Computational models for anti-air and anti-submarine warfare simulation

Modelos computacionales para simulación de guerra antiaérea y antisubmarina

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Abstract

This paper describes the generation and simulation process of computational models oriented to the analysis of the operational situations (OPSIT) of anti-air warfare (AAW) and antisubmarine warfare (ASW), with the purpose of evaluating the effectiveness of different combinations of threats, weapons, and sensors of the Colombian Navy. A detailed description of the OPSITs modeling process is presented by using the selected discrete events simulation tool. The experiments design process and the statistical analysis of the results is also described, using a statistical analysis tool. All this to provide the Colombian Navy with a tool it can use to evaluate the systems that could be part of future units.

Key words: Simulation, discrete events, modeling, antisubmarine warfare, anti-air warfare, experiment design

Resumen

El documento describe el proceso de generación y simulación de modelos computacionales orientados hacia el análisis de unas situaciones operacionales de guerra antiaérea (AAW) y Antisubmarina (ASW), con el fin de evaluar la efectividad de diferentes combinaciones de amenazas, armas y sensores de la Marina Colombiana. Se presenta una descripción detallada del proceso de modelación de las situaciones operacionales en la herramienta de simulación de eventos discretos seleccionada, así como también se describe el proceso de diseño de los experimentos y el tratamiento estadístico de los resultados, empleando una herramienta de análisis estadístico. Lo anterior tendiente a proporcionar a la Armada Colombiana, una herramienta para la evaluación de los sistemas que podrían componer las futuras unidades.

Palabras claves: simulación, eventos discretos, modelación, guerra antisubmarina, guerra antiaérea, diseño de experimentos.

Date Received: December 2nd, 2010 - *Fecha de recepción: 2 de Diciembre de 2010*
Date Accepted: March 6th, 2012 - *Fecha de aceptación: 6 de Marzo de 2012*

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Introduction

Simulation tools allow modeling phenomena or events of different complexity and are used as support tools in the decision making process because they base their predictions on mathematical methods that yield results that are very close to the real ones. In fact, simulation can be defined as the act of imitating a real system, representing certain characteristics or its behavior.

This document seeks to describe the process of generating and simulating computational models of antisubmarine (ASW) and anti-aircraft warfare (AAW) by using discrete event simulation. The aim of the development of such models is to use them as tools for conceptual exploration of future units to evaluate the effectiveness of different weapons system configurations considered at this stage. That means that these models will be other tools to optimize processes of conceptual design of units afloat.

The methodology used to develop the models begins with the selection of operational situations to simulate, then it is necessary to identify the different threats, weapons, and sensors and their possible combinations within the selected scenario; this is introduced to the selected simulation tool and results obtained will undergo statistical processing to successfully analyze them.

Conceptual Framework

Some key concepts related to this topic are presented to provide tools to improve understanding of the paper.

Discrete Event Simulation

Discrete event simulation is a computer technique for dynamic systems modeling. In this type of simulation, events are generated and managed over time using an event queue ordered by the simulation time in which events must occur, thus, the simulator can read the queue and trigger new events.

Operational situation (OPSIT)

Operational situations are the scenarios used as base for evaluating different configurations of weapons, sensors, and threats for both ASW and AAW.

OPSIT Selection and Description

To select OPSITs that will be simulated, it was necessary to gather a group of experts in ASW, which comprised ASW officers and petty officers from ARC Almirante Padilla type frigates of the Colombian Navy and for a submarine warfare expert from the Colombian submarine fleet. For AAW, it was possible to obtain technical advice from an officer from DARET and an officer who is studying in the Naval Postgraduate School (NPS).

