Commando Materieel en IT
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Selection and distribution of weapon systems for early stage ship design

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by

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DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN WRITING

During the preparation of this work the author used ChatGPT and Claude in order to help formulate certain sentences better and improve the efficiency of the code. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Abstract

The technological advancements in weapons and weapon systems continues to increase, and with these advancements the risk in safety increases as well. In naval warfare various types of attacks can occur, these include air, surface and subsurface attacks. In this report the focus is on the aerial attacks the naval task forces may encounter. The advancements of missiles, drones and super-sonic weapons creates a big problem for the safety capabilities the current navy possesses.

This research focuses on the selection and distribution of air defense weapon systems within a task force to increase the safety of the task force during operations. The current approach of allocating air defense weapon systems is done through analyzing intelligence and determining which weapon system would be best for the vessel based on potential scenarios. However, this approach is only suitable for one vessel and not for an entire task force. Therefore, a model has been developed to optimize the selection and distribution of the weapon systems across the task force. The selection and distribution is based on the effectiveness of protecting the task force and the costs of operating the weapon systems.

A literature research has been done to establish the foundation of the model. The literature focused mainly on the Weapon Target Allocation (WTA) problem. The WTA models determine which weapon systems engage the threats and provide insight of the effectiveness of the assigned weapon systems. Additionally, various optimization algorithms have been analyzed. The algorithms can optimize the chosen weapon systems and are able to analyze the effectiveness and overall costs of the weapon systems. Based on the available literature a model was designed. The model originated from a static WTA model which has been altered to meet the requirements of a simplistic dynamic model. Additionally, the NSGA-II algorithm has been externally applied to the WTA model for effectiveness and cost optimization.

Four test cases have been conducted using the model, focusing on the various inputs involving the task force. The analysis of the test cases show that the selection and distribution of the weapon systems is heavily influenced by the desired costs and effectiveness. The two objective functions create the most suitable selection and distribution of weapon systems based on the all the iterations of the simulation. Additionally, the results show the importance of cooperation between the vessels in the task force which in itself increases the effectiveness of neutralizing the threats while reducing the costs.

Ultimately, the application of the developed model gives an insight into the selection and distribution of the weapon systems within a task force. The model can assist in the design process for the selection of the weapon systems and the minimum amount of ammunition needed to successfully complete an operation, based on achieving maximum effectiveness and minimizing the costs.

Contents

1. Introduction

1.1 Background Information

Modern naval warfare has evolved into a complex environment due to the increase in more advanced and diverse attacks. Anti-ship missiles, unmanned aerial vehicles, swarm attacks and even hyper-sonic weapons will keep advancing (Materak, 2023) and increase their interception difficulty. The advanced aerial attacks pose a great threat for naval task forces. Therefore, it is of high priority to develop, refine and analyze the air defense systems. These air defense systems are essential for the protection of the naval task forces, which are coordinated groups of navy vessels organized to accomplish a specific goal or mission. Within the task force, some of the vessels can be classed as high value units (HVU). These units will rely on the other vessels within the task force to protect them from the different aerial attacks. The HVU's usually have their own self-defense systems, but these air defense systems are typically for short distance situations and not as advanced as the air defense systems onboard an air defense frigate (Ministry of Defense Personnel, 2024). The air defense frigates main priority is area defense of the task force. These air defense frigates are specialized units with the purpose of countering aerial threats across medium to long range distances (Leonardi, 1996). The air defense systems onboard the vessels are a mix of soft and hard kill systems. The cooperation of the vessels in the task force and the utilization of both the soft and hard kill systems ensure sufficient coverage against the different types of threats the task force can encounter. Analyzing the effectiveness of the soft and hard kill systems, especially the integration and cooperation of both systems, is an important part of creating an efficient air defense system for the task force.

Soft kill air defense systems are used to divert incoming missiles using decoys and jammers (Tashakori et al., 2024), with deception being their main mode of action. Hard kill air defense measures are used when the incoming threats cannot be deceived by the soft kill measures. These systems are categorized based on the range of the encountered threats. The type of threat and the scenario under which it occurs determines which system will be used to neutralize the threat, be it soft kill, hard kill or a joint effort of soft and hard kill systems (National Research Council, 1992).

The task force relies heavily on the cooperation and integration of the systems within the group, equipping every vessel in the task force with defense systems is not always the most effective and cost-friendly solution (Karasakal, 2006). In recent years the new radar technology and air defense systems are being developed to counter the increase in technological advancements of the aerial threats. Unfortunately, the costs of the new radar and air defense systems are higher than expected (Ministerie van Defensie, 2022). Every vessel class will eventually be replaced by their newer versions, these new vessels will be equipped with similar but state-of-the art equipment. It is essential to equip the vessel with air defense systems that are optimally located for extensive coverage across the task force while balancing the costs of the systems with the effectiveness of covering the task force air defense area.

To ensure an effective defense against aerial threats, the selection of weapon systems for navy vessels is based on intel gathered by the naval intelligence service. The acquired intelligence on adversary threats require careful analysis. Various potential encounter scenarios are put together based on the information gathered from the analysis. With these scenarios the counter weapon systems will be selected based on their capabilities to stop the threats under any circumstance. Ultimately, the best suitable weapon systems will be installed on the vessel in question. This process is done for each vessel type the navy has in its fleet.

1.2 Research Goal

1.2.1 Research Gap

The optimization of weapon system selection within a task force based on neutralization effectiveness and costs is where the research gap lies. The research into the selection and distribution of weapon systems across a task force is lacking. Many studies mainly focus on the Weapon Target Allocation (WTA) problem. The purpose of the WTA model is to identify which available weapon system in a group of weapon systems is best to engage with incoming targets/threats. Unfortunately, this is only a part of the solution of the optimization problem. The research gap is determining the optimal selection and distribution of air defense weapon systems for naval vessels within a task force, while balancing the effectiveness and the costs of these systems.

1.2.2 Research Questions

The main research question of this thesis is as follows:

How can layered air defense systems be designed, including the selection and distribution of weapon systems across a task force, to achieve high coverage protection while finding a balance between effectiveness and costs?

The objective of this research is to explore the optimal allocation of the soft and hard kill systems in a task force while keeping the costs low and the kill efficiency high. This is done by analyzing the task force and available air defense systems, developing a method to assess the highest efficiency of the layered air defense systems.

Two sets of research sub-questions will be used to investigate and address the main question, the first set will be answered during the literature review:

1. How is a Naval Task Force structured?
2. What aerial attacks does a task force encounter during operations and what air defense measures are used to counter the attacks?
3. What is the WTA problem?
4. Which modeling approaches would be most effective for optimizing air defense distribution?

The second set of sub-questions will be investigated and answered during the research phase:

1. How can the effectiveness of the air defense distribution model be evaluated and validated?
2. How will the distribution of air defense systems affect the task force's overall coverage?
3. How will the cost of equipment impact the operational efficiency?

1.3 Scope of Work

The first part of the research is the literature research. During this period the main focus is on gathering information about weapon systems and task force compositions. In particular, the task force composition of near-shore engagement and the types of threats the task force may encounter are of great interest. Furthermore, it is important to understand what types of air defense systems can be utilized by the different vessels of the task force, whether that is soft kill or hard kill. The next step is to look into the how the soft and hard kill systems work and how they can modeled. The final step of the literature research is to investigate which model type can be implemented for a clear and functional model.

Using the information acquired from the literature research the model can be set up. Different parameters including vessel types, air defense systems and threats will be modeled accordingly. The purpose of this model is not to simulate a war gaming type of behavior, nor is it purely about strategy. Instead, the model is designed to simulate scenarios and assess which air defense weapon system is necessary to counter the threats effectively. The model will indicate which systems will be used and where they will be allocated in the task force, balancing the operational costs and effectiveness of kill.

2. Problem Definition

This chapter aims to answers the following sub-questions:

1. How is a Naval Task Force structured?
2. What aerial attacks does a task force encounter during operations and what air defense measures are used to counter the attacks?
3. What is the WTA problem?

The first section outlines the structure of a naval task force and which vessels can be deployed within the task force of the Royal Netherlands Navy (RNLN). Section 2.2 describes the various aerial attacks the task force may encounter during an operation, providing information concerning the technological advancements of the threats. To counter these threats, the task force relies on various air defense systems, which are detailed in Section 2.3. However, the air defense systems cannot operate effectively without sensor systems, which play a vital role in situational awareness by mapping the nearby objects. The important sensor systems used by the RNLN are described in Section 2.4. Section 2.5 explores the WTA problem, which focuses on optimizing the assignment of available weapon systems to the incoming threats to maximize the defensive effectiveness. Section 2.6 discusses the current method of equipping weapon systems on ships and the section discusses the difference between effectiveness and costs. With all the information gathered, the research gap is identified and described in Section 2.7. Finally, Section 2.8 identifies the model requirements based on the previous sections.

2.1 Task Force Composition

The composition of the Task Force (TF) is an important element of the overall efficiency and effectiveness to complete the mission. The composition is about strategy and integration of various types of vessels to collectively fulfill a specific goal or mission. Each vessel in the task force has their own role, each with unique capabilities and with these capabilities a balanced and versatile group can be formed. Therefore, understanding the composition will lead to a highly functioning group of vessels.

Within the task force there is a command structure to ensure that the task force will have good operational coordination and decision making. This command structure is needed for authority and responsibilities of the task force, as good authority leads to greater operational efficiency. The hierarchy is usually structured as follows (Ministry of Defense Personnel, 2024):

1. Force Commander, responsible for the entire task force.
2. Commanding Officer, responsible for the individual vessel.
3. Staff Officers, supporting the Force Commander in specialized areas.

Many different types of vessels can be used to form a task force, in this case fleet of the RNLN will provide the diverse range of vessels. Each of these vessels has their own role and contribute to the task force in unique ways.

While the current fleet of the RNLN comprises many different types of vessels, the main focus is about the task force compositions and how various vessel types would interact with each other. Therefore, the following list is made up of vessel types still in design or production phase.

1. Amphibious Transport Ship (ATS)
2. Future Air Defender (FuAD)
3. Combat Support Ship (CSS)

4. Orka-class Submarine
5. Anti-Submarine Warfare Frigate (ASWF)
6. Multirole Support Ship (MSS)

Task forces can be utilized for different types of missions, from combat operations to escorting and convoy protection. The focus in this chapter will be a combat operation specific task force, in particular amphibious operations. The reason for the amphibious task force is due to the high level of coordination required between the vessels and during the amphibious operation different types of aerial threats can occur which is helpful in determining an all-round air defense system setup within a task force (Ministry of Defense Personnel, 2024).

The amphibious operations can be performed with task forces of various sizes. A task force is comprises various vessels, each with their unique ability and chosen to enhance the operational efficiency. The smaller task force can be composed of just one transport ship and one air defense frigate. The transport ship provides the connectors to transport the troops and equipment to shore (FIN, 2025). The connectors are smaller vessels (and helicopters) such as landing crafts for personnel and mobility. The air defense frigates provides the main air defense capabilities of the task force (FIN, 2025). The large task force groups can be composed of multiple vessels of each type, ensuring high protection of the task force and support for extended mission durations. A scenario of a small task force during an amphibious operation can be seen in Figure ...

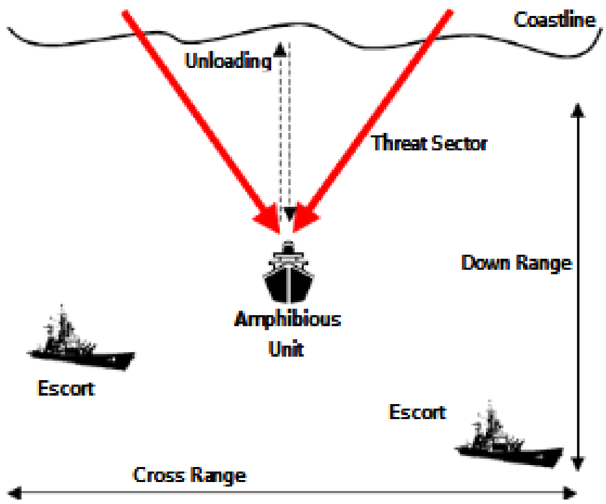


Figure 2.1: Amphibious scenario of a small task force (West, 2003)

2.2 Aerial Threats

Aerial threats can be categorized into two groups: symmetrical and asymmetrical attacks. While these types of threats are typically not deployed simultaneously, the possibility of their combined use cannot be entirely ruled out and should be considered during the missions (Romaniuk and Bobić, 2015).

Symmetrical threats arise from peer or near-peer opponents, also known as state actors. State actors are typically forces with similar advanced capabilities and technology. The state actors are often predictable and will follow traditional warfare. Asymmetrical threats originate from adversaries with less advanced technologies and often do not have similar capabilities of defending their assets. They rely on unconventional and innovative technologies that are difficult to predict and analyze (Merriam-Webster, 2025). Examples of these adversaries utilizing the asymmetrical threats are terrorist or insurgent groups.

2.2.1 Sea Skimming Missiles

The sea skimming missiles are anti-ship missiles that fly at low altitudes and very close to the surface to avoid detection through radar and infrared (Chandrayan, 2025). By staying low to the surface the sea skimmers use the curvature of the earth and the radar clutter of the waves to reduce the reaction time of the target. The sea skimmers can be put into two types, the subsonic missile and the supersonic missile known as "Sprinters". Normally while trying to neutralize the sea skimmer a predicted intercept point, the pip, will be determined. Once the pip is calculated the countermeasure can be launched to take care of the incoming missile. However, the supersonic sea skimming missile increases the difficulty of intercepting the missile. The sprinter missiles can boost themselves at a seemingly random moment during the attack, the calculated pip will change as soon as new knowledge of the sea skimming missile's location and velocity have been analyzed (Zarchan, 1998). While the pip can be altered during the launch of the countermeasure, the sudden increase in speed of the sea skimmer might be too late to act upon and thus penetrating through the first layer of defense. One of such sea skimmers is the CX-1 missile, traveling with speeds up to Mach 3 and a maximum range of 280 KM (Chhatwal, 2015).

2.2.2 Anti-ship Ballistic Missiles

The ballistic missile is similar to the high diving missile, the ballistic missile is however usually used for long range targets. During boost phase the missile is propelled to high altitudes with either a single stage rocket or multi stage rockets, after the fuel has been burned completely the missile will set course to the target guided by the gravity of the earth. The path of the ballistic missile does not change much after the launching sequence, the accuracy of these missiles is therefore not as great as opposed to cruise missiles. Newer and more advanced models of the ballistic missiles will have a higher accuracy when equipped with a GPS mid-course guidance or terminal radar-aided guidance system (Weimar, 2012).

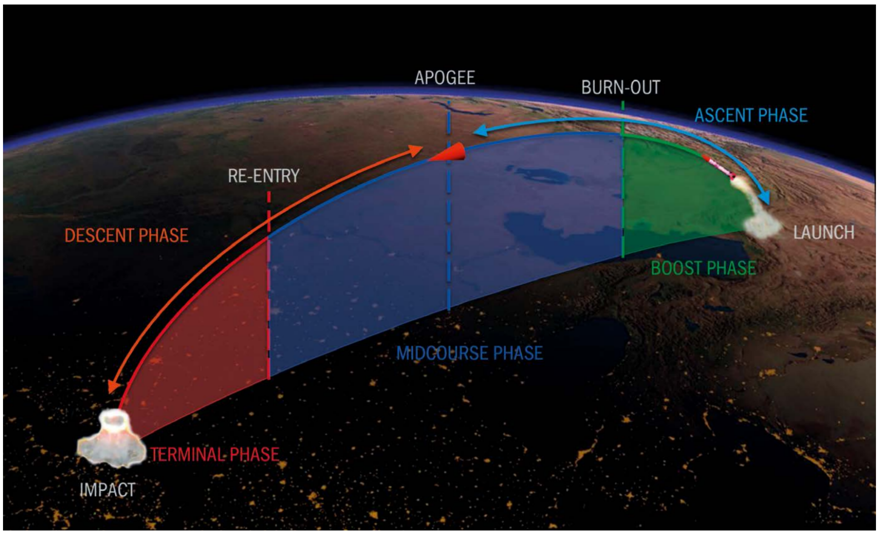


Figure 2.2: Ballistic missile trajectory (Weimar, 2012)

Additionally, the ballistic missile can follow multiple basic trajectories. The first trajectory is to gain the maximum range the missile can reach, this is achieved by having the missile reach the optimal angle at the burn out point. For a higher accuracy, the lofted trajectory is applied, the lofted angle reaches a higher altitude which increases the detectability of the ballistic missile by the sensor systems of the target vessels. The last basic trajectory is the depressed trajectory, the ballistic missile flies at a lower altitude thus reaching the target sooner than the other trajectories and also decreasing the detectability at the cost of a lower accuracy. An example of an anti-ship Ballistic Missile is the Chinese DF-26. This missile is considered an intermediate range missile, having a range of 4000 KM. The accuracy of the missile is classified, but the estimated accuracy is between 150 - 450 m circular error probable (CSIS, 2025b). The step up from the intermediate is the intercontinental ballistic missile, the American Titan 2 has a range of 15000 KM (CSIS, 2025d).

2.2.3 Hypersonic Glide Vehicles

The hypersonic glide vehicle (HGV) is an advanced missile technology that pushes the missile speed to at least 5 Mach and unlike the ballistic missile they do not follow the basic ballistic trajectory and maneuver unpredictably towards their target when required to decrease the interception likelihood. The hypersonic glide vehicle starts the initial launch with a suppressed flight path and ultimately determines it's own path to the target at a low altitude to reduce the detectability of the missile. The combination of the speed, maneuverability and low altitude flying makes the hypersonic glide vehicle an incredibly dangerous aerial threat (Service, 2024). The difference of flight paths between the ballistic missile and the HGV can be seen in Figure 2.3.

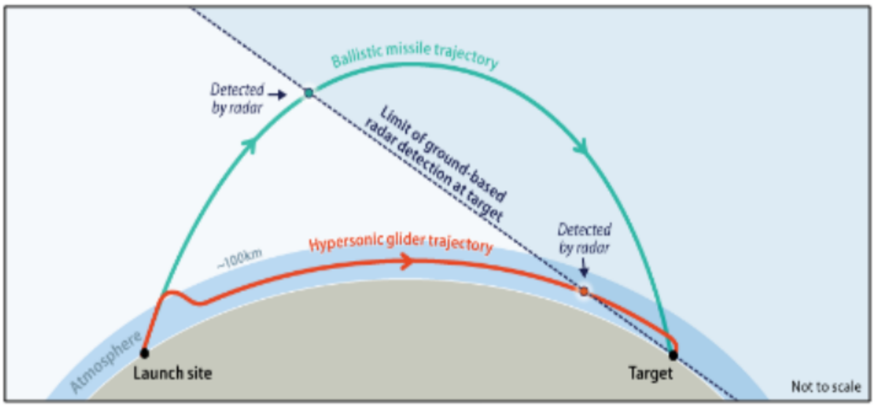


Figure 2.3: Detection of Ballistic Missiles vs Hypersonic Glide Vehicles ('Gliding missiles that fly faster than Mach 5 are coming', 2019)

The Avangard is a Russian HGV with a range over 6000 KM. The HGV is boosted to a suborbital apogee of 100 KM, at the apogee the HGV separates from the rocket and starts the descend on momentum and gravity. It has been claimed that the Avangard can maintain a speed of up to 20 Mach, still capable of high maneuverability increasing the difficulty of interception even further (CSIS, 2025a).

2.2.4 Unmanned Aerial Vehicle

The Unmanned Aerial Vehicle (UAV) is the only asymmetrical aerial threat that will be discussed in this chapter due to the unpredictable nature of the asymmetrical threats. The UAV's have become a favorite of the non-state actors due to the accessibility, low costs and high operational flexibility (Integrated Air and Missile Defence Centre of Excellence (IAMD COE), 2024). These drones can be used in various ways, however the kamikaze drones are of most importance since they deliver the biggest potential impact on the vessels in the task force. Additionally, the UAV can be equipped with an AI to increase the precision by using real-time intelligence and targeting algorithms (insideFPV, 2024). The low costs of the drones allows the non-state actors to manufacture and deploy many drones simultaneously, also known as swarming. The drone swarms can overwhelm the air defense systems, increasing the difficulty of neutralizing the threats effectively. Swarm attacks rely heavily on the use of AI, the communication and cooperation of the drones will allow the AI to dynamically optimize the flight paths, tactics, formations and even identifying high value targets (Bilar, 2024).

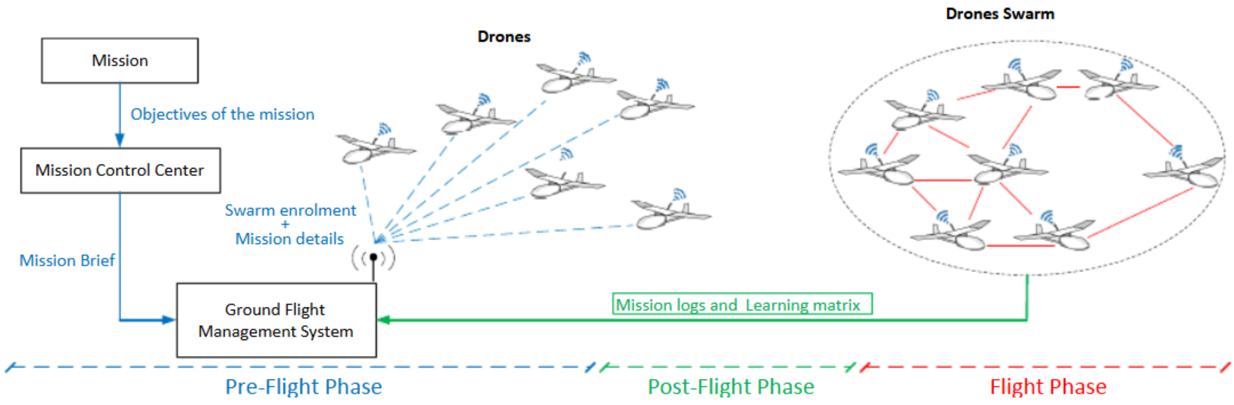


Figure 2.4: Operational Profile of the UAV Swarm (Akram et al., 2017)

2.3 Air Defense Systems

The RNLN currently uses a small variety of air defense systems, consisting of soft and hard kill measures. However, it is important to recognize that advancements in offensive technologies require similar improvements in defensive technologies. The current state-of-the-art air defense measures, as well as the future technology, will be examined.

2.3.1 Soft Kill Systems

Soft kill systems can be described as non-kinetic countermeasures, the focus of these systems is on electronic warfare and decoys. The soft kill systems prevent incoming threats from targeting or hitting a ship, the systems are used to disrupt, deceive and even misdirect the guidance and targeting of the incoming threats (Kumek, 2007).

The benefit of the soft kill systems is the re-usability of the majority of the countermeasures such as jammers and laser dazzlers, the decoy systems are not reusable but still relatively inexpensive compared to the ammunition of the hard kill systems. Additionally, soft kill systems are more efficient in engaging the targets when large numbers of threats have been detected and moving towards the ship. The hard kill systems will be overwhelmed and reduce the ability of engaging the incoming threats (Tashakori et al., 2024). However, the soft kill systems are not sufficient on their own, they can lack the efficiency if missiles use a dual-mode seeker (using radio frequency and infrared) or carry anti-jamming technologies.

High Power Microwave

The High Power Microwave (HPM) is a non-kinetic system designed to counter incoming threats by disrupting or even destroying their electronic systems. According to Colin Whelan of Raytheon (Szondy, 2023): "The new iterations of Raytheon's high-power microwave systems are cost-effective and reliable solutions that operate at the speed of light – enabling our war-fighters to defend against faster and more maneuverable threats." The main advantage of using an HPM system is the "unlimited" supply of ammunition, and the operating costs are considerably more favorable than a hard kill system. Additionally, the capability of neutralizing fast and highly maneuverable threats is a must in defense technology considering the advancements in aerial attacks.

