VALUE-FOCUSED APPROACH TO THE TRAINING WITH FLIGHT SIMULATORS IN THE BRAZILIAN AIR FORCE

by

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A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at George Mason University

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DISCLAIMER

This work contains fictional representations of future situations/scenarios. Any similarities to real people or events are unintentional and designed for illustration purposes only. The views expressed in this Thesis are those of the author and do not reflect the official policy or position of the Brazilian Air Force, Ministry of Defense, or the Brazilian government.

DEDICATION

This work is dedicated to my wife, Debora, without whom it could never be completed; and to my son, Fernando, the greatest motivation I could ever wish for.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF EQUATIONS

LIST OF ABBREVIATIONS

Air Combat Maneuvers .... ACM
Air Combat Simulator .... ACS
Air Combat Tactics .... ACT
Air Force Strategic Military Plan .... AFSMP
Aircraft Handling Characteristics .... AHC
Aircrew Training System .... ATS
Basic Fighter Maneuvers .... BFM
Beyond Visual Range .... BVR
Brazilian Air Force .... BAF
Defensive Counterair .... DCA
Distributed Mission Operations .... DMO
Distributed Training Operations Center .... DTOC
Gross Domestic Product .... GDP
Instrument Flight Rules .... IFR
Instrument Meteorological Conditions .... IMC
Large Force Employment .... LFE
Life-Cycle Cost LCC
Live, Virtual and Constructive LVC
Long-Range Air-to-Air Missile .... LRAAM
Medium-Range Air-to-Air Missile .... MRAAM
Mission Training via Distributed Simulation .... MTDS
North Atlantic Treaty Organization .... NATO
Offensive Counterair .... OCA
Second World War .... WWII
Swedish Air Force .... SAF
Tactical Intercepts .... TI
United Nations Mission of Support in East Timor .... UNMISET
United Nations Stabilization Mission in Haiti .... MINUSTAH
United States Air Force .... USAF
Value-Focused Thinking .... VFT
Within Visual Range .... WVR

ABSTRACT

VALUE-FOCUSED APPROACH TO THE TRAINING WITH FLIGHT SIMULATORS IN THE BRAZILIAN AIR FORCE

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George Mason University, 2015

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This Thesis proposes a new approach for employing flight simulators in the Brazilian Air Force (BAF), and describes the benefits that could be obtained by adopting it.

Until the time of this Thesis writing, the BAF's flight simulators have been used primarily, and almost exclusively, to help pilots in their learning program of a new aircraft during their operational formation. More specifically, simulators are used extensively in the initial missions of the new aircraft's learning program, facilitating the development of the basic piloting skills.

However, after this initial period, the use of flight simulators decreases drastically. This happens because by the time they take the more advanced missions, pilots already acquired a substantial amount of piloting skills, and it is thus not possible to obtain the same gains they achieved in the beginning of the course. This stems from the doctrinal

view for applying simulators the BAF had when it acquired its flight simulators, constrained by the capabilities of the equipment acquired.

This Thesis brings an analysis of how the adoption of more advanced flight simulators, capable of reproducing the environment of more complex missions, would impact the operational capabilities of the BAF, specifically regarding the fighter pilots' readiness, and the long-term costs associated with the adoption of that equipment. To perform the analysis, a multiobjective value model was developed, with the purpose of quantifying and evaluating the benefits that could be achieved by the adoption of more modern flight simulators. The model was then used to support a comparison between adopting the proposed approach and maintaining the current one.

BACKGROUND

As the largest country in South America and the fifth largest in the world, both by population size and geographic dimensions (Wikipedia, 2015), Brazil's influence in Latin America is evident, and its influence worldwide has been expanding in the past few years. The increasing participation of Brazilian military personnel in United Nations Peacekeeping Missions, such as the MINUSTAH (Haiti) and the UNMISET (Timor-Leste), is a clear indication of this trend. By "aspiring to become a world power, Brazil has assumed a role in peace and security that is more consistent with enhanced international responsibility" (Santos & Cravo, 2014).

Brazil has the third largest Armed Forces in America in number of military personnel and equipment, after United States and Colombia (Wikipedia, 2015). Composing the three Brazilian Armed Forces with the Army and the Navy, the Brazilian Air Force (BAF) is currently the largest air force in Latin America, with around 78,000 active-duty personnel (Brazilian Air Force, 2015).

The BAF was created in 1941, and it has contributed to the allied war effort during the Second World War (WWII) in Italy, equipped with the American aircraft Thunderbolt P-47 (Brazil, *Instituto Histórico-Cultural da Aeronáutica*, 1990). After the WWII, the BAF purchased the British fighter Gloster Meteor, which was replaced by the American F-80 Shooting Star and its two-seat derivative TF-33A in the mid-sixties.

Few years later, a new generation of fighter aircraft arrived to the BAF: the MB-326 "Xavante," the French supersonic Mirage-III and the American Northrop F-5 (Brazil, *Instituto Histórico-Cultural da Aeronáutica*, 1990). Equipped with more modern aircraft, new concepts had to be developed by the Brazilian fighter aviation regarding the training of the pilots. Also, the new capabilities and technology now available required a greater level of preparation from the pilots to accomplish their missions satisfactorily.

Concomitantly with the arrival of the new fighters, the first flight simulators were purchased by the BAF. Unlike current high-fidelity flight simulators, that machinery was not capable of reproducing the external environment for the pilots in large screens, but could replicate a close-to-reality behavior of the aircraft during instrument flight rules (IFR) conditions, for example. The purpose of these old-generation simulators was mainly to facilitate the pilot's adaptation to the cockpit, and to allow the practice of standard and emergency procedures.

The situation did not change with the next fighter acquisition, the AMX, a fighter aircraft built through a partnership between the Brazilian company Embraer and the Italian Aeritalia during the nineties (Gunston, 1995). Even with the new fighter, Brazilian fighter pilots would still employ flight simulators the same way, since the simulation hardware was not meant to go beyond the basic training of the aircraft procedures.

However, with the development of the ALX "Super-Tucano" by Embraer, Brazil would finally enter a new era in the usage of flight simulators. Providing a "latest generation Human-Machine Interface designed to minimize pilot workload," (Embraer, 2012) the ALX featured a "state-of-the-art avionics system" (Embraer, 2012) for the time it was manufactured and went into operation in the BAF, in 2004 (*Força Aérea* Magazine, 2004).

At the same time the ALX operations started, replacing the MB-326 as the basic fighter trainer, the modern flight simulator system developed for the new aircraft was purchased. Much more advanced than its predecessors in the BAF, it has three large screens that present to the pilot a 150 degrees field of view simulating a real flight. Also, it is capable of replicating the behavior of the aircraft in most of the situations the pilot will face during a real single-aircraft mission. A very helpful tool it provides for the instruction of new fighter pilots is the capability of reviewing the action after the training, improving the quality of the mission debriefings.

As a result of all the improvements in the flight simulator capabilities, the amount of hours of training using this equipment was increased in the BAF. Although the main purpose of this type of training remained the same as before, which is the practice of standard and emergency procedures, there was now the possibility of practicing other types of missions, such as navigation and instrument flight, with very realistically simulated instrument meteorological conditions (IMC).

The experience with the ALX flight simulator was a success, as expected, and it was expanded and enhanced for the other fighter aircraft in the BAF, that were passing through a modernization process. The Mirage-III, in operation only until 2005, and its substitute, the Mirage-2000, taken out of operation in 2013 (Castro, 2013), were the only exceptions: the simulator of the former was not modernized, and for the latter, the pilots had to go to France to practice in the aircraft simulators.

The modernization of the Northrop F-5 fleet was started in 2006, and the last F-5M (new designation of the aircraft after passing through the modernization process) was delivered to the BAF in 2013 (Brazilian Air Force, 2015). The modernization occurred in total commonality with the ALX program, and obviously, the same process happened to its flight simulator.

As for the other high-performance fighter still in operation in the BAF, the AMX, the first modernized aircraft was delivered in 2013 (Embraer, 2013), and the modernization process is currently still in progress.

Due to the deactivation of the Mirage-2000, and also the estimate of deactivating both the AMX in 2023 and the F-5M in 2025, the BAF decided to purchase the Swedish Gripen-NG, a "last generation fighter that will fully meet the operational needs of the BAF for the next 30 years" (Brazilian Air Force, 2015). The estimate for the delivery of the first aircraft is 2019 (Brazilian Air Force, 2015).

After the acquisition of the Gripen-NG, the BAF will be equipped with one of the "most advanced combat aircraft in the world" (Brazilian Air Force, 2015), and will be capable of operating in more complex war scenarios than it could do before. This will demand a much higher level of preparation from the pilots assigned to fly in the new fighter aircraft. To accomplish that, an optimal use of the flight simulators will undoubtedly be essential.

PROBLEM DESCRIPTION

The Benefits of Training Using Flight Simulators

The evolution of the warplanes, especially after the Cold War, has turned the flight simulators into a necessity for Air Forces around the globe. The complexity of aerial missions performed nowadays, and consequently, the complexity of the training required to accomplish those missions, has increased exponentially, and simulators can help to alleviate it. Also, they can contribute to enhance the operational capabilities of the aircrews.

There are many advantages in training aviators using flight simulators, some of which are (National Training and Simulation Association, 1995), as follows:

- more effective interaction between instructor and student than during a real flight;
- the design of the scenario is very flexible, not constrained by safety, diplomatic or security real-world limitations;
- tasks that are not central to the training can just be skipped (such as refueling, repositioning, etc.), providing the student more trials for the most important exercises during a given amount of time;
- more precise debriefing of the missions, since they can be reviewed after the action.

Depending on the capabilities of each system even more benefits might be available, but the main reason Air Forces around the globe use flight simulators to train their pilots is the substantial reduction in operational cost they provide for the same level of operational readiness. According to Simpson et al., "in aggregate, simulators provide significant beneficial transfer from simulator to aircraft at a median operating cost of about one-tenth of an aircraft." (Simpson & West, 1995)

Reinforcing the use of flight simulators with the objective of decreasing costs while keeping the operational levels, in 2012 the U.S. Air Force (USAF) estimated "it could save about $1.7 billion over five years by reducing flying hours by five percent and shifting more of its pilots and crew training to simulators". (Erwin, 2012)

This was also recognized by the Brazilian Government, in its decision to purchase flight simulators for the three fighter aircraft currently in operation in the BAF (ALX, F-5M and AMX).

Budget Limitations during Peacetime

During peacetime, defense budget tends to decline. However , if not properly implemented, the reduction of government expenditures can have some pitfalls. Although during peacetime the amount of money designated for the military can be reduced causing only minor impacts, the readiness of the forces could be seriously compromised if there is not enough investment to keep it at a reasonable level. The most critical problem is that assessing the appropriateness of this level will usually occur in the worst possible time, which is when the nation engages in a conflict.

Brazil has been experiencing a very long period of peace. It can be read on the Brazilian National Defense Strategy that "Brazil is peaceful by tradition and by conviction" (Brazil, *Ministério da Defesa*, 2008). However, it can also be read that "it needs to be prepared to defend itself not only from attacks, but also from threats" (Brazil, *Ministério da Defesa*, 2008), which implies in a proper preparation of its Armed Forces during peacetime.

In analyzing the evolution of the Brazilian military expenditures since the year 2000, it can be observed that it has increased at an almost constant pace until the year 2011, when it started to be reduced, albeit still maintaining a value relatively close to the peak reached in that year.

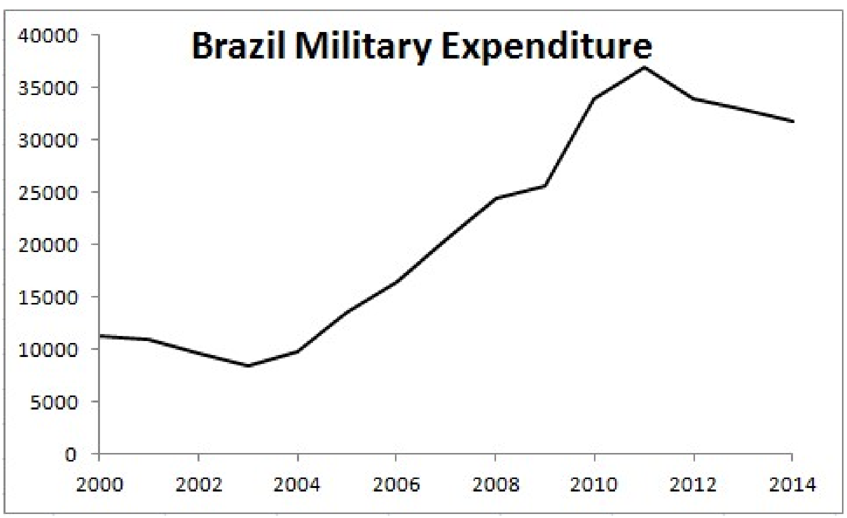

Figure 1: Military Expenditure in $ Millions (2014 Current Dollars) (SIPRI, 2015)

Comparing these numbers to the evolution of the Brazilian Gross Domestic Product (GDP), it can be observed that they presented similar growth: the GDP for the year 2011 ($2,476 Billion) is slightly less than four times the GDP for the year 2000

($644 Billion) a proportion very close to the one that exists between the military expenditures for these same two years (The World Bank, 2015). This suggests that the increment in the military expenditures until 2011 could have been just an effect of the GDP evolution.

Actually, in terms of percentage of the GDP, the investment Brazil makes in defense is being reduced over the years, and not increased, as the numbers above might suggest. This means that the money invested in the evolution and preparation of the Brazilian Armed Forces is not following the growth rate of the economy of the nation.

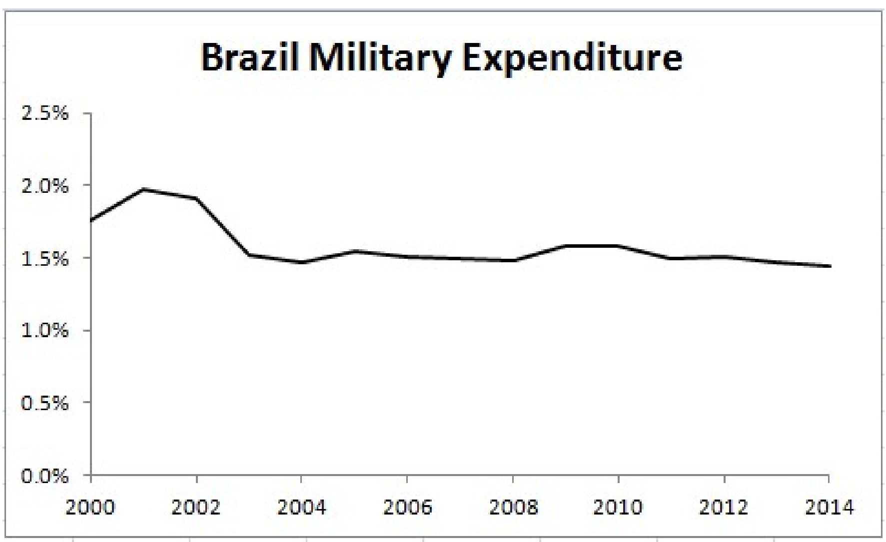

Figure 2: Brazilian Military Expenditures in Percentage of the GDP (SIPRI, 2015)

Also, compared to the percentage of the GDP other nations invest in the military field, it can be observed that the amount Brazil invests is lower than many of them. For example, among the five countries that compose the block denominated BRICS (Brazil, Russia, India, China and South Africa), in the year 2014 only South Africa, with 1.2%, invested less than Brazil in defense (Russia 4.5%, India 2.4%, and China 2.06%) (SIPRI, 2015).

The conclusion of this brief analysis is that efficient and low-cost alternatives should be searched by the Brazilian Armed Forces, and more specifically the BAF, in order to maintain the level of readiness and preparation of its fighter.

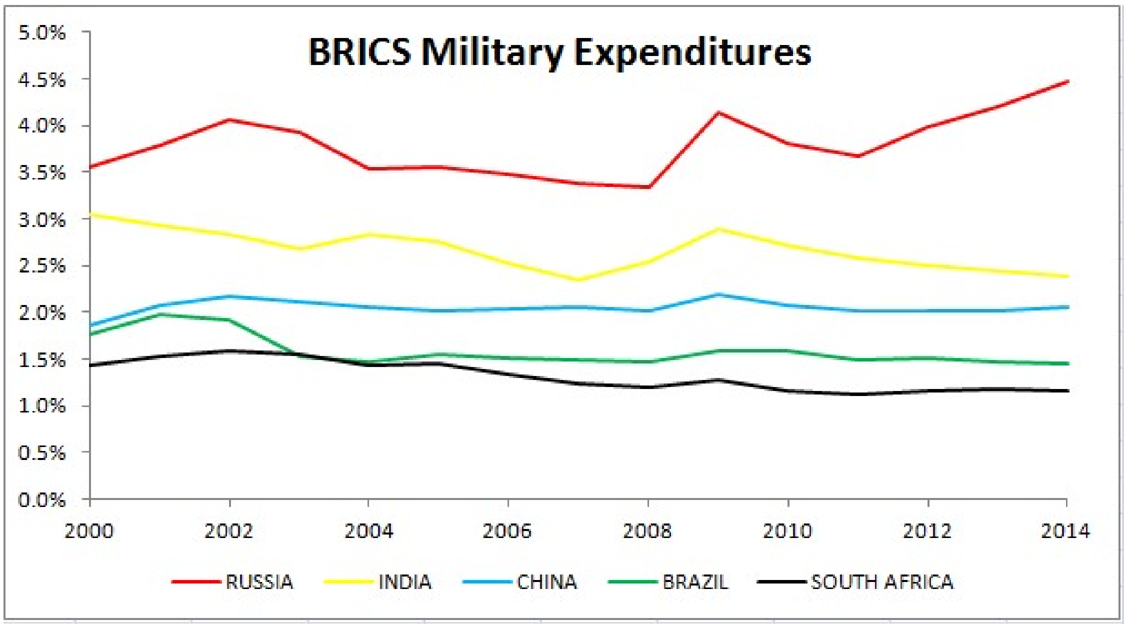

Figure 3: BRICS Military Expenditures in Percentage of the GDP (SIPRI, 2015)

The Evolution of the Aerial War

To prepare a pilot for the combat in the past was a considerably easier task than it is today. The airplanes were much simpler, with less instruments and equipment to be operated. The weapons available were also easier to master, such as guns and "dumb bombs", that were only as precise as the aiming system of the aircraft and the pilot's ability could make them be.

The level of training of a post-WWII pilot could be summarized simply by one single index, the flight-hours number: the more hours of flight the warrior had, the more experienced he was. Nevertheless, although more flight-hours usually meant increased skill, a reasonably satisfactory level of preparation could be achieved with a relatively small amount of hours, since the equipment was not very complex.

Over the years, with the fast-paced technological evolution, more and more equipment were added to the aircraft, a process that obviously included combat airplanes. Onboard radars, data-link systems, multi-function displays, and many others, are innovations made with the purpose of improving some of the aircraft's functionality. However, they produced the collateral effect of requiring extra training from the pilots to learn how to operate the equipment properly and effectively.

One of the biggest innovations of all, in the military aviation, was the invention of the medium-range and the long-range air-to-air missiles (MRAAM or LRAAM). Although they exist since the fifties, the evolution of such weapons after the seventies and eighties increased considerably the complexity of the aerial war. A completely new group of tactics had to be developed due to these new weapons, as well as to the guidance and target-acquisition systems designed to improve them. A new type of aerial combat was created, the so-called Beyond Visual Range (BVR) combat. Coping with its complexity requires a very specific training from the pilots, one that enables them to master the new tactics and techniques.

After all the improvements made to the aerial war tactics and to the fighter aircraft themselves, the result is a much more effective fleet. The world sees incomparably better equipped Air Forces now than there was seventy years ago, with pilots that are better prepared for the combat than their antecessors. However, to achieve this level of readiness many flight-hours are required, resulting in increased costs to afford this extended time of training and operation.

The Need for Simulators to Maintain Readiness

When the increased demand for flight hours, required to make the fighter pilots reach and maintain their readiness, meets the limited defense budgets in many countries, including Brazil, a problem emerges. More flight hours mean increased costs on fuel, maintenance, and so on. Depending on the airplane, these costs can become prohibitive: in the Brazilian case, for example, while the flight hour of the ALX costs around US$500 (Godoy, 2011), one hour flying the future Brazilian fighter Gripen-NG will cost slightly less than US$4,000 (Brazilian Air Force, 2015), almost eight times the cost of the former.

One known solution widely adopted to address this problem is to increase the amount of simulation-based training. "When it comes to flight training, one of the most common cost-saving suggestions is the increased use of simulators" (Tegler, 2011), even though most fighter pilots would not admit that the training in the simulator could be considered exactly equivalent to the training in the real aircraft. Apart from any controversy, the fact is that proper simulation-based training can reduce the number of live-training hours needed for the pilots to achieve the required level of efficiency in a determined task.