For ASW the publication MXP-1 (D) (Navy) (Air) of the U.S. Navy (Multi-National Submarine and Anti-Submarine Exercise Manual) was taken as reference from which two operational scenarios were selected among several proposed. For ASW, the OPSITs selected are:

1. Port leaving with submarine opposition. (Similar to Casex C-7)
2. Coordinated submarine search in an area.

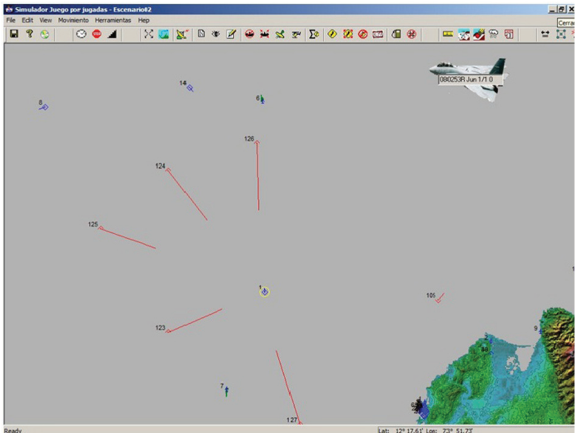
The configuration of each OPSIT depends on the specific need to be evaluated. For cases presented in this document, the units involved in the first OPSIT are: two ships (with Helicopters), one tanker (main body), and one submarine.

In the second OPSIT had: one ship (with helicopter) and one submarine.

The first OPSIT mission is the main body protection and neutralization of the threat, while for the second OPSIT, the only objective is to neutralize the threat.

Fig. 1 provides an overview of the AAW OPSIT, showing enemy aircraft in red and the unit attacked is in the center in blue. In this case, the unit's fundamental mission is to defend itself against the attacks.

Fig. 1. Panorama of the AAW OPSIT



For AAW, the OPSIT was basically modeled as missile air defense, where a ship is the target of a coordinated enemy aircraft attack, using air-surface missiles (ASM).

Mission Evaluation

In order to have metrics to evaluate each mission, some requirements have been designed to determine its success, based on the calculation of measures of performance (MOP) and a measure of effectiveness (MOE) for each OPSIT.

The measure of effectiveness is defined by the weighted sum of the measures of performance established; that is:

$$MOE = W_1 \cdot MOP_1 + W_2 \cdot MOP_2 + \cdots W_n \cdot MOP_n \qquad (1)$$

Where W_1, W_2, W_n are factors representing the importance of each MOP. For ASW, these values were determined from surveys made in that regard to two of the commanders of Almirante Padilla type frigates of the Colombian navy.

In the ASW OPSIT, the MOPs are:

- MOP_1 = Tanker survival probability
- MOP_2 = Survival probability of the ships
- MOP_3 = Threat neutralizing probability

And the MOE of this OPSIT is:

$$MOE = 0{,}25 \cdot MOP_1 + 0{,}25 \cdot MOP_2 + 0{,}5 \cdot MOP_3 \qquad (2)$$

For the second ASW OPSIT, the MOPs are:

- MOP_1 = Survival probability of ships
- MOP_2 = Threat neutralizing probability
- MOP_3 = Time to detect the submarine

And the MOE of this OPSIT is:

$$MOE = 0{,}25 \cdot MOP_1 + 0{,}34 \cdot MOP_2 + 0{,}41 \cdot MOP_3 \qquad (3)$$

Finally, for the AAW OPSIT, the MOP is equal to the MOE; due to this, only one MOP will be evaluated:

- MOP1 = Survival probability of ships

And the MOE is:

$$MOE = MOP_1 \qquad (4)$$

Threat Characterization

The AAW OPSIT takes into account three possible threats. Bear in mind that for this particular case, ASM missiles and not the planes are assumed as direct threats, given the assumption that a plane is not going to approach within the range of the ship guns.

Data presented in Table 1 are some of the features of the threats selected.

Table 1. AAW OPSIT threats characteristics

Threat	Characteristics	Values
MISSILE 1	Speed	0.88 Match
	Range	62 MN
	RCS	0.2 m
	Shooting distance	60 MN
	Final phase height	18 ft

MISSILE 2	Speed	2.5 Match
	Range	27 MN
	RCS	0.1 m
	Shooting distance	25 MN
	Final phase height	15 ft
MISSILE 3	Speed	0.93 Match
	Range	36 MN
	RCS	0.2 m
	Shooting distance	35 MN
	Final phase height	9 ft

Both ASW OPSITs take into account two possible threats. The general characteristics of the two submarines, which are relevant to the appropriate development of the models, are presented in Table 2.

