ENHANCING THE EFFECTIVENESS OF AIR DEFENSE SYSTEMS

by

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Dedication

I dedicate this thesis to my mother Bernadete and my grandmother Dulce, who always supported me in every aspect and assured that I received the best education as possible; my father Sergio, who taught me to always seek my objectives and love my family above anything; my wife Ariadne, who quit her career to be with me and stood by my side no matter the circumstances; and my son Thomas, who made my life happier than I ever thought it could be.

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This work results from the effort of many people. First, my friends (new colleagues at George Mason and old pals who came all the way from Brazil to visit) and family, which have always been my base of support and encouragement.

Secondly, I would like to thank the Brazilian Air Force, which is not only responsible for my undergraduate and graduate education, but also where I learned propitious and profuse professional values. In especial, the pilots and officers in the 1^{st} Fighter Aviation Group, who supported me while I was studying and preparing myself to be here.

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Finally, I'd like to thank God, who provided me with a loving family and everything else I needed to achieve this accomplishment.

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List of Abbreviations

The next list describes several abbreviations used in this research:

A/A	Air-to-Air
A/G	Air-to-Ground
AD	Air Defense
AEW&C	Airborne Early Warning and Control
AoA	Analysis of Alternatives
ASCM	Anti-Ship Cruise Missile
ATC	Air Traffic Control
C2	Command and Control
C4I	Command, Control, Communications, Computers, Intelligence
C4ISR	C4I, Surveillance and Reconnaissance
COA	Course of Action
CONUS	Continental United States
DoD	Department of Defense
GLCM	Ground-Launched Ballistic Missile
HGV	Hypersonic Glide Vehicle
ICBM	Intercontinental Ballistic Missile
IFF	Identification Friend of Foe
IRBM	Intermediate Range Ballistic Missile
LACM	Land Attack Cruise Missile
MOE	Measures of Effectiveness
MOP	Measures of Performance
MRBM	Medium-Range Ballistic Missile
MT	Mission Task
NATO	North Atlantic Treaty Organization

NEZ	No-Escape-Zone
NM	Nautical Miles
OpsCon	Operational Concept
QRA	Quick Reaction Alert Aircraft
RCS	Radar Cross Section
ROE	Rules of Engagement
SAM	Surface-to-Air Missile
SE	Systems Engineering
SRBM	Short-Range Ballistic Missile

Abstract

ENHANCING THE EFFECTIVENESS OF AIR DEFENSE SYSTEMS

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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 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 chosen 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

Chapter 1: Introduction

1.1 Background

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 [2].

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 [3].

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.

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].

At its core, an AD system is a system of systems. It uses a network of satellites, ground-based radars, airborne radars, 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 [3].

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 [3].

For instance, in the '90s the number of fighter wings dedicated to Air Defense missions in the 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 air defense 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 [3].

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 [3].

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 [4].

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 [5]. 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 [4].

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"[4]. 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

[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.

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 [4].

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 [4]. 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 [6]. 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 [7].

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.

But before jumping into the search for a possible solution to this matter, it is important to correctly define the problem - meaning the study of these types of system and the determination of their true purpose. Hence, it is paramount to know in which historical context they were first introduced and which role they play nowadays.

1.2 History of Air Defense Systems

A system can be conceived either to provide a solution to an identified problem or gap - commonly defined as “pull”; or to create a solution to address a perceived opportunity - commonly defined by “push”[8]. After World War 2, many countries identified a missing capability in their defense assets: the power to overthrow new aerial threats. From that perspective, it is safe to state that AD systems were first introduced as a “pull” solution to an identified problem.

As many nations started to develop their AD systems, it didn’t take too long until it was clear that these systems had to be constantly upgraded in order to protect their skies from fast-evolving airborne threats, from propeller air-to-ground attack aircraft to long-range bombers and ultimately cruise missiles: new aerial weapons were being developed at an unprecedented rhythm.

Due to the researcher’s background and personal experience, the history of the AD systems of USA and Brazil were elected to be studied. These two countries reflect how different realities of the western world required similar ways of protecting the homeland against aerial threats.

1.2.1 United States of America

In the United States, the North American Aerospace Defense Command was established in 1958 as a bi-national organization that would implement air shield for the American and Canadian airspace in the post-World War II scenario [9].

Air Sovereignty Alert Missions were first developed in the early 60’s during the Cold War. This mission was the main Air Defense activity that could protect the continental US against the Soviet long-range bomber fleet after USSR detonated its first atomic bomb in

1949 [3].

Given their geographical position and mutual needs, Canada and the U.S. agreed that both countries would benefit from the cooperation in repelling the Soviet nuclear threat. In 1954, an air defense planning group with members of the Royal Canadian Air Force and the United States Air Force concluded that defending the North American airspace would be most efficient if the forces were deployed under one single commander who could conduct a coordinated air battle. This scenario provided the conditions that led to the creation of NORAD (North American Air Defense Command) on May 12, 1958 [10].

At first, extensive lines of radars were established in both Canada and the continental U.S. However, the advancements in the aerospace sector were quickly increasing bomber aircraft speed and range, while also introducing nuclear-capable missiles. Waiting for these new threats to fly over one of the radar lines in order to react would mean giving the Soviets the opportunity for a first strike. Hence, early warning radar lines were established further to the north up to the Arctic. In addition, naval barriers with radar-equipped planes started patrolling the skies over the Pacific and Atlantic oceans [10]:

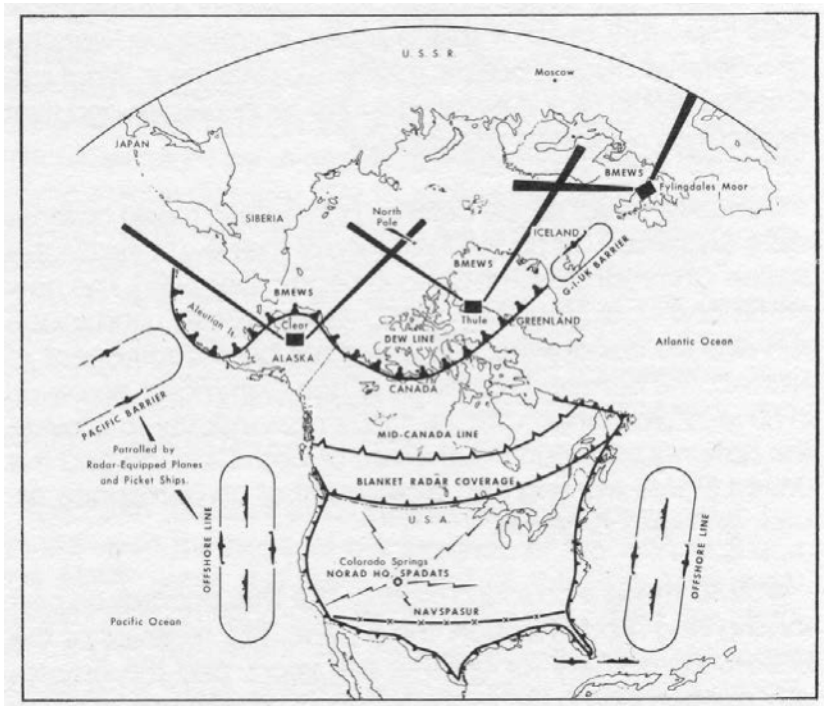


Figure 1.1: North American AD system in the mid-'60s

As technology continued to develop, NORAD's mission and design also evolved from "air defense" to "aerospace defense". Space-based systems were developed and incorporated to detect and provide an effective warning system against cruise and ballistic missiles that could be launched from anywhere in the world [10].

With the collapse of the USSR, the role of NORAD became less clear. And as a whole NORAD's importance started to be questioned. The mission shifted from deterring a powerful nuclear-capable enemy to small scale counter-drug operations [10].

However, after the terrorist attacks on September 11, 2001, the illusion of a low-threat environment was destroyed. This event changed the way of viewing the enemy, as it became clear that an air threat wouldn't necessarily come from overseas [10].

The slow decision-making process and the identified dysfunctions between NORAD divisions and FAA sectors as the attacks were ongoing also led to a review of organizational doctrine and procedures. It became clear the military partnerships with multiple law enforcement agencies, intelligence agencies and other civilian agencies were crucial to the accomplishment of the complex task of defending the North American airspace [10].

The renewal of the U.S.-Canada agreement in 2006 initiated the inclusion of maritime warning assets to NORAD. The naval components' contribution led to the direct enhancement of the shared situational awareness for both countries by the monitoring of activities conducted in continental and international waters [10].

Ultimately, even though NORAD was created as a solution to a problem arising from a specific scenario, the organization has evolved not only by adjusting its assets, but also its own structure, as the needs changed over time. In other words, AD systems must be perfected as the world changes, not only in the U.S. but in any country.

1.2.2 Brazil

The Cold War was also a key factor for the creation of the AD system in the developing countries. To face the Soviet threat, which had just established a military alliance with Cuba, Brazil started developing its SISDACTA (Integrated System of Air Defense and Air Traffic Control) in the late '60s. This organization was responsible for both the defense of the Brazilian air space (through the Air Defense Command) and the civilian air traffic control (ATC). The SISDACTA was composed of an integrated infrastructure counting with a network of radars, communication lines and command centers [11].

The first quick reaction alert jets started operating in the '70s, but the system was not considered fully operational until 1980. In April 1982, an irregular military aircraft was intercepted by the Brazilian Air Defense for the first time: a soviet made IL-62 with a Cuban crew. The invader was located, intercepted, identified and persuaded to land at a Brazilian Air Force Base [11]. Other countries in South America were considered a potential threat at the time:

Figure 1.2: A color-coded map of Latin America in 1970

The image above shows the countries grouped depending on their position in the Cold War. In green: non-self-governing possessions of US allies. Gray: US and US allies. Red: communist allies of USSR. Pink: non-communist allies of USSR.

Due to the evolution of air threats, the Air Defense Command was later re-designated as the Aerospace Defense Command, which incorporated new radars, fighter jets and other assets such as air-to-air refueling tankers, reconnaissance aircraft and surface-to-air artillery.

Similarly to NORAD, the Brazilian AD system changed its focus after the end of the Cold War. As the likelihood of a military conflict in South America decreased, the system started paying more attention to the Amazon region, an area of approximately 3,800,000 km^2 with extremely low demographic density where illegal activities, such as drugs and arms trafficking, were increasing.

As a result, in the late '90s the Brazilian Air Force started a modernization program to operate mobile radars, AEW&C aircraft and low-speed capable interceptors. Since then, these new assets have been very successful in detecting and intercepting small airplanes crossing the border with illegal material, even at low altitudes.

Nowadays, the social, political and economic uncertainties in different parts of the world - as well as the increased capabilities of new and near-future aerial threats - make it very hard to predict when the AD system of a country will be needed. In this context, force modernization is again taking place in Brazil. The Air Force went recently through a profound restructuring process in order to enhance its operational capabilities, while new tankers and fighter jets procurement programs are progressing. New radar technologies, space-based surveillance systems, SAM batteries and C4I supporting assets are also being analyzed to reinforce the Brazilian AD system, preparing it for the upcoming challenges of the next decades.

These two AD systems were developed under different conditions, but they had the same goal: maintaining the sovereignty of the airspace in each country. Technologies and threats have drastically changed since those systems were first conceived, so it is important to analyze them through the optics of the modern conjuncture. The AD systems in both the USA and Brazil have gone through many changes since they were created, and they must continue to do so. To that end, Systems Engineering provides important tools that can be extremely helpful to support decisions regarding these changes and enhance the effectiveness of AD systems.

1.3 Research Objectives

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 outcomes of this process will serve as the basis for the Concept Definition of the system, as well as to 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.

1.4 Overview of the Thesis

1.4.1 Thesis Structure

To guide this research, the following specific objectives were determined:

O1: Define the high-level requirements of an Air Defense System.

In Chapter 2, Systems Engineering practices driven by Dick, Hull and Jackson [12] will be employed to delineate the problem space and perform a mission analysis. A preliminary Concept of Operations will enable the development of high-level requirements, as well as the definition of an adequate lifecycle model of the system.

O2: Develop the system functional e physical architectures.

Given the strategic objective of the system and its high-level requirements, the structured analysis and the modeling techniques presented by Buede [13] will be applied in Chapter 3 to design the Air Defense System of a fictional country. The functional decomposition and physical architecture of the system will serve as the basis for the development of the value models.

O3: Define a formal analytical structure.

In Chapter 4, a qualitative model of the value measures will be presented. The attributes of each component that address a specific capability will be identified. The measures of performance of each asset in the physical architecture will be used in an Additive Value

Function - the quantitative model [14]. The results produced will preliminary represent the overall effectiveness of each instantiated model of the AD system.

O4: Simulate the systems and compare their effectiveness.

Chapter 5 will introduce Law's[15] simulation techniques that drive the setups of multiple scenarios. A powerful simulation tool - the software *MAK VR-Forces* - will be used to assess and compare the effectiveness of different alternatives of AD systems, considering the previously established scenario. The simulation outcomes will serve as a rich source of data that will be compared to the expected values of the systems from the Additive Model.

The methodology applied in this research is expected to contribute to the decision-making processes for the modernization programs, as well as to optimize the use of existing assets of AD systems. The framework below summarizes the approach taken:

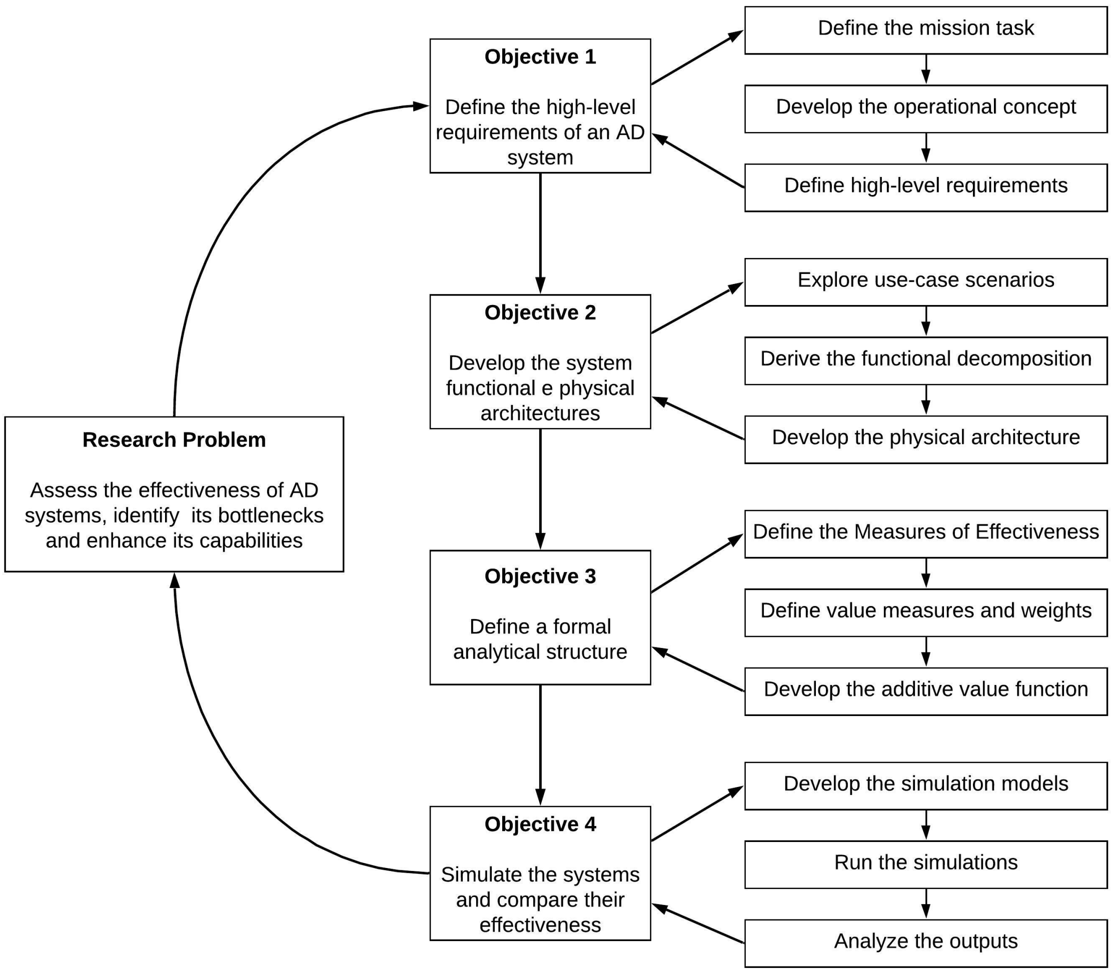


Figure 1.3: Thesis framework

1.4.2 Research Limitations

The first limitation aspect that must be pointed out in this study is that no classified data is present in the analysis. AD systems carry a lot of sensitive information that is not to be made public, so all the data used in this study come from unrestricted sources available to the general audience. To create the models and conduct the simulations, a fictional scenario with plausible threats was created. The methodology presented by this research aims to be clear and explicit, so that the adaptation to any real AD system is expected to be a trivial process.

Secondly, time constraints dictate that the discussions must be conducted from a strategic level perspective. The temptation of detailing activities down to the operational and/or tactical levels will be avoided, so that the boundaries of the scope are respected, and the study can be completed in time with the expected quality.

Another important aspect that is not within the scope of this research is the cost. Needless to say, cost is a major determinant when it comes to procuring new assets for a system. But given its nature and complexity, the cost analysis must be conducted separately from the effectiveness analysis. Even though the assets to be considered for the AD system were assessed in terms of unit cost (Table 4.5), those numbers mean only to give an initial prospect of the values. However, the program costs incorporate many other stages of the subsystems' lifecycle - such as research and development, integration, training, operation, maintenance, disposal, etc - that are beyond the boundaries of this study.

Finally, it is paramount to state that the outcomes of the simulations measuring the overall system effectiveness cannot be used to predict the results of a military campaign. Therefore, the focus of the simulation results will be on the comparisons and sensitivity analysis, which carry information that is useful to the purposes of this research, such as better alternatives, existing bottlenecks and unveiled system malfunctions, for instance [15].

1.4.3 Research Contributions

This study is intended to demonstrate how consolidated knowledge in Systems Engineering and Operations Research can be applied to ameliorate an AD systems. To that matter, decision-makers can implement the effectiveness assessment techniques presented in this research in order to improve current capabilities and plan ahead for homeland defense against airborne threats from the present and near-term future.

Given the bibliographical research conducted in this study, no other academic papers were applying these analytical methods specifically to assess the effectiveness of AD systems.

Ironically, Systems Engineering originated from the DoD first developments of air defense and missile systems that culminated in the Atlas Project in 1954, the first intercontinental ballistic missile developed in the US [13]. To that extent, it makes perfect sense to apply this knowledge, which has now been perfected through all these years, to the optimization of current and future AD systems.

Chapter 2: 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 define the gap between what exists and what is desired from the system before a potential solution is considered [16]. Hence, it is paramount to accurately identify what problem an Air Defense 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 Air Defense 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"[4].

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 air defense 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. [16].

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 [16].

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 [16].

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

2.1 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 aforementioned "push" and "pull" paradigms) [16].

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) [16].

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 [16].

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 [16]. Thus, this methodology will be implemented in the analysis of an Air Defense System.

2.1.1 Defining Problem Space

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 Air Defense System to be a simplified version of the US DoD definition of Counter-Air and Integrated Air and Missile Defense [4]:

"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].

Given this mission, the purpose of the system is explicit and straightforward. There is an identified need to protect the homeland specifically from both air and missile threats. This demand will drive the whole process of the system development. In addition, the mission statement also provides a good starting point for the identification of the stakeholders.

2.1.2 Identifying of the Stakeholders

Stakeholders are any person or organization that has a responsibility, opinion, or may be affected or influenced by the proposed system [12]. As this definition includes a very broad group of people, given that anyone can be affected and have an opinion on their country's AD system, it is necessary to specify the stakeholders that will be taken into consideration in the concept definition.

Therefore, the following stakeholders - as indicated by Dick [12] - will be considered relevant for AD systems:

1 - Managers: People who have a responsibility for either the development budget or the operational budget. For this study, this group will be represented by the decision-makers with high command positions in the military rank who are responsible for the national AD.

2 - Investors: This group is responsible for financing the enterprises; hence they obviously have a direct interest in the capabilities provided by the system. Usually, the National Congress has this incumbency when it comes to directing funds to defense systems.

3 - System Users: People who, directly or indirectly, interact with the system. This group has a great interest in the system capabilities as well. Even though this definition still incorporates a wide range of people, this research will consider as system users only the personnel who operate the detection and interception assets of the system, as well as the ones acting in the C2 structure.

4 - Maintenance Staff: Maintainers have the primary responsibility of keeping the system running after it's been delivered. However, they play an extremely important role much earlier than that: it is paramount to consider this group in the requirements definition, so that they can perform their activities effectively later on the system lifecycle.

Other groups of stakeholders include product disposers, training personnel, system buyers, marketing, usability and efficiency experts, operational environment experts, government, standards bodies, public opinion and regulatory authorities. Whereas none of them are unimportant to the overall success of the system, they are not considered within the scope boundaries of this paper, since the four above nominated groups provide sufficient information to the high-level development of an AD system, allowing for the construction of a preliminary Operational Concept.

2.1.3 Preliminary Operational Concept

The Operational Concept (OpsCon) is the first step in the design process of a system. It is a general vision of what the system is, providing a graphical representation of the mission requirements and describing how the system will be used through a set of use cases that define the interactions with other systems [13].

