ANALYSIS OF AIR DEFENSE EFFECTIVENESS OF A NAVAL TASK GROUP UNDER PARTIAL AND FULL COORDINATION

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Approval of the thesis:

ANALYSIS OF AIR DEFENSE EFFECTIVENESS OF A NAVAL TASK GROUP UNDER PARTIAL AND FULL COORDINATION

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ABSTRACT

ANALYSIS OF AIR DEFENSE EFFECTIVENESS OF A NAVAL TASK GROUP UNDER PARTIAL AND FULL COORDINATION

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The purpose of this thesis is to analyze the air defense effectiveness of a naval task group (TG) under different coordination levels. Event Graphs methodology, and component-based discrete-event simulation modeling techniques are used. The simulation model is built using Simkit, an open-source java package, which enables the use of component-based modeling. TG is analyzed under different coordination policies consisting of no-coordination, partial coordination, and full coordination within TG, then these coordination policies are compared to each other. Partial coordination within TG is provided with sector allocation, and full coordination within TG is achieved with BMRP (bi-objective missile rescheduling problem) model.

Keywords: Discrete Event Simulation, Air Defense Systems, Simulation Modeling, Naval Task Group¸ Artificial Neural Network

ÖZ

BİR DENİZ GRUBU HAVA SAVUNMA ETKİNLİĞİNİN KISMİ VE TAM KOORDİNASYON ALTINDA ANALİZİ

Köse, Bala İlkim
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Mayıs 2022, 80 sayfa

Bu tezin amacı, bir deniz görev grubunun (TG) hava savunma etkinliğini farklı koordinasyon seviyelerinde analiz etmektir. Olay Grafikleri metodolojisi ve bileşen tabanlı kesikli olay simülasyonu modelleme teknikleri kullanılmıştır. Simülasyon modeli, bileşen tabanlı modelleme kullanımına olanak sağlayan açık kaynaklı bir java paketi olan Simkit kullanılarak oluşturulmuştur. Deniz Görev Grubu, gemiler arasında koordinasyon olmadan, kısmi koordinasyon ve tam koordinasyon var iken analiz edilmiş ve bu farklı koordinasyon politikaları birbirleri ile karşılaştırılmıştır. Kısmi koordinasyon gemilerin sektörlere tahsis edilmesi ile, tam koordinasyon BMRP (iki amaçlı füze yeniden planlama) modeli ile sağlanmıştır.

Anahtar Kelimeler: Kesikli Olay Simülasyonu, Hava Savunma Sistemleri, Simülasyon Modelleme, Deniz Görev Grubu, Yapay Sinir Ağı

To my family.

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LIST OF ABBREVIATIONS

ABBREVIATIONS	
AAW	Anti-Air Warfare
ANN	Artificial Neural Network
ASM	Anti-Ship Missile
BMRP	Bi-objective Missile Rescheduling Problem
CEH	Change and Exchange Heuristic
CFCU	Central Fire Control Unit
DES	Discrete Event Simulation
DM	Decision Maker
MAP	Missile Allocation Problem
MOE	Measure of Effectiveness
No-C	No Coordination
NRH	New and Replace Heuristic
IRST	Infrared Search and Track
PNL	Probability of no-leaker
SA	Sector Allocation
SAM	Surface-to-Air Missile
SAP	Sector Allocation Problem
SLS	Shoot-Look-Shoot
SSAD	Ship Self Air Defense
SSDM	Ship Self Defense Model

SSKP	Single Shot Kill Probability
SSL	Shoot-Shoot-Look
TG	Task-Group
TGAAWC	Task-Group Anti-Air Warfare Coordinator

CHAPTER 1

INTRODUCTION

The serious leap in the defense industry especially after the Second World War required the further developments of the ships' defenses against air attacks to improve survivability. The enhancements in speed, accuracy, range, intelligence, and destructiveness in anti-ship missiles (ASMs) have required improvements in surface-to-air missiles (SAMs). Although the development and increase in the number of ship ammunition have improved the defense capacity of the ship, it never loses its importance to decide on the most effective use of limited ammunition. For a good warfare strategy, fleets consisting of ships must decide and implement the best decision in the minimum time under different attack scenarios.

Simulation modeling is a widely used method for investigating various warfare engagement policies because in the real world it is almost impossible to create the same warfare environment. Even if it would be, it will not be cost-efficient and flexible enough for any changes. That is why simulation models are very effective tools to analyze air defense systems under different engagement policies.

In naval anti-air warfare (AAW), ships form TG to accomplish a specific mission or missions. TG is a group of combatant and auxiliary ships that are organized in a region. We assume that full coordination in TG improves the communication between ships via the TG AAW Coordinator (TGAAWC). TGAAWC gathers all information from ships, schedules engagement plan according to the selected engagement policy, then commands ships in TG. Since command and control are provided from a common central unit, TG can operate as if it was one unit and respond more quickly to ASM attacks. The collection of data gathered from ships is combined for the best engagement plan.

This thesis aims to analyze the air defense effectiveness of a naval TG. To do this, we modeled various operational environments and compare these designed scenarios to each other under different coordination levels. We analyzed the results of different scenarios by discrete event simulation modeling. In the simulation model, engagement plans are obtained for different coordination policies consisting of full coordination, partial coordination, and no coordination of TG.

For full coordination of TG, the engagement plan is scheduled according to the bi-objective missile rescheduling problem (BMRP) model developed in Silav et al. (2019) and Karasakal et al. (2021b). In the BMRP-model, SAM rounds are dynamically allocated to incoming ASMs, and the engagement plan is rescheduled if any disruption occurs. The main concerns are the stability of the initial plan and the efficiency of air defense. Two heuristics solution procedures, i.e., New and Replace Heuristic (NRH) and Change and Exchange Heuristic (CEH), are developed for producing possible non-dominated solutions in a short period of time. Then, an artificial neural network (ANN) algorithm which is trained according to prior articulated preferences of the decision-maker (DM) whose preferences are assumed to be consistent with quasi-concave utility function chooses one of the non-dominated solutions, and the existing engagement plan is updated. For our study, we integrated the BMRP-solution into the simulation model.

For partial coordination of TG, the problem is solved according to the sector allocation of ships. In sector allocation policy, ships are responsible for neutralizing the targets passing through the sector they are assigned to. In case of no coordination of TG, each ship makes its engagement plan only considering the SAM systems and the available rounds onboard. Each engagement plan in partial, and no coordination of TG is made according to some myopic algorithms such as time-on-target (TOT), and closest-point of approach (CPA). Besides, all engagements for all coordination levels are planned subject to shoot-look-shoot (SLS) firing policy.

The next chapter contains the literature review on mathematical and simulation models in air defense problem. In Chapter 3, we briefly explain the Event Graphs approach and present the problem definition, and the assumptions. We demonstrate the event graph of our problem and describe the main components. Chapter 4 includes validation of the simulation model and detailed explanations of the validation cases. Alternative air defense coordination policies are evaluated and compared to each other. In Chapter 5, we present conclusions and future research areas.

CHAPTER 2

LITERATURE REVIEW

In this chapter, we review the literature related to the background of Event Graph methodology, and mathematical and simulation models for air defense problem.

Schruben (1983) introduces Event Graphs for graphical representation of discrete-event simulation models. Schruben and Yücesan (1993) extend and renames Event Graphs as Simulation Graphs. Simulation Graphs mainly consist of vertices representing events and edges showing state variables. For instance, for the fundamental simulation graph representation given in Figure 2.1. below, whenever Event A occurs and its state transitions are completed, if “Condition” is true Event B is scheduled after specific “Time” units later.

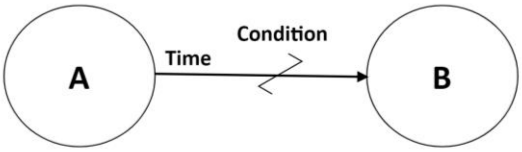

Figure 2.1. Fundamental Simulation Graph Representation

Buss (1995) improves the simulation graphs with two new enhancements. One enhancement provides the capability to pass attributes on edges between the vertices, and the other provides the capability to cancel events. Buss and Stork (1996) introduced Simkit which contains a library written in Java programming language for component-based discrete event simulation (DES) models. The interaction between components of the model is provided with Listener Event Graph Objects (LEGO) connections Buss and Sánchez (2002) and these LEGOs are based on listener patterns Buss (2002). Buss and Sánchez (2005) demonstrate simple movement and detection modeling with discrete event approach. Interested readers are referred to Buss (2001a), Buss (2001b), and Buss (2017).

Arntzen (1998) develops Modkit, Modeling Kit, which is a prototype software component architecture and component library including sensors and airborne weapons for exploratory analysis on the impact of a network of infrared search and track (IRST) sensors.

Turan (1999) develops Ship Self Air Defense system simulation model (SSAD-Sim) which is a modular discrete event simulation model and implements it in the Java programming language and Modkit which is a Java package. He compared SLS and shoot-shoot-look (SSL) firing policies, active and semi-active missiles with different scenarios, and made sensitivity analysis for SAM inventory levels, track number, and track delay.

Kulaç (1999) developes a model to compare the effectiveness of radar and IR sensors. He used component-based approach and Java Programming language for their scalability and flexibility. He designed Ship Self Defense (SSD) Model to evaluate sensors in different anti-air warfare defense scenarios.

Opçin (2016) builds a flexible, scalable, and expandable AAW simulation model to analyze different screen dispositions, screen ship properties, and HVU properties in convoy operations. He developed the model using the Simkit library in Java programming language as a tool for analyzing AAW tactics for various combat scenarios and the effectiveness of sensors, missiles, and combat ships.

PFM, Dongen, and Kos (1995) simulate a single ship defending itself using all relevant defense systems onboard the frigate in various geographical areas. Since the “Simulation, Evaluation, Analysis, and Research on Air Defence Systems” (SEAROADS) model has a modular structure, different systems and tactics are analyzed on a single ship to increase surviving ability.

Boinepalli and Brown (2010) develop Ship Air Defense Model (SADM) and mainly focuses on the hard-kill and soft-kill weapon coordination and its effects.

Bourassa (1993) uses The Extended Air Defense Simulation Model (EADSIM) which is a theater-level AAW model and analysis tool that includes different hard-kill and soft-kill weapons, defensive and offensive counter-air operations, radars, etc. to develop AAW scenarios for specific weapon use.

Karasakal (2008) revises a naval TG under the SLS engagement policy to maximize the air defense effectiveness by developing two integer programming models. Karasakal, Kandiller, and Özdemirel (2011b) consider sector location of ships and solve sector allocation problem to determine robust air defense formation. Karasakal, Kandiller, and Özdemirel (2011a) define missile allocation problem as the optimal assignment of SAMs to incoming ASMs and propose efficient heuristic procedures.

Silav et al. (2019) present a dynamic missile allocation model that updates the initial engagement plan whenever a disruption occurs. The model aims to maximize the TG's effectiveness while maintaining the stability of the existing plan. Silav et al. (2021a) also consider engagement sequences so that re-tracking of targets is not required. Karasakal et al. (2021b) propose a novel approach that extends previous works. In this study, dynamic responses for rescheduling are received from an artificial neural network (ANN) which is trained according to the decision maker's priori articulated preferences.

CHAPTER 3

AIR DEFENSE SIMULATION MODEL

3.1 Simulation Conceptual Modeling: Event Graphs

In this thesis, the air defense simulation model is developed using the techniques of discrete-event simulation (DES), and the Event Graph methodology which is first described by (Schruben, 1983) is used to represent the model since it is modular, flexible, and scalable. Event Graphs, which are renamed as Simulation Graphs, are graphical representations of DES models, and DES is implemented in Simkit, an open-source java package, which was developed by (Buss & Stork, 1996).

Interested readers may find more information related to DES, Event Graph methodology, and Simkit from (Buss, 1996), (Buss, 2001b), (Buss, 2001a), (Buss, 2000), (Buss & Sánchez, 2002), (Buss, 1995), (Buss & Sánchez, 2005), (Buss, 2002).

Simulation Graphs consist of simulation components and show the interaction between these components. Each simulation component includes events and state variables defined for itself.

For instance, Figure 3.1 shows the ASM component. In the figure, nodes represent events, directional arrows show cause and effect relation between events, and the letter inside the small box points out the event parameter. The explanation above the arrows indicates the condition for the next events. The time value on the arrows shows the required time for the next event.

Considering this information, Figure 3.1 demonstrates the followings: Firstly, ASMs are initialized and generated after ASM-specific *generation times*. Then, each ASM starts to move toward its target ship k. For the move of the ASM, *Start Move* and *End Move* events are generated simultaneously. *End Move* event is scheduled *flight* *time* later than *Start Move*, and *flight time* is calculated according to the speed and current location of the ASM, and the location of the target ship.

If an ASM is a *new ASM*, which means that it is not known and detected by any sensor at time 0, a D*isruption* occurs. Also, if the value of P_{tc}, probability of changing the target ship, is greater than the generated uniform linear random number, then the target changes its target ship and moves toward a new target ship. Thus, we can follow the events from the event graph of a component. Events in each event graph of components are listed in the Future Event List.

Further explanation of ASM and other components will be given in Chapter 3.3.

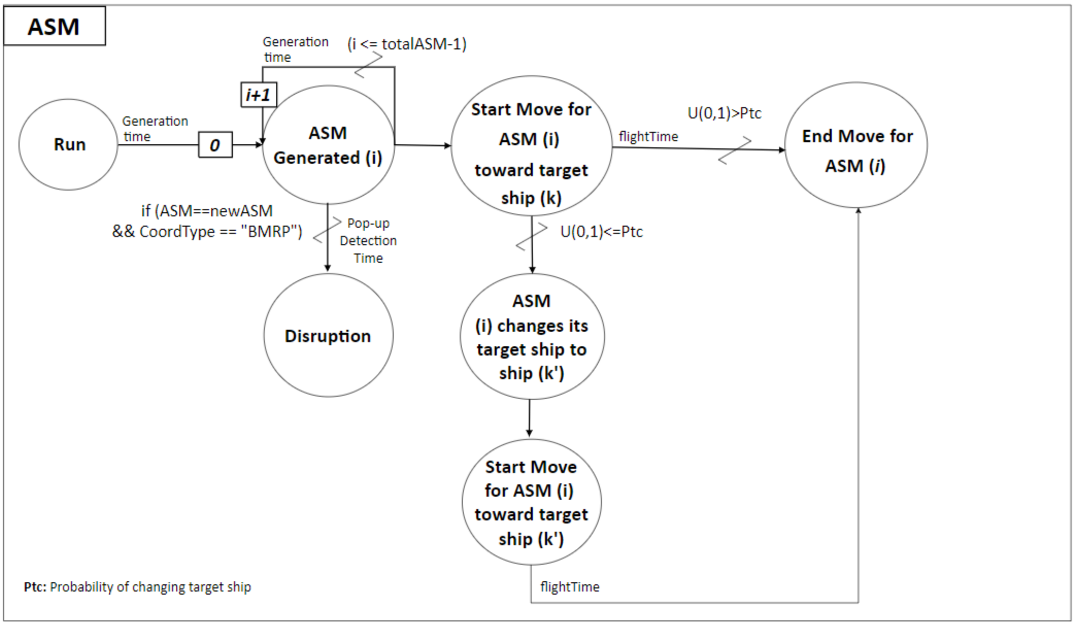

Figure 3.1. ASM Component

Another important characteristic of Event Graphs is that they can listen to each other, and the event list is updated based on these listeners. Figure 3.2 shows a listener relation between Mover and ASM component. *Mover* component is a listener of the ASM component, and its graphical representation can be shown in Figure 3.2.

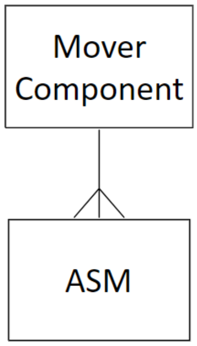

Figure 3.2. Listener of ASM Component

In Figure 3.1. and Figure 3.3., it is seen that they have *Start Move* event with the same signed ASM and target ship parameters in common. Therefore, if a *Start Move* event is scheduled from the *ASM* component, the same signed event is called from the *Mover* component, and the *Mover* component moves the object to the given target ship location.

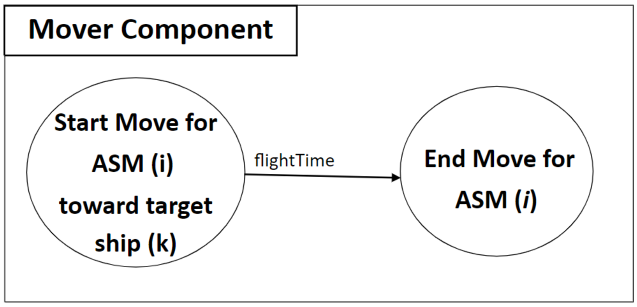

Figure 3.3. Mover Component

3.2 Problem Definition

TG is a group of ships located at sea with a given formation to accomplish a mission or missions. Consider several ships that form a naval TG to defend themselves against targets. Positions of ships in TG are called as formation, and typically the most important unit High-Value Unit (HVU) is settled in the center surrounded by the other defensive ships. These defensive ships may have self-defense or area-defense capabilities against air threats. Self-defense ships have only self-defense type SAMs on them and defend only themselves, whereas area-defense ships have at least one kind of area-defense type SAMs onboard and can also defend other ships within their effective ranges. SAMs have minimum and maximum effective ranges to shoot down incoming target ASMs. Ships have a sensor(s) on them for detecting targets' type, speed, and range. They also have a tracker(s) to track the targets and control the launched SAM to the interception point. Each ship has a Central Fire Control Unit (CFCU) for commanding tracker, launcher(s), and missiles based on the scheduled engagement plan. When there is full coordination in naval TG, ships share all the information and communicate with each other via TGAAWC. This improves the reaction time and efficiency of the TG.

For instance, consider a TG consisting of 4 ships including an HVU and 3 attacking ASMs as demonstrated in Figure 3.4. Ship 1 is HVU and protected by escorting vessels. Ship 2 has a long-range SAM 1 area defense system, Ship 3 has a short-range SAM 4 self-defense system, and Ship 4 has a SAM 2 self-defense and SAM 3 area defense system. Therefore, Ship 3 is a self-defense ship where Ship 2 and Ship 4 are area-defense ships. Black-dotted circles represent the maximum ranges of SAM systems. For Ship 4, it is the maximum effective range of SAM 3 area defense system. ASM 1, ASM2, and ASM 3 attack Ship 1, Ship 4, and Ship 3, respectively. Red-dotted lines show the way between an ASM and its target ship. Ship and ASM locations are indicated with cartesian coordinates.

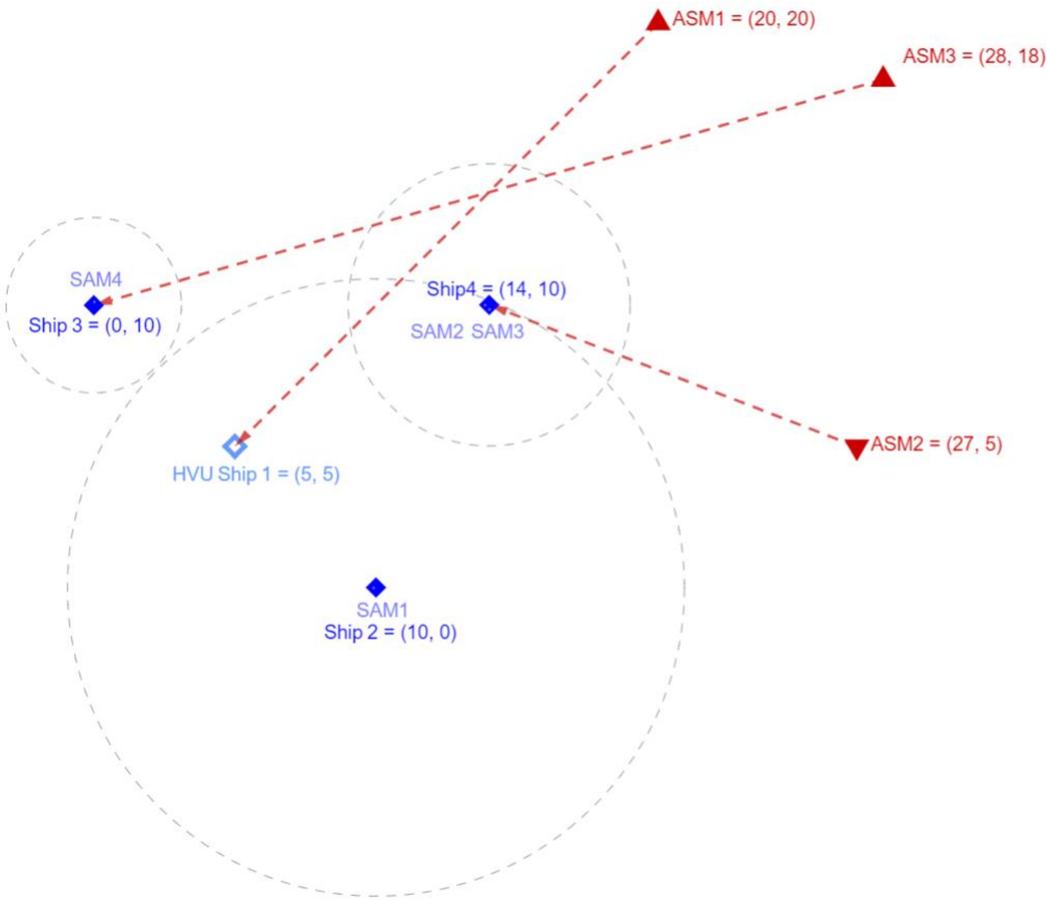

Figure 3.4. An Example of an Air Defense Scenario

ASM 1 can be neutralized by SAM 1 or SAM 3 area defense systems since HVU has no defensive systems. ASM 2 can be engaged by only Ship 4 with SAM 2 self-defense or SAM 3 area-defense system. It cannot be shot from Ship 2 because SAM 1's maximum effective range does not contain the flight path of ASM 2 through Ship 4. ASM 1 can be engaged by SAM 3 or SAM 1 when it is in their effective SAM ranges. Figure 3.5 depicts with a pink-dotted line segment that ASM 1 can be neutralized by SAM 2, and a purple-dotted line segment that ASM 1 can be shot by only SAM 1. Similarly, ASM 3 can be engaged by SAM 3 and SAM 4 in their effective ranges.