It is worth stating that the selection of the threat and its operating characteristics are subject to change, depending on the needs of the situation.

Table 2. ASW OPSITs threats characteristics

	Submarine 1	Submarine 2
Sonar:	STN Atlas DBQS40 sonar suite: detection sonar	Integrated Lira system, incorporating the hydrophones horseshoe and flank arrays;
Torpedo:	12 [maximum speed 35 kt; range 28 km at 24 kt; 12 km at 35 kt]	18 [Speed: 30-50 kt, Range: 27 n miles/13.5 n miles]
Missile:	Optional.	10 VLS cells.
Counter-measures:	Defense system Tau torpedoes	N/A.-
Speed:	12 kt (surface) 20 kt (submerged)	10 kt (surface) 19 kt (submerged)
Range:	8,000 Mn at 8 kt (surface); 420 Mn at 8 kt (submerged)	6,000 Mn at 7 kt (surface); 650 n miles at 3 kt (submerged)
Operational depth:	700 m	300 m

Technological Options

For the ASW OPSITs, the technological weapons and sensors options taken into account are presented in Table 3.

Table 3. ASW Technological Options

	Technological Options	Variable
Hull sonar	Option 1	Frequency: (4.5 kHz) Power: 96 kW
	Option 2	Frequency: (7. 5 kHz) Power: 36 kW
VDS	Option 1	Frequency: (12 kHz)
	Option 2	Frequency: (5 kHz) Power: 96 kW(peak)
TAS	Option 1	Frequency: (< =1 kHz)
	Option 2	Frequency: (< =1 kHz)
Ship torpedo	Option 1	Speed: 28 kt Range: 13.5 Km
	Option 2	Speed: 29 kt Range: 23 Km
	Option 3	Speed: 45 kt Range: 11.11 Km
ASW Helo.	Option 1 (8 sonobuoys 1Torpedo)	Autonomy: 1.4 Hours Torpedo: Option 2
	Option 2 (VDS 1Torpedo)	Autonomy: 2 Hours Torpedo Option 1

For the AAW OPSIT, configurations of the ship weapons and sensors that will be evaluated in the simulation are shown in Table 4 and technological options taken into account appear in Table 5.

Table 4. Ship configuration options

	Radar	**ESM**	**SAM**	**CANNON**	**CWIS**	**ECM**	**CHAFF**
Config. 1	Opt. 1	Opt. 1	Opt. 2	Opt. 1 and 2	NO	Opt. 1	Opt. 1
Config. 2	Opt. 2	Opt. 2	Opt. 1	Opt. 1 and 2	NO	NO	Opt. 2

Table 5. AAW technological options

		Options	**Characterístics**	**Values**
SENSORS	**Radar**	Option 1	Maximum Theoretical Range	10.79 MN
			Antimissile probability	80%
		Option 2	Maximum Theoretical Range	10.79 MN
			Antimissile probability	80%
	ESM	Option 1	Sensitivity	-75 dBm
			Minimum Frequency	1 GHz
			Maximum Frequency	18 GHz
		Option 2	Sensitivity	-65 dBm
			Minimum Frequency	0.5 GHz
			Maximum Frequency	40 GHz
WEAPONS	**SAM**	Option 1	Range	8.09 MN
			Speed	2.5 Match
			Impact probability	30%
			Minimum distance	0.4 MN
		Option 2	Range	8.09 MN
			Speed	2.5 Match
			Impact probability	30%
			Minimum distance	0.4 MN
	CANNONS	Option 1	Caliber	127 mm
			Shots per minute	40
			Effective range	16.19 MN
			Minimum distance	0.3 MN