High Energy Lasers

A High Energy Laser (HEL) is often used as a soft kill system to disable or impair incoming threats without destroying them. Often this involves dazzling or disrupting sensors, optics and guidance systems of threats such as missiles, UAVs/drones. The high energy laser is used for high precision, minimal collateral damage, rapid engagement (travels at the speed of light) and reducing the operational costs of neutralizing threats. Unfortunately, the lasers are limited in operation due to atmospheric interference, heat management and power generation. Another problem for the HEL is the laser-light source, this light source is usually a solid-state laser (Venugopal, 2024). Due to the high power demand of the HEL, the light sources may risk overheating. To counter the overheating sources, the HEL should be used in pulses giving the source time to cool down in addition of a cooling system to cool the sources continuously.

2.3.2 Hard Kill Systems

The hard kill systems operate with kinetic countermeasures, designed to destroy or neutralize the incoming threats. These measures ensure the complete removal of the threats and can often be used in a layered defense setup, deploying hard kill systems at various ranges. Unlike the soft kill systems, the hard kill measures have a high OPEX and a low CAPEX. The ammunition is expensive to produce and deploy, increasing the costs during the mission. Furthermore, the vessels deployed with the hard kill systems can only carry a limited stock of missiles and interceptors.

Hard kill systems can be categorized based on their engagement range: long range, medium range and short range. These ranges help structure a layered air defense strategy, increasing the interception of threats at different ranges. An overview of the hard kill systems are presented in Table 2.1, including the ranges and altitudes when available.

Table 2.1: Overview of Hard Kill Systems

Type	Range (KM)	Altitude (KM)	Velocity (Mach)
SM-6	370	34	3.5
SM-2	166	20	>3
Barak LRAD-ER	150	30	UNK.
Aster 30	150	20	4.5
CAMM-MR	100	UNK.	3
Barak LRAD	70	20	UNK.
ESSM	50	UNK.	4
CAMM-ER	40	UNK.	3
Barak MRAD	35	20	UNK.
Aster 15	30	13	3
CAMM	25	UNK.	3
RAM	10	UNK.	>2
76mm	10	-	-

Long Range Systems

Long range hard kill systems are designed to engage the aerial attacks at distances exceeding 70 KM. These systems are crucial for engaging high speed, long range missiles before they reach closer engagement zones. The long range missiles travel with speeds exceeding Mach 3 and are equipped with advanced guiding systems such as the active radar homing and semi-active radar homing, to track and neutralize the threats effectively.

The Standard Missile 2, also known as SM-2, is a long range surface-to-air defense system primarily used for fleet area defense and ship self defense. The SM-2 can be used against high speed, high maneuverable missiles (Raytheon Technologies, 2025). The range of the SM-2 is up to 90 nautical miles (166 KM) and has the ability to reach a speed of at least 3 Mach ('SM-2 Standard Missile', 2024). The SM-2 is equipped with a semi-active radar homing guidance, tail controls and a solid fuel rockets, sometimes an additional booster present for extended ranges. The SM-2 is compatible with the MK41 Vertical Launch System (VLS). The MK41 VLS is a missile launch system capable of launching multiple types of missiles, allowing for a fast reaction to threats (BAE Systems, 2025).

The Standard Missile 6, also known as SM-6, is an advanced multi-mission missile designed for extended range anti-air warfare. The SM-6 can be used to neutralize aircraft's, unmanned aerial vehicles, cruise missiles and terminal ballistic missiles. Unlike the aforementioned SM-2, the SM-6 is equipped with an active radar homing guidance. The active radar homing (ARH) guidance is an onboard radar system which can locate and track targets autonomously in the terminal phase (terminal phase is when the missile reenters the earth's atmosphere as the final stage of the flight), the semi-active radar homing (SAHR) guidance system is reliant on the illumination radar of the vessel from which the missile was launched from (Kopp, 2014). The AHR will therefore be better suited to counter highly agile targets and targets that exceed the range of the onboard illumination radars. It is important to note that the SM-6 will not replace the SM-2, but merely provides additional range and firepower for the total air defense of the task force (CSIS, 2025c). Like the SM-2, the SM-6 is also compatible with the MK41 VLS.

The Barak MX is a modular system with a single central command and control structure that combines the overlapping battle management, detection and interception coverage. The Barak MX is comprised of three components, the first is the Battle Management Center (BMC) which creates and manages a unified air picture from all the sensors linked to the system, the BMC will also prioritize coordinates and allocates engagements to the effectors and ultimately manages the interceptors launch (IAI, 2024b). The second component is the sensors and the final component is the effectors. These effectors are advanced Barak interceptors with different ranges; the Barak MRAD is used for short ranges up to 35 KM, the Barak LRAD used at medium ranges up to 70 KM and the Barak LRAD-ER used for long ranges up to 150 KM and countering ballistic missiles. The Barak LRAD-ER is equipped with an active RF (Radio Frequency) seeker, for a high precision counter against highly maneuverable targets. The LRAD-ER can be used against various threats such as sea-skimming missiles, UAVs and HGVs (IAI, 2024a). All three missile types of the Barak MX will be launched by a VLS.

The Aster 30 missile can be divided into multiple types of ranges, all designed for long range interception. The Aster 30 Block 0 is designed to intercept aerial threats up to a range of 120 KM and a maximum altitude of 20 KM (MBDA, 2024). The Aster missile has additional variations for Anti-Tactical Ballistic Missile (ATBM) protection. These anti-ballistic missile variants are the Aster 30 Block 1 and Aster 30 Block 1 NT. The range of the new variants is in excess of 150 KM (EUROSAM, 2024).

Medium Range Systems

Medium range systems typically engage the threats between 30 KM and 70 KM. They provide the second line of defense, aiding the long range systems when the threats have managed to penetrate the first layer of defense. Medium range missiles travel with velocities of Mach 3 and sometimes even Mach 4 and similarly to the long range operate with active and semi-active radar homing guidance systems.

The Evolved Sea Sparrow Missile, also known as ESSM, comes in two variants: the Block 1 and Block 2. The ESSM Block 1 is an air-to-surface interceptor to counter threats such as anti-ship cruise missiles and drones. The missile can reach a speed of 4 Mach with a range of 45-50 KM and utilizes an semi-active radar homing guidance system. The semi-active guidance system partially limits the Block 1 variant against advanced and highly maneuverable threats. The ESSM Block 2 is equipped with an active radar homing guidance system to increase the likelihood of countering the maneuvering threats ('Evolved Sea Sparrow Missile (ESSM)', 2024). Additionally, the Block 2 can be modified through software in real time to match the advancements of the aerial threats (Ministerie van Defensie, 2023).

The Common Anti-Air Modular Missile (CAMM) is a supersonic missile used for counter threats within 25 KM of the vessel or task force (MBDA, 2018b). The missile uses an active RF seeker, ensuring high operating capabilities in all weather conditions. The missile is launched with a Soft Vertical Launch (SVL) technology to reduce the weight of the missile and provides a flexible installation of the missile. The SVL ejects the missile pneumatically, the missile can then orientate itself in the correct direction before engaging the rockets and setting course to the incoming threat. The CAMM has two other variants for additional range; the CAMM-ER (Extended Range) is used to intercept threats up to 40 KM and the CAMM-MR (Medium Range) is used to intercept threats up to 100 KM.

Short Range Systems

The short range systems engage threats below 30 KM, when the threats have managed to penetrate all previous layers. Potentially in addition to available soft kill systems, these systems are usually last resort measures.

The Rolling Airframe Missile (RAM) is a fire-and-forget Close-in Weapon System (CIWS) (MBDA, 2018c). Unlike the other mentioned hard kill systems, this system is a self-defense missile to counter anti-ship missiles. The missile is equipped with a Radio Frequency (RF) and Infra-Red (IR) seeker, the missile has a range up to 10 KM (Seaforces, 2025). Usually, multiple RAM missiles can be deployed at once to counter multiple and high density raids.

The Aster 15 missile is the short range air-to-surface missile of the Aster family, compared to the previously described Aster 30 the Aster 15 has a range of 30 KM, maximum altitude of 13 KM and will reach a top speed of Mach 3 (MBDA, 2024). The Aster 15 is a highly maneuverable missile due to the Pilotage en Force - Pilotage Aerodynamique Fort (PIF-PAF) technology. The PIF-PAF is a missile steering system, using a combination of aerodynamic control and direct thrust vector control allowing the missile to undergo high G maneuvers (EUROSAM, 2024). Furthermore, the Aster 15 is equipped with an active RF seeker, capable of tracking stealthy targets.
The 76-mm cannon is a weapon system capable of short range anti-missile point defense and anti-aircraft defense. This is strictly for self-defense and will only be used as a last resort when all other measures have failed. The 76-mm cannon uses a particular type of ammunition called the DART (Driven Ammunition Reduced Time of flight), the DART ammunition is highly accurate and maneuverable due to the real time trajectory corrections via a radio frequency beam. This radio frequency beam is provided by the PHAROS radar which is capable of tracking multiple targets simultaneously. The ammunition includes proximity and impact detonation designed to be programmed during flight for an optimized counterattack. The range of the 76-mm cannon equipped with the DART ammunition is 8-10 KM, ranges can vary depending on the ammunition varying from 8 to 40 KM (SeaForces, 2025).

2.4 Sensors

Radars and sensors play a crucial role in ensuring the safety of naval vessels. These systems continuously scan the surrounding area for potential threats, including ships, drones, and incoming missiles. Advanced radars can detect missiles from long distances (TNO, 2025), providing early warnings that allow for a quick and precise response. By identifying threats as early as possible, these systems increase the ship's defensive capabilities and overall situational awareness. As a result, the radar system is an essential component of every vessel within a naval task force. The RNLN equips their vessels with a variety of advanced sensors. This section will cover some of the sensors.

2.4.1 APAR

The APAR, Active Phased Array Radar, is an X-band Active Electronically Scanned Array (AESA) radar (MDAA, 2024). The system has many capabilities such as air and surface tracking, horizon search, missile guidance and gunfire support. The system is excellent in detecting and tracking a broad range of threats including supersonic missiles and ballistic missiles. In addition, the APAR system can operate in a complex environment and track multiple threats simultaneously. Due to the X-band frequency, the system excels in tracking of threats, which is essential for coordinating with the ESSM and SM-2 hard kill systems. The APAR has a range of 150 KM.

2.4.2 SMART-L

The SMART-L is another AESA radar that is often paired with the APAR system. The purpose of the SMART-L is to provide long-range detection up to 2000 KM, being able to detect and track a wide range of threats from air breathing targets, stealth targets, and ballistic missiles (Thales, 2024b). The SMART-L radar has the ability to look forward, backward, and stare, can detect and track threats from the horizon to the zenith. The extended long range version of the SMART-L, the SMART-L ELR, is able to provide detecting surpassing the 2000 KM of the standard SMART-L. The ELR is therefore particularly effective for Ballistic Missile Defense (BMD).

2.4.3 ARTEMIS

The ARTEMIS system is a static-head infrared search and track system (IRST) used to detect conventional and asymmetric threats. Unlike older similar systems, this surveillance sensor provides 360 degrees of continuous coverage due to the static heads of the sensor. With use of sophisticated algorithms, the sensor is capable of early detection of super- and hypersonic missiles, monitor UAVs, manage multi-directional attacks and rapid and precise target designation (Thales, 2024a). Each sensor head is equipped with cooled IR technology cameras. With these cameras, the system can detect, track and classify threats based on the infrared signature (Thales, 2024a).

2.5 Weapon Target Allocation

The Weapon Target Allocation (WTA) problem, sometimes described as the Missile Allocation Problem (MAP), is designed to assign missiles/weapons to incoming threats with the purpose of minimizing the probability of a threat destroying an asset. This problem was originally introduced by Alan Manne in 1958 (Manne, 1958), due to limited computing power the model was forced to have restrictive constraints and small scale data. The model by Manne (1958) set the foundation of the Static Weapon Target Allocation (SWTA) model. The static model works with a known amount of incoming threats and a fixed amount of interceptors with known probabilities of destroying the threats (Kline et al., 2019). The outcome of the SWTA model describes how many shots of each available weapon type are needed to destroy the incoming threats, it can occur that the outcome proposes more weapons to be needed in that specific scenario. It is important to note that each calculation is performed with the same set of weapon systems. Figure 2.5 presents an example scenario of the SWTA problem, illustrating the allocation of available weapon systems to incoming threats.

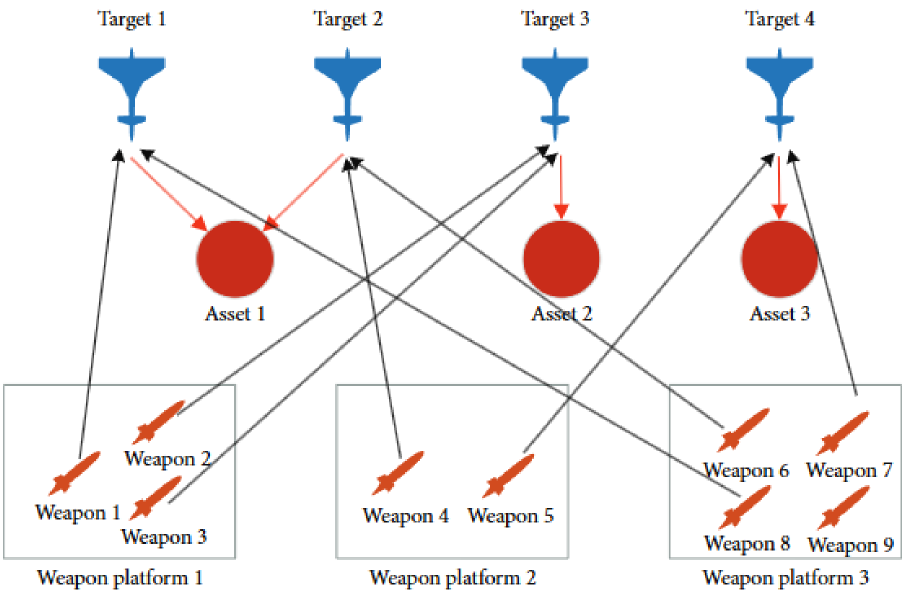


Figure 2.5: Illustration of the SWTA problem (X. Li et al., 2018)

One of the main limitations of the SWTA model is the single stage encounter. The static model will not continue any further after the model has been run. To fully assess the overall the efficiency of the weapon systems within the task force, it is important to calculate the WTA for the surviving threats after the initial engagement. This is where the Dynamic Weapon Target Allocation (DWTA) problem comes into play. The DWTA introduces time as a dimension (J. Li et al., 2024), with notable variants including the m-stage and the shoot-look-shoot approaches.

In m-stage model, the first stage works similarly to the static model, while the subsequent stage which engages with incoming threats based on a probability distribution. The DWTA is divided into multiple SWTA stages (J. Li et al., 2024). The outcome of the m-stage model displays the allocated weapons of the first stage and the additional reserve weapons allocated weapons in the next stage.

An alternative variant is the shoot-look-shoot (SLS) model, this model also continues with the basis set by the static model, however the SLS observes which threats survived the initial engagement and allows the weapons to be assigned again to further minimize the probability of the threats destroying an asset (Kline et al., 2019). Similarly to the m-stage, the outcome displays which weapons have been allocated in the initial engagement and how many additional reserve weapons are required to further reduce the probability of survival of the incoming threats.

2.6 State-of-the-Art Approach in Air Defense Weapon Allocation and Efficiency

2.6.1 Air Defense Weapon Distribution

The current approach by the Dutch Ministry of Defense to determine the optimal distribution of layered air defense systems within a task force is not fully available. The lacking factor in their current method is the distribution of the weapon systems within a task force. The ministry's current method is by analyzing individual ships and not taking into account cooperation between the vessels within a task force setting. The Ministry of Defense starts by analyzing acquired intelligence regarding potential threats the navy may encounter during operations. They will carefully create scenarios with the gathered intelligence and run simulations to determine which air defense systems will ensure the highest overall survivability of the vessel.

This information has been gathered during an interview with personnel of the Ministry of Defense (Ministry of Defense Personnel, 2024). The complete process of air defense weapon selection is heavily classified, and as a result, additional sources on this topic are therefore not available online.

2.6.2 Costs vs Effectiveness

The distribution and utilization of the weapon systems may be influenced by their costs. As a result, the cost-effectiveness of each system is often evaluated by comparing its expense to its performance (Ford, 2016). According to my definition, the costs are determined by the number of missiles deployed during the engagement, while the effectiveness is measured by the probability of successfully intercepting an incoming threat. In some WTA models, the trade-off between costs and effectiveness is considered when multiple weapon systems are capable to engage the same threat (Yang et al., 2021).

2.7 Research Gap

The literature review identified a research gap, as the current state of the research is lacking. Many papers focus heavily on the WTA problem, without fully going into detail concerning the weapon system selection and distribution. To cover the research gap, this paper will provide information about determining the optimal selection of air defense weapon systems for naval vessels within a task force, while balancing the effectiveness and the costs of these systems.

The research gap covers the group format of the selection and distribution of the weapon systems. As described in Section 2.6.1, the current approach focuses on determining the optimal allocation of weapon system on an individual vessel, not taking into account the cooperation with other vessels. Determining the effectiveness and cost of operating the weapon systems is not a new concept. The WTA problem already addresses the optimal pairing of the weapon systems with aerial threats. However, the WTA problem does not account for variations in the weapon systems combinations and typically performs the calculations with the same set of weapon systems. The research gap will also include an exploration of various combinations of the available weapon systems within the task force, ensuring that each weapon system within the task force gets optimally utilized based on the effectiveness of neutralizing the incoming threats and the costs of the weapon system.

2.8 Model Requirements

To effectively optimize the distribution of air defense systems, a mathematical model is essential. Developing such a model requires a well-defined set of requirements to serve as its foundation, ensuring accuracy and practical applicability. These requirements should account for factors including aerial attack composition, equipped air defense weapon systems, weapon target allocation and optimization of the allocated weapon systems, forming a comprehensive framework for the model's design and implementation. Based on the information presented in this chapter, the following requirements have been identified and defined:

Requirement 1: Group Analysis

The model shall incorporate a group analysis approach, recognizing that navy vessels usually operate in coordinate settings. Unlike the current approach, which allocates air defense weapons on a navy vessel by analyzing data and running scenarios for this particular vessel (Ministry of Defense Personnel, 2024), the model shall account for cooperation of vessels within a task force. The group analysis approach can alter the outcome of the selection of the air defense weapon systems.

Requirement 2: Vessel Location

The model shall account for the positioning of the vessels and the task force configuration. The vessels can be tens of nautical miles apart from each other. A variation in distances between the vessels will alter which vessel will intercept incoming threats. This model shall be able to model the vessel location up to 25 nautical miles between each vessel.

Requirement 3: Threat Composition

The model shall represent various compositions of aerial threats. The aerial threats arsenal is composed of different types of attacks, including all threats described in Section 2.2. The task force shall be capable of defending itself against all types of aerial attacks, including combinations of different threat types.

Requirement 4: Air Defense Systems

The model shall evaluate the combination of hard and soft kill air defense systems to increase the survivability of the vessels, both in area defense and self defense. The combination of air defense weapon systems shall include all described weapon systems in Section 2.3.

Requirement 5: Weapon Target Allocation/Assignment

The model shall incorporate a WTA model that determines which air defense system engages which incoming threat. This is not limited to just one vessel, the weapon target allocation will pick the best option per threat from all the weapon systems within the task force. It is important that the WTA allows a single weapon system to engage multiple threats simultaneously.

Sub-Requirement 5A : Sensor System

The model should incorporate sensor systems to determine when the aerial threats are detected and when the threats can be engaged, depending on the range of the air defense systems. The sensors used will be based on sensor systems described earlier in this chapter. This requirement enhances the WTA scenario, creating a more realistic engagement. The model can function fine without the requirement, thus this is not an essential requirement to implement.

Requirement 6: Layered Defense

The model shall incorporate a layered air defense system, where the air defense of the task force is divided into long, medium and short range. The WTA is merely to pair the air defense weapon system to an incoming threat. The WTA determines which threat is or is not neutralized based on the probability of kill. Due to working with probabilities, the chance of a threat surviving the initial engagement in the long range section is always possible. The chance of survival of the threat in the long range section means the model should be prepared to engage this threat again in the next layer.

Requirements 7: System Allocation

The model shall account for the varying carrying capabilities of different vessel types within the task force, as not every vessel is capable of carrying all the available options of air defense systems. The model shall moderate the selection of weapon systems on each vessel in the task force.

Requirement 8: Costs

The model shall keep track which set of weapon systems yields a satisfactory survivability rate. Each set of weapon systems will therefore also have fixed set of costs for equipment installation and a variable cost for ammunition used in the scenario. Ultimately, the model shall display the costs of each weapon set of the task force for each scenario.

Requirement 9: Optimizing System Allocation

The model shall provide an outcome of the weapon target allocation that offers an overview of the survivability of the vessel within the task force, given a certain set of weapon systems used in a particular scenario, along with the costs of the weapon set. An algorithm should be used to pick an improved set of weapons, either based on the survivability or the costs of the weapons and ammunition. The outcome of each cycle will be stored and a Pareto front should be made displaying the survival rate against the costs.

2.9 Conclusion

In conclusion, the structure of the naval task force is carefully designed to successfully complete an operation utilizing various types of vessels, ranging from support vessels to air defender frigates and submarines. The task force operates under a hierarchical command structure, including a force commander, commanding officers and staff officers, all working together to achieve the operational objective.

During operations, the task force may encounter a variety of aerial attacks, both symmetrical and asymmetrical. These attacks include sea skimming missiles, ballistic missiles, hypersonic glide vehicles and unmanned aerial vehicles. To counter these attacks, the task force can use a combination of soft and hard kill systems. The soft kill systems, for example the high powered microwave and high energy laser, offer an alternative approach of neutralizing the aerial attacks without destroying them. The hard kill systems, usually kinetic missiles, provide a direct interception across various ranges from 10 KM to even 370 KM. A layered defense system integrates all weapon systems across long, medium and short range ensuring high coverage protection of the task force.

Finally, the weapon target allocation (WTA) problem solves for the optimal assignment of weapon systems to a set of threats. The WTA problem is a key part in the distribution of weapon systems based on the neutralization of threats and establishment of the operating costs of the weapon systems within the task force.

3. Model Analysis

This chapter aims to answer the following sub-question:

4. Which modeling approaches would be most effective for optimizing air defense distribution?

The first section provides on overview of research conducted throughout the years regarding the main research question. Section 3.2 provides information regarding the allocation of the weapon systems to the aerial threats. This is vital for determining the optimal usage of the weapon systems. Section 3.3 discusses how wargames can aid in building the operation environment. The final section provides information concerning the optimization the model, aiding in determining the selection of weapon systems based on effectiveness and costs. A literature search was carried out using various search terms in Google Scholar, World Cat and the TU Delft Library. Using various search terms, the starting point was analyzing what the WTA models calculate and determine how this could be implemented in the model. Wargame simulation were also analyzed to get a better understanding of simulating the scenario. Finally, optimization algorithms were research for optimizing the effectiveness and costs of each weapon system within the task force. The search terms are as follows: *optimal distribution, placement, allocation, air defense systems, weapon systems, task force, military units, distribution strategy, wargame, probability, probability of kill, optimization & algorithms*.

3.1 Current Research

The current research about the optimal distribution of air defense weapon systems within a task force is scarce. The focus is usually on the weapon target allocation and optimizing which system would be best suited to engage a particular incoming threat. The secondary objective focusing on the balance between effectiveness and costs are typically researched as the main objective, as seen in the study by Colonel C. Ford (Ford, 2016).

The WTA problem by Karasakal (Karasakal, 2008) is specifically for a naval task force and thus the location is mentioned, albeit not extensively. The positioning of vessels and task force is typically not the main objective of the WTA model. The WTA problems are more interested in finding the optimal assignment, implementing an NSGA-III algorithm (Hu et al., 2023) or an improved ant colony algorithm (Yang et al., 2021) to improve the assignment process. The mapping of vessels and threats is done particularly well in wargame simulations and models, either with a hexagonal grid (Mann, 1991) or a square grid (Rao and Ravishankar, 2020).