The initial definition of the OpsCon can be very abstract, presenting no quantitative procedures, but only what the system should do based on a set of general objectives. As the design process advances, this definition becomes more specific [13].

The development of the OpsCon starts with a mission statement followed by the description of the necessary capabilities to accomplish this mission, as well as the way these capabilities interact among themselves and with the external environment. A narrative that clearly states every aspect of the graphical representation is paramount to explain exactly what is being described [13].

The vision of an AD system is derived from its mission, which is to defend the homeland by negating an enemy's ability to create adverse effects from their air and missile capabilities. Therefore, the system shall be able to detect, identify, intercept and, if necessary, engage any airborne entity that threatens the homeland at any time and any condition.

From that vision, the following preliminary graph represents the entities which are part of the system and those which interact with it:

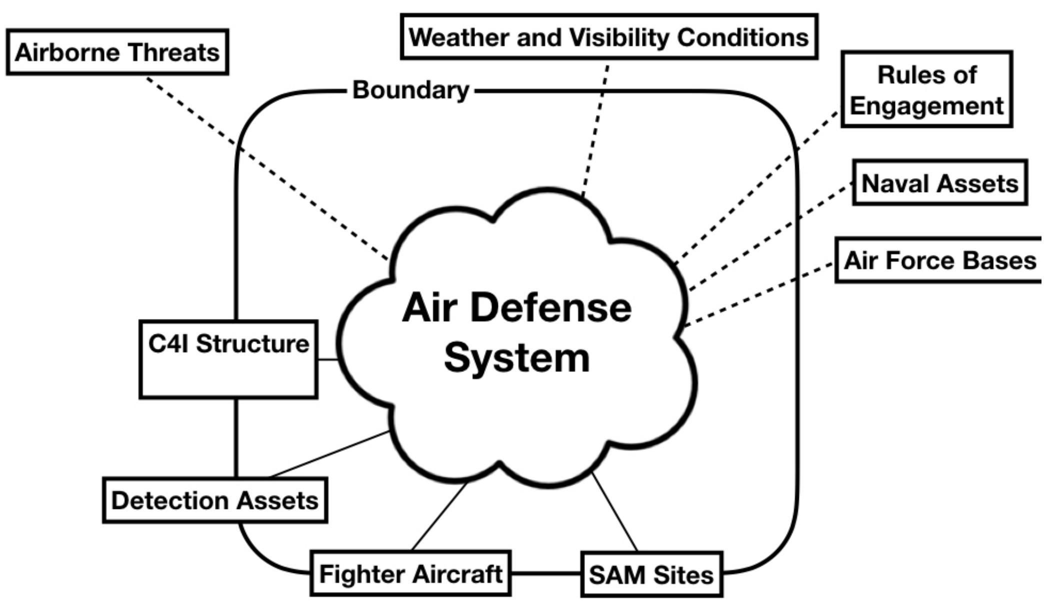


Figure 2.1: Preliminary Operational Concept of an Air Defense System

The dotted lines represent entities that are not part of the system, but whose interactions are of main importance to it:

Airborne Threats: Mentioned in the mission as well as in the vision, the air and missile capabilities of the enemy were grouped into this entity. Despite being far from a component of the system, this entity is of enormous importance in the definition of the requirements, since the result of its interactions will ultimately determine whether the mission is accomplished or not.

Weather and Visibility Conditions: The vision statement defined that the mission should be accomplished at any time and under any circumstances. Being very sensitive to meteorological conditions, air defense assets must operate independently of adverse weather conditions, 24 hours a day, 7 days a week. Different regions of the world impose different weather environments, so that parameter must be taken into account when planning the AD system of a particular country.

Rules of Engagement: The political level will determine the guidelines that will establish the rules of engagement. These rules will determine which capabilities the air defense assets shall have to fulfill the system's mission according to the political interests.

Naval Assets: These resources expand detection and interception capabilities of an AD system. While they can be sometimes assigned to perform exclusively air defense tasks, they are not considered part of the system because they are a platform from where the asset - a radar, a missile or an aircraft - will operate.

Air Force Bases: Similarly to the naval assets, the air force bases provide the infrastructure necessary to the operation of air defense assets.

The continuous lines connect the entities that are part of the system. Despite that, these entities will not necessarily be developed with the design of the system. Instead, these subsystems can be chosen among existing assets that are available for procurement, according to the established capabilities required to conduct successful AD operations.

C4ISR Structure: the C4ISR structure (derived from the C2 concepts) aims to focus the efforts of all the entities towards the achievement of the task. They are a key integrating function of complex systems, supporting solid and efficient decision making. As the C4ISR is not an end itself, but means that lead to an end, an effective structure will not guarantee the success of the AD, but is necessary to the proper operation of all the system entities.

Detection Assets: Detection is the first system capability stated in the vision. If a threat can't be detected, it can't be monitored, intercepted, engaged or destroyed, preventing the AD from fulfilling its mission.

Fighter Aircraft: As aforementioned, these assets are paramount to correctly classify an unknown object that was detected, which may or may not be hostile. They can also engage enemy threats - both aircraft and missiles.

SAM Sites: SAM can be very effective when used for destroying hostile aircraft or cruise/intercontinental enemy missiles. However, it takes more time to move them to different positions as the new circumstances may demand, and they have limitations when it comes to engaging unidentified objects.

Having defined all the entities presented by the OpsCon graph, it is necessary to establish relations among them. In a simple way, the activities of an AD system start with the detection of a possible airborne threat at any weather and visibility condition. Then, a C4ISR structure will allow for the headquarters to use the rules of engagement in order to overcome this possible threat. If the unknown flying object is promptly identified as hostile, it can be shot down by a SAM. If the possible threat needs classification, a fighter aircraft must be deployed to intercept and identify it. Naval assets and Air Force Bases will be used as the platforms from where detection and interception assets will operate.

The definition of the problem space, the identification of the stakeholders and the development of the OpsCon do not exhaust all the possible activities that can be implemented during the mission analysis [16]. However, they provide a good understanding of what the system should do, so it is now possible to move onto the definition of the AD system requirements.

2.2 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 [12].

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 formal definition of a requirement is: "A statement that identities a product or process operational, functional or design characteristic or constraint, which is unambiguous, testable or measurable and necessary for the product or process acceptability (by consumers or internal quality assurance guidelines)"[12].

From this definition, it is unquestionable that the three listed characteristics - unambiguous, measurable and necessary - must never be neglected when defining the requirements of an AD system.

Another important aspect that also depends upon effective requirements engineering is risk management. When the processes and activities in this matter are properly executed, the identification of risks to core aspects of the system can be tracked, its impacts assessed, and the effects of mitigation understood long before substantial development efforts and costs have been incurred [12].

Ultimately, requirements form the basis for the planning, acceptance testing, risk management and change control throughout the entire lifecycle of a system [12]. Therefore, in order to fully understand and develop the AD system of a country, decision-makers cannot abstain from conferring the special attention demanded by all the activities involved in the requirements definition.

However, it is important to point out a common misconception regarding that matter. As opposed to what many would think, the definition of requirements is not a single phase to be carried out and completed before the next step of the project starts. It is, instead, an iterative process that may be revisited at any point during the system progress, depending on the way it was planned. To that end, a correct system development approach that enables requirements management activities to be conducted at any point in the system lifecycle must be defined .

2.2.1 System Development Approach

In order to allow the realization of a successful system, Systems Engineering presents reference models of different approaches on the way the system should be planned, organized, orchestrated and implemented. those strategies are commonly referred to as lifecycle models, and are one of the key concepts of Systems Engineering. A lifecycle of a system consists of a series of stages regulated by a set of management decisions that confirm that the system is mature enough to leave one stage and enter another [16].

The lifecycle of a system must be accurately designed, and all of its stages, from definition and realization to retirement, must be meticulously planned and thoroughly controlled, so that the system can be effective and efficient [17].

Being complex, expensive and yet vital for any country, an AD system requires these management activities to be carefully planned and controlled so that the desired level of effectiveness can be achieved with the allocated resources.

Many lifecycle standards have been developed and supported by different problem-solving methodologies. Despite presenting divergences in so many aspects, all of these models have applications depending on the characteristics of the system to be designed. Undoubtedly, that there is no single model that will cover every aspect of a particular system. In fact, many attempts to include extensive processes for all kinds of possible activities in the system development resulted in overly bureaucratic and inefficient models [16].

Oppositely, high-levels of proactive systems engineering efforts must be continuously pursued throughout all the phases of the system development - not just at the early stages (although these are, unquestionably, the most important stages for applying such knowledge). As the system evolves, activities addressing the system integration, testing, change management and feasibility assessment must be performed, making the lifecycle management process incremental. Nowadays, systems engineers are actually expanding the single-step lifecycle choice strategy to evolutionary approaches that employ traditional models' practices - such as the V&V (Verification and Validation) or Agile - as they fit the needs that are created as the system develops [16].

That being said, it is possible to use the V&V (also known as the V-model) as the basis for the lifecycle management activities to be used in the development of an AD system. The V&V model is a highly iterative model that allows loop-backs and course corrections while the workflow progresses to delivery and acceptance of the system. It requires a decomposition of initial high-level requirements into multiple abstract levels of solution designs of more detailed aspects of the system:

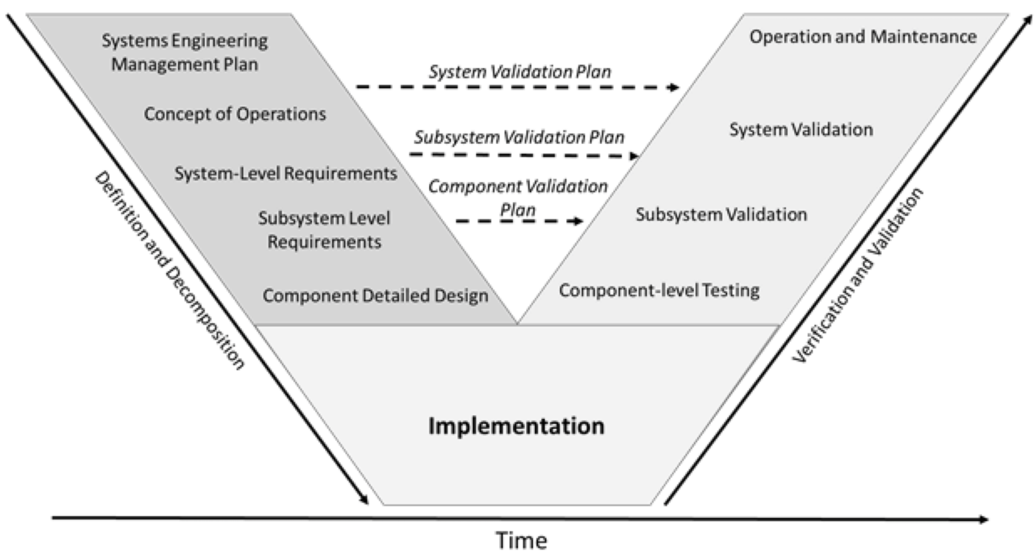


Figure 2.2: V-Model for System Development [1]

The figure above expresses the main aspects of the V&V model that should initially drive the management activities and stage gates for the development of an AD system.

Since the SE management plan and the high-level operational concept are already established, the next step for advancing in the model is to clearly define the system requirements.

2.2.2 Air Defense System Requirements

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 [18].

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 [18]. As previously mentioned, 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 [18].

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 [18]:

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 [18].

As previously mentioned, 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 [18], this objective can be decomposed into the following high-level requirements, achieving the first research objective (O1):

Table 2.1: 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

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 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 in the next chapter. The physical architecture of the system will also be presented in order to define the assets that are paramount to accomplish the stated mission.

Chapter 3: Structured Analysis and 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 - such assessment will be addressed in Chapter 4.

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 will be determined through a structured analysis, starting with use-case scenarios that represent situations in which the system is likely to be employed.

3.1 Use-Case Scenarios

Appendix A presents a fictional scenario where Blueland has to protect its airspace from some potential enemies. Decision-makers in Blueland need an assessment on their current system efficacy in overthrowing possible aggressions from neighbors. They've provided some intelligence about the countries which threaten Blueland's airspace. This information was used to build use-case scenarios.

The next level of system requirements will be derived from use-cases, considering the higher-level requirements listed in Figure 2.3. As aforementioned, the more use-case scenarios are analyzed, the better outcomes are expected. Consequently, the process of deriving needed capabilities from use-cases should be repeated for different environments and numerous hypothetical situations, so that the set of requirements is complete. In this study, two use-case scenarios - one for missile threat and another one for aircraft threat - were chosen.

Even though the number of scenarios is low, they provide enough complexity in order to present this approach and produce key requirements of an Air Defense System.

Cockburn [19] has defined some best practices on how to write use-cases. In short, it is imperative to make the use-case readable, with a clearly defined goal and primary actor, worry about the actors' objectives (and not about the interfaces), consider the information flow and indicate step sequencing. The following use-cases have been written in accordance with Cockburn's methods:

Use-Case 1: Ballistic Missile Attack

Goal in context: An ICBM launched from Redland and targeting a city in Blueland must be detected, intercepted and destroyed before it causes any harm to Blueland

Scope: Blueland Air Defense System

Level: Strategic

Precondition: The enabling infrastructure and operational procedures are established and ready to support the operations of Blueland AD assets

Success end-condition: Incoming ICBM destroyed

Minimal guarantees: The ICBM must be detected at least 6 minutes before it achieves Blueland's airspace.

Primary actor: SAM batteries

Trigger event: ICBM launch

Main Success Scenario

Step	Primary Actor	Action Description
1	Detection Asset	An ICBM launch is detected
2	C4I Structure	The C2 Center is informed
3	Detection Asset	The ICBM is monitored and its flight information is assessed
4	C2 Center	Possible targets in Blueland are calculated
5	C2 Center	The decision of destroying the ICBM is made
6	C2 Center	The most suitable SAM battery is engaged
7	SAM Battery	The ICBM flight data is used to calculate the SAM trajectory
8	SAM Battery	SAM is launched
9	SAM	SAM intercepts and destroys the ICBM

Scenario Extensions and Variations

Step	Condition	Description
1a	ICBM detected too late	Automated SAM battery response
4a	Target out of Blueland (allied country)	Do not engage. Pass the information to the targeted country
4b	Target out of Blueland (non-allied country)	Do not engage. Monitor ICBM and keep SAM batteries on full alert
9a	SAM misses the ICBM	Launch a second SAM
9b	ICBM out of SAM range	Scramble alert aircraft

Related Information

Schedule:	Dec-18-2019
Priority:	Must
Performance Target:	100% of incoming ICBM
Frequency:	Every enemy ICBM launch
Super Use-Case:	General
Sub Use-Cases:	24/7 Alert and Warn, Detection, C4I, SAM Launch
Channel to Primary Actor:	C4I structure
Secondary Actor:	Sramble aircraft
Channel to Secondary Actor:	C4I structure

Use-Case 2: Unknown Aircraft crossing the border

Goal in context: An unknown aircraft flying towards the homeland must be identified and, in case it is classified as hostile, engaged before it causes any harm to Blueland

Scope: Blueland Air Defense System

Level: Strategic

Precondition: The enabling infrastructure and operational procedures are established and ready to support the operations of Blueland AD assets

Success end-condition: Incoming aircraft identified and properly dealt with

Minimal guarantees: The aircraft must be identified before it enters in sovereign Blueland space.

Primary actor: C2 Center

Trigger event: Unknown aircraft detected

Main Success Scenario

Step	Primary Actor	Action Description
1	Detection Asset	An unknown aircraft flying towards Blueland is detected
2	C4I Structure	The C2 Center is informed
3	Detection Asset	The aircraft is monitored and its flight information is assessed
4	C2 Center	Aircraft is classified as a hostile
5	C2 Center	Possible targets in Blueland are calculated
6	C2 Center	The decision of engaging the aircraft is made
7	C2 Center	The most suitable alert aircraft is scrambled
8	C2 Center	The interception is controlled
9	Alert aircraft	Launches a missile and destroy the hostile aircraft

Scenario Extensions and Variations

Step	Condition	Description
1a	Aircraft detected too late	If hostile, automated SAM battery response
4a	Aircraft needs classification	Do not engage until visual identification is performed
7a	Severe weather	Don't scramble aircraft. Engage threat with SAM.
9a	Hostile engages alert aircraft	Engage with SAM and deploy a second alert aircraft
9b	Hostile retreats	Monitor and follow it until it is no longer a threat

Related Information

Schedule:	Dec-18-2019
Priority:	Must
Performance Target:	100% of incoming aircraft identification
Frequency:	Every unknown aircraft
Super Use-Case:	General
Sub Use-Cases:	24/7 Alert and Warn, Detection, C4I,
	Alert Aircraft Scramble, SAM Launch
Channel to Primary Actor:	C4I structure
Secondary Actor:	SAM battery
Channel to Secondary Actor:	C4I structure

3.2 System Architecture

The next steps towards the definition of Blueland's AD system design is to derive the needed capabilities from the use-case scenarios and develop the architecture models.

The functional architecture is the centerpiece of the structured analysis approach: it defines the activities that, when activated, provide the system with the capabilities needed to achieve the defined objective [13].

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.

3.2.1 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 [13].

Initially, the Capabilities Taxonomy Table 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 3.1: Capabilities Taxonomy 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
		Reload SAM battery	A314
	Operate AD aircraft	Take-off	A321
		Navigate to interception point	A322
		Acquire target	A323
		Destroy target	A324
		Return to base	A325

The following figure represents the functional architecture, which contains a hierarchical model of the functions to be performed by each part of the system [13]:

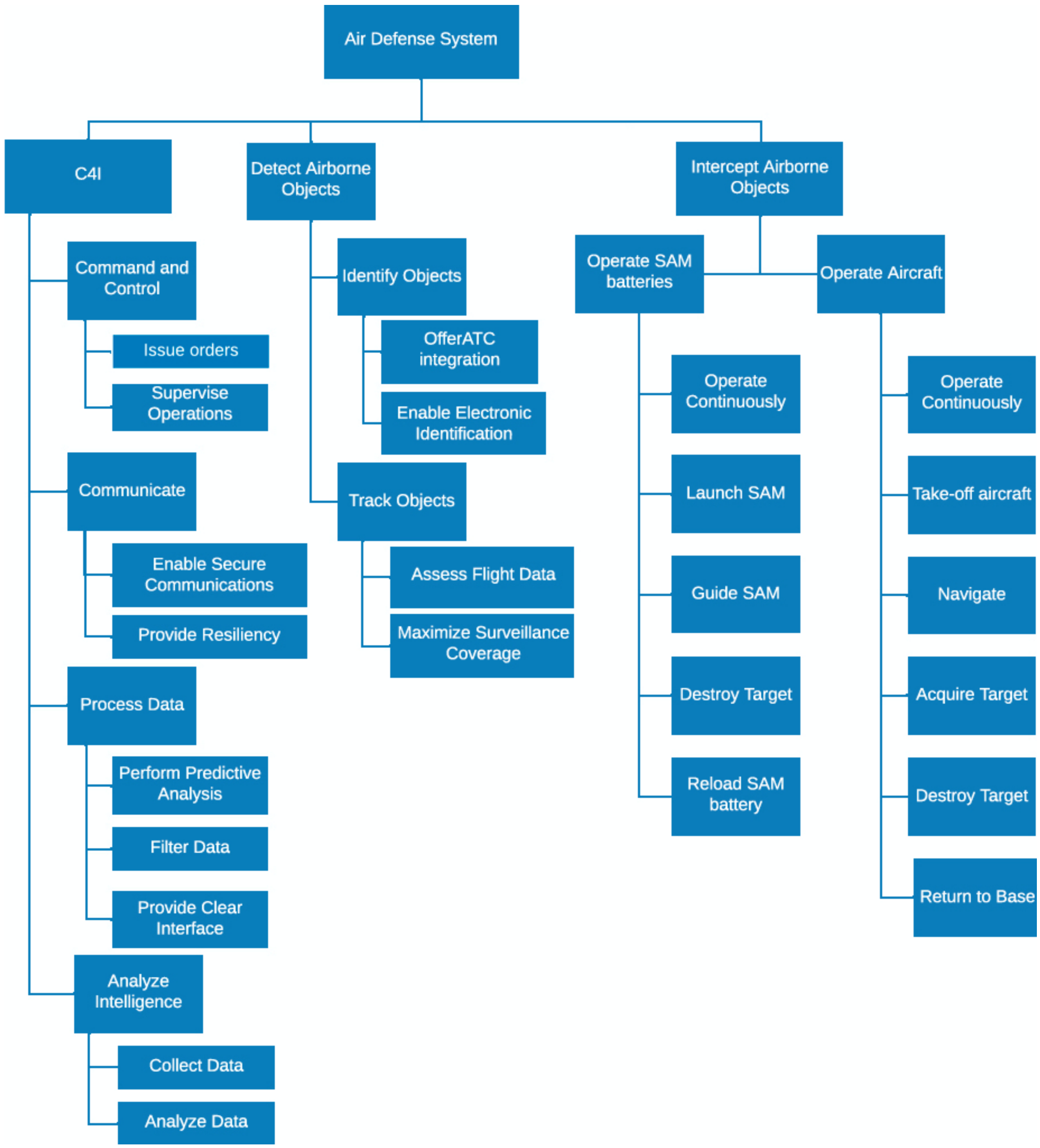


Figure 3.1: AD System Functional Decomposition

3.2.2 Functional Requirements

The following table relates all the capabilities identified in the functional decomposition with a formally written functional requirement for the Air Defense System:

Table 3.2: System Capabilities and Functional Requirements

CODE	CAPABILITY	FUNCTIONAL REQUIREMENT
A111	Give Orders	The system shall be able to generate and assign orders from the command center to each node or asset.
A112	Supervise Operations	The system shall enable the command center to assess whether the orders given are producing the expected results or not.
A121	Enable Secure Communications	The system shall be able to enable the flow of information in a way not susceptible to eavesdropping or interception.
A122	Provide Resilient Communications	The system shall be able to maintain the flow of information with an acceptable level of service in the face of faults and cyber-attacks.
A131	Perform Predictive Analysis	The system shall be able to employ techniques from data mining, statistics, modeling, machine learning, and artificial intelligence to analyze current data to make predictions about thefuture.
A132	Filter Data	The system shall be able to reduce the content of noise or errors from measured process data.
A133	Provide Clear User Interface	The system shall be able to allow the users to interact with the software and hardware in a naturally and intuitively.
A141	Collect Data	The system shall be able to gather and collect information of value through multiple sources of intelligence: human, signals, imagery, open sources, surveillance and cyber.
A142	Analyze Data	The system shall be able to process the information collected about an enemy and use it to answer tactical questions about current operations or to predict future behavior.