WEAPONS	**CANNONS**	Option 2	Caliber	40 mm
			Shots per minute	300
			Effective range	3.2 MN
			Minimum distance	0.3 MN
		Option 3	Caliber	76 mm
			Shots per minute	120
			Effective range	16.19 MN
			Minimum distance	0.3 MN
		Option 4	Caliber	20 mm
			Shots per minute	450
			Effective range	1.07 MN
			Minimum distance	0.2 MN
	ECM	Option 1	Reaction time	1 sec
			Simultaneous threats	Yes
	CHAFF	Option 1	Cloud time	40 sec
			Fake target size	10,000 m2
			IR Signature	yes
		Option 2	Cloud time	40 sec
			Fake target size	10,000 m2
			IR Signature	yes

Simulation Models

To make the OPSITs models in the simulation tool it was necessary to develop a logic diagram to have greater clarity on the logical relationships among the different processes occurring in each. Fig. 2 presents one example.

The general scheme for the development of simulation models is presented in Fig. 3.

Endogenous variables that constitute the inputs or the simulation model are on the left side of Fig. 3; the state variables, which condition the simulation process, are on the central part, and – finally – the exogenous variables as result of the process are in the right side of the figure.

Then, the modeling process begins in the simulator. An example of the blocks created in the simulator is presented in Fig. 4 (see pag. 36).

For the AAW OPSIT, the model starts with the creation of a couple of objects, which will be necessary for assigned properties, these properties are read from an Excel spreadsheet that has all the values needed for the model to function. Once read, these properties are stored in the object in form of attributes.

