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MODELING ANTI-AIR WARFARE WITH DISCRETE EVENT SIMULATION AND ANALYZING NAVAL CONVOY OPERATIONS

Ali E. Opçin

Turkish Naval Forces
Scientific Decision Support Department
Turkish Naval HQ
Bakanliklar
Cankaya, Ankara 06570, TURKEY

Arnold. H. Buss

Department of Computer Science
MOVES Institute
Naval Postgraduate School
1 University Circle
Monterey, CA 93943, USA

Thomas W. Lucas

Department of Operations Research
Naval Postgraduate School
1 University Circle
Monterey, CA 93943, USA

Paul J. Sánchez

Department of Operations Research
Naval Postgraduate School
1 University Circle
Monterey, CA 93943, USA

ABSTRACT

Using anti-air warfare tactics and concepts of operations, we explore the dominant factors for convoy operations. A discrete event simulation that facilitates modern analysis was built to model ships, their sensors, and their weapons. The model was used to simulate over 1.5 million naval battles in which we varied 99 input variables using a nearly orthogonal nearly balanced (NOB) Latin hypercube design of experiments. Metamodels were then constructed to study what impact the factors have on the survival of a High Value Unit and give guidance for which factors offer the most improvement. In addition to our specific findings, this study can be used as a guide for how to conduct future analyses.

1 INTRODUCTION AND BACKGROUND

Convoy operations under various threats are among the most critical naval missions. The spatial and temporal nature of the problem, including non-linearities and interactions of numerous factors, make simulation ideal for analyzing this type of scenario (Lucas et al., 2015). Within a carrier group or task force, air defense in naval tactics is typically provided via layered defense to protect a High Value Unit (HVU). The outermost layer is generally handled by aircraft, if available. The next layer consists of long-range surface-to-air missiles (SAMS), such as the Standard Missile-1 (SM-1) with a range of up to 100 nm. Threats which leak through these outer layers are handled by gun systems such as the76 mm Oto Melara, short-range missiles like the rolling airframe missile (RAM), and Close-In Weapon Systems (CIWS).

Simulation is an ideal methodology capable of comprehensively addressing the complexities of such a system. A well-designed simulation model permits external control of inputs in a structured fashion to facilitate the design and analysis of high-dimensional experiments. It should also be modular, scalable, flexible, and provide extensibility for future growth. The Anti-Air Warfare Analysis Model (AAWAM) was developed to meet these objectives using Simkit (Buss, 2016).

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AAWAM was initially built to analyze the effectiveness of a given screen disposition, screen ship properties, and HVU properties in convoy operations. It can also be used to identify the most impactful factors on the success of convoy operations. AAWAM is unique in that it explicitly models the effects of screen disposition and a layered defense policy in surface warfare, including enemy ships and their engagement factors.

2 LITERATURE REVIEW

There are many studies devoted to anti-air warfare (AAW). Kulac (1999) built an analysis tool to compare active and passive sensors in AAW, specifically infrared and radar sensors. However, his study only focused on the sensors and two primary classes of weapons, ASMs and SAMs. Modern warships are such complex systems that their AAW capabilities are not limited to that extent. Aydin (2000) modeled the screen dispositions of naval task forces to investigate effective defensive dispositions. His model lacked the fidelity of the engaging unit that sent the ASMs to the convoy and ship's layered defense models. Turan (2002) developed a simulation to analyze two different Ship Self Air Defense (SSAD) system selection process and firing policies. His model did not take the layered defense policy into consideration and did not model the gun and CIWS of a ship. Townsend (1999) developed an analysis tool called ASM Defense Model. His work was solely focused on ASM raids, and did not consider a layered defense policy. The only objects in his simulation were ASMs, ships and SAMs. Bloeman and Witberg (2000) focus on AAW for a single ship. In contrast to these prior works, the study presented here generalizes to an arbitrary number of ships and is unique in its focus on building a discrete event simulation (DES) tool that permits a complete analysis of AAW utilizing data farming techniques to identify the dominant factors responsible for system behaviors.