Furthermore, depending on the type of mission, modern simulators available for most types of aircraft can replace almost completely the live-training. Examples include, but are not limited to, practicing instrument approaches and navigation. For these missions that can be replicated very realistically, the use of flight simulators can help to reduce, or even eliminate, any lack of preparation due to cuts or restrictions in the number of flight hours, an increasingly common scenario in most nations.

Nevertheless, there are still a few types of missions that cannot be reproduced realistically enough by flight simulators, even the most advanced ones.

One aspect that illustrates why it is so complex to use simulation in some specific types of training missions, is the difficulty to replicate the behavior of an enemy aircraft during a visual air-to-air combat, or "dogfight", as it is usually called. As practicing with another real pilot (instead of a virtual entity) is essential in this case, one possible simple solution could be to link two simulation stations to provide the dogfight training for two pilots at the same time, who would then be combating against each other. However, there are still some issues that prevent this to be done properly for this specific type of mission. A major reason behind these issues is the fact that physical sensations of the pilot during the flight are really essential, discouraging the use of simulators.

This is valid for a variety of missions in which complexity requires a higher cognitive load from pilots, such as air-to-ground attack missions. Although the procedures applied by the pilot in these missions can be satisfactorily practiced using simulation, dealing with the real operational situation is undoubtedly essential, and the flight hours in the aircraft cannot be reduced after some training missions on the ground.

However, there is a particular case in which the use of flight simulators to enhance the preparation of the fighter pilots could be substantially useful: the BVR combat. Due to the characteristics of the simulation environment, during this type of training it is possible to perform a more detailed development of tactics and techniques, essential to any performance improvement in this mode of combat. Some advantages of the simulator-based BVR training include: the possibility of assessing the real effectiveness of the weapons launched during the combat (many times it is not possible to assess the result of a shot during the live-training); the after-action review, with the "God's view" (a from-the-top visualization of the scenario), makes more accurate the assessment of the effectiveness of the tactics that were developed; the flexibility provided by the simulator to rapidly implement changes to the scenario (such as including new enemy or friendly aircraft) can help to increment the quality of each training session, adapting it quickly to each pilot's needs.

Also, due to the large number of aircraft involved, the live-training of BVR combat does not occur as often as it should be to provide an optimal preparation, and when it does, it is extremely costly. The use of simulators can help to increment the frequency pilots practice the tactics inherent to this mission.

The Swedish Air Force (SAF) and the United States Air Force (USAF) already use simulation environments to provide this type of training for their fighter pilots. Experience with linked high-fidelity simulators shows that it helps pilots "develop tactics and learn how to behave in different kinds of threat environments" (Crane *et al*, 2006), while operating on BVR combat scenarios.

BVR Simulators in the BAF

The BAF made the acquisition of a very modern aircraft, the Gripen-NG. This is a multi-role fighter that will surely be extensively employed in BVR combat scenarios. The evolution of the air-to-air missiles, and specifically of the MRAAMs, makes the BVR combat capability a key aspect for the successful completion of any type of mission, no matter whether in a defense or an attacking role.

The upcoming latest generation platform puts a strong pressure on the BAF to fast developing an increased BVR training program, as well as the ability of designing, testing and implementing new concepts that are key to the Gripen-NG's operational portfolio. Therefore, it will certainly be beneficial to the BAF to establish a simulation center capable of providing a BVR combat training similar to the one provided by the Swedish and the American Air Forces. For accomplishing this goal, a modern type of flight simulator would have to be acquired, with better capabilities than the ones used currently in the BAF.

Besides substantially reducing costs to provide an adequate BVR combat training to the pilots, other benefits of using modern simulation environments could be obtained by establishing a simulation center with these characteristics, as follows (Crane *et al*, 2006):

- develop tactics and learn how to behave in different kinds of threat environments;
- repeatable scenarios could be used to assess the effectiveness of emerging technologies;
- better preparation for different theaters deployments.

Problem Statement

The focus of this Thesis is to determine how beneficial for the BAF it would be the adoption of a modern approach to the use of flight simulators, making use of more advanced simulation stations, in contrast to the approach currently employed, constrained by the simulators presently used in the BAF. This problem is defined as:

Given:

- The new operational capabilities and associated tactical and training demands incurred after the acquisition of the aircraft Gripen-NG
- The estimated 30 years operational life-cycle for the Gripen-NG
- The characteristics of BAF current flight simulators and its simulated training programs
- The characteristics of linked high-fidelity flight simulators, currently employed in the USAF and in the SAF

The problem is to:

- Develop a model capable of providing an evaluation of the benefits each specific type of flight simulator and simulated-based training can bring to the BAF, based on the objectives involved with the acquisition and operation of that equipment
- Determine the benefits that could be achieved for each proposed alternative, based on the characteristics of the different types of flight simulators

By the choice of:

- Objectives relevant to this type of decision problem
- Proper measures of achievement of the objectives involved with the mentioned acquisition

Subject to:

- BAF's doctrines and regulations

METHODOLOGY

Assuming that having and operating flight simulators is advantageous for any Air Force, which has been empirically demonstrated over the years in different countries, the goal of the following chapters is to describe the model developed to determine how beneficial it would be for the BAF the adoption of different types of flight simulator, taking advantage of the currently in-progress acquisition of the Gripen-NG.

The first step was to define the objectives involved with this type of decision problem, to help in the subsequent identification of the most appropriate parameters to measure the desirability of the possible alternatives. This procedure was performed in accordance to the Value-Focused Thinking methodology, presented by D. Keeney in the book "Value-Focused Thinking: A Path to Creative Decision Making" (Keeney, 1992).

Following, a multiobjective value model was developed, using the parameters defined in the previous phase, to evaluate the overall desirability of the alternatives. This model was developed using the method created by Dr. Kirkwood, and explained in his book "Strategic Decision Making" (Kirkwood, 1997).

The next part of this work was to introduce possible alternatives to the acquisition of flight simulators, with different characteristics, and the insertion of the estimated levels of accomplishment of the selected attributes into the model, in order to compare the benefits each of the alternatives could provide to the BAF. One of the alternatives was intentionally based on the modern linked high-fidelity flight simulators, used currently by the USAF and the SAF in the preparation of their fighter pilots. The goal of selecting this modern equipment was trying to identify if the introduction of these simulators could bring a relevant evolution to the BAF's fighter aviation.

Finally, a sensitivity analysis was performed on the model, to determine how large the impacts in the final results would be, if small variations occurred to the proposed parameters. A secondary objective of the sensitivity analysis was to provide credibility to the model developed and to the selection of the methodology.

THEORETICAL FOUNDATIONS

Why Value-Focused Thinking?

To recognize and identify decision opportunities, to create better alternatives for the decision problems, and to develop an enduring set of guiding principles. This are the three major ways Dr. Ralph Keeney claims that Value-Focused Thinking (VFT) can improve the decision-making process (Keeney, 1992).

VFT is a decision-making methodology that focuses on the values associated with the objectives of a given decision, instead of focusing only on the alternatives available to the decision maker. The proposed approach is to "first deciding what you want, and then figuring out how to get it" (Keeney, 1992).

When the decision maker figures out "what he wants," or, in other words, when he identifies his objectives, he is able to define the values that will guide the decision process, and that are the basis for the application of the VFT methodology. By thinking about the values related to a problem, not only it will be possible to better evaluate the alternatives, but also other advantages will arise, some of which are as follows: possibility of creating new alternatives; improved communication among the stakeholders, which facilitates their involvement in the decision; and identification of hidden objectives and other decision opportunities.

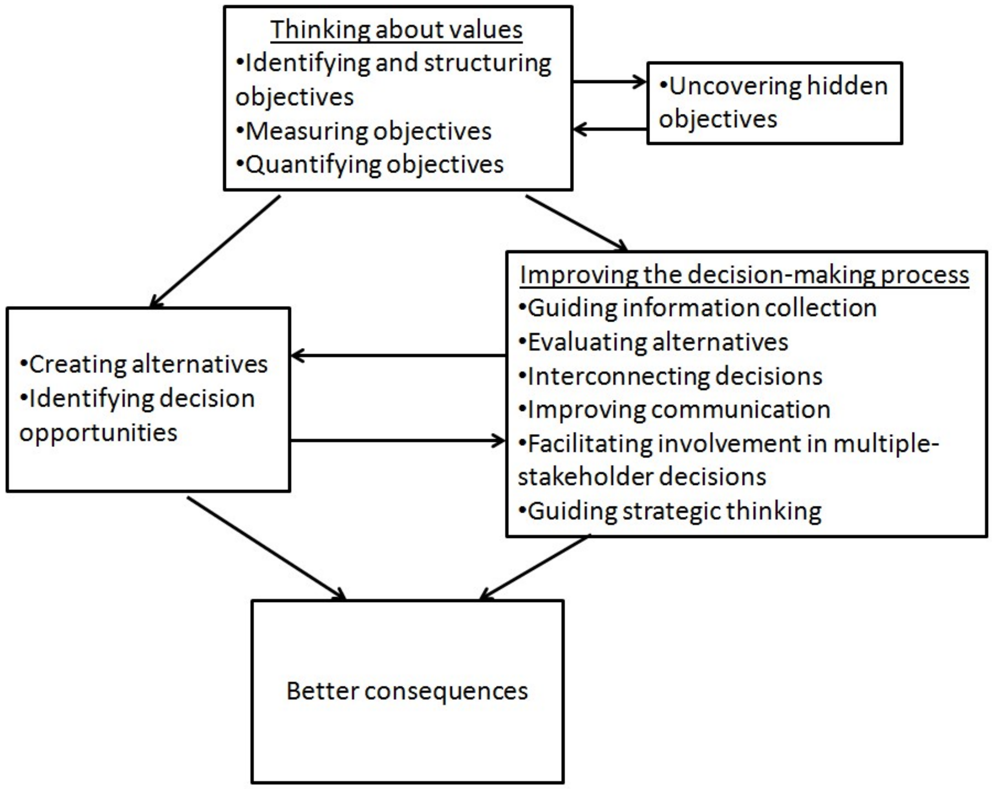

Figure 4: The influence of value-focused thinking on the process of decision-making (Keeney, 1992)

Defining "What You Want": Decision Context and Objectives

After identifying a specific decision problem, the first step of VFT is to define the decision context and the objectives that are being pursued. The objectives can be defined simply as the statement of what the decision maker is trying to achieve in the specific situation, and the decision context is the set of alternatives that are considered appropriate for the given problem.

Dr. Keeney differentiates between fundamental objectives and means-ends objectives, and the relation that exists between both can help to define what exactly is the decision context. The fundamental objectives convey qualitatively what is supposed to be achieved in a specific problem; they provide the basis for the definition of the attributes and values in a subsequent phase of the VFT process, since they are the main reason the decision is being made. On the other hand, the means-ends objectives refer to the more concrete actions or procedures that will be undertaken in order to achieve the fundamental objectives. The means-ends objectives are taken within the decision context, which together with the fundamental objectives, defines the decision frame of the problem.

In the book, these definitions are explained by using the example of an individual deciding how to invest his personal funds. The fundamental objective is simply to maximize the return of the investment. The decision context, in this case, is the set of all the ways he can invest his money, such as invest with banks, invest in stocks, in real state, and so on. If the decision context was not limited by the wish of the individual to invest the money, it could be broader, with more alternatives, as buying a small business or just keeping the money. Likewise, if other objectives were present, such as leaving the maximum amount possible of the funds for the heirs, for example, the decision context of the problem could also be different.

It is not uncommon to think about means-ends objectives and fundamental objectives together when first stating the goals of a decision problem. However, they shall be separated, so a structure of objectives can be created, which will provide a more deep understanding of the problem. This separation can be performed simply by asking, for each objective, "why is this objective important". If the answer is that it is important because of its influence in some other objective, it is almost certainly a means-ends objective. On the other hand, if a given objective is important only because it is essential to the specific decision, it is most probably a fundamental objective.

After defining and classifying the objectives, they shall be organized in two different structures, the fundamental objectives hierarchy and the means-ends objectives network. To create the structures for both fundamental objectives and the means-ends ones, the starting point is the same overall objective, which is the main reason the decision is being taken. After this point, they become distinct structures: the fundamental objectives relate to each other in a hierarchical manner, in which the lower-level objectives are parts of the one in the level directly above, and by doing so, fully define it, as being the set of objectives directly below in the hierarchy. Meanwhile, the means-ends objectives relate to each other in a causal network, in which the achievement of a lower-level objective has a direct impact in the achievement of a higher-level one.

Many differences arise from these definitions. For example, one level of the fundamental objectives hierarchy has to completely define the level above it in the hierarchy, whereas one level of the means-ends objectives network does not necessarily have to include every factor that can affect the upper-level objective in the structure.

Dr. Keeney illustrates the differences between the two structures through examples, one of which is illustrated in figures 5 and 6, below. They show the diagrams for a decision regarding a specific air pollution problem, in which the overall objective of the decision maker is to minimize the health impacts and the costs. It can be seen that this is the top-level goal in both structures.

In the fundamental objectives hierarchy, each objective, except the ones in the lowest level, has at least two lower-level objectives that completely define it. Also, it can be seen that they do not relate to each other, or to objectives other than their respective predecessor. Using Dr. Kirkwood words, "each layer of a value hierarchy must be collectively exhaustive and mutually exclusive" (Kirkwood, 1997).

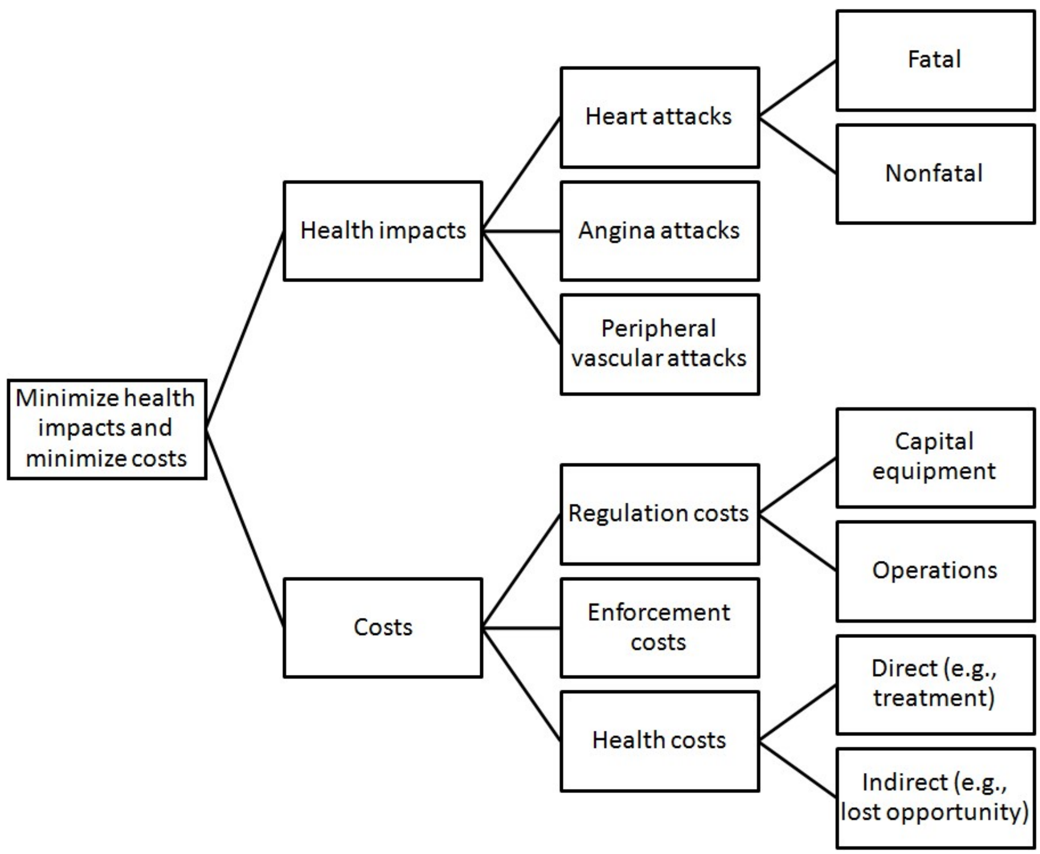

Figure 5: A Fundamental Objectives Hierarchy (Keeney, 1992)

For the same problem, it can be observed that, in the means-ends objectives network, the objectives are more specifically related to each action needed to achieve the objective in the level above. For example, reducing the carbon monoxide emissions would, by consequence, affect the carbon monoxide concentration in the air, impacting afterwards the doses of the gas in the blood of the population, and so on. Differently from the fundamental objectives hierarchy, in this network, an objective can have only one single objective in the level below, since the levels do not necessarily have to include all the factors that can affect the achievement of the objective directly above. Also, the objectives can be related to each other in directions other than the hierarchical relationship, another characteristic that differentiates this structure from the previous one.

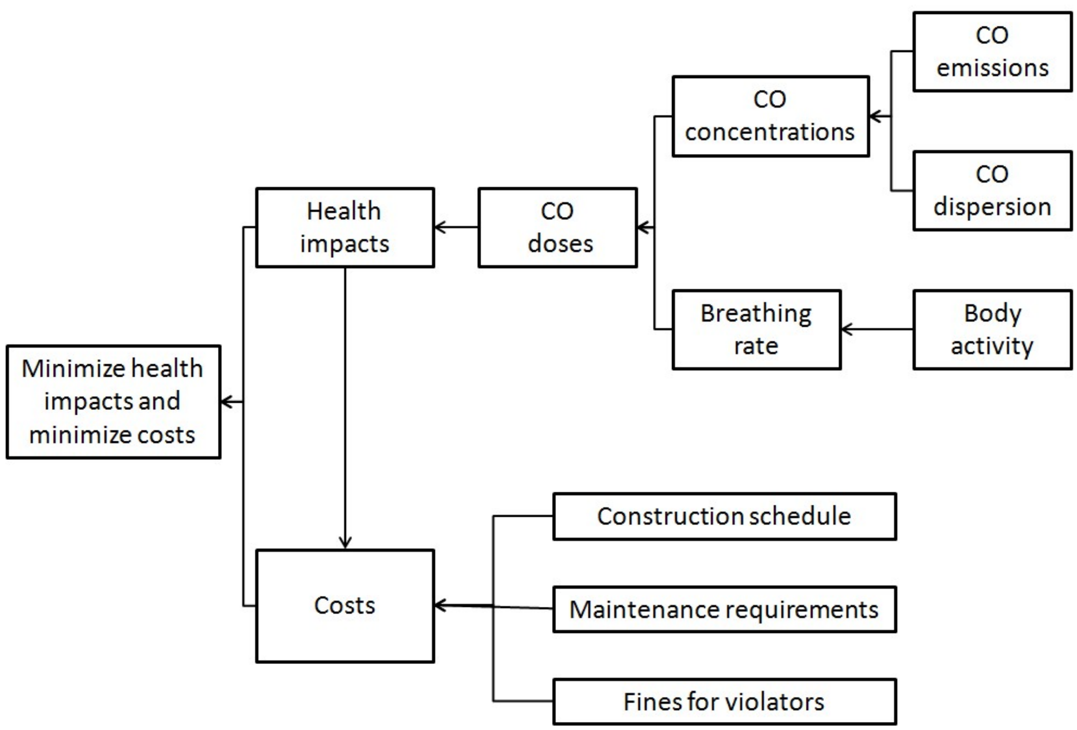

Figure 6: A Means-Ends Objective Network (Keeney, 1992)

Defining the Attributes

The importance of identifying thoroughly the objectives is that it will provide a very clear understanding of what is to be achieved in the decision problem. To determine until what extent the proposed objectives are accomplished, for every possible alternative, attributes must be created for each of the objectives. These attributes, often referred to as measures of effectiveness, or measures of performance, will be used to evaluate how much each particular objective is satisfied by a given alternative.

There are three types of attributes: natural attributes, constructed attributes, and proxy attributes. The decision of what type to use depends on the specific decision problem. Nevertheless, this selection must be done carefully by the analyst, since it will be essential for the development of a consistent value model, which will be constructed based on the quantification of the attributes chosen.

The natural attributes are generally the more obvious to be used for problems in which they are apparent, and by consequence, they are less prone to misinterpretation. For example, when the objective is to minimize the fatalities in a risk management context, the "number of fatalities" is a natural attribute that can be used to measure the objective achievement (Keeney, 1992).

When no natural attribute is available, or it is not proper to use it for the given problem, one of the alternatives the analyst has is to construct a new attribute. Constructed attributes have the interesting characteristic of being developed specifically for the proposed problem evaluation, making them a valuable tool for the decision makers. However, the meaning of each level of the attribute must be minutely described in order to avoid ambiguity in its interpretation. Also, care must be taken during the definition of the scale that will be used to distinguish the levels of impact on the objective.