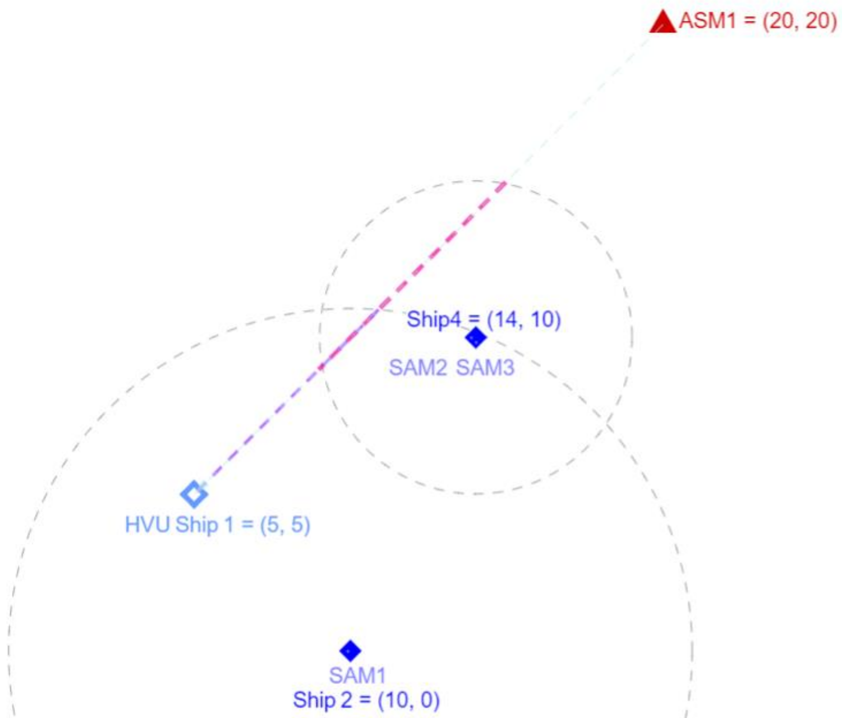

Figure 3.5. Line segments where ASM 1 is engaged by SAM 1 and SAM 3

Besides this information, sensor detection ranges take an important role because air defense operation starts after the detection of the attacking ASMs. CFCU of the ship attains detection information and shares it with TGAAWC. Then, according to the selected air defense strategy, TGAAWC plans the engagement and sends this information to ships.

Assumptions of the model which can be seen below are for focusing only on the critical parts of the problem.

- SAMs and ASMs move linearly without acceleration.
- Ships are assumed to be stationary since their velocities are negligible compared to SAMs and ASMs.
- ASMs are detected with a certain detection probability $P_d = 1$ when they enter any sensors' range.
- Kill probability, P_k, between an ASM and SAM is known.
- ASMs' initial location, speed, and target ship are known.

- ASMs and SAMs are assumed to fly at constant altitudes. Therefore, distance calculations are made in a 2D cartesian coordinate system.
- Breakdown probabilities of SAMs are known.
- SAMs are semi-active missiles.
- Engagement policy is SLS.
- Soft kill weapons such as decoys and jammers are not considered.

3.3 Event Graph of the Problem

The Event Graph representation of our model can be found in Figure 3.6. In a naval TG, there are 1 to n defensive ships each of which contains related sensor(s), tracker(s), launcher(s), CFCU, and SAM(s) to defend themselves from incoming targets.

The simulation starts with *Initialize* and then *ASMs* are generated and start to move. Moving components such as ASM and SAM are listened to the *Mover* component to manage movements. *Sensor-ASM Mediator* informs *Sensor(s)* about targets in sensor's range, and *Sensor* sends this detection notice to *CFCU* of the ship. CFCU gets related information about track (from *Tracker*), launch (from *Launcher*), and missiles (from *SAM*), and shares it with *TGAAWC*. According to the coordination level, *TGAAWC* schedules the engagement plan. *CFCU* commands *Tracker* and *Launcher* for the firing process. Engagement result is evaluated by *SAM-ASM Mediator* and based on the result necessary actions are taken.

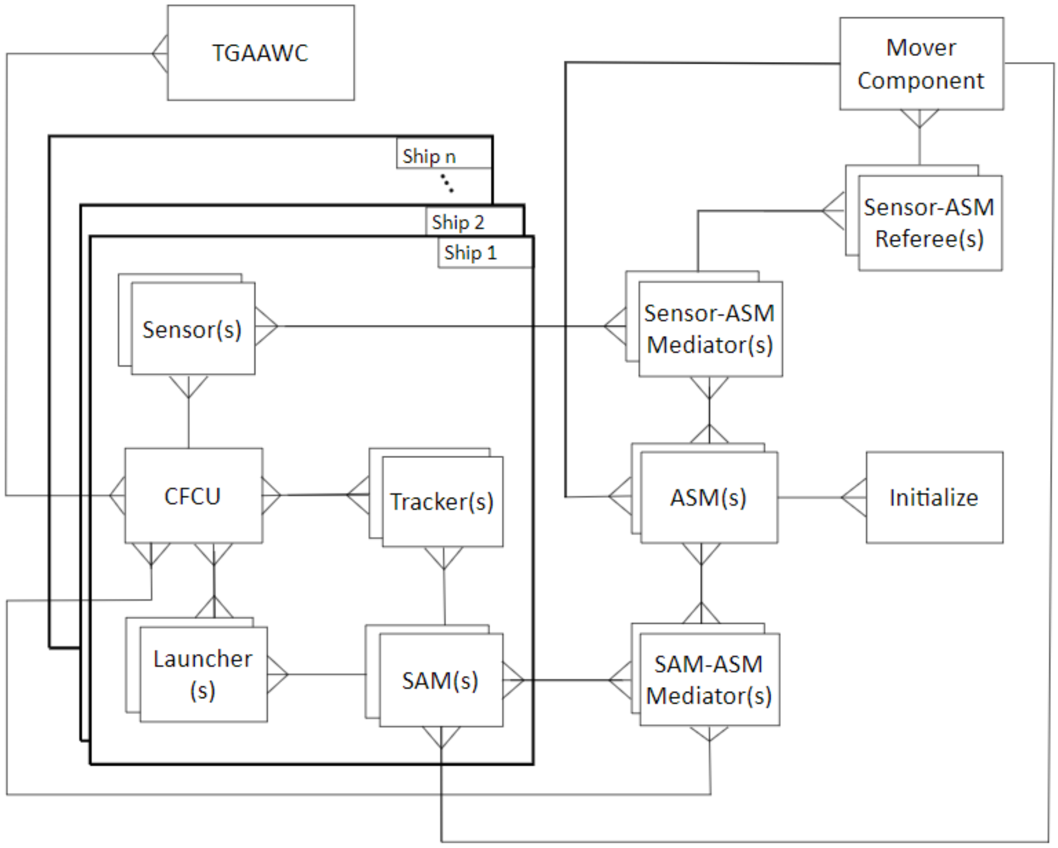

Figure 3.6. Detailed Event Graph of the Model

The main components of the event graph model are listed below, and detailed descriptions of the main components are explained after that.

1. Initialize
2. ASM
3. Sensor-ASM Referee
4. Sensor-ASM Mediator
5. Sensor
6. Central Fire Control Unit
7. TG AAW Coordinator
8. Tracker
9. Launcher
10. SAM

11. SAM-ASM Mediator
12. Mover Component

Initialize Component

Initialize component sets the initial values of parameters of model components such as ships, sensors, trackers, launchers, SAMs, and ASMs, and the definition of component parameters can be found in Figure 3.7 below. The detailed *Initialize Process* can be seen in Figure 3.8.

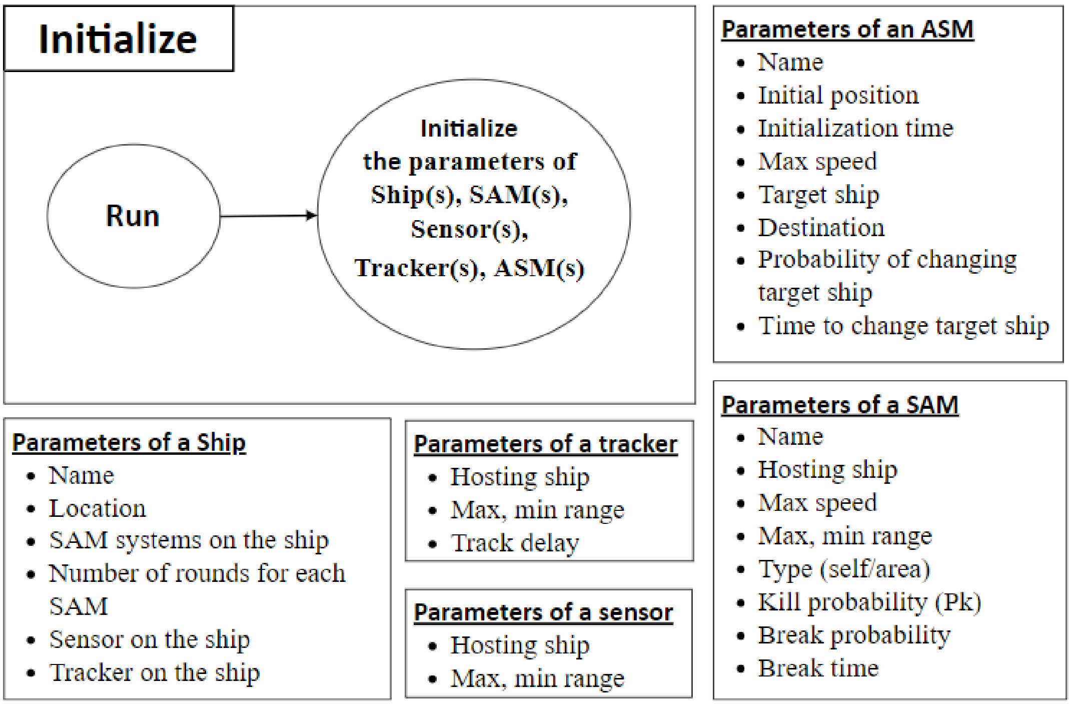

Figure 3.7. Initialize Component

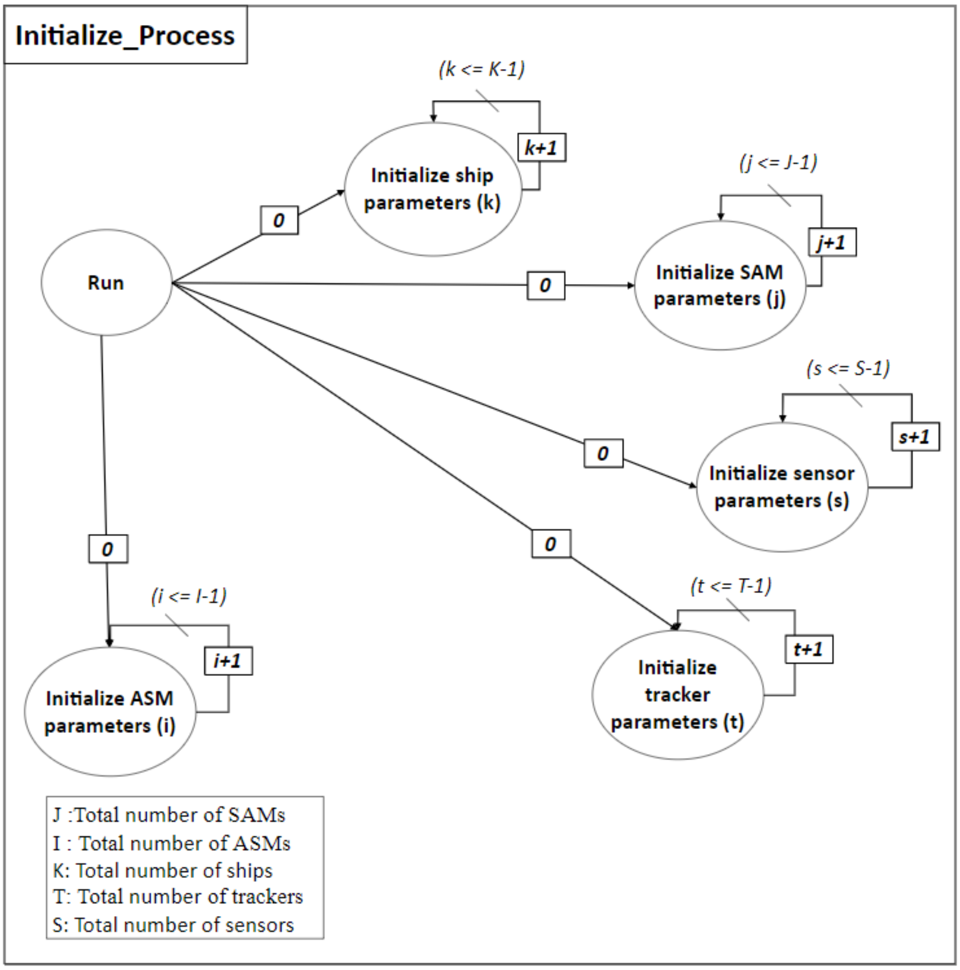

Figure 3.8. Initialize Process

ASM Component

ASM component in Figure 3.9. starts with the *Run* event which is heard from *Initialize* component by listening to it. Then *ASM Generated* event is fired at generation times. Generation time is an ASM-specific property and ASMs are initialized at these times.

ASMs which are not detected by sensors at time zero are called as New ASM, and if a new ASM is detected then a *Disruption* occurs after pop-up detection time later.

The main mission of the *ASM* component is to make ASMs move toward their target ship. *Start Move* event is heard by the *Mover* component, and thus ASMs move toward their target ships.

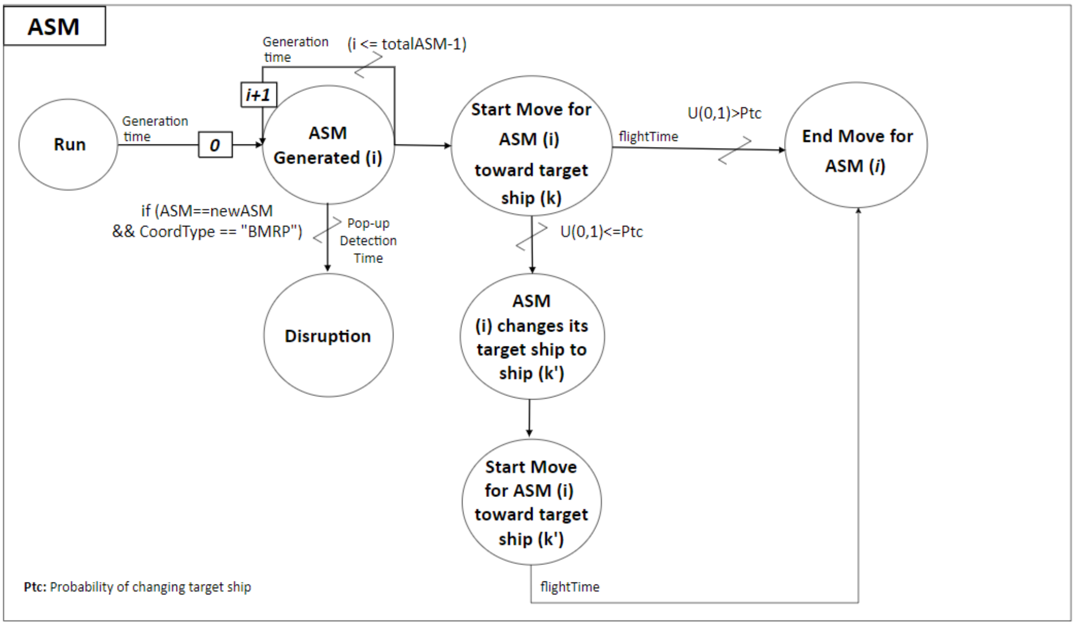

Figure 3.9. ASM Component

Sensor-ASM Referee Component

Sensor-ASM Referee Component listens to the *Mover* component and hears the same-named and signed *Start Move* and *End Move* events. If *Start Move* event causes ASM to enter a sensor's range, then *Enter Range* event is scheduled, and after the time which is required for the ASM to leave the range of the sensor, TimeToExit, passes *Exit Range* Event is scheduled.

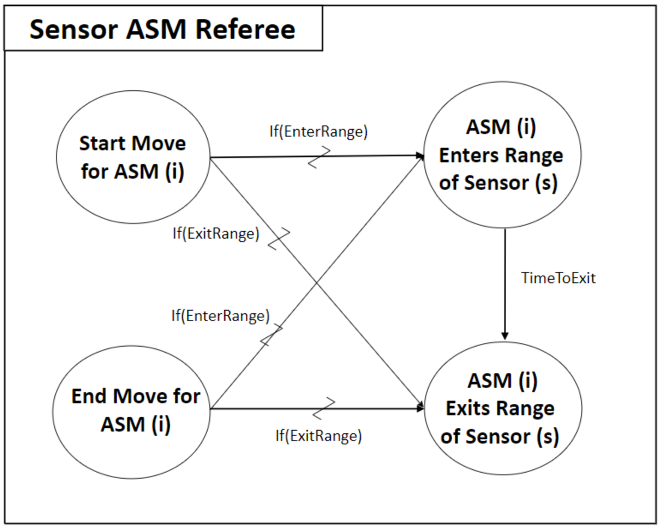

Figure 3.10. Sensor ASM Referee

Sensor ASM Mediator Component

Sensor-ASM Mediator listens to *Sensor-ASM Referee* for *Enter Range* and *Exit Range* events, and it receives the probability of detection information from the *Sensor* component, gives detection or non-detection decision, and sends this response to the Sensor. Since detection probability is always equal to 1 for our problem, whenever a target enters a sensor's range it is always detected.

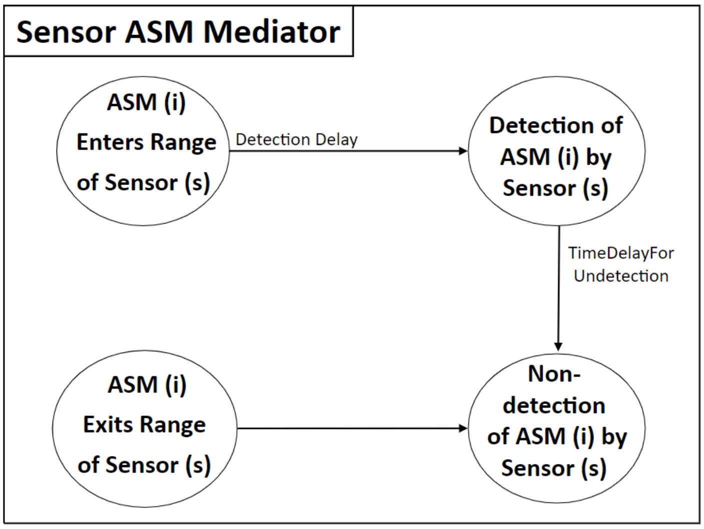

Figure 3.11. Sensor ASM Mediator

Sensor Component

Sensor component which is shown in Figure 3.12 shares *Detection* or Non-*detection* information of an ASM in the sensor's range to CFCU.

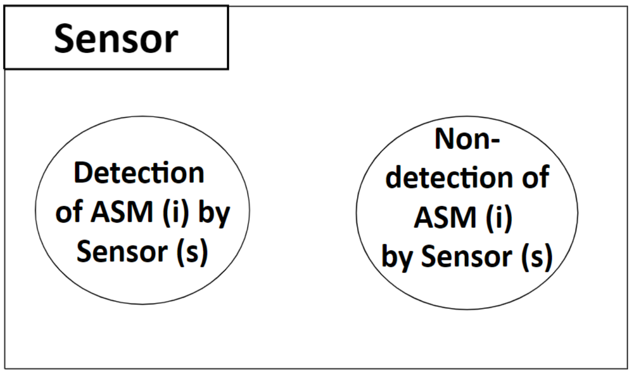

Figure 3.12. Sensor Component

Central Fire Control Unit (CFCU) Component

CFCU is activated with the detection of the target entering the Ship's sensor range. Each ship has a CFCU to control the firing process and command tracker and launcher.

It receives launch delay, characteristics of SAM, and the number of available SAM rounds from the *Launcher* component and gets track delay and the number of available track capacity from the *Tracker* component. The gathered information is shared with *TGAAWC* to get the engagement plan.

CFCU also listens to *ASM-SAM Mediator* to get the result of the engagement. If the target is killed, it is simply removed from the system. However, if the incoming ASM is not killed, the *CFCU* component requests for re-engagement plan and gets the updated plan from *TGAAWC* (if the BMRP model is not used).