In summary, no studies have been found that perform a complete analysis of complex AAW scenarios with formation movement models and ship layered defense models with SAMs, guns, and CIWS. Therefore, AAWAM was developed to fill this gap.

3 DESIGN OF AAWAM

AAWAM is a stochastic DES developed to investigate factors affecting the protection of an HVU in convoy operations. Three types of ships are currently modeled: a Blue (friendly) HVU and frigates for both Blue and Red (enemy) forces. Note that classification of a ship's type is a matter of how it is parameterized, and other types of ships could easily be modeled. The primary scenario is protection of an HVU by friendly frigates against enemy frigates. The HVU has a predefined path for each scenario and the simulation run terminates when either the HVU is destroyed or reaches the last waypoint. Each enemy frigate patrols along predefined paths. Friendly frigate initial positions are determined by a screen formation around the HVU, and they dynamically maintain their positions relative to the HVU. Their goal is to protect the HVU by engaging enemy ships and destroying their ASMs.

One scenario we investigated consists of three Blue frigates, an HVU, and two Red ships. Upon engagement, the forces might be positioned as seen in Figure 1. Incoming threats are eliminated by ships according to the layered defense policy.

In Figure 2, concentric circles represent each ship's sensor ranges. A blue circle is a ship's surveillance sensor range, within which an entity can be detected and classified. A red circle represents a SAM's engagement sensor range, a yellow circle represents gun engagement range, and a black circle represents a CIWS engagement sensor range. Frigates of both sides have one of each of these sensors. The HVU has only a surveillance sensor and CIWS engagement sensor. Orange squares represent ASMs, blue squares represent SAMs red squares represent gun rounds, and black squares represent CIWS rounds.

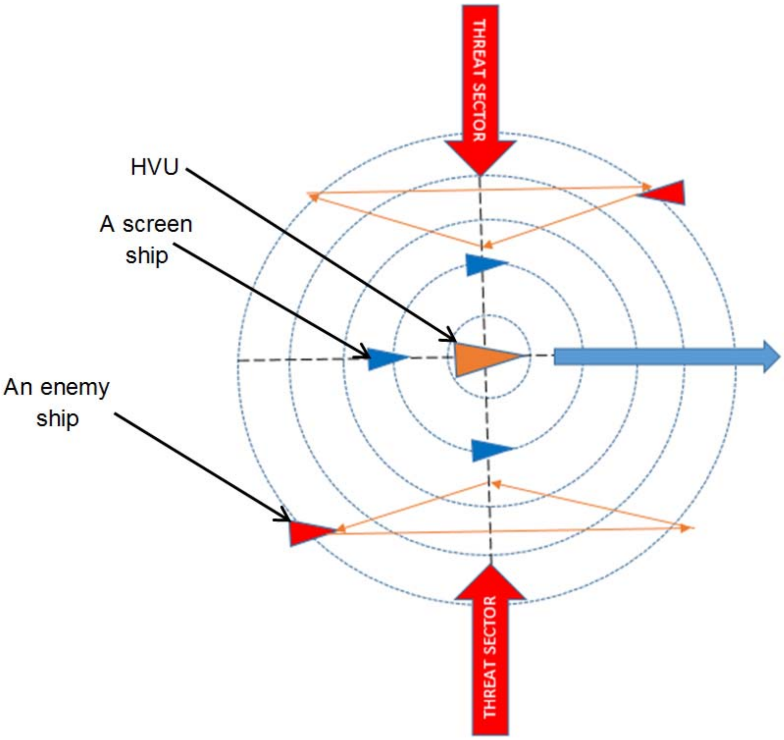


Figure 1: Possible Scenario for AAWAM.