Fig. 2. Logical diagram for variable initialization of AAW OPSIT

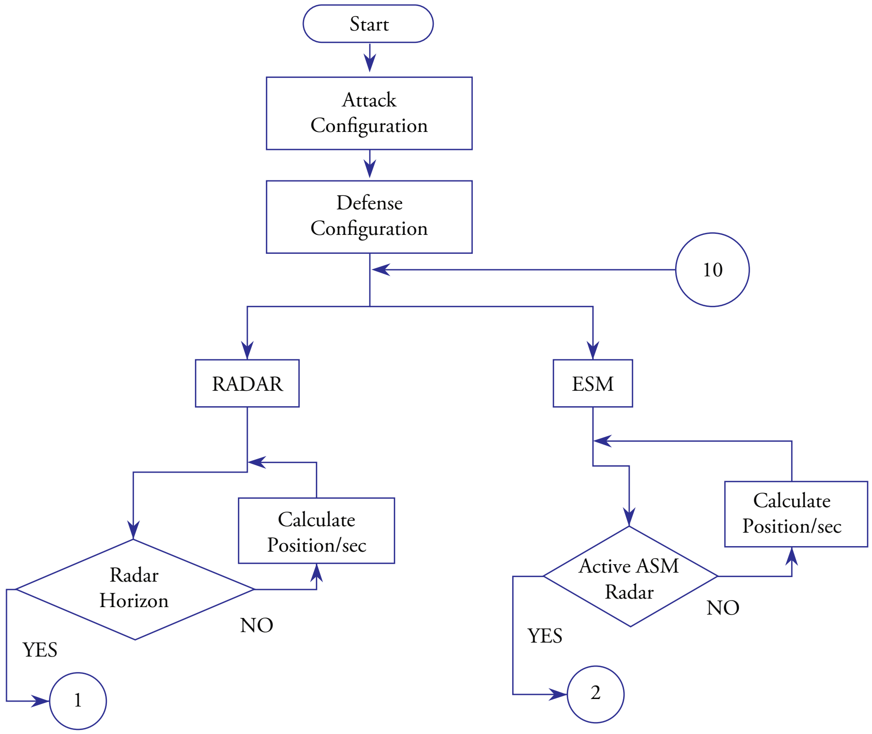


Fig. 3. General diagram of the simulation process

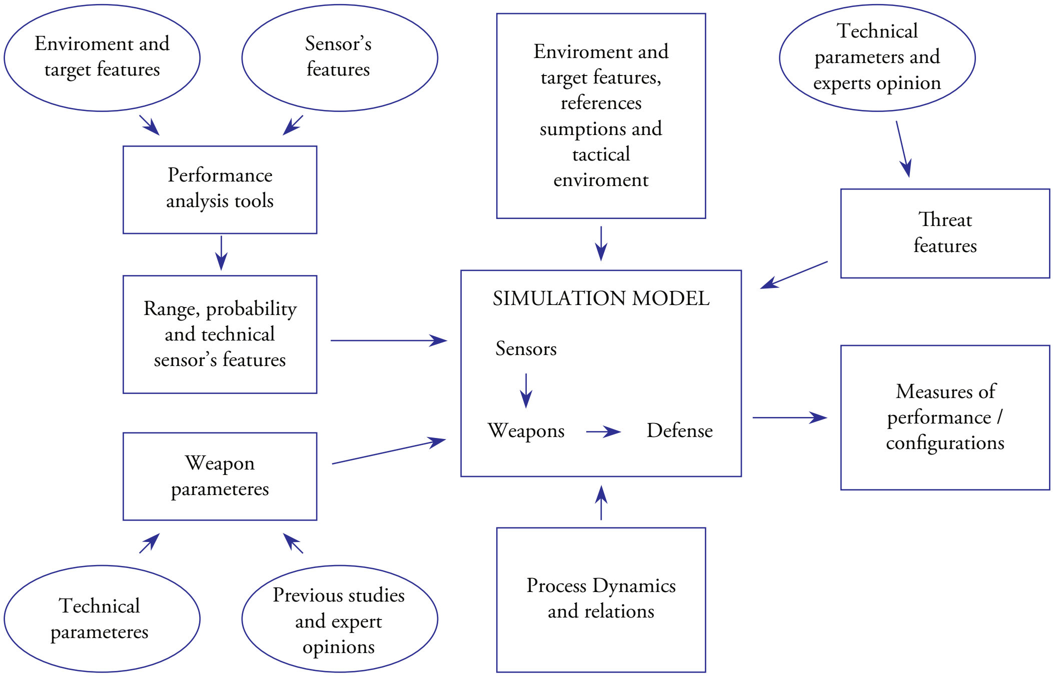
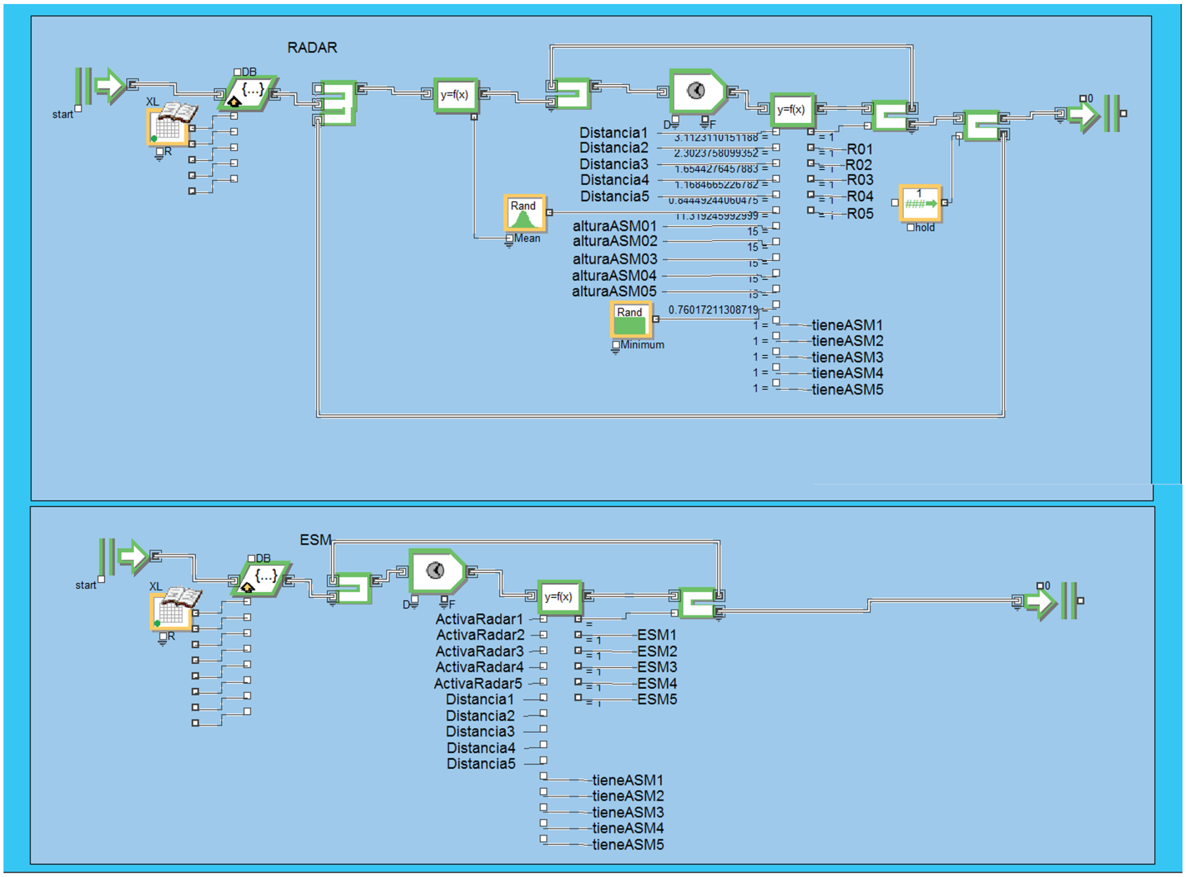