When full coordination policy is applied with the BMRP model, if the target ASM is killed, a *Disruption* occurs, and the engagement plan is updated.

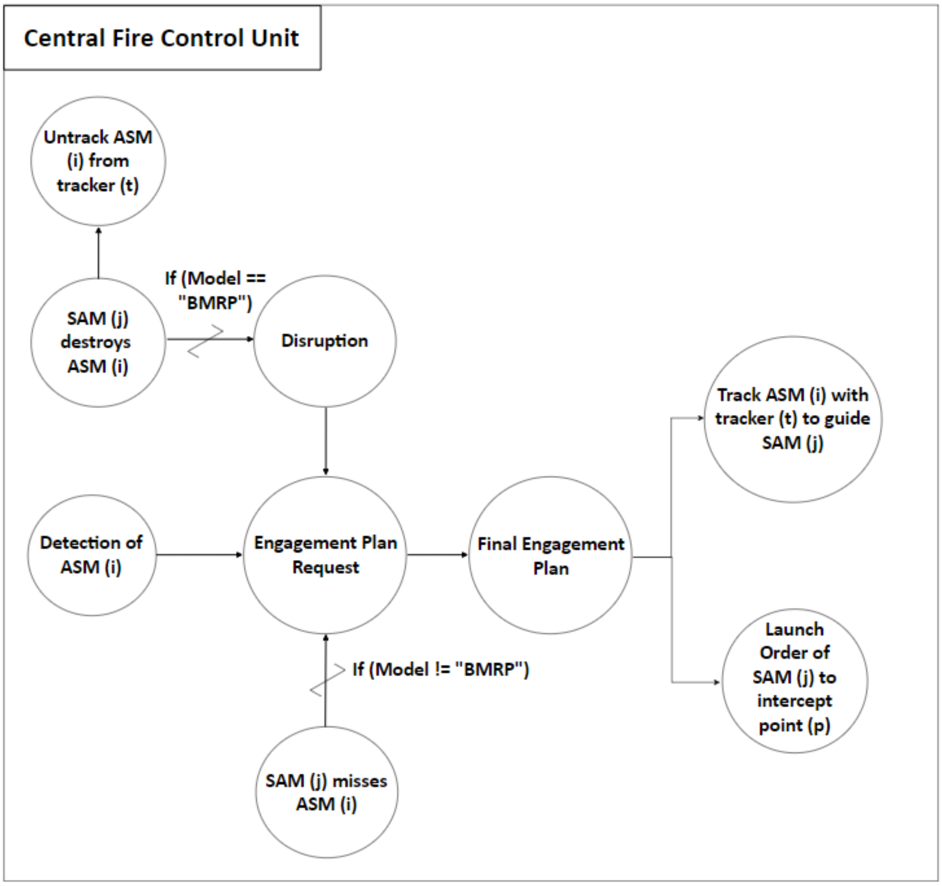

Figure 3.13. CFCU Component

TG AAW Coordinator (TGAAWC) Component

TGAAW takes the listed information from CFCU by *Engagement Plan Request*:

- Characteristics and number of available SAM rounds
- Distance, speed, and type of detected ASM
- Number of available trackers
- Firing policy (which is always considered as SLS for our problem)
- Coordination level
- Engagement rule

Coordination levels can be one of the followings:

- No coordination in TG
- Partial coordination (Sector allocation) of TG
- Full coordination with the BMRP model with different risk levels

The engagement rule determines the order of the engagement plan, and it is used with no and partial coordination levels.

- TOT
- CPA
- HVU-Ship Prioritized

With this information, *TGAAWC* considers all the valid SAMs in TG and schedule the best engagement plan according to the chosen coordination level and selected rule.

When a *Disruption* occurs, *TGAAWC* updates the BMRP model's engagement plan and sends the updated schedule to *CFCU*.

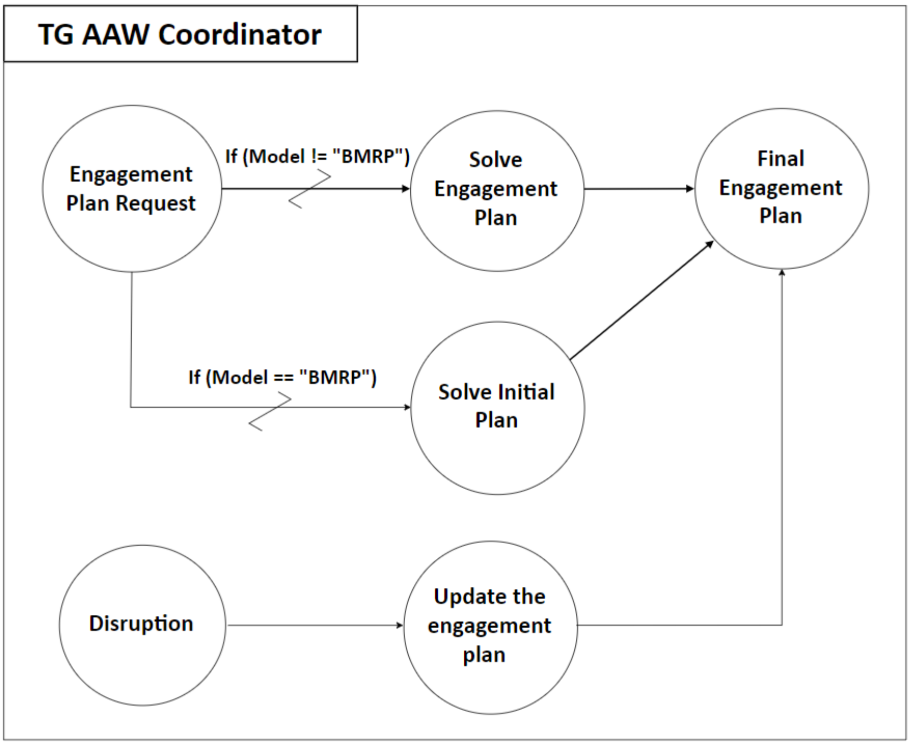

Figure 3.14. TGAAWC Component

Tracker

Tracker component's main mission is to keep track of the target's position to inform the launched SAM for the interception point. While doing this, trackers must not exceed the track capacity which means the number of targets that can be tracked at the same time. To control this capacity, whenever a target is tracked number of track capacity is decreased by one, and when the tracked target exits the sensor range or becomes dead, track is stopped, and track capacity is increased by one. Hence, the tracker component increases track capacity in the following situations: when the ASM which is being tracked leaves the sensor's range, is killed, or hits a ship.

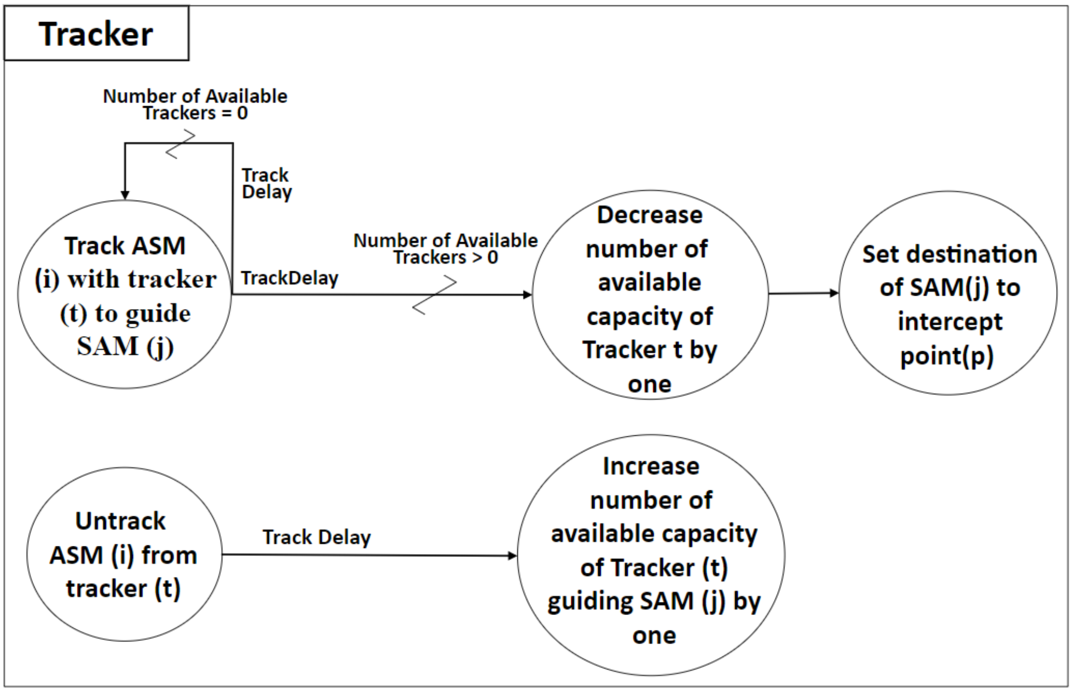

Figure 3.15. Tracker Component

Launcher Component

Launcher hears the Launch Order from *CFCU*, and with the SAM Launched event, the *SAM* component is notified. After Launch Order the number of available SAM is decreased by one and this updated information is shared with CFCU.

If a SAM system is broken, it is removed from the available SAM list, and if the BMRP model is used a *Disruption* occurs, and *CFCU* requests for the updated engagement plan from *TGAAWC*.

Launcher component can be seen in Figure 3.16.

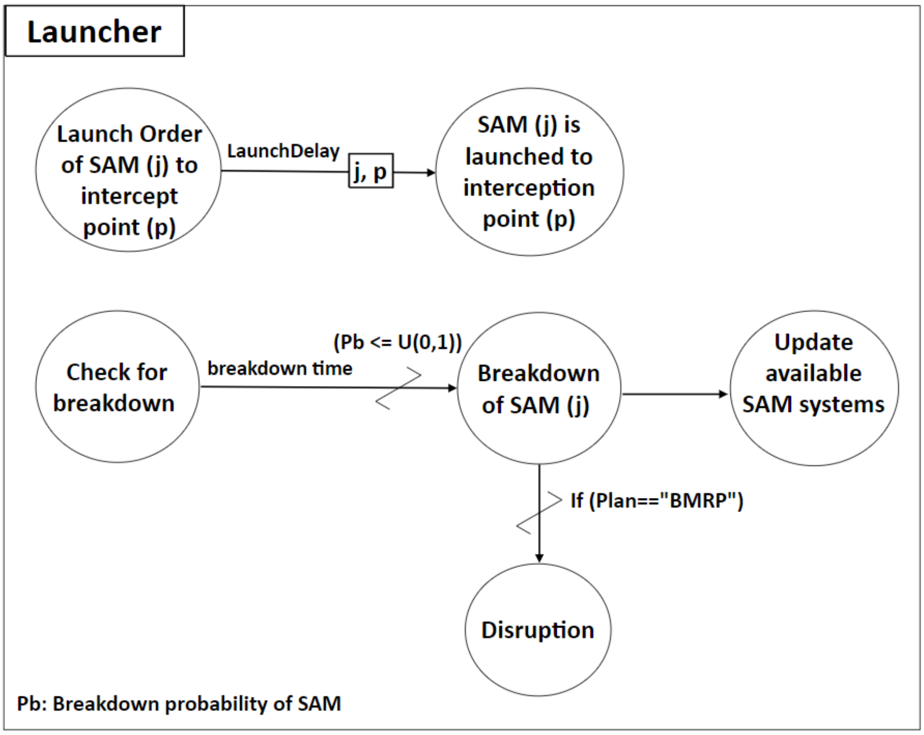

Figure 3.16. Launcher Component

SAM Component

Its main mission is to make the missile move toward its target ASM, and *SAM* component uses *Mover* component to conduct this movement. It receives destination information from *Tracker* and is launched from *Launcher*. *SAM* component which is seen in Figure 3.17 ends its move after the required time to arrive at interception point passes.

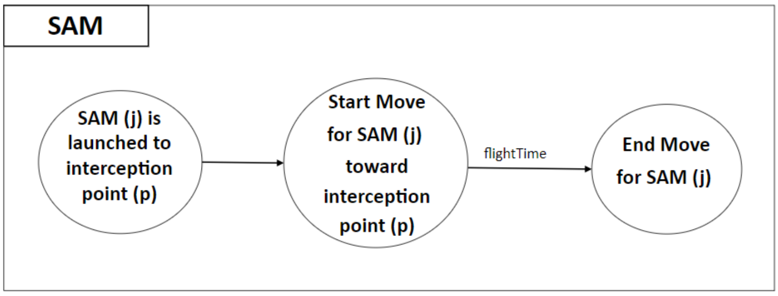

Figure 3.17. SAM Component

SAM-ASM Mediator Component

It is instantiated by SAM Launch event fired from *Launcher*. Firstly, it compares interception point, SAMs, and ASM's location to confirm that they intercept in the SAM's effective ranges and exactly on the determined engagement point. Then, it adjudicates the engagement result by comparing the kill probability of the SAM-ASM pair with a generated uniform random number to give a hit or miss decision and sends this result to the CFCU of the ship that the SAM is launched from. *SAM-ASM Mediator* component can be found in Figure 3.18.

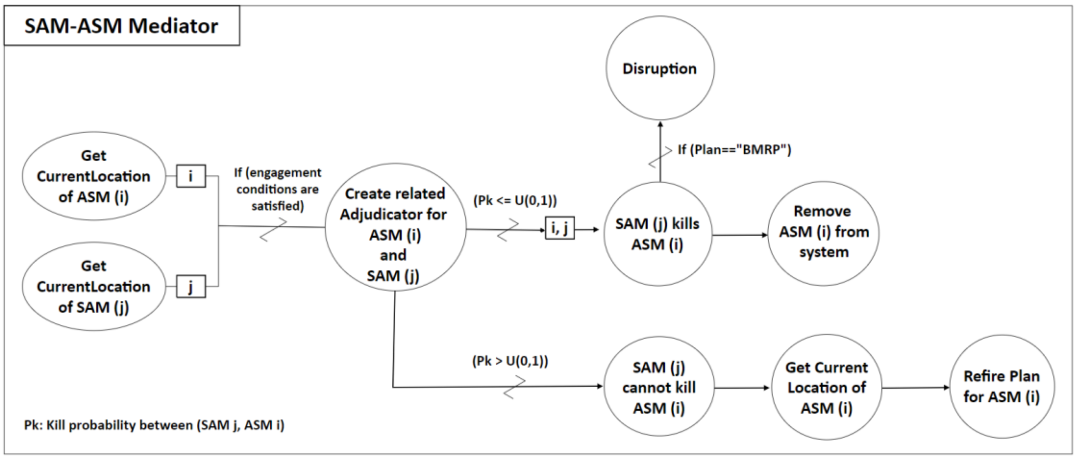

Figure 3.18. SAM-ASM Mediator Component

Linear Mover Component

Mover component given in Figure 3.20 controls and simulates the movements of the mover ASM and SAM by listening to the related components. It does not explicitly show and update the position of movers constantly, instead, it updates and shows movers' location when an event occurs since event-based simulation is done instead of time-based simulation. This is accomplished by only knowing the time interval between events, starting position, and velocity of the movers. Since the relative velocities of the ships are too small to consider when compared to the SAMs' and ASMs' velocities, ships are deemed to be immobile.

When *Start Move* event is generated by *SAM* or *ASM* component, since they are listened to, the *Mover* component hears this event, and *End Move* event is generated according to arrival time to interception.

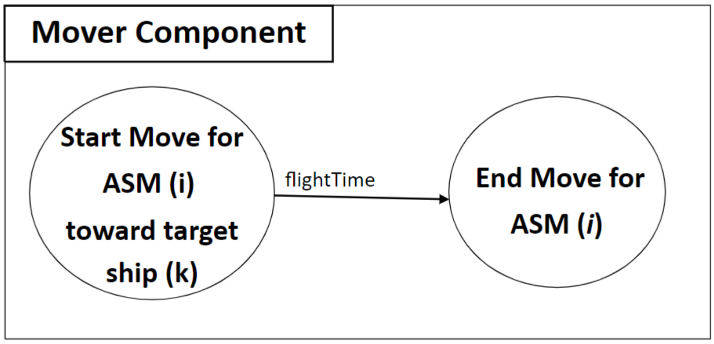

Figure 3.19. Mover Component

CHAPTER 4

SCENARIOS AND COMPARISON OF MODELS

4.1 Validation of The Model

Before evaluating and comparing the alternative models we verify and validate our model to be sure that our model is close enough to the real system and represents the real system's behavior correctly. This part is particularly important, and we must increase the model's credibility to an acceptable level so that we can use this model as a decision tool, predict the system behavior, and analyze the real system with its correct responses. For these reasons, we first verified the model by comparing the conceptual model and the computer representation as explained in the Banks et al. (2014, 5th ed.). For validation, we evaluated the model using face validity and examine the models' outputs consistency. We validate model assumptions and demonstrate the designed sample cases for validation of the model assumptions in the following sections of this chapter.

4.1.1 Evaluated Validation Cases

Designed cases are examined in Java using Simkit. Additionally, cases are mathematically coded and visually presented using GeoGebra (https://geogebra.org). To simplify the calculations and make easier the face validity, scenarios are designed as follows:

SAM and ASM speeds are assigned to values between 1 to 5. The ship, SAM, and ASM locations are given with cartesian coordinates. Target ship is generally selected as HVU and located at the origin. Set up time is assumed as zero for most of the cases.

Aim Point Calculation

Firstly, we need to calculate the aim point regarding the sensor detection range, SAM effective range, SAM, and ASM speeds and locations. For the aim point calculation, we use the sine rule which can be seen in Figure 4.1.

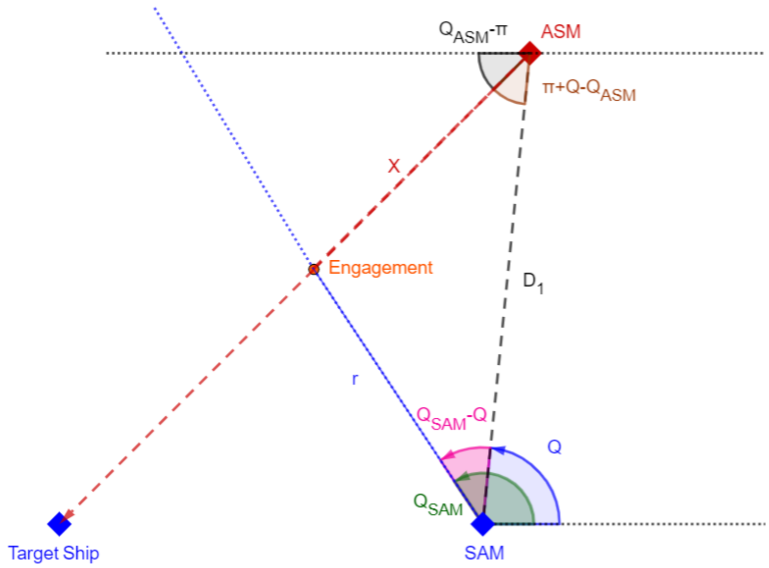

Figure 4.1. Aim Point Calculation

The knowns and unknowns can be seen below, and calculations are made as follows:

knowns: $V_{ASM}, V_{SAM}, Q, Q_{ASM}, D_1$

unknowns: Q_{SAM}, x, r

$$\frac{x}{sin(Q_{SAM} - Q)} = \frac{r}{sin(\pi + Q - Q_{ASM})} = \frac{r}{sin(Q_{ASM} - Q)} \quad and \quad \frac{x}{r} = \frac{V_{ASM}}{V_{SAM}}$$

$$\frac{V_{ASM}}{V_{SAM}} = \frac{sin(Q_{SAM} - Q)}{sin(Q_{ASM} - Q)}, then \;\; Q_{SAM} = Q + \arcsin\left(\frac{V_{ASM} \cdot \sin(Q_{ASM} - Q)}{V_{SAM}}\right)$$

The aim point is calculated dynamically using the equations above. Aim point calculations are graphically proved by using GeoGebra. In GeoGebra, SAM and ASM speeds, SAM, ASM and ship positions are changed manually, and the corresponding updated aim point is calculated.

Description of the Validation Cases

In the figures, red triangles show the initial ASM locations, blue rhombuses represent ships, red dotted lines indicate the line between ASM and its target ship, and blue dotted lines point out the line between the shooting ship and the aim point. Yellow points represent the ASM's location when ASM is detected. Similarly, light-orange points show ASM's location when SAM is fired, and dark-orange points demonstrate the interception point. Blue dotted circles or circular arcs indicate detection, min, and max SAM ranges.

Unless otherwise specified for the validation cases, speeds of ASM and SAM are equal to one, and detection, solution, setup, launch, and damage assessment times are zero, min SAM range is zero, and max SAM range is 100. Although detection, solution, setup, launch, and damage assessment times cannot be zero, they are assumed as zero for the simplicity of the face validation. Also, kill probabilities are set to zero for all cases to see all possible engagements.

The detailed outputs and explanations related to the engagements in the cases are given in Appendix A.

Validation Case - 0: Ship Self Defense

When ships defend themselves aim point is found on the linear line connecting the ASM and target ship, i.e, the aim point solution is solved linearly.

For the example in Figure 4.2, the ship is on the center (0, 0) and ASM is on (20, 20). The distance between ASM and the target ship is 28.3, and the speeds of ASM and SAM are given as 1. Linear aim point solution gives us the middle points (10, 10), (5, 5), (2.5, 2.5), and so on. Since the speeds of SAM and ASM are equal, aim point is found as half of the distance as long as the min SAM range is not exceeded, and we have enough SAM rounds. Therefore, we have checked this case, and see that the aim point calculations are correct.

