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Enhancing the Effectiveness of Air Defense Systems through Simulation Analysis

F. Felipe

Abstract—Air Defense Systems contain high-value assets that are expected to fulfill their mission for several years - in many cases, even decades - while operating in a fast-changing, technology-driven environment. Thus, it is paramount that decision-makers can assess how effective an Air Defense System is in the face of new developing threats, as well as to identify the bottlenecks that could jeopardize the security of the airspace of a country. Given the broad extent of activities and the great variety of assets necessary to achieve the strategic objectives, a systems approach was taken in order to delineate the core requirements and the physical architecture of an Air Defense System. Then, value-focused thinking helped in the definition of the measures of effectiveness. Furthermore, analytical methods were applied to create a formal structure that preliminarily assesses such measures. To validate the proposed methodology, a powerful simulation was also used to determine the measures of effectiveness, now in more complex environments that incorporate both uncertainty and multiple interactions of the entities. The results regarding the validity of this methodology suggest that the approach can support decisions aimed at enhancing the capabilities of Air Defense Systems. In conclusion, this paper sheds some light on how consolidated approaches of Systems Engineering and Operations Research can be used as valid techniques for solving problems regarding a complex and yet vital matter.

Keywords—Air defense, effectiveness, system, simulation, decision-support.

I. Introduction

THE modern world is home to constant political and economic changes. In this volatile environment, nations have the lofty challenge to keep their armed forces operating with effectiveness within a limited budget. This reality is particularly impactful for the aerospace segment due to rapidly developing and constantly evolving technology for satellites, aircraft and weapons. Due to the complex nature of these assets, they require regular component and system upgrades which are not only complex, but also very expensive [1].

The changing security conditions around the world saddle militaries with ever-new mission requirements. Rapid, constant changes in technology and a finite amount of resources force the issue for internal efficiency to ensure that the Air Defense (AD) system can keep up with new challenges and maintain technological superiority without relying on drastic increases in its budget [2].

Consequently, the AD system of a country needs to be permanently evaluated and revised so that it can evolve in order to optimize the use of new technologies, overcome new threats and fit in the Defense Department's budget.

Felipe Flaminio is with the Volgenau School of Engineering, George Mason University, Fairfax, VA, 22030 USA (e-mail: felipeflaminio@gmail.com).

An AD system is defined as the capability of a country to defend the homeland and areas of interest, protect the joint force, and enable freedom of action by negating the enemy's ability to create adverse effects from their air and missile capabilities [3].

At its core, an AD system is a system of systems. It uses a network of satellites, ground-based radars, airborne radars, Surface-to-Air Missile (SAM) sites, and fighter jets to detect, intercept and, if necessary, engage any enemy air-breathing threat. There are two kinds of assets that provide the capability of engaging airborne threats: fighter aircraft performing air sovereignty alert missions; and ground-based or sea-based SAM systems [2].

Fighter aircraft are an effective but costly way of ensuring domestic air sovereignty. Engaging these assets comes at not only a great monetary cost, but also a large swath of personnel, infrastructure, and logistical support from other defense activities [2].

For instance, in the '90s the number of fighter wings dedicated to AD missions in the Continental United States (CONUS) was drastically reduced. Some units which initially had the mission of supporting two expeditionary conflicts overseas received the additional task of maintaining part of their crew and aircraft on alert status, meaning the pilots had to share their training time and resources with this new assignment. As a result, not only the number of scramble sites decreased (in the days before 9-11, NORAD had armed fighters on call at just seven locations in the US), but also their operational readiness were compromised due to the reduced hours of daily training: for a unit to train their pilots, another one had to cover their AD sector. Having too many fighter aircraft sharing their primary activities with air sovereignty missions may erode the capability of the Air Force to maintain its lethality and effectiveness in other areas [2].

It is, however, important to recognize that fighter aircraft offer a capability that SAM systems do not: the capacity to visually identify possible threats. When applying lethal force is required, it is imperative to accurately classify an unknown object before engaging it. Therefore, the use of aircraft for the visual identification and classification of a possible threat is essential to AD systems. Since overusing them to that end may negatively impact the overall force effectiveness, the allocation of fighter aircraft as assets of an AD system must be carefully planned [2].

Similarly, SAM systems do require that this same care. In order to keep these systems up to the task of facing the rapidly evolving missile threats, sharpening the competitive edge of it is imperative. Military superiority is not guaranteed simply by the acquisition of a system - it is the result of diligence, creativity, and sustained investment. The management of SAM systems requires critical thinking and swift action in order to find solutions that expand the competitive space and leave no vulnerability gaps that could be exploited by enemies. Only then can those assets better defend the homeland, enhance deterrence and adapt to the needs of this new era [3].

Needless to say, no fighter aircraft nor SAM battery can perform their missions without precise detection and monitoring of air-breathing threats. Increasing the effectiveness of surveillance radars, airborne early warning and control (AEW&C), shipborne radars and satellites can provide maximum reaction time for friendly forces to take appropriate actions against enemy attacks.

This is especially important when considering the compressed timelines for the detection and engagement of cruise and ballistic missiles. For example, a new class of missiles, the hypersonic glide vehicle (HGV) was built to penetrate current AD systems by traveling and maneuvering at cruise speeds greater than Mach 5, at much lower altitudes than regular ballistic missiles [4]. In a rough approximation, if a country detects this kind of threat 500 NM away from its border, the time until it reaches a target in the homeland can be less than 8 minutes. Therefore the range, response speed and effectiveness of detection and warning assets are crucial to the mission accomplishment of an AD system [3].

Finally, C4ISR[1] systems are also essential as they enable mission accomplishment through collaborative planning and synchronization of integrated forces and operations. Command and control is defined as "the exercise of authority and direction by a properly designated commander over assigned and attached forces in the accomplishment of the mission"[3]. They are composed of an arrangement of personnel, equipment, communications, facilities and procedures employed by a commander in planning, directing, coordinating and controlling forces and operations in the accomplishment of the mission.

Despite the broad recognition of how important C2 systems are to the overall success of a military operation, it is a common misconception that, once an effective C2 structure is established, the simple ability to correctly operate it will be sufficient to accomplish the mission. Nevertheless, without innovations, the ability to effectively command and control airpower in the future may be seriously challenged. Technology advances with increasing speed in the fields of communications, computers and networks, allowing combat organizations to flatten their operations more and more into essentially two echelons. On the top tier is the centralized air operations center; and at the bottom tier, the multiple combat forces in the theater [3].

The success obtained in C4ISR systems is precariously based on secure operational environments, with unchallenged C2, robust communications and powerful cyberspace capability. Unfortunately, potential enemies will challenge the dominance of our cyberspace and communications, which in turn threatens the whole system [3]. It is tempting, but unrealistic, to believe that future operations will take place in secure environments. Therefore, continuously assessing the effectiveness of the C4ISR structure in order to improve its capabilities is something that modern air forces cannot abdicate.

Ultimately, there is no one-size-fits-all solution for the challenge of optimizing the capacity of the airpower. As established by the father of modern management, Peter Drucker, what can't be measured can't be improved [5]. The capabilities of an AD system must be accurately assessed so that it can be appropriately improved to optimize how a country spends its limited resources while providing appropriate protection of the homeland. However, it is not always simple to determine how effective these systems truly are.

After being put into combat or operational training, it is relatively easy to see how a particular military force performed and contributed to the overall results of the operation. However, circumstances such as the development a system that doesn't currently exist or hypothetical situations which cannot be realistically reproduced in exercises - like an intensive missile attack, for instance - make it very difficult to determine how effective a system actually is, or how much a new asset would to contribute to a specific objective [6].

Therefore, a proper method that correctly assesses the effectiveness of an AD system needs to be established. Such an approach could evaluate how the system performs under a massive attack on the homeland, or which effects the addition of new equipment would produce.

The aim of this research is to propose a methodology that assesses the effectiveness and provides decision support to enhance the capabilities of an AD system. Ergo, the following research question will guide this academic paper:

- Considering modern days' axioms, technologies and threats, how can the effectiveness of an AD system be properly assessed, its bottlenecks identified, and its capabilities enhanced?

To answer that question, Requirements Engineering techniques will be applied to delineate the high-level requirements of an AD system. The structured analysis and the modeling techniques will be applied to design the AD System of a fictional country (Blueland). The outcomes of this process will serve as the basis for the characterization of the functional and physical architectures, presenting all the subsystems of which it consists.

Then, Operations Research methods will be adopted to assess the subsystems' measures of performance (MOP) and determine instantiated models of the system. Furthermore, these models will be used in simulations, which will provide the measures of effectiveness (MOE) of the system as well as identify the key barriers preventing it to perform better.

II. Concept Definition

Concept definition is the set of systems engineering activities in which the problem space and the needs of stakeholders are closely examined. It is necessary to clearly

[1]Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance. For the sake of simplicity, in this research the terms C2, C4I and C4ISR and will be interchangeable.

define the gap between what exists and what is desired from the system before a potential solution is considered [7]. Hence, it is paramount to accurately identify what problem an AD System should solve, what it is needed for, and what it should accomplish, before any design, change or procurement is taken into consideration by the decision-makers.

Something that clearly addresses such matters is the AD System mission, which is formally defined at the political level. Though each nation establishes that mission in different terms, those hardly deviate from the US Department of Defense definition of Counter-Air and Integrated Air and Missile Defense: "To defend the homeland and U.S. national interests, protect the joint force, and enable freedom of action by negating an enemy's ability to create adverse effects from their air and missile capabilities"[3].

While it is helpful to have the formal mission of the system explicitly stated, that is not enough to satisfy this preliminary analysis. Taking a shortcut that leads directly to a possible solution - which, in this case, could be a new AD asset, a modification of the system structure, etc - will prevent the managers to apply the problem-solving and solution development methodologies that approach technical decision-making in a logical and insightful manner, in which decisions are made with minimal redesign and rework [8]. Therefore, concept definition activities are paramount, even if the mission is clearly established.