CODE	CAPABILITY	FUNCTIONAL REQUIREMENT
A211	Provide ATC Integration	The system shall be able to coordinate air traffic control (ATC) procedures with the military C2 center.
A212	Electronic ID	The system shall be able to interrogate a particular aircraft and unambiguously identify its reply.
A221	Assess Flight Data	The system shall be able to detect air targets and determine their position, altitude, course and speed.
A222	Provide Detection Coverage	The system shall be able to detect approaching enemy aircraft or missiles at any point of Blueland's areas of interest.
A311	Launch SAM	The system shall be able to launch Surface-to-Air Missiles when ordered by the command center.
A312	Guide SAM	The system shall be able to provide guidance to Surface-to-Air missiles towards the interception point of a threat.
A313	Destroy Target	The system shall be able to create enough damages to a threatening aircraft or missile so that it can no longer cause any harm.
A314	Reload SAM Battery	The system shall be able to reload the Surface-to-Air Missiles batteries after a SAM is launched.
A321	Take-off	The system shall be able to take-off an air sovereignty alert aircraft quickly enough to intercept a threat before it causes any harm.
A322	Navigate to interception point	The system shall be able to enable the air defense alert aircraft to navigate towards the interception point of a threat.
A323	Acquire Target	The system shall have aircraft capable of detecting and guiding Air-to-Air (A/A) missiles towards a threatening aircraft or missile.
A324	Destroy Target	The system shall have A/A missiles capable of creating enough damages to a threatening aircraft or missile so that it can no longer cause any harm.
A325	Return to Base	The system shall be able to provide safe conditions for the air sovereignty alert aircraft to safely land at an airfield.

This table aims to be a starting point for creating a set of clear, unequivocal and measurable requirements that address specific capabilities. Many of these requirements shall be decomposed multiple times until a document presenting all these characteristics is obtained. However, the information presented so far is enough for the analysis to move forward and allow the development of the physical architecture of the system.

3.2.3 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 [13].

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 [13].

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 the following image:

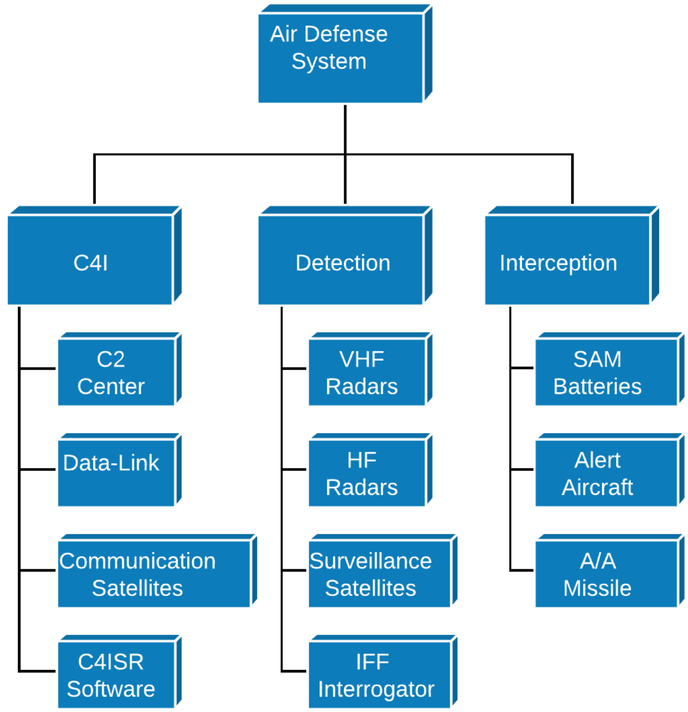


Figure 3.2: AD System Physical Architecture

At this point, the second objective of this research (O2) was achieved. 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 [13], which will be explored in the subsection 3.2.5.

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.

3.2.4 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 3.3: 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									

3.2.5 Morphological Box

The morphological analysis divides the problem into different segments and then provides alternatives that solve each part [13]. To create an instantiated model of Blueland's Air Defense 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 come from Appendix B, which presents a selection of air defense assets available for procurement by NATO members and allies

Table 3.4: 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	-

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 worse, every row can be decomposed multiple times in order to make specific choices for the elements in each segment of the system [13]. 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 [13]. Chapter 4 will assess such parameters for elected instantiated models of Blueland's AD system.

Chapter 4: Value Model

Establishing a criterion that complies with the stakeholders' expectations by explicitly showing that a requirement has been met is essential. The qualification strategy consists of a set of tests, trials, demonstrations and/or pass marks to requirements attributes that shall convince the stakeholder that a particular need has been fulfilled [13].

Each requirement must have its own acceptance criteria which, when satisfied, proves that the associated capability has been acquired. Measuring the success of each activity (that provides such capabilities) in instantiated models of the system will regulate its MOP and MOE, addressing the research problem.

The determination of these instantiated models requires a sound analytical effort and profound knowledge of the system requirements and the alternatives' parameters[13]. The alternatives for each row of the morphological box must be considered in terms of attributes and capabilities that enable them to perform the necessary tasks. Ultimately, the decision about the best composition of assets for an AD system depends upon the Analysis of Alternatives (AoA), which aims to support the authorities in the decision-making process.

The AoA is 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 [20]. As previously established, 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 (Table 4.5) 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 (MOE) and measures of performance (MOP). The MT of the AD system was already defined in Chapter 2 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 [20].

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 [21].

That approach will be used in the AoA that will support decisions regarding the determination of the assets of Blueland's AD system.

4.1 Value Focused Thinking

Keeney [21] defines the typical decision analysis techniques as "alternative-focused thinking", in which the definition of possible alternatives is followed by the determination of a criteria to evaluate them. That is a backward approach, since it "puts the cart of identifying alternatives before the horse of articulating values"[21].

On the other hand, value-focused thinking is an approach that considers the values as the fundamental force that should drive the decision-making process. Even though this technique does recognize the importance of multiple iterations of values and alternatives, it emphasizes the concept of "values first"[21].

Value-focused thinking presents three major ideas that are used to support the decision-making process in the definition of any system [22]:

1 - Define the values: start with the mission analysis, which clearly defines the objectives and goals of the system, which are the elements that generate value to the stakeholders.

2 - Generate better alternatives: use the identified objectives to generate alternatives that correctly address them.

3 - Use the values to evaluate the alternatives: use the mathematical technique of multiple objective decision analysis as a tool for the evaluation of alternatives.

Fortunately, the first two steps were addressed in Chapters 2 and 3 of this research. Even though the Systems Engineering approach that was used slightly differs from the Operations Research methods presented by Keeney [21], they both provide similar outputs such as the strategic objective, specific goals, needed capabilities, and possible alternatives. Now it is time to proceed to the mathematical evaluation of alternatives that is established in step 3.

4.2 Multiple Objective Decision Analysis

Multiple Objective Decision Analysis is an Operations Research approach that relies on four basic concepts: values, alternatives, information and assumptions about the future. The last concept has a major influence on the other three, so it is important to clearly state the analyst's beliefs regarding the future. Given its importance to the decision support system, these hypotheses should result from probabilistic reasoning, scenarios examinations, cogitation of alternate futures and sensitivity analysis [22].

The data presented in Appendix A contains information regarding all the possible threats to Blueland, considering the near to mid-term future. That assumption is paramount to the Value Models to be developed: once there is an unexpected change and new threats arise, a new analysis must be conducted.

4.2.1 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 [21].

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 [22].

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 defined in Chapter 2. 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 conducted in Chapter 3 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 3.1 shows hierarchically all the high-level functions of the system.

3 - Objectives: The objectives that create value to the system must be identified and structured by grouping the high-level functions defined in the structured analysis. The affinity diagram presented in figure 4.1 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:

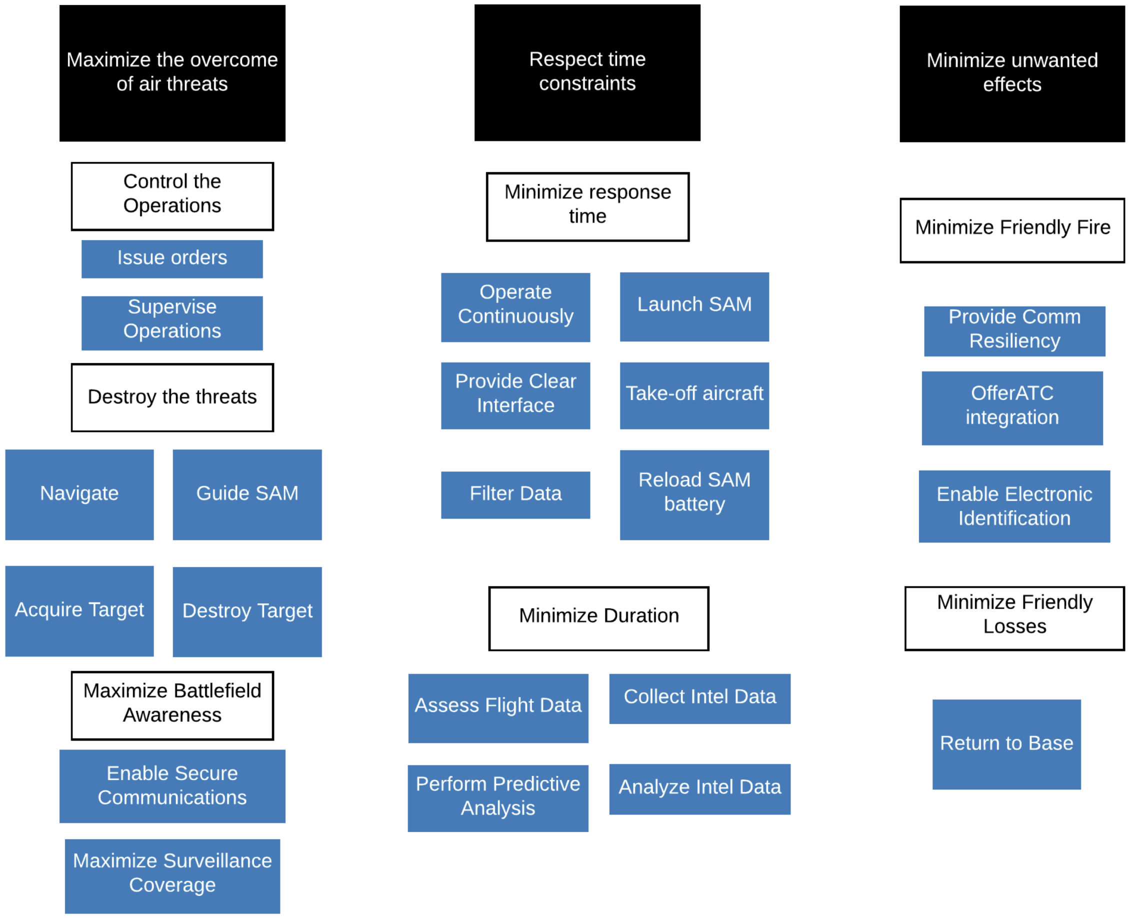


Figure 4.1: AD System Affinity Diagram

The objectives in the affinity diagram must be prioritized in order to determine a ranking. These priorities come from interviews, gold-standard documents and multiple interactions with decision-makers, system users and experts. The objectives rank higher when they are natural and directly aligned with the strategic goal; and lower when they are constructed and proxy aligned with the strategic goal. The qualitative value model below presents the objectives, from the highest priority 1 to the lowest priority 4:

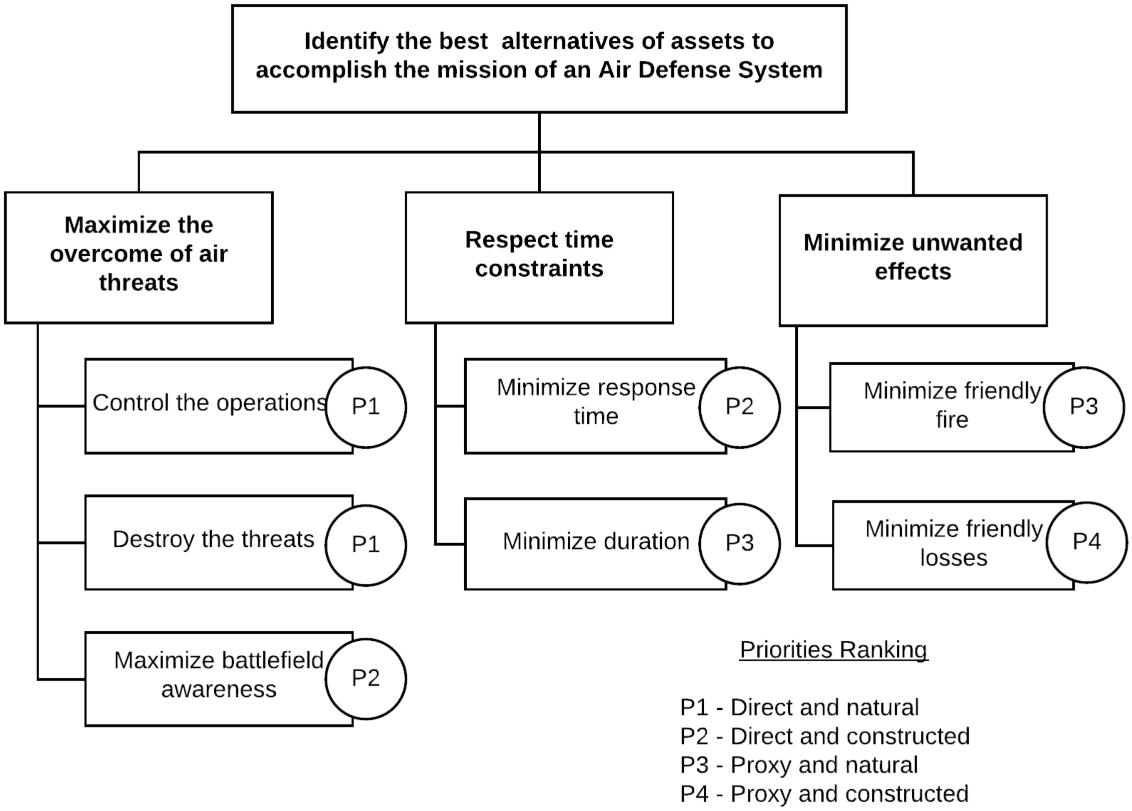


Figure 4.2: AD System Qualitative Model and Objectives Priorities

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. The following table presents the MOE for the identified objectives that contribute to the MT of an AD system:

Table 4.1: 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.

4.2.2 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[22].

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[22].

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 [22].

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 [22].

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[22].

Considering the aforementioned assumptions, the equation that calculates each alternative's value in the additive model is [22]:

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

$v(x) \rightarrow$ overall value added of the alternative x
i to n $\rightarrow$ the ith (i to n) value measure
$k_i \rightarrow$ weight of the ith value measure
$x_i \rightarrow$ score of alternative x on the ith value measure
$v_i(x_i) \rightarrow$ value added of the alternative x for the ith 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 [21].

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.

The utility value functions have four basic shapes: linear, concave, convex and S-curve. The linear functions uniformly return values with the same rate as the measures increase. The concave shape decreases these values return per increment, making each one of them smaller than its predecessor. The convex function is quite the opposite, with each increment returning a greater value to the function. The S-curve gives increasing and then a decreasing value returns.

The shape of the value function depends on the assessment of subject matters experts, who are able to tell by how much a measure increment will affect the relative value in importance and range regarding the pursued objective - it depends on their attitude towards risk, political factors, impact on public affairs, among other aspects that can influence the decision-making process[22]:

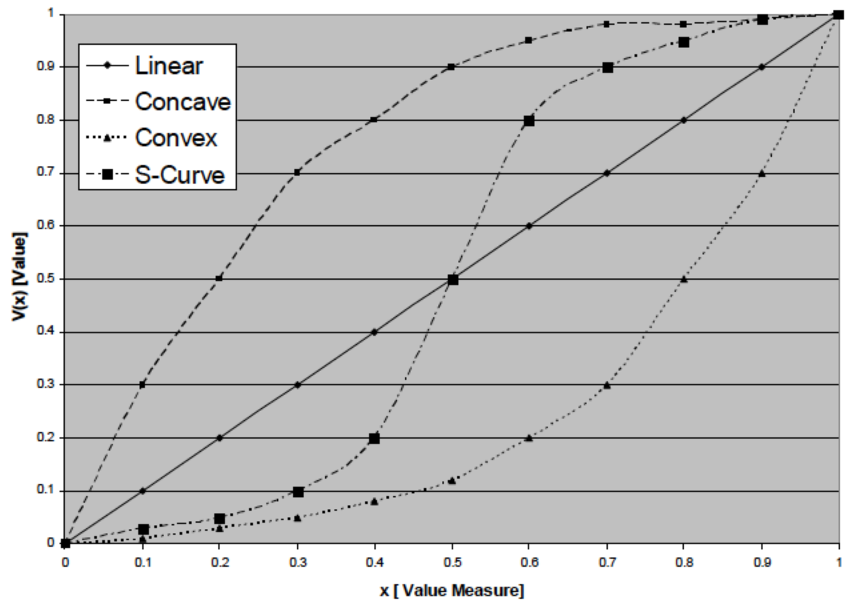


Figure 4.3: Utility Value Function Types

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 *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*, smaller numbers are better. The same methodology is applied to all of the attributes:

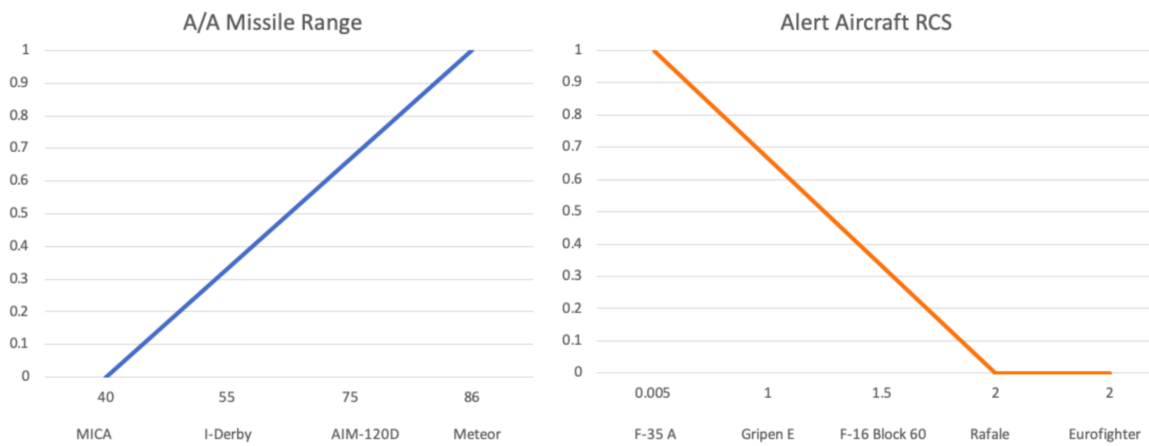


Figure 4.4: Value Measure Returns to Scale

After obtaining the value measures, the weights must be assessed to fill the quantitative value model with all the necessary numbers and calculate the results of the value-focused thinking approach.

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 [21].