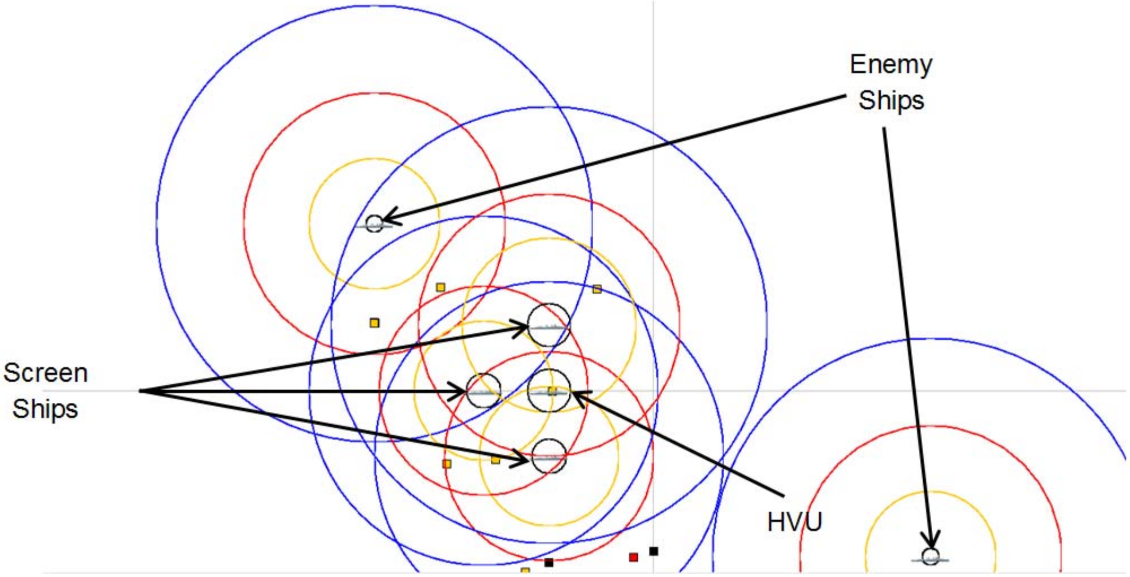


Figure 2: Screenshot of an AAWAM Engagement.

Ships may engage each other with ASMs and guns when they are in range. A ship may be hit by an ASM if it "leaks" through the layered defense. A ship is hit by a gun when a shell achieves an impact point sufficiently close to the ship's center. An ASM is eliminated when a SAM, gun round, or CIWS round detonates close enough to successfully damage it. All-told, AAWAM models five types of engagements: ASM against ship, gun against ship, SAM against ASM-SAM, gun against ASM, and CWIS against ASM.

AAWAM is comprised of 15 component types: ship, ASM, SAM, missile mover manager, follower mover manager, HVU mover manager, gun round, round mover manager, ship surveillance sensor, ship sensor for SAM engagement, ship sensor for gun engagement, ship sensor for CIWS engagement, contact, policy, and adjudicator. Among those components, the stochastic elements are: ship surveillance sensors, ASMs, SAMs, gun rounds, contacts, and adjudicators. Detection events inside the ship surveillance sensor are scheduled according to an exponential distribution. The ASM, SAM, and gun round components have their own damage functions which return damage amounts when they successfully hit their targets. The damage amounts follow a truncated normal distribution (Armstrong, 2005). Errors in knowledge of a target's actual location are modeled by adding random deviations to the actual position. These deviations are generated using a rotated bivariate normal distribution. The adjudicator component uses engagement-specific probability models to determine outcomes. See Opçin (2016) for detailed explanations of each of these model components.

4 ANALYSIS OF AAWAM

The primary purpose of the simulation is to gain insight into the factors affecting AAW. Our analysis is based on statistical models of the input/output relationships. Using modern design of experiments (DOE) enables efficient and effective determination of causal relationships between the input factors and the output measures. Each unique configuration of input factor settings is called a *design point*, and can produce distributions of results for one or more output measures.