Since detection and setup times (sum of the track, solution, and launch time) are equal to zero, ASM detection, the first engagement planning solution time and the first SAM launch events happen at time zero. Therefore, the first engagement occurs at point (10, 10).

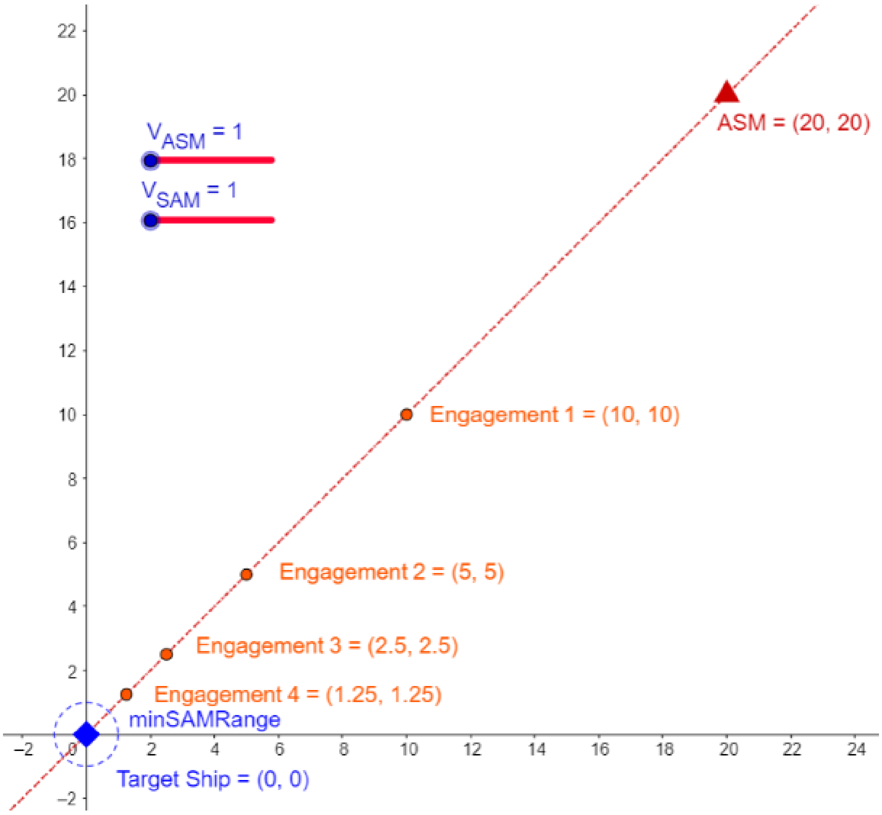

Figure 4.2. Interception Points for Ship Self-Defense Case

Validation Case - 1: Effects of the Change in SAM Speed

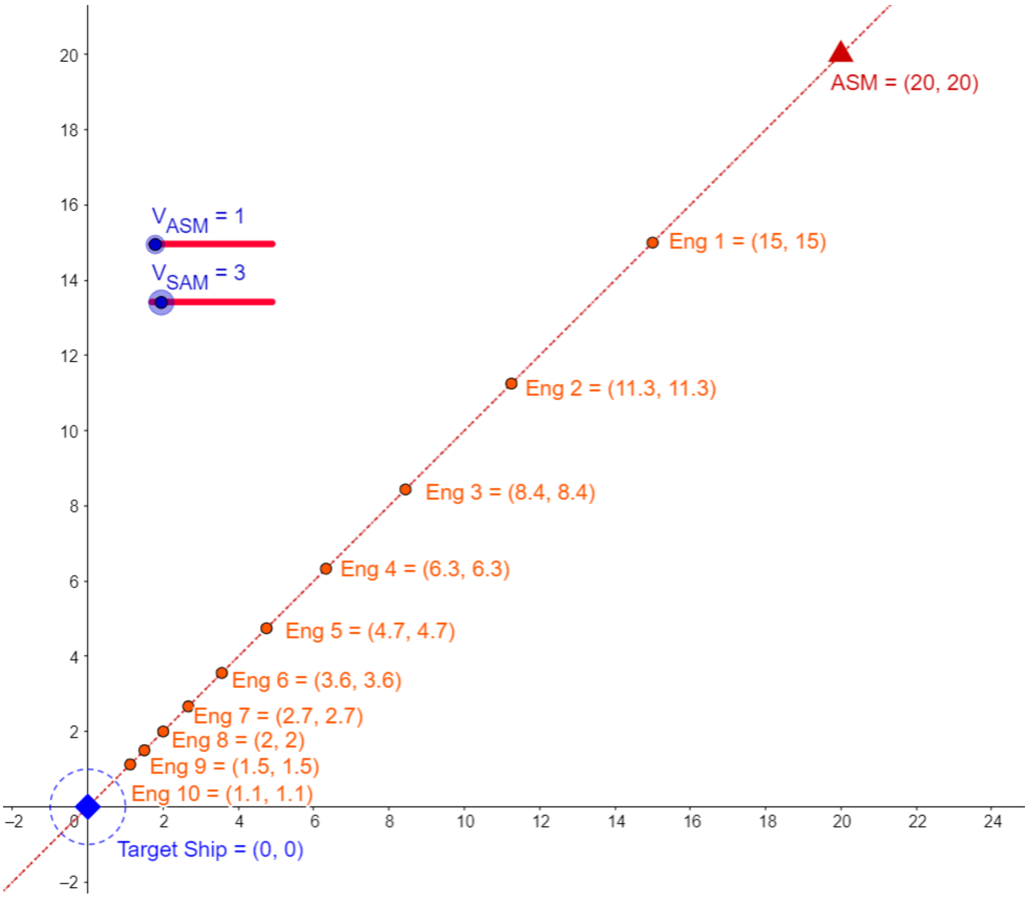

Figure 4.3. Effect of SAM Speed

Changes applied for the validation case: $V_{SAM} = 3$

If the SAM speed is increased to 3, the aim point changes to (15, 15), as it is supposed to. We can easily find the interception points by the proportion of SAM and ASM speeds. Since SAM speed is increased, the number of engagements also increases. While in the previous case, there were four engagements, in this case, 10 engagements occur. The engagement plan is shown in Figure 4.3.

Validation Case - 2: Effects of Change in ASM Speed

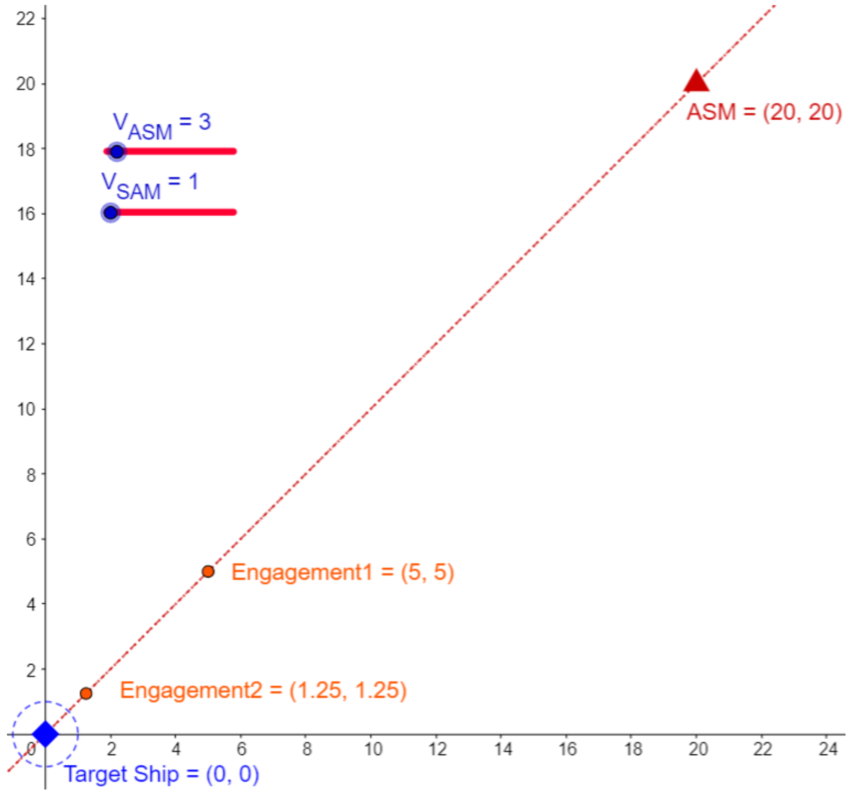

Figure 4.4. Effect of ASM Speed

Changes applied for the validation case: $V_{ASM} = 3$

Conversely, if ASM speed is increased to 3 while keeping the SAM speed at 1, the number of engagements decreases to 2. This was expected because ASM gets closer in a shorter time, and the ship has less time to shoot. We again confirm that the engagements occur at the points proportional to SAM and ASM speeds. These proportional distances can be shown in Figure 4.4.

Validation Case - 3: Effects of Detection and Setup Time

In this case, we increase detection time from 0 to 0.5, and setup time from 0 to 0.5. When an ASM is identified in the range of a sensor, it is detected after detection delay by this sensor. The ship taking information from this sensor finds the best engagement solution with feasible SAMs. Then, the tracker on the ship tracks this target by arranging direction and altitude, and the SAM system is launched. If we increase the time-related metrics, we see the changes in the engagement times and points. Updated engagement points is shown in Figure 4.5.

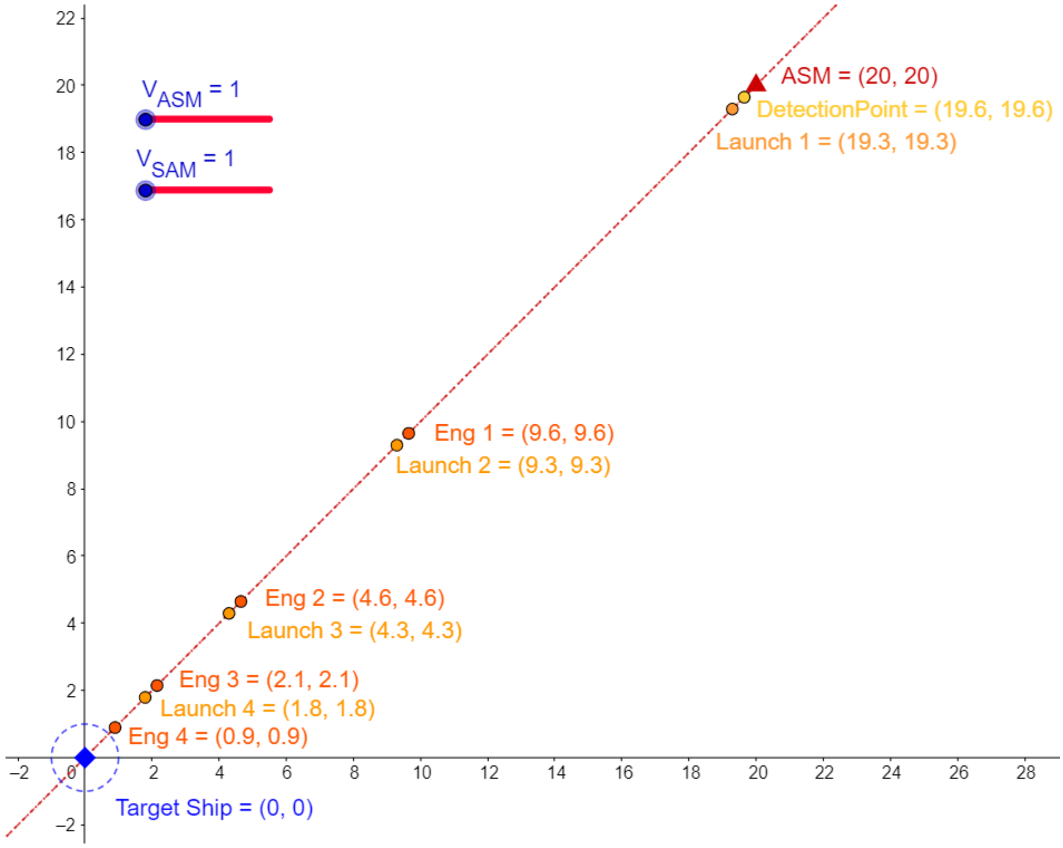

Figure 4.5. Effect of Detection and Setup Time

Changes applied for the validation case: Detection Delay = 0.5, Track Delay = 0.2, Solution Delay = 0.1, Launch Delay = 0.2

Validation Case - 4: Effects of Greater Detection and Setup Time

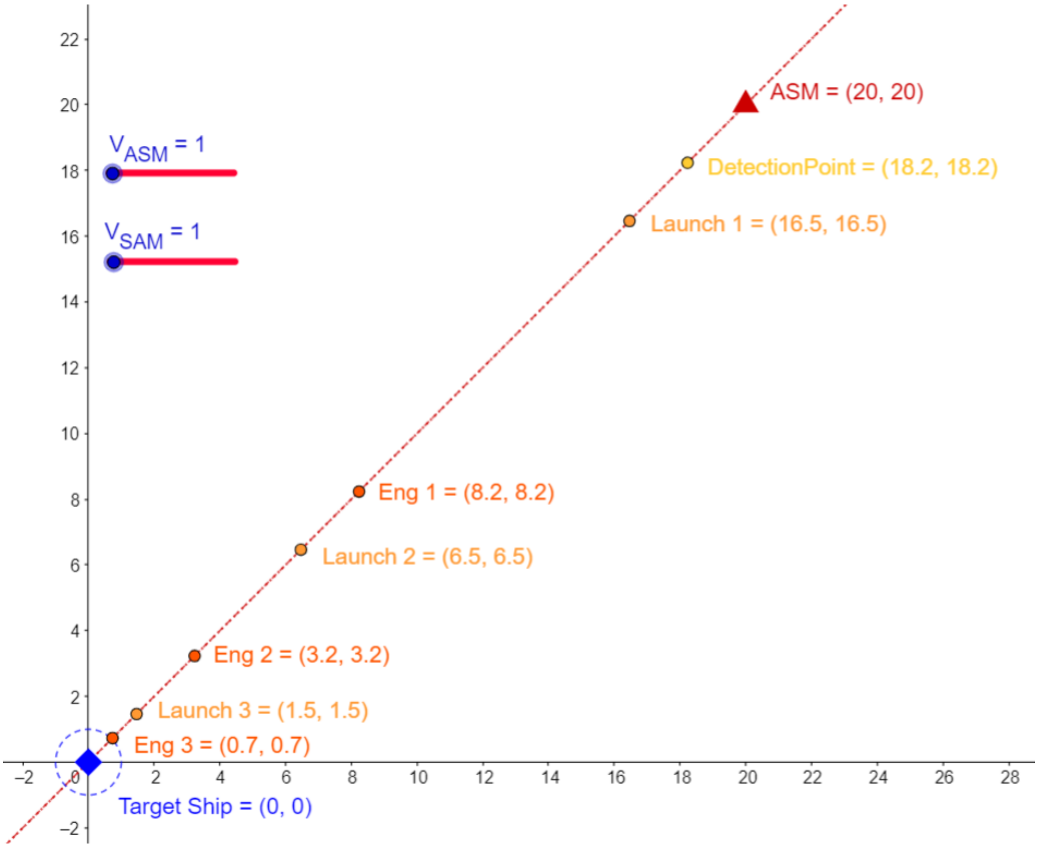

Figure 4.6. Greater Setup Time

Changes applied for the validation case: Detection Delay = 2.5, Track Delay = 1, Solution Delay = 0.5, Launch Delay = 1

To see the time-related difference in engagements clearly, we increase detection and setup times from 0.5 to 2.5. Therefore, it is seen in Figure 4.6. that number of engagements decreases by one, and the ASM is detected 2s later compared to the previous case.

Validation Case - 5: Effect of Damage Assessment Delay Time

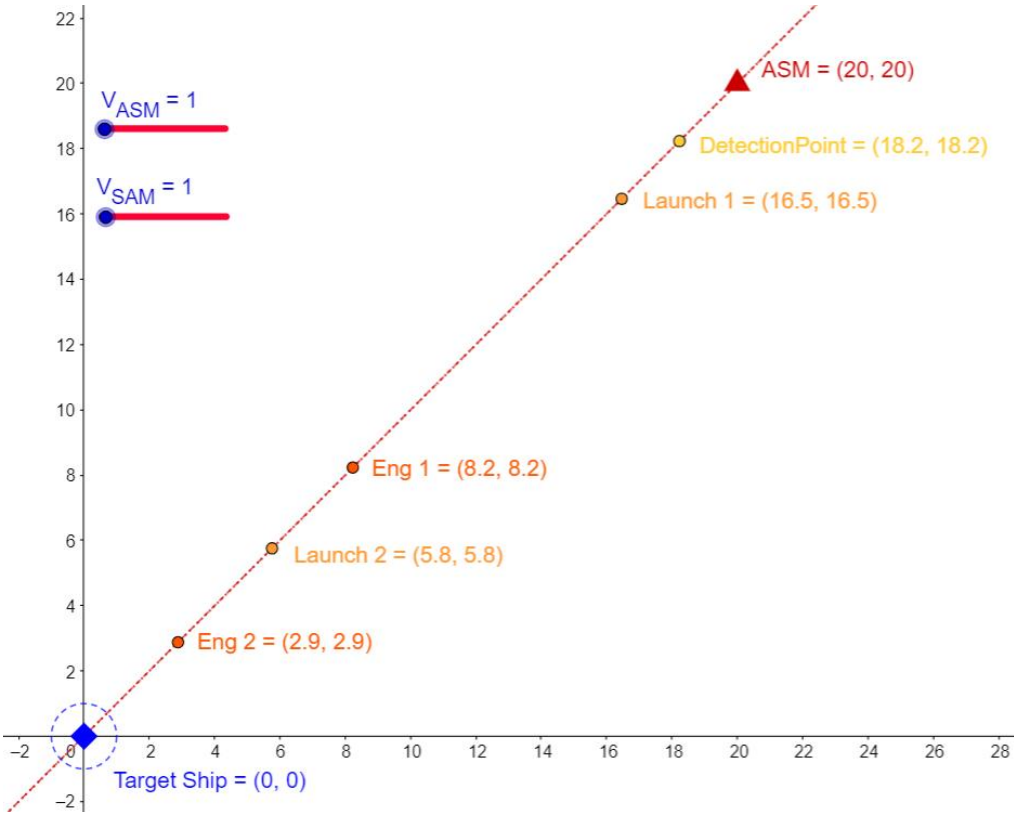

Figure 4.7. Addition of Damage Assessment Delay

Changes applied for the validation case: Damage Assessment Delay = 1. Keep detection and setup time as 2.5.

After every interception, the engagement result is evaluated. If damage assessment time increases, the time between engagements also increases.

We can see the damage assessment time difference after the first engagement. As is seen in Figure 4.7., the second launch is done when ASM is at (5.8, 5.8), while in the previous case the second launch is at (6.5, 6.5). We expected ASM to go 1 more unit from the first engagement point to the second launch since the damage assessment delay is 1 and $V_{ASM} = 1$, and we can see the distance between the coordinations (5.8, 5.8) and (6.5, 6.5) is 1. Therefore, we prove that launch points and damage assessment time effect are also calculated correctly.

Validation Case - 6: Ship Area Air Defense

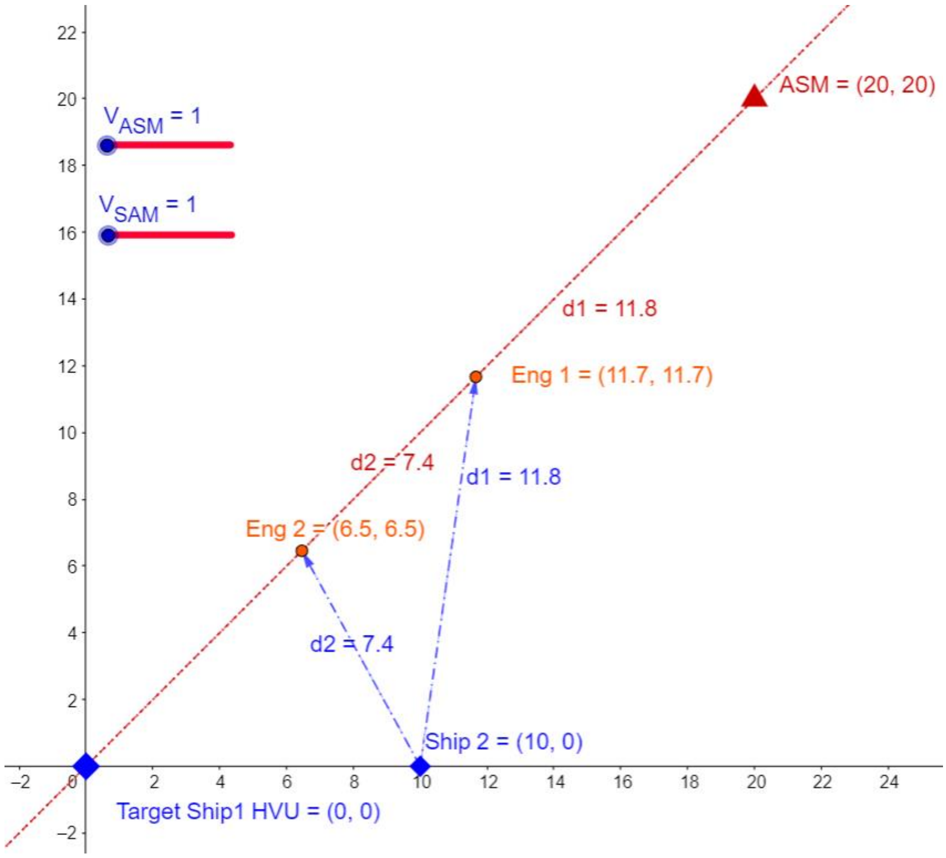

Figure 4.8. Area Air Defense Aim Point Calculation

Changes applied for the validation case: Ship1's type is turned to HVU, therefore it has no munitions on it. Area defense type Ship2 is added to point (10, 0), that is why Ship2 can also defend HVU-Ship. Detection, setup, and damage assessment times are zero.