A thesis from the Naval Postgraduate School in Monterey, California (Townsend, 1999) discusses the necessity of an Anti-Ship Missile Defense (ASMD) model, this model allows for an analysis to be performed in a task force setting and models how the anti-ship missiles select their targets and which vessels engage the missiles. The foundation of this model is yet again a weapon target allocation model and not necessarily discussing which weapon systems are needed for a good survivability rate of the task force after engagement.

Another thesis focuses heavily on the self defense of a vessel for different operation conditions (Kumek, 2007). The combination of layered air defense and detection of the threats play a major role in the research the paper is conducting. Unfortunately, the research is for specific hard kill systems only, neglecting the soft kill weapon systems. Furthermore, it only covers the self protection of one vessel, it does not include multiple vessels in any of the scenarios.

3.2 Weapon Target Allocation Models

Various models of the WTA problem have been defined over the years, both for the static as the dynamic models. Both the static and dynamic models will be analyzed in the following section. The initial introduction of various WTA models was provided in overviews by (Kline et al., 2019) and J. Li et al., 2024. Additionally, the

Hughes Salvo Model (HSM) can be used to determine the kill effectiveness of the weapon systems within the task force.

3.2.1 Manne (1958)

The original WTA formulation was defined by Manne in 1958 (Manne, 1958), this formulation describes a scenario of a defender with a defined amount of weapon types (w_i) against targets (j). Each weapon and threat combination has their own probability of kill (p_{ij}), and each threat has a destructive value (V_j). The last variable, the decision variable (x_{ij}), indicates the number of weapon types i that have been assigned to the threat j. The formulation is given in Equation 3.1:

$$\min \sum_{j=1}^{n} V_j \prod_{i=1}^{m} (1-p_{ij})^{x_{ij}} \tag{3.1}$$

$$\text{s.t.} \quad \sum_{j=1}^{n} x_{ij} \leq w_i, \quad \text{for } i = 1, ..., m$$

Equation 3.1 calculates the probability of survival of the incoming threat, the goal is to minimize the survival value of the threat. Every threat's destructive value is multiplied by the probability of survival of the threat, depending on how many weapons have been assigned to the threat as indicated by the decision variable (x_{ij}). Furthermore, the number of weapons i allocated to the threat cannot exceed the number of available weapons indicated by w_i.

3.2.2 Li et al. (2009)

The WTA formulation defined by Li et al. (P. Li et al., 2009) is similar to the formulation of Manne (Manne, 1958). However, this formulation limits the number of weapons per weapon type to 1, the problem now becomes a binary program. The advantage of a binary program is the reduced complexity of the model, and it can be easier to solve due to the binary decision making. The trade-off is that the binary model only allows one weapon system to be assigned to the threat, which could lead to higher survivability rate of the threat. The formulation of Li et al. (P. Li et al., 2009) moves the decision variable (x_{ij}) making it a binary decision variable. Furthermore, the number of weapon types can be transformed to the total number of weapons. For instance, the original problem has $w_i = 2$ with $m = 3$ can be transformed to $w_i = 1$ with $m = 6$ (Kline et al., 2019). The transformed formulation increases the number of the decision variables of the problem, fortunately the binary program makes more efficient solution techniques possible.

$$\min \sum_{j=1}^{n} V_j \prod_{i=1}^{m} (1-p_{ij}x_{ij}) \tag{3.2}$$

3.2.3 Karasakal (2008)

The main distinction of the formulation by Karasakal (2008) is that is does not account for the destructive value for the targets. The model treats each target as having an identical destructive capacity. Each set of feasible solutions is defined as F, and the number of weapons assigned to target j is limited by s_i. Additionally, the formulation introduces an upper bound on the number of weapons i assignable to targets j, marked as u_{ij}. The formulation is given in Equation 3.3:

$$\max \prod_{j=1,..,n} \left[1 - \prod_{\{i=1,..,m|(i.j)\in F\}} (1-p_{ij})^{x_{ij}} \right] \tag{3.3}$$

$$\text{s.t.} \quad \sum_{\{i=1,..,n|(i.j)\in F\}} x_{ij} \leq w_i, \quad \text{for } i = 1, ..., m$$

$$\sum_{\{i=1,..,m|(i.j)\in F\}} x_{ij} \leq s_i, \quad \text{for } i = 1, ..., n$$

$$0 \leq x_{ij} \leq u_{ij}, \quad \forall i, j \in f \text{ and } x_{ij} \text{ is integer}$$

The problem description of Karasakal (2008) differs from the other two stated above. While the other two, especially Manne (Manne, 1958), set up the problem and how the WTA problem can be computed, Karasakal (2008) actually applies it to a task force. The model solution describes the cooperation between vessels, deciding which SAM (Surface-to-Air Missile) of which vessel will engage the threat when both vessels have the same opportunity to engage. Theoretically this is very similar to the other solutions provides by Manne (1958) and Li et al. (2009), the difference lies in the setup of the vessels and weapon systems and getting close to a dynamic WTA problem while still operating in a static environment.

3.2.4 Xin et al. (2011)

Adding a time dimension to the WTA problem alters the static model into a dynamic model. Unfortunately, dynamic WTA models often make the assumption that each weapon system has the same probability of kill (Kline et al., 2019). Fortunately, the dynamic model of Xin er al. (2011) allows for a variation of probability of kill between different weapon systems and even between the various stages of engagement. The time dimension and variation in probability of kill increases the complexity of the model and the difficulty of obtaining feasible solutions (J. Li et al., 2024). The dynamic WTA formulation is given in Equation 3.4:

$$J_t(X^t) = \sum_{k=1}^{K(t)} v_k \prod_{j=1}^{T(t)} \left[1 - q_{jk} \prod_{h=t}^{S} \prod_{i=1}^{W(t)} (1 - p_{ij}(h))^{x_{ij}(h)} \right] \tag{3.4}$$

with $t \in$ {1,2,...,S}

The constraints for the model are as follows:

- The weapons can only shoot one threats at the same time. Weapons with the ability to engage multiple threats will be viewed as separate weapon systems.
- The weapon cost per threat is set to 1, this can alter depending on the type of weapons. The cost refers to how many shots are needed to neutralize the threat, assuming the threat is hit.
- Each weapon has a limited amount of ammunition.
- Each weapon has a time interval between each shot fired.

3.2.5 Park & Choi (2023)

The WTA model proposed by Park and Choi (2023) focuses on the decision making problem of the WTA problem. The model determines which weapon system engages which threat and in what order this occurs. The order of which weapon system engages the threat is described as the firing schedule. The decision making is based on the location and velocities of the threats, the interception time interval and launch interval of the weapon systems. While the WTA formulation itself is not explicitly stated, the model operates as a DWTA. The engagement of the weapon systems continues until all engagements are terminated (2023). The main take away of this model by Park and Choi (2023) is the engagement order of the weapon systems in a layered air defense strategy. Figure 3.1 shows the layered defense system of the model. The mapping of engagement is done with a coordinate system.

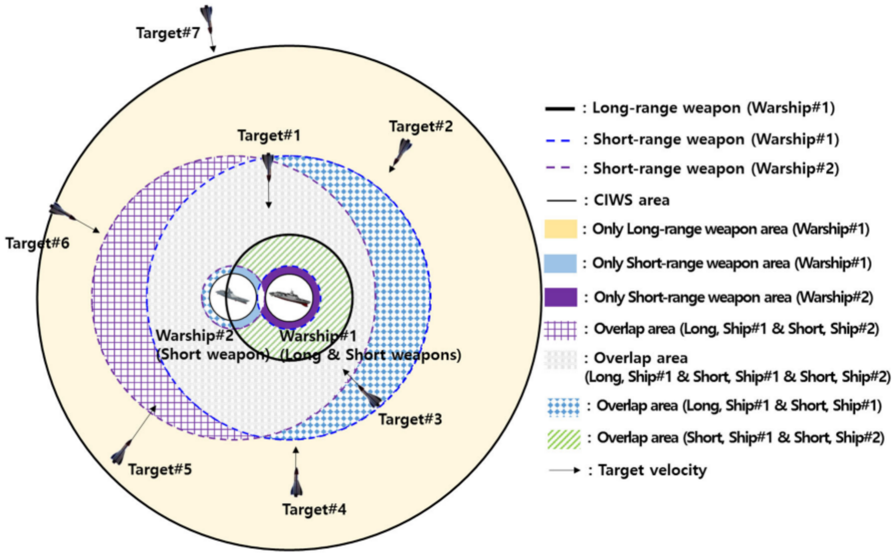


Figure 3.1: Layered air defense illustration (Park and Choi, 2023)

3.2.6 Soft Kill Systems

The aforementioned WTA problems are modeled with hard kill weapon systems only. The modeling of both soft and hard kill weapon systems in the WTA increases the complexity of the model due to the fire compatibility (Guo, 2022). The fire compatibility takes into account if soft and hard kill weapons can be used simultaneously, this adds another level of complexity to the models. The probability of kill and therefore the effectiveness of the soft kill systems are highly dependent on the distance between the weapon system and the target, the maximum range of the weapon system and the minimum system of the weapon system (Tashakori et al., 2024).

A book by Adamy (2001) provides a nice overview of soft kill specific simulation. The example in the book describes a scenario in which a chaff cloud is used to redirect the missile in order to predict the ship. The engagement calculation spreadsheet of the simulation can be seen in Figure 3.2.

	Column A	Column B	Column C	Column D
1	Initial Conditions			
2	Ship travel (azimuth)	0		
3	Ship speed (m/sec)	12		
4	Missile x value (m)	-6000		
5	Missile y value (m)	1		
6	Missile azimuth (deg)	90		
7	Missile speed (m/sec)	250		
8	Radar frequency (GHz)	6		
9	Radar PW (usec)	1		
10	Radar beam width (deg)	5		
11	Chaff cloud x value	-125		
12	Chaff cloud y value	-250		
13	Chaff cloud RCS	30000		
14	Wind direction (azimuth)	225		
15	Wind speed (m/sec)	2.83		
16	Ship RCS to missile (sm)	100000		
17				
18	Engagement calculations			Formulas
19	Time (sec)	0	1	
20	Missile x value	-6000	-5750	=B20+$B$7*SIN(B24/57.296)
21	Missile y value	1	1.001511188	=B21+$B$7*C0S(B24/57.296)
22	Ship in cell? (1=yes)	1	1	=IF(AND(C39<(C33/2),C40<(C32/2)),1,0"
23	Chaff in cell? (1=yes)	1	1	=IF(AND(C41<(C33/2),C42<(C32/2)),1,0"
24	Missile vector azimuth	90	90.59210989	=IF((C27-C20)>0,IF((C28-C21)>0,ATAN ((C27-C20)/(C28-C21))*57.296,180+ATAN ((C27-C20)/(C28-C21))*57.296),IF((C28-B21) <0,ATAN((C27-C20)/(C28-C21))*57.296+180, 360+ATAN((C27-C20)/(C28-C21))*57.296))"
25	Chaff x value	-125	-127.0010819	=$B$11+$B$15*SIN($B$14/57.296)*C19
26	Chaff y value	-250	-252.0011424	=$B$12+$B$15*COS($B$14/57.296)*C19
27	Center radar cell x value	-96.15384615	-29.30794199	=C25*($B$13*C23/($B$13*C23+C30*C22))
28	Center radar cell y value	-192.3076923	-58.15410979	=C26*($B$13*C23/($B$13*C23+C30*C22))
29	Bow-to-radar angle (deg)	90	90	=ABS(180-B24)
30	Ship RCS (to missile)	100000	100000	=IF(B29<88,10000,IF(B29<92,100000, 10000))"
31	Missile-to-ship distance	6000	5750.000087	=SQRT(C20^2+C21^2)
32	Radar cell width	523	515.3183339	=2*SIN($B$10/(2*57.296))*SQRT((B27-B20)^2 +(B28-B21)^2)
33	Radar cell depth	305	305	=$B$9*305
34	a in **Figure 11.11**		65.12185462	=SQRT(C27^2+C28^2)
35	b in **Figure 11.11**		282.1947034	=SQRT(C25^2+C26^2)-B34
36	c in **Figure 11.11**		5720.997903	=SQRT((C27-C20)^2+(C28-C21)^2)
37	d in **Figure 11.11**		5750.000087	=C31
38	e in **Figure 11.11**		5628.687873	=SQRT((C25-C20)^2+(C26-C21)^2)
39	f in **Figure 11.11**		29.2978125	=(C36^2-C34^2-C37^2)/(-2*C37)
40	g in **Figure 11.11**		58.15921365	=SQRT(C34^2-C39^2)
41	h in **Figure 11.11**		98.52509165	=(C38^2-C36^2-C35^2)/(-2*C36)
42	i in **Figure 11.11**		264.4364894	=SQRT(C35^2-C41^2)

Figure 3.2: Calculation spreadsheet of soft kill engagement (Adamy, 2001)

The engagement shown in the spreadsheet operates based on locations, velocities and Radar Cross Sections (RCS). These parameters can be seen in the Initial Conditions of Column A (lines 2-16). The RCS is the area seen by a radar (H.-J. Li and Kiang, 2005), it determines the detectability of the object. The calculation of the engagement starts by determining the distance the missile travels during the time step. The chaff moves with the wind, thus the location for the chaff is also calculated during the same time step. The aim of the chaff is to draw attention of the missile, ensuring the missile will travel in the direction of the chaff and ultimately missing the vessel.

3.2.7 Hughes Salvo Model

The HSM set of equations are used to represent key dynamics in modern naval surface combat. The model is often used to simulate the exchange of missiles between naval forces. The model incorporates the the number of units of each force, the well-aimed missiles fired by each unit, the number of hits required to put a unit of of service, the number of well-aimed missiles destroyed and finally the total number of units out of service after each salvo. The base form of the model is as follows (Jr., 1995):

$$\Delta A = \frac{\beta B - a_3 A}{a_1},\ \beta = b_2 P_{hb} \tag{3.5}$$

$$\Delta B = \frac{\alpha A - b_3 B}{b_1},\ \alpha = a_2 P_{ha} \tag{3.6}$$

A, B = Number of units in each force.

α, β = Number of well-aimed missiles fired, known as striking force.

a_1, b_1 = Number of hits needed to put one unit out of action.

a_2, b_2 = Number of shots per salvo.

a_3, b_3 = Number of well-aimed missiles destroyed by each unit, known as defensive power.

ΔA, ΔB = Number of units in a force out of action from the opponent's salvo.

P_{ha}, P_{hb} = Probability of hit.

The equation stated above considers offense and defense as either fully active or inactive, introducing certain multipliers allows the model to explore the partial effectiveness of offense and defense. This can be done through the scouting effectiveness (σ) or the defender alertness (δ). The scouting effectiveness values lie between 0 and 1, this multiplier impacts the striking power of the incoming missiles due to accuracy of the missiles and the targeting distribution. The defender alertness also lies between 0 and 1, and this multiplier affects the defense fire power due to late detection and imperfect target allocation. The model does also have a few limitations, especially when it comes to the simplified representation of the incoming threats and the defense weapon systems. The basic model uses striking and defensive powers, it does not specify which threats and weapon systems are used. The differences between the threats and weapon systems used in the engagement is a major part of the main research question. Furthermore, in the basic model described by Hughes (1995), there is no clear distinction between the vessels in the task force group.

3.3 Wargame

A wargame is "any game simulating war, or any exercise by which military strategy is examined or tested" (OED, 2025). Compared to the WTA problems, the wargames focus on the entire process including strategic locations, mapping, detection and movement of equipment and troops. The mapping, locations, movement and detection are part of the situational awareness. The situational awareness shows which targets have entered the area and follows their movement. The mapping and detection draws the main focus of the wargames for the main research and model requirements. The mapping is typically done with hexagonal shapes due to more movement and flexibility, however squares are used occasionally as well. The two variants can be seen in Figure 3.3.

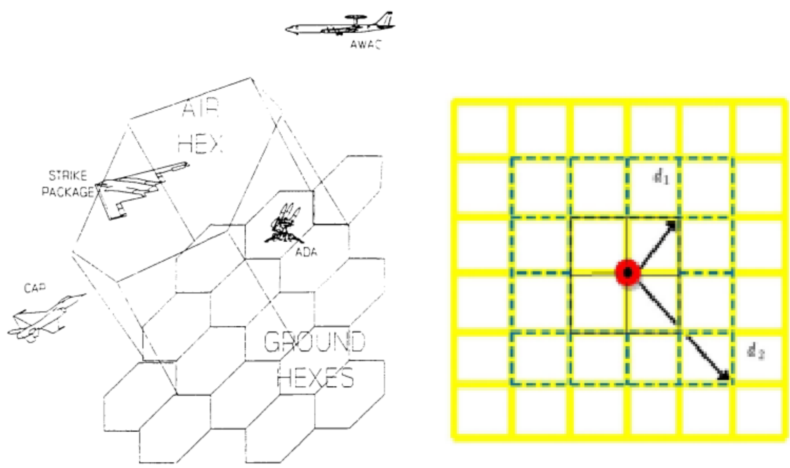


Figure 3.3: Hexagonal mapping (Mann, 1991) (Left), Square mapping (Rao and Ravishankar, 2020) (Right)

The wargame by Mann (1991), is designed for military operations on land and in the air, it consists of ground units and air units. The WTA models use surface-to-air missiles (SAM), fortunately the wargame also makes use of SAMs alongside other variations of weapons used for ground and air combat. Mann (1991) uses hexagonal shapes to map the environment, it is composed of two different types, namely the ground and air hexes, every seven ground hexes represents one air hex. Additionally, the air hexes are stacked on top of each other, allowing for multiple levels of altitude (Mann, 1991). The detection is rather simple, it depends on the predefined detection levels of the air (or ground) vehicles.

The study by Rao and Ravishankar (2020) focuses on the optimal location of radar systems. The wargame simulations makes use of threats and defense weapon systems to determine the optimal placement of radar systems. The wargame makes use of weapon systems to neutralize the threat, the chance of neutralization depends on the player's choice. Even though there is weapon-threat interactions, it is unfortunately not fully applicable to the main research question due to game theory and lack of a fully fleshed out weapon target allocation model. The positives of the study include the mapping of environment, as can be seen in Figure 3.3 (Left). Furthermore, there is a variation of layered strategies utilized. The wargame operates with long, medium and short range radar systems (Rao and Ravishankar, 2020), allowing for full radar coverage when the placement of the systems has been optimized.

3.4 Multi-Objective Optimization Algorithm

Optimization problems can be solved using various algorithms, each has its own strengths and applications. Certain algorithms are used to improve the WTA problem itself, optimizing the weapon system to threat assignment process. For example, the genetic algorithm NSGA-III has been implemented in the WTA problem to achieve more efficiency and refinement in the decision-making and command structure of the kill chain (Hu et al., 2023). Another type of algorithm, known as the Particle Swarm Optimization (PSO) has been implemented in the WTA problem to increase the convergence time and accuracy (Zhai et al., 2021). The NSGA-III is part of the Genetic Algorithm (GA) and the PSO is part of the Swarm Intelligence (SI) algorithm. Therefore, these types of algorithms are of interest for the main problem and will be analyzed. This is not an exhaustive list of algorithms. This merely describes a particular set of algorithms that have been partially applied to the problem numerous times, as described by Hu et al. (2023) and Zhai et al. (2021). Subsections 3.4.1 through 3.4.3 are versions of the GA, and subsections 3.4.4 and 3.4.5 are SI algorithms.

3.4.1 NSGA-II

The Non-dominated Sorting Genetic Algorithm (NSGA) combines the GA with a non-dominated sorting method. Each solution of the NSGA is assigned a cost value based on dominant factor of the solution in question. The NSGA operates by randomly generating a solution N, and for all the solutions the objective function values are calculated. A new set of solutions T is formed by temporarily storing the solutions, in this set the non-dominated solutions can be found. The set of non-dominated solutions is then named set B with an assigned cost value of 1. The set B is removed from T and the new non-dominated solutions can be found in reduced set T, assigned the cost value of 2 (Ma et al., 2023). This process of removing and finding the non-dominated solutions will occur until all solutions have been assigned a cost value. The recombination and mutations of the solutions can be done by using the acquired cost values for all the solutions. After the recombination and mutation process, the new generation of solutions will undergo the objective function calculations.

Where the NSGA-II method differs from the NSGA, is that NSGA-II also considers the solutions dominated by solution x and not just which solutions have dominated solution x. Additionally, a crowding distance is computed, meaning the distance between the solutions in close proximity to each other along the objective functions (Deb et al., 2002). The crowding distance is applied to alter the fitness of each solution. The NSGA-II relies on the non-dominant factor of the solutions as well as the crowding distance between the solutions, ultimately the recombination and mutations of the offspring population depend on these 2 factors. Figure 3.4 displays a basic NSGA-II flowchart. The Genetic Operator in the figure shows the process going from a population to a new population through the use of the crossover and mutation. This process is repeated until the model converges or the requirements have been met.

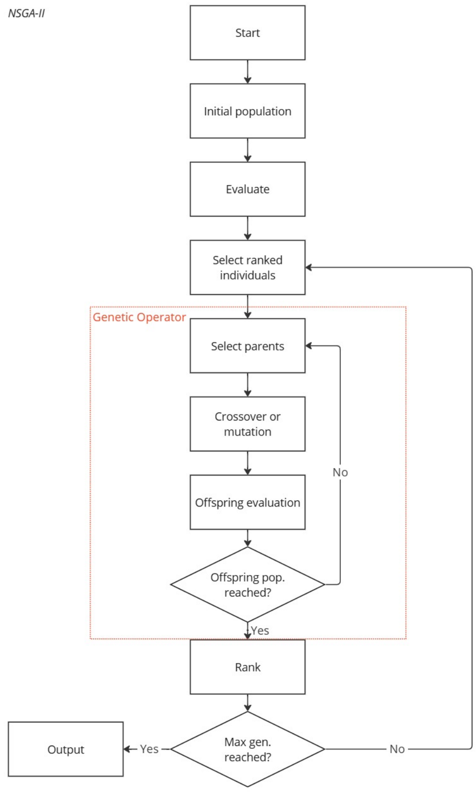


Figure 3.4: NSGA-II process (Chang et al., 2015)

The NSGA-II method will be working alongside the WTA model, aiding in determining which weapon systems are effective and cost friendly to use during the operation. The WTA model calculates effectiveness of the weapon sets used in the engagement and keeps track of how many weapons have been used. Based on the information provided by the WTA model, the NSGA-II can perform crossovers or mutations to the weapon sets of the engagement. The alterations of the weapon sets will be determined by the effectiveness and the costs of each weapon system in the total set of weapons.

3.4.2 NSGA-III

The NSGA-III is very much similar to the NSGA-II, they use recombination and mutation to create the offspring solutions. Applying the non-dominated sorting method to assign values to each solution. However, the sorting method is different for NSGA-III. While NSGA-II uses the crowding distance for non-dominated solution selection, the NSGA-III bases their non-dominating solutions on a reference point system (Deb and Jain, 2014). The reference point system works as the name suggest with a reference point. This reference point is the current non-dominating set of solutions for the temporary population. If the solutions are greater than the reference point, they will be discarded. If the solutions are smaller, the new solutions will be used in the new offspring population.

The main difference between the NSGA-II and NSGA-III comes from the utilization of multiple objective optimization. For smaller problems containing two to three objectives the outcome of the optimization will be fairly similar for both algorithms, for a problem with many objectives the NSGA-III will be more accurate. NSGA-II struggles with more objectives due to the exponentially large number of non-dominated solutions resulting in a exponentially large increase in calculating the crowding distance (Ma et al., 2023). In this case, the reference point system of NSGA-III is more beneficial in solving the problem.

The reference points are based on information given at the start, this information is often provided by experts in the field of the problem (Ma et al., 2023). Without proper knowledge of the problem requiring optimization, the NSGA-III will most likely output the wrong information if the starting point is already not correct.

The application of the model to the WTA problem, to determine the solutions based on effectiveness of kill and costs is similar to the application of NSGA-II, described in subsection 3.4.1.