AAWAM is a terminating simulation—the termination state is triggered by the HVU either reaching its goal or being destroyed by enemy ships—so transient behavior in the measures of effectiveness (MOEs) is an integral part of its behavior (Nakayama, 2008). It was constructed to produce two primary MOEs:

- The HVU's survival is a binary measure.
- The HVU's efficiency at termination of the run, a continuous measure, is defined as the remaining percentage of resilience against enemy missiles and gun rounds.

Replications at all design points are seeded independently, so the resulting data can be analyzed using traditional statistics assuming independence (Sanchez, 2007).

4.1 Scenarios

Three different scenarios were built to conduct the analysis. In each scenario, Red forces patrol in their predefined areas of operation. Red's mission is to engage any Blue ships detected in their patrol area and destroy them. Engagement priority is simple—Red engages upon classification of a Blue unit, in order of detection.

The initial battle orientation is as seen in Figure 1. Based on Blue maneuvers and Red patrol patterns, the relative positions can change over time. In all scenarios, Blue screen ships protect the HVU so it can reach the predefined goal, a specific location. If the HVU is destroyed by Red prior to reaching the goal, the mission fails. Table 1 summarizes the three scenarios that we explored.

Table 1: Force composition for the three scenarios explored.

	Blue force	**Red force**
Scenario 1	HVU + 3 Frigates	2 Frigates
Scenario 2	HVU + 4 Frigates	4 Frigates
Scenario 3	HVU + 3 Frigates	4 Frigates

4.1.1 Design of Experiment

Many design alternatives are available in the literature. AAWAM includes 99 factors with 8 discrete and 91 continuous ones that we wish to explore. We therefore require a design which can handle such a large number of inputs with a mix of continuous and discrete factors, has good space-filling properties, is orthogonal or nearly so, and does all of these in a parsimonious fashion. Such a design was created by Vieira et al. (2012) and is called a Nearly Orthogonal Nearly Balanced (NOB) design. It is freely available in a spreadsheet format (SEED Center, 2016). The NOB supports designs for up to 10 blocks of 20 *k*-level factors (*k*=2,3,…, 11) and 100 continuous factors, using a mere 512 design points. The maximum absolute pairwise correlation is 0.0356, which ensures minimal confounding of main effects in linear models. We ran AAWAM for 1000 replications at each design point to ensure a standard error on the probability of the binary outcome HVU survival was no greater than 0.016.This resulted in 1,536,000 simulated AAW battles. Each run took an average of three milliseconds on a personal computer with an Intel (R) Core (TM) i7–4810MQ 2.8 Ghz CPU and 8 GB RAM. Actual run times varied depending on the number of ships instantiated.

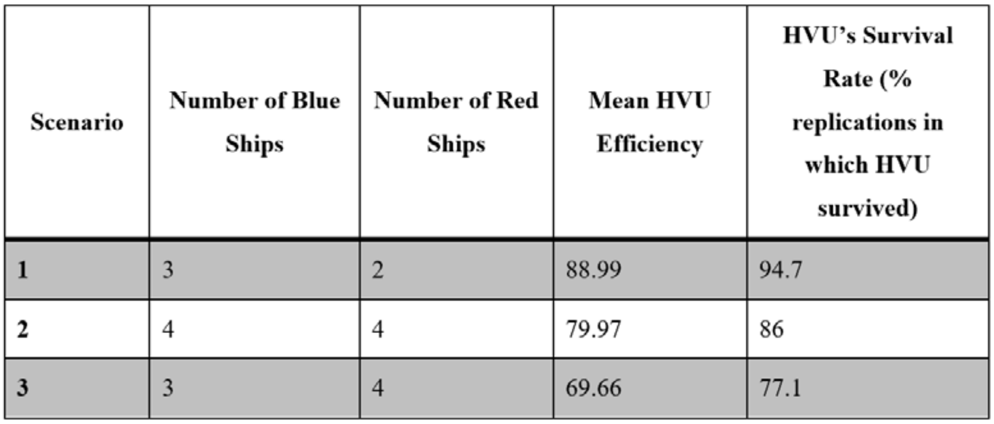
4.2 Analysis of Results

4.2.1 Overview of Results

In this section a very preliminary analysis which aggregates across the factor settings is made at the scenario level. Averages of the two MOEs are found in Table 2. The results clearly show that as the number of Blue ships increases relative to Red, both the rate of HVU survival and the mean efficiency level increase.