In area air defense engagement solutions, aim point calculations are done according to the sine rule. Red d_1 shows the distance between ASM's initial position and the first engagement, and red d_2 indicates the distance between first and second engagements. Similarly, blue d_1 and d_2 represent the distances between the Ship2 and the first and the second engagement points, respectively.

Since SAM and ASM speeds are equal, and there is no time delay related to operations, we can clearly see in Figure 4.8. that the aim point is calculated correctly because SAM and ASM have equal d_1 and d_2 distances to arrive at engagement points.

Validation Case - 7: Max SAM Range > Detection Range

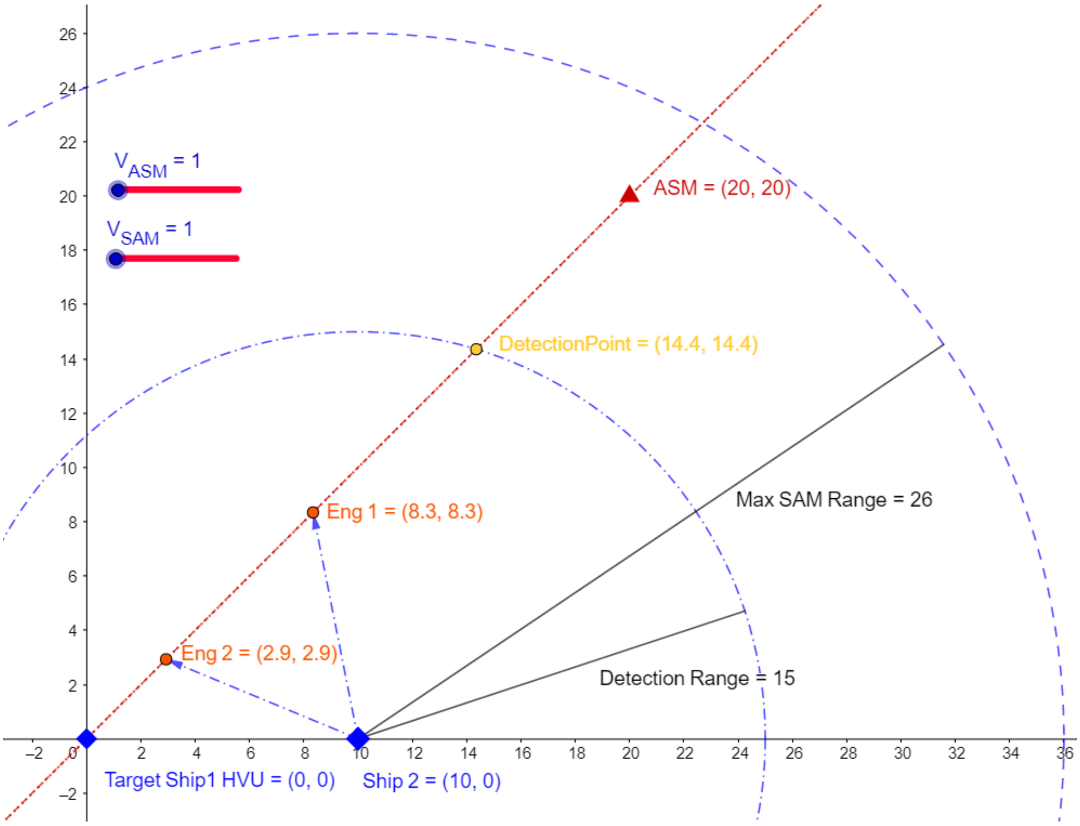

Figure 4.9. Max SAM Range > Detection Range

Changes applied for the validation case: Sensor's Range = 15, max SAM range = 26, detection and setı time are zero

Even if SAMs have greater range capability compared to the sensor's detection range, it is of no use because targets should have been detected first. As a result, engagements happen after the detection point. We see in Figure 4.9 that this logic applies and engagement points are calculated correctly.

Validation Case - 8: Detection Range > Max SAM Range

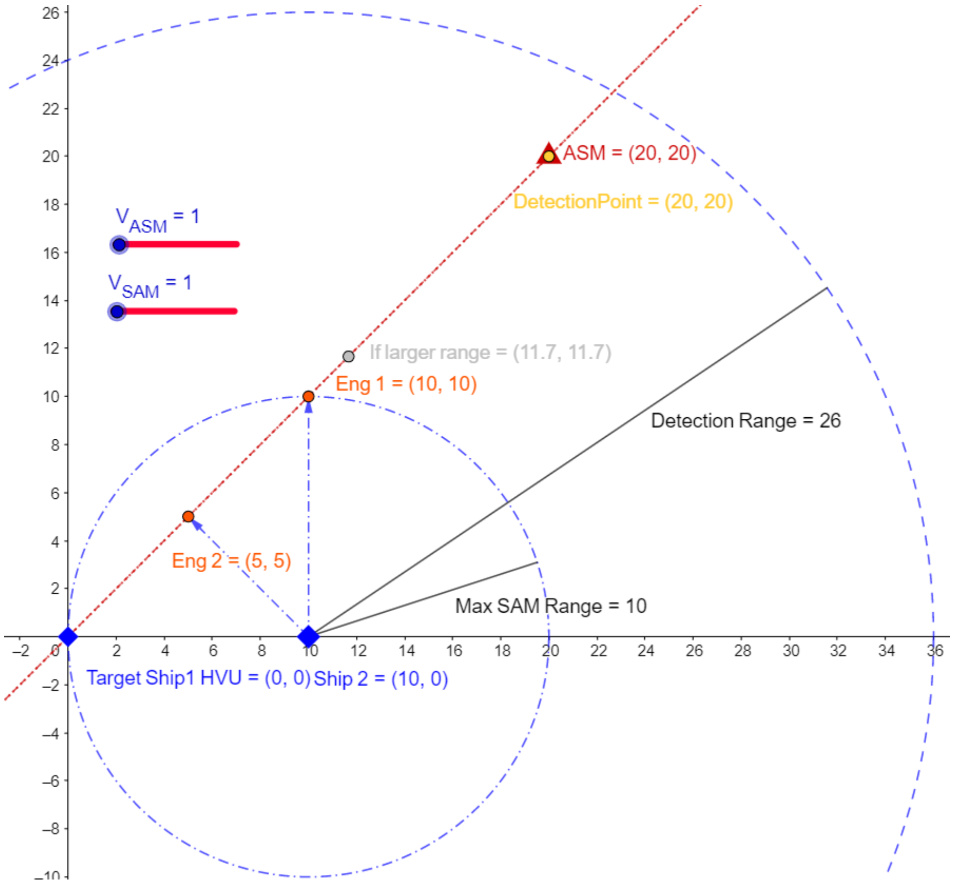

Figure 4.10. Detection Range > Max SAM Range

Changes applied for the validation case: Max SAM Range = 10, Sensor's Range = 26, detection and setup time are zero.

Contrary to the previous case, the sensor detection range is arranged smaller than the max SAM range, and this time SAM range becomes a constraint for the engagement since it is smaller. Therefore, first, the target is detected, and the engagement plan is scheduled as soon as the ASM enters the maximum range of the SAM system.

In this case, if the max SAM range was not a restrictive constraint, the engagement point will be the same as Validation Case - 6, and engagement will happen at (11.7, 11.7) which is shown with the grey point. However, since the max SAM range is 10, the engagement plan is scheduled according to the earliest time that the target can be shot. This point is (10, 10) and we see it in Figure 4.10 that the engagement occurs at that point.

Validation Case - 9: Wait Time

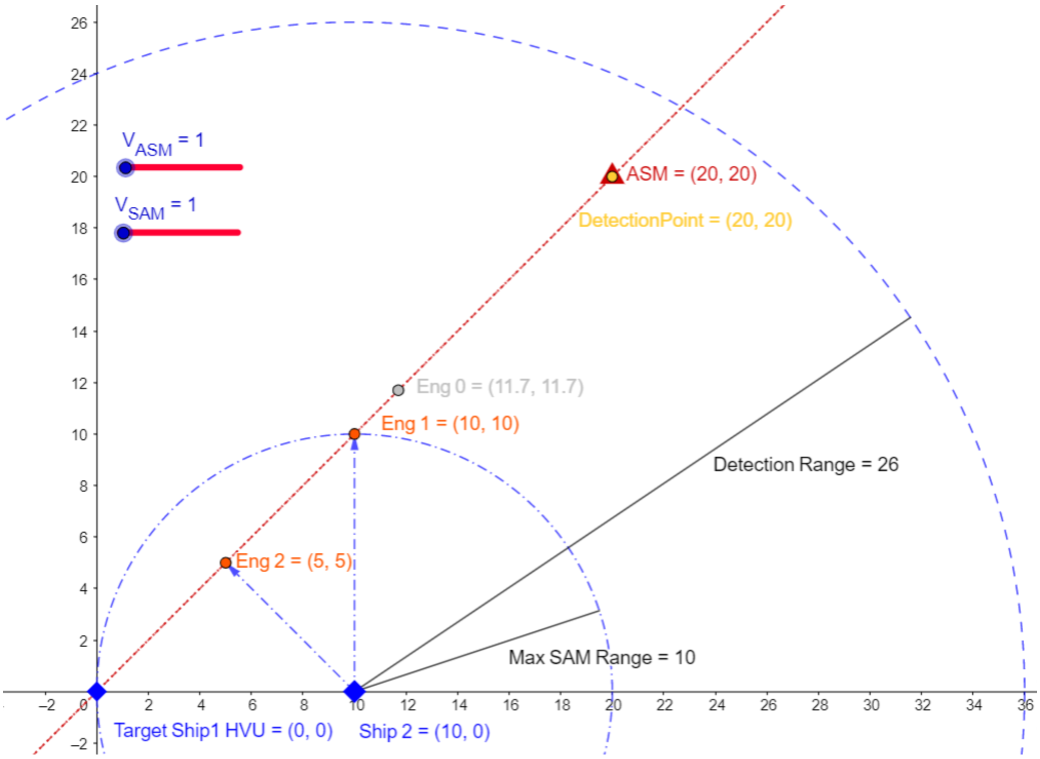

Figure 4.11. Wait Time demonstration

Changes applied for the validation case: Nothing is changed compared to the previous case.

Wait time equals the difference between the arrival times of SAM and ASM to the aim point.

$$wait\ time = arrival\ time\ of\ SAM\ to\ aim\ point\ - arrival\ time\ of ASM\ to\ aim\ point$$

For the example in Figure 4.11, the shooting ship has to wait for ASM to enter its max SAM range. If the max SAM range was not restrictive, engagement happens at (11.7, 11.7). However, the ship has to wait for 4.14 seconds for ASM to get close enough to encounter the ASM at (10, 10). Therefore, the detection time is 0 and the first launch time is 4.14. These times and other details corresponding to the engagement can be found in Appendix A.

Validation Case - 10: Min SAM Range - Max SAM Range

The minimum and maximum SAM range of a SAM system indicate the engageability area where engagements can occur. To see this clearly, SAM speed is increased to 3 to increase the number of engagements. As can be seen in Figure 4.12, no engagements occur closer than the min SAM range, and engagements are only scheduled at points between min and max SAM ranges.

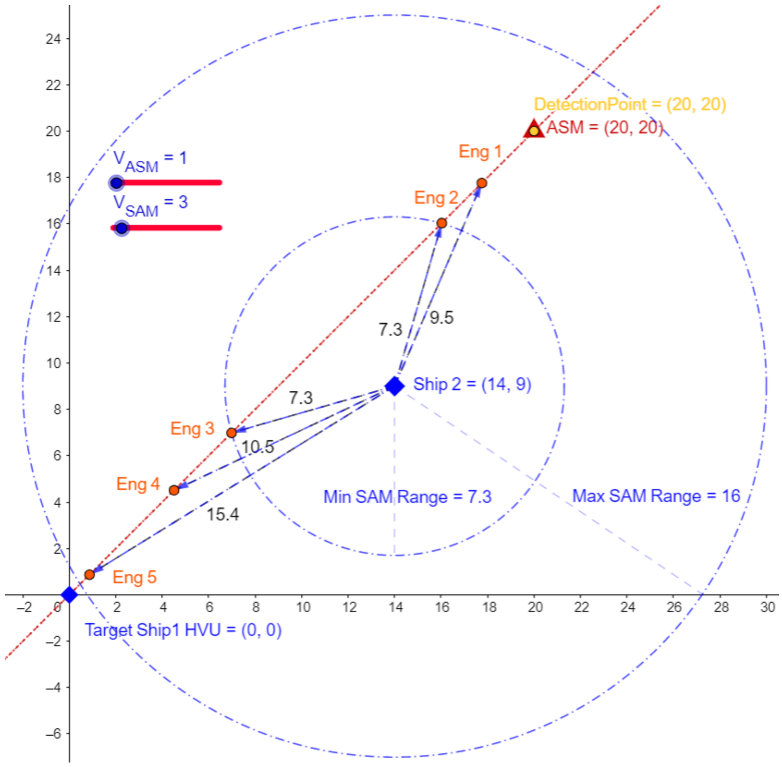

Figure 4.12. Engagements between min and max SAM ranges

Changes applied for the validation case: $V_{ASM} = 1$, V_{SAM} =3, detection range = 100, max SAM range = 16, min SAM range = 7.3

Validation Case - 11: Sector Allocation

To validate engagements are scheduled to the sector that the SAM system is responsible for, Ship2 is assigned to the sector between 270 and 330. Figure 4.13. shows that the engagement is scheduled to shoot the ASM as soon as it enters the sector, and of course, the ASM is already detected, and it is in between the minimum and maximum SAM ranges. Since the engageable area gets smaller, the number of engagements decreases to 1.

This case is extended so that once an ASM enters the sector, the SAM system keeps engaging even if the target exits from the sector in addition to the option that engagements are scheduled only to the sector.

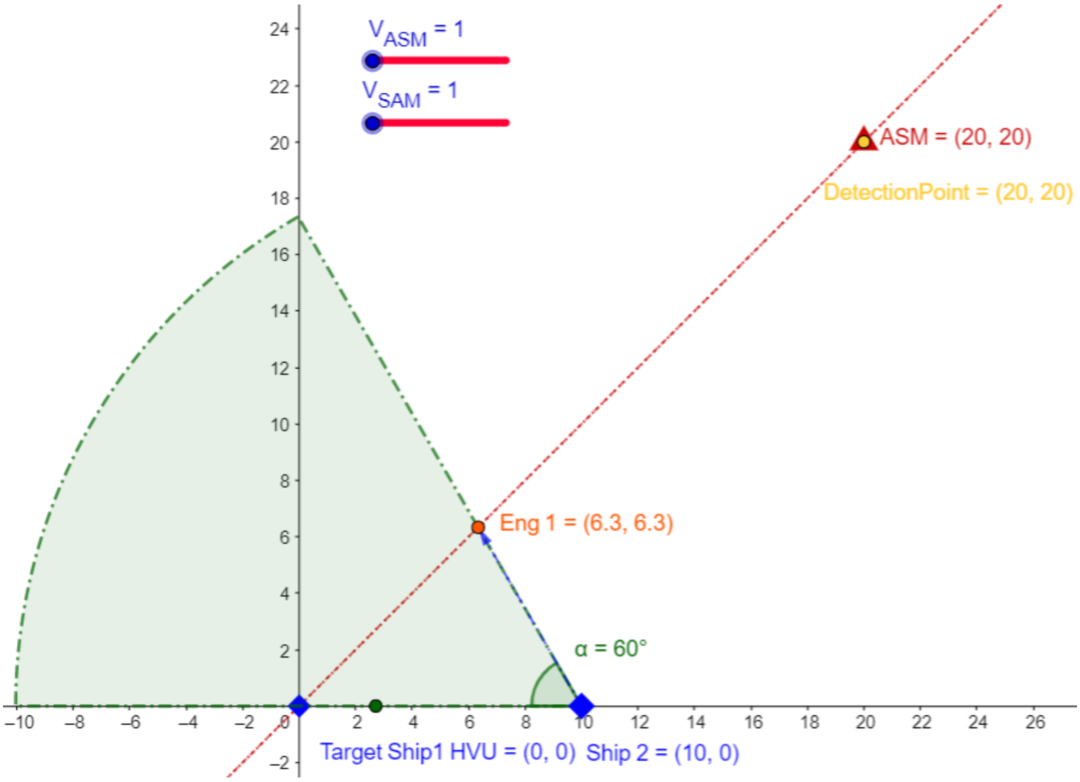

Figure 4.13. Compatibility of Sector Allocation

Changes applied for the validation case: Ship2 is assigned the sectors between 270 and 330.

Validation Case - 12: Effect of the Full Coordination in TG

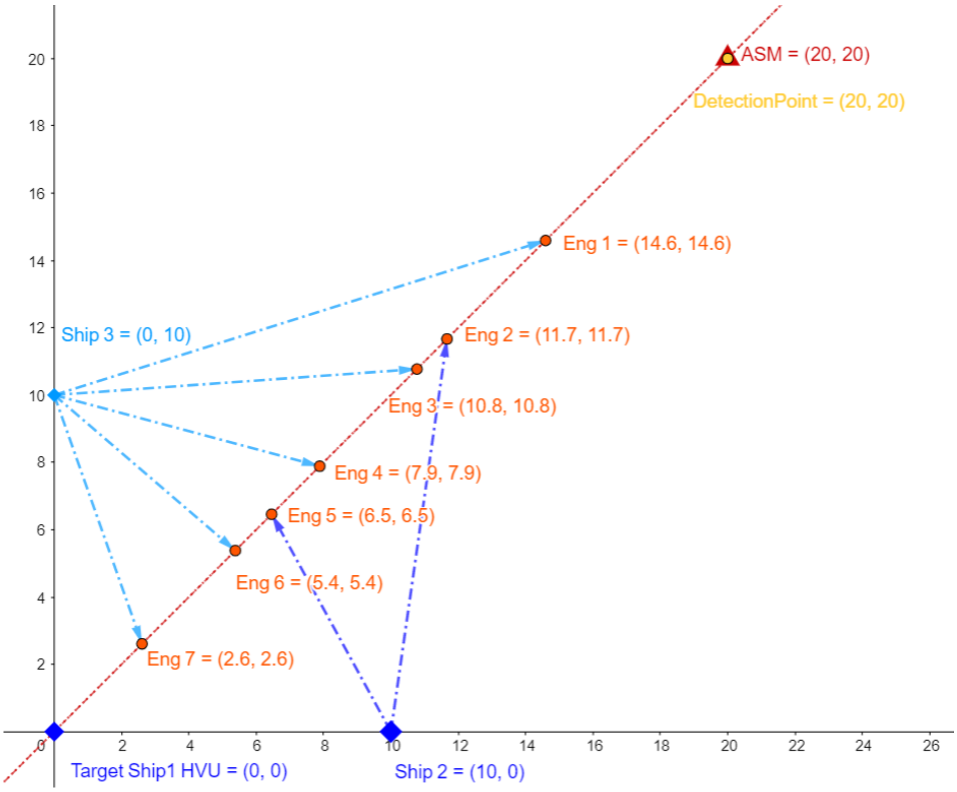

Figure 4.14. No coordination in TG

Changes applied for the validation case: Area defense Ship3 joins the TG. $V_{ASM} = 1$, $V_{SAM\_onShip2} = 1$, $V_{SAM\_onShip3} = 2$.

No coordination in TG causes overlapping engagements to the same target. Figure 4.14. shows no coordination of TG therefore Ship2 and Ship3 schedule engagements independent from each other. For example, Ship2 and Ship3 attack the target at the same time before seeing the result of one of their first engagement. Ship2 makes 2 engagements, Ship3 makes 5 engagements according to their speeds, and a total of 7 missiles expended.

If engagements are planned with full coordination of TG, this prevents overlapping engagements to the same ASM, because TGAAWC considers all SAMs on the ships and decides the best feasible plan according to the selected coordination policy. For instance, in Figure 4.15. TG aims to fire to the ASM in the shortest time, hence SAMs on Ship3 are used because they are faster than the SAMs on Ship2. Total number of expended missile rounds decreases to 5 by this policy and overlapping engagements done from Ship2 are prevented.