Fig. 4. AAW ship sensor model in the simulator



When each object has its attributes, it is necessary to calculate whether threats are within the detection range of each sensor. If threats are within range, the sensor determines the distance and sends the information to a queue of weapons that will assign the appropriate defense (defense of barriers concept); otherwise, the sensor will continue sweeping the area until achieving detection.

In general, the AAW model block presented in Fig. 4 was used to simulate the dynamic approach (simulation sampling) of enemy missiles fired. When these missiles are within range of the sensors, detection occurs. This detection activates a weapons assignment queue, which is another object or event in the simulation.

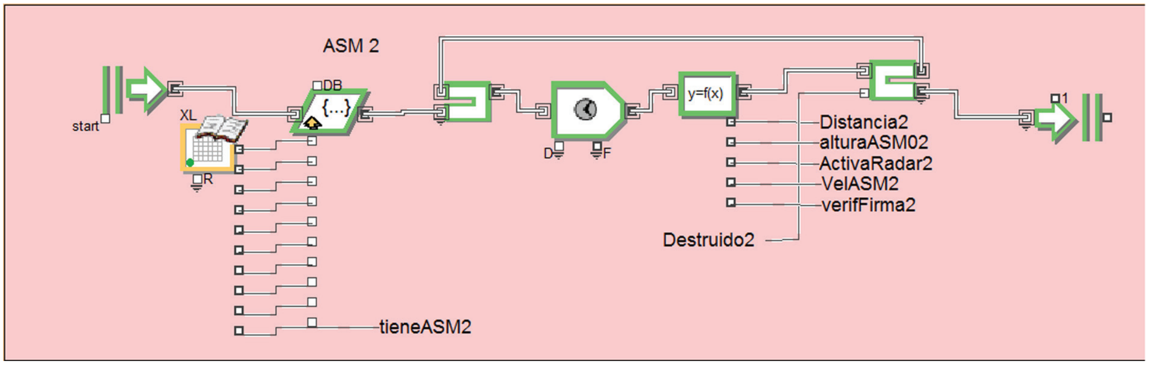
Likewise, all OPSIT threats were modeled in the simulator. The activation of each threat constitutes an event in the simulation. For the AAW OPSIT, the specific threats are ASM missiles; therefore, these were modeled in the simulator, as shown in Fig. 5.