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:

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

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

The table below weighs the objectives and sub-objectives and associate 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:

Table 4.2: AD System Value Measures Weights

Objective	Local weight	Sub-objective	Local weight	Type	Value Weight	MOE	Weight
Maximize the overcome of air threats	0.6	Control the operations	0.2	Direct Natural	0.12	Number of threats destroyed	0.6
		Maximize number of threats destroyed	0.6	Direct Natural	0.36		
		Maximize battlefield awareness	0.2	Direct Constructed	0.12		
Respect time constraints	0.2	Minimize response time	0.6	Direct Constructed	0.12	Targets attacked by hostile missiles and aircraft	0.2
		Minimize duration	0.4	Proxy Natural	0.08		
Minimize unwanted effects	0.2	Minimize friendly losses	0.8	Direct Constructed	0.16	Friendly aircraft losses	0.16
		Minimize fratricide	0.2	Proxy Natural	0.04	Fratricide avoidance	0.04

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:

Table 4.3: Assets Attributes to Objectives Allocation

Objectives	C2 Center	Data-Link	Communication Satellites	C4I Software	VHF / HF Radars	Surveillance Satellites	IFF Interrogator	SAM Batteries	Alert Aircraft	A/A Missiles
Control the operations	Accuracy			Accuracy						
Maximize number of threats destroyed								Range, Pkill	Radar range, Thrust-to-weight	Range, NEZ
Maximize battlefield awareness			Resiliency		Range	Availability				
Minimize response time	Response Time			Usability						
Minimize duration	Decision Process				3D Capability				Weapon payload	
Minimize friendly losses		Extent							RCS	
Minimize fratricide		Stability					Accuracy			

Once again, the value added by each attribute needs to be quantified with local weights. The attribute weights are the lowest level of measures in this methodology, and are also known as “bottom row weight”:

Table 4.4: Attributes 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**

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 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 4.4. 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 in Appendix B, which are summarized in Table 4.5. Then, the attributes are allocated to the most fit 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:

Level of importance of the value measure

Attribute variation in measure range	Critical factor	Critical factor -	Important factor +	Important factor	Important factor -	Minor factor +	Minor factor
High	SAM battery Pkill Alert Aircraft RCS 100	Alert aircraft radar range 95	A/A missile range 80	60	C4I software usability C4I software accuracy 50	A/A missile NEZ IFF interrogator accuracy 40	Radar 3D capability Data-link stability 30
Medium	C2 center response time 90	SAM battery range C2 center accuracy 85	VHF radar range 65	Alert aircraft thrust-to-weight Communication satellite resiliency 50	Alert aircraft weapon payload 35	Surveillance satellite availability 25	20
Low	70	65	C2 Center decision process 50	Data-link extent 40	25	15	HF radar range 10

Figure 4.5: 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.

4.3 Alternatives Rank

The table below 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:

Table 4.5: Alternatives Values and Rank

	ki	0.071		0.042		0.075						
	Type	Accuracy	$v_i(x_i)$	Decision Process	$v_i(x_i)$	Response Time	$v_i(x_i)$			$\sum k_i v_i(x_i)$	Rank	Unit Cost (M of USD)
C2 Center	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								
	Type	Extent	$v_i(x_i)$	Stability	$v_i(x_i)$					$\sum k_i v_i(x_i)$	Rank	Unit Cost (M of USD)
Data-Link	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										
	Type	Resiliency	$v_i(x_i)$							$\sum k_i v_i(x_i)$	Rank	Unit Cost (M of USD)
Communication Satellites	Shared Use	Medium	0							0.000	2	15.00
	Exclusive Use	High	1							0.042	1	120.00
	ki	0.042		0.042								
	Type	Accuracy	$v_i(x_i)$	Usability	$v_i(x_i)$					$\sum k_i v_i(x_i)$	Rank	Unit Cost (M of USD)
C4I Software	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								
	Type	Range (nm)	$v_i(x_i)$	3D Capability	$v_i(x_i)$					$\sum k_i v_i(x_i)$	Rank	Unit Cost (M of USD)
VHF Radars	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										
	Type	Range (nm)	$v_i(x_i)$							$\sum k_i v_i(x_i)$	Rank	Unit Cost (M of USD)
HF Radars	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										
	Type	Availability	$v_i(x_i)$							$\sum k_i v_i(x_i)$	Rank	Unit Cost (M of USD)
Surveillance Satellites	Shared Use	Partial	0							0.000	2	60.00
	Exclusive Use	Total	1							0.021	1	120.00
	ki	0.033										
	Type	Accuracy	$v_i(x_i)$							$\sum k_i v_i(x_i)$	Rank	Unit Cost (M of USD)
IFF Interrogator	Mark X	Low	0							0.000	2	0.40
	Mark XII	High	1							0.033	1	0.78
	ki	0.071		0.083								
	Type	Range (nm)	$v_i(x_i)$	Pkill	$v_i(x_i)$					$\sum k_i v_i(x_i)$	Rank	Unit Cost (M of USD)
SAM Batteries	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				
	Type	Radar range (nm)	$v_i(x_i)$	Thrust-to-weight	$v_i(x_i)$	Weapon payload (lb)	$v_i(x_i)$	RCS (m2)	$v_i(x_i)$	$\sum k_i v_i(x_i)$	Rank	Unit Cost (M of USD)
Alert Aircraft	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								
	Type	Range (nm)	$v_i(x_i)$	NEZ (nm)	$v_i(x_i)$					$\sum k_i v_i(x_i)$	Rank	Unit Cost (M of USD)
A/A Missiles	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

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.

4.4 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:

Table 4.6: Instantiated Physical Architecture for System A

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	-

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:

Table 4.7: Instantiated Physical Architecture for System B

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	-

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 (Figure 4.6) and then altogether in a single graph (Figure 4.7).

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:

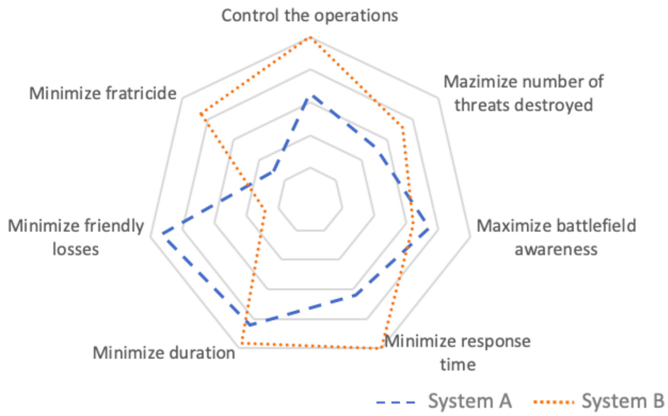


Figure 4.6: Additive Model Comparison between Systems A and B by Value Measure

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:

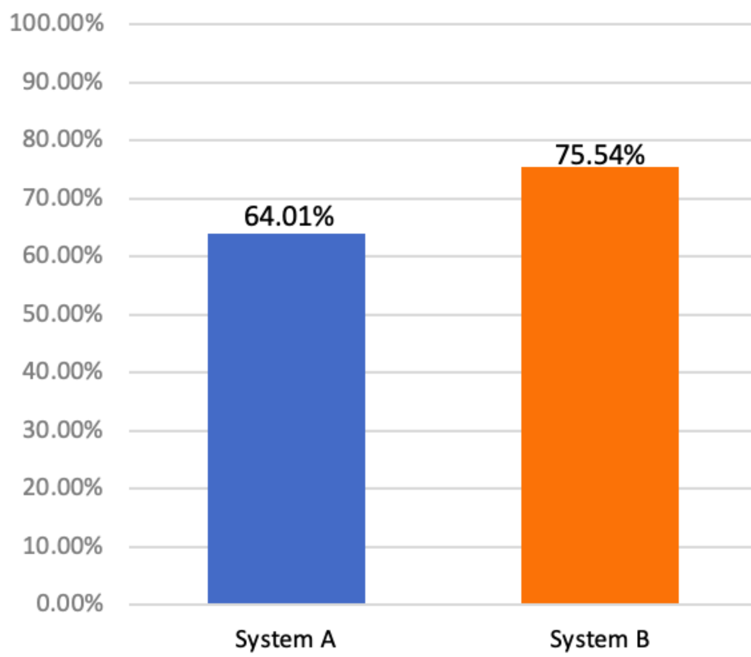


Figure 4.7: Additive Model Overall Comparison between Systems A and B

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 4.3, 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. After the development of this formal analytical structure, the third objective of this study (O3) was achieved.

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. This will be the goal of the simulations conducted and analyzed in Chapter 5.

Chapter 5: 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 a 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 4.5 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 approach, the analysis on the previous chapter and the results shown in Figure 4.7 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 the ROE, 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 conducted in Chapter 4 - can be good enough for presenting satisfactory results regarding exact information on questions of interest - that is called the analytic solution [15]. And, as aforementioned, 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 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.

5.1 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].

5.1.1 Purpose

Professor G. Box stated that "all models are wrong, but some are useful". A model is, by definition, a partial representation of a limited number of characteristics of the system that are necessary to achieve some objective. Even if it was feasible to capture and simulate all the possible behaviors of the system in its operational environment, that would be neither cost-effective nor desirable. Not only the time - thus, the cost - to create such a model would make the analysis very unlikely to be conducted for most projects, but also the amount of data produced would make the process of gathering useful information very difficult [15].

Still on the subject of quotes, common knowledge credits to Albert Einstein the aphorism "everything should be made as simple as possible, but not simpler". Even though there is no evidence that Einstein did in fact write this phrase, its content is undeniably wise. A model should be as simple as required, but not simpler. The simulation practitioner must clearly define with subject matter experts and decision-makers which aspects of the system must be incorporated in the model, and which can be safely ignored without jeopardizing the results or preventing them to be used according to the initial intent. Thus, the complexity requirements of the model depend upon the set of purposes it is intended to satisfy [15].

Thereafter, it is necessary to define what will be extracted from the simulation outputs before the input modeling starts. Given that the goal of this study is to assess the system effectiveness, it can be established that the purpose of the simulations is to determine the MOE of Blueland's AD System, as identified in Chapter 4:

1) Number of threats destroyed

2) Targets attacked by hostile missiles and aircraft

3) Friendly aircraft losses

4) Fratricide avoidance

Thereafter, it is necessary to define which modeling technique will be used: the event-scheduling approach or the object-oriented approach.

Discrete-event simulations are based on iterative events that change the state of the entities: the arrival rate of clients to the bank makes the queue longer, while the service rate of the clerk makes it shorter. This simulation approach is useful for simpler models that can use general-purpose simulation software [15].

Oppositely, the object-oriented approach is more adequate to model complex systems. In this kind of simulations, objects carry attributes and flow in the model while interacting with other objects as the simulation evolves through time. To enable such a method, a more powerful and specific simulation software that accurately captures all these characteristics of the system is required [15]. Hence, the choice of the software is crucial to the success of the simulation analysis.

5.1.2 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 [23].

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:

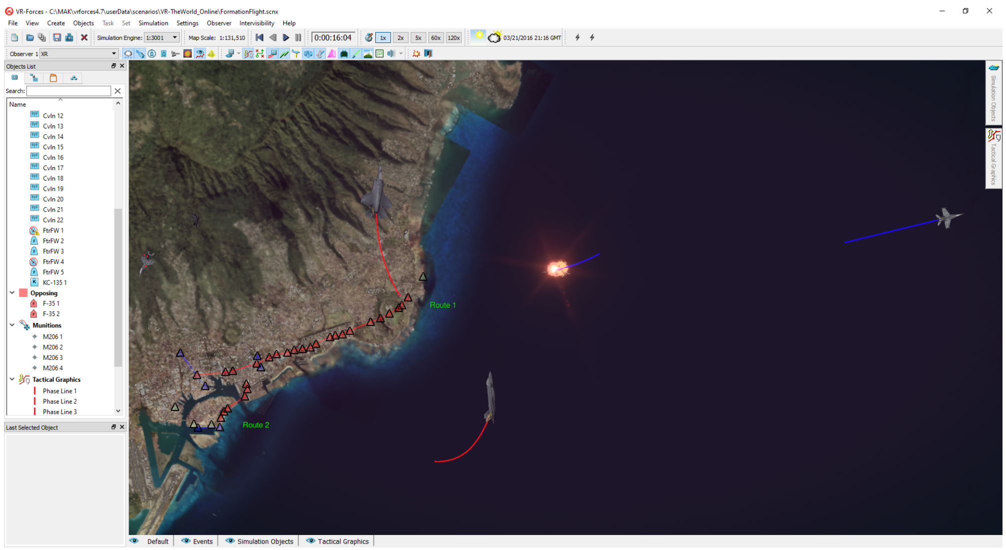


Figure 5.1: MAK VR-Forces Entity-Level Simulation

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:

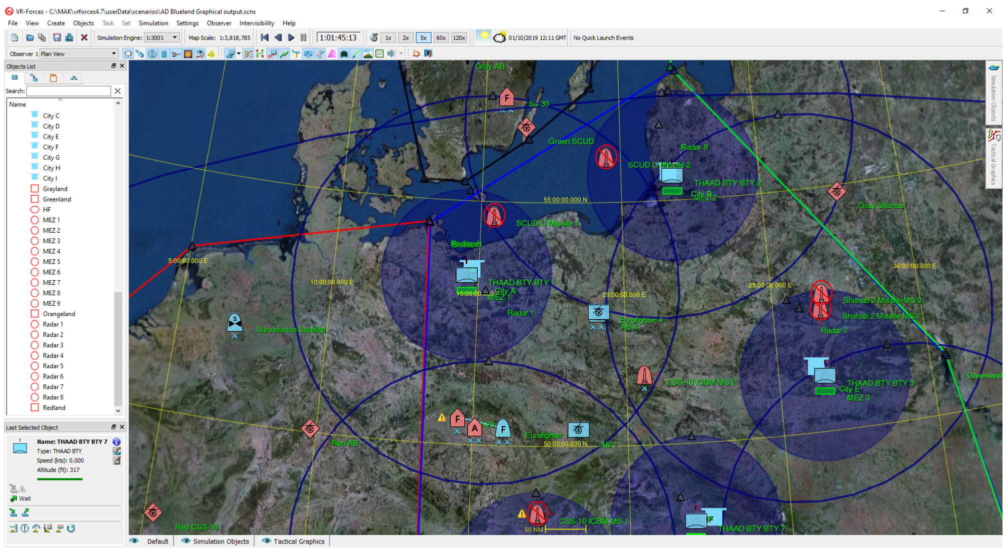


Figure 5.2: MAK VR-Forces Aggregate Level Simulation

The *MAK VR-Forces* also offers a *Simulation Object Editor* that allows the programming of entities that are not in the original data package, making it possible to model any real or fictional unit. In addition, the software presents several tools to define and control behavior, such as plans (for specific units or groups of them), triggers, script sets, crowd behaviors and many others[23].

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.

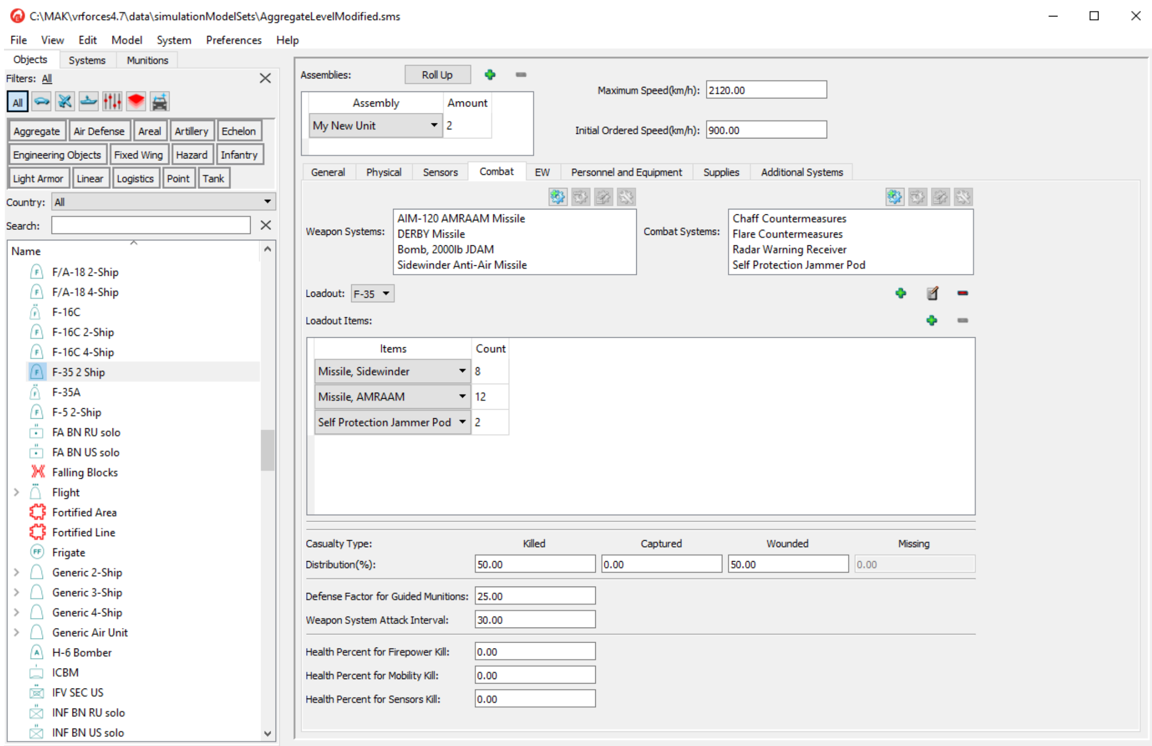


Figure 5.3: MAK VR-Forces Simulation Object Editor

5.1.3 Entities

The next step is to determine which assets will be modeled. The physical architecture developed in Chapter 3 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 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.

Each component of the system is represented as shown below:

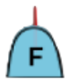
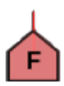
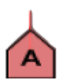
Aggregate Level Symbol	Entity Class	Entity Types
	Air Base	Blue Air Base / Red Air Base / Green Air Base / Gray Air Base / Orange Air Base
	Friendly Fighter Aircraft	QRA (current) / F-35A / Eurofighter
	Friendly SAM Battery	Patriot / THAAD
	Friendly Satellite	Surveillance Satellite
	Friendly City	Cities A to I
	Enemy Fighter Aircraft	J-20 / Mig-29 / Su-30 / F-7
	Enemy Striker Aircraft	H-6 / Su-24
	Enemy Missile	CSS-10, Shahab-2, Scud-C, Scud-ER

Figure 5.4: Entities Symbols in the Aggregate Level Simulation Model

5.1.4 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 the stakeholders. To prevent such mistakes, an assumptions document - also known as 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 were already made during the previous chapters: the system's strategic objective, the system architecture and the MOE. In addition, the Appendixes present the data summaries that were used to program the entities and their attributes.

Other important assumptions are listed below:

1 - That is not a full-scale war model. The scenarios established contemplate isolated incursions from enemy countries:
- 4 aircraft and 3 missiles from Redland
- 4 aircraft and 2 missiles from and Greenland
- 2 aircraft and 3 missiles from Orangeland
- 2 aircraft and 2 missiles from Grayland

2 - Blueland has 4 Air Bases from where the alert aircraft depart. Each enemy country has one Air Base from where the hostile aircraft depart.

3 - Each Air Force Base maintains 4 QRA, and the standard procedure is to scramble 2 aircraft at a time. The second batch is scrambled if the first one does not succeed in intercepting the threat.

4 - The time to scramble depends upon the C2 system (8, 10 or 15 minutes). The time count starts when the threat enters the detection range of any Blueland's detection asset - radar or satellite.

5 - Aircraft do not engage cruise or ballistic missiles. SAM batteries can engage both missiles and aircraft (even the THAAD, which in reality can only engage missiles).

6 - Incoming missiles will randomly target one of the 9 Blueland's major cities. Each of these cities is protected by one SAM battery (expect in the Base-case scenario).

7 - The enemy strikers from Redland and Greenland - H-6 and Su-24 - will be escorted by enemy fighter aircraft - J-20 and Mig-29.

8 - Grayland and Orangeland do not possess aircraft dedicated to strike or AD missions. Their jets - Su-30 and J-7 - are employed as multi-role fighters that perform both tasks.

The assumptions presented so far - in this section as well as in the previous chapters and Appendix - 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.

5.1.5 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 table below presents some examples of triggers that were used - some of them to explore even more the unpredictability of stochastic events, others to determine different behaviors of entities:

Table 5.1: Examples of triggers in the model logical behavior

Entity	IF	THEN
QRA1	hostile entity detected	wait: 480 and air-to-air attack: entity detected
H-6	random probability: 0.25	attack cityA / cityC / cityD / AB1
AB4	entity destroyed: Su-30	send radio task: QRA4: air-to-air attack: J-20
SCUD ER	random probability: 0.33	attack cityD/ cityI / cityH
F-7	random probability: 0.33	attack cityI / cityH / AB3
F-7	ot QRA 3 in area AB3	air-to-air attack: QRA3

Several other triggers similar to these 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.

5.1.6 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 defined in Chapter 3, the following system was modeled:

Table 5.2: Base-case Scenario 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.

5.2 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 an 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].

5.2.1 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]:

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

$\bar{X}(n) \rightarrow$ 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]:

$$\beta = |\bar{X} - \mu|$$

$$\text{such that: } 1-\alpha \leq P(|\bar{X} - \mu| \leq \beta)$$

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]:

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

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 the table below:

Table 5.3: 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%.