3.4.3 MOEA/D

Decomposition Multi-Objective Evolutionary Algorithm, known as MOEA/D, is an algorithm used to solve multi objective problems by splitting up the problem into small sub-problems and optimizing each sub-problem simultaneously (Zhang and Li, 2007). The sub-problem optimization is performed by using the information from the neighboring sub-problems, this reduces the computational complexity for each generation during the optimization compared to other multi-objective genetic algorithms such as the NSGA-II. As mentioned earlier, the MOEA/D starts by decomposing the multi-objective problem into smaller scalar optimization sub-problems, these sub-problems will then be solved simultaneously by applying an evolutionary algorithm to it. Each sub-problem has its own individual solution, they are connected with the neighboring solutions based on the distances of their weight vectors. During the optimization process the solution uses the information of their neighboring sub-problem, this information can be used due to the close similarity of each sub-problem.

The main problem will be split up in multiple sub-problems, namely the effectiveness of kill and the costs. Each sub-problem shall be calculated and optimized, based on the neighboring solutions. The genetic algorithm ultimately provides multiple generations of solutions, each generation improved through crossover or mutation. The solutions will be represented in a Pareto front, balancing the effectiveness of kill and costs.

3.4.4 Artificial Bee Colony

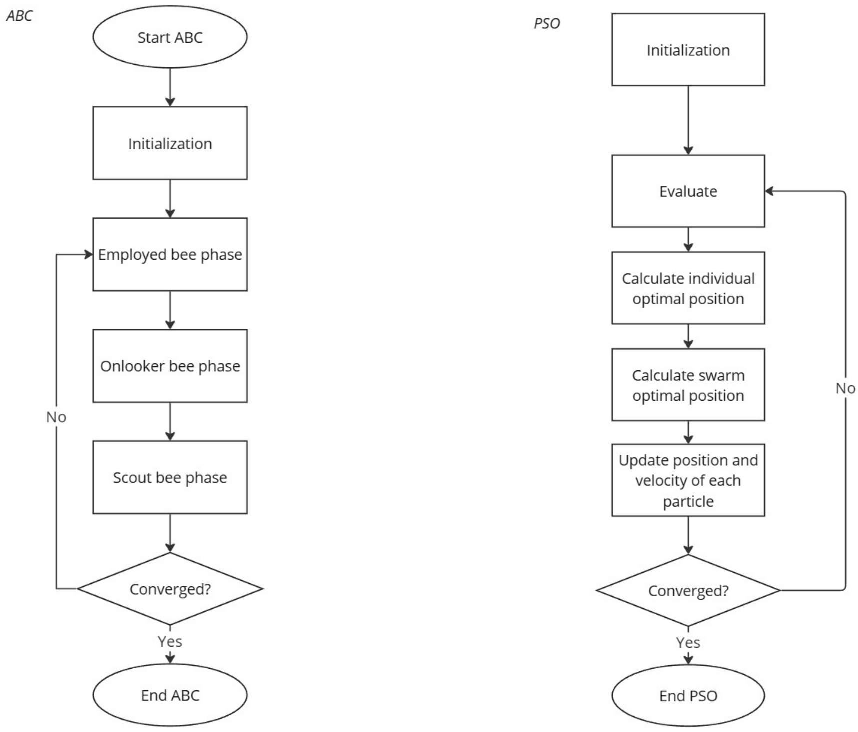
The Artificial Bee Colony (ABC) algorithm is a swarm intelligence algorithm based on the working principle and behaviour of the honey bee swarm. The artificial bee colony consists of three groups of bees: the employed bees, the onlookers and the scouts. The principle of this algorithm is based on food sources for bees and figuring out which food source is the best in the hive. The employed bees are the connection between the food source and the hive, the onlookers choose a food source based on the information given by the employed bees and the scouts are looking for new food sources. Each employed bee has a food source, therefore the amount of food sources is equal to the amount of employed bees (Karaboga and Basturk, 2007). Furthermore, once a food source is depleted, the employed bee will abandon their food source and become a scout (Gao and Liu, 2012). The process of the model can be seen in Figure 3.5a. The flowchart displays the steps the model has to follow to reach optimization.

The working principle of the ABC algorithm starts by sending the employed bees to their own food source where they determine the amount of nectar of that specific food source. Once the amount of nectar is determined, the employed bees return to the hive. The employed bees perform a dance, the purpose of the dance is to share the information with the onlookers concerning the amount of nectar of the food source. After the dance, the employed bees return to food source area that has been visited by them before and chooses a new food source in the neighboring area based on visual information (Karaboga and Basturk, 2007), provided the new food source has a higher nectar count. The onlookers determine the best food source based on the information provided by the employed bees at the hive, the higher the nectar amount the higher the probability of choosing the food source.

The food sources represent the weapon systems available in the engagement. The nectar amount of the food source determines the effectiveness of kill and costs of the weapons system. The weapon systems will be evaluated in the WTA, showing the effectiveness and the weapon system utilization costs. The information will be shared and based on the solution's performance, the weapon system can be chosen by the "onlookers". The weapon systems that are either too expensive or not effective will be replaced and new weapon system will be implemented in the process. The whole process continues until it converges and a Pareto front has been established. A Pareto front is a set of optimal solutions in the space of the objective functions (Yao et al., 2023).

3.4.5 Particle Swarm Optimization

The Particle Swarm Optimization (PSO) is an algorithm able to perform multi-objective optimization problems by creating a swarm of particles which are free to move around in a space, in search of the best place that matches the requirements defined by a fitness function. Similarly to the ABC algorithm, the PSO also bases the approach on a nature analogy, in particular a bird flock. The bird flock is represented as a swarm of particles that move around in a defined problem space. Each particle can be seen as a possible solution to the problem, these particles evaluate their own position based on the fitness function (Pereira, 2011). The evaluation of the positions will ultimately lead to the best solution.



(a) ABC (Lauer et al., 2016) (b) PSO (Wang et al., 2018)

Figure 3.5: Basic processes of SI algorithms

The PSO algorithm works in a similar fashion as the ABC algorithm. However, the PSO relies on particles updating their positions based on the velocity, the fitness function. This velocity is based on the best found solution of the particle and the global solution of the swarm (Wang et al., 2018). The information on both solutions, their own and the global best solution, is shared between the particles. The particles explore the other options, weapon systems, based on the updated velocities. The exploration is a continuous process, eventually converging to a set of Pareto optimal solutions, represented in a graph. The flowchart of the total process can be seen in Figure 3.5b.

3.5 Conclusion

The Weapon Target Allocation (WTA) problem is a major aspect of optimizing air defense distribution. The WTA determines an optimal allocation of weapon systems to protect a task force while keeping track of the budget. This problem can be defined as either static or dynamic, with models provided by (Manne, 1958), (P. Li et al., 2009), (Karasakal, 2008) and (Xin et al., 2011) offering great insight into what the problem is and how the models can be applied in determining the distribution of the weapon systems in a task force. The concept of mapping and detection of the environment can be inspired by wargame simulations.

The other component, and equally important as the WTA problem, is the optimization algorithm. The multi-objective optimization algorithms are capable of solving problems with more than one objective. Certain algorithm types, in particular the genetic algorithm and swarm intelligence algorithm, have been implemented in WTA problems to improve the convergence and accuracy of the model. The algorithms can most certainly be applied to find the optimal distribution of weapon systems while balancing multi-objectives such as the effectiveness of kill and costs. The combination of the WTA problem model and genetic or swarm based optimization algorithm would provide an effective solution for the optimization air defense distribution.

4. Final Model

This chapter aims to answers the following sub-question:

1. How can the effectiveness of the air defense distribution model be evaluated and validated?

In this chapter the models described in Chapter 3 will be evaluated based on the requirements described in Chapter 2.8. The final model will be formed based on the strengths and weaknesses of the evaluated models. Additionally, a detailed breakdown of the important parts of the model will be discussed. Starting with Section 4.3, which provides information concerning the inner workings of the chosen WTA model. To complete the total model, the implementation of the NSGA-II algorithm is discussed in Section 4.4. Section 4.5 explains the various inputs of the model and how these are constructed within the model. And lastly, the verification and structural validation are provided in Sections 4.7 & 4.8.

4.1 Model Analysis

The accuracy of the entire model depends on the basic working principles of the model and the combination of models. In this section the various models will be evaluated for their strengths and weaknesses.

4.1.1 Weapon Target Allocation

The weapon target allocation models can be divided into two types of models: the WTA problem and the HSM. The HSM is in principle a model focused on two forces fighting against each other. In the model, the defensive power of each side is a part of the total engagement. However, the model can be modified to represent one force solely defending while the other force is purely attacking. The main limitation lies in the specificity of the incoming threats and the defensive weapon systems, which is a significant drawback. The second type is the WTA problem model itself, designed to assign a weapon system to a threat based on the highest likelihood of neutralizing the incoming threat. As stated in Chapter 3, the WTA models share similar features. The similarities of the models are confirmed in Table 4.1 by checking which requirements are met.

Table 4.1: Requirement Analysis

		Weapon Target Allocation						Wargame	
Requirement		HSM	Manne	Li et al.	Karasakal	Xin et al.	Park et al.	Mann	Rao et al.
1	Group Analysis	√	±	±	√	±	√	√	√
2	Vessel Location	×	×	×	×	×	√	√	√
3	Threat Composition	±	√	√	√	√	√	√	±
4	Air Defense System	±	×	×	×	×	×	×	×
5	WTA	√	√	√	√	√	±	±	±
5A	Sensor System	±	±	±	±	±	√	√	√
6	Layered Defense	±	×	×	×	√	√	±	±

Table 4.1 provides an overview of how well the models meet the specified requirements. Green indicates that the requirement is fully met, orange indicates the requirement is partially met, and red indicates that the requirement is missing in the model.

There are a few requirements that stand out, these requirements are either partially being met or not at all. Starting with Requirement 1. Group Analysis, the basic WTA models are not specifically meant for group settings. Even though Manne (1958), Li et al. (2009) and Xin et al. (2011) can perform calculations with multiple weapon systems, the other approaches define the group setting better.

The second requirement, Vessel Location, is not incorporated in most of the WTA problem models. The model by Park and Choi (2023) works with a coordinate system. Another approach of modeling vessel locations takes the inspiration from the wargame simulation, operating in a map designed with hexagonal areas or square areas.

Requirement 3 is for the most part fulfilled by each model. The requirement requires a selection of aerial threats to be defined for engagement. The basic model of HSM does not differentiate between the aerial threats. However, HSM can be altered to allow a distinction between the various threats.

For Requirement 4, the primary objective of the model is to assign a weapon system to an incoming threat, typically a hard kill weapon system such as a missile. The HSM usually operates with hard kill systems like the WTA models. However, unlike the WTA models, the HSM can be modified to integrate both hard and soft kill systems. The WTA models calculate the assignment using either hard kill or soft kill, rarely does the model implement both. Therefore, implementation of hard and soft kill weapon systems in the model will require additional steps.

All the WTA models meet Requirement 5, concerning WTA, for the most part. Each model has a limitation, whether it is a simplified analysis or focusing on different aspects. The wargaming WTA is reliant on the input of the players in the game. Therefore, it cannot fully be applied to the simulation models.

The Sensor Systems, Sub-Requirement 5A, is fully met by Park and Choi (2023) and the wargaming models. All three models operate with areas of engagement. The location and direction of the threat are determined and engaged as soon as the threat enters the area. These areas are determined by hexagonal and sqaure shapes, and by a coordinate system. The area of engagement represent the detection of the threats.

Lastly, Requirement 6, the HSM functions using salvos, which can be seen as layered defense. However, the HSM simulates multiple rounds of attacks instead of penetrating layers of defense. On the other hand, the static WTA models stop calculating when the best solution of the assignments have been found. Since the model works with probability of kill, some of the threats may survive the engagement. And due to the static nature of the models, there is no further engagement of the surviving threats. The dynamic WTA models by Xin et al. (2011) and Park and Choi (2023) do provide layered defense strategies. It is important to keep in mind that the time dimension, which changes the static to the dynamic, increases the complexity of the model significantly.

4.1.2 Algorithm

Requirements 7 (System Allocation), 8 (Costs) and 9 (Optimizing System Allocation) can be all be accounted for by each listed algorithm of Chapter 3. However, the genetic algorithm lines up more due to the combination of weapon sets compared to finding the best weapon. Starting with random sets of weapon systems per vessel, each iteration of running the model will improve the selection of the weapon systems when using the genetic algorithm. The swarm intelligence algorithms work well in improving the assignment of the weapon systems to the target.

The effectiveness and accuracy of the genetic algorithms are dependent on the number of objectives of the problem. The main problem has two objectives, namely the effectiveness and costs. NSGA-III can be ruled out since it performs better with a higher objective count. Additionally, the NSGA-III has added risk of wrong output based on the input due to the extra knowledge required to set up the input. Since the number of objectives is low, the choice between the NSGA-II and MOEA/D comes down to the diversity of the algorithm. The crowding distance of the NSGA-II ensures a well-distributed set of solutions across the Pareto front. A well-distributed Pareto front of the problem is highly favourable to find the best distribution of weapon systems with a task force.

4.2 Final Model

The final mathematical model is composed of the WTA problem model by Karasakal (2008), and the optimization will be carried out by the NSGA-II algorithm. The model by Karasakal (2008) is a static model.

Unfortunately, a static model is not enough to carry out the full WTA optimization while still adhering to the predetermined requirements. Therefore, the model has been altered to fit the dynamic model preferences. Originally the model by Park and Choi (2023) would have been used in combination with the model by Karasakal (2008) to solve the lack of dynamic capabilities of the static model. The paper by Park and Choi (2023) discusses a dynamic model featuring a firing schedule, without mentioning a probability of kill model. Therefore, combining the model by Park and Choi (2023), the dynamic model, and the model by Karasakal (2008), the probability of kill model, results in a complete dynamic WTA model. However, it became apparent that the conversion from static to dynamic was more straightforward and less complex than combining the two WTA models. The combined model of the WTA and NSGA-II can be seen in Figure 4.1.

The model bridges the formulated gap, determining the optimal selection and distribution of weapon systems across a task force, balancing the costs and effectiveness of kill. The model is split into three sections: the Input, the Genetic Algorithm (GA) and the WTA.

The Input sets up how many and which vessels will participate, and how many weapon systems are placed on the vessel. Based on the random set of threats and the available weapon systems of the task force, the initial population of weapon systems is determined. The Situational awareness detects the incoming threats and links the information to the task force, with both locations and characteristics of the threats and weapon systems known the distance can be calculated. The distance will determine which available weapon system has the highest chance of neutralizing the threat, based on the predetermined probability of kill. Once the weapon system has been assigned to the threat, the WTA model will output how many of the threats have been neutralized. In case some threats survive the engagement, the model will determine the new location and calculate the distance to re-engage. This process continues until all the threats have been neutralized or if the threat has reached the vessels and no further engagement is possible.

The WTA is integrated in the GA, determining the distribution of the weapon systems with each new generation within the GA. The final step is to save the outcome of the WTA, improving the weapon selection by applying the GA model. All solution sets will be displayed on the Pareto front, providing an overview of the weapon sets based on the costs of the weapon systems and the effectiveness of kill.

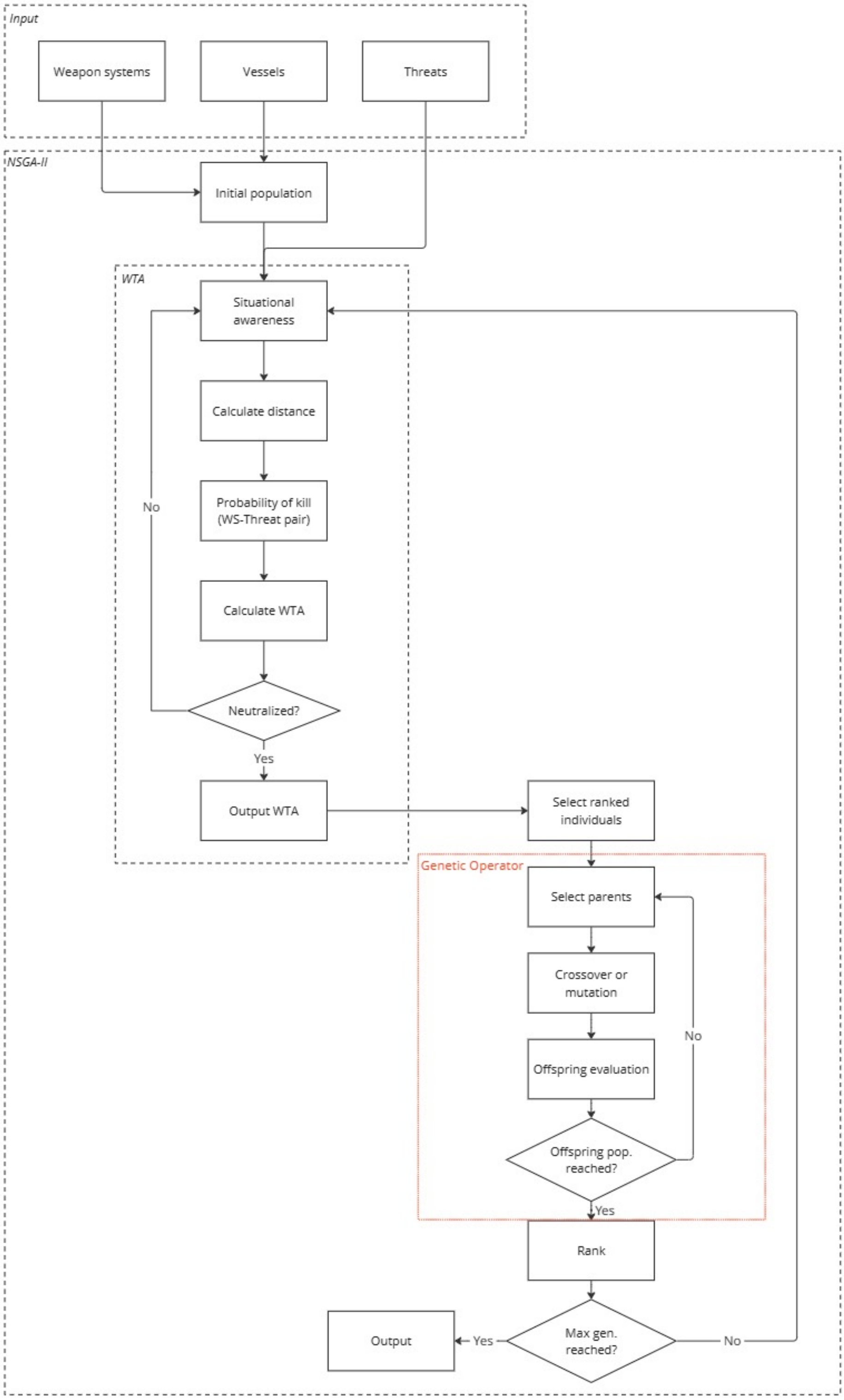


Figure 4.1: Proposed model

4.3 Inner workings - WTA

The WTA model is based on the model made by Karasakal (2008). The model has been altered to fit the requirements as has been stated in Chapter 4. This section explains how the model has been established, in order to get a better understanding of the WTA model.

4.3.1 Important Equations - WTA

The basic equation (4.1) given by Karasakal (2008) focuses on maximizing the probability of neutralizing incoming threats for each vessel within the task force "n". The model operates with three main constrains namely, the total number of shots each weapon system has available (w_i), the total number of engagements against each threat (s_i) and the upper and lower limits of the decision variables concerning the possible weapon-threat combinations ($v(i,j)$) and the total number of shots a weapon system can shoot(u_{ij}).

Equation 4.1:

$$\max \prod_{j=1,..,n} \left[1 - \prod_{\{i=1,..,m|(i.j)\in F\}} (1-p_{ij})^{x_{ij}} \right] \tag{4.1}$$

$$\text{s.t.} \quad \sum_{\{i=1,..,n|(i.j)\in F\}} x_{ij} \leq w_i, \quad \text{for } i = 1, ..., m$$

$$\sum_{\{i=1,..,m|(i.j)\in F\}} x_{ij} \leq s_i, \quad \text{for } i = 1, ..., n$$

$$0 \leq x_{ij} \leq u_{ij}, \quad \forall i, j \in v(i,j) \text{ and } x_{ij} \text{ is integer}$$

The model is described as a "nonlinear integer-programming model" (Karasakal, 2008), with an objective function "P" (Equation 4.2). The objective function compares the calculated probability of kill against a minimum desired probability of kill (h_i).

$$1 - \prod_{\{j\in M|(i,j)\in v(i,j\}} (1-p_{ij})^x_{ij} \geq h_i \quad \text{for all } i \in N \tag{4.2}$$

Karasakal (2008) uses two versions of his model to calculate the outcome of the engagement, these versions are described as P1 and P2. The P1 model uses artificial weapon systems that aid the "real" weapon systems and ensuring a feasible outcome. The formulation of model P1 is given in Equation 4.3.

$$\text{(P1)} \quad \min \sum x_{ij^*} \tag{4.3}$$

$$\text{s.t.} \quad \sum_{\{j\in M|(i.j)\in v(i,j)\}} a_{ij}x_{ij} \geq b_i, \quad \text{for all} \in N,$$

$$a_{ij} = -\ln(1-p_{ij}), \qquad b_i = -\ln(1-h_i)$$

Model P2 introduces a new variable "e", this variable represents the maximum deviation from the desired probability levels. The model P2 wants to minimize "e" and thus reducing the gaps within the defense and creating a better weapon balance within the task force. Ultimately, model P2 aims to achieve a balanced defense effectiveness within the task force and therefore model P2 has been used as the basis for the model in this thesis. The formulation of "e" of model P2 is given in Equation 4.4:

$$\text{(P2)} \quad \min e, \qquad \text{for } e \geq 0 \tag{4.4}$$

$$\text{s.t.} \quad \sum_{\{j\in M|(i.j)\in v(i,j)\}} a_{ij}x_{ij} + e \geq b_i, \quad \text{for all} \in N,$$

4.3.2 Static to Dynamic

The basic model is a static model, performing the calculation for one "round". Once the calculation is completed the threats have either been neutralized or they are still active. The desired model should represent a dynamic model, this means running the engagement multiple rounds until all the threats have been neutralized. Figure 4.2 depicts a simplified dynamic WTA model.

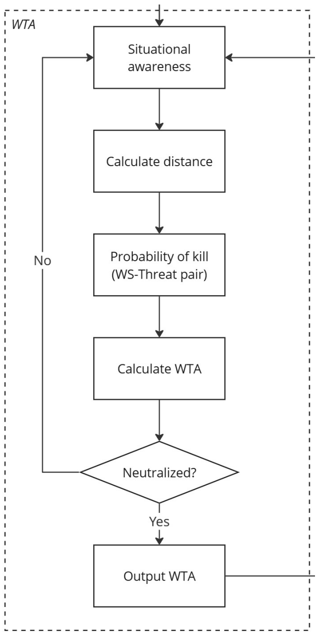


Figure 4.2: Flowchart of the WTA

The altered model starts out with mapping the locations of the task force vessels and the threats, creating a clear overview of the engagement at the beginning of the round. The locations of both are then used to calculate the distances between all the threats and all the vessels, taking into account all the possible combinations. Each weapon system and threat have their unique probability of kill, this will be explained later in this chapter. Based on the distance and their probability of kill, the best suitable combination of threat to weapon system will be picked for the engagement, this is the weapon target allocation. The probability of kill is ultimately the main decider in which target is neutralized and which is not. At the end of each round the threats are analyzed and the remaining threats will continue into the next round. The next round starts with mapping the locations of the remaining threats and vessels. The threats will have moved closer to the vessels and the distance is based on the type of threat and the speed at which they travel during the 5 second gap between the rounds. By allowing the threats to close in on the task force the dynamic model is reached, albeit a very basic version of a dynamic model.

The original static model consists of the "Probability of kill" and "Calculate WTA" blocks depicted in Figure 4.2. In order to change the static model to the desired dynamic model, additional blocks have been added to the flowchart. The altered model incorporates the situational awareness and distance tracking to create the task force encounter and by looping the WTA calculation until all the threats have been neutralized establishes the dynamic element of the model.

