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Using modeling and simulation to optimize naval defense systems

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Abstract. The article addresses the issue of modeling and simulation for establishing naval defense systems, highlighting how the AnyLogic program can be effectively used for this purpose. Firstly, the essential components of naval defense systems are described, covering the types of ships, weapons, and sensors used. Secondly, the importance of modeling and simulation in designing and implementing naval defense systems is emphasized, demonstrating how simulations can facilitate strategic decision-making processes.
The case study provides an applied perspective by using AnyLogic to simulate naval defense systems. The study provides a clear picture of the potential of modeling and simulation in addressing modern naval defense challenges and optimizing strategic and operational decisions.
Keywords: *naval defense, modeling, simulation, optimization*

1. Introduction

The modeling and simulation domain has become a prominent study area, with a growing community of researchers focusing on its current applications and trends. This sector is under continuous analysis, comparing its advancement and implementations to those observed in recent years.

Grigoryev defines modeling as a methodological approach to solve real-world problems, through the abstraction of original systems, but including its main properties [1]. The simulation of systems involves operating a model with spatial and temporal conditions, facilitating the analysis of the proposed system's performance. This process includes both software and hardware components, using mathematical relationships to create a virtual representation that allows to observe and evaluate the behavior of the system [1] [2]. Using modeling and simulation can optimize the created system, by reducing the number of errors that can be observed later in the real projection process.

There are many areas of study and industrial sectors where simulation is developed and implemented with very good results. It has an important role in decision support and risk assessment in applications of logistics, military operations, training and support, telecommunications, civil engineering projects, public policy, and electronic business models [2].

In military applications, there are numerous contexts in which simulation technology is more effectively used in the optimization of strategic processes. In cases such as testing the functioning of combat techniques, developing and implementing battle plans, and planning force deployments, simulation is a fundamental element for military strategy and command [2].

In conflicts, military or civil harbors often become primary targets, so their protection is a priority. There are several factors to consider when it comes to defending harbor areas, one of which is critical infrastructure and access routes.

Ports serve as crucial hubs, not only for maritime transport but also for securing energy supplies or supporting essential data and power cables [3]. Critical infrastructure protection involves measures that are aimed to secure maritime infrastructure, including ports, shipping lines, and broader maritime security systems vital for the functionality of a region. As the main component in ensuring the defense in maritime operations, maritime critical infrastructure protection is integrated into national security strategies, particularly because threats in maritime environment are more challenging to address than those on land [4].

This article aims to improve military research by introducing modeling and simulation software to analyze the probability of developing defense strategies using agent-based modeling. The model could be effectively deployed in military contexts to detect maritime and aerial threats, playing a crucial role in protecting critical infrastructure of maritime ports. By enhancing threat detection capabilities, the model can help ensure the security and operational integrity of these vital facilities against potential attacks or incursions. Moreover, experts can use the developed models to experiment the efficiency of strategic placement of the defense systems and can analyze several conditions. The objective of the experiments is not to draw conclusions that can be directly applied but rather to demonstrate the probability of implementing the developed model in real-world scenarios. This approach highlights the model's potential for practical application and its adaptability to various situations. Additionally, the challenges and the limitations identified in modeling and simulation of naval defense are addressed, along with potential solutions and future research directions.

2. Modeling and simulation in defense operations

The literature related to the simulation applied defense sector underlines the complexity of optimizing defense systems, including simulation-based methods such as discrete-event, system dynamic, and agent-based models. Additionally, virtual reality and artificial intelligence have an extensive application to improve systems modeling [5]. Several studies highlight the application of modeling and simulation as an important tool for optimizing defense systems and addressing the associated challenges [6] [7].

Hall et al. (2019) provided a methodology in their study based on optimization through simulation with EADSIM program, focusing on a scenario involving a national Anti-Air Warfare in which a ship is targeted by anti-ship cruise missiles [6]. In 2020, Li and Epureanu used the agent-based approach in order to optimize and manage the resupply, demand forecasting, and schedule the processes. The strategy was to analyze the feasibility and adaptability of modular military vehicle fleets during different mission scenarios [7].

J. Choi et al. (2022) proposes the use of system dynamics as a method of constructing digital twin simulation models with application in naval ship operations. The authors analyze the operation and maintenance system of Republic of Korea naval ships by integrating challenges of multi-scale and multi-physics data in digital twin modeling. It is demonstrated how to create a high-fidelity digital twin model to reproduce real-world systems, and at the same time to optimize non-intuitive correlations and optimize the strategies of maintenance. The method allows to continuously calibrate the data and to make real-time updates, enhancing the model’s accuracy [8]. Also, D. Yang et al. (2022) proposes an overview of the logistic processes of military airports to simulate the possibility of operating them by using Internet of Things [9]. The analysis conducted by the authors expects to simulate airport operations and receive immediate feedback after completing a task or facilitate the receipt of orders to deploy to specific areas for task execution. This approach is designed to optimize the time efficiency in the dynamic and rapidly evolving battlefield context [9].