For objectives similar to "maximize user satisfaction," for instance, there is no established natural attribute. In such cases, constructing an attribute would provide the required means for assessing each alternative the decision maker has available. Dr. Kirkwood illustrates this situation using the example of a company deciding about the implementation of an internal computer network. The impact of the alternatives on the computer users is measured by the constructed attribute "user satisfaction." The levels and descriptions are presented on table 1 (Kirkwood, 1997).

Table 1: "User Satisfaction"; Example of Constructed Attribute

Attribute level	Description of attribute level
- 1	A significant number of user-group members do not accept use of the network or feel the network is a detraction from their work environment.
0	No noticiable change in user-group satsifaction with their personal computer resources.
1	Many user-group members believe the addition of the network has enhanced their work environment.
2	Virtually all user-group members believe the addition of the network has moderately or significantly enhanced their work environment.

The second option the analyst has when no natural attribute is appropriate for a given objective is to use a proxy attribute. The proxy attribute is an indirect measure of achievement of an objective. It could be a natural or a constructed attribute already chosen to evaluate a means-ends objective, but that is somehow associated to the fundamental objective whose achievement it is also able to measure, although indirectly.

A very good example of a proxy attribute is the use of the gross national product to measure the economic well-being of a country.

The classification of attributes as one of the three mentioned types is not always as evident as it seems, and it can change depending on the problem and on the stakeholders. For instance, the gross national product was first developed as a constructed attribute, but it was also used as a proxy attribute to measure the economic well-being of a country; however, over time it became so widespread that it may now be accepted as a natural attribute regarding the countries' development.

The decision maker must make the selection of the attributes not only based on the most appropriate type for each given objective, but also on the desirable properties of the attributes, which are, as defined by Dr. Keeney, measurability, operationality and understandability. All three are necessary to make the attribute unambiguous.

Regarding measurability, "an attribute that is measurable defines the associated objective in more detail than that provided by the objective alone" (Keeney, 1992). The use of the gross natural product as a measure of the well being of a country, for example, can raise some problems of measurability, since it does not take into account the distribution of the wealth, and could yield distorted results.

Operationality refers to the possibility of an effective evaluation of the consequences regarding an objective by assessing the attribute values, and also to the use of the attribute as a consistent support to the judgment about the desirability of the alternatives.

Understandability refers to the selection of attributes that are not open to misinterpretation. Once a value is assigned to the attribute, everyone involved with the decision will be able to understand it, and the assessment of the consequences and desirability of each value can be made unmistakably. For example, for the fundamental objective "minimize fatalities", a unitary scale could be a suitable option; while a scale that is divided in groups of ten (i.e. from 0 to 10, 11 to 20, and so on) could not be considered as good. For instance, the decision maker might consider not realistic to compute 11 fatalities as having the same value, in the context, as 20 fatalities.

Building the Value Model

The main reason to build a value model is to facilitate the decision making process. The model is supposed to express the qualitative and quantitative relationships between the objectives. By consequence, it will make the objectives clearer, providing some insight to the problem, while also helping to uncover new objectives.

According to Dr. Kirkwood, the following procedure to the formulation of the value model is appropriate for situations in which "there are multiple, conflicting objectives and no uncertainty about the outcome of each alternative" (Kirkwood, 1997).

After the identification of the set of objectives relevant to the decision problem, each of which is defined as O_i, $i = 1, \ldots, N$, and also after performing the selection of the attributes X_i for each of the objectives, the development of a multiobjective value function can be initiated.

"To conduct a multiobjective value analysis, it is necessary to determine a value function, which combines the multiple evaluation measures into a single measure of the overall value of each evaluation alternative" (Kirkwood, 1997). This multiobjective value function *v* will assess the single dimensional value functions *v(x)* for each x_i, i = 1, ... , *N*, which are the levels of the attributes X_i. Also, it will take into account the weights, or scaling constants, defined for each objective O_i, i = 1, ... , *N*. The general form of the multiobjective value function, when there is no uncertainty involved, is presented below, on equation 1.

Equation 1: Multiobjective Value Function

$$v(x_1, x_2, \dots, x_N) = \sum_{i=1}^{N} w_i v(x_i) \text{ , } i = 1, \dots, N,$$

where:

$v(x_1, x_2, \dots, x_N)$ is the multiobjective function,

x_i is the level of the attribute X_i,

w_i is the weight, or scaling constant, defined for the objective O_i,

$v(x_i)$ is the single dimensional value function for the attribute X_i.

The final value obtained for the multiobjective value function *v* could be "thought of as a constructed attribute for the entire set of objectives" (Keeney, 1992). It is supposed to be, in the end of the process, the main support to the decision maker, and that is the reason why it is so important to spend the necessary amount of time in the definition of the single dimensional functions and the weights inserted in the formula, so the model can represent the desirability of the outcomes to the stakeholders as close to the reality as possible.

The main difficulty in the definition of the multiobjective value function is that different attributes are usually measured in different units, with different ranges. For example, suppose that for the objectives "minimize fatalities" and "minimize cost", the attributes "number of fatalities" and "cost" are aggregated in the same multiobjective model with their original units. Since the cost could be close to the millions of dollars for the available alternatives, most probably it would be the only attribute defining the final result, because the fatalities would presumably be far less than these high values. On the other hand, if the unit of cost in this case was "millions of dollars", for example, the situation could be totally reversed, and the fatalities could become the only relevant attribute to the final result.

According to Dr. Kirkwood, "this difficulty can be addressed by normalizing the ratings on each evaluation measure scale" (Kirkwood, 1997). This can be simply stated as defining the range of values each attribute can assume, and checking what is the proportion of achievement of the objective yielded by each alternative, in this scale. The result will be a value ranging from zero to one for each of the attributes. Usually, higher scores are assigned to results that are more desirable for the stakeholders. If, for example, for the objective "minimize cost", the range defined for the attribute "cost" is zero to one hundred, the most preferred result will obviously be zero; if a given alternative has a cost of 20, the score for this attribute would be 80%, or 0.8.

In his explanation, Dr. Kirkwood suggests that the range for the attributes should be calculated using the highest and the lowest values the available alternatives can yield for each attribute. However, following the value-focused thinking concepts, in this work, the range will be calculated using the maximum and the minimum values the attribute can assume in the best and worst case scenario, even if neither of the available alternatives are capable of reaching these levels.

It is worth observing that variations in some attributes can be considered more relevant to the stakeholder than variations in others, but the impact all these variations would cause in the final result of the multiobjective value function would be equivalent, if only the proportion of the ranges is used to calculate the overall result. This problem is solved by assigning weights for each attribute in the multiobjective value function. The assignment of weights is made by determining how important variations in a given attribute are in comparison to variations in the other attributes. By convention, the definition of the weights is done so the sum of them is equal to 1. This yields the convenient consequence that, as the single dimensional value for each attribute ranges from 0 to 1, the worst possible alternative for a problem will have an overall value of zero, and the best possible alternative will have an overall value of one.

Finally, a single dimensional function has to be developed for each attribute to address the issue of the so called "return to scale" effect. This effect is the result of equal increments in the scores of the attributes being perceived differently by the stakeholders, concerning the desirability of the resulting scores. For example, still using the "minimize cost" objective, an increment from 50 to 80 million dollars can be considered, by the stakeholder, worse than an increment from 20 to 50 million dollars, even though the difference between the values is the same.

Defining the Single Dimensional Functions and the Weights

The two types of formulations widely used for determining the most appropriate single dimensional function for each attribute are the piecewise linear function and the exponential function. Piecewise linear functions are used when there is a limited number of possible scores for a given attribute. When the attribute can assume a large, or even an infinite amount of scores, exponential functions are considered more appropriate.

To create a piecewise linear function, the first step is to consider each of the single successive increments in the score of the attribute, and sort them out by order of preference. For the increment the least desirable, or the "smallest increment", it is assigned a variable value x. The next step is to assign a multiple of the value x for each of the other increments in the scale, based on "how much more preferable" they are compared to the smallest increment. That being done, the variable value x will assume a value such that the sum of the increments values is equal to 1.

For example, if there are three possible increments for a given attribute, and the first increment is twice as preferred by the stakeholder as the two following ones, the value of x would be 0.25 ($2x + x + x = 1$). A graphical depiction of this example is provided below, on figure 7.

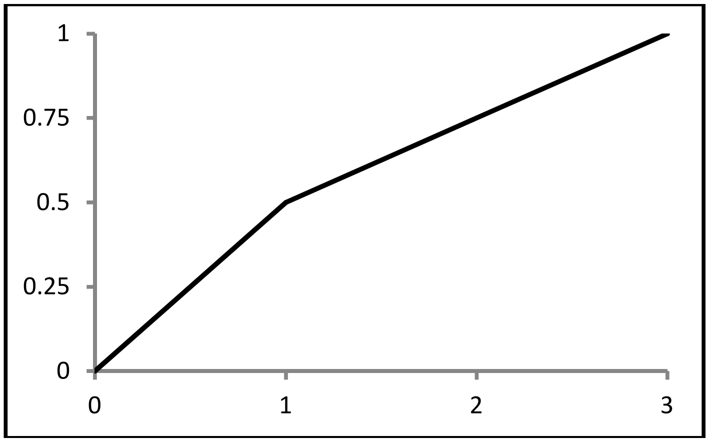

Figure 7: Example of piecewise linear function

In this example, a score of 1 has a value of 0.5 in the function, and a score of 2 a value of 0.75. Clearly, a score of zero has value zero, and a score of 3, being the most preferred, has a value of 1.

To develop the second type of single dimensional value function, the exponential one, a constant called ρ (rho) will have to be defined, which will shape the function curve in the graph. Very large values of ρ make the value function approach the shape of a straight line, and values close to zero make it more curved.

For attributes in which lower valuables are preferred (cost, for example), and with ρ different than infinity, the exponential single dimensional function equation has the format shown on equation 2.

Equation 2: Exponential Single Dimensional Value Function - Decreasing Preference

$$\boldsymbol{v(x)} = \frac{\mathbf{1} - \boldsymbol{e}^{-\frac{\boldsymbol{High - x}}{\boldsymbol{\rho}}}}{\mathbf{1} - \boldsymbol{e}^{-\frac{\boldsymbol{High - Low}}{\boldsymbol{\rho}}}},$$

where,

$v(x)$ is the single dimensional exponential value function,

$High$ is the highest possible score for the attribute,

Low is the lowest possible score for the attribute,

ρ is the exponential constant.

To determine the value of the constant ρ it is necessary to define the midvalue of the possible scores for the given attribute. This value is defined as "the score such that the difference in value between the lowest score in the range and the midvalue is the same as the difference in value between the midvalue and the highest score" (Kirkwood, 1997). Hence, the function value for the midvalue is 0.5. It is worth noting that, if the midvalue is the average of the highest and the lowest possible scores, the single dimensional function is a straight line, and the value of ρ is equal to infinity.

After defining the midvalue, it is possible to plug it together with the known values for the *High* and *Low* into equation 2, displayed above, to find the value of ρ. However, there is no closed form to solve this equation, and consequently, it will have to be done numerically.

Figure 8, below, presents some of the possible shapes the exponential single dimensional value function can assume, depending on the value of ρ.

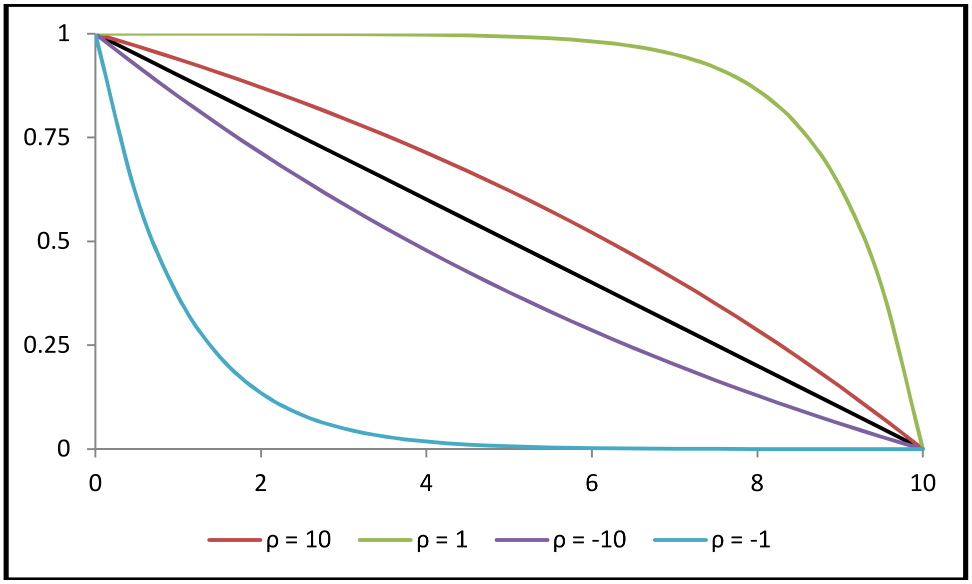

Figure 8: Example of Exponential Single Dimensional Function

For attributes measured by exponential functions in which higher values are preferred, the equation is slightly different, as shown below. The procedures to determine the midvalue and the value of ρ are identical to the ones described previously.

Equation 3: Exponential Single Dimensional Value Function - Increasing Preference

$$\boldsymbol{v(x) = \frac{1 - e^{-\frac{x - Low}{\rho}}}{1 - e^{-\frac{High - Low}{\rho}}}},$$

where,

$v(x)$ is the single dimensional exponential value function,

$High$ is the highest possible score for the attribute,

Low is the lowest possible score for the attribute,

ρ is the exponential constant.

The procedure to determine the weights associated to each objective is very similar to the one described for the piecewise single dimensional functions. The only difference is that, instead of using the single increments in the scores of the attributes, the total range of scores must be considered. More specifically, the increment of the scores from the least preferred level to the most preferred one will be considered by the analyst in this case. Based on consultation of the stakeholders opinion, the attributes must be ranked in order of preference of this increment (or "swing") of the level of the attributes, from the worst score possible to the best one.

After this point, the procedure is identical to the one described previously: assign a variable value to the weight of the least preferred attribute, assign multiples of this value to the weights of the other attributes, and then use this relation to determine the value of the variable, so the sum of the weights is equal to 1.

Performing the Sensitivity Analysis

In this proposed work, the model does not include uncertainty in its parameters. Therefore, the sensitivity analysis will be performed with two main purposes: increasing the understanding of the relationships between input and output variables; and enhancing the communication of the model design and rationale, making its resulting recommendations more credible and understandable to the stakeholders.

The main parameters of interest are the weights assigned to the attributes. More specifically, it is important to determine whether small increments or decrements in the weights selected would have a significant impact in the overall appreciation of the alternatives. This evaluation can also be useful to enhance the credibility and robustness of the model.

The difficulty with varying the weights is that, after changing one of them, the other weights have also to be changed to keep their sum equal to 1. To perform a reasonably consistent sensitivity analysis of each parameter separately, Dr. Kirkwood suggests to keep the ratio between the parameters not under analysis unchanged (Kirkwood, 1997). This can be done using some algebraic manipulation, as can be seen on equation 4, presented below, for $N + 1$ different weights:

Equation 4: Calculation of the Weights for the Sensitivity Analysis

$$\boldsymbol{w_x = (1 - w_c) \times \left(\frac{w_x^o}{\sum_{i=1}^{N} w_i^o}\right)},\ i = 1, \ldots, N,$$

where,

w_x is the new weight assigned to the attribute x, for $x = 1, \ldots, N$,

w_c is the new weight assigned to the attribute c, that is being analyzed ($c \notin \{1, \ldots N\}$),

w_x^o is the weight of the attribute x in the original formulation,

w_i^o is the weight of the attribute i in the original formulation.

BUILDING THE MODEL

Defining the Objectives

To determine the fundamental objectives that are being pursued with the acquisition and operation of a flight simulator, and also the attributes and values associated with this decision problem, as explained in the theoretical foundation, first it is essential to define the main mission of the BAF, which would be the top-level fundamental objective.

According to the Brazilian Air Force's Basic Doctrine, the basic mission of the BAF is to "keep the sovereignty over the national airspace aiming the defense of the homeland" (Brazil, *Comando da Aeronáutica*, 2012). The White Book of National Defense adds to this mission the following: "to prevent the use of the Brazilian airspace for the practice of hostile acts or contrary to the national interests" (Brazil, *Ministério da Defesa*, 2012).

To achieve such a high-level goal, many fundamental objectives have to be derived. The accomplishment of a mission as broad and complex as the one mentioned above involves a wide spectrum of factors, as it can be observed below, in table 2, which presents the factors that are considered the "critical factors to the success" in the vision of the Brazilian Air Force.

Table 2: Critical Factors to the BAF Mission Success (Brazil, *Comando da Aeronáutica*, 2010)

Critical Factors to the BAF's Mission Success
Command and Control capabilities
Combat capabilities
Operational capability in electromagnetically hostile environment
Crisis or conflict areas visualization capabilities
Land and anti-aircraft self-defense capabilities
Combined and joint operation capabilities
Intelligence capabilities
Logistic support capabilities
Deployment capabilities
Operational planning capabilities
Security and redundancy of communications systems
Troop morale
Historical and current financial resources
Human and material resources
Information technology capacity
Technological capacity
Financial situation
Organizational structure
Rationality, modernity, efficiency and administrative effectiveness
Institutional relations
International relations
Reliability of likely allies
Internal politics coordination capacity

After defining the basic mission, the critical factors listed above, and the principles and values of the Brazilian Armed Forces, and also after the analysis of the current situation and of the likely future scenarios, the fundamental and the means objectives of the BAF were derived, as pointed in the Air Force Strategic Military Plan (AFSMP). The high-level objectives of the BAF, also referred to as strategic objectives in that document, are presented below, on table 3.

Table 3: Brazilian Air Force Strategic objectives (Brazil, *Comando da Aeronáutica*, 2010)

BAF Strategic Objectives
1. Achieve excellence in the control of the airspace under responsibility of the Brazilian Air Space Control System
2. Achieve excellence in the operational capabilities of the BAF
3. Optimize the organizational management of the BAF
4. Improve the support to military and civilian personnel in the BAF
5. Modernize the human resources formation and graduation systems
6. Expand the scientific and technological capabilities of the BAF
7. Strengthen the Brazilian airspace and defense industries
8. Enable the country to develop and construct airspace devices
9. Integrate permanently the defense mentality development in the Brazilian society
10. Maximize the acquisition of strategic budgetary and financial resources

The relationship between these high-level objectives and the basic mission of the BAF are showed on figure 9. The ten listed strategic objectives are subdivided into lower-level objectives, referred to as "strategic measures", in the AFSMP. Even these strategic measures can still be considered very broad objectives, that will have to be later subdivided. However, they are specific enough to allow the identification of the contribution to each one of them of a more quantifiable and lower-level decision, as an acquisition of material, for example.

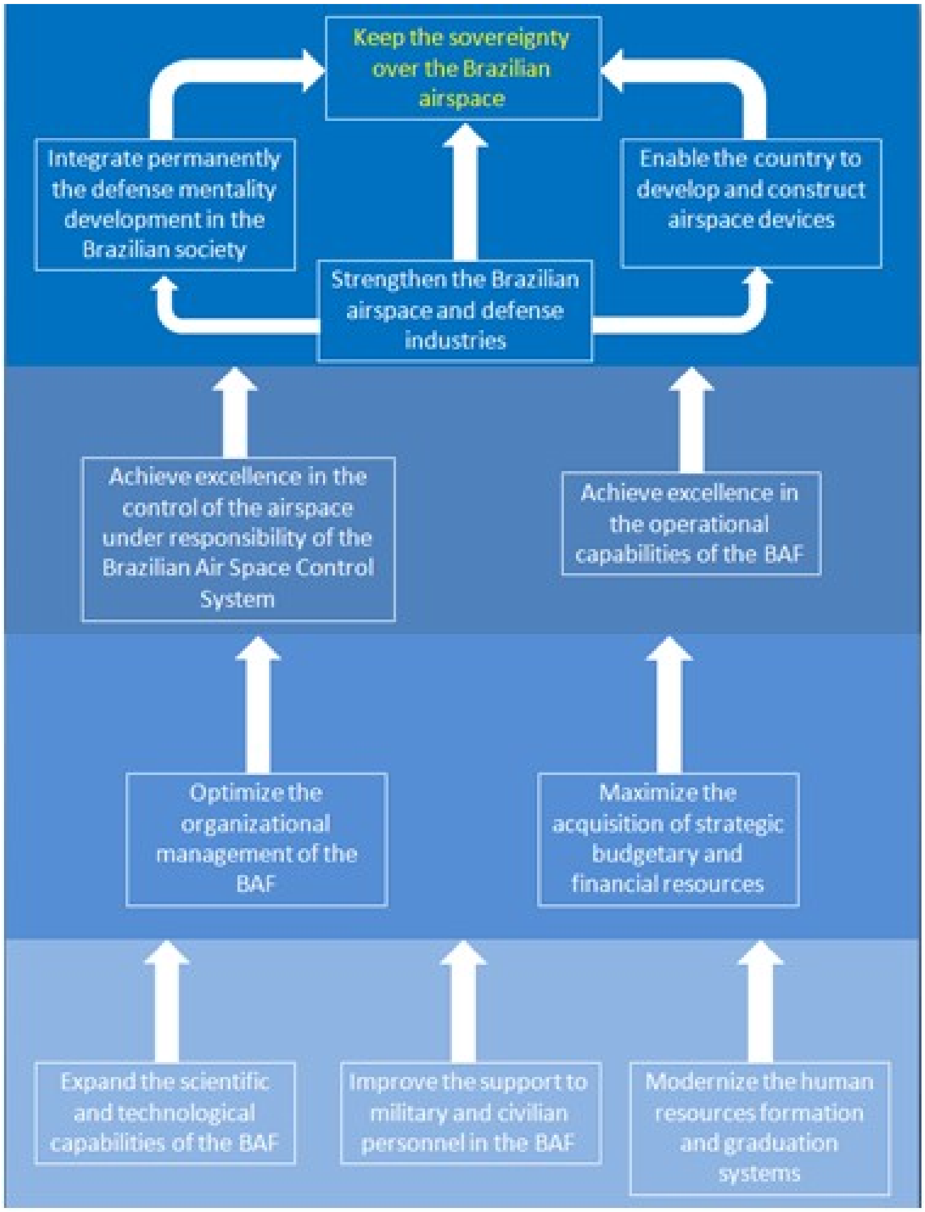

Figure 9: BAF Strategic Objectives (Brazil, *Comando da Aeronáutica*, 2010)

Within the scope of this Thesis, there is one specific strategic objective that is mostly of interest, which is to "achieve excellence in the operational capabilities of the BAF". This objective is subdivided into three strategic measures (Brazil, *Comando da Aeronáutica*, 2010), as follows:

- Optimize the operational processes, systems and activities;
- Optimize the aeronautical and airport infrastructure;
- Perform the BAF's operational equipping.