4.3.3 Assumptions and Limitations

The simplicity of the model leaves some gaps, in order for the model to work assumptions have to be made. The model starts by analyzing the locations and calculating the distances between each threat and vessel. The model assumes that the closest threat is of the highest importance, so these threats are prioritized even if further threats of a higher threat type are also in range of the weapon systems within the task force. A dynamic model means the model works on time, as mentioned earlier, between each round are 5 seconds allowing the threats to move in. But there is no time between firing the weapon systems and hitting the threat. Realistically there would be time and a covered distance, but this has been simplified and not been implemented. Additionally, only one weapon system per vessel can be shot during the round, otherwise all weapon systems will be fired simultaneously which can cause unrealistic results. Though, each weapon system can engage multiple threats in one round.

The dynamic model comes with one big limitation that occurs a handful of times, the limitation can be described as overshooting the target. The overshooting occurs when the target is close to the task force and the time jump in between the rounds causes the threat to be placed behind its target due to the speed it travels during the time jump, resulting in continuing the trajectory in a negative direction away from its target. This continuation of the threat can be counted as a hit on the vessel even though the model does not process this information accordingly. The overshooting problem remains in the final version of model, which does not affect the final outcome. The overshooting occurs when the weapon systems are unable to neutralize the threat, from which can be concluded that the selection and distribution of the weapon systems is under-performing.

4.4 NSGA-II

The NSGA-II model used, is created by Mostapha Kalami Heris (2015). The original code provided by Heris (2015) is a MATLAB code. In order to integrate this model into the WTA model, the algorithm needs to be converted into a Python code. The conversion from MATLAB to Python alters the code in very small ways. Therefore, in order to check if the conversion has been done correctly, a comparison between the MATLAB and Python output graph has to be made. The algorithm uses two objectives provided by the original code of Heris (2015). The objectives are unrelated to this thesis, they are purely used to check the internal mechanisms of the model and compare the results of both versions. The two graphs can be seen in Figure 4.3. The Python outcome closely matches the MATLAB outcome, thus the code is ready to implemented into the WTA model.

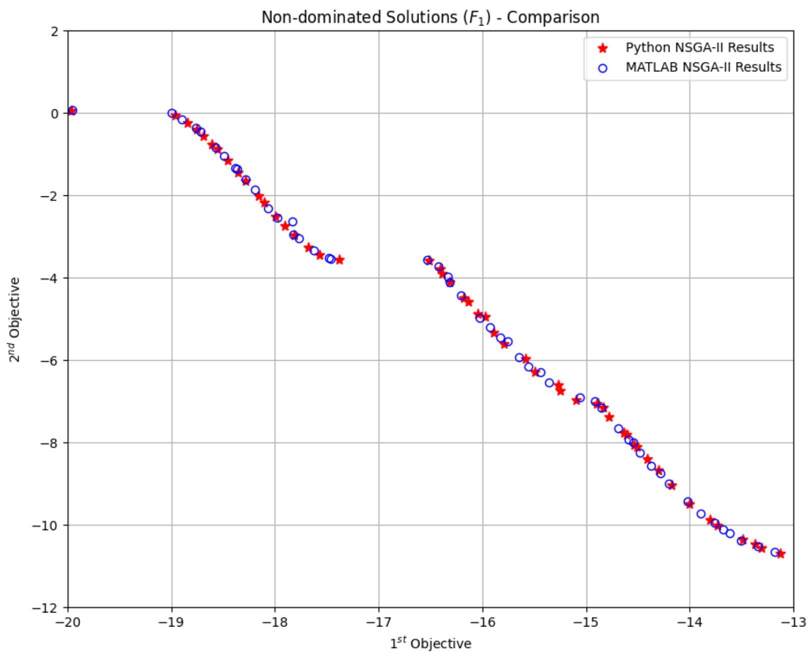


Figure 4.3: Comparison between the MATLAB and Python NSGA-II

4.4.1 NSGA-II Implementation

Combining the WTA and NSGA-II models results in the flowchart depicted in Figure 4.4. The first step of the NSGA-II model is creating the initial population, this population contains individuals. Each individual in the population is a task force group, consisting of various vessels and weapon systems. Each vessel in the initial population contains a random set of selected weapons, depending on the vessel types the amount of weapon systems will vary slightly. The total number of weapon systems in the task force is equal to the vector length, as the vector length represents the number of decision variables within the optimization problem. For example, a task force containing 3 vessels, including two air defenders and one support vessel, has a total capacity of 10 weapon systems and therefore the vector length of this task force setup is equal to 10. All of the individuals, in the initial population, are tested in the WTA model. The results of the WTA model depicts the effectiveness and costs of all the individuals, in Figure 4.4 these results are called ranked individuals.

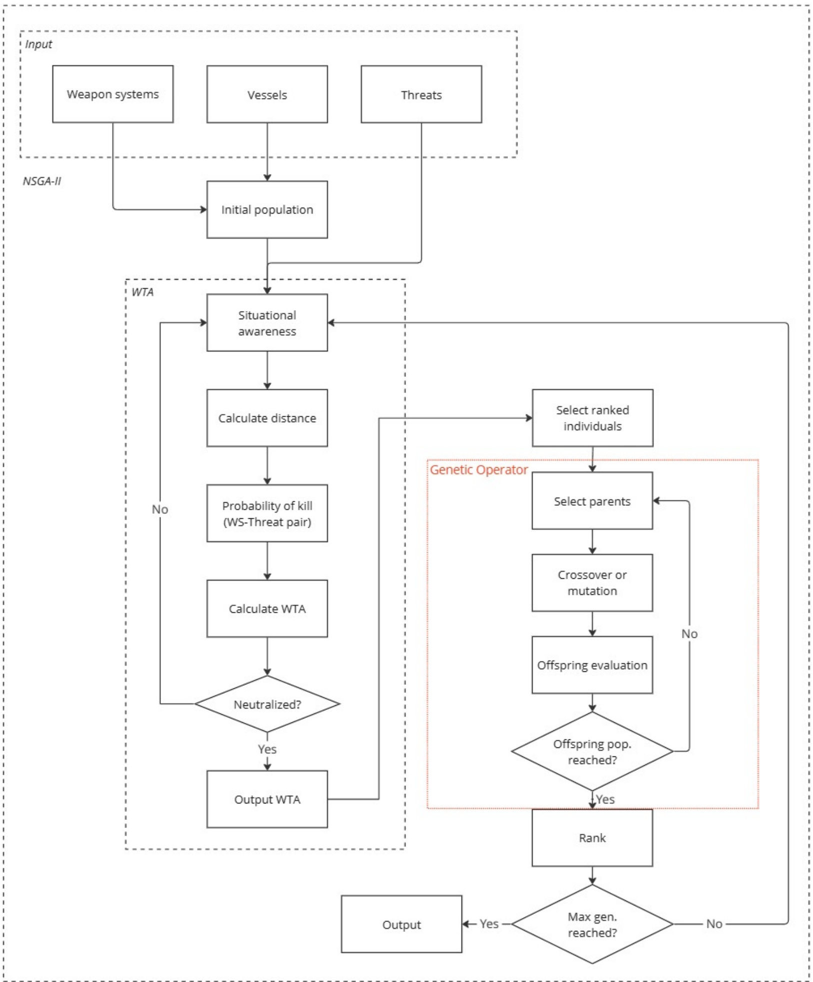


Figure 4.4: Implementation of the NSGA-II and WTA models

The ranked individuals are used to select the parents in the Genetic Operators. These parents are picked based on the effectiveness and costs, depending on which objective is prioritized for that set of offspring. The fitness function containing the two objective functions can be seen in Equation 4.5. By allowing the parent set of individuals to mutate or crossover, a new offspring individuals are created in which certain weapon systems can be preferred over other weapon systems based on their performance or expenses until the desired population size is reached. The new population has to be tested to determine their performance in the WTA model. The outcome of the WTA model with the offspring population creates a new set of ranked individuals which are put through the Genetic Operator to create a new and hopefully improved set of new offspring. This cycle of passing through populations in the WTA and Genetic Operator allows to come up with the best solutions of weapon systems divided across a task force. The cycle ends when the predetermined number of iterations has been reached. The number of iterations has been set to 2000, the justification and convergence can be seen in Section 4.4.3.

$$f(\mathsf{x}) = \begin{cases} \text{Minimize:} & \text{Total Cost } (f) \\ \text{Minimize:} & \text{Surviving Threats} \end{cases} \tag{4.5}$$

Initial testing produced, at first glance, unexpected results. The solutions of the final iterations featured similar weapon systems. However, after further analysis and understanding the mechanics of the NSGA-II algorithm, the results were consistent with the algorithm's logic. With each iteration, the best weapon systems for this scenario are picked in order to improve the overall efficiency and costs of the task force. During these tests certain weapon systems perform better on both the effectiveness, which is linked to probability of kill, and the costs, which is linked to the number of shots each weapon system uses during the total engagement. As a result of many iterations, a few weapon systems appear to make a larger difference in the engagement than others, thus these are the weapon systems passed down from the parents population to the offspring population. In conclusion, the last iteration solutions should be and are very similar due to the evolutionary aspect of the NSGA-II algorithm. However, while the selection of the weapon systems are similar, the distribution of the weapon systems across the task force will differ and creates unique solutions.

4.4.2 NSGA-II Parameters

The NSGA-II has a number of parameters that can and will influence the algorithms results based on the values given to them. It is therefore important to understand what these parameters are and how they work. The parameters are as follows:

- Maximum iterations: The number of iterations the algorithm will go through until the desired amount has been reached. The iterations can be seen as generations, each parent group will create an offspring group which is one generation.
- Population size: The number of individuals within the iteration.
- Cross-over probability: The chance the genetic information will be exchanged to the new population.
- Mutation probability: The chance a random mutation occurs in the new population.
- Mutation mu: Allows for a bias in the solution, can be both positive and negative. In this thesis, the bias would be for choosing certain weapon systems more often.
- Mutation sigma: Allows for fine-tuning of the selection process. In this thesis, the sigma indicates the jumps in picking weapon systems. A small sigma would not skip a weapon system as much as a large sigma would.

The number of iterations and individuals in the population are important parameters to create an elaborate result, but the remaining parameters are what makes or breaks the outcome of the algorithm. It is important that the cross-over happens frequently, allowing for the populations, and generations, to keep the top performers in the pool while simultaneously bringing in new weapon systems with the mutation step. The combination of the cross-over and mutation ensures a good mix of new and reappearing weapon systems in each generation.

As for the mutation itself, the decision was made to not have any bias towards weapon systems at all. The bias ends up interfering with the selection process of weapon systems within the task force while the only factors of the selection should come from the effectiveness and the costs. The mutation sigma is kept very small, to make sure each weapon system is used within the population without being skipped during the fine-tuning of the selection and distribution across the task force.

The parameters of the NSGA-II algorithm will remain constant during the calculations of the test cases in the next chapter. The values of the parameters can be found in Table 4.2, with a brief justification.

Table 4.2: NSGA-II Parameter Values

Parameter	Value	Justification
Max. Iterations	2000	Convergence around 2000 iterations
Population Size	75	Large enough for many combinations
Cross-over Prob.	0.7	Cross-over main driving force in algorithm
Mutation Prob.	0.5	Allows for many weapon system combinations
Mutation Mu	0.0	No bias towards any weapon system
Mutation Sigma	0.1	Very small tendency to skip weapon systems

4.4.3 Convergence

The maximum number of iterations influences the time the algorithm has to assess all possible combinations within the model. Therefore, a high iteration count would theoretically correlate to a more precise result. There is naturally a limitation to more iterations, this is the time it takes to complete the calculations of all iterations. Therefore, running the model for an extremely long time might not be justified by the results.

A small test has been conducted where the outcome of the calculations is matched to the iterations, at some point the result should converge and past that particular point, any further iterations is not as efficient to run. Figure 4.5 clearly illustrates the convergence. The effectiveness of the model converges very early, but the costs output is what primarily drives the higher iteration count. The average and max cost both show the convergence around the 2000 iterations. Therefore the NSGA-II algorithm will run for 2000 iterations to complete the simulation. On the test system (AMD Ryzen 7 7700, 32 GB RAM, single core execution), the 2000 iterations correspond to a runtime of roughly 6 hours total, which is approximately 11 seconds per iteration.

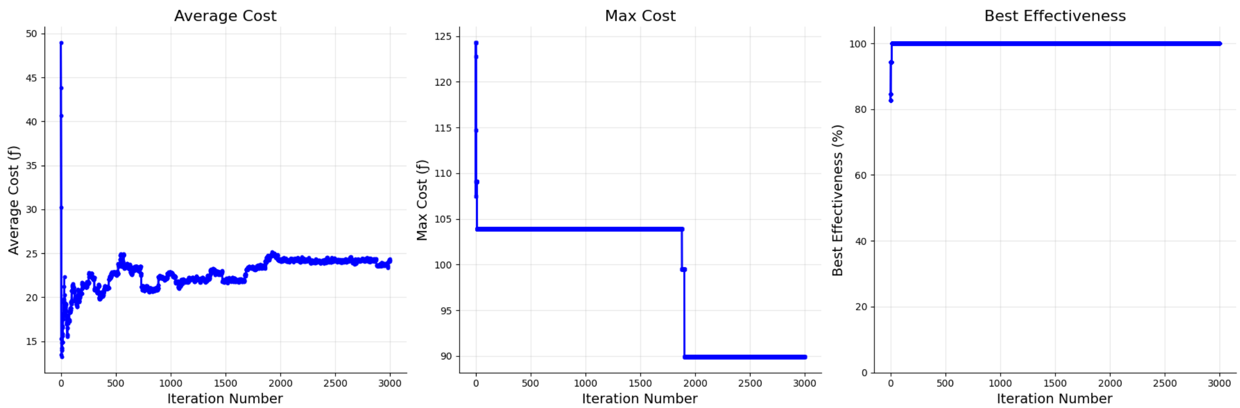


Figure 4.5: Convergence of the costs and effectiveness for 3000 iterations

4.5 Input Setup

The model has three inputs categorized as Threats, Weapon Systems and Vessels as depicted in Figure 4.6. The weapon systems and vessels are important inputs for the NSGA-II as described in the previous section. The threat input is the primary objective of the situational awareness, these threats create the environment of the scenario in the WTA model. Each of these inputs are built in a particular way, these are described in the following paragraphs.

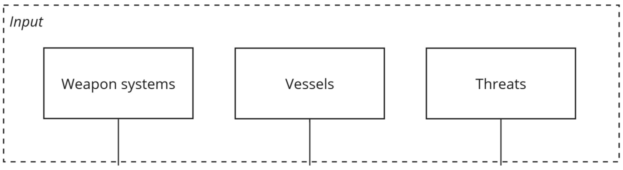


Figure 4.6: Flowchart of the model's Inputs

4.5.1 Threat Setup

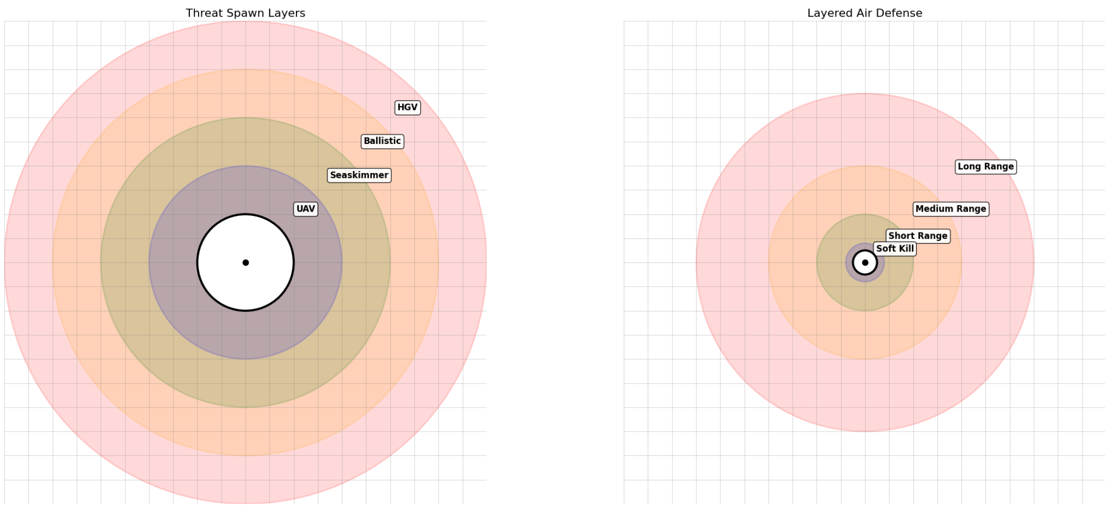
The four threats described in Chapter 2.2 are made into categories based on their descriptions. Each threat has an assigned target ID, this ID is purely for data tracking only. The environment in which the task force and threats appear in, can be seen as a circle with multiple layers. The defense layers, which will be discussed in the next paragraph, and the threat layers. The threats layers are determined based on the characteristics of the threats, these characteristics include range, altitude and velocity. There are four threat layers, one for each threat type. These threat layers act purely as their spawn location, after the start of the engagement the layers do not mean anything. With this circular layer, the threat can take a position in the north side of the circle and in the south. Depending on the number of threats in the engagement, the dispersion will be different. A schematic drawing of the spawn layers for each threat type can be seen in Figure 4.7a. Each ring represents a spawn layer where only the depicted threat can spawn. Therefore, the UAV will always spawn closest to the the task force (center of the circles) and the HGV will always spawn at the furthest distance.

Threat Input Parameters

The threat input parameters are the predefined numbers of threats per threat type for the test cases in the next chapter. These numbers of threats remain constant throughout the test cases unless the test case specifically states a change of input parameters. The parameters of the threats can be seen in Table 4.3.

Table 4.3: Threat Input Parameters

Type	Seaskimmer	Ballistic	HGV	UAV
# of Threats	14	12	8	16



(a) The threat spawn layers (b) The four defense layers of the Task Force

Figure 4.7: Schematic representation of the threat and defense layers

4.5.2 Weapon Systems Setup

The weapon systems have a comparable setup to the threats. The weapon systems are divided into four defense layers, namely the long range, the medium range, the short range and the soft kill weapons. The air defense layers can be seen in the schematic drawing in Figure 4.7b. Each layer has a small overlap with the adjacent layers. When a threat appears in this overlapping zone, the vessel has the ability to engage the threat with either weapon system's range of the region. The exception of this is the crossover between the short range and soft kill, the soft kill will only engage when the threats get too close to the vessels where engaging with short range weapon systems is no longer a safe and viable option. Each layer has a small selection of weapon systems as shown in Table 4.4, the characteristics and in particular the ranges of each weapon system have been described in Chapter 2.3 and can be found in Appendix A.

Table 4.4: Weapon systems categorized based on their defense layer

Defense Layer	Weapon Systems
Long Range	SM-6, SM-2, LRAD-ER, Aster 30, CAMM-MR
Medium Range	LRAD, ESSM, CAMM-ER, MRAD
Short Range	Aster 15, CAMM, RAM, 76mm Canon
Soft Kill	HEL, HPM

Probability of Kill

To simplify the probability of kill in the model, the probability of kill for each weapon system and threat pair will be the same for a predefined area based on distances and altitudes. The area is defined by the maximum and minimum distance and altitude of the weapon system, an example of the area can be seen in Figure 4.8.

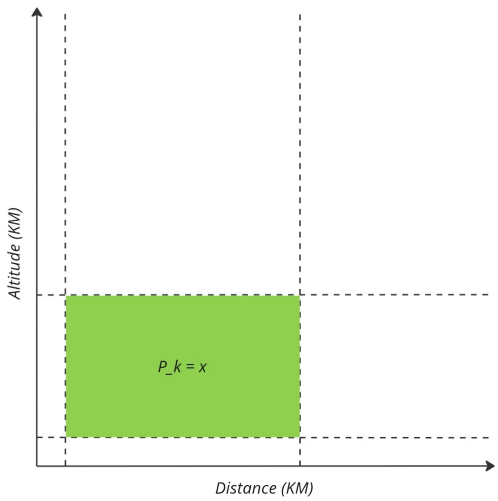


Figure 4.8: Probability of kill example graph

The values of the probability of kill are based on the abilities of the weapon system against each threat. The ability can be categorized as follows:

- Great: $0.8 \leq P_k < 1$
- Good: $0.55 \leq P_k < 0.8$
- Not Good: $0.3 \leq P_k < 0.55$
- Bad: $0.1 \leq P_k < 0.3$

Each weapon system will have a unique probability of kill for each threat. The ranges for each category are defined by myself, with the values of each weapon system's probability of kill based on literature. In this particular setting each weapon system has a chance to neutralize a threat. Therefore, there is no zero probability of kill value. An overview of each weapon system and threat linked probability of kill can be found in Appendix B.

4.5.3 Vessel Setup

The vessels are divided into two types, the "Air Defender" and the "Support" vessel. The difference between the two types is the capacity to carry weapon systems. The "Air Defender" vessel is able to carry one weapon system of each defense layer, while the "Support" vessel can only carry the short range and soft kill weapon systems. Keep in mind that this decision is purely for this thesis, the model can be altered to accommodate more or less weapon systems per vessel type.

The position of the vessels are the other half of the start parameters for the situational awareness. The center of the task force is the same center as that of the threat layers. While the position has been chosen to be located around the center of the circle, the vessels can be placed in various locations if desired. Each vessel will have their own layered air defense system, with overlapping coverage zones to enhance the overall protection through task force coordination. A schematic engagement scenario, depicting the overlapping coverage zones, can be seen in Figure 4.9.

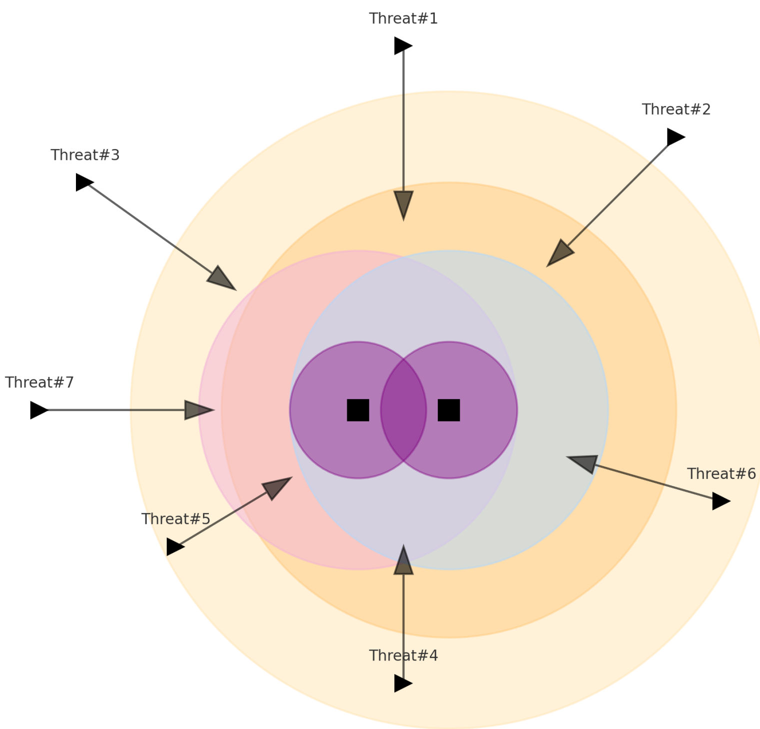


Figure 4.9: Schematic representation of an engagement

Ammunition Stockpile Input Parameters

The ammunition stockpile of the vessels are the same for each type of vessel. However, this only holds true for the weapon types the vessel has onboard. Thus, the support vessel will not carry ammunition for long and medium range weapon systems. The values of the ammunition stockpile per vessel type can be seen in Table 4.5. The soft kill ammunition is a bit special, they typically operate on stored energy. Therefore, to simplify the ammunition, the stockpile is set to two in order to balance the very high effectiveness of these weapon systems. Unless stated otherwise, these parameters are used in the test cases of the next chapter.

Table 4.5: Ammunition Stockpile Input Parameters

Type	Air Defender	Support
Long Range	12	-
Medium Range	25	-
Short Range	20	20
Soft Kill	2	2

4.6 Requirement Check

Table 4.6 summarizes the requirements formulated in Chapter 2.8, which were established to visualize the model in the early stages of the design. The table analyzes the final model presented in Figure 4.1, indicating which requirements have been met and further highlights the requirements that are lacking in this design.