To that extent, two primary processes take place in the concept definition: the mission analysis and the delineation of stakeholders' needs and requirements. Those activities begin before any formal definition of the system is developed. They determine whether a new system, a change to an existing system, a service, an operational change or some other solution is needed to satisfy the enterprise strategic goals. [7].

If a new demand is identified, then definition activities are performed to assess the problem. Those specific activities include system definition tasks and their involvement in the lifecycle, which will be dependent upon the type of development model being utilized [7].

In order to explore the operational aspects of a potential solution for the defined problem, it is necessary to define the stakeholders' needs and requirements from their point of view. They describe "what" the system should accomplish. Both "why" and "what" need to be answered before consideration is given to how the problem will be addressed [7].

All in all, mission analysis and system requirements are the starting point for assessing and improving the effectiveness of an AD System.

A. *Mission Analysis*

Mission analysis starts as an iteration of the lifecycle of a potential system that could solve an identified problem or realize a new opportunity for developing an innovative product, service, or operation (the "push" and "pull" paradigms) [7].

In other words, it identifies an enterprise capability gap and defines the problem in a manner that provides a common understanding. This activity focuses on determining the primary purpose(s) of the solution (its mission) [7].

In addition, mission analysis focuses not just on analyzing the problem space, but also on understanding the constraints and boundaries of the solution space. It examines why a solution is desired and what problem or opportunity it will address [7].

The activities to be performed at this point include the definition of the problem space, the identification of the stakeholders and the development of a preliminary operational concept [7].

Different organizations conduct different kinds of missions that require systems, products or services to fulfill the mission objectives [8]. This study considered the mission of an AD System to be a simplified version of the US Department of Defense (DoD) definition of Counter-Air and Integrated Air and Missile Defense [3]:

"To defend the homeland by negating an enemy's ability to create adverse effects from their air and missile capabilities".

This organizational objective drives the need for the system capabilities and its performance requirements. It serves as the benchmark frame of reference for scoping what is and isn't relevant to the mission accomplishment. Understanding why a system exists and what purpose it serves, while maintaining those concepts in mind throughout all the stages of the system lifecycle, are paramount to the overall success of the enterprise [8].

B. *System Requirements*

Requirements are the basis for every project. As the complexity of systems increases and the time steps between the activities to be performed decrease, good practices of requirements engineering become more important to the overall success of any organization or enterprise [9].

The definition of requirements is not a trivial activity. Failing to capture what the stakeholders in a current or potential new system need and also what the system must do to satisfy those needs - in a set of complete, clear, traceable and manageable elements - has been the cause of a considerable number of project failures throughout history.

The armed forces have struggled with requirements for a long time. However, the ways to deal with this matter have greatly changed as technology evolved. In the past, the main concern was to raise and maintain the military forces strong enough to achieve a particular strategic goal. Before the cold war, major theorists of military strategy used to consider technology as an important aspect to be taken into account when developing military strategies and courses of action, but none of them were able to predict the major role it would play in modern systems and weapons that can define the combat nowadays [10].

Writing requirements poorly has caused many problems in the past, and unfortunately that is an ongoing issue. It is not uncommon for manufacturers to find subjective, unclear or incomplete information in the documents that should specify the requirements of systems to be procured [10]. A requirement should be unambiguous, measurable and necessary. But that is not all it takes to have a good requirements statement, since it is possible to have well-written requirements that don't address at all the question defined in the problem space.

The approach taken on how to find the correct set of requirements has been recently going through changes and reviews in order to optimize this activity. In the traditional approach, requirements are defined after a specific objective (that can be individually defined by decision-makers in the strategic, operational or even tactical levels) gives origins to a first document - such as a Mission Needs Statement - which progresses through approvals, verification and validation, until it becomes an Operational Requirements Document and finally a Capstone Requirements Document. However, that method has often faced criticism, especially because those specific goals and needs can greatly vary when different services have to work together on the battlefield. This bottom-up approach has been proven to be inefficient and created many coordination issues among different branches and units [10].

In 2001, the US DoD has reorganized the way it defines requirements to a capabilities-based approach, a top-down process that defines a requirement as a deficiency in a capability. This new system, which is not fully developed, divides the functional capabilities into six different groups [10]:

1) Force application
2) Force protection
3) Battlespace awareness
4) Network-centric operations
5) Focused logistics
6) Command and Control

Either by taking the traditional approach or the yet to be finished capabilities-based process, requirements are identified by analyzing possible scenarios and use-cases. As history has proven, forecasts about scenarios that are likely to take place in the future are often spectacularly wrong. For that reason, a good practice for requirements is to measure the importance of proposed performance parameters using as many strategically plausible scenarios as possible. The risk of establishing an incorrect or irrelevant requirement decreases as the number of scenarios analyzes increases [10].

The scope of this research limits the analysis to a strategic perspective, so details concerning lower-level developments of scenarios will not be discussed. However, it is important to stress the importance of doing so when applying this methodology to define the requirements of the AD system for a country in the real world.

From the mission statement, it was defined that the primary purpose of an AD system is to deny the enemy's ability to create adverse effects from their air and missile capabilities. Given the functional capabilities presented by Yost [10], this objective can be decomposed into the high-level requirements as listed in Table I.

This list touches capabilities from four functional groups of the capabilities-based approach: force application, battlespace awareness, network-centric operations and command and control. Force protection and focused logistics, which are also essential to the development of system requirements, will not be in the scope of the study. Those groups are related to functions that support the system - also known as enabling

TABLE I
HIGH-LEVEL AD SYSTEM REQUIREMENTS

User Need	Level 1 Requirements	Level 2 Requirements
Overcome air and missile threats	- Detect air and missile threats	- Detect flying objects
		- Identify threats at a safe distance
		- Monitor detected threats and asses their flight data
	- Command and control activities	- Distribute the information regarding threats
		- Define the readiness level of AD assets
		- Manage the system activities
	- Intercept air and missile threats	- Intercept air and missile threats
		- Visually identify air threats
		- Destroy air and missile threats

requirements -, as opposed to the mission requirements which will be considered as the key elements that define the effectiveness of an AD system.

Needless to say, these requirements are far from being complete, unambiguous or measurable. They are a starting point from which the requirements statement will be developed, depending on the specificities of the scenarios where the system will take place.

In order to assess which values constitute measures of the system effectiveness, these requirements will be developed into a functional architecture. The physical architecture of the system will also be presented in order to define the assets that are paramount to accomplish the stated mission.

III. System Architecture

As previously stated, requirements result from missing capabilities that are necessary to the accomplishment of the system mission. They are not only fundamental to the system development, but also form the basis for the evaluation methods and acceptance criteria that usually bind the formal agreement between the contractor and the stakeholders.

First, it is necessary to define how the system shall be constituted and organized so that the capabilities required to satisfy the set of requirements are enabled. The subsystems and assets composing the AD system functional and physical architectures have to be determined through a structured analysis, starting with use-case scenarios that represent situations in which the system is likely to be employed.

After analyzing the scenarios in which an AD system are likely to operate, including extensions and variations, it is possible to derive the needed capabilities of the system and develop its architecture models.

The functional architecture is the centerpiece of the structured analysis: it defines the activities that, when activated, provide the system with the capabilities needed to achieve the defined objective [11].

This structure presents critical elements for the design process, enabling the development of the physical architecture of the system as well as the instantiated models to be evaluated.

A. Functional Decomposition

The functional decomposition is a top-down approach that starts with the high-level system functions and then partitions them into several sub-functions. The use-cases provide all the data containing the key activities the system must perform in order to fulfill its mission [11].

Initially, the Capabilities Taxonomy Table (Table II) will allow the determination of the needed capabilities so that the system can accomplish its strategic goal. For future references, hierarchical codes are assigned for each system function.

TABLE II
CAPABILITIES TAXANOMY TABLE

Command and control	Coordinate activities	Issue orders	A111
		Supervise operations	A112
	Exchange information	Provide secure communications	A121
		Provide resilient communications	A122
	Human-machine interaction	Perform predictive analysis	A131
		Filter data	A132
		Provide clear user interface	A133
	Acquire information	Perform intelligence collection	A141
		Analyze data	A142
Detect threats	Identify airborne objects	Provide ATC integration	A211
		Identify electronically	A212
	Detect airborne objects	Assess flight data	A221
		Provide detection coverage	A222
Destroy threats	Operate SAM	Launch SAM	A311
		Guide SAM	A312
		Destroy target	A313
		Reaload SAM battery	A314
	Operate AD aircraft	Take-off	A321
		Navigate to interception point	A322
		Acquire target	A323
		Destroy target	A324
		Return to base	A325

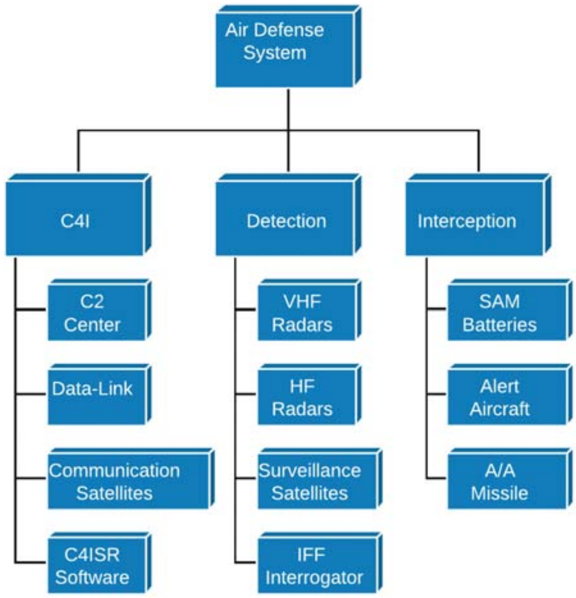

Fig. 1 AD System Physical Architecture

B. Physical Architecture

The physical architecture hierarchically presents the resources which enable the system to meet the functional requirements. This model is a top-down approach that must be decomposed until the definition of basic elements that interact and generate desired behaviors in the multiple parts of the system [11].