With the implementation of the very advanced flight simulators proposed in this Thesis, the operational processes and activities could be largely enhanced, impacting directly on the first mentioned strategic measure. Also, the "combat capabilities" and the "combined and joint operation capabilities" are mentioned in the Air Force Strategic Military Plan as "critical factors to the success" (Brazil, *Comando da Aeronáutica*, 2010). The use of linked high-fidelity flight simulators could also contribute substantially to the increment of both.

However, to improve the operational capabilities of the Air Force is not the only objective involved in the acquisition of a flight simulator. Actually, although it can be used for the purpose of enhancing the operational capabilities, as it is being done currently by the USAF and the SAF, this use would be an innovation in the BAF's fighter aviation.

As stated previously, in the problem description, the main reason that leads an Air Force to make the acquisition of a flight simulator is to reduce costs with the training of the crews. Besides, as mentioned in that same chapter, the budget available to the Ministry of Defense in Brazil is not increasing at the same rate as its economy, what suggests that alternatives to achieve the organization objectives that are less costly would probably be not only desirable, but almost a necessity to the BAF. In this context, the reduction of costs seems to be a considerably important objective in the acquisition of any equipment, especially the ones related to fighter aircraft, which are highly expensive to purchase, and equally or even more expensive to maintain.

Regarding the use of financial resources, the strategic objective number 10, "maximize the acquisition of strategic budgetary and financial resources", is subdivided into two strategic measures (Brazil, *Comando da Aeronáutica*, 2010):

- Carry out the political management, through the Ministry of Defense, on behalf of the BAF's budget;
- Optimize the budgetary and financial management.

Thus, to purchase an equipment that is supposed to provide the required training to the crews spending the minimum resources possible is definitely desirable, since it would be a sort of optimization of the financial resources.

Therefore, there are two very clear objectives regarding any purchase of a flight simulator: enhance the operational capabilities of the aviators, and reduce the costs with their training. In other words, a model that accounts for the influence of a given flight simulator in these two objectives can be used to compare the available alternatives, when the decision to be made concerns the acquisition of this type of equipment.

Depending on each specific situation, other objectives could arise. For example, if the acquisition of the equipment could bring technological innovations that would facilitate the development of other fields, strategic objective number 6 ("expand the scientific and technological capabilities of the BAF") could have to be assessed, and an attribute (or more than one) related to that goal incorporated into the model. Also, due to the nature of the business itself, objectives external to the BAF could appear, such as giving preference to a specific manufacturer in exchange of some type of benefit to another department of the government, for example. Although unrelated to the organization's objectives, this type of objective would be part of the decision, and consequently would have to be incorporated to the model.

As already mentioned, these are very specific situations, although conditions similar to those will be present in the majority of the decisions. The model proposed in this work will take into consideration only the two main objectives of the acquisition of a flight simulator, which are the increment of the operational capabilities and the decrement of the expenditures. It will be up to the decision maker to analyze any specific decision opportunity and incorporate to the model other objectives and attributes that can have an influence in the final result.

Decomposing the Objectives: Increase the Operational Capabilities

It has already been stated that the two objectives, or strategic measures, as they are called in the AFSMP, involved with the given decision problem, are still relatively broad to be worked with; hence, they will have to be broken down into lower levels, so attributes can be properly defined to measure their accomplishment.

The first objective that was analyzed was "optimize the operational processes, systems and activities”, which is part of the strategic objective number 2, "achieve excellence in the operational capabilities of the BAF" (Brazil, *Comando da Aeronáutica*, 2010). For simplicity, this strategic measure was simply called "optimize operational activities", and the focus was only in the air combat activities, since the proposed flight simulators are intended to be used for the training of fighter pilots.

The derivation of that strategic measure could occur in many different manners, but the one that seemed the more logical was the division into lower level objectives related to the optimization of the aerial missions for each specific type of air mission currently executed or possible to be executed by the BAF's fighter pilots.

Regarding the fundamental hierarchy, to avoid making this research very extended, it was focused on the objectives that could be related to the purchase of an air superiority fighter aircraft only. The main reason for this choice was that the air-to-air combat training is the field in which the biggest evolutions in flight simulators occurred in the recent years, and thus, objectives unrelated to this specific type of combat would probably aggregate very little to the model, in this case. Hence, for the purposes of this Thesis, the only operational activities considered relevant to the decision maker were the ones related to the air-to-air combat capabilities.

Prior to building the fundamental objectives hierarchy, it is important to understand clearly the objectives being pursued. It is not evident, at first, how a flight simulator can be used to increase the operational capabilities of the pilots. After all, the main purpose of operating these equipment is to save a portion of the resources spent with the preparation of the aviators. This is achieved by enhancing the productivity of the live-training missions with the previously executed simulated training. From this simple statement, it could be inferred that, if there were unlimited time and money available, everything the pilot does in the simulator could be done equally on the aircraft, and the simulators would not be necessary. However, this conclusion is completely mistaken.

The reason why it is wrong is that there are many important procedures that can be efficiently practiced in the simulator, but not in a live-training situation. The more apparent one is the training of emergency procedures. For obvious reasons, it cannot be practiced in an aircraft, and the benefits of practicing it under simulated conditions, instead of only knowing the theory without any further practice, are invaluable. Boeing once reported that, after landing successfully a C-17 with a damaged engine, the pilot said: "It was nothing different because I was so used to the simulator" (Marken *et al*, 2007).

Also, many of the limitations encountered during the live-training in an aircraft are not constraints for the simulated missions. The safety constraints are almost inexistent, making it possible to practice emergency procedures under very realistically simulated aircraft-damage conditions, for example. Equally, the environment and the war scenario expected to be found in a particular mission can be reproduced to the pilot in the simulators, improving the preparation for a scheduled deployment; on the other hand, during the live-training missions, besides the impossibility of practicing in the real combat areas, the training is usually limited by the regular aviation policies.

Another benefit provided by the use of simulators is that the missions that are denominated Large Force Employments (LFE), such as the Red Flag, a very famous advanced aerial combat training exercise, can be practiced much more frequently than it is possible to do in live-training campaigns. These missions are characterized by, as its name suggests, the use of a massive number of flight assets in the same air theater, creating a complex aerial war scenario that tries to replicate a close-to-reality situation of combat. Although the live-training of this type of mission provides more improvement to the pilots' capabilities than the simulated training, it is infeasible to take part of a campaign this large on a regular basis; however, a frequency of one mission a month, for example, can be easily achieved with simulated missions. And this can help to improve and maintain the operational capabilities of the fighter pilots, surely raising it to higher levels than it would be if the frequency this type of mission is practiced was limited by the live-training campaigns participation only.

Although the use of simulation in the preparation of fighter pilots can be considered a relatively new field, some research has already been done to try to determine more precisely the effects it can have in the increment of the piloting skills. According to a survey conducted by RAND Corporation with USAF fighter pilots, the "live training that is supported and augmented with appropriate high-fidelity simulator training profiles can be more effective in preparing pilots for the imminent combat operations than live training alone" (Marken *et al*, 2007). It is important to observe that, what is being suggested by this statement, and that is in complete accordance with what is being proposed in this work, is that the high-fidelity simulators are not supposed to replace the live-training, but to enhance the operational preparation of the pilots by providing specific scenarios and conditions that cannot be experienced in the real aircraft, and the training of missions that are too expensive to be practiced on a regular basis.

The increment in the aviators' experience due to the use of flight simulators, as mentioned above, will depend on the training profile adopted. It is not the focus of this work to find the optimal training profile for each specific flight simulator and Air Force;

hence, it will be assumed that the flight simulators will be used in their optimal capacities, or in other words, the benefits achieved by the training will be the maximum possible that each different machine is capable to provide.

Although it is now clear that the objective "optimize operational activities" can be pursued with the usage of flight simulators, it is not as clear until what extent it can be accomplished. For example, the current simulators used by the BAF are an excellent tool to help in the development of basic piloting skills, such as standard and emergency procedures, and IFR training; however, they lack most of the features needed to practice an LFE mission. The high-fidelity trainers used by the SAF can reproduce LFE scenarios in a manner that facilitates enormously the development of the skills related to that specific type of missions; in contrast, unless the operator is a pilot of the Gripen aircraft, it will be virtually useless in the adaptation of the pilot to his aircraft's basic procedures.

From this brief explanation, it was possible to infer that the objective "optimize operational activities" should be broken down into lower level objectives, and one form this lower level could assume is the division into every possible type of training missions the simulators could be used to practice, and consequently, enhance the pilots' capabilities.

Different Air Forces provide different denominations for their sets of training flight missions, and also, distinctions exist between what is practiced by each of them, since varied objectives are pursued in the preparation of distinct Air Forces' pilots. Thus, in this Thesis, a frame composed by sets of the main training missions practiced by the USAF F-15C flight squadrons was used. The selection of this frame was made essentially for two reasons: the main mission of the USAF F-15C Air Units is air superiority, which is directly related to the overall objective of the BAF, and to the type of operational activities this research is focused on; and second, these squadrons were the first to operate high-fidelity flight simulators in the USAF, making the training profiles they use more adapted to these equipment.

The sets of training missions, and their respective descriptions (Bigelow *et al*, 2003) are, as follows:

- Aircraft Handling Characteristics (AHC): most basic missions, intended to familiarize the new pilot to the performance of the aircraft. The training of standard procedures such as departures and landings, and also of emergency procedures, is part of this set of missions, which is composed mostly by single-aircraft sorties. It is also intended to familiarize the pilot with the flight maneuvers and equipment that will be used in the air-to-air combat;
- Basic Fighter Maneuvers (BFM): missions designed to develop the air-to-air combat techniques required by the isolated aircraft to fight against a single enemy (1 x 1);
- Air Combat Maneuvers (ACM): exploration of the combat techniques to properly maneuver a two-aircraft formation against a hostile single aircraft, stressing the provision of mutual support (2 x 1);
- Tactical Intercepts (TI): the objective of this type of missions is to familiarize the pilots with the non-visual methods to execute the sorting,

targeting and the engagement techniques employed against an enemy threat. The sorties can be made by a single aircraft, or a multi-ship formation;

- Air Combat Tactics (ACT): designed as a step above in difficulty to the TI missions, the main purpose of this type of training is to insert the pilots into a more complex and realistic aerial war scenario. Sorties are made with a two-ship formation (2 x X) or a four-ship formation (4 x X);
- Large Force Employment (LFE): preplanned training missions with very complex scenarios, in which one or more four-aircraft friendly formations combat against an also large-force threat. It enables the practice of the rules of engagement and situation awareness that are inherent to this type of mission only.

Each is of these types of missions is essential to the development of the operational capabilities of the fighter pilots, and the more basic missions provide the foundations for the more advanced ones. This means that, although the ACT and the LFE are the missions that are more closely related to the preparation for a real combat situation, the less complex missions must also be practiced regularly, in order to maintain, in a satisfactory level, the skills required to a better accomplishment of the more advanced ones. For a better understanding, the six types of missions can be arranged in a building-block model, as displayed on figure 10.

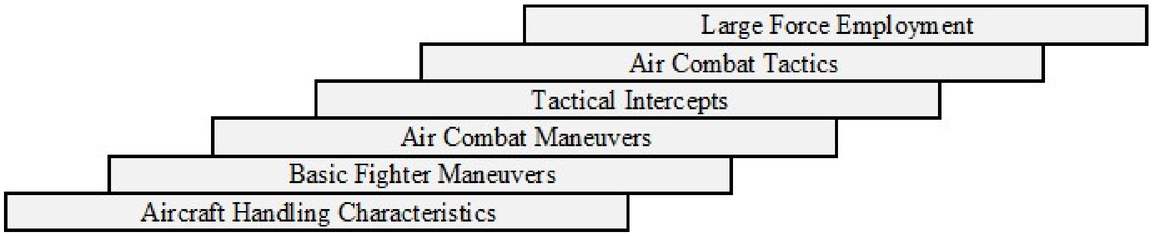

Figure 10: Building-Block Model of Training Missions for the F-15C (Marken *et al*, 2007)

The optimization of the operational capabilities of the pilots, regarding each of these types of missions, can be defined as the fundamental objectives in the level directly below the strategic measure "optimize operational activities". Hence, after reducing the more broad fundamental objectives hierarchy of the BAF to include only the objectives that are relevant to the decision context of the acquisition of flight simulators for the fighter aviation, and with respect only to the objectives that are related to the increment of the operational capabilities, with focus on the air-to-air combat, a graphical representation of the levels of more interest of the objectives hierarchy would be depicted as shown below, on figure 11:

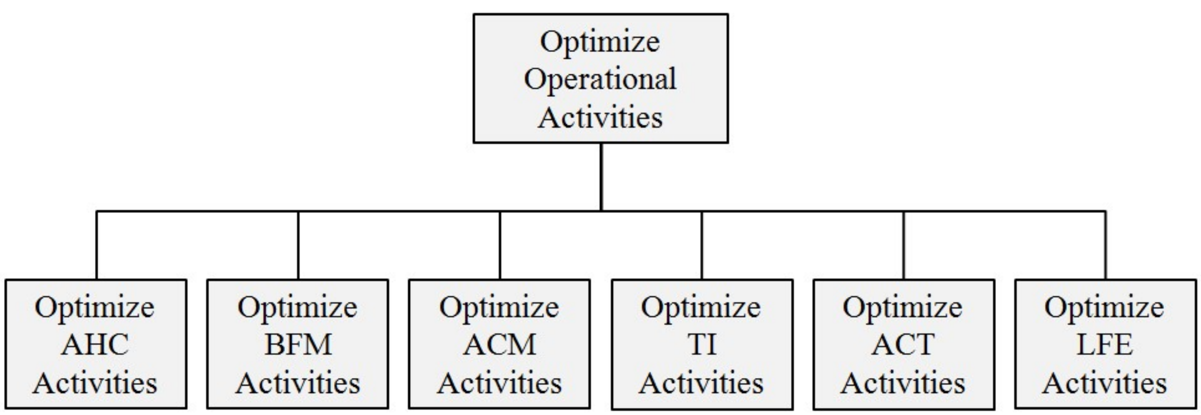

Figure 11: Operational Activities Fundamental Objectives Hierarchy.

These six objectives are detailed enough to allow the development of associated attributes intended to measure their accomplishment, for each of the available alternatives.

Defining Attributes: Operational Capabilities

A large number of researches, intended to define the most appropriate measures to evaluate the contribution of flight simulators to the training of combat pilots, has been done since this contribution has been acknowledged, starting around the seventies. In 1977, Paul W. Caro identified and described 10 different methods to perform the evaluation of the effectiveness of the simulated flight training (Caro, 1977).

Two decades later, all those approaches were grouped in only three categories: utility evaluations, in-simulator learning and transfer of training (Bell & Waag, 1998).

Utility evaluations are made based on the opinions of the experts in the field of interest, after using the simulators for a specified number of missions. It is the most straight forward approach to perform this type of evaluation, and consequently, it is the most frequently applied method. Although the data produced could be considered somewhat subjective, the "positive user acceptance is a necessary condition for the acceptance of a simulator" (Bell & Waag, 1998), and the proper analysis of the data can provide very consistent results.

In-simulator learning refers to the measurement of the improvement of the performance of the pilots after each session of simulated training. The theory involved is that, if no improvement is observed from one simulated mission to the next, there will be no transfer of learning to ameliorate the performance in the real aircraft.

Transfer of training is the same as in-simulator learning, but the performance of the pilot during the live-training missions is the object of evaluation this time. Many researchers think that this is the best way to prove the effectiveness of simulator training, but such evaluations are very difficult to be conducted. In addition, in the case of a decision regarding the acquisition of a new simulator, for example, this analysis cannot be made prior to owning the equipment, what makes this method useless to help in the decision process.

The approach adopted in this Thesis was the first one, utility evaluations. This method was used, more specifically, to assign scores to the single dimensional value functions, that will be developed to quantify the level of accomplishment of each of the six blocks of missions described previously, for each type of flight simulator (the available alternatives).

The characteristic that better defines the value of the training provided by a flight simulator is, in few words, "how realistically it can reproduce the situations and conditions that are relevant for a specific type of mission to the pilot", or in other words, the level of "fidelity" of the simulation. For example, for an IFR mission (part of the AHC), the capability of reproducing properly the weather conditions, as reduced visibility, and also to emulate the behavior of the instrument aids on the ground, could be considered the most relevant aspects. For an ACT mission, the capability of the simulator to emulate the enemy aircraft's behavior, and the proper simulation of the weaponry systems, could be considered some of the more relevant characteristics.

To determine the scores for each available alternative, a survey was conducted with fighter pilots that have some experience with the proposed equipment. It was up to the operators that took the survey to define what are the most relevant characteristics for each set of missions, according to their experiences. They were provided a description of the intended meaning of each score in the range, and then, asked to assign a score for each block of missions, according to their prior trainings and experience with the flight simulators involved in the decision problem.

The scores defined for the proposed decision problem ranged from negative 1 to 4. The choice to start the scale with a negative value was made to account for the effect of the possibility of negative transfer. Negative transfer is defined as "the learning, in simulation, of behavior that is rewarded with success on the simulated battlefield but is inappropriate on a real battlefield" (US Congress, Office of Technology Assessment, 1995). It is, consequently, even less desirable than the complete lack of simulation capabilities.

The next value on the range is zero, corresponding to the total lack of simulation capabilities for that specific block of missions. The following scores correspond to increasing levels of simulation capabilities. Table 4, below, presents the possible scores and their respective descriptions. The exact same table was provided to the experts, so they could use it as a basis for the scores they assigned.

Table 4: Level of Fidelity of the Simulator Reproduction of the Live-Training Conditions

Attribute score	Description of attribute score
-1	The simulator reproduces the flight conditions and situations very differently than the ones encountered during the live-fly, and its use can result in a negative transfer of skills to the live-fly.
0	The simulator does not reproduce the conditions or situations related to that mission.
1	Some of the situations and conditions encountered in this type of mission are reproduced by the simulator in an acceptable manner, but there are many relevant distinctions. Its use does not aggregate much value to the performance of the pilot during the live-fly.
2	The majority of the situations and conditions encountered during the live-fly are reproduced by the simulator, but there are few relevant distinctions. Its use aggregates value to the performance of the pilot during the missions in the aircraft.
3	The reproduction of the type of mission by the simulator is almost perfect, and the distinctions with the live-fly are irrelevant. The use of the simulator aggregates value to the perfomance of the pilot equally or more than the live-fly would do.

Regarding the single dimensional value function, the value of a score of negative one (lowest score) was set to zero, and the value of a score of three (highest score), to one, as explained previously.

To define the values associated with the intermediary scores, it has been taken into consideration that, although negative transfer is the less desirable possible consequence of the use of flight simulators, the impossibility of reproducing any aspect of the training missions, which means the uselessness of the equipment for that end, is almost as undesirable as the negative transfer. Thus, the increment from negative 1 to zero was set as the "smallest increment" in value.