For the case shown in Fig. 5, the simulation begins with the activation of each threat in the Excel spreadsheet. The model loads the properties of each missile, which are read from the Excel spreadsheet that has all the values needed to run the simulation. Once the properties have been read, they are stored in the object (an object for each threat) in the form of attributes.

Subsequently, the algorithm that allows:

- Calculate the path of the trajectory of the missile's towards the vessel.
- Activate the missile radar when is located at a specified distance from the ship.
- Activate the missile's Electronic Counter-Countermeasures systems (ECCM).
- Placing missiles in the final height, stipulated in the Excel document.

Fig. 5. Threats simulator model



Finally, the algorithm receives from the weapons queue the weapons assignment, the missile deactivation order, in case this was shot down by the weapon system.

Experimental Design and Results

To define the configurations of the experiments to be run in the discrete event simulator, it was necessary to perform an experimental design for which we used the JMP software, a tool for data statistical analysis.

Basically, the process consists of introducing the variable names that will result from the experiments, which in this case are the MOP raised on initial sections for each OPSIT and, factors that intervene in the experiments, which in this case are the different sensors and weapons selected for evaluation.

Once we have the necessary data, the experimental design is generated and a list of data is obtained for each experiment. Each experiment is run the necessary number of times to obtain acceptable statistical data.

For the first ASW OPSIT, the resulting design of experiments is 18, which means that it is possible to evaluate 18 possible scenarios. For each of them, Table 6 presents its measures of performance. In the second ASW OPSIT, the software showed that 30 experiments would be needed. The results of MOP for this scenario are presented in Table 7.

Finally, for the AAW OPSIT, six experiments were made, considering the two specific vessel configurations of sensors and weapons that were shown in Table 5, only varying the threat.

The results for this MOP scenario are shown in Table 8.

For these OPSITs, the reliability of the models simulated was evaluated in the statistical analysis software and the relative importance of each variable in each configuration was verified.

Table 6. ASW OPSIT1 Experiment Design Results

Experiment	MOP 2	MOP 1	MOP 3
1	27.60%	28.30%	0.00%
2	43.30%	44.40%	54.40%
3	30.85%	30.70%	28.60%
4	41.10%	40.20%	50.30%
5	27.45%	27.50%	0.70%
6	43.85%	44.50%	49.40%
7	34.50%	34.20%	26.40%
8	27.85%	28.70%	0.00%
9	33.95%	33.90%	30.00%
10	40.65%	41.30%	21.70%
11	31.25%	31.60%	24.90%
12	44.50%	43.90%	21.30%

13	49.50%	49.10%	49.10%
14	28.35%	29.50%	4.00%
15	50.00%	52.30%	45.50%
16	43.85%	43.40%	50.40%
17	36.30%	38.00%	0.00%
18	38.40%	37.50%	0.00%

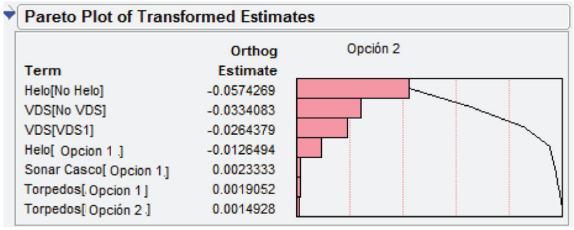
Table 7. ASW OPSIT2 Experiment Design Results

Experiment	MOP 1	MOP 2	MOP 3 (Min)
1	25.00%	12.40%	2453.253
2	84.48%	63.14%	912.747
3	32.10%	16.26%	2305.71
4	59.36%	42.38%	1525.92
5	83.10%	62.46%	973.896
6	49.74%	26.22%	2065.041
7	52.72%	31.72%	1912.449
8	50.64%	28.44%	2003.331
9	32.12%	15.36%	2367.981
10	50.64%	28.44%	2003.331
11	75.46%	54.44%	1205.028
12	70.12%	51.12%	1275.153
13	48.90%	32.96%	1808.103
14	52.96%	31.24%	1924.791
15	15.14%	3.24%	2703.459
16	75.96%	56.44%	1162.953
17	69.56%	50.28%	1306.008
18	55.42%	32.28%	1828.86
19	49.88%	37.84%	1739.661
20	49.88%	27.44%	2030.259
21	70.94%	54.38%	1170.246
22	73.32%	49.88%	1440.648
23	85.28%	65.20%	908.259
24	56.96%	32.88%	1809.225
25	50.86%	39.14%	1702.074
26	48.74%	24.70%	2107.677
27	51.92%	29.92%	1962.378
28	83.74%	59.62%	1075.437
29	75.58%	56.56%	1153.416
30	66.94%	50.92%	1271.226