It brings combinations of hardware, software and services to explain how each function of the system is performed, including the enabling requirements that arise as the system lifecycle develops, such as operations, maintenance, logistics, and training [11].

The physical architecture can be either generic or instantiated. Generic models provide high-level views of the physical components of the system. A generic model of Blueland's AD system is shown in Fig. 1.

Even though this model introduces the description of the physical elements of the system, it does not bring any specifications or parameters of any resource. The instantiated physical architecture will add such performance aspects of each component to make the model specific - of course, that must be done after the requirements document is complete. A very useful tool for choosing specific components of a system is the morphological box [11].

Before moving towards that direction, however, it is necessary to verify whether the generic components of the system do provide all of the required functional capabilities. To that end, the system functional allocation must be established.

C. Functional Allocation

The functional allocation is used not only to verify whether all the required capabilities are addressed, but also if all the components are necessary. To justify their existence, each node of the physical architecture needs to be allocated to one or more tasks of the functional decomposition; in addition, all of the functions must be assigned to at least one physical asset.

TABLE III
AD SYSTEM FUNCTIONAL ALLOCATION TABLE

Asset	Capability	Issue Orders	Supervise Operations	Secure Communications	Resilient Communications	Perform Predictive Analysis	Filter Data	Provide Clear Interface	Collect Data	Analyze Data	ATC Integration	Identify Electronically	Assess Flight Data	Provide Detection Coverage	Perform Continuous Operations	Launch SAM	Guide SAM	Destroy Target	Reload SAM Battery	Take-off	Intercept Navigation	Acquire Target	Destroy Target	Return to Base
Command and Control, Communications, Computers and Intelligence	C2 Center	X	X							X					X						X			
	Data-Link			X	X										X									
	Communication Satellites			X	X										X									
	C4I Software					X	X	X			X				X									
Detection	VHF Radars										X	X	X	X	X									
	HF Radars											X	X	X	X									
	Surveillance Satellites								X		X	X	X	X	X									
	IFF Interrogator										X	X			X									
Interception	SAM Batteries														X	X	X	X	X					
	Alert Aircraft														X					X	X	X		X
	A/A Missiles														X								X	
		C4I									Detection				Interception									

D. Morphological Box

The morphological analysis divides the problem into different segments and then provides alternatives that solve each part [11]. To create an instantiated model of Blueland's AD physical architecture, a table with one row for each physical component of the system and competing candidate elements in each cell of these rows will now be presented.

The alternatives were selected among possible AD assets available for procurement by NATO members and allies

The table above displays the second level of the system's generic components and some possible choices. However, just these 11 rows, with a very limited number of alternatives, produce a total of 155,520 different compositions. To make it

TABLE IV
MORPHOLOGICAL BOX

Level 1	Level 2	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Command and Control, Communications, Computers and Intelligence	C2 Center	Centralized	Mixed	Decentralized	-	-
	Data-Link	Partial A/A	Total A/A	Total A/A + Ground Link	-	-
	Communication Satellites	Shared use	Exclusive use	-	-	-
	C4I Software	Software A	Software B	Software C	-	-
Detection	VHF Radars	AN/FPS-65	AN/TPS-77	AN/SPS-52	-	-
	HF Radars	OTH-B	Jindalee	NOSTRADAMUS	-	-
	Surveillance Satellites	Shared use	Exclusive use	-	-	-
	IFF Interrogator	Mark X	Mark XII	-	-	-
Interception	SAM Batteries	Patriot PAC-3	THAAD	Aegis SM-2	Aegis SM-6	-
	Alert Aircraft	F-16 Block 60	F-35 A	Typhoon	Rafale	Gripen E
	A/A Missiles	AIM 120D AMRAAM	Meteor BVRAAM	MICA	i-Derby ER	-

worse, every row can be decomposed multiple times in order to make specific choices for the elements in each segment of the system [11]. For instance, each choice of alert aircraft will present different combinations of equipment, external pods and subsystems.

In the end, millions of alternatives are possible in the definition of instantiated models of the system physical architecture. Even though not all the combinations will necessarily be studied and/or considered, the morphological box provides all these combinations in a simple manner so that a good selection that fits the system can be properly achieved. To make these choices, it is paramount to know in depth the parameters and characteristics of each component, as well as the result of their interactions [11]. To that end, such parameters for the alternatives composing elected instantiated models of Blueland's AD system will be assessed.

IV. ANALYSIS OF ALTERNATIVES

The Analysis of Alternatives (AoA) must be divided into two parts that cover different aspects of the problem: effectiveness analysis and cost analysis. Being extremely complex and critical to the success of the system, the cost analysis must be conducted separately and comprehend the costs for all the phases of the system lifecycle: planning, design, development, production, operations, maintenance and disposal [12]. That aspect of the analysis is not in the scope of this research - although, due to its importance, the unit costs for each asset were included in the Alternatives Rank (Table VII) for general information only.

The operational effectiveness analysis, which is the goal of this study, focuses on the Mission Task (MT) and two kinds of measures that are useful for evaluating the alternatives: the measures of effectiveness and measures of performance. The MT of the AD system was already defined as the system mission: "To defend the homeland by negating an enemy's ability to create adverse effects from their air and missile capabilities". Once again, that strategic objective, which was defined in the problem space, must guide the analysis.

The MOE are the gauges that assess how well a set of alternatives achieves a given MT - in other words, they represent the actual effectiveness of a system, and will ultimately be used to answer the research problem. At lower levels, the MOP are task-oriented measures which are come from straightforward data regarding an asset capability that will be useful for achieving a specific assignment [12].

Strictly speaking, the choice of alternatives is made based on the expected values of these measures. Therefore the values, not the alternatives, should be the primary focus of the decision analysis. That is the approach taken in the so-called "value-focused thinking", which is a technique for creating better alternatives for decision problems and then for identifying which options provide more advantageous solutions to these problems [13].

That approach will be used in the definition of the qualitative and quantitative models that will support decisions regarding the determination of the assets of Blueland's AD system.

A. Qualitative Value Model

In value-focused thinking, delineating correctly the values is just as important as considering them first in the decision analysis. To that end, a proper qualitative value model must be developed. The decision-makers' and stakeholders' values must be correctly defined qualitatively, under the penalty of creating a completely useless quantitative model otherwise [13].

The five fundamental aspects of the value model are: **why** the decision has to be made; **what** will be measured; **where** the objectives will be achieved (in the air, space, on the surface or at the sea); **when** the objectives must be achieved; and **how much** is the gain obtained by the achievement of each objective. This model must satisfy the criteria of being collectively exhaustive (it must consider all essential values to be assessed), mutually exclusive (values should not overlap), operable and as small as possible [14].

Given the previous analysis conducted in the concept definition, system development and qualification strategy, it is possible to delineate the fundamental aspects of an AD system:

1 - Fundamental Objective: The strategic goal of the system was previously defined. All the decisions must take into consideration that the system must fulfill its MT: "to defend the homeland by negating an enemy's ability to create adverse effects from their air and missile capabilities".

2 - Functions: The system development is based on a process-oriented structured analysis that emphasizes the importance of the functions that are paramount to the mission accomplishment. The functional architecture presented in Figure 1 shows hierarchically all the high-level functions of the system.

3 - Objectives: The objectives that create value to the system must be identified a nd s tructured b y g rouping the high-level functions defined in the structured analysis. An affinity diagram (Fig. 2) uses the functions identified in the functional architecture to create mutually exclusives and collectively exhaustive objectives that, when achieved, produce values that move the system towards the accomplishment of its strategic goal.

4 - Identify the Value Measures: The objectives established in the affinity diagram must be assessed somehow. To that end, value measures that directly address how well the objectives are accomplished must be defined - the MOE of the system. In this specific case, the objectives are divided into sub-objectives in order to allow their assessment, but they still represent the highest level value measures. Table V presents the MOE for the identified objectives that contribute to the MT of an AD system:

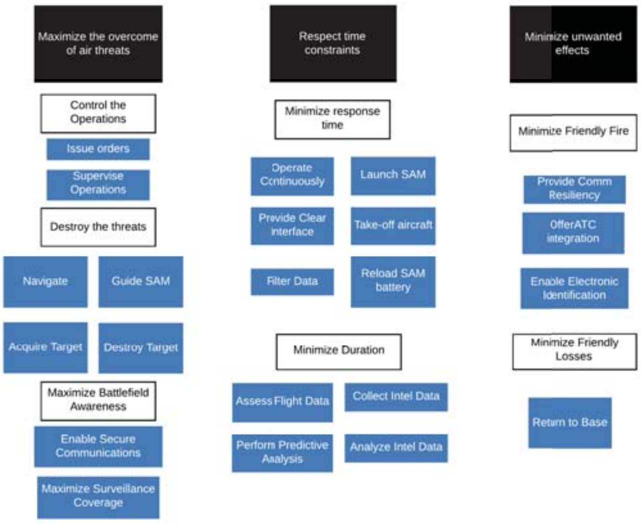

Fig. 2 AD System Affinity Diagram

TABLE V
MEASURES OF EFFECTIVENESS OF AN AD SYSTEM

Objective	Sub-objective	Type	MOE
Maximize the overcome of air threats	Control the operations	Direct Natural	Number of threats destroyed
	Maximize number of threats destroyed	Direct Natural	
	Maximize battlefield awareness	Direct Constructed	
Respect time constraints	Minimize response time	Direct Constructed	Targets attacked by hostile missiles and aircraft
	Minimize duration	Proxy Natural	
Minimize unwanted effects	Minimize friendly losses	Direct Constructed	Friendly aircraft losses
	Minimize fratricide	Proxy Natural	Fratricide avoidance

5 - Verification of Values: The values, and priorities and measures assigned to the objectives must be verified with key decision-makers and stakeholders, which must agree with the qualitative value model before the analysis moves any further.