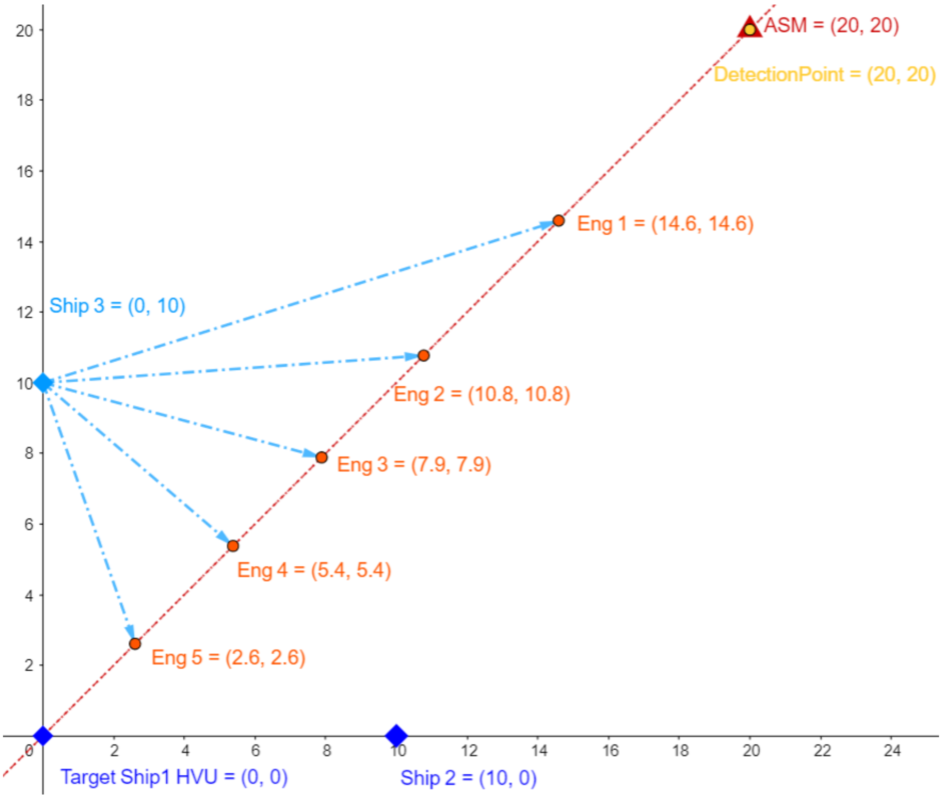

Figure 4.15. Full Coordination in TG

Another benefit of full coordination of TG is that since all TG shares information with TGAAWC, all TG constantly communicates with each other. Therefore, even if only one ship detects a target, all TG has target information, and the engagement can be planned for any valid ship in TG.

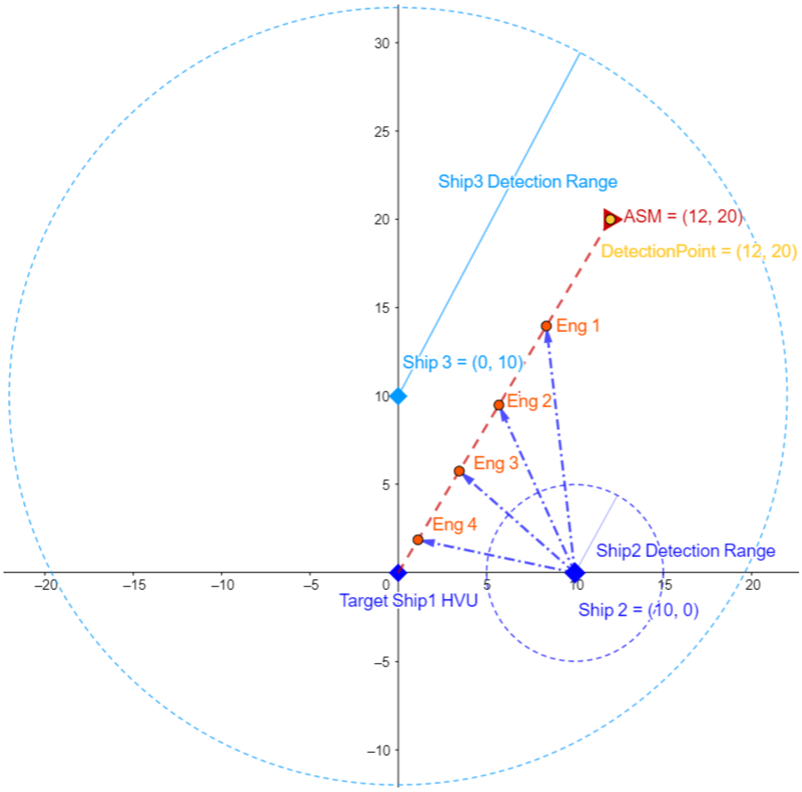

Figure 4.16. Engagements planned via detection information share

Changes applied for the validation case: $V_{ASM} = 1$, $V_{SAM\_onShip2} = 2$, $V_{SAM\_onShip3} = 1$.

Figure 4.16. shows that the target is detected by only Ship3, not by Ship2, and target information is sent to TGAAWC. Then, missiles are launched from Ship2 which has not detected the target yet because the missiles on it shoot the ASM in less time than the missiles on Ship3.

Validation Case - 13: Effects of Track Capacity

Track capacity means the total number of targets that a tracker is capable of at the same time. To observe the effects of track capacity, first, we equalize the track capacity to the total number of ASMs. Then we assume track capacity as 1.

Track Capacity = 3

Since all the ASMs are initially in the detection range of the ship, they are all detected by the sensor after the simulation began, and since track capacity is (greater than or) equal to the number of targets, all the ASMs are tracked at time zero simultaneously. Speeds and distances of all ASMs in Figure 4.17. are equal, therefore all first missile launches are done to these ASMs at the same time. Also, second engagements with each ASMs occur at equal distances at the same time.

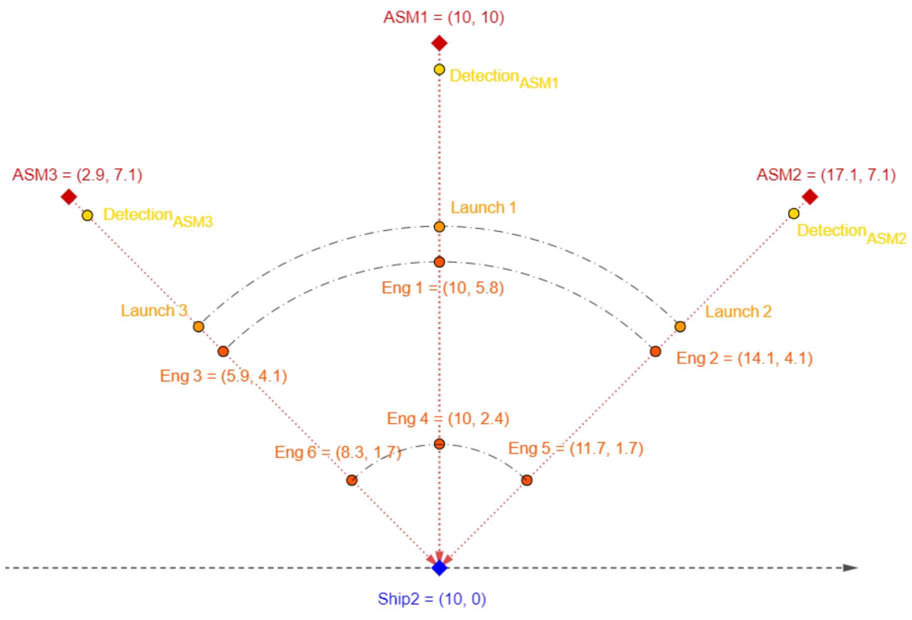

Figure 4.17. Track Capacity = 3

Changes applied for the validation case: Detection Delay = 0.5, Track Delay = 2, Solution Time = 0.5, Launch Delay = 0.5, Damage Assessment Delay = 0, V_{ASM} = 1, V_{SAM} = 5

Track Capacity = 1

If track capacity is set to a capacity less than the number of targets, the ship must track and shoot one by one or according to its track capacity. To see the difference apparently, damage assessment delay is increased. Dotted circular arcs in Figure 4.18. represent the launch distances to ship, and also the launch time differences caused by track capacity. Compared to the previous case, total SAM rounds expended decreases from 6 to 4, and engagements occur.

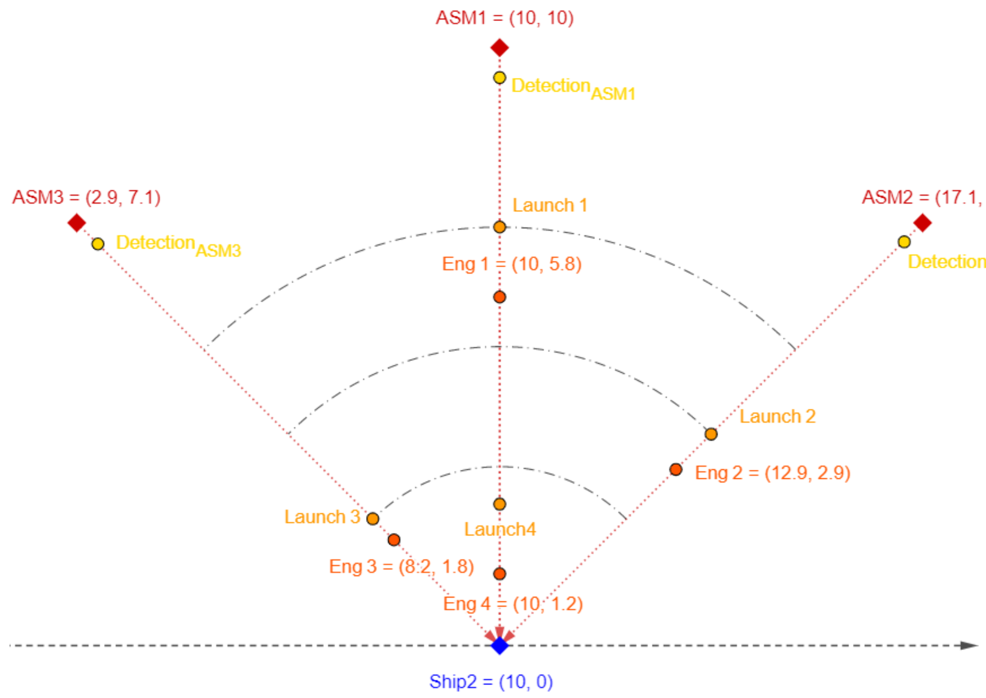

Figure 4.18. Track Capacity = 1

Changes applied for the validation case: Damage Assessment Delay = 0.5

Validation Case - 14: Time-on-Target (TOT) Approach for ASM Selection

Time-on-Target implies the required time for an ASM to reach its target ship. In this case, all targets aim at Ship2 as their target ship. All distances between the ship and the targets are equal to 10, and $V_{ASM1} = 1.5 > V_{ASM2} = 1.2 > V_{ASM3} = 1$. Therefore, $TOT_{ASM1} = 6.67 < TOT_{ASM2} = 8.33 < TOT_{ASM3} = 10$. Then, the priority order for the ship to fire is as follows: $Priority_{ASM1} \gg Priority_{ASM2} \gg Priority_{ASM3}$. Ship launches SAMs to ASM1, ASM2, and ASM3 respectively. The engagement orders are seen in Figure 4.19.

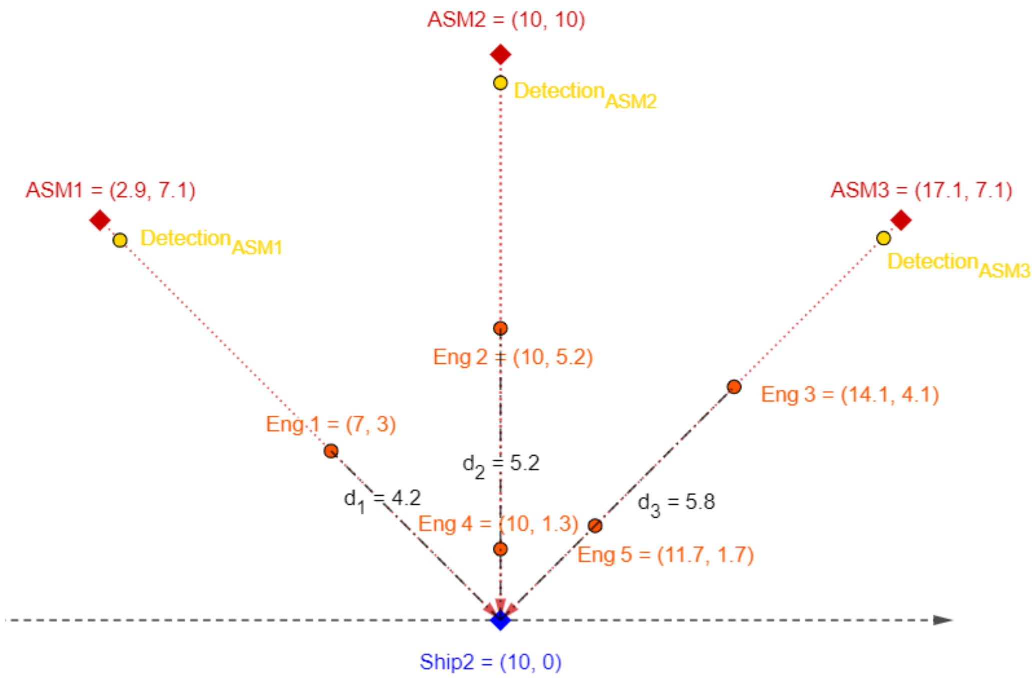

Figure 4.19. Time-on-Target Approach

Changes applied for the validation case: $V_{ASM1} = 1.5$, $V_{ASM2} = 1.2$, $V_{ASM3} = 1$, $V_{SAM} = 5$, Detection Delay = 0.5, Track Delay = 2, Solution Time = 0.25, Launch Delay = 0.25, Damage Assessment Delay = 0.5

Validation Case - 15: Closest Point of Approach for ASM Selection

Closest point of approach searches for the closest point of an ASM to a SAM system, i.e., the perpendicular distance between the line from the ASM to its target ship and the SAM system. The closest the distance gets, the higher the priority is given. In Figure 4.20. below, ASM1's, ASM2's, and ASM3's closest points are 9.5, 7.1 and 3.1, respectively. Therefore, $Priority_{ASM3} \gg Priority_{ASM2} \gg Priority_{ASM1}$.

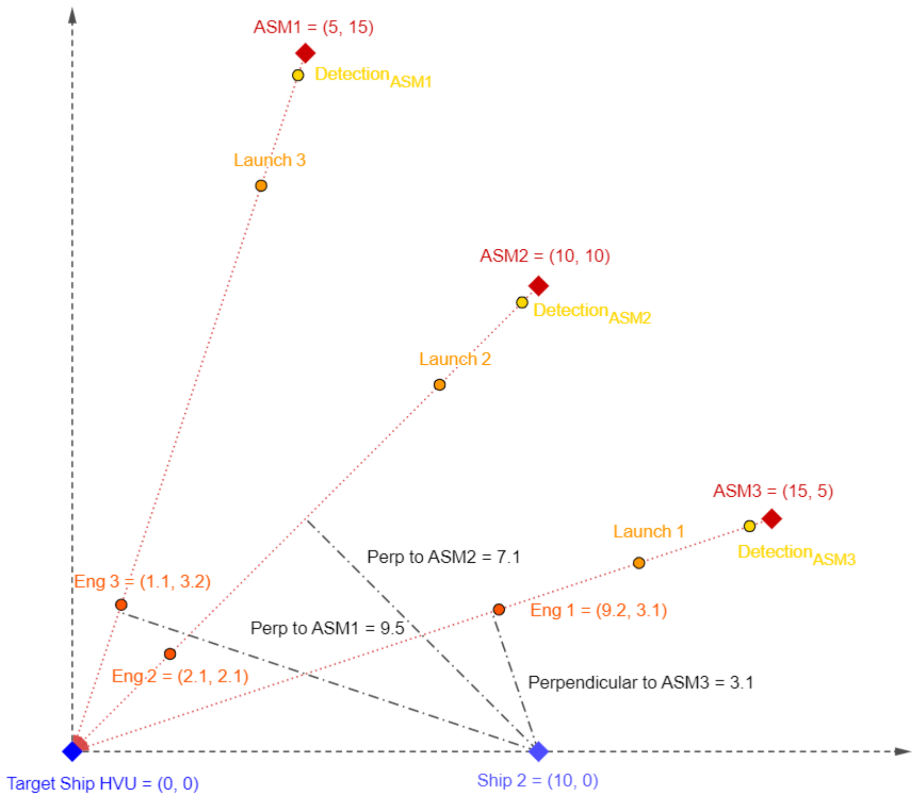

Figure 4.20. Closest-Point of Approach for ASM Selection

Changes applied for the validation case: $V_{ASM1} = 1, V_{ASM2} = 1, \; V_{ASM3} = 1, V_{SAM} = 1$, Detection Delay = 0.5, Track Delay = 2, Solution Time = 0.25, Launch Delay = 0.25, Damage Assessment Delay = 0.5

Validation Case - 16: HVU-Prioritized Approach for ASM Selection

HVU-Prioritized Approach prioritizes the ASMs aiming HVU-Ship. In this case, ASM1 and ASM2 aim at HVU-Ship, hence they have greater priority compared to ASM3. That is why the last launch is planned for ASM3. Since ASM1 and ASM2 have equal priority according to the HVU-Priority rule, we make TGAAWC compare their priorities based on a second rule such as CPA. Here, CPA values are used to decide which ASM to shoot first, and since ASM2 has a smaller closest perpendicular distance as can be seen in Figure 4.21 ASM2 is shot first.

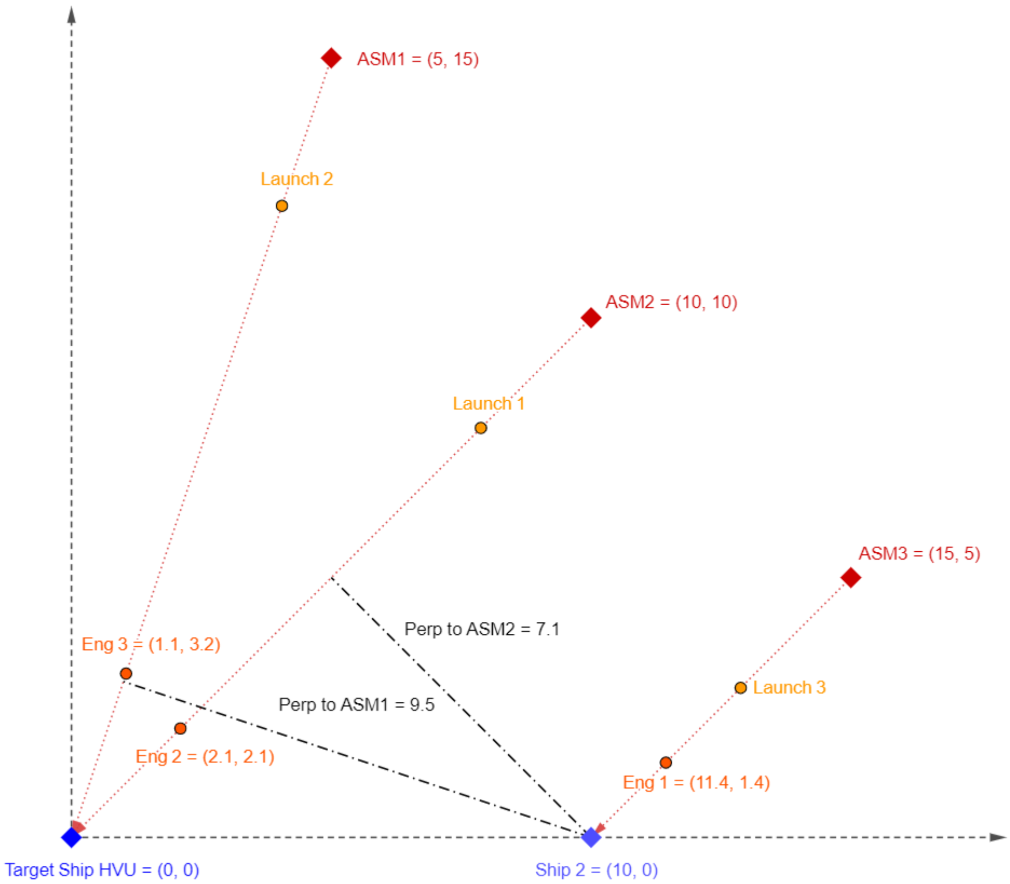

Figure 4.21. HVU-Priority Approach for ASM Selection

Changes applied for the validation case: ASM3's target ship changes to Ship2.

Validation Case - 17: New Target ASM (Pop Up Detection)

ASMs are detected whenever they enter the maximum sensor range. However, it is possible that they suddenly appear closer than the maximum sensor range after the simulation has started. For instance, a submarine may emerge from a closer point than the maximum sensor range, or an ASM can be distinguished suddenly at a closer point than the maximum sensor range after some time later. After detection, the engagement process is applied as the same.

At the beginning of the simulation, no ASM is detected. Then suddenly at time 5, an ASM appears closer than the max sensor range, and it is detected at time 5.5 after detection delay (0.5 sec). The engagement can be seen in Figure 4.22.