A systematic literature review conducted by Steven et al. (2023), drew attention to combat and tactical operations, simulating warfare areas with virtual reality technology. It was evaluated the success of implementing these training methods by analyzing studies published between 2010 and 2021, presenting positive outcomes in maintaining and developing personnel skills [5].

Among the vulnerabilities of defense systems, it is the exposure to new forms of warfare, such as cyberattacks, which can disable advanced systems without engaging conventional forces. High costs can also restrict public investment, and additionally, advanced technology demands continuous personnel training and adaptation to rapid technological advancements, being a challenging situation for defending forces [10].

As demonstrated, a variety of perspectives exist for simulating diverse operations within defense sector involving multiple aspects that can be developed in order to optimize strategic outcomes and increase security efficiency.

3. Problem description and methodology

To project the following scenarios, the authors used AnyLogic modeling and simulation software, a program that offers possibilities for modeling training environments and analyzing the impact on the studied agents. AnyLogic is included in various sectors such as industry, healthcare, transportation, logistics, and notably, defense. In the defense sector, it enables the analysis of military operations, strategic and tactical planning, and crisis management. It supports the identification of the optimal force deployment strategies and the optimization of the military supply chain. By simulating different conflict scenarios and defense operations, AnyLogic helps in the development of planning actions in a dynamic operational environment.

The study examines two scenarios to assess the potential of protection using two different defense systems in the event of a harbor being assaulted by maritime and aerial attacks.

Initially, the logical framework of the models is developed, creating the principle of the entire operation and activating all components as it is presented in Figure 1. Without this structure, simulation is not possible. Blocks are added by drag-and-drop in the Main tab and incorporated between input and output ports. Each block has specific attributes defining factors, in particular the location of appearance, arrival frequency, the appropriate speed, initial speed, and agent behavior, all of which shape decisions that can impact the simulation's outcome.

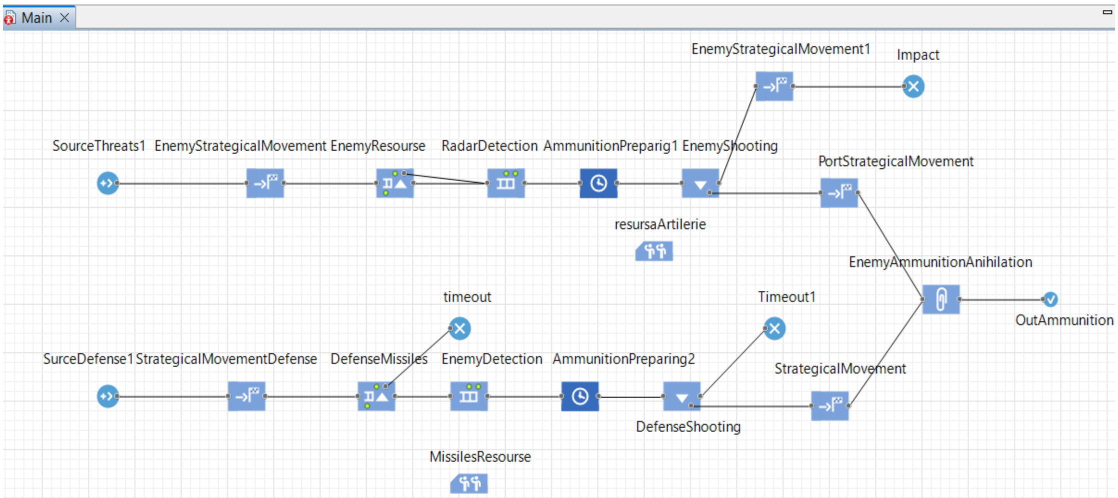

Figure 1. The logical framework of the model

Additionally, design elements were defined to represent a potential port terminal, including various workstations, buildings, warehouses, hangars, and roadways. To create a realistic simulation, it is important to carefully adjust the spatial boundaries. This adjustment is essential not only for visual accuracy but also to ensure that the dimensions are precise, facilitating a better interpretation of the simulated data.