Normal Quantile plots for mean HVU efficiencies and survivals show skewed distributions. Because they are not normally distributed, we used non-parametric comparisons for each pair using the Wilcoxon method (Wackerly, Mendenhall, and Scheaffer, 2002) to compare the means of HVU efficiencies and survivals for each scenario. The results show a significant difference among all pairs of means for efficiencies. We see that four Red and four Blue frigates yielded the lowest success rate for Blue. As the Red frigates increased relative to Blue frigates, both the HVU survivability and efficiency deteriorated.

Table 2: Summary Statistics for Three Scenarios.



Scenario	Number of Blue Ships	Number of Red Ships	Mean HVU Efficiency	HVU's Survival Rate (% replications in which HVU survived)
1	3	2	88.99	94.7
2	4	4	79.97	86
3	3	4	69.66	77.1

4.2.2 Analysis of Scenarios

In this subsection, analyses were based on the raw data from all three scenarios. Both partition trees and logistic regression were applied to the combined data, with HVU survival as the dependent variable. Each model was initially fit using both Blue and Red ship factors as predictors, to identify *all* factors affecting HVU survival. A second fit was then performed with only factors controllable by Blue, to focus on Blue's policy options.

4.2.2.1 Analysis of All Factors Including Enemy Ship Factors

The analysis with partition trees produced new insights. The Red ship's ASM Probability of Kill has the largest effect on HVU survival. Additional Red ship properties with significant effects include ASM Range, ASM Damage Mean after a successful hit, Gun Damage Mean after a successful hit, ASM Maximum Speed, SAM Launch Delay Time, and the Total Number of ASMs. Taken as a whole, the lethality of the Red ships' ASMs is critical in reducing the HVU's probability of survival. However, given that there were multiple sequential splits on some of the factors, it is likely that some of the variables might be better modeled with continuous effects.

We next fit a nominal logistic regression on HVU survival, with a total of 101 explanatory variables—the 99 factors of the NOB design augmented with the number of Red ships and the number of Blue screen ships. After performing a stepwise regression (Faraway, 2015) and additionally removing any factors that were deemed practically insignificant, the nominal regression fit includes the variables presented in Table 3.

Results of both models agree on seven of the factors. Among those, three are related to Blue ships and the HVU, and the remainder are related to Red ships. The most influential Blue factors for HVU survival are SAM Probability of Kill, SAM Range, and HVU Efficiency Threshold. The most effective Red factors are ASM Probability of Kill, ASM Range, Total Number of ASM, and ASM Damage Mean. Both models agree that Red ASM properties have the greatest effect on the likelihood of HVU survival.

4.2.2.2 Analysis on Blue Ship Factors

To focus on Blue's policy options, models of HVU survival were constructed using only Blue ship factors. There are a total of 52 Blue factors when HVU ship parameters and the number of Blue screen ships are considered.

Table 3: Results Summary for Most Important Factors Among All Factors. Bold items are common to both methodologies.