Table 4.6: Requirement check of the model

Requirement	Check	Additional information
1. Group Analysis	√	The task force setting has been obtained, allowing for various group sizes and formations.
2. Vessel Location	√	The location of each vessel in the task force can be manually altered.
3. Threat Composition	√	The number of threat types and threats can be updated manually.
4. Air Defense Systems	±	The hard and soft kill weapon systems are included and can work together. However, much improvement is needed.
5. WTA	√	The WTA model works as intended, a more complex rework could benefit the analysis.
5A. Sensor System	×	There is a situational awareness aspect, but this does not involve sensor systems.
6. Layered Defense	√	The task force works with a layered air defense strategy.
7. System Allocation	√	The system allocation can be manually adjusted per vessel.
8. Costs	±	The costs only includes the ammunition used and not the installation costs of the weapon systems themselves.
9. Optimizing System Allocation	√	All outcomes of the model are stored and a Pareto front will be formed at the end of the simulation.

4.7 Verification

The verification of the model is an important step in the process of creating a reliable outcome. The goal of the verification is to check the internal consistency of the model.

4.7.1 WTA Verification

Two separate tests have been conducted to test the internal consistency of the WTA model. Each test will have an assumption about the input and output correlation. If this assumption is correct, the internal consistency of the model is verified.

Threat-Shot Correlation

The first verification test involves the threats the task force will encounter during the engagement. The task force comprises 3 vessels in total, with 2 Air Defenders and 1 Support vessel. The formation of the task force is a simple horizontal line, each vessel spaced out with a distance of 4 KM. The threats are spawned in their corresponding spawn layers.

The assumption of first verification test is: The number of shots fired by the task force will go up when the number of threats are increased. The task force has a combined total available shot count of 152. The initial threat count equals 12, each threat type has 3 active threats in the first scenario. The second engagement the threat count rises to 24, each threat type now has 6 active threats. The last engagement has 36 active threats, 9 threats of each threat type. The results of the test can be found in Table 4.7.

Table 4.7: Verification Test 1: Threat-Shot Correlation

Test	# of Threats	# of Shots	Assumption?
3 of each threat	12	18	-
6 of each threat	24	48	√
9 of each threat	36	72	√

Table 4.7 shows the response of the task force to the increase in threats. The number of shots increases with the increase in threats as assumed. The last column of the table confirms whether the assumption has been met or not, the first row of the table is left blank due to it being the first step in the verification process.

Task Force Size

The second verification test focuses on the size of the task force. The assumption for this test is as follows: The effectiveness of the task force will increase as the task force grows in size. The effectiveness is defined as neutralizing the incoming threats.

The test consists of increasing the task force with vessels. The first scenario involves a single Air Defender vessel, the second scenario consists of one Air Defender (AD) and one Support (S) vessel, from there each scenario adds another vessel to the task force until the total of vessels equals 5. The number of threats is kept constant in all scenarios at 30 total. The results of the effectiveness of the task force is shown in Table 4.8.

Table 4.8: Verification Test 2: Task Force Size

Test	# of Vessels	TF Setup	Effectiveness (%)	Assumption?
Scenario 1	1	1 AD	73.3	-
Scenario 2	2	1 AD, 1 S	93.3	√
Scenario 3	3	2 AD, 1 S	100	√
Scenario 4	4	3 AD, 1 S	100	√
Scenario 5	5	3 AD, 2 S	100	√

The test concludes that the effectiveness of the task force indeed increases when the number of vessels in the task force is increased. The last column of the table confirms whether the assumption has been met or not, the first row of the table is left blank due to it being the first step in the verification process. It is interesting to note that scenario 4 and 5, have the exact same result as scenario 3. During the test it became evident that only 3 vessels are actively defending the task force during the engagement, thus increasing the number of vessels past 3 vessels, including Air Defenders, renders the additional vessels as passive and do not interact with any threat.

4.7.2 NSGA-II Verification

The verification of the NSGA-II model has been conducted in Section 4.4. In particular, Figure 4.3 demonstrates the verification. The original code for the NSGA-II algorithm comes from a reputable source, created by Heris (2015). The verification of the converted python code is therefore verified by comparing the outputs of both versions.

4.8 Structural Validation

The total implemented model only means something when the model can be properly used to solve the intended problem. However, the nature of this type of model, a design based model, can be difficult to validate. The reason for this difficulty is that the usefulness of the model relies on subjective statements as well as mathematical modeling (Pedersen et al., 2000). The definition of usefulness of a design based model as per Pedersen et al. (2000) is that the model should provide solutions correctly, in other words how effective is the model, and the model provides correct solutions, which comes down to how efficient the model is. The effectiveness and efficiency of the model are validated in two different validations, these are the Structural Validation, for effectiveness, and the Performance Validation, for the efficiency. Each validation consists of three steps. The total validation is a construction designed by Pedersen et al. (Pedersen et al., 2000), named the Validation Square. The Structural Validation will be discussed in this current Section. The Performance Validation will be discussed after the model has provided the results, due to the validation requires the evaluation of the model's solutions.

The Structural Validation is as follows:

- *Accepting the construct's validity:* The first step of the Structural Validation is building confidence in the validity of individual parts of the the model. The model consists of two major components, the WTA model and the NSGA-II model. The WTA model is based on the functions derived by Karasakal (2008), the purpose of the model is to determine the weapon allocation in a task force setting. While the model of Karasakal (2008) has been altered, the foundation is very much inspired by Karasakal's (2008) work. The NSGA-II model is made by Mostapha Kalami Heris (2015), the code was uploaded to a reputable site called Yarpiz. Yarpiz provides many source codes and tutorials on a professional and academic level. The combination of the models and the reputation both of the sources have, increases the confidence of the total model and the solutions the model will ultimately provide.
- *Accepting method consistency:* The second step is building confidence in the assembly of the individual parts to create the model. This is done through a flowchart. The flowchart of the entire model has been shown multiple times in the previous chapter, as well as the current chapter. The flowchart is shown in Figure 4.1 and in Figure 4.4. The explanation of the flowchart has been explained in this chapter, Chapter 4.
- *Accepting the example problems:* The third and final step of the Structural Validation is building confidence in suitability of the chosen example problems for the model performance validation. These examples are called test cases in this research thesis. The test cases will be explained in the next chapter. The test cases will resemble problems for which the model is intended. Focusing on the distribution and selection of the weapon systems within the task force. The problems range from task force sizes to ammunition stockpiles onboard, each problem will aid in understanding where and which weapon system is needed to create a multi-layer air defense system within a task force.

4.9 Conclusion

The final model consists of various existing models found through doing extensive literature research. The existing papers and methods were thoroughly analyzed and compared to the predefined requirements. The analysis concluded that the model should consists of the WTA problem model by Karasakal (2008) and the NSGA-II algorithm, with the basic model provided by Heris (2015).

In order for the components of the model to work together effectively, certain assumptions had to be made, in particular for the WTA model. The model by Karasakal (2008) provided a great foundation to build from. The biggest change involved altering the static model to a dynamic model, achieving the desired functionality of the WTA model. Additionally, the NSGA-II model had been converted to work properly with the WTA model. The final model required some small test to identify the basic inputs including the threats, weapon systems, vessels and NSGA-II parameters.

Lastly, the verification and validation of the model were required to determine if the model is quantitatively and qualitatively correct. The verification process consisted of predicting outputs of the model by looking at the inputs. In other words, the outputs provided by the model should correspond to the given inputs and any changes to the input should result in a certain output. The verification of the model fortunately worked as intended, and the outputs of the model were correctly predicted. The validation of the model consists of two parts, the structural and performance validation. This chapter focuses on the structural validation, including checking the validity of the papers and methods used to design the final model of this thesis, checking the flowchart and how each component of the model interacts with each other and finally looking into test cases which are problem sets which are intended for the model specifically. The combination of the verification and the validation, the model can be evaluated and validated accordingly.

5. Test Cases

This chapter aims to answer the following sub-questions:

2. How will the distribution of air defense systems affect the task force's overall coverage?
3. How will the cost of equipment impact the operational efficiency?

The chapter covers four test cases in Section 5.1 through 5.4, followed by a summary of these test case results. The last part of the validation process, known as the performance validation, will be completed in Section 5.6.

The test cases have been designed to perform a sensitivity study of the model's parameters and scenarios. Each test case focuses on a specific aspect of the model to evaluate the various inputs of the models and how these inputs affect the results. Detailed points of interest are included within each test case. A brief overview of the test cases can be seen in Table 5.1.

Table 5.1: Test Case Overview

Test Case	Description
Probability of Kill	Aims to identify the influence of the probability of kill.
Current Weapon System Setup	Aims to connect the model with currently active weapon systems.
Task Force Sizes	Aims to identify the impact of the size and composition of the task force.
Ammunition Stockpile	Aims to identify the influence of various ammunition stockpiles.

5.1 Test Case 1: Probability of Kill

The probability of kill of the weapon systems is a major component of the effectiveness for neutralizing incoming threats. The purpose of this test case is to identify what the impact of the probability of kill is, but also to investigate how the distribution and selection of weapon systems is influenced if the weapon systems perform better or worse than expected.

The standard version of the probability of kill (P_k) has been established in Chapter 4.5.2, the overview of the standard P_k can be seen in Appendix B . The first simulation has been calculated with the standard values of P_k, this set the baseline of this test case. In order to determine if and how the P_k influences the outcome, additional simulations have been calculated. There are four other simulations beside the baseline simulation. Two of the additional simulations examines the influence of P_k by increasing the standard values with 25% and 50%, the other two simulations look into the differences of the outcome when the P_k values are decreased by 25% and 50%.

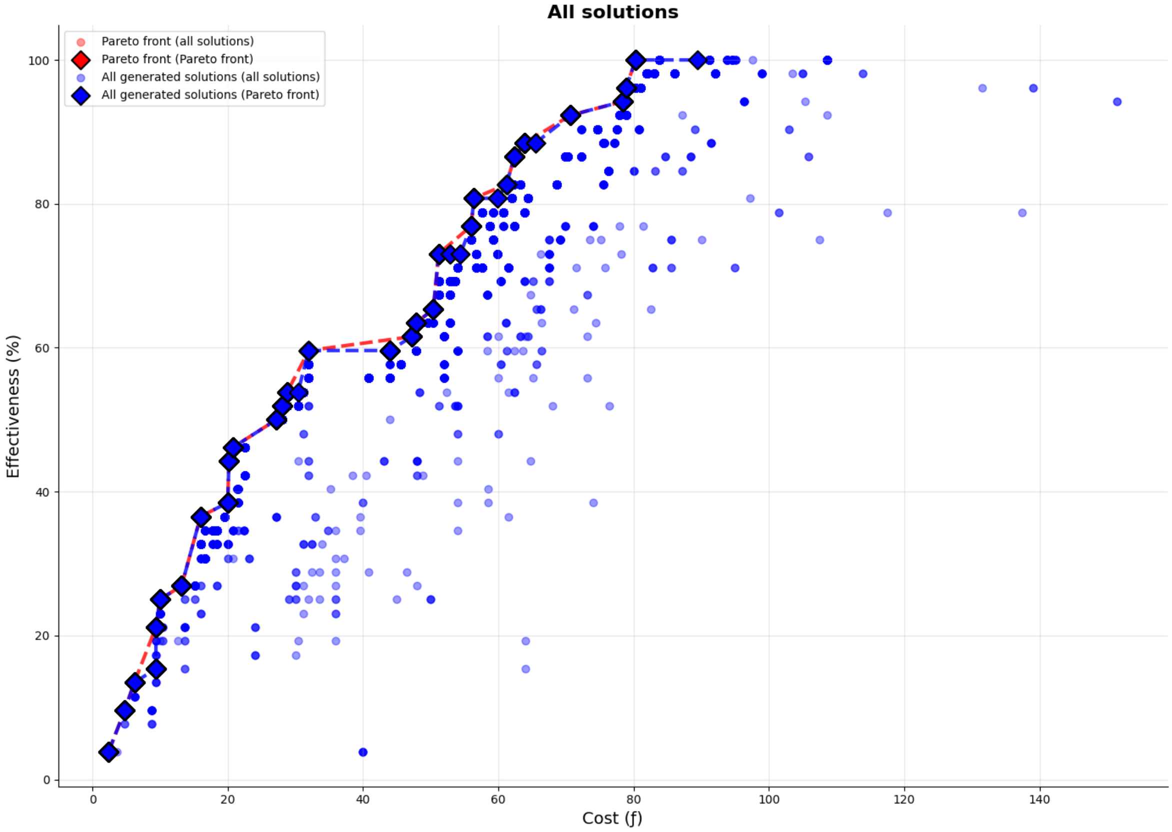


Figure 5.1: All iterations of one simulation

With each iteration only the top performing weapon systems continue into the next iteration based on the objective functions, defined by costs and effectiveness of the weapon systems. This claim is justified by Figure 5.1, in this figure all the solution points of one simulation are plotted together in one Pareto front. It clearly illustrates that the Pareto front shows the best solutions based on the two objective functions. The other points of the previous iterations aided in getting towards this Pareto front by allowing the NSGA-II algorithm to continue analyzing the weapon systems used during the engagements. Once all iterations have been completed, the algorithm presents the best findings in a Pareto front. However, showing all iterations of all the simulations would result in an unclear graph. Therefore, all Pareto front graphs forward will only show the last iteration Pareto front solutions to keep the overview clear.

The outcome of all simulations concerning the influence of the probability of kill can be seen in Figure 5.2, in the form of a Pareto front plot. The plot only depicts the results of the last iteration. This iteration represents the best outcome of the entire simulation due to the nature of the NSGA-II algorithm.

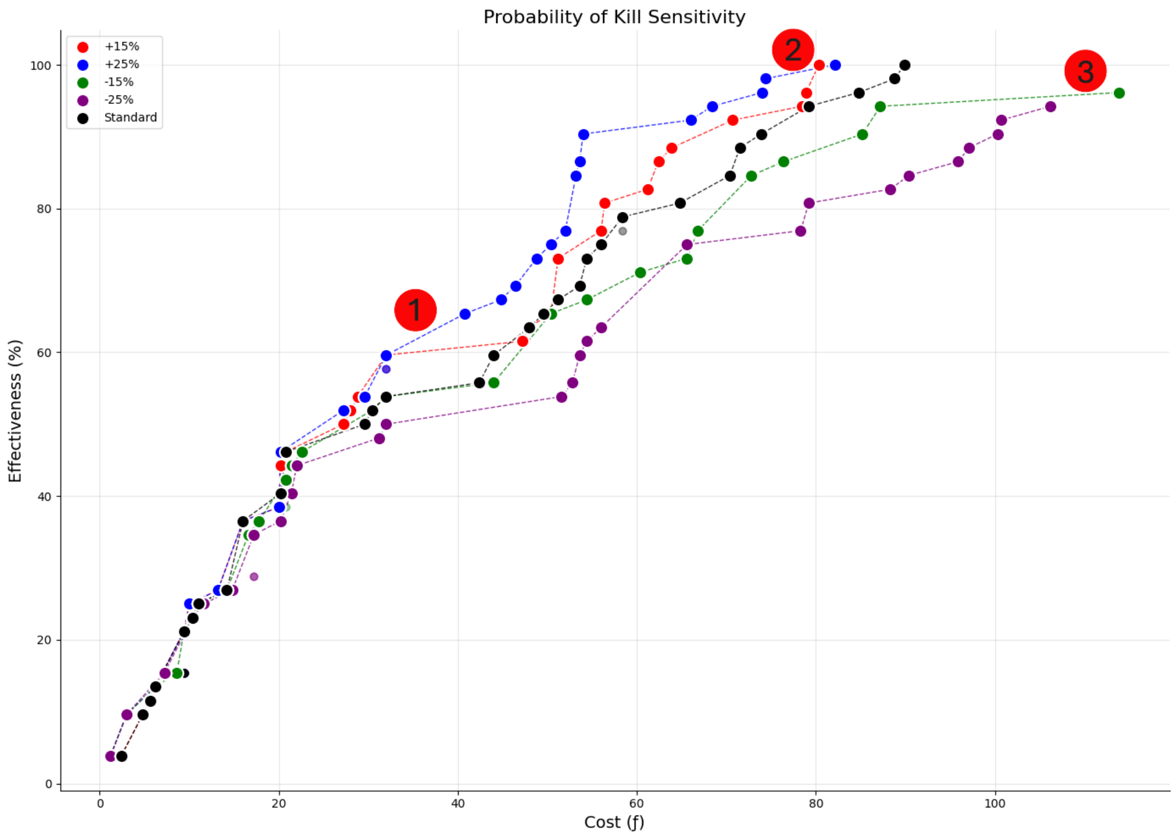


Figure 5.2: Probability of kill sensitivity - five P_k value sets

In Figure 5.2 three points of interest are marked, namely:

1. *Jump in costs around 50-60% effectiveness:* The lower left corner of the figure shows all lines very close together, rapidly increasing the effectiveness of the weapon systems in the task force while keeping the costs relatively low. However, reaching the 50-60% effectiveness mark increases the costs across all simulations. The reason for this is the addition of a new active weapon system within the task force. While each vessel in the task force carries multiple weapon systems, not all are active in the engagement. Only a select few in the simulation are "active". Before the 50% effectiveness, each solution only uses the short range weapon systems in order to minimize the costs. This is the reason why all simulations are close to each other in the lower left corner, the task force only operates on the short range weapon systems of the air defender vessels. Thus when a new active weapon system is added to the engagement, the costs increase significantly compared to the effectiveness. The effectiveness will eventually increase again when the weapon target allocation gets improved. Ultimately, the top performing solutions have more active weapon systems, therefore also increasing the costs.

2. *The increased probability of kill differences:* The increased probability of kill acts as expected, it is more cost efficient than the standard probability of kill simulation. However, it is interesting to note that the 100% effectiveness of +15% increase is more cost efficient than the 100% effectiveness of the +25% increase. The reason for this is a difference of one weapon system within the task force, this particular weapon system is the short range RAM. In other simulations, with a lower probability of kill, the RAM is not selected as much due to a lower performance in the engagement. Now that the probability of kill is increased by 25%, the RAM is more useful compared to the other simulations. Unfortunately, the RAM is still lacking in terms of P_k, causing the increase in engagement of other weapon systems within the task force and thus increasing the costs. This is confirmed by the solution at 98% effectiveness, in which the RAM is not used in the task force at all.

3. *The decreased probability of kill differences:* Similarly to the increased probability of kill, the decreased simulations perform as expected. The -25% probability of kill, is more expensive than the standard and -15% simulations. However, the top performing solution of the -15% probability of kill is more costly than the -25%. The reason for the sudden spike in costs, for the -15% probability of kill between the last solution and the second to last solution, is the use of a soft kill weapon system. The soft kill weapon systems are much more expensive to use than the other weapon systems within the task force. The last and top performing solution managed to neutralize an additional threat, but at a higher cost that ultimately puts the top performing solution at a higher cost than the -25% probability of kill top performing solution.

The evaluation of the results indicate that, throughout all the iterations, a selection of weapon systems is preferred and therefore continuously gets used in the top performing solutions. The probability of kill plays a major factor in this selection, especially for the maximization of the effectiveness of the weapon systems in the task force. In Table 5.2 the active weapon classes of the top performers are shown.

Table 5.2: Active weapon classes of top performers - divided over 13 vessels total

Weapon Class	Air Defender	Support
Long	-	-
Medium	10	-
Short	10	2
Soft kill	-	1

In the final iteration, the long range weapons have not been used at all. There are potentially two reasons for this. The first reason for the absence of long range weapon systems in the engagement has to do with the threat distances. The model focuses on neutralizing the threats with the highest priority, and while certain threats have a higher priority than others, the distance of the threat will outweigh this priority when its close to the task force. As stated in Chapter 4, the threats spawn in certain layers. Meaning that some threats will be closer to the task force and are engaged with first. Therefore, the task force will operate with the medium and short range weapon systems to eliminate the threats in close proximity. To confirm this hypothesis, a small simulation has been performed with the threat spawn locations pushed back into the long range area. The results of this simulation confirm the use of long range weapon systems, but not as much as one would expect. While long range weapon systems have been used, the usage of medium and short range weapon systems is still in the majority. The usage of the top performer's weapon systems can be seen in Table 5.3. Additionally, the costs of reaching the highest effectiveness has increased due to the usage of the long range weapon systems.

Table 5.3: Top performers ammunition usage

Weapon Class	Ammunition (%)
Long	15.2
Medium	63.3
Short	21.5
Soft kill	0

This leads into the second reason for the absence of long range weapon systems, the costs minimization. The NSGA-II algorithm works with two objectives, the effectiveness and the costs. The results of this test case and the small simulation investigating the absence of long range weapon systems show that the costs will be higher due to using long range weapon systems. In this model, the long range weapon systems are more expensive to use than the medium and short range. Clearly, the advantage of neutralizing the threats at larger distance does not outweigh the costs of using long range weapon systems, especially when the combination of medium and short range weapon systems result in the same effectiveness but at a reduced cost.

5.2 Test Case 2: Current Weapon System Setup

This test case differs from the other test cases in this chapter. This test case only involves the WTA model and calculates the outcome of an engagement of a task force with weapon systems the current vessels have equipped. The current RNLN vessels have a variety of weapon systems but in this thesis only a select few have been modeled. These weapon systems are the **SM-2**, **ESSM** and the **76mm cannon**. The task force can be composed of an air defender, an M-frigate and a support vessel. The ammunition stockpile of these vessels can be seen in Table 5.4, these values are determined by myself for this test case.

Table 5.4: Ammunition Stockpile

Range	Air Defender (AD)	M-Frigate (M)	Support (S)
Long	12	-	-
Medium	25	25	-
Short	20	20	40

The threat setup alters from the setup provided in Chapter 4.5, the new threat setup for this test case can be seen in Table 5.5.

Table 5.5: Threat Input Parameters Test Case 2

Type	Seaskimmer	Ballistic	HGV	UAV
# of Threats	5	5	3	5

The test case is divided into multiple simulations, each simulation is a different task force size or configuration with the vessels mentioned in Table 5.4. The calculation of the WTA model only needs to be performed once per simulation, due to the fact the WTA model should and does present the same output. The results of all the simulations can be seen in Table 5.6.

Table 5.6: Results of the WTA model

Task Force Setup	Effectiveness (%)	Costs (ƒ)
1 AD	83.3	37.5
1 AD, 1 S	83.3	37.5
1 AD, 1 M	94.4	49.5
2 AD, 1 S	94.4	49.5
3 AD, 1 S	94.4	49.5

The results shown in Table 5.6 are very similar for multiple task force setups. The main reason is the singular use of the ESSM weapon system in the engagement, for each simulation done. The long and short range weapon systems have not been used in the engagement. As explained in Section 5.2, the model focuses on the threats in close proximity of the task force and neutralize them accordingly. This results in a very one sided engagement of weapon systems. Additionally, the model prefers to use the ESSM over the SM-2 based on their performance against the threats. Furthermore, adding more vessels with good defense capabilities appears to have a smaller effect than anticipated, the effectiveness remains the same for task forces the size of 2, 3 and 4 vessels.

5.3 Test Case 3: Task Force Sizes

The sizes, and the compositions, of the task force have an influence on the total defense capabilities. The purpose of this test case is to identify how the defensive effectiveness of the task force alters by changing not just the size of the task force, but also by changing the composition of the task force.

The task force can consist of an air defender or a support vessel. The total task force size is limited to four vessels, due to models limitation and overloading the assignment possibilities of the WTA model. The ammunition stockpile of the vessels and the threat counts remain the same as described in Chapter 4. Furthermore, while the composition of the task force changes throughout the simulations, the task force maintains a horizontal formation for simplicity. The outcome of the simulations concerning the the changes in task force sizes and compositions can be seen in Figure 5.3.