3.1 Scenario 1: Maritime attack

The initial scenario illustrates an assault by enemy vessels on the port area, which is monitored by radar systems. Upon the identification of these vessels, the defense ships are alerted to start defensive operations. In the model there are used six different agent populations, each representing critical entities within the simulated scenario: warehouses, radar units, defense ships, enemy ships, missiles, and bombs. Further, it was created the control panel for managing the essential parameters set in the main agent, including the number of ships, their speed, missile speed, radar range, and the maximum missile capacity of the defense ship. This panel allows users to make real-time adjustments, giving the opportunity to explore various scenarios and outcomes to identify optimal solutions. The deployed vessels are warships, though their specific characteristics remain undefined, and the types of missiles and bombs are also unspecified. This aspect leads to inability to fully analyze the situation from a tactical perspective.

The visual analysis of the combat scenario, illustrated in Figure 2, includes the defensive and the enemy warships that are designed to interact within the simulation as they are engaged in conflict. The radar systems activate the detection of enemy units and coordinate the response of the defensive warships, providing a realistic representation of the battlefield’s dynamics.

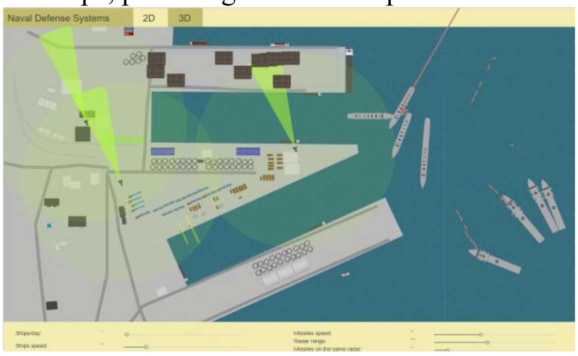

Figure 2. 2D representation of the model

Figure 3. Engaging in combat, 3D representation

The increasing of the radar range, as shown in Figure 3, enhances the operational effectiveness of the defensive warships. Additionally, the combat scenario is presented in 3D view, giving a detailed perspective on the tactical engagement between ships.

This section highlighted the model's ability to simulate complex interactions and defense strategies, demonstrating the applicability of advanced modeling and simulation in assessing and optimizing naval defense operations.

3.2 Scenario 2: Air attack

The second scenario aims to evaluate the effectiveness of an aerial attack and the resilience of the defense forces. The scenario involves an enemy aircraft that can be detected and neutralized, initially using a single defense system (radar units equipped with guided surface-to-air missiles). The bombers are generated at a specific rate and conduct raids on the harbor area. If the bomber approaches the objective, it will release a bomb designed to destroy the target. If the defense system has available missiles (there is a limited launch capacity), it will intercept and neutralize the bomber. Each radar can simultaneously guide up to two missiles. Radars should have a visibility range of 50 km from their position and exclude the ability to see aircraft flying below or directly above the radar. A missile is launched as soon as the bomber enters the radar’s coverage area. The missile detonates when it reaches proximity to the aircraft. When the missile exits the radar’s range before intercepting the target, it self-destructs.

Before starting the simulation, the air defense agents are placed in the port zone and their appropriate properties are set.

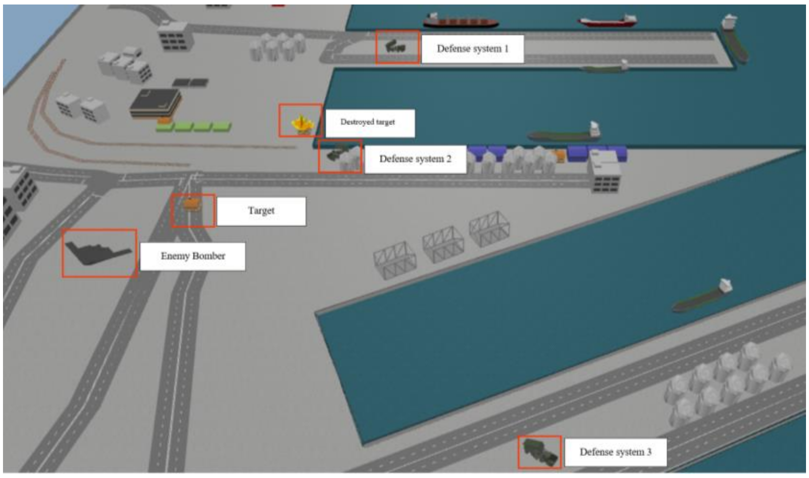

Figure 4. Representation of an aerial attack on the harbor area

This scenario includes simulation covering five distinct situations, each designed to analyze various outcomes:

- Simulation 1 – Establishing baseline parameters: The situation begins with two anti-aircraft defense systems, each equipped with a radar range of 50 km and capable of launching missiles with a flight speed of 2000 km/h. The enemy bombers Fly at 1500 km/h and release bombs on designated target buildings. By the end of the simulation, the targets are destroyed within a 60-minute time frame.
- Simulation 2 – Extending defense range: The range of the defense systems is increased to 200 km, while keeping the other parameters constant, to evaluate changes in the detection of enemy aircraft. It is observed that the rate and timeframe of target destruction remain consistent, despite earlier aircraft interception.
- Simulation 3 – Deployment of a third defense system: Adding a third defense system with 200 km range and missile speed of 2000 km/h and reducing enemy aircraft speed to 700 km/h, leads to the following result: only the closest target is destroyed. This means 10% destruction within 60 minutes.
- Simulation 4 – Adjusting defense systems placement: With the same parameters as in the previous simulation, the locations of defense systems 2 and 3 are repositioned. This adjustment results in a target destruction rate of 20%.
- Simulation 5 – Reducing bomber's speed: Using the same settings from the third simulation, this situation lowers the speed of the enemy aircraft to 600 km/h. The simulation outcome shows that all aircraft entering in the defense systems' range are neutralized. This is the ideal scenario, achieving a 100% destruction rate of the enemy targets while fully securing the harbor area.

4. Result analysis and limitations

Modeling and simulation using AnyLogic or similar specialized software can be an essential tool in increasing the security of maritime ports by using air or naval defense systems. The simulations represent a foundation for developing, testing, and implementing optimized strategies in the operational environment.

The present study focused on the importance of optimizing the performance of naval systems by using simulations to evaluate different configurations and operational strategies. The level of details of scenarios taken into consideration affected current simulation capabilities, and the accuracy of the input data used to model was on a high level in order to achieve reliable results.

The created models do not use complex tactical methodologies to receive real results and conclusions. The development of the models and their study aimed to analyze the possibility of application in order to optimize defense systems and to offer perspectives for future development.

The initial scenario was built to investigate various possibilities by using the control panel to adjust the essential parameters – number of ships, their speed, missile speed, radar range, and the maximum missile capacity of the defense ship. The model offers a wide range of options. By future enhancement of the model, users could highly achieve realistic results that may be effectively applied in optimizing real-world situations.

In the second scenario, the model meets the requirements established within this study. However, it is essential to understand that the results from the individual tests do not fully correspond to real-world conditions, as the model involves a certain level of abstraction. Additionally, various algorithms for efficient implementation do not rely on all possible training approaches.

Furthermore, certain aspects affecting the accurate operation of the simulation may have been overlooked in the modeling process. It is possible that in data entry process to leave out specific characteristics of the systems used in the simulation, which need to be considered to get results more closely aligned with reality. Based on the analysis conducted, simulation 5 appears to be the optimal defense scenario against aerial attacks, resulting in the lowest destruction rate. The five most representative situations were selected after testing several possibilities and highlighting key factors such as variations in the flight speed of enemy aircraft, the positioning and the range of defense systems, as well as the speed of the launched missiles.

After using modeling and simulation for optimizing naval defense the following recommendations are proposed: National defense institutions should adopt an integrated approach in the use of modeling and simulation, incorporating this method in all phases of naval defense systems development to maximize the decision-making processes efficiency. Additionally, modeling and simulation systems should be periodically evaluated and updated to align to technological advancements and evolving operational scenarios.

The created models provide a foundation for future studies and demonstrate the potential of using the AnyLogic software for optimizing naval defense systems, as well as in other applications.

5. Conclusions and future development

This work presented a comprehensive analysis of how modeling and simulation is conducted using the AnyLogic software. The program can effectively support the design, testing, and optimization processes of naval defense systems. Advanced technologies, such as AnyLogic, are essential for improving strategic decision-making, optimizing resource allocation, and maximizing operational efficiency in the complex context of naval defense.

When integrating modeling and simulation into the naval defense systems, a deeper understanding of potential challenges is necessary. The method provides a foundation for rigorous exercises of operational scenarios, that lead to effective reduction of uncertainties and maximize the system's usage.

As a result, naval forces can anticipate and adapt to the changing dynamics of the security environment, maintaining the training and ensuring an effective response to threats.

Despite significant advances in this area, challenges and limitations persist, including the importance of keeping up with rapid technological development and ensuring the accuracy of data used in simulations. Future perspectives suggest that there is a potential for integrating artificial intelligence and automation, which can lead to the improvement of the analytic process and unlock new opportunities for efficiency and innovation within naval defense systems.

A potential future development of the study would be to improve the models by adding more detail on military strategies and carefully analyzing military technology options. This requires a more in-depth analysis on capabilities of both local forces and potential adversaries. Once these aspects are fully resolved, it will be possible to develop additional scenarios that include a wider range of weapon types and explore new strategic areas.

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