B. Quantitative Value Model

Once a qualitative model is defined and validated by the decision-makers, the analysis can advance to the quantitative model. The quantitative value model uses different types of mathematical equations, value functions and weights to calculate each alternative's numerical value[14].

The simplest of these equations is the additive value model, which uses the same equation to evaluate all the alternatives. The additive model brings the discussion over three important issues of value-focused thinking: preferential independence, measurable value and utility[14].

The mutual preferential independence assumption means that the preferences of one attribute do not depend on the measures of the other attributes. For instance, if an aircraft creates a value of X for *Maximize number of threats destroyed* and a value of Y for *Minimize friendly losses*, the values for X and Y will be considered in the additive model as independent variables - even if X is very high or very low, it will not affect the evaluation of Y. They can even be probabilistically dependent, but still must remain preferentially independent [14].

Measurable values are essential to create an ordinal ranking of alternatives. To that end, functions that use performance data and weights provide scaled values for each alternative. It is important to note that if alternative A has a value of 4 and alternative B has a value of 8, it is safe to assume that B is a better alternative than A; however, it can't be said it is twice as good [14].

Finally, utility is different than value. The values are assessed to define the alternatives and choose the preferable ones, and usually that is sufficient to the decision support. Utility, however, is much harder to be assessed, since it involves the risk preferences and other subjective criteria which are not built into the model[14].

Considering the established assumptions, the equation that calculates each alternative's value in the additive model is [14]:

$$v(x) = \sum_{i=1}^{n} k_i v_i(x_i) \tag{1}$$

$v(x) \rightarrow$ overall value added of the alternative x
i to n $\rightarrow$ the $\mathrm{i}^{th}(iton) value measure$
$k_i \rightarrow$ weight of the $\mathrm{i}^{th} value measure$
$x_i \rightarrow$ score of alternative x on the $\mathrm{i}^{th} value measure$
$v_i(x_i) \rightarrow$ value added of the alternative x for the $\mathrm{i}^{th} value measure$
(single dimensional value function)
$\sum_{i=1}^{n} k_i = 1 \rightarrow$ all the value measure weights add to one

Defining the value function (measures and weights) for each alternative means evaluating its contribution towards the achievement of the strategic goal, making it is possible to quantitatively assess the trade-offs between assets that contribute differently to conflicting objectives of the system [13].

1) Value Measures:

The value measures are a quantitative assessment of the alternatives' attributes that contribute to the achievement of the associated objectives. To that end, utility value functions are used to normalize the attributes variation in measure range for the group of alternatives to be compared. For the alternatives considered in this research, it was assumed that the stakeholders' assessment resulted in linear value functions, which return the values to scale with constant increments.

However, the x-axis is different for each attribute in the value function. Depending on the type of measure, a greater score is given to a higher measure or a lower measure. For instance, for *Air-to-Air (A/A) Missile Range*, higher values are better. So, the greatest missile range among the alternatives to be compared - which is the *Meteor BVRAAM*, with 86 NM - receives a score of 1. The *MICA* has the smallest range of 40 NM, receiving a score of 0. The other options are linearly positioned between the best and the worst alternatives, receiving a score from 0 to 1. Oppositely, when analyzing the *Alert Aircraft RCS (radar cross-section*, smaller numbers are better. The same methodology is applied to all of the attributes:

After obtaining the value measures, the weights must be assessed to fill the quantitative value model with all

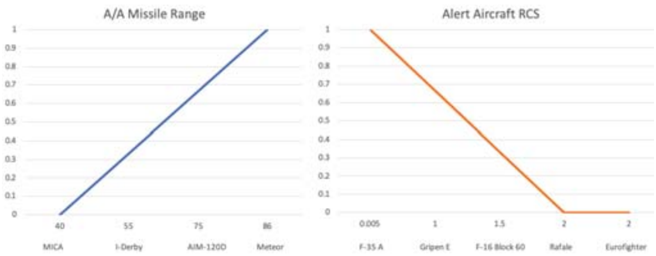

Fig. 3 Value Measure Returns to Scale

the necessary numbers and calculate the results of the value-focused thinking approach.

2) Weights:

Weighting the objectives is a process that plays a major role in the analysis. If the relative importance of one objective (or sub-objective) increases, the weight of the others (at the same level) automatically decreases, since the weights must add up to 1 [13].

Again, the experts' assessment is necessary to successfully capture this aspect of the value function. Depending on their priority and relative importance, the objectives and sub-objectives must be weighted at their hierarchical levels - that gives us the local weights. Finally, the value measure associated with each sub-objective receives a value weight by multiplying the respective local weights:

$$k_i = \prod_{w=1}^{p} k_w \tag{2}$$

$k_i \rightarrow$ overall weight of the value measure i
w to p $\rightarrow$ the wth (w to p) hierarchical level
$k_w \rightarrow$ local weight of the value measure at the wth hierarchical level
$\sum_{w=1}^{p} k_w = 1 \rightarrow$ all the weights add up to 1 at each hierarchical level

First, the objectives and sub-objectives were weighted and associated them with the value measures that assess how effective the system is in achieving its fundamental objective - in other words, the MOE. The weights are given accordingly to their importance, broadness, and added value towards the achievement of the strategic goal of the system.

The weight of each value measure needs to be associated with one or more attributes of the assets that contribute to that function of the system. Therefore, it is necessary to allocate all the assets' attributes to the objectives affected by them.

Finally, the value added by each attribute needs to be quantified with local weights. Table VI has the attribute weights, which are the lowest level of measures in this methodology, also known as "bottom row weights":

However, the measures provided by that approach only consider the importance of the attributes. In order to increase the accuracy of the model, the weights must be obtained by taking into consideration not only the importance, but also the range variation of the attributes' measures. For example, the distance range of a SAM battery is an attribute that greatly contributes to the objective *Maximize number of Threats Destroyed*. However, suppose we are comparing a set of alternatives in which the change in this attribute ranges from

TABLE VI
ATTRIBUTE WEIGHTS IN THE QUANTITATIVE VALUE MODEL

Objective	Value Weight	Asset	Attribute	Local Weight	Bottom Row Weight
Control the operations	0.12	C2 Center	Accuracy	0.8	**0.096**
		C4I Software	Accuracy	0.2	**0.024**
Mazimize number of threats destroyed	0.36	SAM Batteries	Pkill	0.3	**0.108**
			Range	0.2	**0.072**
		Alert Aircraft	Radar Range	0.2	**0.072**
			Thrust-to-weight	0.08	**0.0288**
		A/A Missiles	Range	0.16	**0.0576**
			NEZ	0.06	**0.0216**
Maximize battlefield awareness	0.12	Communication Satellites	Resiliency	0.3	**0.036**
		VHF Radars	Range	0.35	**0.042**
		HF Radars	Range	0.15	**0.018**
		Surveillance Satellites	Availability	0.2	**0.024**
Minimize response time	0.12	C2 Center	Response Time	0.8	**0.096**
		C4I Software	Usability	0.2	**0.024**
Minimize duration	0.08	C2 Center	Decision Process	0.45	**0.036**
		Radars	3D Capability	0.2	**0.016**
		Alert Aircraft	Weapon Payload	0.35	**0.028**
Minimize friendly losses	0.16	Alert Aircraft	RCS	0.7	**0.112**
		Data-Link	Extent	0.3	**0.048**
Minimize fratricide	0.04	Data-Link	Stability	0.5	**0.02**
		IFF Interrogator	Accuracy	0.5	**0.02**

distances that vary from 97 NM to 100 NM (worse and best choice of assets). In that case, the decision about which *SAM Battery Range* would contribute more to the objective would not have a great impact on the model, since any choice would result in a system with a similar MOP on that parameter.

The Swing Weight Matrix method is an effective technique for defining the weights of each alternative by considering both the importance and range variation of the attributes.

In that approach, the values are assigned to the columns in the matrix from left to right, in order of their importance - which were obtained by the importance weights in Table VI. The rows correspond to the variation range of the attributes, from higher at the top to the lower at the bottom - these ranges were obtained by comparing the performance of each set of alternatives, which are summarized in Table VII. Then, the attributes are allocated to the fittest cell - higher when they have a wider range, more to the left when they add more value. Finally, numerical values are assigned to each cell, usually from 100 to 0:

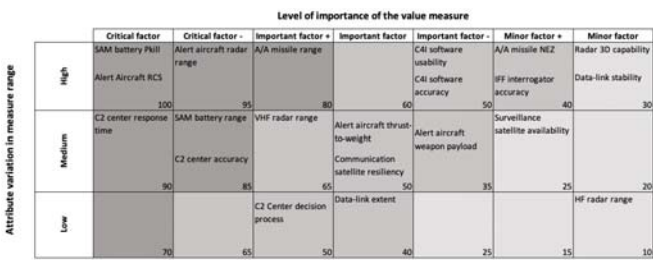

Fig. 4 Swing Weight Matrix

By normalizing the values in the Swing Weight Matrix, we obtain the final weight of each attribute - the weights should again add up to 1.

C. Alternatives Rank

Table VII provides the performance data for the set of alternatives for all the assets in the physical architecture which are able to provide the required capabilities of Blueland's AD system.

For each set of alternatives, the performance scores were scaled into value measures ($v_i(x_i)$), the final weights were assigned (k_i) and the additive functions were used to quantify each alternative's contribution to the accomplishment of the AD system mission ($\sum k_i v_i(x_i)$). The assets ranks provide an assessment on which options are better for composing instantiated models of the AD system.