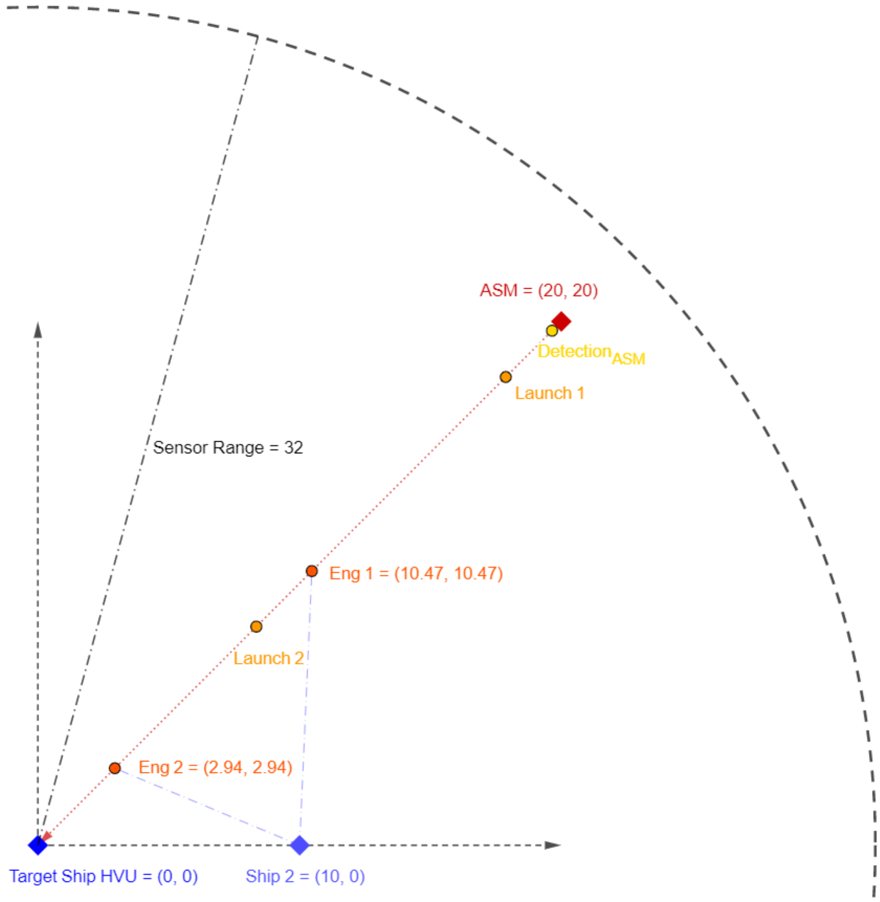

Figure 4.22. Pop Up Detection

Changes applied for the validation case: $V_{ASM} = 1,\ V_{SAM} = 1$, Sensor Range = 32, Detection Delay = 0.5, **Detection Time = 5.5**, Detection Distance = 28.28, Track Delay = 2, Solution Time = 0.25, Launch Delay = 0.25, Damage Assessment Delay = 0.5

Validation Case - 18: SAM Breakdown

If a SAM system gets broken, it is removed from the valid SAM list. If the SAM system becomes broken but the SAM has launched before the breakdown of the system, then the launched SAM goes to its target ASM and engages.

In this validation case example, TGAAWC prioritizes missiles on Ship2, because SAMs on Ship2 are faster than SAMs on Ship3. That is why the first engagement is done from Ship2. After the breakdown of the SAM system on Ship2, TGAAWC continues to schedule engagements with SAMs on Ship3. The engagement plan can be seen in Figure 4.23.

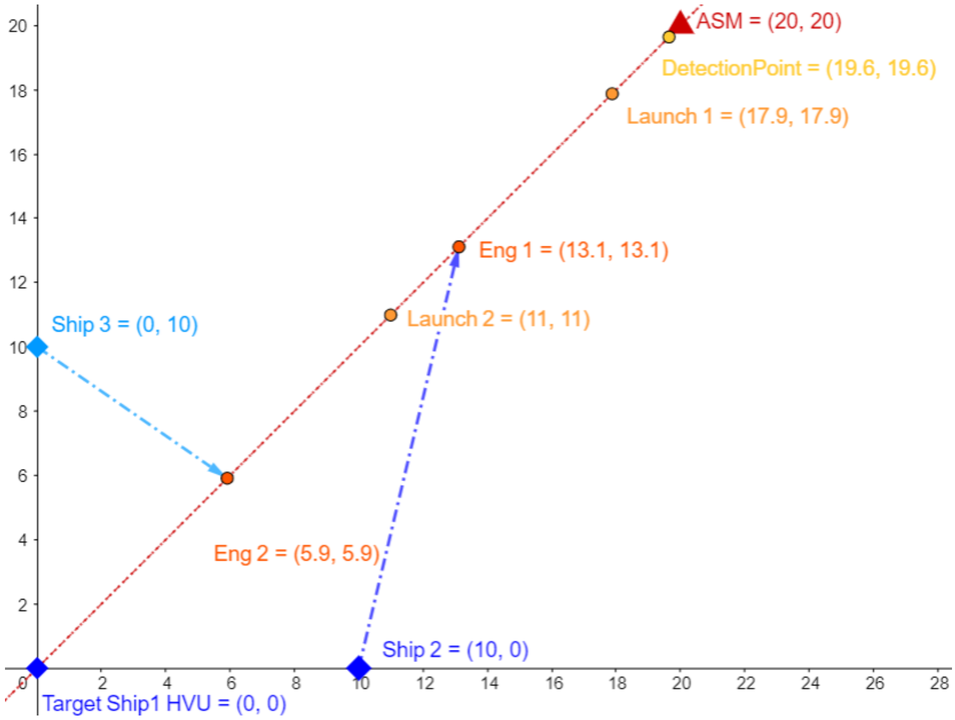

Figure 4.23. SAM Breakdown

Changes applied for the validation case: $V_{SAM\_onShip2} = 2$, $V_{SAM\_onShip3} = 1$, $V_{ASM} = 1$,

break time = 10.7, detection delay = 0.5, track delay = 2, solution time = 0.25, launch delay = 0.25, damage assessment delay = 0.5

Validation Case -19: Changing Target Ship of ASM

Targets may change their target ship at a random time to a random alive ship with a given probability. For this case, change time is deliberately arranged at the time that the first engagement happens.

To see the effects obviously, all ships are considered as self-defense ships. Since each ship defends itself, engagements are only planned by the target ship of the ASM. Incoming ASM aims Ship2, and the first engagement occurs with the SAM on Ship2.

After the first engagement happened, the ASM changes its target ship to Ship3. Since Ship2 is a self-defense ship, it stops firing. Ship 3 cannot engage with the target immediately because it has not detected the target yet, and there is no full coordination between ships. After the target has entered the sensor detection range of Ship3, then it is detected, and the engagement is planned from Ship3. Till the minimum SAM range of Ship3, one engagement happens as seen in Figure 4.24.

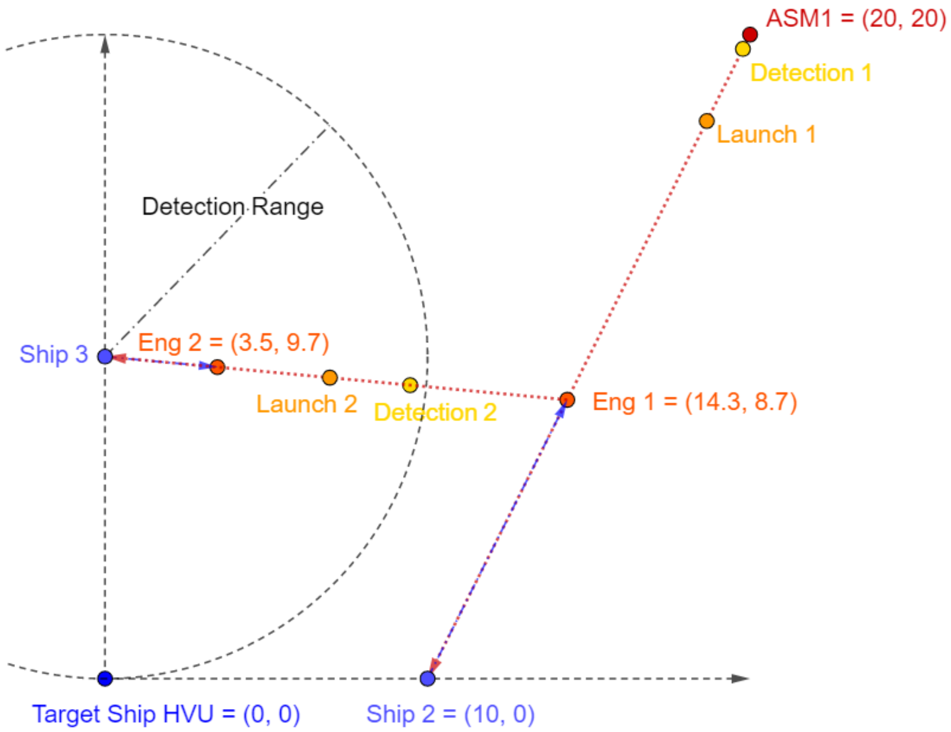

Figure 4.24. Changing Target Ship of ASM

Changes applied for the validation case: Detection Delay = 0.5, Track Delay = 2, Solution Time = 0.25, Launch Delay = 0.25, Damage Assessment Delay = 0.5

4.2 Test Scenarios and Defense Engagement Policies

The analyzed coordination levels are as follows.

- No coordination within TG
- Partial Coordination within TG (Sector Allocation)
- Full Coordination (BMRP model)

No coordination within TG

If there is no coordination between the ships in TG, ships detect targets and plan engagements independent from each other. In no coordination policy, first, we determine which target is the first to be shot. To do this, we apply myopic algorithms such as TOT, CPA, or HVU-Prioritized (see Section 4.1.1). Secondly, valid missiles are determined. A SAM system is valid if it is an area defense type missile or self-defense type missile on a ship which is aimed directly by a target. Within these valid SAM systems, the ones whose effective ranges contain the incoming target's trajectory and have available are selected. Then, the SAM which has minimum time for engaging the target is chosen. If there are more than one SAM systems having the shortest time, then the one with highest single shot kill probability (sskp) is chosen. If their sskp values are equal, then one of them is selected randomly.

Sector Allocation of TG

In sector allocation, ships are responsible for different sectors to protect the TG. The targets passing through more than one sector are attacked by different ships responsible for these sectors. The same target selection and SAM selection approaches are applied for the sector allocation of TG. The only difference between no coordination and partial coordination policies is the selection of valid SAM systems. A self-defense SAM system is valid if a target aims the ship on which the SAM system is allocated even though the target is not in the sector. On the other hand, an area defense SAM system is valid only if the target enters the sector.

BMRP Model

In full coordination policy, first, the mathematical formulation of the BMRP model which can be shown in Figure 4.25 is solved and the initial engagement plan is generated. Then, whenever a disruption occurs, non-dominated solutions are generated using NRH and CEH algorithms. NRH algorithm allocates valid SAM systems which are not included in the initial engagement plan, whereas the CEH algorithm rearranges the target of SAM systems by switching in the initial schedule. Among generated non-dominated solutions one of them is selected with the ANN algorithm. DM decides the importance (i.e., the weights) of the objectives, the ANN algorithm is trained according to the DM's priori articulated preferences. If the weight of the efficiency objective is higher, the ANN algorithm selects the non-dominated solution to obtain better PNL values. On the other hand, if the weight of the stability objective is higher, ANN chooses the non-dominated solution to minimize the number of changes in the updated engagement schedule. The plan is updated dynamically according to the ANN algorithm's selection.

The following events are considered as disruptions:

- Breakdown of a SAM system,
- Destroying the target ASM,
- New target ASM.

In the BMRP model, PNL and sskp are the main concerns for SAM allocations. Steps of the NRH and CEH algorithms and a detailed explanation of the BMRP model can be found in Silav et al. (2019).

(BMRP)

$$\min \; Z_{ND} = \sum_{i \in A} \sum_{j \in S} \sum_{k \in T} \left| Y_{ijk} - x_{ijk} \right|$$

$$\max \; Z_{PNL} = \prod_{i \in A} \left(1 - \prod_{k \in T} \prod_{j \in S} \left(1 - p_{ijk}\right)^{Y_{ijk}} \right)$$

subject to

$$\sum_{\substack{k \in T \\ i \in A}} Y_{ijk} \le d_j - f_j \qquad \forall j \in S$$

$$\sum_{(j,p) \in J_{ik}} Y_{ijp} \le 1 \qquad \forall i \in A, k \in T$$

$$\sum_{k \in S_{ij}} Y_{ijk} \le \mu_{ij}^{RT} \qquad \forall (i,j) \in V$$

$$Y_{ijk} \in \{0,1\} \qquad \forall (i,j) \in V, k \in T$$

Figure 4.25. Mathematical Formulation of the BMRP Model

4.3 Comparison of Alternative Coordination Policies

Determine Performance Measures

For the comparison of alternative coordination policies, first, measures of effectiveness (MOEs) are determined as follows:

- Mean kill range of targets
- Mean number of killed targets
- Mean number of ships survived
- Mean number of expended missile rounds
- Mean probability of no-leaker (PNL)
- Mean killed targets per missile

Determine Number of Required Runs

For each performance measure, we decide the maximum error values, and measure the required number of runs for these maximum error values with a 95% confidence interval level. The number of iterations is calculated by the formula given below.

$$R \geq \left(\frac{t_{\alpha/2,R-1} * S_0}{\in} \right)^2$$

$R: required\ number\ of\ runs$

$t_{\alpha/2,R-1}: z - value\ for\ the\ desired\ confidence\ interval\ level\ \alpha$

S_0: standard deviation of the sample

$\in$: $maximum\ error\ value$

We decided initial run number as 20 and ran the simulation 20 times with varying within replication numbers changing between 20 and 100 (20, 40, 60, 80, and 100). Error values for each MOE and the corresponding minimum required number of runs can be seen in Figure 4.29. Then we found the most critical MOE is average kill range of targets since it needs the highest run numbers. According to the total run time and line-of-sight (100 m), we determine to run the scenarios 25 times with 60 within replication.

	Error Values	Required Number of Runs Based on Within Replication Numbers for Each Error Value				
Kill Range of Targets	50 m	272	178	96	94	79
	75 m	121	79	43	42	35
	100 m	68	44	**24**	24	20
Number of Killed Targets	0.025	128	89	74	63	38
	0.050	32	22	18	16	10
	0.075	14	10	8	7	4
Number of Ships Survived	0.025	204	114	77	68	48
	0.050	51	29	19	17	12
	0.075	23	13	9	8	5
Total Number of Expended Missiles	0.125	58	20	24	21	12
	0.250	15	6	6	5	3
	0.375	6	3	3	1	1
Actual PNL	0.010	5	5	5	2	2
	0.025	1	1	1	-	-
	0.050	-	-	-	-	-
Within Replication		**20**	**40**	**60**	**80**	**100**
Initial Replication Number		20	20	20	20	20

Figure 4.26. Calculation of Required Number of Runs

Designed Scenarios

In each scenario, average detection range of ASMs are approximately taken as 20 km, and ships are located at the center close to each other. Properties of targets such as initial location, speed, target ship, and properties of missiles such as hosting ship, speed, minimum and maximum effective ranges are known. Other known parameters at the beginning of the simulation can be found in Figure 3.7. All incoming targets are subsonic except new target ASM. The properties of ASMs and SAM systems used in scenarios can be found in Appendix B.

In these scenarios, we only consider kill target and new target ASM cases as disruptions. We do not allow breakdown of SAM systems to observe the full potential of the policies. As mentioned in the assumptions, the ships in no-coordination and sector allocation policies have only self-defense SAM systems onboard because in no-coordination policy, we arrange the missiles such that there is exactly no coordination between ships hence each ship defend only itself. For partial coordination, there is again no communication between ships, but partial coordination is provided by only assigning ships to sectors. In full coordination, we assign both self and area defense missiles to ships, and full coordination within TG is provided.

We design our scenarios by considering order of three attackers per ship. To see the performance, we increased the incoming targets up to 6 times of ship numbers. Exceptionally, for Scenario-1, we investigate the defense of 2 ships against 2 to 18 incoming targets. Scenario designs can be seen from Table 4.1.

Table 4.1 Designed Scenarios

	Number of Ships in the TG	**Number of Targets**	**Total Number of SAMs in the TG**
Senaryo-1	2	2, 6, 12, 18	36
Senaryo-2	5	15, 30	50
Senaryo-3	8	24, 48	100
Senaryo-4	10	30, 60	120

In the tables, No-C, SA, and BMRP represent the abbreviations of no-coordination policy, sector allocation and BMRP models respectively.

For the comparison of all policies, we compare policy 1 and 2, 2 and 3, and 1 and 3 respectively. Additionally, each policy is compared relative to performance measures. For example, for the comparison of policy 1 and 2, we made 5 tests for each MOE. Therefore, we applied 15 tests for each case of a Scenario, and 150 tests in total for 4 Scenario consisting of 10 cases. All 150 comparison results can be found in Appendix C.

Table 4.2 Comparison Table

	Policy		
Replication	**No-C**	**SA**	**BMRP**
1	Y_{11}	Y_{12}	Y_{13}
2	Y_{21}	Y_{22}	Y_{23}
…	…	…	…
25	Y_{251}	Y_{252}	Y_{253}
Sample Mean	$\bar{Y}_{.1}$	$\bar{Y}_{.2}$	$\bar{Y}_{.3}$
Sample Variance	S_1^2	S_2^2	S_3^2

Y_{ri}: Average value of related MOE for policy *i* during replication *r*

$\bar{Y}_{.i}$: Sample mean of 25 replications for policy *i*

S_i^2: Sample variance of 25 replications for policy *i*

Q_i: Estimation of Y_{ri}

$Q_1 = E(Y_{r1}),\quad Q_2 = E(Y_{r2}),\quad Q_3 = E(Y_{r3}),\quad$ r = 1, 2, …, 25

We compute the confidence interval for $Q_i - Q_j$ as below for comparing the performance measures of policy *i* and j.

$$\bar{Y}_{.i} - \bar{Y}_{.j} - t_{\alpha/2} \cdot \sigma(\overline{Y_{.i}} - \overline{Y_{.j}}) \leq Q_i - Q_j \leq \bar{Y}_{.i} - \bar{Y}_{.j} + t_{\alpha/2} \cdot \sigma(\overline{Y_{.i}} - \overline{Y_{.j}})$$

- If the computed confidence interval is less than zero, as seen in the Figure 4.30 below, then $Q_i - Q_j < 0$ and $Q_i < Q_j$. This implies that the mean performance measure of Q_i is smaller than the mean of Q_j.

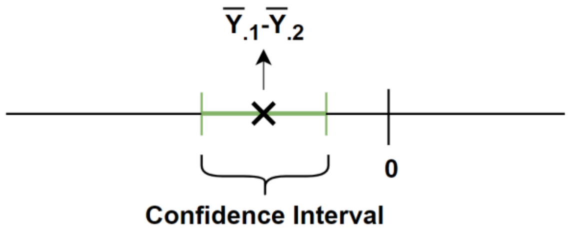

Figure 4.27. Confidence interval to the left of zero

- If the computed confidence interval is greater than zero, as seen in the Figure 4.31 below, then $Q_i - Q_j > 0$ and $Q_i > Q_j$. This implies that the mean performance measure of Q_i is bigger than the mean of Q_j.

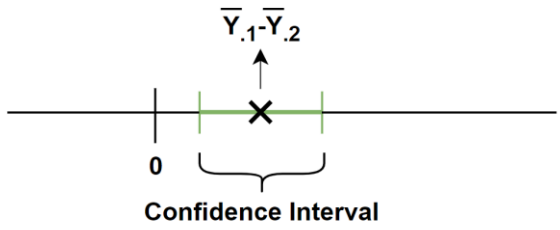

Figure 4.28. Confidence interval to the right of zero

- If the computed confidence interval contains zero, we can say that there is no strong evidence that one system is better than the other. Some say that this is the weak conclusion of $Q_i = Q_j$, but if replication number is increased, confidence interval may shrink in length and would shift to the left or right side of zero. Then, we can draw the conclusion of one of the systems gives better result.

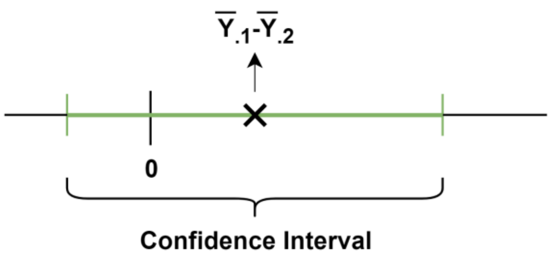

Figure 4.292. Confidence interval that contains zero

Statistical results of the comparisons computed according to the explanations above are shown with colored lines. If the calculated confidence interval is greater or less than zero, it can be interpreted that one policy is better than the other. Otherwise, if the confidence interval contains zero, we cannot say that one of them is better. In the tables, green bars represent the ones that give the best statistical result, whereas red bars represent the ones giving the worst results statistically. If only green bar is shown for a result, we can only determine the best policy and cannot compare the remaining ones. Similarly, if only red bar is shown, then it can be interpreted that we can decide only the worst policy among all. Increasing the number of simulation runs may improve the results.

Scenario-1

In Scenario-1, we consider a TG consisting of 2 ships. One of them is HVU, so it does not have any munitions on it. The other ship has different SAM systems onboard. These SAM systems may be self or area defense missiles according to the policy. Half of the targets aim HVU, and the other half aim escort ship for the cases under Scenario-1. This scenario consists of 4 cases that have 2, 6, 12, and 18 targets respectively.

Case-1 of Scenario-1

	2 targets		
MOEs	**No-C**	**SA**	**BMRP**
kill range of targets (m)	10210 (red)	10210 (red)	15665 (green)
number of killed targets	1.00 (red)	1.00 (red)	1.96 (green)
number of ships survived	1.00 (red)	1.00 (red)	1.97 (green)
total number of expended missiles	1.70 (green)	1.70 (green)	2.59 (red)
PNL	0.00 (red)	0.00 (red)	0.97 (green)
avg. killed target per missile	0.59 (red)	0.59 (red)	0.76 (green)

Figure 4.30. Comparison Results for Case-1 of Scenario-1

In Figure-4.33, we see that number of killed targets and number of ships survived is equal to 1. This is reasonable because the escort ship only defends itself and kills the incoming target. Meanwhile, the other target reaches HVU because no engagement is planned for this target.