5.2.2 Final Simulation Results

By replicating the 3 scenarios 25 times - which was the highest number of required replications calculated - the following results were obtained:

Table 5.4: 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

5.3 Output Analysis

For the Base-case scenario, only 23.3% of the aircraft which invaded Blueland were destroyed, while the friendly attrition was of 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 defined in Chapter 3 and the final simulation results, the overall effectiveness of Blueland's current AD System is of 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 of 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 of 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 an overall effectiveness of 96.24%:

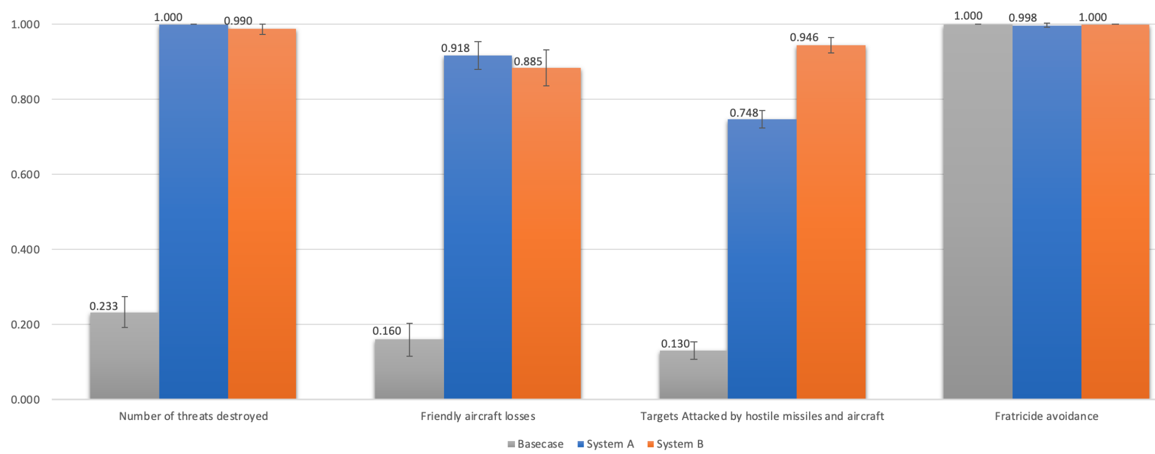


Figure 5.5: Comparison of the MOE of Systems A and B

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 satisfactory results with an overall effectiveness of 96.24%:

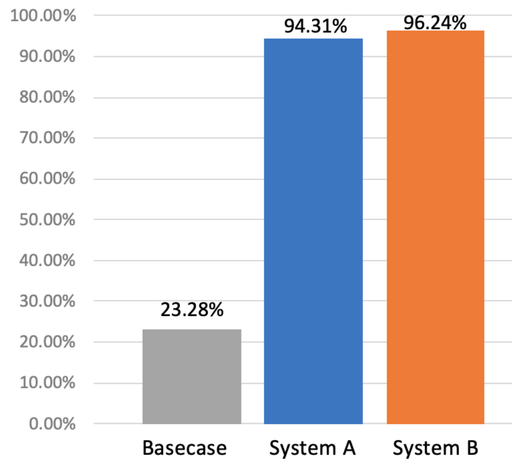


Figure 5.6: Comparison of the overall effectiveness of Systems A and B

After simulating the systems and comparing their effectiveness, the last specific objective (O4) of this research was achieved.

Chapter 6: Conclusion

6.1 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 [3]. 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 [5].

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, four specific objectives were established:

O1: Define the high-level requirements of an Air Defense System.

O2: Develop the system functional e physical architectures.

O3: Define a formal analytical structure.

O4: Simulate the systems and compare their effectiveness.

Chapter 2 explored the problem space and conducted a mission analysis, in which the mission task 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"[5]. From that mission, the high-level requirements of an AD system were established, accomplishing O1.

Chapter 3 presented use-case scenarios and from which the functional requirements were derived. 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 are necessary granted the achievement of O2.

In Chapter 4, an Analysis of Alternatives using value-focused thinking was 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. The development of this formal analytical structure accomplished O3.

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 the 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. At this point, O4 was attained.

6.2 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 in Chapter 5 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 a 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.

Appendix A: Fictional Scenario

The scenario below was established with Blueland as the home country to be defended from and the opposing forces of Redland, Orangeland, Greenland and Grayland.

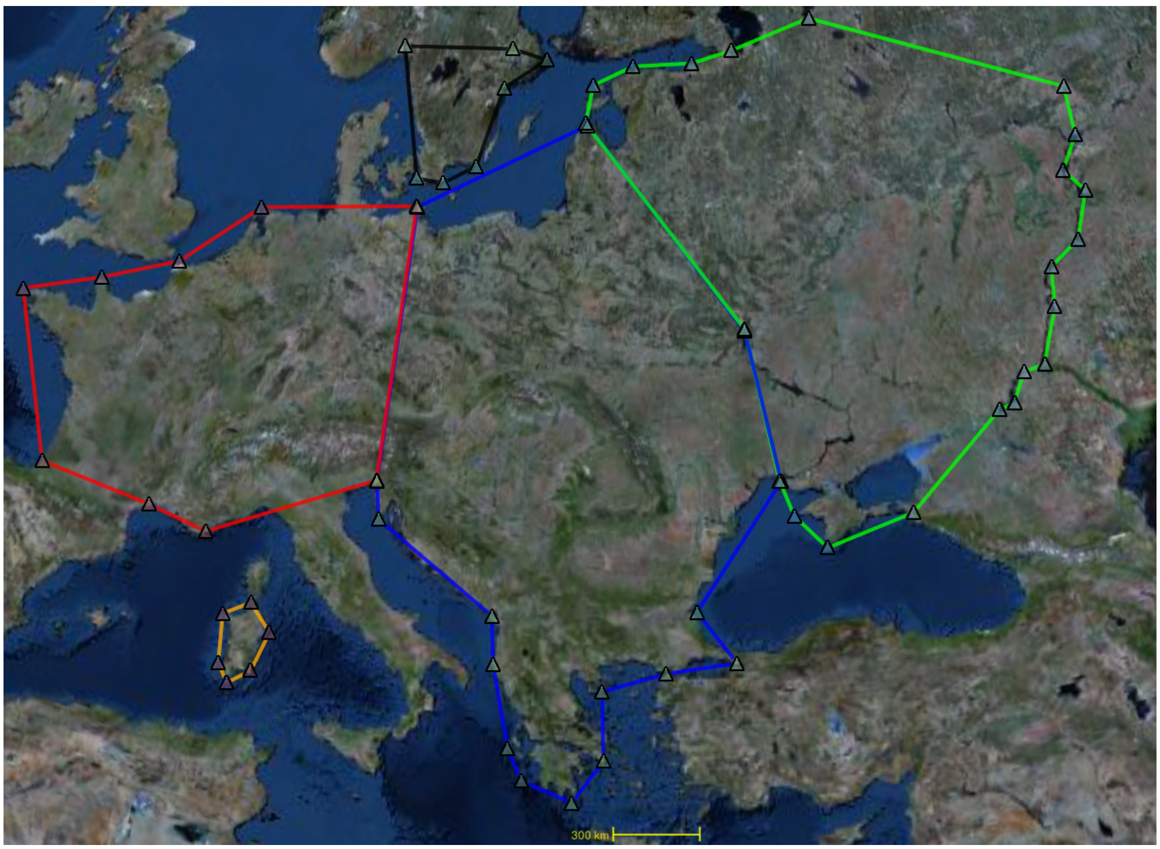


Figure A.1: Blueland Scenario

Blueland is a peaceful country that will only respond to a military aggression. It has to defend its 3300 miles of borderlines, including 520 miles of frontier it shares with Redland and 770 miles it shares with Greenland.

This scenario starts with a state of peace, but at increased level of readiness of all the military forces involved.

Redland was always an economic, political and military adversary of Blueland. It is by far the richest and most threatening of all the countries.

Orangeland is a close ally of Redland, possessing a vast number of military equipment from that country and usually following its politics without pondering.

Greenland has been in the past a valuable ally to Blueland, but its new government has demonstrated a political alignment with Redland as well.

Grayland is considered a neutral country, and it is the smallest threat to Blueland. However, it has taken part in some military exercises with Redland, Orangeland and Greenland. Intelligence sources state that Grayland has now a military alliance with them.

Parameters: - number of intruders - expected inter-arrival time - number of interceptors - processing time and resource allocation

Appendix B and Appendix C present some of the current missile and air threats to the United States homeland. A selection of these weapons was assigned to fictional scenario countries in order to determine the performance characteristics of the assets of the Blueland's Air Defense System.

Country	**Missile**	**Fighter**	**Bomber**
Redland	CSS-10 Mod 2	J-20	H-6
Orangeland	SCUD C	F-7	-
Greenland	Shahab 2	Mig-29	Su-24
Grayland	KN-SS-X-9	Su-30	-

Appendix B: Selected Air Defense Assets

The selection of air defense assets presented is based on current technologies which available for procurement by NATO members and allies. It does not cover all the types of aircraft and missiles, but this list provides a fair range of alternatives that can illustrate the effectiveness evaluation method developed in this research.

The information in this Appendix is notional, and it comes from technical data collected on the Wikipedia [24] and other sources available to the general audience:

F-35 Lightning II

Role	Stealth multirole fighter
National origin	United States
Manufacturer	Lockheed Martin Aeronautics
First flight	15 December 2006; (F-35A)
Introduction	F-35B: 31 July 2015 (USMC) F-35A: 2 August 2016 (USAF) F-35C: 28 February 2019 (USN)
Status	In service
Primary users	United States Air Force United States Marine Corps United States Navy Royal Air Force
Produced	2006–present
Number built	500 as of 3 March 2020
Program cost	US$428.4 billion (through 2044 in then-year dollars), $1,196.4B for operations & sustainment (through 2077 in then-year dollars) (2019 estimate)
Unit cost	F-35A: US$103.10
Developed from	Lockheed Martin X-35

General characteristics

- **Crew:** 1
- **Length:** 51.4 ft (15.7 m)
- **Wingspan:** 35 ft (11 m)
- **Height:** 14.4 ft (4.4 m)
- **Wing area:** 460 sq ft (43 m^2)
- **Aspect ratio:** 2.66
- **Empty weight:** 29,300 lb (13,290 kg)
- **Gross weight:** 49,540 lb (22,471 kg)
- **Max takeoff weight:** 70,000 lb (31,751 kg)
- **Fuel capacity:** 18,250 lb (8,278 kg) internal
- **Powerplant:** 1 × Pratt & Whitney F135-PW-100 afterburning turbofan, 28,000 lbf (120 kN) thrust dry, 43,000 lbf (190 kN) with afterburner

Performance

- **Maximum speed:** Mach 1.6 / 700 kt at sea level
- **Range:** 1,500 nm (1,700 mi, 2,800 km)
- **Combat range:** 669 nm (770 mi, 1,239 km) on internal fuel
  760 nm (870 mi; 1,410 km) interdiction mission on internal fuel, for internal air to air configuration
- **Service ceiling:** 50,000 ft (15,000 m)
- **g limits:** +9.0
- **Wing loading:** 107.7 lb/sq ft (526 kg/m^2) at gross weight
- **Thrust/weight:** 0.87 at gross weight (1.07 at loaded weight with 50% internal fuel)
- **Armament**
- **Guns:** 1 × 25 mm (0.984 in) GAU-22/A 4-barrel rotary cannon, 180 rounds
- **Hardpoints:** 4 × internal stations, 6 × external stations on wings with a capacity of 5,700 pounds (2,600 kg) internal, 15,000 pounds (6,800 kg) external, 18,000 pounds (8,200 kg) total weapons payload, with provisions to carry combinations of:

Missiles:

- Air-to-air missiles:
- AIM-120 AMRAAM
- AIM-9X Sidewinder
- AIM-132 ASRAAM
- MBDA Meteor (Block 4)
- Air-to-surface missiles:
- AGM-88G AARGM-ER (Block 4)
- AGM-158 JASSM
- SPEAR 3
- Joint Air-to-Ground Missile (JAGM)
- Joint Strike Missile (JSM, planned)
- SOM
- Anti-ship missiles:
- AGM-158C LRASM

Avionics

- AN/APG-81 AESA radar
- AAQ-40 E/O Targeting System (EOTS)
- AN/AAQ-37 Distributed Aperture System (DAS) missile warning system
- AN/ASQ-239 Barracuda electronic warfare system
- AN/ASQ-242 CNI suite, which includes
- Harris Corporation Multifunction Advanced Data Link (MADL) communication system
- Link 16 data link
- SINCGARS
- An IFF interrogator and transponder
- HAVE QUICK
- AM, VHF, UHF AM, and UHF FM
- GUARD survival radio
- A radar altimeter
- An instrument landing system
- A TACAN system
- Instrument carrier landing system
- A JPALS
- TADIL-J JVMF/VMF

Figure B.1: F-35 Lightning II Fact Sheet

F-16 Fighting Falcon

Role	Multirole fighter, air superiority fighter
National origin	United States
Manufacturer	General Dynamics Lockheed Martin
First flight	20 January 1974; 46 years ago(unplanned) 2 February 1974; 46 years ago (official)
Introduction	17 August 1978; 41 years ago
Status	In service
Primary users	United States Air Force 25 other users (see operators page)
Produced	1973–2017, 2019–present
Number built	4,604 (June 2018)
Unit cost	F-16A/B: US$14.6 million (1998) F-16C/D: US$18.8 million (1998)
Variants	General Dynamics F-16 VISTA
Developed into	Vought Model 1600 General Dynamics F-16XL Mitsubishi F-2

General characteristics

- **Length:** 49 ft 5 in (15.06 m)
- **Wingspan:** 32 ft 8 in (9.96 m)
- **Height:** 16 ft (4.9 m)
- **Wing area:** 300 sq ft (28 m^2)
- **Airfoil:** NACA 64A204
- **Empty weight:** 18,900 lb (8,573 kg)
- **Gross weight:** 26,500 lb (12,020 kg)
- **Max takeoff weight:** 42,300 lb (19,187 kg)
- **Fuel capacity:** 7,000 pounds (3,200 kg) internals
- **Powerplant:** 1 × General Electric F110-GE-129 afterburning turbofan (Block 50), 17,155 lbf (76.31 kN) thrust dry, 29,500 lbf (131 kN) with afterburner
- **Powerplant:** 1 × Pratt & Whitney F100-PW-229 afterburning turbofan (Block 52), 17,800 lbf (79 kN) thrust dry, 29,160 lbf (129.7 kN) with afterburner

Performance

- **Maximum speed:** Mach 2.05 at altitude, clean
  Mach 1.2, 800 kn (921 mph; 1,482 km/h) at sea level
- **Combat range:** 295 nm (339 mi, 546 km) on a hi-lo-hi mission with 4x 1,000 lb (454 kg) bombs
- **Ferry range:** 2,277 nm (2,620 mi, 4,217 km) with drop tanks
- **Service ceiling:** 59,055 ft (18,000 m) plus
- **g limits:** +9.0 (limited by flight control system)
- **Rate of climb:** 72,000 ft/min (370 m/s)
- **Wing loading:** 88.3 lb/sq ft (431 kg/m^2)
- **Thrust/weight:** 1.095 (1.24 with loaded weight & 50% internal fuel)

Armament

- **Guns:** 1 × 20 mm (0.787 in) M61A1 Vulcan 6-barrel rotary cannon, 511 rounds
- **Hardpoints:** 2 × wing-tip air-to-air missile launch rails, 6 × under-wing, and 3 × under-fuselage pylon (2 of 3 for sensors) stations with a capacity of up to 17,000 lb (7,700 kg) of stores,
- **Rockets:**
  - 4 × LAU-61/LAU-68 rocket pods (each with 19/7 × Hydra 70 mm/APKWS rockets, respectively)
  - 4 × LAU-5003 rocket pods (each with 19 × CRV7 70 mm rockets)
- **Missiles:**
  - Air-to-air missiles:
    - 2 × AIM-7 Sparrow
    - 6 × AIM-9 Sidewinder
    - 6 × AIM-120 AMRAAM
    - 6 × IRIS-T
    - 6 × Python-4
    - 6 × Python-5
- **Bombs:**
  - 8 × CBU-87 Combined Effects Munition
  - 8 × CBU-97 Sensor Fuzed Weapon
  - 4 × Mark 84 general-purpose bombs
  - 8 × Mark 83 GP bombs
  - 12 × Mark 82 GP bombs
  - 8 × GBU-39 Small Diameter Bomb (SDB)
  - B61 nuclear bomb
- **Others:**
  - SUU-42A/A Flares/Infrared decoys dispenser pod and chaff pod *or*
  - AN/ALQ-131 & AN/ALQ-184 ECM pods *or*
  - LANTIRN, Lockheed Martin Sniper XR & LITENING targeting pods *or*
  - Up to 3 × 300/330/370/600 US gallon *Sargent Fletcher* drop tanks for ferry flight/extended range/loitering time *or*
  - UTC Aerospace DB-110 long range EO/IR sensor pod on centerline

Avionics

- AN/APG-68 radar
- MIL-STD-1553 bus

Figure B.2: F-16 Fighting Falcon Fact Sheet

JAS 39E/F

Role	Fighter, attack, and reconnaissance aircraft
National origin	Sweden
Manufacturer	Saab Group
Design group	JAS, FMV
First flight	9 December 1988
Introduction	9 June 1996
Status	In service
Primary users	Swedish Air Force South African Air Force Czech Air Force Hungarian Air Force
Produced	1987–present
Number built	306
Program cost	US$ 13.54 billion (2006)
Unit cost	US$ 30–60 million for JAS 39C

General characteristics

- **Crew:** 1 **JAS 39E** / 2 **JAS 39F**
- **Length:** 15.2 m (49 ft 10 in) **JAS 39E**
  15.9 m (52 ft) **JAS 39F**
  - **Wingspan:** 8.6 m (28 ft 3 in)
  - **Height:** 4.5 m (14 ft 9 in)
  - **Wing area:** 30 m² (320 sq ft)
  - **Empty weight:** 8,000 kg (17,637 lb)
  - **Max takeoff weight:** 16,500 kg (36,376 lb)
  - **Internal fuel capacity:** 3,400 kg (7,500 lb)
  - **Powerplant:** 1 × General Electric F-414G afterburning turbofan engine, 98 kN (22,000 lbf) with afterburner

  Performance
  - **Maximum speed:** 2,460 km/h (1,530 mph, 1,330 kn) +
  - **Maximum speed:** Mach 2
  - **Combat range:** 1,500 km (930 mi, 810 nm) +
  - **Ferry range:** 4,000 km (2,500 mi, 2,200 nm) +
  - **Service ceiling:** 16,000 m (52,000 ft)
  - **g limits:** +9 -3
  - **Wing loading:** 283 kg/m² (58 lb/sq ft)
  - **Thrust/weight:** 1.04

- **Takeoff distance:** 500 m (1,640 ft)
- **Landing distance:** 600 m (1,969 ft)

Armament

- **Guns:** 1 × 27 mm Mauser BK-27 revolver cannon with 120 rounds (single-seat models only)
- **Hardpoints:** 10 (three hardpoints under the fuselage, two under and one on the tip of each wing; with one dedicated for FLIR / LD / Recon pod.) with a capacity of 5,300 kg (11,700 lb),with provisions to carry combinations of:
  - **Rockets:** 4 × rocket pods, 13.5 cm rockets
  - **Missiles:**
    - 6 × IRIS-T (Rb.98), AIM-9 Sidewinder (Rb.74) or A-Darter
    - 7 × MBDA Meteor, AIM-120 AMRAAM (Rb.99) or MBDA MICA
    - 4 × AGM-65 Maverick (Rb.75)
    - 2 × KEPD.350
    - 6 × Rbs.15F anti-ship missile
  - **Bombs:**
    - 7 × GBU-12 Paveway II laser-guided bomb
    - 2 × Bk.90 cluster bomb
    - 8 × Mark 82 bombs
    - 16 × GBU-39 SDB
    - 12 × Alternative small-diameter glide bomb

Avionics

- Selex ES-05 Raven AESA radar
- Skyward-G IRST system
- Air-to-air and air-to-surface tactical data link system

Figure B.3: JAS-39 E Gripen NG Fact Sheet

Eurofighter Typhoon

Role	Multirole fighter
National origin	Multi-national
Manufacturer	Eurofighter
First flight	27 March 1994
Introduction	4 August 2003
Status	In service
Primary users	Royal Air Force German Air Force Italian Air Force Spanish Air Force
Produced	1994–present
Number built	565
Unit cost	€90 million (system cost Tranche 3A) £125 million (including development + production costs)
Developed from	British Aerospace EAP

General characteristics

- **Crew:** 1 or 2
- **Length:** 15.96 m (52 ft 4 in)
- **Wingspan:** 10.95 m (35 ft 11 in)
- **Height:** 5.28 m (17 ft 4 in)
- **Wing area:** 51.2 m^2 (551 sq ft)
- **Empty weight:** 11,000 kg (24,251 lb)
- **Gross weight:** 16,000 kg (35,274 lb)
- **Max takeoff weight:** 23,500 kg (51,809 lb)
- **Fuel capacity:** 4,996 kg (11,010 lb) / 6.215 l (1.642 US gal; 1.367 imp gal) internal
- **Powerplant:** 2 × Eurojet EJ200 afterburning turbofan engines, 60 kN (13,000 lbf) thrust each dry, 90 kN (20,000 lbf) with afterburner

Performance

- **Maximum speed:** 2,495 km/h (1,550 mph, 1,347 kn) / Mach 2.0+ (2,495 km/h or 1,550 mph at 10,975m altitude)
- 1,530 km/h (950 mph; 830 kn) / Mach 1.25 at sea level (1,530 km/h or 950 mph)
  Mach 1.5: Supercruise
- **Range:** 2,900 km (1,800 mi, 1,600 nm)
- **Combat range:** 1,389 km (863 mi, 750 nm) Air defense with 10-min. loiter / Ground attack, hi-lo-hi (with 3 × external 1,000 l tanks)
  185 km (100 nm) Air defence with 3-hr combat air patrol (with 3 × external 1,000 l tanks)
  601 km (325 nm) Ground attack, lo-lo-lo (with 3 × external 1,000 l tanks)
- **Ferry range:** 3,790 km (2,350 mi, 2,050 nm) + with 3 × drop tanks
- **Service ceiling:** 19,812 m (65,000 ft)
- **g limits:** +9 -3
- **Rate of climb:** 318 m/s (62,600 ft/min)
- **Wing loading:** 312 kg/m^2 (64 lb/sq ft)
- **Thrust/weight:** 1.15 (interceptor configuration)
- **Brakes-off to Take-off acceleration:** <8 s
- **Brakes-off to supersonic acceleration:** <30 s
- **Brakes-off to Mach 1.6 at 11,000 m (36,000 ft):** <150 s