TABLE VII
ALTERNATIVE VALUES AND RANK

	ki	0.071		0.042		0.075				$\sum k_i v_i(x_i)$		Unit Cost
C2 Center	Type	Accuracy	vi(xi)	Decision Process	vi(xi)	Response Time	vi(xi)				Rank	(M of USD)
	Centralized	70%	0	85%	0	15 min	0			0.000	3	50.00
	Mixed	90%	1	90%	1.000	8 min	1			0.188	1	85.00
	Decentralized	85%	0.75	95%	0.857	10 min	0.714			0.142	2	75.00
	ki	0.033		0.025						$\sum k_i v_i(x_i)$		Unit Cost
Data-Link	Type	Extent	vi(xi)	Stability	vi(xi)						Rank	(M of USD)
	Partial A/A	Isolated Groups	0	80%	0					0.000	3	12.00
	Total A/A	Main Groups	0.75	90%	0.667					0.042	2	25.00
	A/A + Ground Link	Total	1	95%	0.667					0.050	1	35.00
	ki	0.042								$\sum k_i v_i(x_i)$		Unit Cost
Communication Satellites	Type	Resiliency	vi(xi)								Rank	(M of USD)
	Shared Use	Medium	0							0.000	2	15.00
	Exclusive Use	High	1							0.042	1	120.00
	ki	0.042		0.042						$\sum k_i v_i(x_i)$		Unit Cost
C4I Software	Type	Accuracy	vi(xi)	Usability	vi(xi)						Rank	(M of USD)
	A	70%	0.5	50%	0					0.021	2	3.00
	B	90%	1	95%	0.9					0.079	1	5.00
	C	50%	0	100%	1					0.042	2	11.00
	ki	0.054		0.025						$\sum k_i v_i(x_i)$		Unit Cost
VHF Radars	Type	Range (nm)	vi(xi)	3D Capability	vi(xi)						Rank	(M of USD)
	AN/FPS-65	200	0	No	0					0.000	3	11.00
	AN/TPS-77	250	1	Yes	1					0.079	1	15.00
	AN/SPS-52	240	0.8	Yes	1					0.068	2	18.00
	ki	0.008								$\sum k_i v_i(x_i)$		Unit Cost
HF Radars	Type	Range (nm)	vi(xi)								Rank	(M of USD)
	OTH-B	1300	0.667							0.006	2	80.00
	Jindalee	1400	1							0.008	1	70.00
	NOSTRADAMUS	1100	0							0.000	3	65.00
	ki	0.021								$\sum k_i v_i(x_i)$		Unit Cost
Surveillance Satellites	Type	Availability	vi(xi)								Rank	(M of USD)
	Shared Use	Partial	0							0.000	2	60.00
	Exclusive Use	Total	1							0.021	1	120.00
	ki	0.033								$\sum k_i v_i(x_i)$		Unit Cost
IFF Interrogator	Type	Accuracy	vi(xi)								Rank	(M of USD)
	Mark X	Low	0							0.000	2	0.40
	Mark XII	High	1							0.033	1	0.78
	ki	0.071		0.083						$\sum k_i v_i(x_i)$		Unit Cost
SAM Batteries	Type	Range (nm)	vi(xi)	Pkill	vi(xi)						Rank	(M of USD)
	Patriot PAC-3	86	0	86%	0.3					0.025	3	2.00
	THAAD	105	0.432	100%	1.000					0.114	1	41.00
	Aegis SM-2	100	0.318	80%	0.000					0.023	4	0.41
	Aegis SM-6	130	1	83%	0.15					0.083	2	4.87
	ki	0.079		0.042		0.029		0.083		$\sum k_i v_i(x_i)$		Unit Cost
Alert Aircraft	Type	Radar range (nm)	vi(xi)	Thrust-to-weight	vi(xi)	Weapon payload (lb)	vi(xi)	RCS (m2)	vi(xi)		Rank	(M of USD)
	F-16 Block 60	70	0	1.095	0.5	17,000	0.58	1.5	0.28	0.061	5	18.80
	F-35 A	125	1	1.07	0.27	18,000	0.68	0.005	1	0.194	1	103.10
	Eurofighter Typhoon	80	0.182	1.15	1	19,800	0.88	2	0	0.082	4	99.78
	Dassault Rafale	86	0.291	1.13	0.82	20,900	1	2	0	0.086	3	76.27
	Saab Gripen E	120	0.909	1.04	0	11,700	0	1	0.49	0.113	2	45.00
	ki	0.067		0.033						$\sum k_i v_i(x_i)$		Unit Cost
A/A Missiles	Type	Range (nm)	vi(xi)	NEZ (nm)	vi(xi)						Rank	(M of USD)
	AIM 120D AMRAAM	75	0.761	28	0.8					0.077	2	1,786,00
	Meteor BVRAAM	86	1	32	1					0.100	1	2,220,000
	MICA	40	0	12	0					0.000	4	2,700,000
	I-Derby	55	0.326	25	0.65					0.043	3	800,000

D. Instantiated Models

Given the analysis results, it is possible to feed the decision-makers with outputs that support their judgment on which compositions should be considered for further analysis. However, it is not always the case that the alternatives presenting the higher values will be chosen. Important factors such as cost and politics, which up until now were not taken into consideration in the analysis, will definitely have a major influence on the decision-making process.

In this research, it was assumed that after the analysis was presented, two possible systems were elected to be evaluated - Systems A and B. Suppose the defenders of System A believe that by acquiring the best fighter jet available, the system will be more likely to be effective - even if they have to compromise SAM batteries and other less expensive assets.

Oppositely, the advocates of System B claim that having the best combination of radars and SAM batteries is the best option in order to increase the capabilities of an AD System, even if that means settling for a less capable aircraft.

E. Value Model Results

Having defined the systems A and B, the additive model that includes all the measures established by the value-focused approach allows a comparison between these two systems. The results present the weighted measures separately for each objective (Fig. 5) and then all together in a single graph (Fig. 6).

The following *Kiviat diagram* shows interesting results on how the accomplishment of some objectives are expected to be better in each candidate system. While System B provides better battlefield awareness and diminishes friendly losses, System A does a better job at controlling the operations and minimizing the response time as well as the occurrence of fratricides:

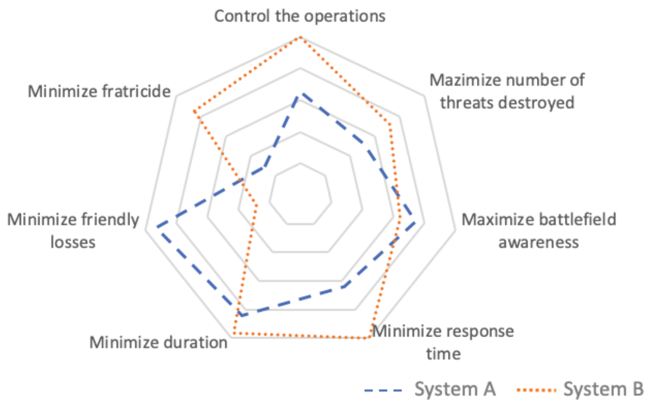

Fig. 5 Comparison between Systems A and B by Value Measure

These results, however, cannot be taken as absolute values that accurately represent the MOE of Systems A and B. What they do is to allow a pragmatic comparison between systems: given that the best possible system has a score of 1 (by picking the alternatives that rank first for all the assets presented in the model), the results of the additive model show that System A has a score of 0.640 and System B of 0.755:

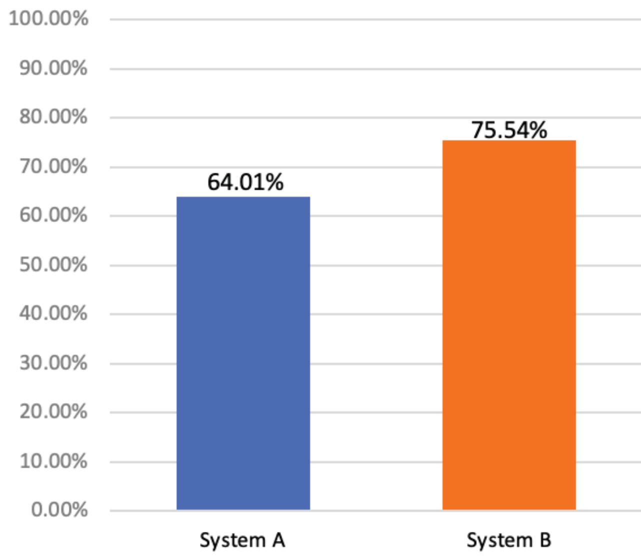

Fig. 6 Overall Comparison between Systems A and B

It is important to point out that, in the real world, the effectiveness of the best AD System (which scores 1) would hardly ever be 100%. Furthermore, its relations with the effectiveness of Systems A and B are not linear, meaning that even if we did have a perfect system as the best one possible in the model, Systems A or B could present results that greatly vary from 64.1% or 75.54%.

The formal analysis conducted in the additive model fails to consider the emergent behaviors that arise from interactions between the multiple assets of the system among themselves as well as with external actors. Moreover, being completely deterministic, this approach does not consider uncertainty in any way. That means, even though the results do represent a strong indication that the alternatives chosen for System B would make it a better system than A, the decision-makers would benefit from also taking into consideration analysis conducted in more complex stochastic models.

That being said, if there were no other tools available for assessing the effectiveness of the AD systems under analysis (or any case in which further analysis could not be conducted), the results from the additive model would provide valuable insights regarding not only the MOE to be expected from Systems A and B, but also about which assets should be changed in order to improve the global score - the bottlenecks that are preventing the system to score better.