No-C and SA cases give the exact same result for this case because the sector of the escort ship is deliberately arranged to the sector that covers the target coming to itself. Otherwise, when the escort ship is arranged to a sector that does not contain the incoming target, then number of ships survived and number of killed targets turns zero, and TG is killed by the targets. Additionally, PNL values of these cases are zero because the HVU is always destroyed.

In the BMRP model, almost all the targets are killed, and the survivability of the ships is provided with the PNL of almost 1. So, it can be said that all the incoming targets are destroyed at a range of approximately 15 km. BMRP uses more missiles however in BMRP model the escort ship protects the TG from 2 incoming targets whereas escort ships defend only themselves from 1 attacking target in No-C and SA policies. Therefore, the BMRP model outperforms the others.

One of the reasons of this difference comes from the effect of area defense missiles because they are generally faster, have higher single shot kill probability, and larger effective missile ranges.

Case-2 of Scenario-1

	2 targets			6 targets		
MOEs	**No-C**	**SA**	**BMRP**	**No-C**	**SA**	**BMRP**
kill range of targets (m)	10210	10210	15665	7934	6973	14050
number of killed targets	1.00	1.00	1.96	2.99	2.75	5.88
number of ships survived	1.00	1.00	1.97	0.99	0.75	1.74
total number of expended missiles	1.70	1.70	2.59	5.14	5.31	8.45
PNL	0.00	0.00	0.97	0.00	0.00	0.77
avg. killed target per missile	0.59	0.59	0.76	0.58	0.52	0.70

Figure 4.314. Comparison Results for Case-1 & 2 of Scenario-1

In the second case of Scenario-1, there are 6 incoming targets. The results can be shown in the right part of Figure-4.34. We can see that BMRP gives better results except for the usage of missiles. We can explain this logically. BMRP model uses more missiles because it protects the TG from 6 incoming targets while the escort ships in non-full coordination policies defend only themselves from 3 targets.

Also, we distinguish that average kill range of BMRP decreases slowly because we do not limit the track capacity. So, the ship may attack all 6 targets simultaneously, and approximately it shoots a target with 1.5 missiles. On the other hand, the decrease is steeper in other policies, even though they are also not restricted by track capacity. This can be explained by the computation of the avg kill range.

mean kill range of targets = avg. kill range of targets / total number of targets

We divide average kill range by total number of targets, not the number of killed targets. If the target is not killed, we wanted to see the reflections of it.

Case-3 of Scenario-1

In the third case of Scenario-1 with 12 incoming targets, we see that SA gives worse results than others except for the total number of expended missiles. We can say that one of the reasons may be related to the coverage of the sectors because more missiles are used in the No-C policy. Therefore, it can be interpreted that overall performance of SA can be enhanced with better coverage.

In the BMRP model, although the number of ships that survived decreased to under 1, the kill range is half of the average detection range, and 75% of the targets were killed. Additionally, we can see that average killed target per missile for the BMRP model maintains its effectiveness contrary to others. The results are shown in Figure 4.35.

	2 targets			6 targets			12 targets		
MOEs	No-C	SA	BMRP	No-C	SA	BMRP	No-C	SA	BMRP
kill range of targets (m)	10210	10210	15665	7934	6973	14050	5184	3764	11373
number of killed targets	1.00	1.00	1.96	2.99	2.75	5.88	5.37	4.27	8.86
number of ships survived	1.00	1.00	1.97	0.99	0.75	1.74	0.60	0.14	0.67
total number of expended missiles	1.70	1.70	2.59	5.14	5.31	8.45	15.68	13.85	13.06
PNL	0.00	0.00	0.97	0.00	0.00	0.77	0.00	0.00	0.06
avg. killed target per missile	0.59	0.59	0.76	0.58	0.52	0.70	0.34	0.31	0.68

Figure 4.325. Comparison Results for Case-1, 2 & 3 of Scenario-1

Case-4 of Scenario-1

In the fourth case whose results are shown in Figure-4.36, we see the upper limits of the policies. Average kill range of SA almost decreases to min SAM range and almost a hundred percent of the ships are destroyed. No-C gives better results than SA but uses more missiles. However, we see that average killed target per missile for No-C and SA policies are incomparable. BMRP outperforms the other policies in terms of each MOEs.

	2 targets			6 targets			12 targets			18 targets		
MOEs	No-C	SA	BMRP	No-C	SA	BMRP	No-C	SA	BMRP	No-C	SA	BMRP
kill range of targets (m)	10210	10210	15665	7934	6973	14050	5184	3764	11373	4231	2818	9213
number of killed targets	1.00	1.00	1.96	2.99	2.75	5.88	5.37	4.27	8.86	6.73	5.17	13.31
number of ships survived	1.00	1.00	1.97	0.99	0.75	1.74	0.60	0.14	0.67	0.09	0.01	0.23
total number of expended missiles	1.70	1.70	2.59	5.14	5.31	8.45	15.68	13.85	13.06	25.14	19.69	23.19
PNL	0.00	0.00	0.97	0.00	0.00	0.77	0.00	0.00	0.06	0.000	0.000	0.011
avg. killed target per missile	0.59	0.59	0.76	0.58	0.52	0.70	0.34	0.31	0.68	0.27	0.26	0.57

Figure 4.336. Comparison Results for Case-1, 2, 3 & 4 of Scenario-1

Scenario-2

In this scenario, TG consists of 5 ships with 50 missiles onboard. There are 15 and 30 incoming targets for case 1 and case 2 respectively. The relevant results are shown in Figure 4.37.

Case-1 of Scenario-2

For the first case with 15 targets, we see that BMRP model gives the best results for almost all MOEs. Since all PNL values are zero, we also check the average killed targets per missile for the performance of the policies. Since we aim for the highest survivability of the ships, and neutralization of attacking units with minimum number of missiles, it is an important performance measure. We can see that the BMRP's result is 2 times more effective than others.

Case-2 of Scenario-2

When the number of targets increases to 30 in the second case, BMRP keeps its efficiency while others become incomparable in terms of killed target per missile. Even though SA seems to be the best in terms of missile usage, we can interpret from the table that SA cannot properly cover the targets, therefore number of ships decreases with the expended number of missiles.

We can see in this scenario and the following scenarios that, No-C within TG results in the highest number of expended missiles. We get these results because the ships in No-C policy are not restricted with the sector assignments, also TG does not have a communication and coordination between ships.

	15 targets			30 targets		
MOEs	**No-C**	**SA**	**BMRP**	**No-C**	**SA**	**BMRP**
kill range of targets (m)	5989	4850	8259	4681	3189	5841
number of killed targets	8.39	6.47	9.85	11.71	8.11	14.63
number of ships survived	1.99	1.87	2.39	0.40	0.42	0.76
total number of expended missiles	34.45	24.45	21.86	47.11	32.78	40.97
PNL	0.000	0.000	0.004	0.00	0.00	0.00
avg. killed target per missile	0.24	0.26	0.45	0.25	0.25	0.36

Figure 4.34. Comparison Results of Scenario-2

Scenario-3 & Scenario-4

In Scenario-3, a TG consisting of 8 ships with 100 missiles defends against 24 and 48 targets. In Scenario-4, the TG consists of 10 ships with 120 missiles onboard and defends itself against 30 and 60 targets respectively. The relevant results are shown in Figure 4.38.

We can make similar interpretations for Scenario 3 and 4. We can say that the BMRP model gives the best results for each size of problems in terms of all performance measures. No coordination and sector allocation give similar results because engagements in these policies are planned according to the same myopic algorithms, differences come from the sector allocation of missiles.

	Scenario-3						Scenario-4					
	24 targets			48 targets			30 targets			60 targets		
MOEs	**No-C**	**SA**	**BMRP**	**No-C**	**SA**	**BMRP**	**No-C**	**SA**	**BMRP**	**No-C**	**SA**	**BMRP**
kill range of targets (m)	5546	4346	10475	4718	3848	8537	7292	4431	10378	5744	3575	8080
number of killed targets	12.95	10.55	18.03	19.45	15.90	31.03	19.14	12.44	22.16	29.30	17.55	37.93
number of ships survived	3.94	3.44	4.81	1.06	0.77	1.42	4.24	2.02	4.99	1.21	0.72	2.25
total number of expended missiles	47.81	39.29	34.17	76.55	61.77	73.17	64.13	42.04	40.90	98.00	55.26	92.88
PNL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
avg. killed target per missile	0.27	0.27	0.53	0.25	0.26	0.42	0.30	0.30	0.54	0.30	0.32	0.41

Figure 4.35. Comparison Results of Scenario-3 & 4

CHAPTER 5

CONCLUSION AND FUTURE RESEARCH

In this thesis, we developed component-based discrete event simulation model of a naval TG with different coordination levels to analyze the effectiveness of the TG air defense. The developed model is flexible, scalable, and expandable since it is component based. Therefore, we can build and compare different air defense coordination policies.

The models with different coordination levels that we analyzed are as follows:

- No coordination within TG
- Partial coordination (sector allocation) within TG
- Full coordination within TG (BMRP model)

According to the simulation results,

- No coordination within TG causes expending more missiles. This policy increases the usage of missiles since the engageable area covered is larger compared to sector allocation, and ships do not have communication within TG as opposed to full coordination policy. More importantly, in the presence of area air defense SAM systems, this policy does not allow us to support other ships with area defense capability.
- BMRP model outperforms other policies in terms of all performance measures independent of problem size. In some cases, more missiles are expended than the sector allocation. However, this does not mean that the sector allocation performs better. On the contrary, it shows that the ships cannot cover the targets properly. Additionally, if the allocated SAM rounds were restrictively small, the cost would be greater for no coordination and sector allocation cases.

- Allocation of ships to sectors is important and has a huge effect on the overall performance of the sector allocation policy. Therefore, before the engagement starts, ships should be carefully assigned to sectors.

The simulation model can be enhanced in several directions.

- We modeled the linear motion in 2-dimensions (x, y) and assumed that ASMs and SAMs move linearly with a constant speed. Motion can be extended to 3-dimensions (x, y, z), and moving objects can move with acceleration. Therefore, the altitude of targets and the changing speeds of targets and munitions should be considered. Also, proportional navigation can be integrated into missiles' movements.
- Blind sector of ships can be considered. Blind sector is the area that ships cannot see and scan. Accordingly, the targets coming from this direction cannot be detected.
- Setup time calculation can be enhanced with the proper calculation of the orientation time of the track radar.
- We only assigned self-defense missiles for no-coordination policy to design a TG that exactly has no communication, and coordination, but this policy can be extended with usage of area air defense missiles.
- Sector allocation problem can be solved by using the BMRP model. Additionally, it can be solved with metaheuristics or custom heuristics.
- Hard kill weapons use destructive force and disable the incoming target by physically intercepting the target. On the other hand, soft kill weapons confuse the incoming target and attack the sensors of targets. We consider only hard kill weapons and defend the TG with SAMs. Soft kill weapons such as decoys, jammers, and smoke can also be integrated to ships' weapons.
- BMRP model can be solved for different risk levels. Risk levels can be arranged by changing the weights of the bi-objective model. For this study,

ANN is trained according to the equal importance of the objectives. This can be examined by giving different weights to efficiency or stability objectives.

- The required number of runs was calculated according to an example scenario, however, required run numbers can be dynamically calculated for each scenario.

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APPENDICES

A. Detailed Result of Validation Cases

This appendix shows the detailed result of validation cases via a Microsoft Excel file.

B. Properties of ASMs and SAM Systems

SAM Systems	Speed (m/s)	Min Range (km)	Max Range (km)	Type
Sea Sparrow	850	1.5	16	self-defense
ESSM	1224	1.5	18	self-defense
Barak	680	1.5	12	self-defense
Aster-15	986	1.5	30	self-defense
SM-1	680	5.0	38	area air defense
SM-2	850	5.0	170	area air defense
Aster-30	1394	3.0	100	area air defense

ASMs	Speed (m/s)
Harpoon	289
MM-38 Exocet	306
Polyphem	221
Gabriel	238
Penguin	238
SS-N-26	1190
Maveric	850

C. Confidence Interval Values

	avg. kill range of targets (m)			number of killed targets			number of ships survived			total number of expended missiles			PNL			killed target per missile		
	0.00	< Q1-Q2 <	0.00	0.00	< Q1-Q2 <	0.00	0.00	< Q1-Q2 <	0.00	0.00	< Q1-Q2 <	0.00	0.00	< Q1-Q2 <	0.00	0.00	< Q1-Q2 <	0.00
2x2	-6159.30	< Q1-Q3 <	-4750.25	-1.01	< Q1-Q3 <	-0.91	-1.01	< Q1-Q3 <	-0.92	-1.12	< Q1-Q3 <	-0.66	-1.01	< Q1-Q3 <	-0.92	-0.25	< Q1-Q3 <	-0.09
	-6159.30	< Q2-Q3 <	-4750.25	-1.01	< Q2-Q3 <	-0.91	-1.01	< Q2-Q3 <	-0.92	-1.12	< Q2-Q3 <	-0.66	-1.01	< Q2-Q3 <	-0.92	-0.25	< Q2-Q3 <	-0.09
	675.63	< Q1-Q2 <	1247.40	0.14	< Q1-Q2 <	0.34	0.14	< Q1-Q2 <	0.33	-0.62	< Q1-Q2 <	0.27	0.00	< Q1-Q2 <	0.00	0.01	< Q1-Q2 <	0.12
2x6	-6598.11	< Q1-Q3 <	-5633.24	-2.63	< Q1-Q3 <	-2.36	-0.89	< Q1-Q3 <	-0.61	-3.85	< Q1-Q3 <	-2.78	-0.88	< Q1-Q3 <	-0.65	-0.13	< Q1-Q3 <	-0.01
	-7468.06	< Q2-Q3 <	-6686.32	-2.87	< Q2-Q3 <	-2.59	-1.13	< Q2-Q3 <	-0.84	-3.66	< Q2-Q3 <	-2.62	-0.88	< Q2-Q3 <	-0.65	-0.18	< Q2-Q3 <	-0.08
	1182.27	< Q1-Q2 <	1657.51	0.87	< Q1-Q2 <	1.31	0.34	< Q1-Q2 <	0.57	1.06	< Q1-Q2 <	2.61	0.00	< Q1-Q2 <	0.00	0.01	< Q1-Q2 <	0.05
2x12	-6564.24	< Q1-Q3 <	-5813.55	-3.77	< Q1-Q3 <	-3.22	-0.23	< Q1-Q3 <	-0.09	1.65	< Q1-Q3 <	3.60	-0.12	< Q1-Q3 <	0.00	-0.37	< Q1-Q3 <	-0.30
	-8012.98	< Q2-Q3 <	-7204.59	-4.87	< Q2-Q3 <	-4.30	-0.66	< Q2-Q3 <	-0.39	0.17	< Q2-Q3 <	1.41	-0.12	< Q2-Q3 <	0.00	-0.40	< Q2-Q3 <	-0.34
	1248.12	< Q1-Q2 <	1580.02	1.18	< Q1-Q2 <	1.93	0.01	< Q1-Q2 <	0.16	4.58	< Q1-Q2 <	6.33	0.00	< Q1-Q2 <	0.00	-0.01	< Q1-Q2 <	0.02
2x18	-5185.69	< Q1-Q3 <	-4778.94	-7.05	< Q1-Q3 <	-6.11	-0.24	< Q1-Q3 <	-0.03	1.27	< Q1-Q3 <	2.63	-0.04	< Q1-Q3 <	0.01	-0.32	< Q1-Q3 <	-0.29
	-6601.89	< Q2-Q3 <	-6190.88	-8.57	< Q2-Q3 <	-7.69	-0.35	< Q2-Q3 <	-0.08	-4.13	< Q2-Q3 <	-2.87	-0.04	< Q2-Q3 <	0.01	-0.33	< Q2-Q3 <	-0.29
	787.50	< Q1-Q2 <	1489.61	1.48	< Q1-Q2 <	2.35	-0.13	< Q1-Q2 <	0.37	9.17	< Q1-Q2 <	10.83	0.00	< Q1-Q2 <	0.00	-0.04	< Q1-Q2 <	0.00
5x15	-2741.11	< Q1-Q3 <	-1800.09	-2.04	< Q1-Q3 <	-0.89	-0.73	< Q1-Q3 <	-0.07	11.78	< Q1-Q3 <	13.41	-0.02	< Q1-Q3 <	0.01	-0.23	< Q1-Q3 <	-0.18
	-3777.35	< Q2-Q3 <	-3040.96	-3.73	< Q2-Q3 <	-3.02	-0.82	< Q2-Q3 <	-0.21	2.02	< Q2-Q3 <	3.17	-0.02	< Q2-Q3 <	0.01	-0.21	< Q2-Q3 <	-0.16
	1223.29	< Q1-Q2 <	1762.49	3.11	< Q1-Q2 <	4.09	-0.18	< Q1-Q2 <	0.14	13.95	< Q1-Q2 <	14.71	0.00	< Q1-Q2 <	0.00	-0.01	< Q1-Q2 <	0.01
5x30	-1466.87	< Q1-Q3 <	-852.37	-3.73	< Q1-Q3 <	-2.12	-0.56	< Q1-Q3 <	-0.15	5.51	< Q1-Q3 <	6.77	0.00	< Q1-Q3 <	0.00	-0.13	< Q1-Q3 <	-0.09
	-2930.33	< Q2-Q3 <	-2374.68	-7.25	< Q2-Q3 <	-5.80	-0.51	< Q2-Q3 <	-0.17	-8.74	< Q2-Q3 <	-7.65	0.00	< Q2-Q3 <	0.00	-0.13	< Q2-Q3 <	-0.09
	999.84	< Q1-Q2 <	1398.68	1.99	< Q1-Q2 <	2.80	0.16	< Q1-Q2 <	0.84	7.44	< Q1-Q2 <	9.60	0.00	< Q1-Q2 <	0.00	-0.01	< Q1-Q2 <	0.01
8x24	-5232.20	< Q1-Q3 <	-4627.17	-5.77	< Q1-Q3 <	-4.40	-1.31	< Q1-Q3 <	-0.43	12.50	< Q1-Q3 <	14.78	0.00	< Q1-Q3 <	0.00	-0.28	< Q1-Q3 <	-0.24
	-6394.65	< Q2-Q3 <	-5863.25	-8.05	< Q2-Q3 <	-6.90	-1.77	< Q2-Q3 <	-0.96	3.79	< Q2-Q3 <	6.44	0.00	< Q2-Q3 <	0.00	-0.28	< Q2-Q3 <	-0.24
	620.22	< Q1-Q2 <	1118.91	2.74	< Q1-Q2 <	4.36	0.05	< Q1-Q2 <	0.52	13.77	< Q1-Q2 <	15.77	0.00	< Q1-Q2 <	0.00	-0.02	< Q1-Q2 <	0.01
8x48	-4016.78	< Q1-Q3 <	-3622.69	-12.37	< Q1-Q3 <	-10.77	-0.72	< Q1-Q3 <	-0.01	2.32	< Q1-Q3 <	4.44	0.00	< Q1-Q3 <	0.00	-0.18	< Q1-Q3 <	-0.16
	-4907.34	< Q2-Q3 <	-4471.26	-15.83	< Q2-Q3 <	-14.41	-0.88	< Q2-Q3 <	-0.43	-12.52	< Q2-Q3 <	-10.26	0.00	< Q2-Q3 <	0.00	-0.18	< Q2-Q3 <	-0.15
	2590.74	< Q1-Q2 <	3131.83	6.04	< Q1-Q2 <	7.36	1.82	< Q1-Q2 <	2.62	20.61	< Q1-Q2 <	23.56	0.00	< Q1-Q2 <	0.00	-0.01	< Q1-Q2 <	0.02
10x30	-3363.88	< Q1-Q3 <	-2807.16	-3.80	< Q1-Q3 <	-2.26	-1.21	< Q1-Q3 <	-0.29	22.21	< Q1-Q3 <	24.23	0.00	< Q1-Q3 <	0.00	-0.26	< Q1-Q3 <	-0.22
	-6167.61	< Q2-Q3 <	-5725.99	-10.25	< Q2-Q3 <	-9.20	-3.27	< Q2-Q3 <	-2.66	0.05	< Q2-Q3 <	2.22	0.00	< Q2-Q3 <	0.00	-0.26	< Q2-Q3 <	-0.23
	1962.15	< Q1-Q2 <	2376.59	10.86	< Q1-Q2 <	12.63	0.21	< Q1-Q2 <	0.78	41.50	< Q1-Q2 <	43.98	0.00	< Q1-Q2 <	0.00	-0.03	< Q1-Q2 <	-0.01
10x60	-2667.61	< Q1-Q3 <	-2003.83	-10.01	< Q1-Q3 <	-7.25	-1.45	< Q1-Q3 <	-0.62	3.77	< Q1-Q3 <	6.47	0.00	< Q1-Q3 <	0.00	-0.13	< Q1-Q3 <	-0.09
	-4748.42	< Q2-Q3 <	-4261.77	-21.41	< Q2-Q3 <	-19.35	-1.89	< Q2-Q3 <	-1.17	-39.10	< Q2-Q3 <	-36.15	0.00	< Q2-Q3 <	0.00	-0.11	< Q2-Q3 <	-0.07