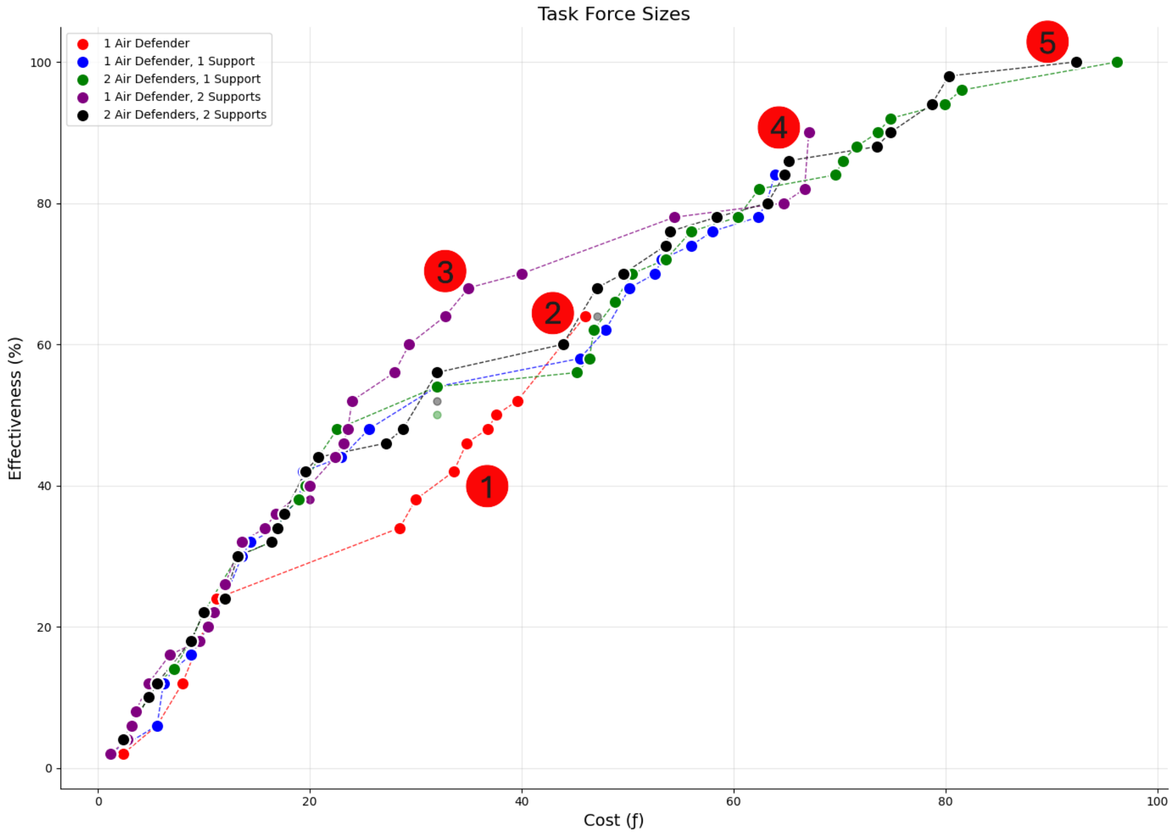


Figure 5.3: Task force size influence - five task force sets

There a five points of interest identified in Figure 5.3, namely:

1. *Under-performing Pareto front:* The **red** Pareto front, consisting of a solo air defender, performed worse than any other configuration. The sole reason for this under-performance is the fact the air defender is alone with too many threats to effectively neutralize. The analysis shows the air defender used two weapon systems, trying to maximize the defensive capabilities. However, the air defender can only use one of these weapon systems at a time. Comparing this to the **blue** Pareto front at the same effectiveness range, the air defender and the support vessel can operate together and neutralize threats more efficiently. While the solo air defender had to use two weapon systems, the air defender and support combo used two short range weapon systems to increase the probability of neutralizing the threats, resulting in the same overall effectiveness but at a lower cost than the solo air defender.

2. *Top result of the Red Pareto front:* The maximum performance of the solo air defender is achieved by shooting all of the ammunition it carried, for both the medium and short range weapon systems. In comparison to the **blue**, **green** and **black** solutions around the 64% effectiveness, the **red** solution performed quite efficiently. These three other solutions all utilized multiple vessels to achieve a similar effectiveness and cost result. And while they are not the most desired solutions, the task force sets used less than half of the available ammunition to achieve the same outcome of a singular vessel using all the ammunition it can carry. Thus, it demonstrates the importance of coordinated group operations to establish a structured defense system.

3. *Best midfield performance:* The Pareto front concerning the task force consisting of one air defender and two support vessels performs better than any other configuration between the 60 and 70% effectiveness. The achieved effectiveness is not any different, but the costs linked to the effectiveness divides this task force from the others. Each solution between the 60 and 70% effectiveness makes use of all the vessels in the task force and only using one defense layer, namely the short range weapon systems. The weapon systems in question are the CAMM and the RAM. The distribution of these weapon systems consists of purely CAMM or a combination of CAMM and RAM in a 2:1 ratio. The difference in costs is linked to the usage of short range weapon systems only, this is evident when comparing the other simulations which use medium range weapon systems and thus increasing the costs.

4. *Top result of the Purple Pareto front:* The task force configuration of one air defender and two support vessels tops out at a 90% effectiveness against 50 threats of various types. There are two other configurations that match a 90% effectiveness, albeit at a higher cost. These two configurations both consist of two air defenders and one or two support vessels. In both instances, the support vessels are not used to achieve the 90% mark, they purely rely on the defensive capabilities of the air defenders. This leads to an increase in costs since they will and are using more medium range weapon systems. That does raise the question of why are they not using the same weapon systems as provided by the **purple** task force setup? That would be the distance of neutralizing the threats. Even though the one air defender and two support vessels has the same effectiveness and a lower total cost, the safety and risk is different compared to the other two task force configurations. The usage of the medium range weapon systems adds a layer of protection by neutralizing the threats at a greater distance, so while these task forces can create the same setup as provided by the **purple** task force, the decreased level of risk seems to be preferred and increases the total costs.

5. *Full effectiveness:* In order to understand the solutions belonging to 100% effectiveness, the solutions prior to these are important to analyze. For both instances, the 96 to 98% effectiveness operates with air defenders only, to get to 100% effectiveness both task forces make use of one support vessel. For the **green** task force, the weapon setup belonging to the 96% effectiveness comprises medium and short range weapon systems, which include the ESSM, CAMM-ER, CAMM and RAM. However, by adding a support vessel the total costs should not be as high as it is at the 100% effectiveness, but yet it is due to the usage of a long range weapon system. The CAMM-MR has replaced a short range weapon system, thus increasing the costs significantly in favor of increasing the effectiveness by 4% and neutralizing all threats. Comparing this to the **black** task force, the 98% effectiveness setup consists yet again of only medium and short range weapon systems, which include the ESSM, CAMM-ER and CAMM. However, by adding a support vessel carrying the RAM short range weapon system and by firing more shots of the medium and short range weapon systems, the effectiveness has increased by 2% to achieve full effectiveness. Similarly to point of interest number 4, choosing to neutralize threats at a greater distance could be preferred but at the cost of increasing the total cost across the task force.

During the analysis of the point of interests it is very apparent that certain weapon systems are used more than others. This is naturally linked to the many iterations the NSGA-II algorithm goes through to ultimately find a combination of weapon systems that maximize the effectiveness of the task force while simultaneously tries to minimize the costs. Keeping in mind that the some weapon system types have not been used much during the last iteration, the previous iterations of the NSGA-II established which weapon system would have been selected in the task force. In Table 5.7 an overview of the active weapon classes can be seen. These are the weapon classes that have been used in all the top performing engagements shown in Figure 5.3.

Table 5.7: Active weapon classes of top performers - divided over 12 vessels total

Weapon Class	Air Defender	Support
Long	1	-
Medium	7	-
Short	6	5
Soft kill	-	-

5.4 Test Case 4: Ammunition Stockpile

The ammunition stockpile of the vessels is an important aspect of the defensive capabilities. The consequences of having a small amount of ammunition due to previous engagements or supply problems could be detrimental to the surviving possibilities of the task force. Having the ability to carry as much ammunition as possible is ideally the best solution, but this could perhaps not be feasible in reality due to storage and weight issues. Therefore, in this test case the ammunition stockpile has been altered in order to figure out what the impact of having more or less ammunition is on the effectiveness of engagement.

The task force consists of two air defenders and one support vessel, with the base ammunition stockpile provided in Chapter 4. The altered ammunition stockpiles range from 25% of the original base ammunition stockpile to 200% of the base ammunition stockpile. The threats remain the same for each simulation, these threats are as described in Chapter 4. In order to keep the graphs readable, the test case has been split into two graphs. In Figure 5.4 the reduction of the ammunition stockpile can be seen, while the increase in ammunition can be seen in Figure 5.5.

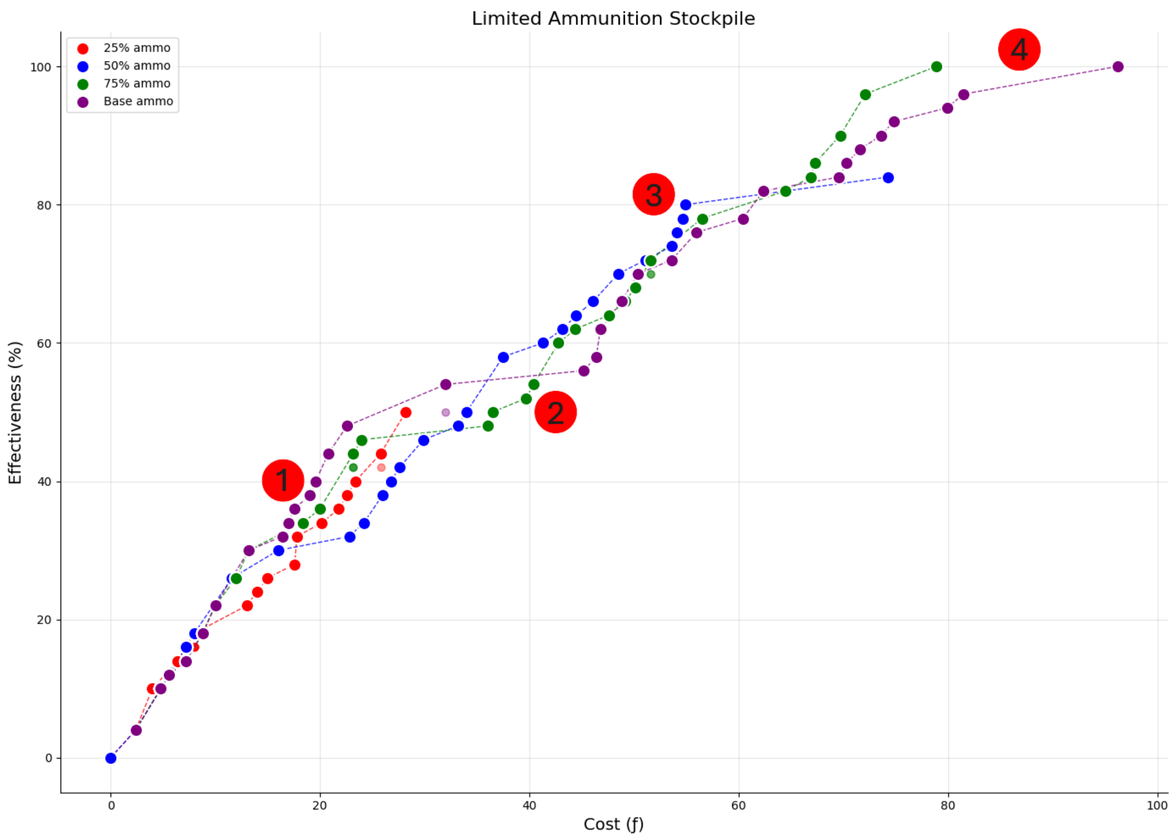


Figure 5.4: Limited ammunition stockpile - four ammunition sets

The Pareto fronts of the limited ammunition stockpile has four identified points of interest which are to be discussed in detail, namely:

1. *Dispersion at 40% effectiveness:* The dispersion of the costs around the 40% effectiveness is the first major deviation of all simulations. The cause for the increase in costs has in fact to do with the limited amount of ammunition. The base and 75% ammunition stockpile have enough of the short range ammunition to counter enough threats for 40% effectiveness. The short range is less expensive and thus a lower cost. Both 25% and 50% ammunition stockpile used medium range weapon systems during the engagement. However, due to the limited amount at 25%, the ammunition used is always going to be less than the 50%. An additional factor for a higher cost is the use of less vessels. At 25% ammunition, all vessels had been used to counter the threats and increasing the efficiency of the task force unlike the solution of the 50% ammunition. This results in a less efficient solution and thus a higher cost due to firing more often to counter the same amount of threats.

2. *Jumps around 50% effectiveness:* Around the 50% effectiveness mark all simulations make a significant jump in costs, some more than others. The outlier is the 25% ammunition at 50% effectiveness, all ammunition of the medium and short range weapon systems have been fired. Any other weapon systems such as long range of soft kill would increase the costs too much to gain a small fraction of effectiveness. For the 50% ammunition stockpile the jump from 52% to 58% comes from the switch in medium range weapon system. Going from the CAMM-ER to the ESSM increases the effectiveness of neutralizing threats, linked to a higher cost. However, by using a more effective medium range weapon system, the short range weapon system used a cheaper option and reducing a big jump in costs. The changes in costs and effectiveness for the 75% ammunition stockpile is purely adding a short range weapon system to the engagement and increasing the number of fired shots. However, the biggest jump in costs is found in the base ammunition stockpile, between 48% and 54%. At 48% the only weapon systems used during the engagement were the CAMM and the RAM short range weapon systems, at 54% both weapon systems were the CAMM. The CAMM weapon system is more effective and more expensive to use. Thus the increase in costs for a small increase in effectiveness is defined in choosing a more expensive combination of weapon systems.

3. *The top-performers of the 50% ammunition stockpile:* The top-performers of the 50% ammunition stockpile have the same weapon selection and distribution, the difference lies in the engagement and the final shot. The solution at 84% effectiveness managed to eliminate two more threats by firing one more short range weapon and using the HPM soft kill weapon system to neutralize one final threat after running out of the short range ammunition.

4. *Maximizing effectiveness:* The base and 75% ammunition stockpile can both achieve 100% effectiveness, but they arrive at it differently. The difference in strategies can already been noticed at 96% effectiveness, in which both solutions use combinations of medium and short range weapon systems. While the effectiveness is the same, the cost gap between the two is large. The reason for this is the increased usage of medium range weapon system. It is clear that the more expensive solution at 96% effectiveness neutralizes the threats at a larger distance and thus decreasing the risk of the threats entering a closer proximity. The 75% ammunition stockpile cannot shoot as many threats at medium range and has to resort to a higher usage of short range weapon systems, the benefit is a lower total cost. The same reasoning can be applied to the 100% effectiveness, in which the base ammunition stockpile can fire more medium range rounds and makes use of a long range weapon system. The increase in ammunition used in combination with a long range weapon system increases the costs significantly.

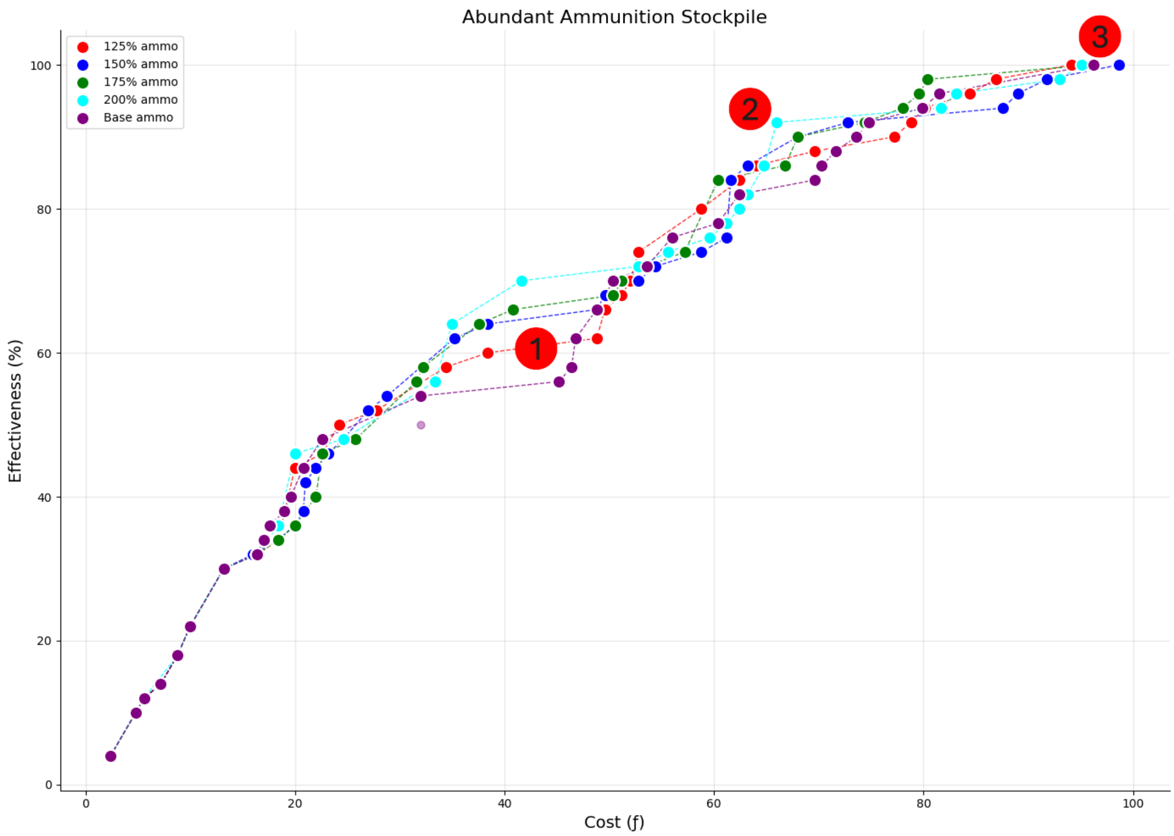


Figure 5.5: Abundant ammunition stockpile - five ammunition sets

The Pareto fronts of the abundant ammunition stockpile has three identified points of interest which are to be discussed in detail, namely:

1. *The 2% increase:* In the effectiveness range from 54% to 72%, all ammunition sets experience a sudden increase in costs while gaining a 2% effectiveness increase. In almost all of the ammunition sets, an additional weapon system is added to the engagement. Originally, only short range weapon systems had been used in the engagement and with the increased ammunition stockpile these become more effective for countering the threats. However, the short range weapon systems have a limit and therefore the medium range weapon system is added. The medium range weapon systems are more expensive to use during engagement, but they allow for a more effective defense. The 2% effectiveness increase is the jump from relying purely on short range to using a combination of short and medium range weapon systems.

2. *The 200% ammunition confidence:* Entering the 90% effectiveness with a 200% ammunition stockpile changes the way the task force operates. In the low nineties, the task force makes use of multiple vessels and multiple weapon systems to neutralize the threats. To further increase the effectiveness, the strategy changes from each weapon system performing roughly 30% of the defense to one weapon system firing 77% of all shots. While this strategy seems to be quite effective in neutralizing the threats, the costs increase with it.

3. *Full effectiveness:* Many of the ammunition sets act similar as described in point of interest number 2 towards to the 100% effectiveness. The final few solutions push towards primarily using medium range weapon systems to full effect, due to the ratio of effectiveness and costs. Therefore, the ammunition sets of 150%, 175% and 200% only engage the threats with two weapon systems in total. The 125% ammunition set wants to act similar to the others, but simply does not have enough ammunition to

achieve a similar engagement. This ammunition set utilizes the short range weapon systems very sparsely to fill the gaps left by the medium range weapon systems.

Throughout the analysis a common theme of weapon systems has been found. The difference between 25% and 200% of the base amount of ammunition is quite large, but the weapon systems used in both instances are very similar. The conclusion can therefore be drawn that certain weapon systems are outperforming others in terms of effectiveness and costs. In Table 5.8 an overview of the active weapon classes can be seen. These are the weapon classes that have been used in all the top performing engagements shown in Figures 5.4 and 5.5.

Table 5.8: Active weapon classes of top performers - divided over 20 vessels total

Weapon Class	Air Defender	Support
Long	1	-
Medium	16	-
Short	10	4
Soft Kill	1	-

5.5 Selection and Distribution

The selection and distribution of the weapon systems within the task force originates from the results found in the test cases. While each test case focused on a different aspect of effectiveness and efficiency, the outcome has similar results across all test cases. As mentioned earlier in this chapter, not every weapon system type has been used to the fullest of their potential due to costs and model preferences. However, the final selection and distribution of the weapon systems will include weapon systems and weapon system types that have not been active during the simulations, but they are included based on the previous iterations. The NSGA-II algorithm goes through many iterations and possibilities to ultimately find the best solutions based on the effectiveness and costs. In order to achieve this goal, each weapon system will at some point have been used to determine which weapon system is worth keeping in the next population of weapon systems. Therefore, in the last iteration some weapon system types will not have been actively used, but they will have been used in previous iterations and performed better than others to a certain extend.

5.5.1 Test Cases

Each test case has been examined separately for their selection and distribution between the ranges of 60-80% effectiveness and 80-100% effectiveness. These ranges have been chosen to create a more unified selection and distribution.

Test Case 1

The purpose of test case 1 is to identify the influence of the probability of kill. This has been achieved by altering the probability of kill and running simulations for each altered set. The selection and distribution of the weapon systems will be slightly skewered towards a number of weapon systems. The 60-80% effectiveness range will involve more of the lower probability of kill sets, resulting in using certain weapon systems more than others based on the probability of kill. The weapon systems that are statistically worse, become even worse and thus the better performing weapon systems are favored.

Table 5.9: The selection and distribution of Air Defenders - Test Case 1 60-80%

Range	Air Defender 1			Air Defender 2		
	Weapon	Appearance (%)	# of Shots	Weapon	Appearance (%)	# of Shots
Long	LRAD-ER	41.4	0	LRAD-ER	48.3	0
Medium	CAMM-ER	48.3	18.8	CAMM-ER	62.1	21.7
Short	CAMM	100	19	CAMM	100	14.5
Soft Kill	HPM	100	0	HPM	100	0

Table 5.10: The selection and distribution of Support vessels - Test Case 1 60-80%

Range	Support 1		
	Weapon	Appearance (%)	# of Shots
Short	CAMM	62.1	4.3
Soft Kill	HPM	100	0

The 80-100% effectiveness range involves more of the high probability of kill sets. However, in this case it tends to favor the better weapon systems even more due to the high probability of kill. The same weapon systems, as the previous range, are used to engage the threats. The main difference is the amount of shots fired in total, this is ultimately the biggest reason for a higher effectiveness and cost rate.

Table 5.11: The selection and distribution of Air Defenders - Test Case 1 80-100%

Range	Air Defender 1			Air Defender 2		
	Weapon	Appearance (%)	# of Shots	Weapon	Appearance (%)	# of Shots
Long	SM-2	56.8	0	LRAD-ER	48.6	0
Medium	CAMM-ER	56.8	24.6	CAMM-ER	78.4	23.5
Short	CAMM	100	14	CAMM	86.5	15.4
Soft Kill	HPM	100	0	HPM	100	0

Table 5.12: The selection and distribution of Support vessels - Test Case 1 80-100%

Range	Support 1		
	Weapon	Appearance (%)	# of Shots
Short	CAMM	51.4	4
Soft Kill	HPM	94.6	1

Test Case 3

The variations in sizes and compositions of the task force introduced many weapon systems in the overall selection. The main reason for this is the number of available spots, although not all of the weapon systems were used during the engagements. Especially in the 60-80% effectiveness range, not every weapon system fired to achieve their total effectiveness. This leads to a broader selection of weapon systems within the task force, but ultimately the main weapon systems introduced in Test Case 1 make appearances again.