Armament

- **Guns:** 1 × 27 mm Mauser BK-27 revolver cannon with 150 rounds
- **Hardpoints:** Total of 13: 8 × under-wing; and 5 × under-fuselage pylon stations; holding in excess of 9,000 kg (19,800 lb) of payload
  Typical multi-role configuration for a Tranche 2-P1E would be 4 × AMRAAM, 2×ASRAAM/IRIS-T, 4 × EGBU-16/Paveway-IV, 2 × 1000-litre supersonic fuel tanks and a targeting pod.
- **Missiles:**
  - **Air-to-air missiles:**
    - AIM-120 AMRAAM (AIM-120C-5/7 planned for P2E)
    - AIM-132 ASRAAM
    - AIM-9 Sidewinder
    - IRIS-T
    - MBDA Meteor
- **Others:**
  - Up to 3 × drop tanks for ferry flight or extended range/loitering time
  - Conformal fuel tanks on Tranche 3 or later

Avionics

- Euroradar CAPTOR Radar
- Passive Infra-Red Airborne Tracking Equipment
- Praetorian DASS
- Damocles (targeting pod)
- LITENING III laser targeting pod
- Sniper Advanced Targeting Pod

Figure B.4: Eurofighter Typhoon Fact Sheet

Dassault Rafale

Role	Multirole fighter
National origin	France
Manufacturer	Dassault Aviation
First flight	Rafale A demo: 4 July 1986 Rafale C: 19 May 1991
Introduction	18 May 2001
Status	In service
Primary users	French Air Force French Navy Egyptian Air Force Qatar Air Force
Produced	1986–present
Number built	201 (as of 12/2019)
Program cost	€45.9 billion (US$62.7 billion)
Unit cost	Rafale B: €74M Rafale C: €68 Rafale M: €79M

General characteristics

- **Crew:** 1 or 2
- **Length:** 15.27 m (50 ft 1 in)
- **Wingspan:** 10.90 m (35 ft 9 in)
- **Height:** 5.34 m (17 ft 6 in)
- **Wing area:** 45.7 m^2 (492 sq ft)
- **Empty weight:** 10,300 kg (22,708 lb) (**B**)
  9,850 kilograms (21,720 lb) (**C**)
  10,600 kilograms (23,400 lb) (**M**)
  - **Gross weight:** 15,000 kg (33,069 lb)
  - **Max takeoff weight:** 24,500 kg (54,013 lb)
  - **Fuel capacity:** 4,700 kg (10,362 lb) internal for single-seater (**C**); 4,400 kg (9,700 lb) for two-seater (**B**)
  - **Maximum fuel:** (**C**): 16,550 l (4,370 US gal; 3,640 imp gal) (5,750 l (1,520 US gal; 1,260 imp gal) internal + 2,300 l (610 US gal; 510 imp gal) in 2x conformal tanks + 8,500 l (2,200 US gal; 1,900 imp gal) in 5 drop tanks)
  - **Powerplant:** 2 × Snecma M88-2 turbofans, 50.04 kN (11,250 lbf) thrust each dry, 75 kN (17,000 lbf) with afterburner

Performance

- **Maximum speed:** 1,912 km/h (1,188 mph, 1,032 kn) / Mach 1.8 at high altitude
  1,390 km/h (860 mph; 750 kn) / Mach 1.1 at low atitude
  - **Supercruise:** Mach 1.4
  - **Combat range:** 1,850 km (1,150 mi, 1,000 nm) on penetration mission with two CFTs (2,300 L), three tanks (5,700 L), two SCALP-EG and two MICA AAMs.
  - **Ferry range:** 3,700 km (2,300 mi, 2,000 nm) with 3 drop tanks
  - **Service ceiling:** 15,235 m (49,984 ft)
  - **g limits:** +9 –3.6 (+11 in emergencies)
  - **Rate of climb:** 304.8 m/s (60,000 ft/min)
  - **Wing loading:** 328 kg/m^2 (67 lb/sq ft)
  - **Thrust/weight:** 0.988 (100% fuel, 2 EM A2A missile, 2 IR A2A missile) version B

Armament

- **Guns:** 1× 30 mm (1.2 in) GIAT 30/M791 autocannon with 125 rounds
- **Hardpoints:** 14 for Air Force versions (Rafale B/C), 13 for Navy version (Rafale M) with a capacity of 9,500 kg (20,900 lb) external fuel and ordnance,with provisions to carry combinations of:
  - **Missiles:**
  - **Air-to-air:**
    - Magic II
    - MBDA MICA IR or EM
    - MBDA Meteor (planned)
  - **Air-to-surface:**
    - MBDA AM 39-Exocet anti-ship missile
  - **Nuclear Deterrence:**
    - ASMP-A nuclear missile
  - **Other:**
    - Thales Damocles targeting pod
    - Thales AREOS (Airborne Recce Observation System) reconnaissance pod
    - Thales TALIOS multi-function targeting pod in the future (F3R Standard)
    - Up to 5 drop tanks
    - Buddy-buddy refuelling pod

Avionics

- Thales RBE2-AA AESA radar
- Thales SPECTRA Electronic Warfare system.
- Thales/SAGEM-OSF Optronique Secteur Frontal infra-red search and track (IRST) system

Figure B.5: Dassault Rafale Fact Sheet

AIM-120 AMRAAM

Type	Medium-range, active radar homing air-to-air missile
Place of origin	United States

Service history

In service	September 1991–present
Wars	Operation Deny Flight Operation Allied Force Syrian civil war

Production history

Manufacturer	• Hughes: 1991–97 • Raytheon: 1997–present
Unit cost	US$1,786,000

Specifications

Mass	335 lb (152 kg)
Length	12 ft (3.7 m)
Diameter	7 in (180 mm)
Warhead	High explosive blast-fragmentation 40 pounds (18.1 kg)
Detonation mechanism	Active RADAR Target Detection Device (TDD) Quadrant Target Detection Device (QTDD) in AIM-120C-6 – lots 13+.
Engine	Solid-fuel rocket motor
Wingspan	20.7 in (530 mm) AIM-120A/B
Operational range	• AIM-120A/B: (30–40 nm • AIM-120C-5: 57 nm • AIM-120D >86 nm
Maximum speed	Mach 4 (4,900 km/h; 3,045 mph)
P_K	63.15%
Guidance system	inertial guidance, terminal active radar homing

I-Derby ER

Type	Beyond visual range air-to-air missile

Service history

In service	2015–present

Production history

Manufacturer	Rafael Defense Systems
Unit cost	$2,220,000

Specifications

Mass	118 kg
Length	3.62 m
Diameter	0.16 m
Warhead	23 Kg High explosive blast-fragmentation
Detonation mechanism	Proximity/impact fuse
Engine	Throttleable ducted rocket (ramjet)
Operational range	100 km (55 nm, 25nm No Escape Zone)
Maximum speed	Mach 4
Guidance system	Inertial guidance, mid-course update via datalink, terminal active radar homing
Launch platform	Eurofighter Typhoon Dassault Rafale Saab JAS 39 Gripen F-35 (Pending)

Figure B.6: AIM-120 / i-Derby ER Fact Sheets

Meteor

Type	Beyond visual range air-to-air missile
Service history	
In service	2016–present
Production history	
Manufacturer	MBDA
Unit cost	€2,000,000 (as of 2019)
Specifications	
Mass	190 kg (419 lb)
Length	3.7 m (12 ft 2 in)
Diameter	0.178 m (7.0 in)
Warhead	High explosive blast-fragmentation
Detonation mechanism	Proximity/impact fuse
Engine	Throttleable ducted rocket (ramjet)
Operational range	150 km (80 nm, 60 km+ No Escape Zone)
Maximum speed	over Mach 4
Guidance system	Inertial guidance, mid-course update via datalink, terminal active radar homing
Launch platform	Eurofighter Typhoon Dassault Rafale Saab JAS 39 Gripen F-35 (Pending)

MICA

Type	Short/medium range air-to-air and surface-to-air missile
Place of origin	France
Service history	
In service	1996
Unit cost	$ 2,700,000
Specifications	
Mass	118Kg
Length	3.1 m
Diameter	160 mm
Warhead	12 kg warhead
Detonation mechanism	Proximity or direct impact
Engine	Solid-propellant rocket motor
Operational range	• Air-launched: 500 m–80 km Vertical-launched: 1–20 km
Flight altitude	• Vertical-launched: 0–9 km
Maximum speed	• Air-launched: Mach 4 • Vertical-launched: Mach 3
Guidance system	• MICA-EM: Active radar homing • MICA-IR: Infrared homing
Launch platform	• Surface ship • Ground batteries • Dassault Rafale • Mirage 2000 • Mirage F1 • F-16E Block 60

Figure B.7: Meteor / MICA Fact Sheets

Patriot missile PAC-3

Type	Surface-to-air missile
Place of origin	United States
Production history	
Designer	Raytheon
Unit cost	US$ 2 million
No. built	over 8,600 (all variations)
Variants	Standard, ASOJ/SOJC, PAC-2, PAC-2 GEM, GEM/C, GEM/T (or GEM+) and PAC-3
Specifications	
Mass	700 kg (1,500 lb)
Length	5,800 mm (19 ft 0 in)
Diameter	410 mm (16 in)
Warhead	M248 Composition B HE blast/fragmentation with two layers of pre-formed fragments and Octol 75/25 HE blast/fragmentation
Warhead weight	200 lb (90 kg)
Pk	86%
Detonation mechanism	Proximity fuze
Wingspan	920 mm (3 ft 0 in)
Propellant	Solid-fuel rocket
Operational range	86 nm
Flight altitude	79,500 feet (24,200 m)
Maximum speed	PAC-3: Mach 4.1
Guidance system	PAC-1: Radio command with Track Via Missile semi-active homing, PAC-3: Ka Band AESA seeker
Launch platform	Mobile trainable four-round semi-trailer

Terminal High Altitude Area Defense (THAAD)

Type	Mobile anti-ballistic missile system
Place of origin	U.S
Service history	
In service	2008–present
Used by	United States Army
Production history	
Designed	1987
Manufacturer	Lockheed Martin
Produced	2008–present
No. built	Numerous
Specifications	
Mass	900 kg
Length	6.17 m
Diameter	34 cm
Engine	Single-stage rocket
Propellant	Pratt & Whitney solid-fueled rocket
Pk	100%
Operational range	105 nm
Flight ceiling	150 km
Flight altitude	93 miles (150 km)
Maximum speed	Mach 8.24 (2.8 km/s)
Guidance system	Indium-antimonide imaging infra-red seeker head
Accuracy	0m (Hit to kill)
Transport	TEL

Figure B.8: Patriot PAC-3 / THAAD Fact Sheets

RIM-67 Standard ER
Standard SM-2

Type	Extended range surface-to-air missile with anti-ship capability
Place of origin	United States

Service history

In service	1981-present (RIM-67B), 1999-present (RIM-156A)

Production history

Unit cost	$409,000

Specifications

Mass	2,980 lb (1,350 kg)
Length	26.2 ft (8.0 m)
Warhead	Proximity fuse, high explosive 137 lb (62 kg) continuous rod, later blast fragmentation
Engine	Two-stage, solid-fuel rocket; sustainer motor and booster motor
Wingspan	5 ft 2 in (1.57 m)
Pk	80%
Operational range	100 nm (185 km)
Flight ceiling	80,200 ft (24,400 m)
Maximum speed	Mach 3.5
Guidance system	Inertial/SARH

RIM-174 *ERAM*
Standard SM-6

Type	Surface-to-air missile Anti-ship missile
Place of origin	United States

Service history

In service	2013–present
Used by	United States Navy Royal Australian Navy Japan Maritime Self Defense Force Republic of Korea Navy

Production history

Manufacturer	Raytheon
Unit cost	US$4.87m
Produced	2009–present
No. built	200 (1,800 planned)

Specifications

Mass	3,300 lb (1,500 kg)
Length	21.5 ft (6.6 m)
Diameter	13.5 in (0.34 m) for Block IA
Warhead	140 lb (64 kg) blast fragmentation
Detonation mechanism	radar and contact fuze
Engine	Two Stage: Solid rocket booster, solid rocket booster/sustainer
Wingspan	61.8 in (1.57 m)
Pk	83%
Operational range	~130 nm (150 mi; 240 km) (Block IA)
Flight ceiling	>110,000 ft (34,000 m)
Maximum speed	Mach 3.5 (2,664.2 mph; 4,287.7 km/h; 1.2 km/s)
Guidance system	Inertial guidance, active radar homing and semi active radar homing

Figure B.9: SM-2/SM-6 Fact Sheets

Appendix C: Current Missile Threats to Occidental Air Defense Systems

This Appendix provides information regarding current missile threats to the U.S. and an overview on the American (and allies) missile defense assets [5]:

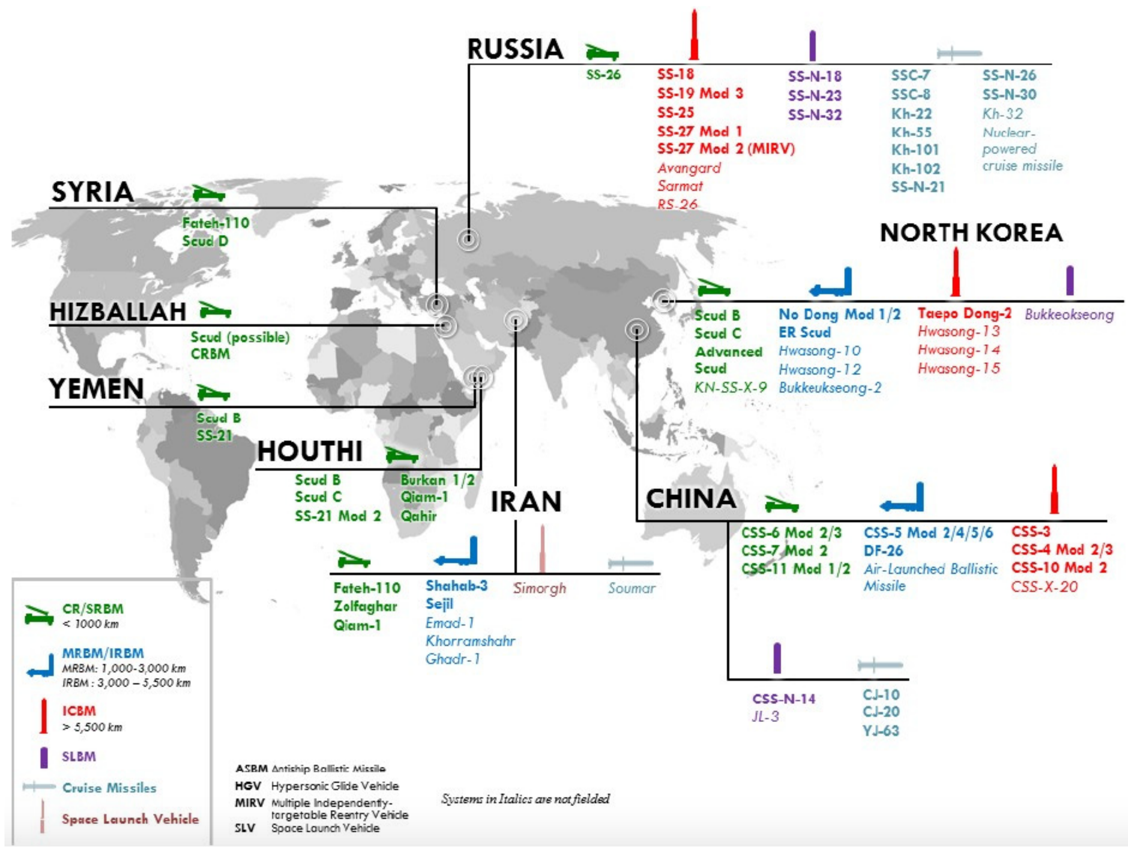


Figure C.1: Current and Future Potential Adversary Offensive Missile Capabilities

Figure C.2: Intercontinental Ballistic Missiles

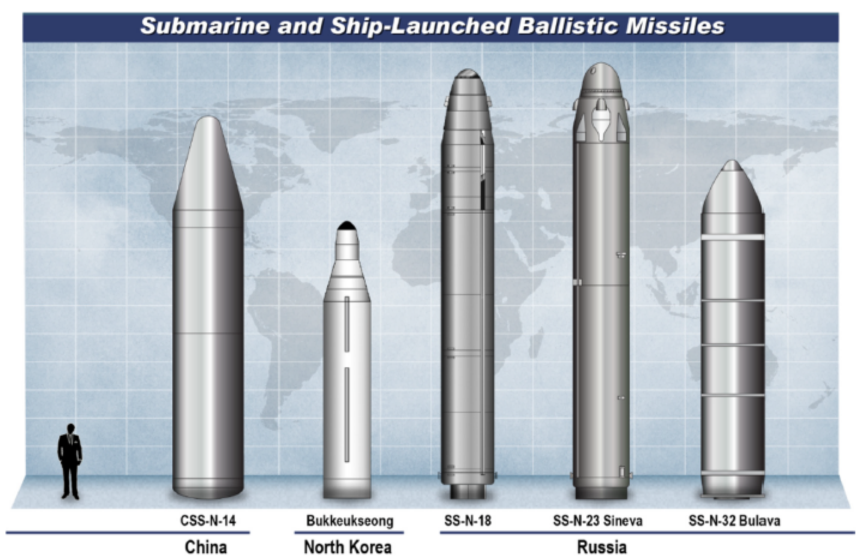


Figure C.3: Submarine-Launched Ballistic Missiles

User	Missile System	Range (nm)
	KN-SS-X-9	200
	SCUD B	300
	SCUD C	500
North Korea	ER SCUD	1000
	No Dong	1200
	No Dong	1200
	Bukkeukseong-2	1200
	CSS 8	150
	Fateh-110	300
	Shahab 1	300
	Shahab 2	500
Iran	Zolfaghar	750
	Qiam	950
	Shahab 3	2000
	Emad-1	2000
	Seiii	2000
	CSS-6, CSS-7, CSS-11	850
	CJ-10 LACM	1500
	JH-7, H-6 with ASCM	1870
	H-6 with LACM	3300
	DF-26 IRBM	4000
China	CSS 5 Mod 6	1,750
	DF-26	4,000
	CSS-3	5500
	CSS-10 Mod 1	7200
	CSS-10 Mod 2	11200
	CSS-4 Mod 3	13000

Figure C.4: Cruise and Intercontinental Ballistic Missiles Range (estimated)