The following increments were considered as having equivalent values, since the increment in the performance of the pilots, and the capability of the simulators to reproduce the live-training conditions increase progressively with the scores. Also, based on experience, these increments were set as having three times the value of the first increment. Thus, the single dimensional value function designed to measure the achievement of the optimization objectives, for each one of the sets of missions, can be graphically represented as shown on figure 12.

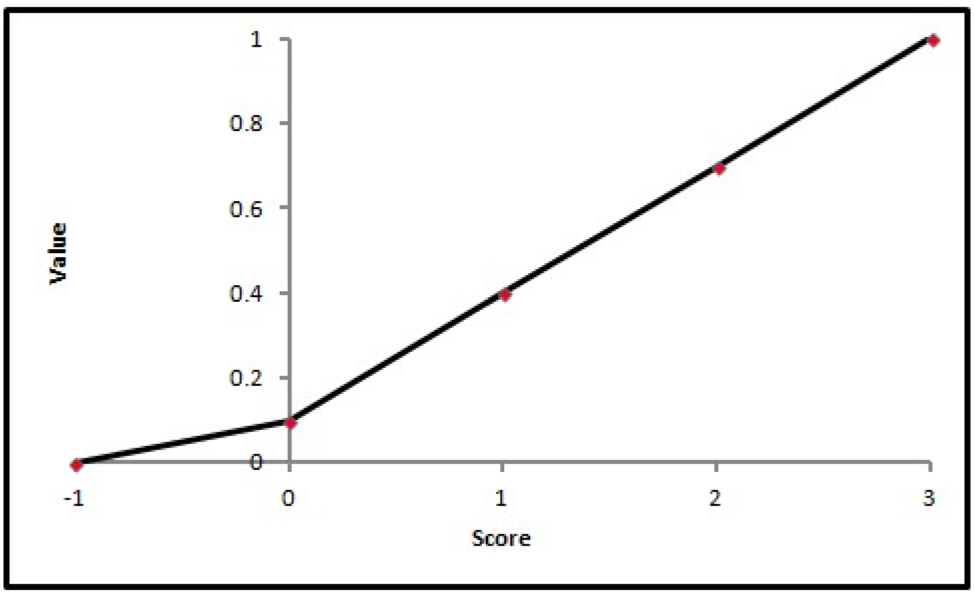

Figure 12: Single Dimensional Value Function for the Operationality Optimization Objectives

For scores lying between the ones defined above, the respective function values were estimated using the straight lines depicted in the graph (in other words, the function value of this score was defined using the function values of the two adjacent scores).

The next step was the definition of the weights associated to each of the attributes. The definition of which type of mission is more important, or more relevant, for the higher objective of optimizing the operational activities, turns out to be a hugely complex task, and two main factors are responsible for this complexity:

- all the sets of missions are related, and failure to provide an adequate training for one of them can affect the foundations needed to achieve a satisfactory performance in the subsequent one. The most advanced sets of missions are the more effective ones in the preparation for a real combat situation; however, if the training missions in the more basic sets are not properly executed, the pilot does not learn the basic skills required to successfully accomplish the following more complex missions;
- within a fighter squadron, there are pilots with many different levels of experience. This results in distinct needs in their preparations for the combat. For example, a more experienced pilot will be required to practice AHC in the simulator less than once every two months, whereas a student pilot (in the first year piloting the specific aircraft) will probably devote the majority of his time in the simulator to AHC training missions.

To find an optimal allocation of weights, surveys could be taken with the experts (the aviators), as it was done for the assignment of scores in the single dimensional value functions. However, one problem very likely to happen would be the influence of the pilots' personal condition or necessities in the result; the problem is that the evaluation the analyst is looking for is more intended to consider the "big picture", instead of each particular situation.

A coherent approach to solve the problem was the use of the proportion of "hours of simulation" spent in the training of each block of missions by the F-15C squadrons. This amount of use does not necessarily corresponds to the importance of each type of missions, but it is reasonable to assume that, the more the flight simulator is used to practice a specific type of mission, the more disadvantageous would be for the squadron not having the simulator available. This is not the same as saying that the more practiced missions are the ones that aggregate more value to the aviators, but it is logical to conclude that, if the missions that have to be practiced more frequently using simulation cannot be executed, other methods will have to be found to provide this same training, assuming it is necessary to provide it; thus, frequency of execution matters, and it is somehow related to the relevance of the type of mission.

Nevertheless, exact data describing how military flight hours are spent, or even how simulated flight hours are spent, is not easily available through open sources, and only estimates, with approximate numbers, can be gathered. For the purposes of this Thesis, these estimates were considered appropriate for the assignment of weights; the impact of small variations in these numbers was object of the sensitivity analysis.

A research conducted by RAND Corporation presented the distribution of the flight hours per type of sorties for the F-15C squadrons in 2009, and included the hours of simulated training, also discriminating the type of mission performed (Ausink *et al*, 2011). After analysis of the graphically depicted distribution, it was possible to draw some conclusions, of interest to the proposed method of assignment of weights:

- the amount of hours spent with Offensive Counterair (OCA) and Defensive Counterair (DCA) missions, which, by definition, belong to the set of ACT training missions, is approximately the double of hours spent with TI simulated missions;
- the amount of hours spent with ACM missions is relatively less (around 2 thirds) of the number of hours spent with TI;
- the hours spent with AHC (which include the IFR training) were considerably less than the hours spent with the other types of mission.

Two other considerations shall be made about this analysis: first, it was assumed that the LFE missions are inserted in the OCA and DCA in the distribution (which also includes the ACT), since LFE missions are, in essence, characterized as one of these two types of more specific (lower-level) mission. Second, it was not explicit if the hours spent by the student pilots were computed or not in this distribution. It was thus assumed they were not, since, depending on the number of new pilots, the amount of hours spent with AHC training could be significantly higher than the one presented.

A survey conducted with F-15C pilots in another occasion provided very similar conclusions to the ones presented above. They were asked to provide the optimum number of simulated training missions they judged should be executed monthly. Again, the survey was not clear about the participation of student pilots. The results provided were: less than one ACM, four ACT, and one LFE. As occurred with the previous distribution, the BFM missions did not appear, what makes sense, since it is very difficult to emulate the most relevant conditions of this specific type of mission using flight simulators. Also, for some reason, TI missions were not part of the survey, neither concerning the simulator, nor the live flight hours. Thus, it was assumed that the TI sorties were included in the number of proposed ACT sorties (by definition, ACT missions are similar, but more complex, than TI missions).

Comparing the collected data, and using reasoning, the weights were defined, as follows: AHC 0.26; BFM 0.02; ACM 0.08; TI 0.17; ACT 0.35; LFE 0.12. A deeper explanation about the reasoning applied to get these values was provided on the Appendix 1.

Finally, for the objectives related to the operational activities optimization, the multiobjective value function was defined as:

Equation 5: Operational Activities Value Function

$$\boldsymbol{v(x_1,\dots,x_6) = 0.26 * v_{AHC}(x_1) + 0.02 * v_{BFM}(x_2) + 0.08 * v_{ACM}(x_3) + 0.17 * v_{TI}(x_4) + 0.35 * v_{ACT}(x_5) + 0.12 * v_{LFE}(x_6)} ,$$

where:

$x_i, for\ i = 1, \dots, 6$, is the score of the attribute X_i, (following the order of the blocks of missions, from AHC to LFE),

$v(x_1, \dots, x_6)$ is the multiobjective value function for the higher objective "optimize operational activities",

$v_{AHC}(x_1)$ is the value function for the objective "optimize AHC activities",

$v_{BFM}(x_2)$ is the value function for the objective "optimize BFM activities",

$v_{ACM}(x_3)$ is the value function for the objective "optimize ACM activities",

$v_{TI}(x_4)$ is the value function for the objective "optimize TI activities",

$v_{ACT}(x_5)$ is the value function for the objective "optimize ACT activities",

$v_{LFE}(x_6)$ is the value function for the objective "optimize LFE activities".

This concludes the definition of the first part of the proposed value model. The next step was to develop the value model for the objectives concerning the costs involved in the acquisition and operation of flight simulators.

Decomposing the Objectives: Optimize Budgetary Management

For the second fundamental objective involved in the decision problem, the strategic measure "optimize budgetary management", that is part of the strategic objective number 10 " maximize the acquisition of strategic budgetary and financial resources", the approach was the same used previously. First, it was decomposed into lower level objectives, in order to allow the identification of attributes, which was the next step of the process.

The basic concept involved with the budgetary management is that the alternatives that can save more resources, or that spend less of them, are more desirable than the ones that are more costly. This concept guides the creation of the attributes, making higher values be assigned to the less costly alternatives.

Through the use of flight simulators, there are two main processes, or objectives, that are somehow related to the budget management: the acquisition and operation of the equipment, and the savings on aircraft flight hours (and all the resources involved with the aircraft operation) that result from the simulated training.

The former refers to the direct and indirect costs related to owning and operating flight simulators. Although the first expenses that come to mind are the ones related to the purchase and the cost of the "simulated flight hour", there are many other expenses that have to be accounted for. The correct term to refer to these expenses is "life-cycle cost", and it can be defined as the "total cost to the government for a program over its full life" (Nelson, 2015). It should, thereafter, include the costs with the acquisition, the operation (including the support) and the disposal of the equipment.

Regarding the decision problem proposed in this Thesis, the objective concerning the life-cycle cost can be summarized by the short statement "minimize the life-cycle cost". The cheapest alternative would be the most desirable one, regarding this objective. However, as it will be explained later, it is not so simple to define all the costs that are associated with each alternative.

The second manner the use of flight simulators can impact the budget is through the savings it can bring to the amount of flight hours spent on the live-training. It is important, though, to make it clear that the simulated training is not supposed to substitute the live-training simply as a cheaper, thus preferable, alternative. There are some characteristics of the missions in the aircraft that cannot be replicated by the flight simulators, and to cut the amount of allocated flight hours due to the simulated training could be extremely harmful to the level of readiness of the pilots. Among all the possible negative effects, the most apparent one is the loss of what is called by the aviators as "airmanship", which "covers a broad range of desirable behaviors and abilities in an aviator" (Wikipedia, 2015).

However, it is undeniable that there are many factors that make the flight simulators necessary and, in some cases, essential, for the pilots to achieve the required level of preparation. This excerpt, taken from a project of RAND Corporation (Ausink *et al*, 2011), makes this problem very transparent:

> "The U.S. Air Force is finding it increasingly difficult to safely and affordably train combat air force aircrews so that they will be prepared for combat conditions. [...] Reduced flying hours are insufficient to meet Ready Aircrew Program training requirements, and training ranges are insufficient to properly train and support new combat capabilities. In addition, safety considerations, mission complexity, airspace and range restrictions, and real-world commitments and costs limit the amount of training that can be accomplished in live aircraft. Air Force training experts believe that the increased use of simulators [...] are required to mitigate training risks."

Thereby, it is clear that the training in flight simulators could be used to complement the real aircraft training, and that determined levels of readiness can be achieved by the pilots with a mix of simulated and live-training missions. This "package" of training missions will include less real aircraft sorties than the same level of training using only the aircraft would require. Consequently, the total amount of resources spent will be reduced, since one hour of simulated training costs only a fraction of the total cost of one hour of flight in the aircraft.

It can be concluded from this reasoning that, although having an inherent life-cycle cost, flight simulators are also means to economize resources. This economy occurs in the long-term, lasting for the time of the life-cycle of the equipment.

Following the same principle applied to every budgetary objective, the objective related to the savings generated by flight simulators could be summarized as "maximize savings with flight hours". Nevertheless, this statement creates a huge problem: to maximize the total savings, the alternative of replacing all flight hours by simulated flight hours would be the most desirable, and that is simply not what is being pursued.

Actually, there is an optimal mix of aircraft training and simulator training, a point after which increasing the number of simulated missions would bring more disadvantages than benefits. For the purposes of this work, the optimal number of sorties, for each block of missions, was defined as the average number of missions considered optimal by the experts, according to the survey taken. Also, ratios were defined for each type of mission, and these ratios will be the factor used to determine the amount of savings that is considered possible for each alternative.

According to the definitions presented, the objectives hierarchy, for the level directly below the strategic measure "optimize budgetary management", regarding the decision problem of the acquisition of a flight simulator, can be depicted as presented on figure 13.

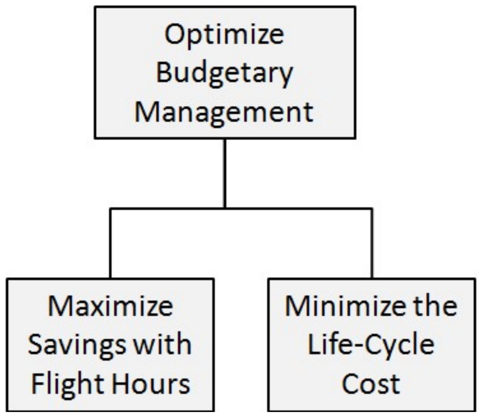

Figure 13: Budget Optimization Fundamental Objectives Hierarchy.

Defining Attributes: Minimize Life-Cycle Cost

The life-cycle cost can be measured by two attributes: the most straight forward is the monetary unit, whether it is in dollars or any other currency; the second attribute that can be used is the fraction, or the proportion, of the budget allocated for the decision problem that is being consumed by each alternative.

For any of the attributes, it is interesting to define the value range using the minimum and maximum possible budgets allocated to the decision, and not only the costs yielded by the alternatives. This way, alternatives other than the ones being considered can be evaluated and ranked without changing the function values of the already evaluated alternatives.

In this work, the attribute used to measure the life-cycle cost was the monetary unit, in US dollars. However, whatever the unit selected to be the attribute for this objective was, the results provided by the model were supposed to be the same.

The calculation of the life-cycle cost includes, as mentioned before, three phases of the project: the acquisition, the operation and the disposal. As the acquisition of an equipment such as a flight simulator has long-term effects, the result obtained by the simple summation of the costs over the years will not provide a satisfactory parameter of evaluation. For costs (and savings) in future years, discounting must be applied. "Discounting is used in valuation because we often want to determine the value today of some future value or cash flow" (Drake & Fabozzi, 2009).

The acquisition and the disposal costs can be provided by the manufacturer, estimated by comparison with similar systems, or gathered using any other method the decision maker judges appropriate. In the end of the process, the final result will be a value (or an interval of values) that assumedly summarize these costs.

However, regarding the operation costs, there exists a problem that has to be addressed with a different method: the amount of use of the simulator will depend on its capabilities. Obviously the amount of use, or hours of use, which will later be expressed as an operational cost, could be generalized to a determined number for every alternative; multiplying this number by the cost of the "simulated flight hour" would yield a result for each one of them. But by doing so, we could be counting hours that would not be aggregating anything to the operational capabilities of the pilots, in the case of a less capable simulator. Assuming that an optimal mix of live and simulated training is adopted by the operators, these hours would not have to be spent; thus, the resulting cost would not be real, or at least, would not reflect the cost of the optimal use of the simulator.

Another way to look at this same problem is to acknowledge that the more capable the simulator, the more simulated missions will be executed, and the less real flight missions will be needed, for the pilots to achieve the same level of readiness. This means that, with the increment of the simulation capabilities, the total cost related to flight hours will decrease, but the opposite will happen with the expenses with "simulated flight hours", and not only because modern flight simulators are more expensive to operate, but also because a larger number of missions will be executed on it.

To account for this difference, many distinct methods could be applied. The one adopted in this work was to make a survey with the experts, pilots who have experience with the flight simulators involved in the decision problem, or similar to them, and ask their opinions. More specifically, they were asked to, for each type of mission, as presented in the previous chapter, specify the number of missions a pilot is required to practice monthly in the simulator to complement his preparation, maintaining his readiness in the optimal combat-ready level.

The data provided in the survey was further analyzed, and the number of simulated missions executed monthly using each of the available alternatives, for the purposes of the model, were defined according to this data. After that point, it was only a matter of multiplying these numbers by the estimated cost of the "simulated flight hour", and also by the estimated number of users.

For student pilots, a greater number of missions is required to enhance their skills until reaching the desired levels of readiness, than for a combat-ready pilot. This number of missions depends on the training profile adopted by the Air Unit; for the purposes of this work, based on experience and opinions of experts, it was considered that this number was twice the amount required for a combat-ready pilot.

After gathering all the costs (acquisition, operation, disposal, and any additional applicable cost), they must be added, applying the discounting whenever needed, and the final results compared to the estimated budget for the project.

After the definition of the highest and the lowest (usually zero) possible values, it is possible to determine the single dimensional function value referent to the life-cycle objective for each alternative. For this end, exponential functions were applied, as explained in the theoretical foundation. The definition of ρ, in the value function, depends on the decision maker preferences. For the purposes of this Thesis, it was assumed a slight aversion to cost increments, represented by a ρ with value equal to negative 200.

Defining Attributes: Maximize Savings with Flight Hours

Another measure that is very complex to be defined exactly is the number of flight hours that can be spared due to the simulated training. In fact, what is being proposed is not to replace flight hours by hours of flight simulator, but to use the flight hours that are not necessary, due to the enhancement of the readiness of the pilots provided by the simulation, to increment their overall level of preparation. The use of the simulator as a substitute to the real flight, although possible, observing the restrictions already mentioned in this work, is not desirable, and should be done only during contingency situations, as when a cut in the flight hours occurs, for instance.

The number of flight hours spared by the simulated training depends basically on one factor: the level of fidelity of the reproduction of the real flight conditions. The higher this level, the higher the number of procedures that can be practiced in a satisfactory level in the simulator. Consequently, the more capable the simulator, the higher the amount of flight hours spared.

As explained previously, the optimal mix between real and simulated training must be taken into consideration to define the flight hours spared. The critical problem here is how to determine the exact amount of missions that would have to be executed in the aircraft if there was no simulator available, since this is the number that is needed to determine how many missions are being spared due to its availability.

This number depends on the training profiles adopted by each squadron. For a combat-ready pilot, who just has to maintain his level of preparation, it can be said that this ratio is close to 1, based on observation of different fighter squadrons training profiles. This means that, if one mission is not trained on the simulator, one extra mission, with a similar profile, should be trained in the real aircraft.

But for student pilots, especially during their first year with the specific aircraft, based on experience, this ratio is less than one. This means that one mission in the aircraft can be spared, for a student pilot, if more than one similar mission is executed in the flight simulator. Again, to determine the precise ratio is very difficult, because of the varied existing training profiles. For the purposes of this Thesis, it was adopted a ratio of 0.5 (two simulated missions spare one live-fly mission).

The result of the survey with the pilots assigning the number of simulated missions, for each set of missions, they think should be executed monthly to maintain their level of preparation, was used for the assignment of values for this attribute.

Actually, it is logical that, for a ratio of 1, as proposed, for each hour the pilots think should be practiced monthly in the simulator, one flight hour is being saved.

For the student pilots, the calculation was a little different. The rates proposed state that twice the number of proposed missions should be practiced in the simulator by them. However, a ratio of 0.5 is assumed for the savings with flight hours. Thus, no conversion was needed to calculate the flight hours spared for them. They will practice for two hours in the flight simulator, for each hour the pilots indicate it is required; however, two "simulated flight hours" save one flight hour in the aircraft for them. Also, it is assumed, for simplification, that one mission corresponds to one hour of training, whether in the simulator or in the aircraft.

The number of hours spared must be added up to account for the entire year (the survey asks for monthly requirements), and multiplied by the estimated number of users (pilots) and by the cost of the flight hour. For future years, discounting must be applied.

To assign the function value for the scores (costs) obtained for each of the alternatives, an exponential function must be used, with the range of values defined over the expected maximum and minimum possible values the savings could yield, and not only on the values provided by the alternatives. In this case, higher values are preferred than lower values; this has to be observed when constructing the function. To keep consistency, as proposed for the previous objective, for the goals of this work, it was assumed a value of ρ equal to 200.

Combining the Cost-Related Attributes

The two objectives discussed above are related to financial expenses. Even if the attributes chosen to measure them were flight hours, or any other constructed attribute, in the end, it could be all translated into financial numbers.

The reason why they were presented separately, the life-cycle costs and the savings with flight hours, is that, although it is all about government expenses, these resources are usually allocated from distinct sources, or distinct budgets. And it could be the case that, for example, a given increment in the expenses with flight hours is preferable to the same increment in the expenses with "simulated flight hours", or vice-versa. The motivations for such preferences are not within the scope of this work, but the model is supposed to account for them.

But it could be the case that these preferences are not present in a given decision problem. It is up to the analyst to observe, based on the stakeholders' desires, if preferences between different types of expenses are part of the problem, or if the only interest involved is the overall cost for the government.

Consequently, there are two possible final equations to determine the score related to the accomplishment of the objective, or strategic measure, "optimize budgetary management", regarding the acquisition of a flight simulator.