For instance, if System B is chosen, an effort to improve the value *Minimize friendly losses* could significantly enhance the overall system effectiveness. By checking Table VI, it is possible to identify that this objective is achieved by the attributes *Alert Aircraft RCS* and *Data-Link Extent*. Given that System B already has the best Data-Link among the possible alternatives, it would be necessary to pick an aircraft with lower RCS - such as the Gripen E, for instance - to improve the results. Of course the aircraft has many attributes that would change other aspects of the system, so the model would have to be run again.

Therefore, the Value Model assuredly is a constructive approach not only for shedding light on the MOE that assess the capabilities of an AD system, but also for presenting results that compute these measures and identify possible ways to enhance them.

However, the actual system success when interacting with air and missile intruders threatening the Blueland's airspace and considers uncertainty is not at all assessed yet. A simulation analysis shall be conducted to capture such complex behaviors of an AD system.

V. Simulation Analysis

The single-dimensional value functions for each asset are strongly tied to their MOP, which are task-oriented measures. For instance, if an aircraft is tasked to patrol an area and create a no-fly-zone, an alternative with better radar, higher thrust-to-weight ratio and A/A missiles with longer range will be likely to do the job better than an aircraft possessing worse characteristics. Hence, the rank obtained in Table VII can in fact be used to predict the MOP of individual assets of the system: an F-35 will be able to destroy more aerial threats than an F-16, so it would be more successful in this the task of maintaining the no-fly-zone.

Some authors advocate that, just by weighting the single-dimensional functions of all the assets in the additive value model, we obtain a result that can be considered the overall system effectiveness - in such an approach, the previously conducted analysis and the results shown in Fig. 6 would answer the research problem. However, it is important to notice that realistic MOE are much harder to be assessed. The multiple interactions of the system components among themselves, as well with external actors - such as rules of engagement (ROE), courses of action (COA), environmental conditions, available infrastructure, enemy threats, and many others - produce results that can be very different from the straightforward values obtained in the additive model. For that reason, simulations that complement the formal methods are needed.

If a system is simple enough to present a set of relationships that can be entirely captured by a thorough analysis, a mathematical model - such as the AoA - can be good enough for presenting satisfactory results regarding exact information on questions of interest - that is called the analytic solution [15]. And that approach is useful for many specific situations.

Unfortunately, most real-world systems are too complex to allow the definition of a realistic mathematical model that captures all the behaviors that are important to the evaluation of the system's effectiveness. To that end, simulation tools allow numerical assessment of the system capabilities in computers in order to estimate the true characteristics and behaviors of the system [15].

Whenever it is possible, it is always preferable to physically implement the new system - or the proposed changes to an existing system - and observe how it performs in real operations. For obvious reasons, that is not the case of AD Systems - it is neither feasible nor cost-effective to do so. Thus, it is necessary to build an accurate model of the system in order to test it in its operational environment [15].

Despite the common misconception that simulation is a "method of last resort", the fact is that this type of analysis is being used more often as systems get more complex. However, the input modeling must be carefully done in order to perform realistic simulations and generate useful outputs.

A. Input Modeling

The most challenging aspect of a simulation analysis concerns the model validation. A model is considered to be "valid" if it represents the system accurately enough so that it can be used in the decision-making process [15].

Systems that can be observed in their actual operational environment are relatively easy to be validated: even if there are complex relationships in the model, the simulation outputs can be compared to what happened with the real system so that the model can be checked in terms of consistency with the real-world [15].

On the other hand, systems that don't currently exist, or which cannot be tested in their physical environment (such as current and future AD Systems), are hard to be validated. No matter how much detail is included in the model, the outputs can only be considered an approximation of the reality, since there are no real results to which they can be compared [15].

In such cases, input modeling has even more importance: the validation will depend on how explicit the assumptions are presented to the decision-makers, who must accept the parameters and the correctness of the model in order to consider it credible [15]. And to start building the model, it is paramount to choose an adequate simulation software that accurately captures all the important characteristics of the system [15].

1) Software:

Given the complex interactions of numerous assets of an AD System as well as its untestable operational environment, building a valid and credible model can be a challenging task. In order to make this process feasible, there is a variety of software products with incorporated object-oriented simulation packages and realistic tools that capture weapons systems behaviors. Some of these simulation software are available from commercial businesses that offer them for purchase and even tailor supplemental content, with specific entities and scenarios, to meet the decision-makers' demands [15].

In this research, the software chosen was the *MAK VR-Forces*, a powerful computer-generated forces platform that is able to represent complex conditions such as the airspace environment. This engine contains several battlefield units, entities, threats, and scenarios. It allows the user to successfully model not only the interactions of the entities, but also C4I systems and detection sensors. The software presents both entity-level and aggregate-level simulations [16].

The entity-level simulates people and vehicles interacting with themselves and the terrain, allowing the analysis of combat, movement, sensor, weather, intelligence and communication models from a tactical point of view. This level of simulation would be useful for air-to-ground missions or air-to-air combat analysis, for instance.

The aggregate-level allows the simulation from the commanders' point of view, enabling the control of large areas with theater-level missions. This high-level architecture package was used for conducting the simulations in this research, as exemplified in Fig. 7.

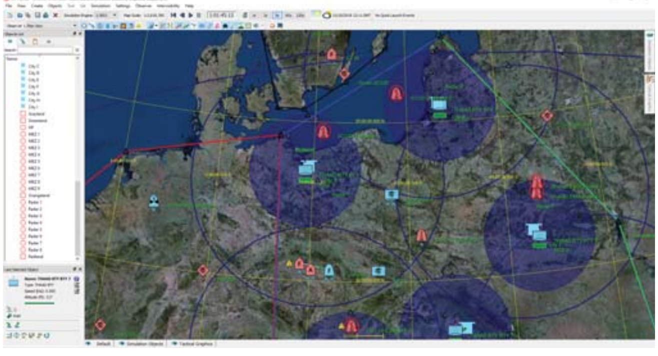

Fig. 7 MAK VR-Forces Aggregate Level Simulation

The simulation package enables the creation of models as complex as the programmers need it to be, making it an adequate tool for the purposes of this study. Due to time constraints and technical limitations - given that complex models can easily require several months of work performed by teams of experienced programmers - it was modeled just the main entities and their basic behaviors, so that the goal of assessing the MOE of Blueland's AD System could be achieved. Needless to say, the models created can be perfected in many ways, and its complexity can be expanded to much more detailed levels. However, the simulations did satisfactorily capture all the characteristics needed to meet the research's demands and provide the MOE of the system. Such measures result not only from the entities behaviors, but also their attributes and the system logic.

2) Entities:

The next step is to determine which assets will be modeled. The physical architecture of an AD system guided the main components represented by the entities in the simulation model.

Therefore, different versions of Blueland's AD System were created with different types of radars, satellites, SAM batteries and alert aircraft armed with A/A missiles. Some assets aren't modeled as entities - such as the C2 processes, data-link capabilities and Identification Friend or Foe (IFF) interrogator - since they can be addressed as attributes and behaviors of the other entities. For instance, the IFF interrogator can be modeled by decreasing the chances of fratricide in the system equipped with the best interrogator - to increase the model's credibility, that has to be made using real MOP of each equipment.

3) Assumptions:

Different models present different results. Such an obvious statement could be mistakenly seen as something that any decision-maker would know, but unfortunately that is not the case. Not seldom, a model credibility will be questioned because some results might look inconsistent when compared to others. And the reason is usually a common factor in such situations: the assumptions established for building the models are different.

Invalid assumptions or critical omissions are usually the result of communication errors between the simulation practitioners and stakeholders. To prevent such mistakes, an assumptions document - also known as the conceptual model - must be created prior to the modeling activities [15].

In this document, both parts must agree to the model's concepts: algorithms, data summaries, concepts and other assumptions that will influence the behaviors of each entity and attribute [15].

This task is much more complex than it seems: subject matter experts and experienced programmers must understand each other's necessities and reach a consensus on every aspect of the model. The assumptions document will serve as a blueprint for creating the simulation program [15].

For Blueland's AD System, several assumptions have already been made explicit: the system's strategic objective, the system architecture and the MOE. In addition, research on technical publications were conducted to program the entities and their attributes.

The assumptions aim to give a general idea of how the model should work. The logical behavior of the entities will complement the understanding of the simulations.

4) Logical Behavior:

The *MAK VR-Forces* provides embodied sets of behaviors that allow the programming of any logical process needed. In addition to the programmable scripts and plans, some patters are inherent of some entities or classes of entities.

Uncertainty is one of the aspects considered by the software over which the user does not have total control. For instance, to define which aircraft will be victorious in an air-to-air engagement, *VR-Forces* uses primarily the entities' attributes: missile capabilities, radar range, RCS, performance, defense factor, attack factor, jamming pods, data-link, among many others. However, for the exact same entities engaging each other, the results are not always the same: the software explores probabilistic environmental aspects to simulate the uncertainty that exists in the real world, increasing the realism of the simulations.

In addition to that, some triggers were added to create uncertainty in some of the modeled plans and processes. The software tools and the added triggers were used to create a complete model with all the characteristics needed to achieve the objectives of this research.

Having defined the simulation purpose, software to be used, entities to be modeled, major assumptions and logical behavior of the model, it is possible to start the set-ups and simulation runs for the scenarios to be analyzed.

5) Base-case Scenario:

To test the model and provide an initial system to which the others can be compared to, a Base-case scenario was established. This Base-case could represent the current AD System of Blueland, and the analysis is supposed to determine the MOE of the current system, as well as how much these measures would increase by modernizing the force structure to System A or B.