Table 5.13: The selection and distribution of Air Defenders - Test Case 3 60-80%

Range	Air Defender 1			Air Defender 2		
	Weapon	Appearance (%)	# of Shots	Weapon	Appearance (%)	# of Shots
Long	LRAD-ER	46.4	0	SM-2	46.2	0
Medium	CAMM-ER	25	23.4	CAMM-ER	76.9	23.4
Short	CAMM	89.3	17.9	CAMM	69.2	12.7
Soft Kill	HPM	100	0	HPM	100	0

Table 5.14: The selection and distribution of Support vessels - Test Case 3 60-80%

Range	Support 1			Support 2		
	Weapon	Appearance (%)	# of Shots	Weapon	Appearance (%)	# of Shots
Short	CAMM	63	9	CAMM	78.6	13.4
Soft Kill	HPM	100	0	HPM	100	0

The increase in total effectiveness of the task force is a result of more engagement. By increasing the engagement, the total selection of weapon systems decreases and the top-performing weapon systems take over. This is most predominant for Air Defender 1, this air defender is in more engagements than Air Defender 2. Beforehand, the selected medium range weapon system had an active appearance of 25%, by increasing the overall engagement the active medium range weapon system went up to 40%. The distribution of weapon systems remains fairly constant between 60 and 100% effectiveness, with a small deviation in one medium range weapon system. It is interesting to note that the increased engagement of support vessels allows for a broader selection of weapon systems. This is partly linked to the overshadowing power of the Air Defenders, allowing the Support vessels to pick potentially cheaper alternatives.

Table 5.15: The selection and distribution of Air Defenders - Test Case 3 80-100%

Range	Air Defender 1			Air Defender 2		
	Weapon	Appearance (%)	# of Shots	Weapon	Appearance (%)	# of Shots
Long	LRAD-ER	54.5	0	SM-2	47.1	0
Medium	ESSM	40.1	25	CAMM-ER	76.5	24.2
Short	CAMM	90.9	14.3	CAMM	76.5	11.5
Soft Kill	HPM	100	0	HPM	100	0

Table 5.16: The selection and distribution of Support vessels - Test Case 3 80-100%

Range	Support 1			Support 2		
	Weapon	Appearance (%)	# of Shots	Weapon	Appearance (%)	# of Shots
Short	CAMM	40.9	9.7	CAMM	54.5	8
Soft Kill	HPM	86.4	0	HPM	100	0

Test Case 4

This test case differs from the others due to the variations in ammunition stockpiles on the vessels. However, the results presented in the tables are not as extreme as expected due to the balance in more and less ammunition compared to the standard stockpile in the other test cases. This test confirms the findings of the other test cases; a certain selection of weapon systems will be chosen more often based on their performance, and the distribution of these weapon systems reflect the cooperation of the vessels, as seen in the other test cases.

Table 5.17: The selection and distribution of Air Defenders - Test Case 4 60-80%

Range	Air Defender 1			Air Defender 2		
	Weapon	Appearance (%)	# of Shots	Weapon	Appearance (%)	# of Shots
Long	SM-2	54.2	0	SM-2	45.8	0
Medium	CAMM-ER	29.1	16	CAMM-ER	52.8	22
Short	CAMM	85.4	15.9	CAMM	97.9	13.1
Soft Kill	HPM	100	0	HPM	100	0

Table 5.18: The selection and distribution of Support vessels - Test Case 4 60-80%

Range	Support 1		
	Weapon	Appearance (%)	# of Shots
Short	CAMM	47.9	5
Soft Kill	HPM	93.8	0

The selection and distribution of the weapon systems is very similar for both effectiveness ranges. Each range depicts a clear medium range domination, followed by the support of short range weapon systems.

As expected, the 80-100% effectiveness range uses more ammunition to achieve the higher effectiveness. The engagement of the medium range weapons is more than the 60-80% effectiveness range, which again, allows for slightly more variation in the short range selection of weapon systems.

Table 5.19: The selection and distribution of Air Defenders - Test Case 4 80-100%

Range	Air Defender 1			Air Defender 2		
	Weapon	Appearance (%)	# of Shots	Weapon	Appearance (%)	# of Shots
Long	LRAD-ER	57.1	0	SM-2	40.5	0
Medium	CAMM-ER	40.5	24.9	CAMM-ER	54.8	26.4
Short	CAMM	88.1	17.1	CAMM	83.3	12.2
Soft Kill	HPM	97.7	0	HPM	97.7	0

Table 5.20: The selection and distribution of Support vessels - Test Case 4 80-100%

Range	Support 1		
	Weapon	Appearance (%)	# of Shots
Short	RAM	45.2	0
Soft Kill	HPM	92.9	0

5.5.2 The Global Selection and Distribution

The final selection and distribution of the weapon systems within the task force is based on the average of all the test cases, this is named the global selection and distribution. The data from the test cases, used for deriving the global selection and distribution, is shown in the previous section.

Table 5.21: The selection and distribution of Air Defenders - Global 60-80%

Range	Air Defender 1		Air Defender 2	
	Weapon	Appearance (%)	Weapon	Appearance (%)
Long	LRAD-ER	40	SM-2	41.1
Medium	MRAD	57.1	CAMM-ER	58.9
Short	CAMM	90.5	CAMM	94.4
Soft Kill	HPM	100	HPM	97.8

Table 5.22: The selection and distribution of Air Defenders - Global 80-100%

Range	Air Defender 1		Air Defender 2	
	Weapon	Appearance (%)	Weapon	Appearance (%)
Long	LRAD-ER	47.5	SM-2	38.5
Medium	CAMM-ER	46.5	CAMM-ER	67.7
Short	CAMM	93.1	CAMM	83.3
Soft Kill	HPM	99	HPM	99

Based on the information provided in the test cases and the results shown in Tables 5.21 and 5.22, it is clear that the short range weapon system is focused on the CAMM. The short range weapon system is used the most in every engagement, particularly in the lower effectiveness regions. Therefore, the 80+% appearance on the air defenders is a result of many iterations and effective behavior in the defense of the task force. The long range weapon selection results mainly from the previous iterations due to the inactivity in the final simulation. This holds partly true for the medium range weapon selection in the 60-80% effectiveness range. The lower end of this range continues to heavily rely on short range weapon systems. Thus, some weapon systems, including the MRAD, are a result of performances of the previous iterations. In the 80-100% range the medium range weapon systems are divided between the CAMM-ER and the ESSM weapon systems. Ultimately, the CAMM-ER is preferred over the ESSM based on the costs differences. The soft kill weapon system selection is unfortunately a broken part of this result. While both the HEL and HPM have been used on occasion, the usage of the weapon systems is extremely under utilized and would require a rework of the model to be more efficiently used during the engagements.

Table 5.23: The selection and distribution of Support vessels - Global 60-80%

Range	Support 1		Support 2	
	Weapon	Appearance (%)	Weapon	Appearance (%)
Short	CAMM	55.8	CAMM	78.6
Soft Kill	HPM	97.1	HPM	100

Table 5.24: The selection and distribution of Support vessels - Global 80-100%

Range	Support 1		Support 2	
	Weapon	Appearance (%)	Weapon	Appearance (%)
Short	CAMM	38.6	CAMM	54.5
Soft Kill	HPM	92.1	HPM	100

The support vessels are quite literally supporting the air defenders in combat. The total engagements the support vessel undergo are decreasing while the total effectiveness of the task force increases. This has everything to do with the active weapon systems of the air defenders and while the air defenders are engaging more with the threats the support vessels are engaging less. This phenomenon can be seen in Tables 5.23 and 5.24. The appearance of the CAMM is decreasing at higher total effectiveness and this has the same reason as the long range weapon systems on the air defenders. When weapon system types are not used as often, the appearances of the weapon systems are relying more on the previous iterations. In this particular case, the CAMM still participates relatively often as a supporting weapon system, but once more weapon systems are engaging with the threats, the support vessel engages less and this leaves the model looking for alternatives in terms of effectiveness and costs. Ultimately, the support vessels opted for the best performing short range weapon system despite the low engagement count in case the extra firepower is needed.

5.6 Performance Validation

With the test cases complete and the results analyzed, the next and last step of the validation process can occur. The last step is the Performance Validation by Pedersen et al. (2000), this step is a quantitative evaluation of the solutions provided in the test cases.

The Performance Validation is as follows:

- *Accepting usefulness of method for some example problems:* The purpose of the method is to find a selection and distribution of weapon systems across a task force, while finding a balance in effectiveness and cost of the weapon systems. The solutions generated by the method during the test cases show a selection and distribution of weapon systems across a task force. The results are displayed in a Pareto front, with the objectives defined as effectiveness and costs.
- *Accepting that usefulness is linked to applying the method:* This step in the validation process requires a comparison to existing methods, unfortunately this is not possible due to the lack of publicly available methods concerning the selection and distribution of weapon systems across a task force. However, the method has been constructed with individual components which have been carefully analyzed. The chosen components of the full method are justified parts. Therefore, the components show evidence that the usefulness is linked to the application of the method.

- *Accepting usefulness of method beyond example problems:* The test cases show that the method is able to work with various inputs, such as threats, weapon systems and vessels to create a task force with the ability to counter the threats. The algorithm can generate solutions based on the outcome of the WTA and the algorithm objectives.

5.7 Conclusion

The test cases, involving the full model, provided great insight into the selection and distribution of the weapon systems across the task force. The selection of the weapon systems resulted in a more one sided event due to the algorithm. The NSGA-II algorithm selected the best performing weapon systems, based on the effectiveness and costs, throughout the iterations. Therefore, the last iteration will show a preference for a select group of weapon systems based on their performance during all the iterations. The distribution of the weapon systems did have an impact of the effectiveness and the defense capabilities of the task force. The lower effectiveness solutions had very limited active weapon systems within the task force. By increasing the active weapon systems, and thus increasing the distribution of the weapon systems, the effectiveness increased and in certain instances increased significantly.

The effectiveness of the task force is directly linked to the costs of the weapon systems. The Pareto front provides a great overview of the all the solutions, with regards to the objective functions. The lower effectiveness solutions are less effective due to the costs limitations. These weapon systems were minimized in costs, resulting in using cheaper and sometimes less effective weapon systems in combination with less engagements with the incoming threats. In order to achieve a higher overall effectiveness of defense within the task force, more weapon systems have to be active and engage with the threats. This results in higher ammunition usage during the engagement and thus more overall costs. It can therefore be concluded that the operational efficiency of the task force is linked to the costs.

6. Conclusion

The objective of this research is to develop a weapon system selection and distribution model meant for task force settings. The integration of the model should result in a selection and distribution based on the effectiveness and the costs of the weapon systems within the task force. This led to the following main research question:

How can layered air defense systems be designed, including the selection and distribution of weapon systems across a task force, to achieve high coverage protection while finding a balance between effectiveness and costs?

Seven research sub-questions were defined to understand the underlying mechanics of the model and to evaluate the model itself and its results.

1. *How is a Naval Task Force structured?*
   The structure of a naval task force is designed to successfully complete an operation utilizing various types of vessels, ranging from support vessels to air defender frigates and submarines. In addition, the task force operates under a hierarchical command structure. This includes the force commander, who is responsible for the entire task force. Second in command structure are the commanding officers, these officers are responsible for the vessels they operate and control. The last in the command structure are the staff Officers and they support the force commander in specialized areas. By working in this command structure, the task force is able to achieve the operational objective efficiently.

2. *What aerial attacks does a task force encounter during operations and what air defense measures are used to counter the attacks?*
   Task forces may encounter various types of aerial threats during operations, symmetrical and asymmetrical threats. The symmetrical threats arise from peer or near-peer opponents and these forces with similar technologies and strategies, examples of these threats are sea-skimming missiles and ballistic missiles. In contrast, the asymmetrical threats arise from lesser advanced opponents which utilize unconventional and innovative technologies that are difficult to predict and analyze. A primary example for asymmetrical threats are UAVs and in particular the cheap commercial drones that operate in swarm formations.

3. *What is the WTA problem?*
   The Weapon Target Allocation (WTA) problem solves for the optimal assignment of weapon systems to a set of threats. The origins are found in the logistics sector, but has been altered to accommodate the military purpose. The WTA model primarily works with probability of kill, determining which weapon to target pair yields the best outcome of surviving the incoming threats.

4. *Which modeling approaches would be most effective for optimizing air defense distribution?*
   Based on the literature review it became evident that the model consists of two parts, namely the WTA problem and the optimization algorithm. The WTA models range from simple static designs to very complex and computational heavy dynamic designs. In order to maintain simplicity, the static models were chosen to continue with and alter them to create a semi-dynamic model to fit the desired needs. The optimization algorithm research led to two types of algorithms, specifically the Genetic Algorithm (GA) and the Swarm Intelligence (SI) algorithm. These algorithms are specially designed to find solutions to multi-objective problems such as the selection and distribution of weapon systems across a task force while balancing the effectiveness and costs.

5. *How can the effectiveness of the air defense distribution model be evaluated and validated?*
   The effectiveness of the model has been evaluated and validated through two processes, the verification and validation process. The verification process focused on the internal effectiveness and efficiency, evaluating the outcome and comparing it to the predicted outcome based on the input of the model. The validation process is based on the works by Pedersen et al. (2000), in which the validation

is split into two parts, namely the structural and the performance validation. The structural validation focuses on the effectiveness of the model and the process does this by analyzing the validity of the individual components and the methods behind them and by checking the interaction of the components through a flowchart. The last part of the validation is providing test cases which the model is build to test and examine. The combination of the verification and the validation processes can determine the effectiveness of the model correctly.

6. *How will the distribution of air defense systems affect the task force's overall coverage?*
   The distribution of the weapon systems across the task force is naturally linked to the protection and coverage of the entire task force. In the test cases it primarily involves active versus non-active weapon system and the result of many iterations from the NSGA-II algorithm. The algorithm picks a set of weapon systems that have performed better than most based on the effectiveness and costs throughout all the iterations. However, the algorithm does not affect the coverage of the task force, this is where the active weapon systems come in. Assuming that most weapon systems are not active leads to a low coverage and therefore low effectiveness of neutralizing the threats. Increasing the active weapon systems, selected and distributed across the task force by the algorithm, increasing the effectiveness of the task force and thus increasing the overall coverage and protection.

7. *How will the cost of equipment impact the operational efficiency?*
   The costs of the weapon systems, and in particular the ammunition, does have an impact on the operational efficiency. This is directly linked to the active and non-active weapon systems within the task force. The high effectiveness of neutralizing the threats comes with a high cost, more threats neutralized means that more shots have been fired by the vessels or more effective and expensive weapon systems have been used to engage the threats. The conclusion is that the cost is linked to the operational efficiency, either by shooting more or using more expensive weapon systems to achieve the highest effectiveness and protection.

The first 4 research questions lead to the design of the selection and distribution model. These provided the input of the model and how the model's components should be interacting with each other in order to simulate the test cases and answering the main research question.

The results of the model coincided with the expectation of similarity. Many of the weapon systems available per vessel in the task force were the same, especially the shorter ranges of defense. As mentioned, this is the result of the genetic algorithm that the NSGA-II works with, to describe it in simple terms: "Survival of the fittest". The best functioning weapon systems, whether that is based on the effectiveness or the costs, are selected for the next population of the NSGA-II algorithm. Therefore, the outcome of the model will have a small selection of weapon systems that is proven to be either most effective or cost-friendly and in some cases a balance between the two. The distribution of these weapon systems partially comes down to the inputs of the model, which vessels are in the task force and what can they carry on board. However, the combination of the NSGA-II and the WTA model provides the reasoning for the distribution. The NSGA-II algorithm creates many individuals in the population, each vessel with a new combination of weapon systems within the task force, and these individuals are plugged into the WTA model where the task force is tested on their behavior against the selected threats.

It can therefore be concluded that a layered air defense system, focusing on the selection and distribution of weapon systems across a task force while balancing effectiveness and costs, can be designed by integrating a WTA problem model with a multi-objective optimization algorithm.

6.1 Scientific Contribution

A thesis pushes for new concepts and alternative models to solve a problem which is either lacking in research or explores new concepts altogether. New research and models lead to scientific contributions by understanding and providing solutions to complex problems.

This research thesis makes the following scientific contributions:

1. *Dynamic WTA:* In this thesis, the WTA model by Karasakal (2008) has been altered from a static model to a dynamic model. This can be seen as a very small contribution. There are very complex and well designed dynamic WTA models that would outperform the WTA of this thesis. Nevertheless, the altered WTA model provides insights into the dynamic models and how they can be used to solve the problem of this thesis.

2. *Integrating NSGA-II and WTA:* Combining a WTA model with an algorithm is a well established practice, in terms of increasing the allocation model by searching for the best possible threat and weapon system combination. This thesis focuses on using an algorithm to find the best weapon systems for each vessel in the task force. Applying an algorithm externally to the WTA model instead of embedding the algorithm in the WTA model represents a gap in the current literature. Thus, by applying the NSGA-II algorithm to the WTA model and finding solutions for weapon system selection and distribution counts as a scientific contribution.

6.2 Recommendations

The model has certain limitations that affect the outcome of the model and by making the correct adjustments the outcome of the model can be improved significantly. The following list will go over the aspects of the model that could benefit the most:

- *Overwhelming WTA model:* The current WTA model is a very simplistic model, able to carry out the calculations for small sets of threats and vessels. The task force size works fine for a combined total smaller than five, increasing the task force size will render the additional vessels as non-active or these newer vessels will replace the first few vessels as active during the engagement. The threat count is steady up to roughly the 50 to 60 mark, increasing the threats will overwhelm the WTA model and no allocation will occur. Increasing the vessels and threat count creates too many possibilities of weapon target allocation to the point of overstimulating the model and effectively rendering it useless. By adjusting the decision making of the model, the allocation can become more efficient with high number of possibilities. An example of this could be incorporating a multistage decision making model, to allocate the weapon target pairs into groups based on the range or threat they pose on the task force.

- *Dynamic model:* The current model is a very basic dynamic model, the model loops the static model multiple times until the threats are all neutralized, the threats have reached the task force or the round has ended with threats still in the environment. Between each round a time step has been added to create the illusion of movement in the model, allowing the threats to come closer to the task force. This approach leads to the extremely fast threats to "overshoot" the task force due to the time skip, resulting in a bad calculation. Altering the WTA model to a full dynamic model, with each second and movement of the threats accounted for, should improve the behavior of the model and produce better WTA results.

- *Predicted Intercept Point (PIP):* The PIP is an additional feature to implement into the true dynamic model. The current model shoots and hits the threat at the same time, between shooting and hitting the threat is no time. By introducing the PIP into the model, the travel time between the moment of firing the defense weapon and eventually hitting the threat would introduce a new level of realism into the model. The time between each shot should become more valuable for the defensive decision making.

- *Soft Kill:* The current model operates with "soft kill" weapon systems, these weapon systems are technically hard kill system but for neutralizing the threats in a non-kinetic way. The true soft kill, including the flares, smoke and decoys, would provide bigger alternatives for the task force to engage with the incoming threats, potentially reducing the costs further by deploying the soft kill measures in close proximity to the vessels in the task force. Additionally, the current soft kill systems (HPM and HEL) operate on stored energy and should not be classed as simple shots as in the current build. Integrating a stored energy system for the vessels could change the utilization of these two soft kill systems.

- *Long range costs:* The current model utilizes many weapon systems across all the weapon classes. The test cases show that the long range weapon systems are not used for the majority of the final iteration. As tested, this problem originates in the WTA model and the preference to eliminate close threats first and allowing the long range threats to enter medium or even short range distances. However, the costs of the long range weapon systems is also too high causing the model to prefer cheaper weapon systems at closer ranges. The medium range costs per shot lies between 1 and 1.8 while the costs per shot for long range lies between 2 and 4. These costs were determined based on their ability to neutralize the threats at long ranges, increased distance equals increased costs. Unfortunately, the costs are too high compared to the medium range weapon systems with similar probability of kill values albeit at smaller distance ranges. Therefore, altering the costs should increase the involvement of the long range weapons.

- *Task force formation:* The formation of the task force in every test case was a horizontal formation. This was purposely done to keep the interaction with the threats constant for each test case scenario. The only test case that differs in interaction is the task force size test case (TC 3). The alternative task force sizes interact differently with the threats based on the location of the vessels, resulting in different layered air defense strategies and systems. Therefore, changing the formation's configuration and composition could potentially lead to alternative allocations of weapon systems within the task force. This aspect of allocating weapon systems by changing the layout of the vessels within the task force is missing in this thesis and the outcome of testing various formations should bring more insights to the overall allocation of the weapon systems.

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A. Weapon System Characteristics

Each weapon system has unique characteristics, that determine when and how they are used to defend the task force. The focus lies on two characteristics in particular, namely the range and the altitude. For simplicity, the minimum altitude is set at 5 meters above sea level and the ranges of the weapon systems are defined by their class:

- Long Range: 70 - 370 KM
- Medium Range: 30 - 70 KM
- Short Range: 5 - 30 KM
- Soft Kill: 2 - 5 KM

The altitude and range characteristics of the weapon systems can be found in Table A.1:

Table A.1: Weapon system characteristics

Weapon System	Max Altitude (KM)	Min Range (KM)	Max Range (KM)	Costs (f)
SM-6	34	70	370	4
SM-2	20	70	166	2.5
LRAD-ER	30	70	150	3
Aster 30	20	70	150	3.2
CAMM-MR	15	70	100	2
LRAD	20	30	70	1.8
ESSM	15	30	50	1.5
CAMM-ER	15	30	40	1.2
MRAD	20	30	35	1
Aster 15	13	5	30	0.9
CAMM	10	5	25	0.8
RAM	5	5	10	0.6
76mm	1	5	10	0.1
HPM	5	2	5	20
HELL	5	2	5	20

The costs of the weapon systems are based on their characteristics and the probability of kill for each threat type. These values are defined by myself and are not backed by any real data.

B. Probability of Kill

The probability of kill is defined by the ability of the weapon system to neutralize the threat. Each weapon system and threat pair will have their own probability of kill value assigned to them. The values are based on literature found describing the abilities of the weapon systems. The weapon system's ability is categorized into four groups, namely:

- Great: $0.8 \leq P_k < 1$
- Good: $0.55 \leq P_k < 0.8$
- Not Good: $0.3 \leq P_k < 0.55$
- Bad: $0.1 \leq P_k < 0.3$

Once the weapon system and threat combination has an assigned group, a randomizer was used to determine the actual value between the ranges of that group. The randomizer is used to ensure unique values for each combination. These values can be seen in Table B.1:

Table B.1: Probability of Kill

	Seaskimmer	Ballistic	HGV	UAV
SM-6	0.78	0.61	0.93	0.72
SM-2	0.86	0.59	0.66	0.79
Aster 30	0.68	0.74	0.56	0.63
LRAD-ER	0.98	0.77	0.42	0.71
CAMM-MR	0.8	0.51	0.33	0.87
ESSM	0.99	0.54	0.39	0.85
CAMM-ER	0.65	0.44	0.27	0.69
LRAD	0.91	0.36	0.14	0.58
MRAD	0.75	0.21	0.19	0.6
Aster 15	0.62	0.47	0.49	0.72
CAMM	0.97	0.3	0.25	0.7
RAM	0.67	0.29	0.22	0.89
76mm	0.18	0.16	0.11	0.76
HEL	0.999	0.999	0.999	0.999
HPM	0.999	0.999	0.999	0.999

The literature used to determine the categories of the weapon systems can be found in Table B.2. The soft kill weapon systems differ from the rest, those values are entirely fictional and therefore have no literature to justify the values. The reason for fictional values for the soft kill weapon systems is due to the last defense measures strategy implemented in the model. The rework of the soft kill is stated in Chapter 6.2.

Table B.2: References

	References
SM-6	(Military Aerospace, 2025), (Naval News, 2025)
SM-2	(The War Zone, 2024), (Raytheon Technologies, 2025)
Aster 30	(Sea Forces, n.d.)
LRAD-ER	(Army Technology, n.d.), (Deagel, n.d.)
CAMM-MR	(Wikipedia, n.d.)
ESSM	(CSIS, n.d.)
CAMM-ER	(Wikipedia, n.d.)
LRAD	(Army Technology, n.d.)
MRAD	(Army Technology, n.d.)
Aster 15	(Sea Forces, n.d.)
CAMM	(MBDA, n.d.)
RAM	(Raytheon Technologies, n.d.), (U.S. Navy, n.d.)
76mm	(SeaForces, 2025)
HEL	-
HPM	-