The first one occurs when there is no differentiation between the expenditures with the simulator life-cycle cost and the savings with flight hours. In this case, all the expenditures must be summed, as in the equation 6, below.

Equation 6: Cost Score - No Differentiation Between Budgets

$$\boldsymbol{x = y_{ACQ} + y_{OPR} + y_{DIS}},$$

where,

x is the total score for the given alternative, regarding this objective,

y_{ACQ} is the acquisition cost for the given alternative,

y_{OPR} is the operational cost for the given alternative,

y_{DIS} is the disposal cost for the given alternative.

As already explained, the costs with acquisition, disposal and the fixed operational costs, such as support and maintenance, have to be provided or estimated. The operational cost for each year will include the cost related to the use, and can be calculated as follows:

Equation 7: Calculation of the Yearly Operational Cost - No Differentiation Between Budgets

$$\boldsymbol{y_{YOP} = y_{FXD} + 12 * (y_{SFH} - y_{FH}) * z * (u_{AHC} + u_{BFM} + u_{ACM} + u_{TI} + u_{ACT} + u_{LFE}) + 12 * t * y_{SFH} * (u_{AHC} + u_{BFM} + u_{ACM} + u_{TI} + u_{ACT} + u_{LFE})},$$

where,

y_{YOC} is the operational cost for the given alternative, for each single year,

y_{FXD} is the fixed yearly operational cost,

y_{SFH} is the cost of one hour of simulated training,

y_{FH} is the cost of one flight hour,

z is the total estimated number of users (pilots),

u is the estimated number of monthly simulated missions executed, for each type of mission (AHC, BFM, ACM, TI, ACT and LFE),

t is the estimated number of student pilots ($t < z$).

After the definition of the yearly operational cost, it should be accounted for the number of years of the estimated life-cycle of the equipment, applying the discounting calculation properly, to find the total operational cost. The next step is to identify the highest and the lowest possible budgets allocated to this particular decision problem, and insert these values into an exponential function, to find the final function value.

The second possible situation occurs if there is a preference for one type of budget compared to the other. Different equations are used to calculate the score for the objective in this case, as presented below.

Equation 8: Cost Function Value With Differentiation Between Budgets

$$\boldsymbol{v(y_{LCC}, y_{FHS}) = w_{LCC} * v(y_{LCC}) + w_{FHS} * v(y_{FHS})},$$

where,

$v(y_{LCC}, y_{FHS})$ is the function value for the given alternative, regarding this objective,

w_{LCC} is the weight assigned to the life-cycle cost,

$v(y_{LCC})$ is the exponential function value for the life-cycle cost y_{LCC}

w_{FHS} is the weight assigned to the savings in flight hours,

$v(y_{FHS})$ is the exponential function value for the savings in flight hours y_{FHS}.

The total life-cycle cost y_{LCC} is defined by the summation of the acquisition, disposal and the operational costs.

Equation 9: Calculation of the Life-Cycle Cost With Differentiation Between Budgets

$$\boldsymbol{y_{LCC} = y_{ACQ} + y_{OPR} + y_{DIS}},$$

where,

y_{LCC} is the total life-cycle cost,

y_{ACQ} is the acquisition cost for the given alternative,

y_{OPR} is the operational cost for the given alternative,

y_{DIS} is the disposal cost for the given alternative.

Again, the acquisition, disposal and the fixed operational costs have to be provided in advance, or have to be estimated. The yearly operational cost is defined by:

Equation 10: Calculation of the Yearly Operational Cost With Differentiation Between Budgets

$$\boldsymbol{y_{YOC} = y_{FXD} + 12 * y_{SFH} * (z + t) * (u_{AHC} + u_{BFM} + u_{ACM} + u_{TI} + u_{ACT} + u_{LFE})},$$

where,

y_{YOC} is the yearly life-cycle cost,

y_{FXD} is the fixed yearly operational cost,

y_{SFH} is the cost of one hour of simulated training,

z is the total estimated number of users (pilots),

t is the estimated number of student pilots ($t < z$).

u is the estimated number of monthly simulated missions executed, for each type of mission (AHC, BFM, ACM, TI, ACT and LFE).

After the definition of the yearly operational cost, it should be accounted for the total number of years of the estimated life-cycle of the equipment, applying the discounting calculation properly, to find the total operational cost y_{OPR}.

To define the yearly savings with flight hours, the equation used is, as follows:

Equation 11: Calculation of the Yearly Saving in Flight Hours With Differentiation Between Budgets

$$\boldsymbol{y_{YFH} = 12 * z * y_{FH} * (u_{AHC} + u_{BFM} + u_{ACM} + u_{TI} + u_{ACT} + u_{LFE})},$$

where,

y_{YFH} is the yearly savings in flight hours,

z is the total estimated number of users (pilots),

y_{FH} is the cost of one flight hour,

u is the estimated number of monthly simulated missions executed, for each type of mission (AHC, BFM, ACM, TI, ACT and LFE).

After the definition of the yearly savings with flight hours, it should be accounted for the total number of years of the estimated life-cycle of the equipment, applying the discounting calculation properly, to find the total savings with flight hours y_{FHS}.

To define the value of the functions $v(y_{LCC})$ and $v(y_{FHS})$, exponential functions should be applied, according to the ranges defined by the stakeholders, and to the preferences for high or low scores, applicable to each specific function.

The definition of the weights for both attributes must be done according to the preferences of the budget managers. In this particular case, it is not appropriate to use the experience or the preferences of the users of the simulators, or even the opinion of experts, since the definition of the weights can depend on external factors, such as economical ones, and also on the budget allocation and management.

When there is a defined preference between the budgets, the final function value is directly defined, and the next step is simply to insert this value into the overall multiobjective value function.

This concludes the development of the second objective related to the acquisition of a flight simulator, and also concludes the creation of the attributes to measure its accomplishment.

The Overall Multiobjective Value Function

After the definition of the function values for each of the two strategic objectives relevant to the given decision problem, "achieve excellence in the operational capabilities of the BAF", and "maximize the acquisition of strategic budgetary and financial resources", the last step required for the calculation of the overall multiobjective function value was to assign weights for each of the strategic objectives.

Once again, the definition of the weights must be done according to the preferences of the stakeholders. The technique of assignment of weights proposed by Dr. Kirkwood is the "swing weighting" (Kirkwood, 1997), but many other techniques can be used to perform this task, and it will be up to the analyst to decide which one is more appropriate for each problem (Buede, 2009).

The decision problem proposed in this work is fictional (though applicable), and the preferences involved in a decision regarding such a big acquisition of equipment usually depends on the current economic situation, and on many other factors, to be properly defined. Also, there is a confidentiality character involved with the definition of the preferences of the decision makers in these cases. Thus, for the purposes of this Thesis, it was assumed that both strategic objectives have the same relative importance, represented by an equal weight value of 0.5.

The same considerations can be made about the definition of the "desirability" of increments in the savings with flight hours compared to increments in the expenses with the life-cycle cost. It was assumed, for the purposes of this work, that there is a differentiation between the budgets, which means that savings with flight hours and the life-cycle cost are seen differently by the stakeholders in terms of their total values.

It was also considered that proportional increments in any of the two types of expenses are perceived equally by the stakeholders. This means that an increment of 50% in the function value of the "savings with flight hours" has the same desirability for the decision maker than a decrement of 50% in the function value of the "life-cycle cost". This property was represented by an allocated weight of 0.5 for both objectives in the cost-related function.

POPULATING THE MODEL

Defining the Alternatives Scores - Operational Capabilities

The main objective of this work was to determine how beneficial for the BAF it would be the adoption of a modern approach to the use of flight simulators, making use of more advanced simulation stations, in contrast to the approach currently employed, constrained by the simulators presently used in the BAF, given the current acquisition of new fighter aircraft. The model presented on the previous chapter was developed with the purpose of serving as a tool to perform this task, more specifically by comparing these modern simulators to the "conventional" ones, currently used by the BAF and by most Air Forces around the world.

The next step was the definition of the scores assigned to the attributes that were chosen to serve as measures of accomplishment of the objectives involved in the decision problem, for each of the alternatives. As it has already been mentioned, for the problem proposed in this work only the two objectives described and detailed previously were considered relevant. For future decisions, in which this type of model happens to be used, other objectives might be relevant in addition to the two goals described, and should therefore be considered. Actually, in any decision problem similar to the one detailed in this work, at least the two objectives described in this work will most certainly be present, but different objectives are very likely to exist in addition to them.

To gather a more accurate estimate of the scores inserted in the model, a survey was conducted with fighter pilots that practice on a regular basis on the currently most used flight simulators, which can be considered these days as a sort of "conventional flight simulators". These simulators will be referred to as Aircrew Training Systems (ATS) in this analysis, since that nomenclature is widely used to denominate the mentioned type of flight simulator.

The surveyed pilots also had the opportunity to execute some training missions using linked high-fidelity flight simulators, that have the capability of creating more realistic environments. These simulation environments are able to support, in addition to complex-behavior entities, more than one live participant in the scenario at the same time, and are known as MTDS (Mission Training via Distributed Simulation) in the SAF and the NATO members, and as DMO (Distributed Mission Operations) in the USAF. For the sake of simplicity, from this point on, these simulators will be referred to as MTDS. A more detailed description of the characteristics of both flight simulators is provided on appendix 3.

The average of the values assigned by the experts to characterize the level of fidelity of each simulator, corresponding to every single block of missions, was used to define the scores in the first part of the multiobjective value function, which is related to the operational capabilities. Each average value corresponds to one of the variables x_i, $i = 1, ..., 6$, in the equation 5 of this work. In addition to the average scores, displayed by the horizontal dashes on the graphs below, the range of the scores that were assigned by the different experts is also represented by the vertical lines.

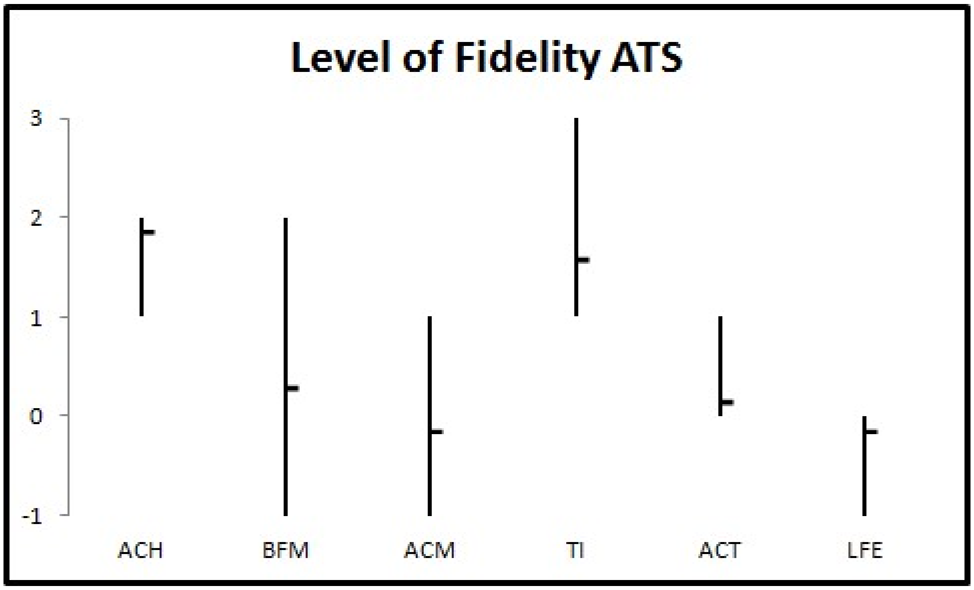

Figure 14: Level of Fidelity - Aircrew Training System

The graph above suggests that there is some variation in how the surveyed pilots see the fidelity, and consequently the benefits, of the ATS for the training of missions that involve within-visual-range (WVR) combat, which occurs more frequently during the BFM and ACM blocks of missions. Informal interviews with the experts suggest that the difference in the values provided results from different perceptions and opinions about what are the most relevant skills for those missions. It is not within the scope of this Thesis to define what are the most relevant skills for any type of mission; thereby, no further clarification was considered necessary to understand the pointed difference of opinions.

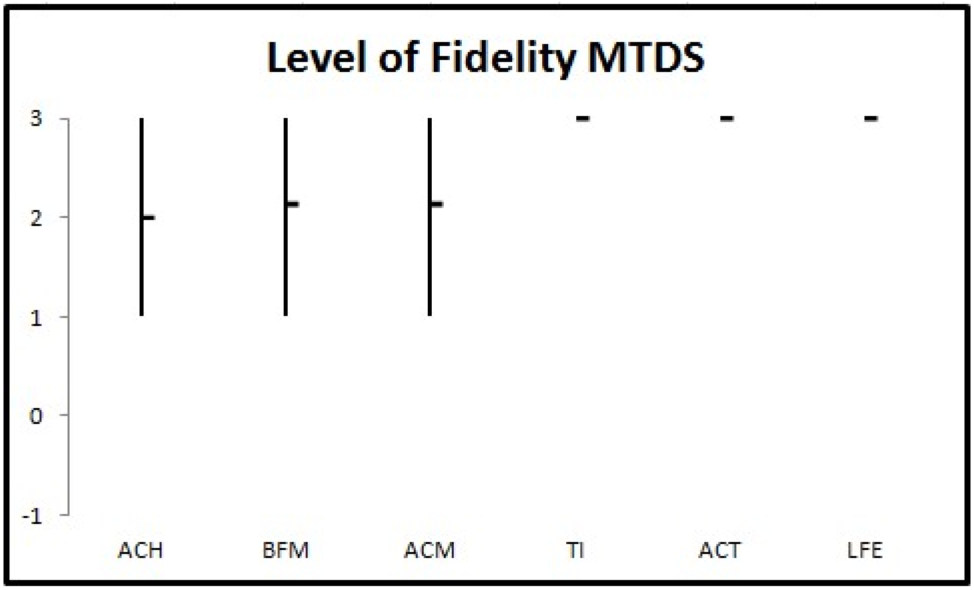

Figure 15: Level of Fidelity - Mission Training via Distributed Simulation

In this graph it can still be observed some variation in the perception of the level fidelity of the simulation for the most basic blocks of missions, but the averages were very close to the middle point of the range line, giving confidence to use this result in the model. On the other hand, the experts were unanimous in their opinions about the high level of fidelity of the simulation for the more advanced blocks of missions.

The average optimal number of monthly missions, required to maintain the optimal level of readiness, was calculated after the survey results. This was the parameter selected to provide the scores used in the second part of the multiobjective value function, related to the costs (they are the variables u on equations 10 and 11, in this work). Figures 16 and 17, below, present the averages through the horizontal dashes, for each block of missions, and also present the range of values suggested by the surveyed pilots for the optimal number of monthly missions, represented by the vertical lines.

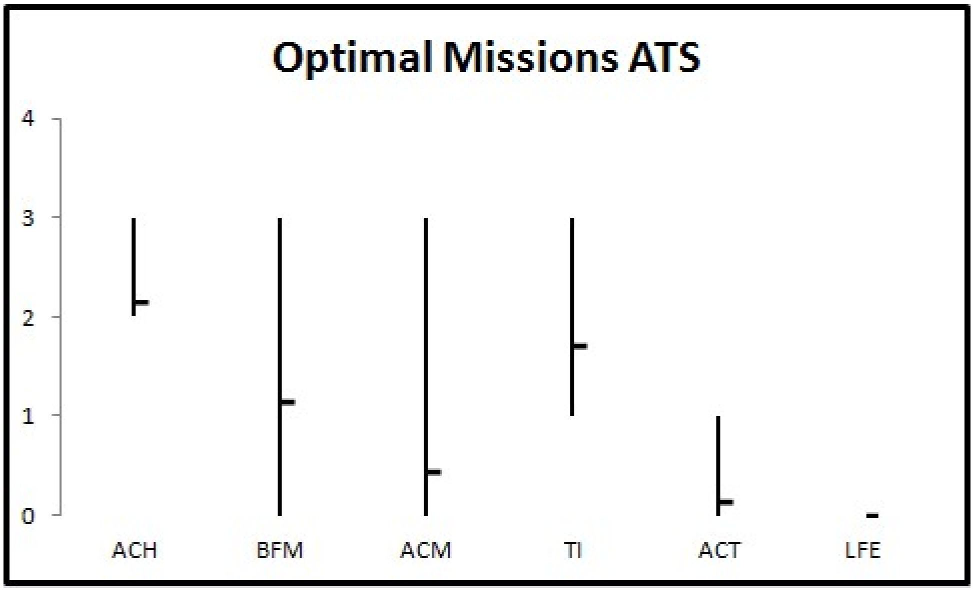

Figure 16: Optimal Number of Monthly Missions - Aircrew Training System

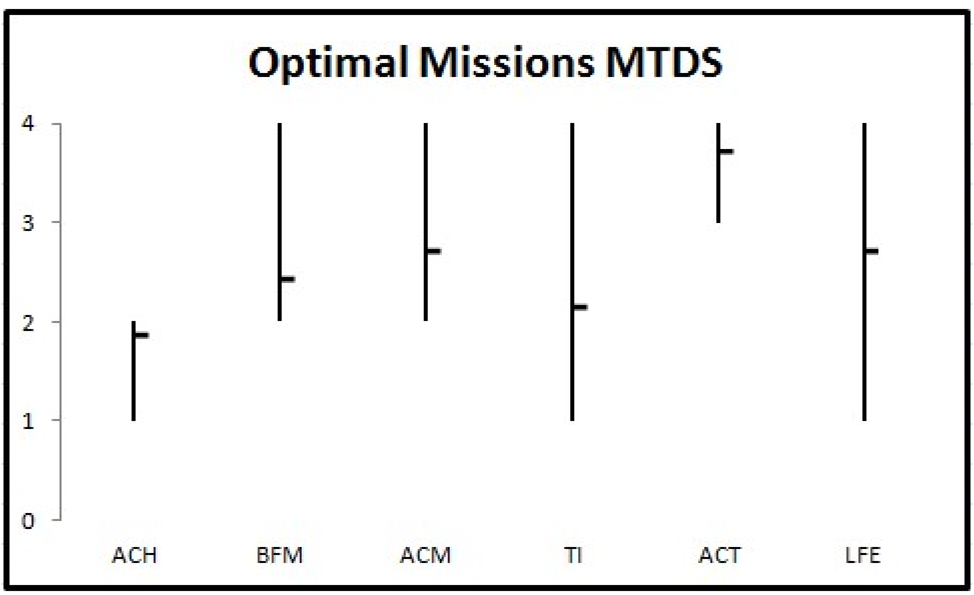

Figure 17: Optimal Number of Monthly Missions - Mission Training via Distributed Simulation

In the first graph, it is possible to observe that the difference of opinions regarding the usefulness of the ATS to the training of BFM and ACM missions results in some disagreement about the number of missions that should be trained using this simulator. Also, the ACT and LFE missions suggested are zero, due to the lack of capability of this equipment to simulate the conditions required for this specific training.

For the MTDS, the highest range of number of missions suggested occurred on the TI and LFE blocks of missions. Again, informal interviews with the pilots suggests that it occurred because, in the present, these missions are not practiced using flight simulators, and there is still some resistance to accept the simulated training as a requirement, instead of only "desirable, but not mandatory".

For this precise reason, and in order to confirm the importance of the simulated missions to the preparation of the fighter pilots, always in association with the live-training, the minimum number of monthly simulated missions required to maintain the readiness of the pilots was also asked in the survey. The result was that the experts unanimously consider that, even for the maintenance of the readiness of the crew in the minimum acceptable level, some missions should be practiced using simulation. Regarding each type of alternative proposed, the total average number of monthly sorties required to keep the minimum level of readiness, considering all the six blocks of missions, was 2.71 for the ATS and 9.71 for the MTDS.

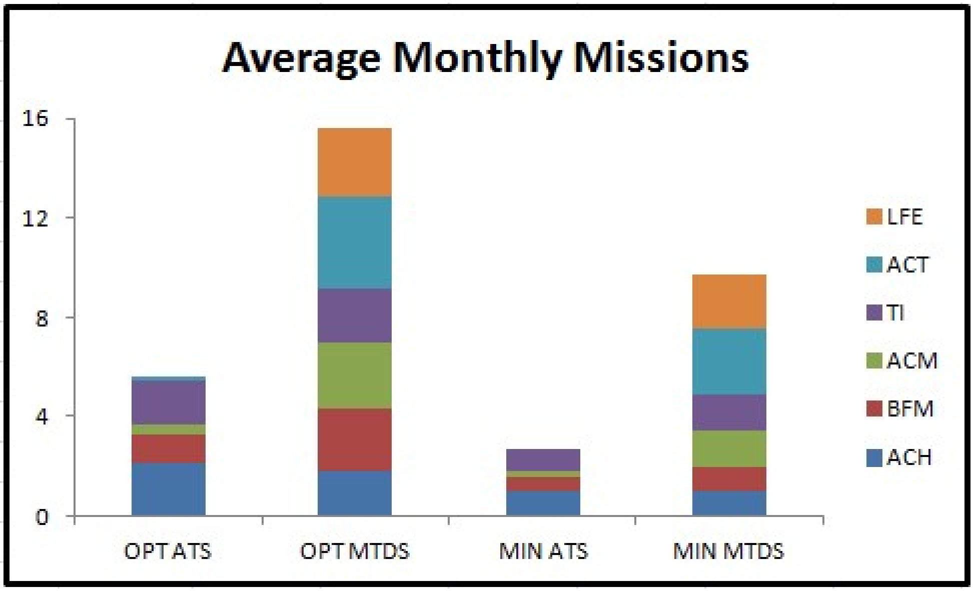

Figure 18: Optimal and Minimum Average Monthly Missions - ATS and MTDS

It can be inferred from the numbers presented above that, in the opinion of the pilots, a more capable simulator would be a valuable tool to help to enhance their operational capabilities, since not only the average optimal number of monthly missions has increased from the ATS (5.57) to the MTDS (15.57), but the average minimum number of monthly missions has also increased in a similar proportion. This just reinforces what is being proposed by this work, regarding the use of flight simulators to increase the operational capabilities of the aviators.