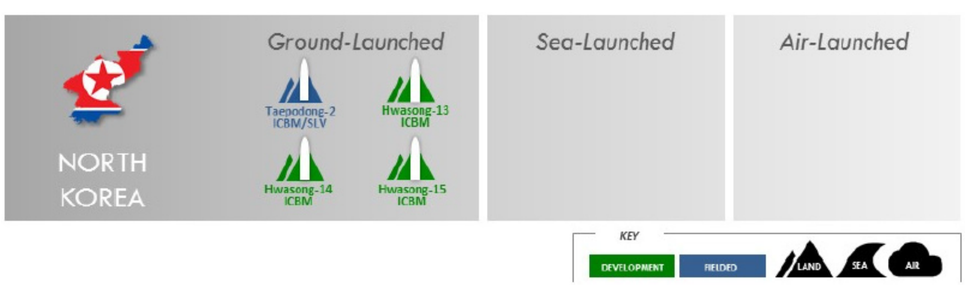


Figure C.5: North Korean Strategic Missile Systems

Figure C.6: Iranian Strategic Missile Systems

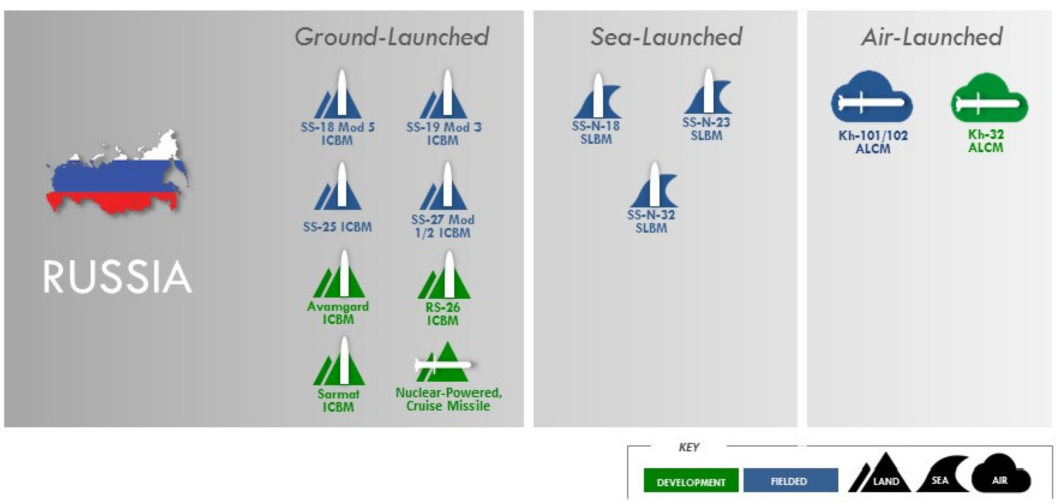


Figure C.7: Russian Strategic Missile Systems

Figure C.8: Chinese Strategic Missile Systems

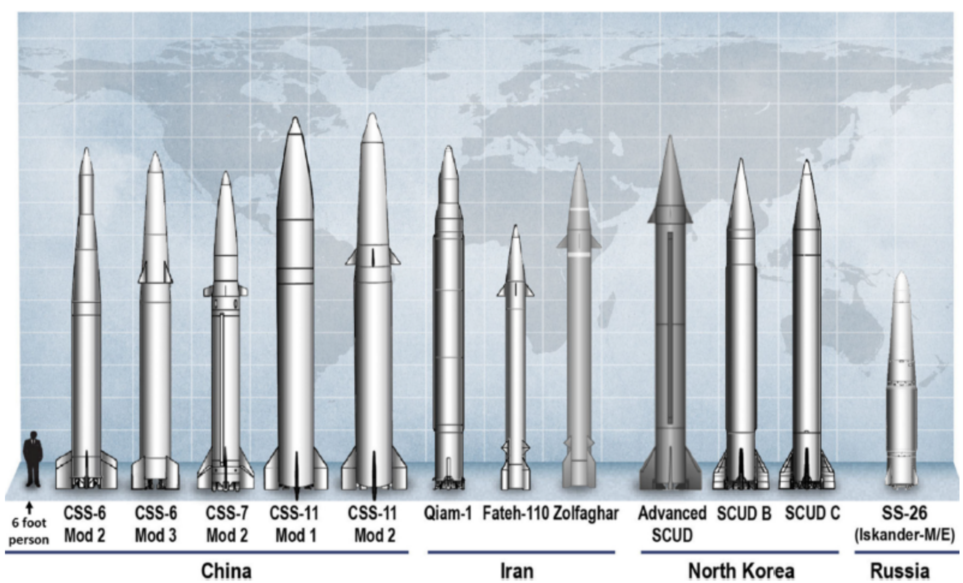


Figure C.9: Short-Range Ballistic Missiles

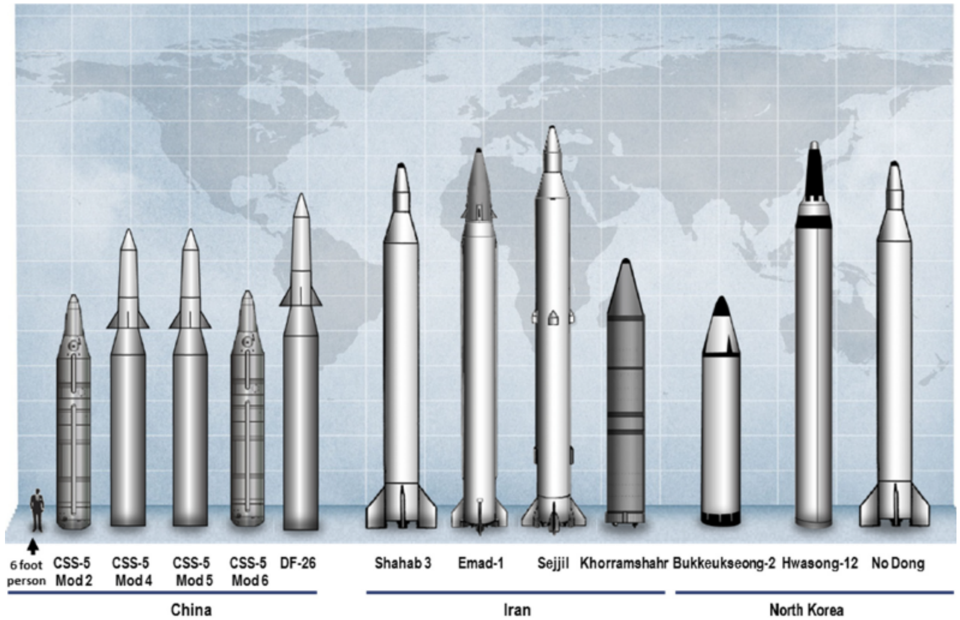


Figure C.10: Medium and Intermediate-Range Ballistic Missiles

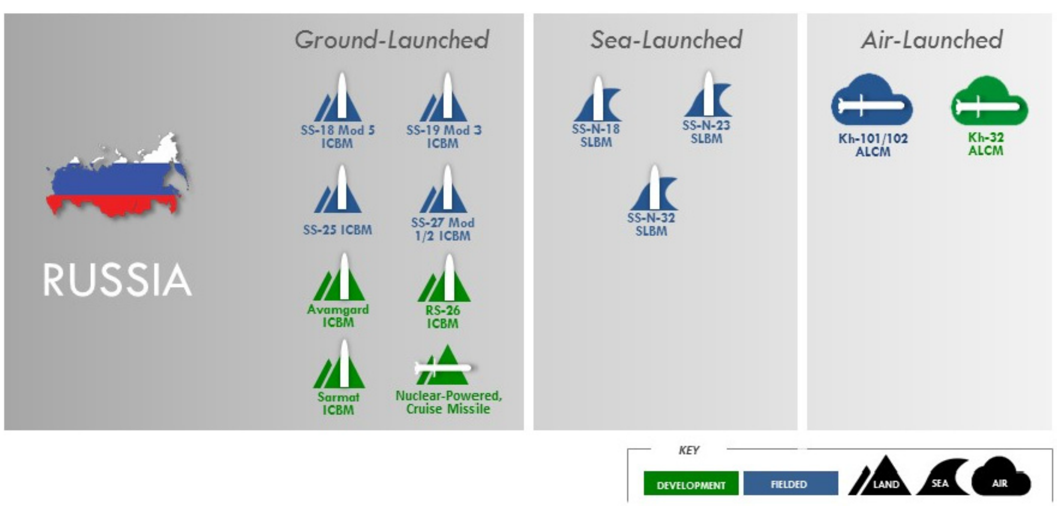


Figure C.11: Russian Strategic Missile Systems

Figure C.12: North Korean Regional Missile Systems

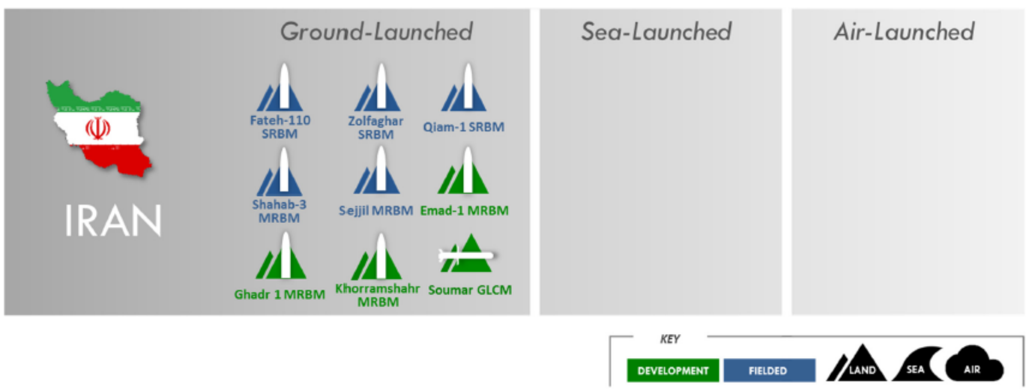


Figure C.13: Selected Iranian Regional Missile Systems

Figure C.14: Selected Russian Regional Missile Systems

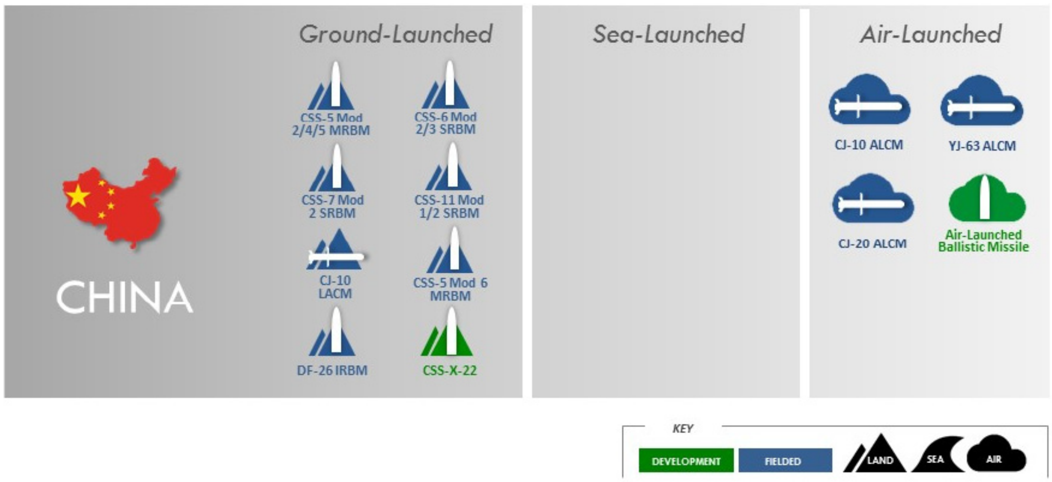


Figure C.15: Selected Chinese Regional Missile Systems

Figure C.16: Russian Missile Defense Systems

Figure C.17: Chinese Missile Defense Systems

Figure C.18: North Korean Missile Defense System

Figure C.19: Iranian Missile Defense System

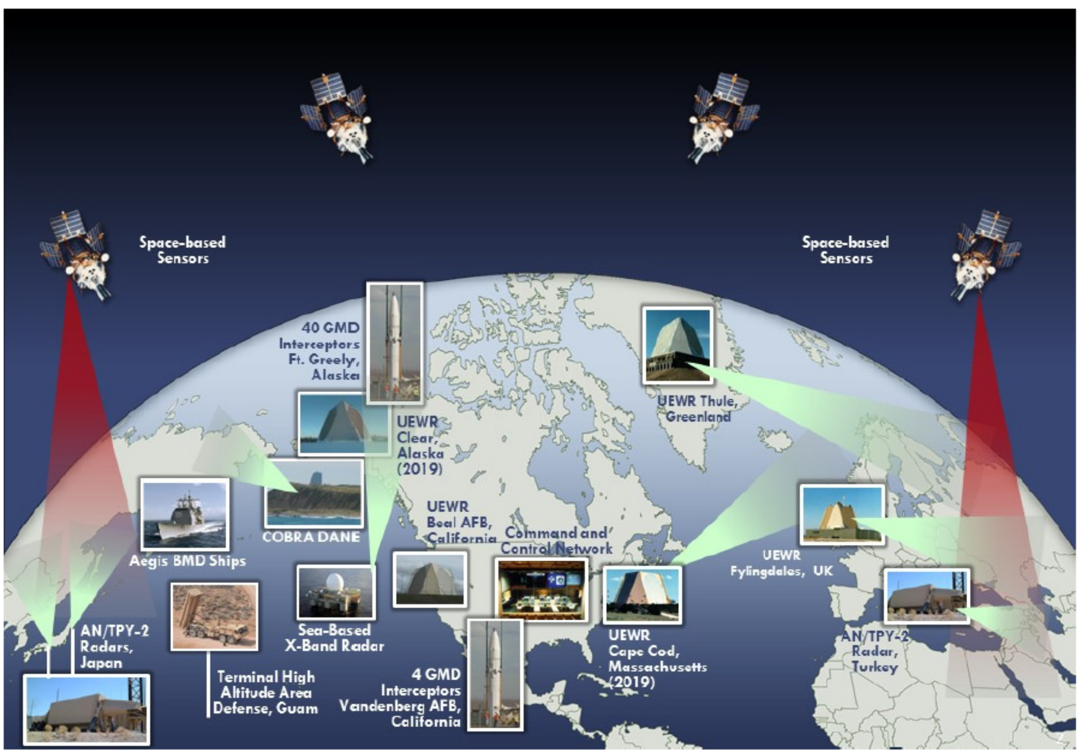


Figure C.20: Current U.S. Missile Defense Architecture

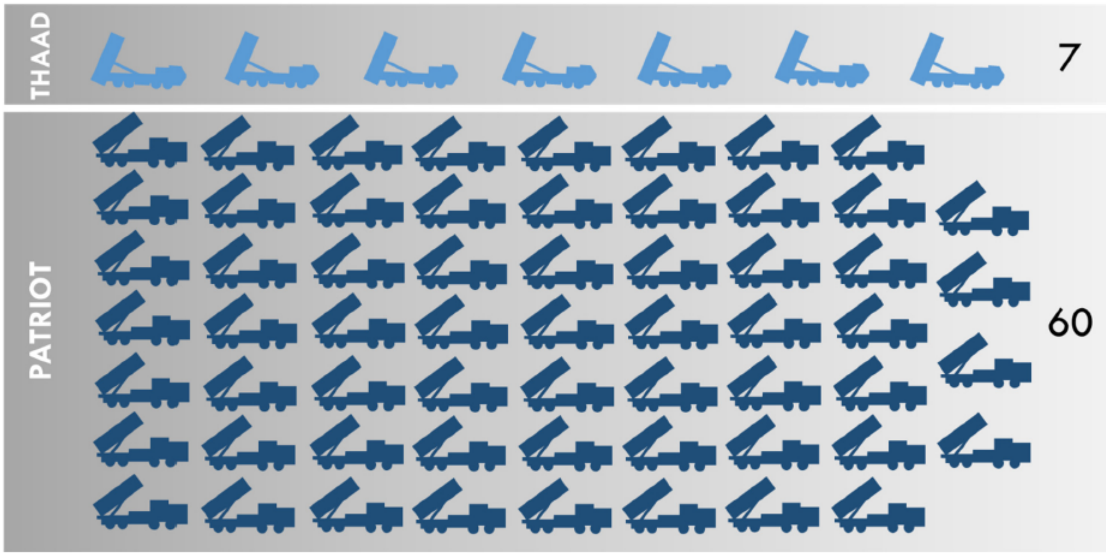


Figure C.21: Current U.S. THAAD and Patriot Batteries

Figure C.22: Select U.S. Missile Defense Assets in Europe

Figure C.23: Select U.S. Missile Defense Assets in East Asia

Figure C.24: Selected U.S. Missile Defense Assets in the Middle East

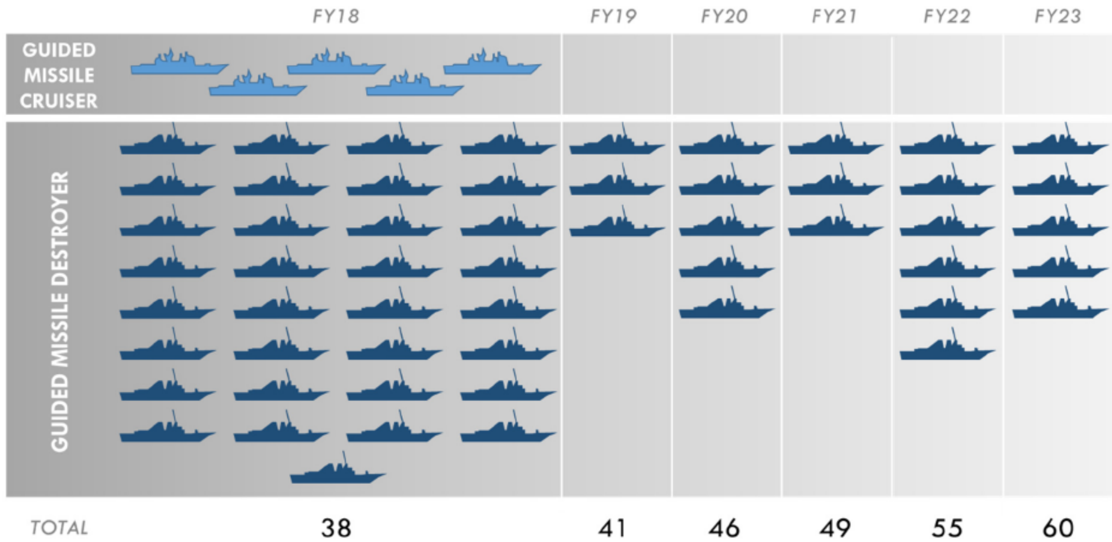


Figure C.25: Ballistic Missile Defense Capable Aegis Ship Count

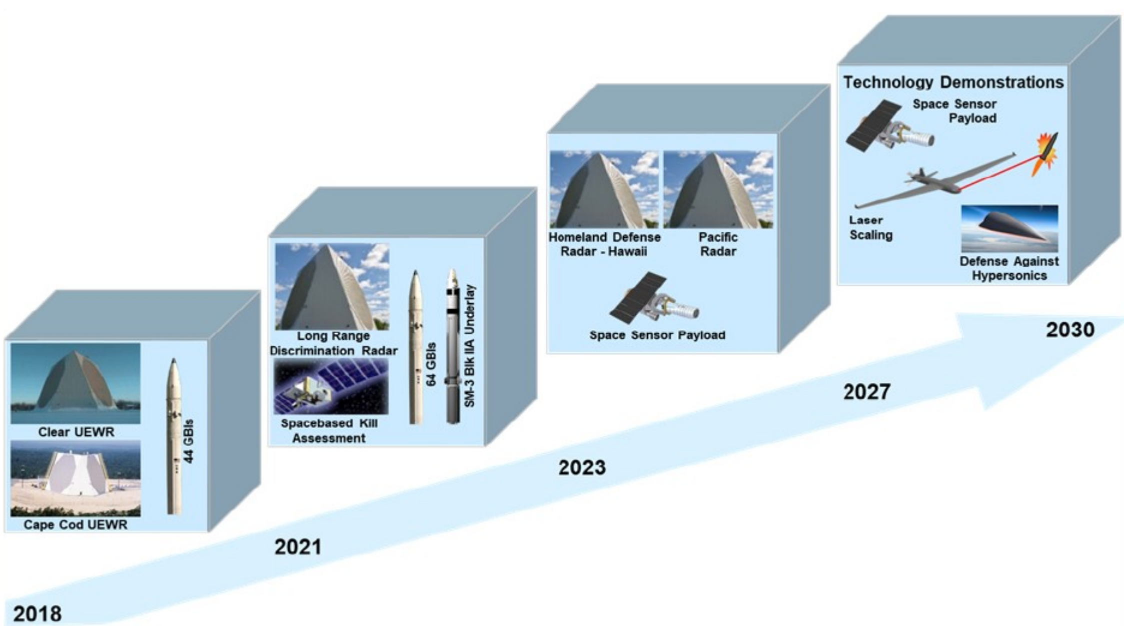


Figure C.26: U.S. Missile Defense Growth

Figure C.27: Foreign Missile Defense Assets in East Asia

Figure C.28: Select Foreign Missile Defense Assets in Europe

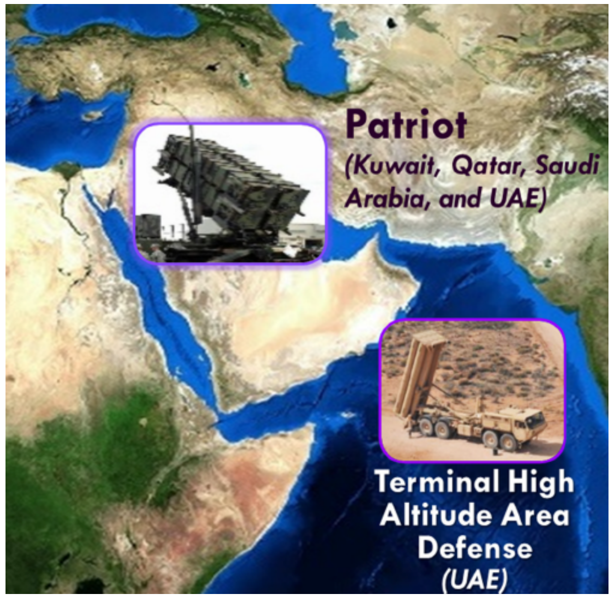


Figure C.29: Select Missile Defense Assets in the Middle East

Figure C.30: Israeli Active Missile Defense Assets

Appendix D: Current Air Threats to Occidental Air Defense Systems

This Appendix provides information regarding the worldwide fleet of air forces (Flight International publication about World Air Forces of 2020 [25]) and technical data about current air threats to occidental air defense systems [24]:

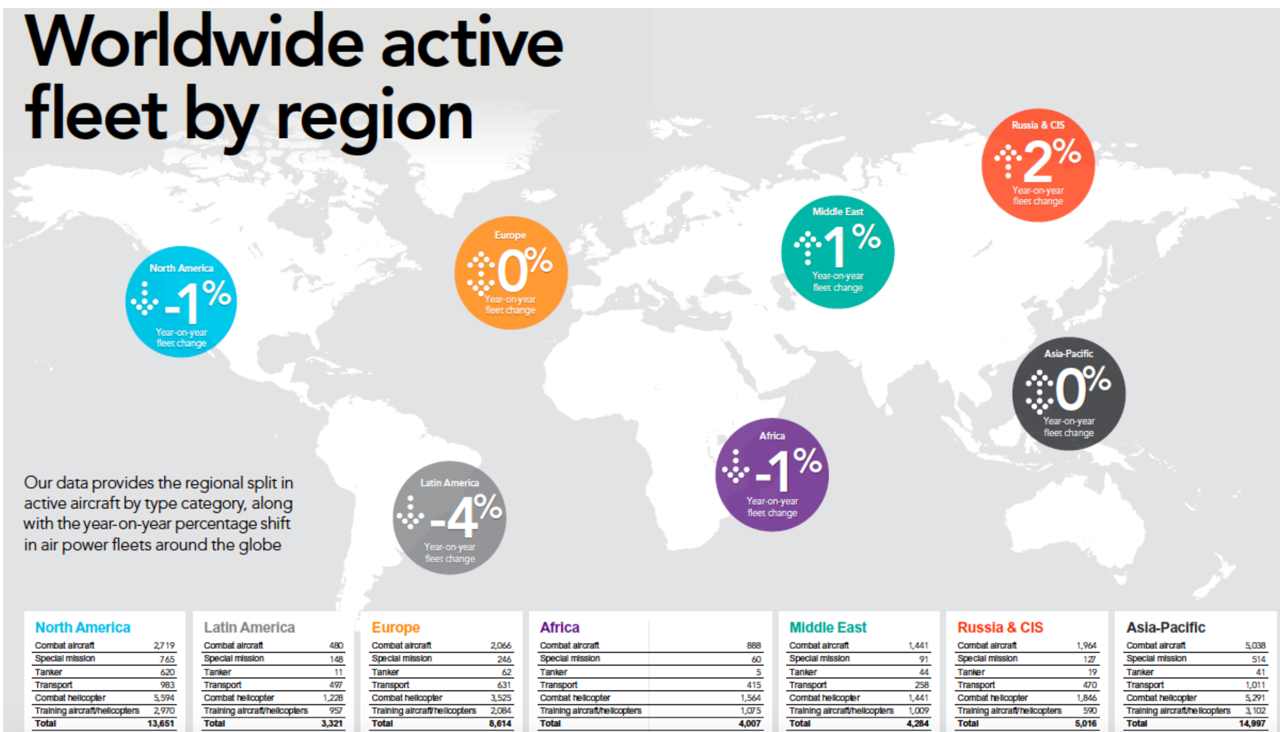


Figure D.1: Worldwide active fleet by region

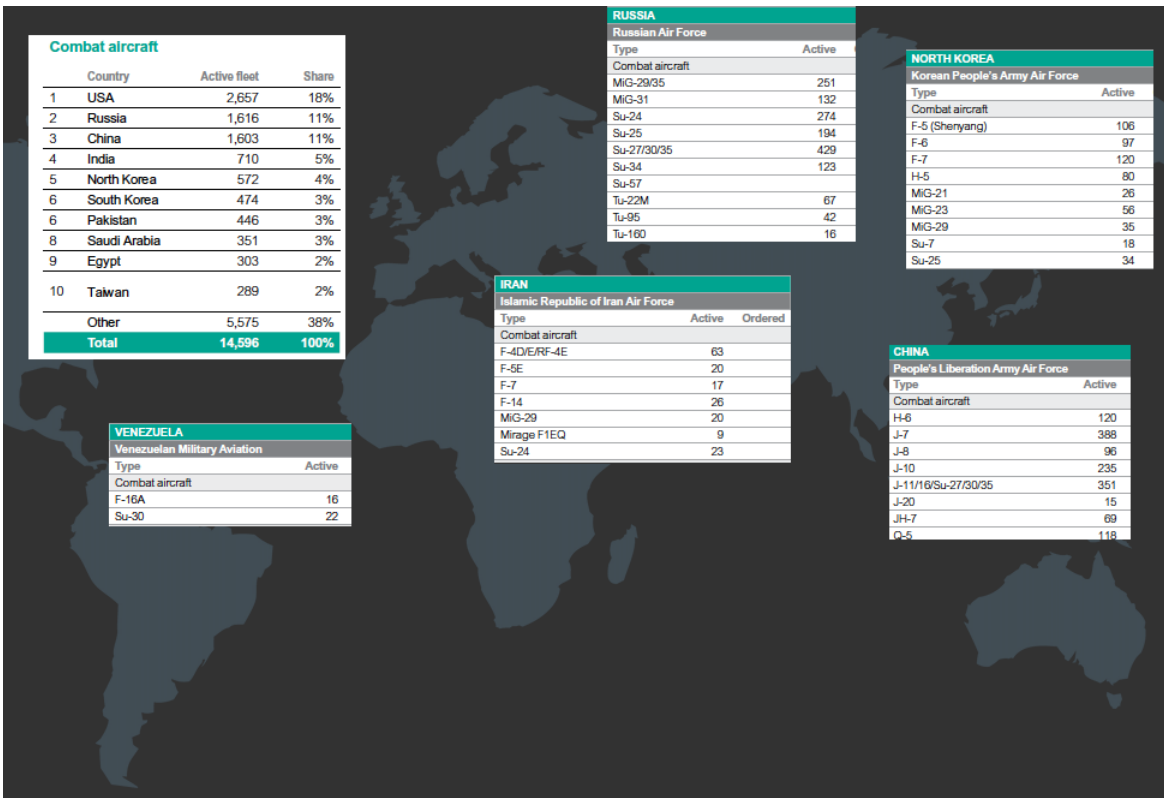


Figure D.2: Select Air Forces' Combat Aircraft

J-20 Mighty Dragon

Role	Stealth air superiority fighter
National origin	China
Manufacturer	Chengdu Aerospace Corporation
First flight	11 January 2011;
Introduction	10 March 2017
Status	In service
Primary user	People's Liberation Army Air Force
Produced	2009–present
Number built	8 prototypes and 20+ initial production fighters (currently the first batch of 28 J-20s in active service)
Program cost	US$4.4 billion
Unit cost	• US$100–$120 million (LRIPestimate as of 2011) • US$30–$50 million (Flyaway cost estimate as of 2016)

General characteristics

- **Crew:** one (pilot)
- **Length:** 20.4 m (66.8 ft)
- **Wingspan:** 13.5 m (44.2 ft)
- **Wing area:** 78 m^2 (840 sq ft)
- **Empty weight:** 19,391 kg (42,750 lb)
- **Gross weight:** 32,092 kg (70,750 lb)
- **Max takeoff weight:** 37,013 kg (81,600 lb)
- **Fuel capacity:** 25,000 lb
- **Powerplant:** 2 × WS-10B or AL-31FM2 afterburning turbofan, 140 or 145 kN (31,000 or 33,000 lbf) with afterburner
- **Powerplant:** 2 × Shenyang WS-15 afterburning turbofan, 180 kN (40,000 lbf) with afterburner

Performance

- **Maximum speed:** Mach 2+
- **Range:** 6,000 km (3,700 mi, 3,200 nm)
- **Combat range:** 2,000 km (1,200 mi, 1,100 nm)
- **Service ceiling:** 20,000 m (66,000 ft)
- **g limits:** +9/-3
- **Wing loading:** 340 kg/m^2 (69 lb/sq ft)
- **Thrust/weight:** 0.92 (1.12 with loaded weight and 50% fuel) with AL-31FM2 (estimated)

Armament

- **Internal weapon bays**
  - PL-10 short range AAM
  - PL-12 Medium Range AAM
  - PL-15 BVR long range AAM
  - PL-21 Long Range AAM
  - LS-6 Precision-guided bomb
- **External hardpoints**
  - 4× under-wing pylon capable of carrying drop tanks.

Avionics

- Type 1475 (KLJ-5) active electronically scanned array
- EOTS-86 electro-optical targeting system (EOTS)
- EORD-31 infrared search and track
- Distributed aperture system

Figure D.3: J-20 Mighty Dragon Fact Sheet

Xian H-6

Role	Strategic bomber
National origin	China
Manufacturer	Xi'an Aircraft Industrial Corporation
First flight	1959
Introduction	1969
Retired	Iraq (1991) Egypt (2000)
Status	Active service with the PLAAF
Primary users	People's Liberation Army Air Force People's Liberation Army Navy Egyptian Air Force (historical) Iraqi Air Force (historical)
Number built	162–180
Developed from	Tupolev Tu-16
Variants	Xian H-6I

General characteristics

- **Crew:** 4
- **Length:** 34.8 m (114 ft 2 in)
- **Wingspan:** 33 m (108 ft 3 in)
- **Height:** 10.36 m (34 ft 0 in)
- **Wing area:** 165 m² (1,780 sq ft)
- **Airfoil: root:** PR-1-10S-9 (15.7%) ; **tip:** PR-1-10S-9 (12%)
- **Empty weight:** 37,200 kg (82,012 lb)
- **Gross weight:** 76,000 kg (167,551 lb)
- **Max takeoff weight:** 79,000 kg (174,165 lb)
- **Powerplant:** 2 × Xian WP-8 turbojet engines, 93.2 kN (21,000 lbf) thrust each

Performance

- **Maximum speed:** 1,050 km/h (650 mph, 570 kn)
- **Cruise speed:** 768 km/h (477 mph, 415 kn) / 0.75M
- **Range:** 6,000 km (3,700 mi, 3,200 nm)
- **Combat range:** 1,800 km (1,100 mi, 970 nm)
- **Service ceiling:** 12,800 m (42,000 ft)
- **Wing loading:** 460 kg/m² (94 lb/sq ft)
- **Thrust/weight:** 0.24

Armament

- **Guns:**
  - 2× 23 mm (0.906 in) Nudelman-Rikhter NR-23 cannons in remote dorsal turret
  - 2× NR-23 cannons in remote ventral turret
  - 2× NR-23 cannons in manned tail turret
  - 1× NR-23 cannons in nose (occasional addition)
- **Missiles:**
  - 6 or 7 KD-88 missile (anti-ship or air-to-surface)
  - YJ-100 (CJ-10) anti-ship missile
  - C-601 anti-ship missile
  - YJ-62 (C-602) anti-ship missile
  - C-301 anti-ship missile
  - C-101 anti-ship missile
  - CM-802A
  - YJ-12 anti-ship missile
  - DF-21D (H-6N)
- **Bombs:** 9,000 kg (20,000 lb) of free-fall weapons
  - Guided bombs
    - GB6
    - CS/BBC5
    - GB2A
    - GB5

Figure D.4: H-6 Xian Fact Sheet

J-7 / F-7 Airguard

Role	Fighter aircraft
Manufacturer	Chengdu Aircraft Corporation/Guizhou Aircraft Industry Corporation
First flight	17 January 1966
Status	Operational
Primary users	People's Liberation Army Air Force Pakistan Air Force Bangladesh Air Force Korean People's Air Force
Produced	1965–2013
Number built	2,400+
Developed from	Mikoyan-Gurevich MiG-21
Developed into	Guizhou JL-9

General characteristics

- **Crew:** 1
- **Length:** 14.884 m (48 ft 10 in) (Overall)
- **Wingspan:** 8.32 m (27 ft 4 in)
- **Height:** 4.11 m (13 ft 6 in)
- **Wing area:** 24.88 m^2 (267.8 sq ft)
- **Aspect ratio:** 2.8
- **Airfoil: root:** TsAGI S-12 (4.2%) ; **tip:** TsAGI S-12 (5%)
- **Empty weight:** 5,292 kg (11,667 lb)
- **Gross weight:** 7,540 kg (16,623 lb) with 2x PL-2 or PL-7 air-to-air missiles
- **Max takeoff weight:** 9,100 kg (20,062 lb)
- **Powerplant:** 1 × Liyang Wopen-13F afterburning turbojet, 44.1 kN (9,900 lbf) thrust dry, 64.7 kN (14,500 lbf) with afterburner

Performance

- **Maximum speed:** 2,200 km/h (1,400 mph, 1,200 kn) IAS
- **Maximum speed:** Mach 2
- **Stall speed:** 210 km/h (130 mph, 110 kn) IAS
- **Combat range:** 850 km (530 mi, 460 nm)
- **Ferry range:** 2,200 km (1,400 mi, 1,200 nm)
- **Service ceiling:** 17,500 m (57,400 ft)
- **Rate of climb:** 195 m/s (38,400 ft/min)

Armament

- **Guns:** 2× 30 mm Type 30-1 cannon, 60 rounds per gun
- **Hardpoints:** 5 in total – 4× under-wing, 1× centreline under-fuselage with a capacity of 2,000 kg maximum (up to 500 kg each),
- **Rockets:** 55 mm rocket pod (12 rounds), 90 mm rocket pod (7 rounds)
- **Missiles:** ** **Air-to-air missiles:** PL-2, PL-5, PL-7, PL-8, PL-9, K-13, Magic R.550, AIM-9
- **Bombs:** 50 kg to 500 kg unguided bombs

Avionics

- FIAR Grifo-7 mk.II radar

Figure D.5: F-7 Airguard Fact Sheet

MiG-29

Role	Air superiority fighter, multirole fighter
National origin	Soviet Union
Manufacturer	Mikoyan
First flight	6 October 1977
Introduction	July 1982
Status	In service
Primary users	Russian Aerospace Forces Indian Air Force Uzbekistan Air and Air Defence Forces Polish Air Force
Produced	1981–present
Number built	1,600+
Unit cost	US$11 million (MiG-29B, 1999) US$22 million (MiG-29S, 2013)
Variants	Mikoyan MiG-29M Mikoyan MiG-29K Mikoyan MiG-35

General characteristics

- **Crew:** 1
- **Length:** 17.32 m (56 ft 10 in)
- **Wingspan:** 11.36 m (37 ft 3 in)
- **Height:** 4.73 m (15 ft 6 in)
- **Wing area:** 38 m^2 (410 sq ft)
- **Empty weight:** 11,000 kg (24,251 lb)
- **Gross weight:** 14,900 kg (32,849 lb)
- **Max takeoff weight:** 18,000 kg (39,683 lb)
- **Fuel capacity:** 3,500 kg (7,716 lb) internal
- **Powerplant:** 2 × Klimov RD-33 afterburning turbofan engines, 81.59 kN (18,340 lbf) with afterburner

Performance

- **Maximum speed:** 2,400 km/h (1,500 mph, 1,300 kn) at high altitude
- **Maximum speed:** Mach 2.25
- **Range:** 1,430 km (890 mi, 770 nm) with maximum internal fuel
- **Ferry range:** 2,100 km (1,300 mi, 1,100 nm) with 1x drop tank
- **Service ceiling:** 18,000 m (59,000 ft)
- **g limits:** +9
- **Rate of climb:** 330 m/s (65,000 ft/min)
- **Wing loading:** 403 kg/m^2 (83 lb/sq ft)
- **Thrust/weight:** 1.09

Armament

- **Guns:** 1 × 30 mm Gryazev-Shipunov GSh-30-1 autocannon with 150 rounds
- **Hardpoints:** 7 × hardpoints (6 × underwing, 1 × fuselage) with a capacity of up to 4,000 kg (8,800 lb) of stores,with provisions to carry combinations of:
  - **Rockets:**
    - S-5
    - S-8
    - S-24
  - **Missiles:**
    - 2 × R-27R/ER/T/ET/P air-to-air missiles
    - 4 × R-60 AAMs
    - 4 × R-73 AAMs
  - **Bombs:** 6 × 665 kg (1,466 lb) bombs

Avionics

- OEPS-29 IRST
- Phazotron Zhuk-ME radar
- SPO-15 'Beryoza' RWR

Related development

- MiG-29K
- MiG-29M
- MiG-35

Figure D.6: MiG-29 Fact Sheet

Su-24

Role	All-weather attack aircraft/interdictor
National origin	Soviet Union / Russia
Manufacturer	Sukhoi
Designer	Ye. S. Felsner (from 1985) L.A. Logvinov
First flight	T-6: 2 July 1967
Introduction	1974
Status	In service
Primary users	Russian Air Force Ukrainian Air Force Islamic Republic of Iran Air Force Syrian Air Force
Produced	1967–1993
Number built	Approximately 1,400
Unit cost	US$24–25 million in 1997

General characteristics

- **Crew:** 2 (pilot and weapons systems operator)
- **Length:** 22.53 m (73 ft 11 in)
- **Wingspan:** 17.64 m (57 ft 10 in) wings spread10.37 m (34 ft) wings swept
- **Height:** 6.19 m (20 ft 4 in)
- **Wing area:** 55.2 m^2 (594 sq ft)
- **Airfoil:** TsAGI SR14S-5.376 ; TsAGI SR16M-10
- **Empty weight:** 22,300 kg (49,163 lb)
- **Gross weight:** 38,040 kg (83,864 lb)
- **Max takeoff weight:** 43,755 kg (96,463 lb)
- **Fuel capacity:** 11,100 kg (24,471 lb)
- **Powerplant:** 2 × Lyulka AL-21F-3A turbojet engines, 75 kN (17,000 lbf) thrust each dry, 109.8 kN (24,700 lbf) with afterburner

Performance

- **Maximum speed:** 1,654 km/h (1,028 mph, 893 kn) / M1.6 at high altitude 1,315 km/h (817 mph; 710 kn) / M1.06 at sea level
- **Combat range:** 615 km (382 mi, 332 nm) lo-lo-lo attack mission with 3,000 kg (6,614 lb) of ordnance and external tanks
- **Ferry range:** 2,775 km (1,724 mi, 1,498 nm)
- **Service ceiling:** 11,000 m (36,000 ft)
- **g limits:** +6
- **Rate of climb:** 150 m/s (30,000 ft/min)
- **Wing loading:** 651 kg/m^2 (133 lb/sq ft)
- **Thrust/weight:** 0.6

Armament

- **Guns:** 1 × internal 23 mm Gryazev-Shipunov GSh-6-23M rotary cannon with 500 rounds
- **Hardpoints:** 9 hardpoints with a capacity of up to 8,000 kg (17,635 lb),with provisions to carry combinations of:
  - **Rockets:**
    - S-5, S-8, S-13, S-24B, S-25-OFM/LD
  - **Missiles:**
  - Air-to-air missiles:
    - 4 × R-60MK, 4 × R-73E
  - Air-to-surface missiles:
    - 4 × Kh-23M, 4 × Kh-25ML,
    - Kh-59ME, Kh-29L/T/D
  - Anti-ship missiles:
    - Kh-31A
  - Anti-radiation missiles:
    - 2 × Kh-28, 2 × Kh-58E, Kh-25MP
    - 2 × Kh-31P, Kh-27PS
  - **Bombs:**
  - KAB-500L laser-guided bomb
  - KAB-500OD guided bomb
  - KAB-500S-E satellite-guided bomb
  - KAB-1500KR TV-guided bomb
  - KAB-1500L laser-guided bomb
  - ODAB-500PM bomb
  - RBK-250 cluster bomb
  - RBK-500 cluster bomb
  - 2 × BETAB-500 bomb

Avionics

- SVP-24 targeting system

Figure D.7: Su-24 Fact Sheet

Su-30

Role	Multirole fighter
Manufacturer	Sukhoi
First flight	31 December 1989
Introduction	1996
Status	In service
Primary users	Russian Air Force Algerian Air Force Venezuelan Air Force Vietnam People's Air Force
Produced	1992–present
Number built	630+
Unit cost	Su-30MK2: US$37.5 million in 2012
Developed from	Sukhoi Su-27
Variants	Sukhoi Su-30MKI Sukhoi Su-30MKK Sukhoi Su-30MKM

General characteristics

- **Crew:** 2
- **Length:** 21.935 m (72 ft 0 in)
- **Wingspan:** 14.7 m (48 ft 3 in)
- **Height:** 6.36 m (20 ft 10 in)
- **Wing area:** 62 m^2 (670 sq ft)
- **Empty weight:** 17,700 kg (39,022 lb)
- **Gross weight:** 24,900 kg (54,895 lb)
- **Max takeoff weight:** 34,500 kg (76,059 lb)
- **Fuel capacity:** 9,400 kg (20,723 lb) internal
- **Powerplant:** 2 × Saturn AL-31FL Afterburning turbofan engines, 74.5 kN (16,700 lbf) thrust each dry, 122.58 kN (27,560 lbf) with afterburner

Performance

- **Maximum speed:** 2,120 km/h (1,320 mph, 1,140 kn) at high altitude
- **Maximum speed:** Mach 2
- **Range:** 3,000 km (1,900 mi, 1,600 nm) at high altitude
- **Service ceiling:** 17,300 m (56,800 ft)
- **g limits:** +9
- **Rate of climb:** 230 m/s (45,000 ft/min)
- **Wing loading:** 401 kg/m^2 (82 lb/sq ft) with 56% fuel 468.3 kg/m^2 (95.9 lb/sq ft) with full internal fuel
- **Thrust/weight:** 1 with 56% fuel 0.86 with full internal fuel

Armament

- **Guns:** 1 × 30 mm Gryazev-Shipunov GSh-30-1 autocannon with 150 rounds
- **Hardpoints:** 12 hardpoints with a capacity of up to 8,000 kg (18,000 lb),with provisions to carry combinations of:
- **Rockets:**
- S-8KOM/BM/OM
- S-13T/OF
- S-25OFM-PU
- **Missiles:**
- Air-to-air missiles:
- R-27R/ER/T/ET/P, R-73E, RVV-AE
- Air-to-surface missiles:
- Kh-29T/L, Kh-59M/ME
- Anti-ship missiles:
- Kh-31A
- Anti-radiation missiles:
- Kh-31P
- **Bombs:**
- KAB-500KR general-purpose bomb
- KAB-500OD bomb
- KAB-1500KR GP bomb
- KAB-1500L laser-guided bomb
- FAB-500T GP bomb
- BETAB-500SHP bomb
- ODAB-500PM bomb
- OFAB-250-270 bomb
- OFAB-100-120 bomb
- P-50T bomb
- RBK-500 cluster bombs
- SPBE-D bomb

Avionics

- Bars planar array radar
- OEPS-27 electro-optical targeting system
- OLS-30 IRST
- SPO-15 Radar Warning Receiver

Figure D.8: Su-30 Fact Sheet

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Curriculum Vitae

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.