Using the same physical architecture as previously defined, the following system was modeled:

TABLE VIII
BASE-CASE SCENERIO PHYSICAL ARCHITECTURE

Level 1	Level 2	Current Asset
Command and Control, Communications, Computers and Intelligence	C2 Center	Mixed
	Data-Link	No data-link
	Communication Satellites	Shared use
	C4I Software	Software B
Detection	VHF Radars	AN/FPS-65
	HF Radars	No HF radar
	Surveillance Satellites	No surveillance satellite
	IFF Interrogator	No IFF interrogator
Interception	SAM Batteries	No SAM batteries
	Alert Aircraft	3rd Generation Fighter
	A/A Missiles	Rafael Derby

After the Base-case scenario, Systems A and B were also modeled in the *VR-Forces*. The entity types and their attributes were reprogrammed in such a manner to represent the assets' characteristics of each system to be evaluated. All the numbers of units, logical behaviors, threats and other assumptions were kept in the exact same way, so that the MOE could be compared fairly. After verifying all the sets of behaviors and characteristics included, the first batch of simulations was ready to run and produce results.

B. Simulation Results

The false impression that simulation analysis starts with complex computer programming and ends with one simulation run which answers the problem has historically led to inappropriate interpretations of simulation results. A common misconception regarding output data is that once a lot of effort is put into the modeling activities and all the important aspects that matter to the analysis are incorporated, a valid model that provides simulation outputs with clear and straightforward information will immediately address the research problem [15].

It's not unusual to make a single simulation run and take the results as absolute truth. As a matter of fact, simulation results can greatly vary from the first run depending on the degree of uncertainty - thus, the level of realism - embedded in the model. As a result, erroneous inferences are not seldom when decision-makers fail to understand that the simulation outputs require further analysis before a conclusion can be reached and have some applicability in the real-world [15].

1) Pilot Run:

The reason for exact same models producing different outputs is simple: stochastic simulations use random number generation with probabilities from the statistical distributions defined by the programmer. Thus, batch simulations with several runs have to be conducted so that the output data can be interpreted with a satisfactory degree of confidence. To that end, a pilot batch run provides an approximation of the confidence interval around the mean of each MOE, which is given by [15]:

$$\bar{X}(n) \pm t_{n-1,1-\alpha/2}\sqrt{\frac{S^2(n)}{n}} \quad (3)$$

$\bar{X}(n) \rightarrow$ sample estimate of the mean μ
n $\rightarrow$ independent number of replications
$(1-\alpha) \rightarrow$ percentage of the confidence interval
$t_{n-1,1-\alpha/2} \rightarrow$ number such that for a t-distribution with n-1 degrees of freedom, $P(t_{n-1} \geq t_{\alpha,n-1})$
$S^2 \rightarrow$ sample variance

The pilot run is important in order to provide the precision of the $\bar{X}$ for the *n* runs. Depending on the variance *Var(X)*, the absolute error β will be greater or smaller. The absolute error is given by [15]:

$$\beta = |\bar{X} - \mu| \quad (4)$$

such that:

$$1 - \alpha \leq P(|\bar{X} - \mu| \leq \beta) \quad (5)$$

As the number of replications increases, the absolute error of a confidence interval decreases. So, to calculate the number of replications $n_a^*(\beta)$ required to obtain a target absolute error β, it is necessary to assume that the estimate S^2 of the population variance will not change significantly [15]:

$$n_a^*(\beta) = min\{i \leq n : t_{n-1,1-\alpha/2}\sqrt{\frac{S^2(n)}{n}} \leq \beta\} \quad (6)$$

To determine $n_a^*(\beta)$, it is necessary to iteratively increase i by 1 until a value of i is obtained such that $t_{n-1,1-\alpha/2}\sqrt{\frac{S^2(n)}{n}} \leq \beta$ for a given target absolute error[15].

In this research, it was specified a precision of $\beta \leq 0.05$ and a t-confidence interval of 95% for all the MOE. In other words, for a 100 simulation runs, it is expected that the average of each MOE has an absolute error of at most 5% in at least 95 cases.

A pilot batch of 10 simulation runs was conducted for each scenario. The results are presented in Table IX:

TABLE IX
PILOT BATCH RUN RESULTS

Basecase - Pilot Run

Measure of Effectiveness	μ	σ^2	Variance	Lower Boundary	Upper Boundary	$t_{n-1,1-\frac{\alpha}{2}}$	Half Width	95% Confidence Interval		n=13
Threats destroyed	0.1917	0.0562	0.0032	0.1354	0.1948	2.2622	0.0402	0.1514	0.2319	
Friendly aircraft losses	0.8500	0.0437	0.0019	0.8063	0.8519	2.2622	0.0313	0.8187	0.8813	0.0221
Friendly kills	0.0000	0.0000	0.0000	0.0000	0.0000	2.2622	0.0000	0.0000	0.0000	0.0000
Targets attacked by missiles	1.0000	0.0000	0.0000	1.0000	1.0000	2.2622	0.0000	1.0000	1.0000	0.0000
Targets attacked by aircraft	0.7750	0.0791	0.0063	0.6959	0.7813	2.2622	0.0566	0.7184	0.8316	0.0496

System A - Pilot Run

Measure of Effectiveness	μ	σ^2	Variance	Lower Boundary	Upper Boundary	$t_{n-1,1-\frac{\alpha}{2}}$	Half Width	95% Confidence Interval		n = 19
Threats destroyed	1.0000	0.0000	0.0000	1.0000	1.0000	2.2622	0.0000	1.0000	1.0000	0.0000
Friendly aircraft losses	0.0625	0.0510	0.0026	0.0115	0.0651	2.2622	0.0365	0.0260	0.0990	0.0265
Friendly kills	0.0063	0.0198	0.0004	-0.0135	0.0066	2.2622	0.0141	0.0000	0.0204	0.0103
Targets attacked by missiles	0.3000	0.0943	0.0089	0.2057	0.3089	2.2622	0.0674	0.2326	0.3674	0.0489
Targets attacked by aircraft	0.0000	0.0000	0.0000	0.0000	0.0000	2.2622	0.0000	0.0000	0.0000	0.0000

System B - Pilot Run

Measure of Effectiveness	μ	σ^2	Variance	Lower Boundary	Upper Boundary	$t_{n-1,1-\frac{\alpha}{2}}$	Half Width	95% Confidence Interval		n=25
Threats destroyed	0.9917	0.0264	0.0007	0.9653	0.9924	2.2622	0.0189	0.9728	1.0000	0.0154
Friendly aircraft losses	0.1250	0.1102	0.0122	0.0148	0.1372	2.2622	0.0789	0.0461	0.2039	0.0499
Friendly kills	0.0000	0.0000	0.0000	0.0000	0.0000	2.2622	0.0000	0.0000	0.0000	0.0000
Targets attacked by missiles	0.0400	0.0516	0.0027	-0.0116	0.0427	2.2622	0.0369	0.0031	0.0769	0.0234
Targets attacked by aircraft	0.0000	0.0000	0.0000	0.0000	0.0000	2.2622	0.0000	0.0000	0.0000	0.0000

As it was expected, the absolute errors are not below 0.05 for all the measures. By using the above-mentioned method, it was obtained the numbers of replications of 13, 19 and 25 for the Base-case scenario, System A and System B, respectively. That number is not particularly big for a model carrying so many variables and that much complexity.

These relatively small numbers of required replications can be explained by the asymmetric difference of performance between the assets of Blueland and its enemies - much worse in the Base-case, much better in the other two scenarios. If a more balanced scenario were created, a number of replications considerably higher should be expected to achieve a precision of 5%.

2) Final Simulation Results:

By replicating the 3 scenarios 25 times - which was the highest number of required replications calculated - the results in Table X were obtained.

TABLE X
FINAL SIMULATION RESULTS

Basecase - Final Results

Measure of Effectiveness	μ	σ^2	Variance	Lower Boundary	Upper Boundary	$t_{n-1,1-\frac{\alpha}{2}}$	Half Width	95% Confidence Interval	
Threats destroyed	0.2333	0.0992	0.0098	0.1341	0.2432	2.0639	0.0409	0.1686	0.2981
Friendly aircraft losses	0.8400	0.1038	0.0108	0.7362	0.8508	2.0639	0.0428	0.7723	0.9077
Friendly kills	0.0000	0.0000	0.0000	0.0000	0.0000	2.0639	0.0000	0.0000	0.0000
Targets attacked by missiles	1.0000	0.0000	0.0000	1.0000	1.0000	2.0639	0.0000	1.0000	1.0000
Targets attacked by aircraft	0.7400	0.1137	0.0129	0.6263	0.7529	2.0639	0.0469	0.6658	0.8142

System A - Final Results

Measure of Effectiveness	μ	σ^2	Variance	Lower Boundary	Upper Boundary	$t_{n-1,1-\frac{\alpha}{2}}$	Half Width	95% Confidence Interval	
Threats destroyed	1.0000	0.0000	0.0000	1.0000	1.0000	2.0639	0.0000	1.0000	1.0000
Friendly aircraft losses	0.0825	0.0897	0.0080	0.0000	0.0905	2.0639	0.0370	0.0240	0.1410
Friendly kills	0.0025	0.0125	0.0002	0.0000	0.0027	2.0639	0.0052	0.0000	0.0107
Targets attacked by missiles	0.2520	0.1159	0.0134	0.1361	0.2654	2.0639	0.0478	0.1764	0.3276
Targets attacked by aircraft	0.0000	0.0000	0.0000	0.0000	0.0000	2.0639	0.0000	0.0000	0.0000

System B - Final Results

Measure of Effectiveness	μ	σ^2	Variance	Lower Boundary	Upper Boundary	$t_{n-1,1-\frac{\alpha}{2}}$	Half Width	95% Confidence Interval	
Threats destroyed	0.9900	0.0366	0.0013	0.9534	0.9913	2.0639	0.0151	0.9661	1.0000
Friendly aircraft losses	0.1150	0.1165	0.0136	0.0000	0.1286	2.0639	0.0481	0.0390	0.1910
Friendly kills	0.0000	0.0000	0.0000	0.0000	0.0000	2.0639	0.0000	0.0000	0.0000
Targets attacked by missiles	0.0440	0.0507	0.0026	0.0000	0.0466	2.0639	0.0209	0.0109	0.0771
Targets attacked by aircraft	0.0100	0.0500	0.0025	0.0000	0.0125	2.0639	0.0206	0.0000	0.0426

C. Output Analysis

For the Base-case scenario, only 23.3% of the aircraft which invaded Blueland were destroyed, while the friendly attrition was 84%. Since there were no SAM batteries, the risk for fratricide was minimized and the simulation didn't show any friendly fire losses. However, 100% of the enemy missiles were successful in reaching their target in the homeland, while 74% of the hostile strikers managed to drop bombs on their targets.