The analysis of variance results provided by the software allows having a high level of confidence on the statistical model because correlation coefficients were obtained between 0.88 and 0.99, meaning that the models in the discrete event simulator produce consistent data.

Considering the results presented in the Pareto plots, similar to what is presented in Fig. 6 for both ASW OPSITs, it was possible to note that at least 45% of the variability of the model depends on the presence or absence of helicopters. Also, it was clear the relevance the VDS/TAS-type sensor has; in fact, at least 18% of the variability of the model depended on the lack of these sensors on the platform.

Fig 6. ASW OPSIT 1 Pareto Plot of MOP_2



Term	Orthog Estimate
Helo[No Helo]	-0.0574269
VDS[No VDS]	-0.0334083
VDS[VDS1]	-0.0264379
Helo[Opcion 1]	-0.0126494
Sonar Casco[Opcion 1]	0.0023333
Torpedos[Opcion 1]	0.0019052
Torpedos[Opción 2]	0.0014928

The results obtained from the AAW simulation model, for characteristics raised in each experiment, show that configuration 1 has the best performance, given that it can attend all missiles simultaneously. This is a significant advantage, given that it reduces weapons reallocating dependence. Similarly, the weapons range of configuration 1 is higher than the weapons range of the other configuration, allowing saving time during the defense process.

Table 8. AAW OPSIT experimental design results

	Missile 1	Missile 2	Missile 3
Config. 1	17%	39%	60%
Config. 1	14%	32%	44%

Regarding threats, missile 2 showed that because of its high speed, the probability of survival of the platform to which it is confronted is greatly reduced and, in some cases, weapons systems are completely ineffective against this threat, given that the highest probability of survival obtained at the end of the simulations does not exceed 20% in any case.

Conclusions

With the tactical situations presented in the paper, it was possible to evaluate the relationships between weapons and sensors systems, which allow inferring that with a common configuration of weapons and sensors, it will be possible to evaluate tactical situations that ultimately lead to a study of doctrine or tactical procedures, using these same models.

The models structured have high flexibility to adapt to any type of analysis; these could be about threats or configuration of the platforms. Excel interfaces facilitate data input process and final statistics.

Also, it was possible to observe, through the experimentation process, that a strong relationship exists between the sensor and weapon selected, *i.e.*, it is not possible to obtain the expected results when the features of one of the two exceeds the other because it is not significant to have a sensor with a long range, if the weapon used cannot neutralize the threat detected.

Finally, it is important to note that the results obtained from the simulation of these models allow validating these methods; however, these are not convincing to make decisions on what is the best configuration because too much of the data or characterizations of the weapons, sensors, and threats provided to the model were speculative due to the absence of information available in the market. This implies that upon making the analysis of real equipment that could be installed in future ships; it is necessary for sensors and weapons manufacturers to provide the necessary information to perform an analysis that could help to conclude about the best configuration.

Acknowledgments

The authors express their gratitude to: engineer *Vladimir Díaz Charris* for his advice on handling the JMP software; Lieutenant Commander *Francisco Gil* for his technical contribution in relation to radar operations, Lieutenant *Francisco Castañeda* for his technical advice about ECCM and Messrs. Gratitude also goes to: ASW officers and Petty Officers of the ARC Almirante Padilla type frigates of the Colombian Navy for their cooperation and assistance in the selection of the scenarios simulated.

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