Methodology	**Most Important Factors**
Partition Tree	***Red ASM Blue Ship Probability of Kill***
	Blue Ship SAM Red ASM Probability of Kill
	Red Ship ASM Range
	Blue Ship SAM Range
	Red Ship ASM Damage Mean
	Blue Ship Gun Range
	Red Ship Gun Damage Mean
	Red Ship ASM Maximum Speed
	HVU Efficiency Threshold
	Red Ship SAM Launch Delay Time
	Red Ship Total Number of ASM
Logistic Regression	***Red ASM Blue Ship Probability of Kill***
	Number of Red Ships
	Blue Ship SAM Red ASM Probability of Kill
	Blue Ship SAM Range
	HVU Efficiency Threshold
	Red Ship ASM Range
	Number of Blue Ships
	Red Ship Total Number of ASM
	Blue Ship Total Number of ASM
	Red Ship ASM Damage Mean
	Red Ship Total Number of SAM
	Blue Ship Total Number of SAM
	Blue Ship CIWS CED for Impact of Rounds

Partition tree results are found in Table 4. The most impactful variables are the SAM ASM Probability of Kill, SAM Range, HVU Efficiency Threshold, CIWS Rounds Inter-Shot Delay Time, Gun range, Engagement Sensor Quality, ASM maximum range, SAM Launch Delay Time, and Surveillance Sensor Quality. As before, the presence of multiple sequential splits for some variables indicates a continuous model may provide additional insight.

The nominal regression on HVU survival was fit using stepwise regression and then removing the practically insignificant factors. The final tally of significant variables is presented in Table 4.

As before, there is a strong overlap on significant factors identified. Both models identify the SAM properties and the HVU's staying power as important. Thus, the frigates defending the HVU need long-range SAMs with a high probability of kill and the HVU needs to have a high staying power.

5 CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

In this study, convoy operations were modeled with AAWAM and analyzed, with a focus on using screen ships to protect an HVU. A more elaborate model of both the sensors and weapons was developed, with particular emphasis on the layered defenses of the HVU. AAWAM was built in a generic manner such that its assets, including screen ships, enemy ships, sensors, and weapons, can be instantiated in any configuration and with any parameterization. AAWAM also uses DES to model the concepts of operations, such as positioning of screen ships, the specific layered defense policy, and SAM shooting policies.

Table 4: Results Summary for Most Important Factors Among Blue Ship Factors.

Methodology	**Most Important Factors**
Partition Tree	***Blue Ship SAM Red ASM Probability of Kill*** ***Blue Ship SAM Range*** ***HVU Efficiency Threshold*** Blue CIWS Inter Shot Delay Time Blue Gun Range Blue Ships Engagement Sensor Quality Blue Ships Surveillance Sensor Quality Blue Ships ASM Maximum Damage Blue Ships SAM Launch Delay Time
Logistic Regression	***Blue Ship SAM Red ASM Probability of Kill*** ***Blue Ship SAM Range*** ***HVU Efficiency Threshold*** Blue Ship Total Number of ASM Blue Ship CIWS Red ASM Probability of Kill Blue Ship Total Number of SAM Blue Ship COD for Impact of CIWS Rounds Blue Ship COD for Impact of Gun Rounds HVU Maximum Speed

A total of 99 factors in AAWAM were analyzed, 52 of which were controllable and 47 of which were uncontrollable. The controllable factors consisted of properties of the Blue side, including screen ship and HVU characteristics, whereas the uncontrollable factors were properties of the Red side.

Nominal logistic regression and partition tree models were fit on the binary response variable of HVU survival. The analysis of controllable factors showed that SAM specifications of screen ships and the staying power of the HVU were the most effective. The analysis of all factors showed that ASM specifications of enemy ships were the most impactful.

The interactions between ASMs and SAMs were decisive on the success of a convoy operation under air threat. These results stress the importance of soft kill methods, such as usage of decoys and electronic warfare, which may be effective in decreasing the probability of successful hit for an ASM. Although soft kills were not explicitly modeled by AAWAM, the analysis indicates that including such countermeasures in further development of the model ought to be a priority.

Returning to controllable factors, the analysis indicates that for screen ship designs we first need to focus on the specifications of existing SAMs. Given a limited budget for research and development regarding screen ships, enhancing SAM capabilities should have top priority. These enhancements could include, but are not limited to, SAM speed, successful hit probability, and range. Additionally, before starting a convoy operation, obtaining intelligence about the enemy's capabilities is paramount. Specifically, if it is known that the enemy ships have ASMs, determining their specifications is key to the success of the mission.

