.2 Recommendations for Further Studies

In real condition ship air self defense consists of complicated elements, so to analyze the whole system is very hard. In this thesis the main structure of this system is analyzed. The details may be analyzed by part. To analyze these parts some modifications can be made as further studies these modifications are as follows:

- Soft kill counter measure system (decoys, chaff, and radar jamming) can be added to the models.
- An analytical approach can be implemented for one of the models. Missile kill probability may change with respect to range and the position of the ship.
- The movement of the ships and threats can be simulated. These movements may be nonlinear.
- Detection probability of surveillance system may be variable. It may change with respect to range, weather condition. Weather condition may be simulated.
- New systems (like IFF and ESM) may be added the system.

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