All the values needed for the first part of the multiobjective value function (the x_i, for i = 1, ..., 6) have been defined, and the scores they yield, according to the methodology presented previously on this work, are displayed on the table below.

Table 5: Scores and Function Values - Operational Capabilities

	ATS		MTDS	
	X	VALUE	X	VALUE
ACH	1.86	0.66	2.00	0.70
BFM	0.29	0.19	2.14	0.74
ACM	-0.14	0.09	2.14	0.74
TI	1.57	0.57	3.00	1.00
ACT	0.14	0.14	3.00	1.00
LFE	-0.14	0.09	3.00	1.00

After applying these values to equation 5, the total function value for the operational activities objective was 0.34 for the ATS, and for the MTDS the function value was equal to 0.90.

Defining the Alternatives Scores - Budget Optimization

The next step for populating the model was to define the values of the cost-related attributes for both flight simulators being evaluated. To accurately define the costs that are applied in government contracts is a very difficult task, especially regarding complex products that cannot be considered off-the-shelf products. Flight simulators could be characterized as one of these complex products, and although there are many of them in operation, different Air Forces usually request some modifications or adaptations to be implemented on them during the acquisition process, what ends up yielding varying acquisition costs.

However, it is possible to use the costs applied to the contracts of acquisition of existent flight simulators to find an approximate relation, or a proportion, between the costs of simulators with different capabilities. Through this information, it is possible to gather an approximation of how costly one simulator would be in comparison to another one that has different capabilities. Notice that the exact costs would depend on an enormous amount of variables, such as what company is the manufacturer, what is the cost to transport the equipment from the facility of origin to the final location, and many others. Nevertheless, since the alternatives have different capabilities, supposedly the more capable will be significantly more expensive, and the expected difference between the prices could be theoretically found by comparing prices practiced in past contracts.

This is the method that was applied to define the costs in this analysis, by comparing the costs informed in past contracts of acquisition of flight simulators that are similar to the ones being proposed. It is not possible to use the Gripen-NG, the aircraft being acquired by the BAF, in this comparison, mainly because it is an aircraft that is still being developed, and consequently, its operational costs are not known yet; the same, consequently, applies to its simulators. Hence, the F-16 Fighting Falcon flight simulators were chosen to perform the cost comparison, due to the extensive use of these equipment by many air forces around the world to complement the training of the fighter pilots, what makes the information about the costs involved in its operation more easily accessible through open sources.

As, for obvious reasons, it is impossible to determine the exact budget the interested governmental agency would allocate to this specific acquisition, it was assumed that the highest cost among the available alternatives, for both types of cost-related attributes (the life-cycle cost and the savings with flight hours), was correspondent to 95% of the total (fictional) budget allocated for this type of expense. The decision to not setting this value to 100% was made mainly to account for eventual (again, fictional) extra costs in the contract. On the other hand, the costs yielded by the most expensive available alternative shall be close enough to the maximum possible budget (100%) to make any other more expensive (and possibly, more effective) alternative unfeasible for the decision maker. In addition, the lowest value considered for the cost-related attributes was set to zero, which would be the cost of not implementing any type of flight simulator (and that will be called the "status quo" alternative).

It is important to observe that all these definitions of values and limits were done by this author. In a real decision problem, the real budgets allocated to the decision (if these numbers are available), and the costs defined for each specific alternative must be used and inserted into the model, in order to provide a final result that is as close to the real preferences of the stakeholders as possible.

Contracts made by the USAF in 2009 show that the proportion between the acquisition costs of the two flight simulators proposed is around 2 to 1, for the MTDS to the ATS. The MTDS acquisition cost was informed to be around 21 million dollars, while the price of one ATS was close to 11 million dollars (U.S. Department of Defense, 2009). Regarding the disposal cost, it is very difficult to estimate it, and scarce information is available about this phase of the life-cycle. Thus, it was assumed that the disposal cost has already been calculated and inserted into the acquisition cost values provided. Also, it was assumed that the payment of these values is made in its totality during the moment of the acquisition; thus, no discounting was applied to the acquisition costs.

About the cost of one flight hour for the F-16, the version of the aircraft chosen to be used in the model was the version "C", and the value that was considered was the "operational cost per flight hour" for the fiscal year 2009, same year the contracts of acquisition mentioned above were firmed. This value is $21,713 per flight hour (Thompson, 2013).

The remaining costs that have to be provided are the costs of the simulated flight hours for each of the alternatives. Similarly to what happens with the disposal cost, it is difficult to obtain official information regarding these specific values; however, a research conducted by RAND Corporation provides good estimates of what these numbers are, and that is the information that will be used in this work (Ausink *et al*, 2011).

For the fiscal year 2008, the cost per hour of use of the DTOC (Distributed Training Operations Center), a flight simulation facility very similar to the MTDS, was estimated to be between $2,100 and $3,100. For the ACS (Air Combat Simulator), a simulator that has the same characteristics as the ATS, the cost per hour of use was estimated to range from $1,200 to $1,800. For the purposes of this Thesis, the average of the values provided was used. Also, it was assumed , for the sake of simplicity, that the fixed yearly cost of operation for the simulators has already been calculated and inserted into the hourly cost provided.

The last parameter that has to be defined to perform the calculations is the number of pilots and the number of student pilots that will use the flight simulators yearly. Based on experience, the assumed number of pilots was defined to be 20, assuming that one single Air Unit will be equipped with the new aircraft, and the number of student pilots was set to be equal to 15% of the former amount.

Thereby, all the values that are necessary for the model calculations were defined. For the calculations of the total cost for the 30-years proposed life-cycle, a real discount rate of 1.4 was used (The White House, 2014). The scores and the respective function values that were applied for the second part of the multiobjective value function are summarized in the tables below.

Table 6: Life-Cycle Cost - ATS and MTDS

	ATS	MTDS
Acquisition + Disposal Cost	10,789,226.50	20,967,607
Simulator Cost/Hour	1,500	2,600
Missions/Month/Pilot	5.57	15.57
Yearly Operational Cost	2,306,571.43	11,174,057.14
30 Years Operational Cost	56,974,130.84	276,008,011.61
Life-Cycle Cost	67,763,357.34	296,975,618.61

Thus, considering a total life-cycle of 30 years, it can be observed that the estimate for the cost of the MTDS is more than four times the estimate for the ATS. Plugging the values into equation 2, with the lowest value set to zero, and the highest one set to 312,605,914.30 (calculated from the assumption that the life-cycle cost (LCC) of the MTDS is equal to 95% of the maximum possible budget), the function values can be found. For the ATS, the function value regarding the life-cycle cost was equal to 0.64; for the MTDS, the value was 0.02.

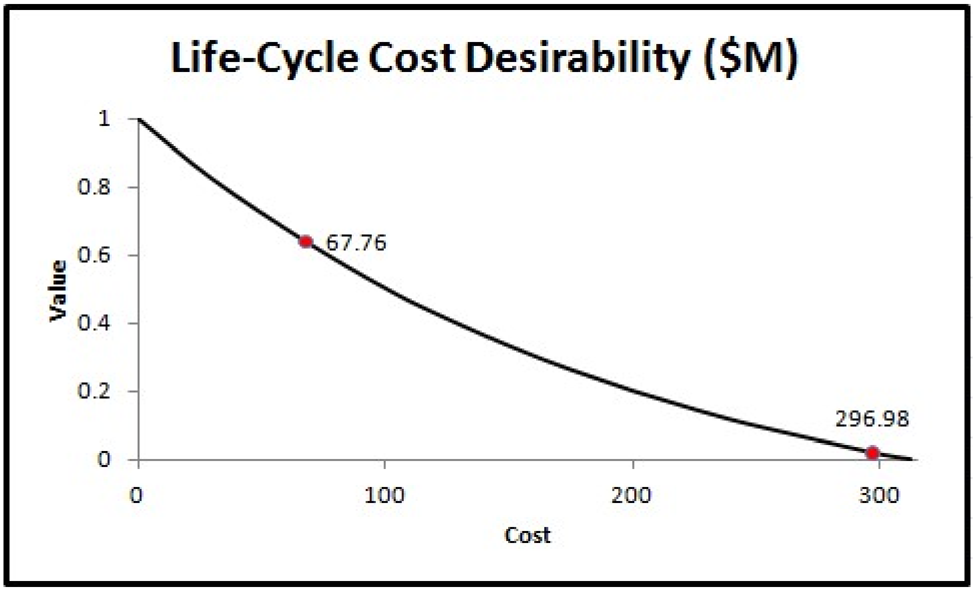

Figure 19: Life-Cycle Cost Desirability (Millions of Dollars)

The values obtained for the 30-years period, regarding the savings with the flight hours due to the simulated training, were of a much higher order, as presented on the table below. As it was assumed that there is a distinction on the preference of the decision maker between the budgets for the flight hours and for the expenditures with the flight simulator, the values are not supposed to be summated, or even compared.

Table 7: Savings with Flight Hours - ATS and MTDS

	ATS	MTDS
Flight Hour Cost	21,713	21,713
Missions/Month/Pilot	5.57	15.57
Yearly FH Expenses Saved	29,033,382.86	81,144,582.86
30 Years FH Savings	717,147,421.96	2,004,335,102.40

Using the same methodology applied above, the maximum possible savings (with a function value of 1) were equal to 2,109,826,423.58, and the minimum was considered to be equal to zero. The function values found (in this case, plugging the scores into equation 3) were 0.46, for the ATS, and 0.97 for the MTDS. The obvious reason for this result is that more types of missions can be practiced in the MTDS than in the ATS, thus more savings occur with live-fly missions.

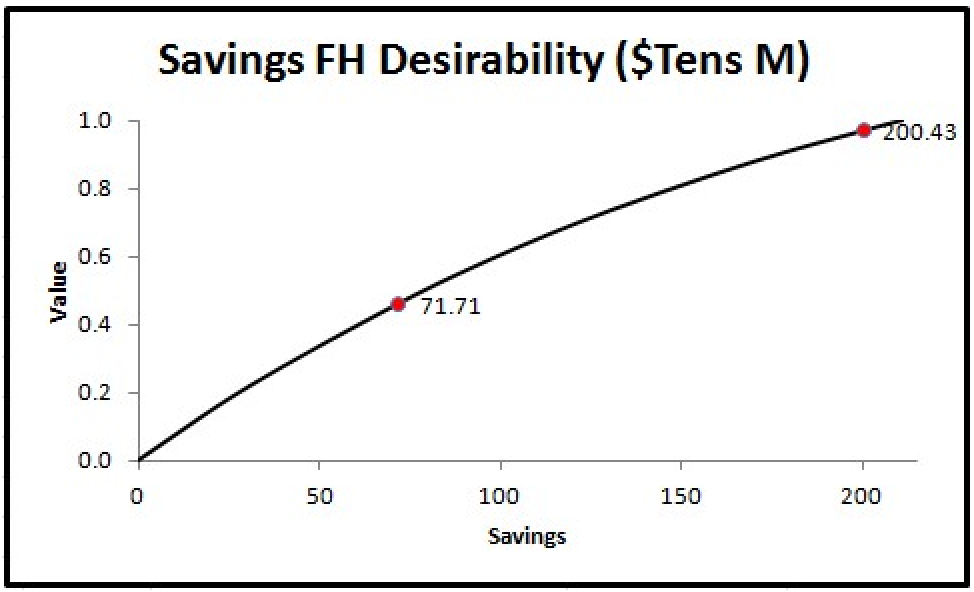

Figure 20: Savings with Flight Hours Desirability (Tens of Millions of Dollars)

Applying equal weights of 0.5 for both objective function values (as defined on the previous chapter), it was obtained, from equation 8, a cost-related function value of 0.55 for the ATS, and of 0.5 for the MTDS.

Calculating the Overall Multiobjective Function Value

The final step was to plug the function values defined for each alternative, regarding the two strategic objectives alone, into the overall multiobjective function, which is detailed on equation 1, of this work. As it has already been stated, an equal weight of 0.5 was assumed for both objectives.

Hence, the overall function value for the ATS was equal to 0.45, and a value of 0.70 for the MTDS.

What this result means exactly can only be acknowledge if the ranges of possible values are considered. "No specific meaning can be given to value numbers without knowing the ranges of the evaluation measures that are being used" (Kirkwood, 1997). Considering a (hypothetical) worst possible alternative, with an overall value of zero, and a (hypothetical) best possible alternative, with an overall value of 1, it can be said that an improvement of 70 percent, in a value sense, is obtained if the MTDS is acquired, relative to an exchange between the worst possible and the best possible alternatives. For the ATS, this value improvement would be only 45 percent.

Thus, according to the model proposed, the acquisition of a simulation equipment with similar capabilities to the ones of the MTDS for a new fighter aircraft would be considerably preferable, compared to the alternative of acquiring the "more conventional" flight simulators, similar to the ones currently used by the BAF. Though there is a significant increment in the expenditures with the more modern equipment, its capabilities would make possible the savings of a higher amount of resources (flight hour cost) that would have to be spent with the live-training otherwise. Also, the increment to the operational capabilities of the fighter pilots would be undeniably substantial.

Another conclusion that can be drawn from the results provided by the model are that both alternatives are preferable to the "status quo", which means not acquiring any simulator. The overall multiobjective function value for the alternative of not having a flight simulator is equal to 0.3: the operational capabilities objective yield a value of 0.1, since there would be no negative transfer, and the value for the budget-related objective is 0.5, because although there would be no savings with flight hours, the lack of flight simulators would imply in no life-cycle costs at all. However, this overall value is considerably lower than the values obtained for the other alternatives, and reinforces the importance, for an Air Force, of owning and operating flight simulators to improve the training of the fighter pilots.

SENSITIVITY ANALYSIS

Operational Capabilities

With the purpose of assuring the robustness of the model, and to increase its credibility, to perform a sensitivity analysis is indispensable. Hence, in this chapter, variations on the parameters previously presented were proposed, to check how the final results would be changed.

The first objective analyzed was the one regarding the operational capabilities. Although varying the weights assigned to each variable could result in changes on the final function value for this objective, the value of the MTDS would always be (significantly) higher than the one of the ATS. This results from the scores assigned to the MTDS, referent to all the attributes, being higher than the scores that were assigned to the ATS.

Even if, for example, the weight assigned to the AHC block of missions, the one that has the most similar scores among the alternatives, was increased by 20% of the total possible value (which can be considered a huge increment), the function value (regarding only this objective) of the ATS would increase from 0.34 to 0.42, while the one for the MTDS would decrease from 0.90 to 0.84; thus, the difference on the overall function value would be minimal.

It is interesting to point that, after the weights were assigned to the blocks of missions, the result and the method used to the assignment of weights were informally showed to the experts (the surveyed fighter pilots), and there was no disagreement about the distribution performed.

Other types of missions that can eventually be inserted into the model could lead to changes on the results. However, the analysis was primarily focused on the simulator capabilities, and the improvement it can bring to the readiness of the pilots. Thus, if the analysis was performed using different missions and skills, or even different aircraft, the results were supposed to remain close to the ones that were presented.

Budget Optimization

Differently from what was showed for the operational capabilities, more significant changes could occur if the cost analysis was conducted in a distinct manner.

First, as it is difficult t obtain accurate information regarding costs, it was checked what would happen if the costs provided were higher or lower for both equipment. Obviously, a lower cost for the MTDS, and a higher cost for the ATS, would increase even more the desirability of the former in comparison to the latter. A 10% differentiation on the costs, on these directions, would change the function values (cost-related) to 0.52 and 0.53 respectively; almost equivalent, thus.

If the changes on the costs occurred on the other direction, the same 10% differentiation (assuming that the upper budget limit would be increased, to allow such analysis to be done) would yield function values of 0.57 for the ATS (increasing 0.02 from the original value) and of 0.50 for the MTDS (unaltered). Thereby, it seems that increments in the order of 10% on the costs presented would not produce significant changes to the model results.

However, changes on the weights could produce more significant alterations on the final results. If, for example, the decision maker thinks that the life-cycle cost objective is twice as important as the objective related to the future savings with flight hours, the cost function value of the ATS would increase to 0.58 (increment of 0.03 compared to the original value), and the value for MTDS would decrease to 0.34 (a decrement of 0.16 from the original one). However, the overall value of the MTDS would still be higher (0.62, against 0.46 for the ATS), but the difference between them would be lower in this case.

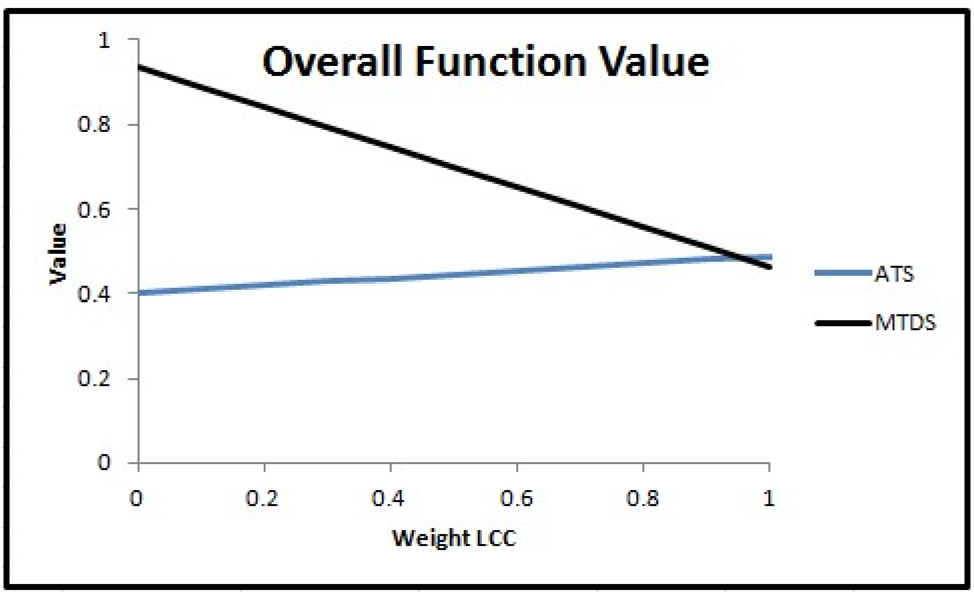

Figure 21: Variation of the Value according to the weight of Life-Cycle Cost

One factor that was observed to have little influence on the cost analysis is the preference of the decision maker regarding increments on the costs (or savings), represented on the equations by the parameter ρ. If there was no preference, the value of ρ would have to be set to infinity, instead of the proposed values of 200 and negative 200 (depending on the direction of preference); however, there would be virtually no difference on the function values provided, with just a slight increment of 0.01 on the ATS value.

The result would be very similar if the parameter ρ was decreased by half of its original value, to 100 (and negative 100). Only, this time, the function value of the ATS would be reduced by 0.02, in comparison to the original value of 0.55.

It is important to notice that all these values were the result of the budget allocation defined by this author. Different upper or lower limits could lead to very different results on the function values definition, and to determine what those values are (or could be) exactly can be extremely difficult. Even during a real decision problem it could become very complex to perform such task because, usually, these limits are not explicitly defined, not even regarding the total cost of the project, and even more rarely they are defined for each specific type of expenditure.

The last situation that was worth analyzing concerning the costs was when the decision maker has no preference between the two different types of budget. In this case, the equation used to define the scores of the alternatives, regarding the budget optimization objective, was equation 6, of this work. Due to the savings with flight hours being so much higher, considering the total 30-years life-cycle, than the cost of operating the simulators, what ends up being compared in this case is how much savings can be achieved by each alternative. Using the same reasoning that was applied to perform the calculations of the cost-related results based on the scores, the function value of the ATS (regarding costs only) would be equal to 0.37, in this situation; for the MTDS, the function value would be 0.95.