Our hope is that the work presented here provides a possible roadmap for future work in AAW. The combination of DES and data farming is extremely powerful, and provides much richer insights than can be obtained from overly simplified analytical models or the scenario-based simulation studies that have been more commonly pursued in the past. This approach has tremendous potential for analysts, operational personnel, and decision makers involved in procurement, strategy, and tactics.

5.2 Future Work

AAWAM is a model of moderate complexity, resolution, and fidelity. Even so, there are a number of enhancements that would substantially increase its applicability and usefulness for future analyses. Toward that end, AAWAM's architecture was designed to facilitate enhancement. The following ideas could be incorporated into the AAWAM to augment its capabilities.

- AAWAM models all movements according to linear motion (Buss and Sanchez 2005). The actual movement of ships, gun rounds, and missiles are known to be non-linear. Introducing non-linearity may increase the fidelity.
- AAWAM ships do not carry out evasive maneuvers. However, these can have a significant impact on the outcome of real engagements. Enhancing AAWAM by modeling evasive maneuvers according to doctrine will increase fidelity and support additional analysis.
- AAWAM does not currently model soft kill methods. Since the analysis indicated that considering soft kill methods could have a potential impact, this would be an important addition to AAWAM. An example of DES modeling of soft kill methods in undersea warfare may be found in Armo (2000), and could be the basis for adding this feature to AAWAM to model soft kill defenses in surface warfare.
- AAWAM currently only models ships as assets and threats. Nevertheless, air threats, such as fighter airplanes and land based missile sites, also pose potential risks to a convoy. AAWAM's modular design easily supports adding these to the model.
- It is important to note that AAWAM's input factors were all created from unclassified, open source data. Therefore, the conclusions expressed must be considered in that context. In order to obtain more conclusive results, AAWAM should be run with actual data in a secure computing environment.
- An important element in any analysis consists of the Verification, Validation, and Accreditation (VV&A) of the model used. While the model's implementation in Java was verified against the event graph designs of the respective components (Opçin, 2016), a comprehensive validation effort was beyond the scope of this study. Before any recommendations from this analysis are taken into serious consideration, such a validation effort would be required. Finally, before any DoD entity were to adopt AAWAM or its successors, the model would also have to be accredited, which is also beyond the scope of this study.

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AUTHOR BIOGRAPHIES

ALİ ERCÜMENT OPÇİN is a Simulation Manager and Operations Analyst at Turkish Naval Forces Headquarters, Ankara/TURKEY. He holds dual M.S. degrees in Modeling, Simulation and Virtual Environments and in Operations Research from the Naval Postgraduate School. His research interests include Statistics, Design of Experiments, Discrete Event Simulation, Simulation Analysis, Artificial Intelligence, and Machine Learning. His e-mail address is a.opcin7110@gmail.com.

ARNOLD H. BUSS is a Research Associate Professor in the MOVES Institute at the Naval Postgraduate School. His interests include component-based simulation modeling, with emphasis on military applications. His e-mail address is abuss@nps.edu.

THOMAS W. LUCAS is a Professor of Operations Research at the Naval Postgraduate School (NPS) in Monterey California. His primary research interests are simulation, warfare analysis, design of experiments, and robust Bayesian statistics. In addition to his regular faculty duties, Professor Lucas is a co-director of NPS's SEED Center for Data Farming—see http://harvest.nps.edu. His research interests include robust statistical methodology, defense and security modeling, high-dimensional design of experiments. His web page can be found at http://faculty.nps.edu/twlucas/. His e-mail address is twlucas@nps.edu.

PAUL J. SANCHEZ is in the Operations Research Department at the Naval Postgraduate School. His research interests include design of experiments, simulation output analysis, and object-oriented modeling. He is an avid reader and collector of science fiction, and enjoys riding recumbent bikes around the Monterey Bay area. His e-mail address is pjsanche@nps.edu.