By using the weights previously defined and the final simulation results, the overall effectiveness of Blueland's current AD System is 23.28%. Hence, it is safe to say that this system is not accomplishing the mission of "defending the homeland by negating an enemy's ability to create adverse effects from their air and missile capabilities", and the system does need to be modernized.

For System A, presented by those who consider the fighter jets to be the fundamental aspect of the system, the results are much better. The F-35's managed to successfully engage and overthrow 100% of the enemy aircraft, including fighters, bombers and strikers. The friendly losses were 8.25%, the lowest attrition rate observed. The SAM batteries, on the other hand, did not perform so well: 25.2% of the incoming missiles were not engaged before they could reach their targets. On top of that, there was one fratricide observed, representing 0.2%. For the established threats, the overall effectiveness of System A is 94.31%.

System B also presented good results, destroying 99.0% of the hostile aircraft which penetrated Blueland's airspace. Not surprisingly, the attrition of Eurofighter in air-to-air engagements were a little higher than the F-35s: 11.5%. However, the confidence interval of these two MOE - number of threats destroyed and friendly aircraft losses - overlap for Systems A and B, meaning that there is no statistical significance in the difference between these results. The same thing happens with the fratricide avoidance; that being said, one aircraft shot down by a friendly SAM in the simulation runs of System A could cause a very negative impact on the way people see the system effectiveness, so that event should be considered even if there is no statistical difference.

Oppositely, the number of targets attacked by enemy missiles is significantly smaller in the scenario with the System B: only 4.4% of them succeed, while only 1.0% of the hostile aircraft managed to attack their targets. As a result, System B did better than System A with overall effectiveness of 96.24%.

Ultimately, considering the established threats to Blueland's airspace sovereignty, the effectiveness of its current AD System is of 23.28%. Given the two possible alternatives for enhancing the MOE of the system, System B presented more

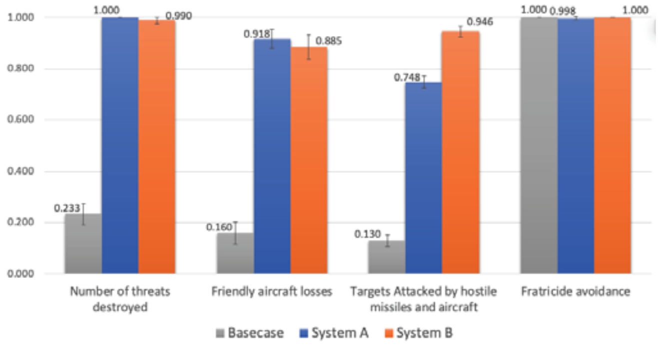

Fig. 8 Comparison of the MOE of Systems A and B

satisfactory results with an overall effectiveness of 96.24%:

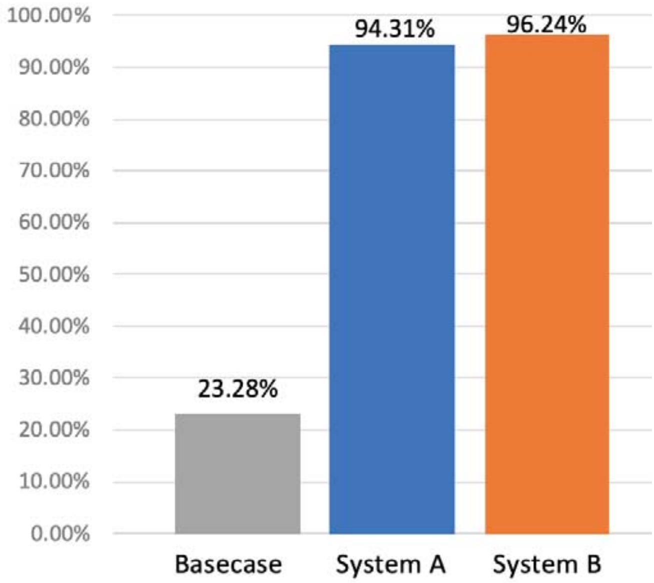

Fig. 9 Comparison of the overall effectiveness of Systems A and B

VI. Conclusion

A. Summary

AD systems are complex, expensive and yet vital to air sovereignty of any country. Most airpower related assets rely on cutting edge technologies that evolve at fast-paced speed. The challenge of keeping such resources up to the task of overcoming new threats with limited budget forces modern Air Forces all around the globe to make assertive decisions regarding force effectiveness [2]. Therefore, AD systems need to be permanently evaluated and revised through consolidated techniques which aim to support decision-making processes.

An AD system is defined as the capability of a country to defend the homeland and areas of interest, protect the joint force, and enable freedom of action by negating the enemy's ability to create adverse effects from their air and missile capabilities [4].

The aim of this research is to propose a methodology that assesses the effectiveness and provides decision support to enhance the capabilities of an AD system. Ergo, the following research question guided this academic paper:

- Considering modern days' axioms, technologies and threats, how can the effectiveness of an Air Defense System be properly assessed, its bottlenecks identified, and its capabilities enhanced?

To address this problem, initially the problem space was defined and a mission analysis was conducted, in which the MT of an AD System was defined as "To defend the homeland by negating the enemy's ability to create adverse effects from their air and missile capabilities"[4]. From that mission, the high-level requirements of an AD system were established.

Then the functional requirements were derived from use-case scenarios. Such capabilities were organized in the functional architecture of the system and allocated to assets in a physical architecture. A verification that all the functions in the functional architecture are addressed and all the assets in the physical architecture ensured the development of an adequate physical architecture.

The Analysis of Alternatives using value-focused thinking was then conducted. First, the objectives which produce value to the achievement of the system's strategic goal were examined and the four Measures of Effectiveness of an AD system were established:

MOE 1: Number of threats destroyed.
MOE 2: Targets attacked by hostile missiles and aircraft.
MOE 3: Friendly aircraft losses.
MOE 4: Fratricide avoidance.

A mathematical structure was established to assess each MOE of two candidate systems deterministically. As a result, System B outperformed System A. The results quantifying the achievement of three objectives were identified as the bottlenecks of System A: maximizing the number of threats destroyed, minimizing response time and avoiding fratricide; System B scored less in minimizing friendly losses and increasing battlefield awareness.

To complement the analysis, these systems were modeled in the simulation software *MAK VR-Forces*, which allows multiple interactions of the system components with expected threats and other external actors in a stochastic environment, accounting for uncertainty and, hence, increasing realism.

The simulation outputs showed that both systems would present similar results in three out of the four MOE. System B, however, performed significantly better in reducing the number of targets attacked by enemy missiles and aircraft. In addition, System A showed one occurrence of fratricide, which is not statistically significant due to the number of events analyzed, but that may have a great negative impact on the decision-makers.

B. Insights and Future Trends

The achievement of all the proposed objectives in this research demonstrated a methodology that properly assesses the effectiveness of an AD system, identifies its bottlenecks and enhances its capabilities, answering the research problem.

The analysis of the simulation outputs shows that they are consistent with the results of the quantitative value model, suggesting that both methods are useful and complementary in an AoA.

The chosen approach has been proven to be valid not only for the procurement of a particular asset of an AD system, but also for determining whether a system achieves its strategic objective, a structural change is required or a force modernization is necessary.

Given the broadness of application of the techniques explored in this research, the methodologies hereby discussed could provide insightful decision support to improve systems in other defense activities, government programs and enterprises from many different areas of knowledge. Future researches could explore the similarities and differences of analyzing such systems through analog optics.

An important aspect that must be emphasized is that the statistical techniques demonstrated have proven to be mandatory in order to reduce the absolute error in stochastic simulation analysis. The importance of that matter must be highlighted so that related researches applying similar approaches to different systems can produce consistent results that enrich these methods.

Needless to say, the gap between discussing the theory of what should be done and the practice of applying these methods to real systems suggests demand for significant effort from decision-makers and analysts. Many steps, which in this study were considered to be "agreed between the experts and analysts" so that the analysis would proceed to the next stage, in reality, could take months of discussions, generate requests for additional studies and demand compromises from people who, in such situations, may not be easy to be dealt with.

Therefore, besides all the theories discussed in this academic work, systems engineers and operations researchers are expected to perform well when gathering important data, discussing assumptions, validating models and presenting results. In fact, the transition from planning the system analysis to each one of these practical steps could serve as an interesting topic for related researches in the future.

Having that said, the importance of systems thinking approaches and value-focused methods applied to analyze complex problems and providing decision support for solutions impacting the near to long term future is undeniable. Consequently, the methodologies explored in this research should always be considered to that end.

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Felipe Flaminio Felipe Flaminio João was born on July 31, 1984 in São João da Boa Vista-SP, Brazil, and is a Brazilian citizen. He received his Bachelor of Science degree from the Air Force Academy, Pirassununga-SP, Brazil, in 2006. Major Flaminio has eleven years of experience flying fighter aircraft for the Brazilian Air Force, having reached the operational status of Fighter Wing Leader and flight instructor in F-5 fighters. In 2017 he received a Certificate of Specialization in Public Management and Air Force Actions from the Air Force University, Rio de Janeiro-RJ, Brazil. In 2018, he was selected by the Brazilian Air Force to pursue a Master of Science degree in Systems Engineering with concentration in Command, Control, Communications and Intelligence at George Mason University.