Thus, if the decision maker has no preference between the two types of budgets, leading to no differentiation between them, the cost-related function value of the MTDS would be significantly higher than the one for the ATS, which, associated with the higher value of the MTDS regarding the operational capabilities, would lead to an even greater differentiation between the overall function values, increasing the desirability of the more modern type of flight simulator.

Although this seems to be the logical way to account for the costs, by summing all the expenditures and subtracting all the savings in one single equation, experience shows that this is not very realistic. First, because, as it has already been mentioned, usually different governmental budgets come from different "sources", or at least, they are treated differently depending on the nature of the expenditure. And second, because when dealing with a problem such as the acquisition of a flight simulator, what the decision maker will be faced with directly is the costs that are implied in the acquisition process; the savings that will eventually become possible after the process is concluded are usually treated as an indirect consequence of the acquisition, thus having a lesser weight in the decision.

The Weights on the Multiobjective Function

Finally, it was analyzed how changing the weights on the overall multiobjective value function would impact the final results.

The weights originally selected were equal for both cost-related and operational capabilities objectives: 0.5. The only way to find a significantly different result than the higher value for the MTDS, compared to the ATS, would be to increase the weight of the cost-related objective by a really large amount.

Actually, to have a situation in which the overall function values of both alternatives are be equal, given the scores obtained previously, the weights would have to be set to around 0.1 for the operational capabilities objectives, and to 0.9 for the cost-related objectives. Although possible, this situation does not seem to be what is expected in a decision problem similar to the one presented.

After checking the possible variations on all the parameters of the model, and more specifically, on the weights assigned to the different levels of the objectives hierarchy, it was possible to conclude that variations on them could lead to different overall multiobjective function values for the available alternatives. However, these variations would not be significant enough to change the desirability ranking of the alternatives proposed, reinforcing that the acquisition of a linked high-fidelity flight simulator could indeed generate significant benefits to the BAF when compared to the other "more conventional" alternatives.

CONCLUSION

The initial motivation of the work hereby concluded was the assumption by its author that the BAF could benefit from the adoption of a more modern type of flight simulator. Further, such benefits include enhancing the manner flight simulators are employed in the training of fighter pilots, with the purpose of improving it, and would clearly compensate for the costs incurred. The assumption was made based on the author's own expertise and reinforced by the experience a few fellow fighter pilots had in the Swedish Defense Research Agency's Air Combat Simulation Centre, near Stockholm.

An initial testing of this assumption was done by performing a comparison between the simulation capabilities of the Swedish equipment with the one currently used by the BAF, where it was observed that the advantages of the former were evident. Yet, it also became evident that the advanced simulation system is considerably more expensive, which immediately brings a couple of questions to the mind of the decision maker: "does the BAF really need it?" and "does it really worth the cost?".

The answer to the first question is extremely situation dependent, and the decision maker can only decide it based on his beliefs and the information available. Yet, to support him on that matter, a reasonable answer to the second question can be provided by adopting a scientific, rigorous approach to investigate it - this was the main thrust of this work.

The approach involved performing a value analysis on the available alternatives, and on the benefits each could bring, and took into consideration the improvements in the training each one could make possible. To avoid discarding potential better alternatives that were not envisioned in the study, the value analysis had to be made with the focus strictly on the objectives, instead of on the benefits of the available alternatives.

Following this rationale, Value-Focused Thinking was the approach chosen to perform the analysis of the given decision problem. The first step was to identify the objectives related to the decision, which was done by assessing publicly available documentation on the strategic directions and priorities adopted by the BAF.

Initially, the research pointed to the two objectives directly involved with the acquisition and operation of a flight simulator, which can be summarized by the brief statements "maximize operational capabilities" and "minimize costs." For the analytical process, these objectives had to be decomposed into more quantifiable objectives.

Regarding the operational capabilities, only the objectives related to the air-to-air missions were considered, and the training framework adopted by the USAF F-15C squadrons was selected to provide a basis for the development of the lower-level objectives. This approach for analyzing the operational capabilities marks a new approach to the employment of flight simulators in the BAF. More specifically, this work proposes to consider flight simulations not only as a tool to help the training of basic piloting abilities, but as an instrument to develop the skills needed for every mission performed by the fighter aviation. The level of fidelity of the simulation, regarding each specific type of missions, was defined to be the most appropriate attribute to measure the accomplishment of these objectives.

For the costs, two distinct lower-level objectives were identified: (1) to minimize the acquisition and operation costs of the simulator, and (2) to maximize the savings on flight hour resources. The latter refers to the economy of resources that usually occurs when simulated training is present. The factors that can influence these lower-level objectives were discussed thoroughly, and alternative ways of defining the parameters were presented. The main goal of this phase was to ensure that the resulting model could reflect the preferences of the decision maker as realistically as possible.

A key part of this study was the development of the model equations, in which the scores associated with each of the alternatives had to be determined. For this purpose, two methods were used: the costs were mainly defined based on research using open sources and past contracts of acquisition of flight simulators; and the measures of effectiveness directly related to the performance of the simulators were provided by experts. As part of the validation of the resulting model, a survey was conducted involving fighter pilots that have experience with both the flight simulator alternatives analyzed in this Thesis.

Once the data gathered was inserted into the model, it yielded a result that was unquestionably consistent with the assumption that originated this work. In other words, the results of the model indicate that the benefits achieved with the use of linked high-fidelity flight simulators justify the increment in the expenses they generate. As mentioned earlier in this document, its dependency on the context and its inherently subjective nature makes the confirmation of this assumption restricted to the decision maker, but the model strongly points to that direction. To assess the robustness of the results, a sensitivity analysis was performed on the parameters of the model, yielding results that enhanced the credibility that the model's conclusions were consistent with the premises.

In addition to providing support to the use of modern flight simulator in comparison with the currently one in use, another interesting conclusion of this work was that the use of either flight simulator alternative (i.e. modern and current in use) is indeed beneficial and justifiable. That is, both scored high in comparison with the alternative of not using simulation in the training of fighter pilots.

Regarding limitations and potential future work, one important aspect regarding the procedures and conclusions of this Thesis is its academic nature. In other words, although the proposed model was developed to - and is ready for - real decision problems, care shall be taken by the analyst before adopting it to support an actual decision of this caliber. For instance, the characteristics of this work limited its scope to the two objectives described above in this document. Yet, although both are very likely to be present, others could also exist, and should therefore be incorporated into the model accordingly.

Another aspect involves the implicit assumptions made in the analysis, which must be present before the adoption of the flight simulators proposed could be considered the final optimal solution for the preparation of fighter pilots. More specifically, the implementation of the simulation-based training would require a careful plan, upon which the benefits of each alternative are dependent. For instance, the benefits considered in this work rely on factors such as the development of proper training profiles, the understanding that a mix of simulation-based and live-training is more beneficial than any of the options alone, and many others that might have some influence on the level of readiness of the aircrews.

A third consideration is the timeliness of this study. Simulation technology is in constant evolution, and what was considered the state-of-the-art by the time of this writing will become obsolete very fast. Indeed, the simulation concept of Live, Virtual and Constructive, usually simply referred to as LVC, is very close to become a reality in the training of combat pilots. This will be a huge step in the evolution of flight simulators, and probably not the last one.

Pursuing the best available flight simulator, or simulated training system, is not a fundamental objective of the BAF, and neither should be of any Air Force. Achieving excellence in its operational capabilities is an example of a real fundamental objective. The proper selection of equipment, under an optimal cost/benefit trade-off, is just a means to achieving it. Nonetheless, and with the fundamental objectives in mind, the influence of the flight simulators in the level of readiness of the fighter pilots is undeniable. This corroborates the importance of the analysis performed in this work.

APPENDIX 1

CONDITIONS AND EQUATIONS ASSESSED TO DEFINE THE WEIGTHS

After collecting the data intended to serve as the basis to the assignment of weights to the attributes related to the objective "optimize operational activities"; and also after analyzing the data, and drawing the conclusions previously presented, the conditions to the definition of the weights were defined, as follows:

- the weight assigned to the BFM attribute would have a low level of significance in the overall result, since this type of missions is virtually not practiced using flight simulators. Also, although this is the smallest value in the model, and should thereafter serve as reference for the definition of the other weights, it was considered too small to be used for the calculation of the weights for the other attributes;
- the reference smallest weight value would, then, be assigned to the ACM missions. Although, according to the distribution of executed missions, there were more ACM sorties than AHC ones, AHC was considered to have a higher weight value than the simply count of sorties can justify (the explanation is below). Also, the definition of "one sortie" for the LFE and

"less than one sortie" for the ACM was the reason it was decided that LFE missions are more relevant than ACM;

- AHC has a not as large number of sorties in the flight hours distribution, and besides, it was not even mentioned by the F-15C pilots on the survey; however, there are two considerably relevant reasons it was considered as a very important set of missions: first, it was not clear, on both data sources, if the missions performed by the student pilots were taken into consideration; also, even if the "official sorties" count does not present high numbers of this type of sorties, by experience, it is known that the capability of executing this training in the simulator is significantly valuable, since there will be many "unofficial sorties" performed by the student pilots in order to prepare themselves properly for the AHC missions in the aircraft, if the flight simulator is capable of providing this training. Thus, it was considered as less valuable only than ACT, and equivalently more valuable than TI;
- LFE was defined as having the second smallest weight value, around 50% more than ACM. Although it is the mission that presents more resemblance with a real war scenario, the research showed that the optimum frequency, appointed by the F-15C pilots, to practice this mission would be around once a month. It can only be speculated that it could be due to the large complexity involved in the planning of this type of mission, even a simulated one, and also the requirement of a large

experience of the pilots to perform it well, what makes the training of the foundations a little more desirable;

- ACT was appointed in both researches as the most practiced mission, and it can be assumed that the reason for a higher number of ACT sorties compared to LFE ones is that it does not require as many people and resources involved in its execution; however, the difference between ACT and LFE missions is basically just the complexity of the scenario, but the tactics trained in both missions are very similar to each other. Also, according to the data, ACT is around twice as valuable as the TI missions;
- The weight value of TI sorties is somewhere in between LFE and AHC. These missions are important specially for less experienced pilots, but also, in a smaller scale, to the more experienced ones. Following the method of assigning the weight value based on the proportion of sorties, TI missions are supposed to be around 50% more valuable than LFE (again, it is a very important foundational mission, though not presenting a very complex scenario to the pilot).

After all this reasoning, the weight values and variables were defined by:

- BFM: 0.02 (final value already defined as significantly low)
- ACM: x (smallest value, set as having value equal to the variable x)
- LFE: 1.5 * x
- TI: 1.5 * (weight of LFE) = 2.25 * x
- ACT: 2 * (weight of TI) = 4.5 * x

- AHC: (weight of ACT + weight of TI) / 2 = 3.375 * x

Setting the sum of the weights to 1, and also considering that the weight of BFM has been defined in advance, the resulting equation is:

Equation 12: Definition of the Weights of the Attributes Related to the Operational Activities

$$\boldsymbol{x + 1.5 * x + 2.25 * x + 3.375 * x + 4.5 * x = 0.98}$$

The resulting value of x is 0.077623. Thus, the weights defined for the attributes, rounded to the second decimal place, are:

- AHC: w_{AHC} = 0.26
- BFM: w_{BFM} = 0.02
- ACM: w_{ACM} = 0.08
- TI: w_{TI} = 0.17
- ACT: w_{ACT} = 0.35
- LFE: w_{LFE} = 0.12

APPENDIX 2

FIGHTER PILOTS SURVEY

The only purpose of this brief survey is to serve as an aid to improve the understanding of the flight simulators capabilities with which few pilots had the opportunity to practice. My interest is precisely the evaluation of such capabilities in the point of view of the end-user. All data requested from you will be used as unofficial information, and not assigned to any specific individual or organization. The work I am developing has a theoretical character, and is open to consultation; however, the insights from those who have used the simulator to which I refer in this Thesis are extremely important, so the theoretical basis is not far from the reality that this study aims to improve.

In this survey, a comparison will be conducted between the conventional flight simulators (such as the ones used by the F-5 and A-29 crews) and the linked high-fidelity simulators known as MTDS (Mission Training through Distributed Simulation), used by the USAF and the SAF.

To perform this assessment, it will be adopted the division into blocks of missions defined by the F-15C squadrons of the USAF, and the focus of this survey will be exclusively the training of air-to-air missions. A brief description of these blocks will be presented in order to clarify the types of missions executed in each block.

For each block of missions, a score related to the degree of simulation fidelity, in relation to the actual flight environment, must be assigned, for each of the two types of flight simulator. The description of the meaning of each score will be presented below. Note that the scores depend not only on the degree of the simulation fidelity, but also on the operational increment provided to the pilots by this training.

Still concerning each block of missions, for each type of simulator it will be asked what is the number of missions that, in your opinion, should be practiced monthly in the simulator to maintain an optimum level of preparation of the pilots, and also, the minimum number of simulated missions needed to maintain the preparation at a "minimum acceptable" level. These numbers should be based on your personal opinion only, more specifically concerning to what could be added to the preparation of the pilot through the simulated training.

When providing your answers and scores, consider only the ready-to-combat pilots (disregard the student ones), and make your evaluations based on what you think is the optimal level and the "minimum acceptable" level, and not based on the current preparation level (even if it corresponds to one of the two definitions).

Thank you for your availability to help me with this survey, spending part of your scarce time on this task. I sincerely hope that, in the end, we are both contributing to the improvement of the operational capacity of the Force.

Table 8: Description of the Blocks of Missions

Blocks of Missions	Description
AHC (Aircraft Handling Characteristics)	Most basic missions, intended to familiarize the pilots with the aircraft performance. The practice of standard procedures, takeoff and landing, and instrument flight, as well as the emergency procedures, are part of this block of missions. It is composed primarily of single aircraft sorties. Basic air combat maneuvers and the familiarization with the equipment used in these missions are also part of this block.
BFM (Basic Fighter Maneuvers)	Missions whose main goal is to develop the skills needed for the air combat against a single enemy aircraft (1 x 1). The training missions are executed against opponents with the same performance, or against dissimilar aircraft.
ACM (Air Combat Maneuvers)	Explores the combat techniques required to maneuver a formation of two aircraft against a single enemy (2 x 1). The missions have different initial display profiles, and also enemies with different performances (includes combat against dissimilar aircraft).
TI (Tactical Intercepts)	The main objective of these missions is to familiarize the pilots with the non-visual methods of sorting, targeting, and the application of engagement techniques, such as the training of threat reactions and obtaining parameters for the use of weapons. The sorties are made with different numbers of aircraft (including single aircraft), and against different enemy formations.
ACT (Air Combat Tactics)	Missions intended to present to the pilots a more complex and realistic environment of air war, with previously unknown threats (2 x X, or 4 x X). Includes the training of OCA and DCA missions.
LFE (Large Force Employment)	Pre-planned missions with very complex war scenarios, in which one or more friendly formations combat against large adversary forces. The training of situational awareness and the application of the rules of engagement in these sorties require a lot of effort and skill, what makes the pilots consider these missions very similar to the war scenario experienced in a real combat situation.

Table 9: Description of the Scores

Attribute score	Description of attribute score
-1	The simulator reproduces the flight conditions and situations very differently than the ones encountered during the live-fly, and its use can result in a negative transfer of skills to the live-fly.
0	The simulator does not reproduce the conditions or situations related to that mission.
1	Some of the situations and conditions encountered in this type of mission are reproduced by the simulator in an acceptable manner, but there are many relevant distinctions. Its use does not aggregate much value to the performance of the pilot during the live-fly.
2	The majority of the situations and conditions encountered during the live-fly are reproduced by the simulator, but there are few relevant distinctions. Its use aggregates value to the performance of the pilot during the missions in the aircraft.
3	The reproduction of the type of mission by the simulator is almost perfect, and the distinctions with the live-fly are irrelevant. The use of the simulator aggregates value to the perfomance of the pilot equally or more than the live-fly would do.

For each block of missions below, select the option that best represents your personal evaluation of the level of fidelity of each simulator. The first sheet refers to the conventional simulators currently used; the following one, to the MTDS, used by the USAF and the SAF. Also, check the number of monthly missions, of each type, which you think must be executed on the simulator to maintain an optimal level of preparation, if each type of simulator is available for this training. In addition, select the number of missions required to maintain the preparation at a "minimum acceptable" level.

The NO fields (not observed), on the scores column, shall be checked if this aspect was not observed. For the numbers of missions columns, the same reasoning applies to the field NA (not applicable).

CONVENTIONAL FLIGHT SIMULATOR			
BLOCK OF MISSIONS	SCORE	MONTHLY OPTIMAL NUMBER OF MISSIONS	MONTHLY MINIMAL NUMBER OF MISSIONS
ACH	-1 0 1 2 3 N.O.	0 1 2 3 4+ N.A.	0 1 2 3 4+ N.A.
BFM	-1 0 1 2 3 N.O.	0 1 2 3 4+ N.A.	0 1 2 3 4+ N.A.
ACM	-1 0 1 2 3 N.O.	0 1 2 3 4+ N.A.	0 1 2 3 4+ N.A.
TI	-1 0 1 2 3 N.O.	0 1 2 3 4+ N.A.	0 1 2 3 4+ N.A.
ACT	-1 0 1 2 3 N.O.	0 1 2 3 4+ N.A.	0 1 2 3 4+ N.A.
LFE	-1 0 1 2 3 N.O.	0 1 2 3 4+ N.A.	0 1 2 3 4+ N.A.

Figure 22: Survey Conventional Flight Simulator

HIGH-FIDELITY SIMULATOR (MTDS)			
BLOCK OF MISSIONS	SCORE	MONTHLY OPTIMAL NUMBER OF MISSIONS	MONTHLY MINIMAL NUMBER OF MISSIONS
ACH	○ -1 ○ 0 ○ 1 ○ 2 ○ 3 ○ N.O.	○ 0 ○ 1 ○ 2 ○ 3 ○ 4+ ○ N.A.	○ 0 ○ 1 ○ 2 ○ 3 ○ 4+ ○ N.A.
BFM	○ -1 ○ 0 ○ 1 ○ 2 ○ 3 ○ N.O.	○ 0 ○ 1 ○ 2 ○ 3 ○ 4+ ○ N.A.	○ 0 ○ 1 ○ 2 ○ 3 ○ 4+ ○ N.A.
ACM	○ -1 ○ 0 ○ 1 ○ 2 ○ 3 ○ N.O.	○ 0 ○ 1 ○ 2 ○ 3 ○ 4+ ○ N.A.	○ 0 ○ 1 ○ 2 ○ 3 ○ 4+ ○ N.A.
TI	○ -1 ○ 0 ○ 1 ○ 2 ○ 3 ○ N.O.	○ 0 ○ 1 ○ 2 ○ 3 ○ 4+ ○ N.A.	○ 0 ○ 1 ○ 2 ○ 3 ○ 4+ ○ N.A.
ACT	○ -1 ○ 0 ○ 1 ○ 2 ○ 3 ○ N.O.	○ 0 ○ 1 ○ 2 ○ 3 ○ 4+ ○ N.A.	○ 0 ○ 1 ○ 2 ○ 3 ○ 4+ ○ N.A.
LFE	○ -1 ○ 0 ○ 1 ○ 2 ○ 3 ○ N.O.	○ 0 ○ 1 ○ 2 ○ 3 ○ 4+ ○ N.A.	○ 0 ○ 1 ○ 2 ○ 3 ○ 4+ ○ N.A.

Figure 23: Survey High-Fidelity Flight Simulator

APPENDIX 3

CHARACTERISTICS OF THE ALTERNATIVES

Conventional Flight Simulator (ATS) (Embraer, 2012):

- 1 or 2 identical pilot stations, equipped with three projectors, providing a horizontal field of view of 150°;
- The pilot station is identical to the cabin of the objective aircraft, and the software can be updated to represent the modifications implemented on the aircraft;
- 1 flight controller/instructor position for each pilot station;
- After Action Review capabilities similar to the debriefing capabilities existent for the real aircraft;
- Capability to insert constructive entities into the scenario, both friendly and enemy ones, with simple behaviors;
- No communication between adjacent pilot stations, or even between the stations and external simulators.

Linked High-Fidelity Flight Simulator (Crane *et al*, 2006) (MTDS):

- 4 pilot stations equipped with domes, with a horizontal field of view of approximately 200°;
- 4 pilot stations equipped with one to three projectors, providing a horizontal field of view varying from 40° to 120°;
- Each pilot station represents a fourth- generation fighter aircraft, and the sensors and weapons can be modified in order to replicate most of the existent ones;
- The cabin interface resembles the Gripen aircraft cabin;
- 4 controller positions;
- After Action Review facilities, including "God's eye" view;
- Capability to insert constructive entities into the scenario, both friendly and enemy ones, with complex behaviors, based on the expected actions of the real fighters;
- Data communication between all the pilot stations and the controller stations, managed by an internal network;
- Capability to connect to external components and simulators.

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