3-24-2016

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Recommended Citation

Scheller, Brian K., "A Time-Variant Value-Focused Methodology for Supporting Pre-Acquisition" (2016). *Theses and Dissertations*. 448.
https://scholar.afit.edu/etd/448

A TIME-VARIANT VALUE-FOCUSED METHODOLOGY FOR SUPPORTING PRE-ACQUISITION

THESIS

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AFIT-ENY-MS-16-M-236

DEPARTMENT OF THE AIR FORCE
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Wright-Patterson Air Force Base, Ohio

AFIT-ENY-MS-16-M-236

A TIME-VARIANT VALUE-FOCUSED METHODOLOGY FOR SUPPORTING PRE-ACQUISITION

THESIS

Presented to the Faculty

Department of Systems Engineering and Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Systems Engineering

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March 2016

DISTRIBUTION STATEMENT A.
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Abstract

Military operations are dynamic in nature, as time-dependent requirements or adversary actions can contribute to differing levels of mission performance among systems. Future military operations commonly use multi-criteria decision analysis techniques that rely on value-focused thinking (VFT) to analyze and ultimately rank alternatives during the Analysis of Alternatives phase of the acquisition process. Traditional VFT approaches are not typically employed with the intention of analyzing time-variant performance of alternatives. In this research, a holistic approach towards integrating fundamental practices such as VFT, systems architecture, and modeling and simulation is used to analyze time-dependent data outputs of an alternative's performance within an operational environment. Incorporating this approach prior to Milestone A of the acquisition process allows for the identification of time-based capability gaps and additional dynamic analysis of possible alternatives that can be implemented as a flexible means of assessment. As part of this research, the pre-acquisition methodology is implemented with a hypothetical multi-domain Intelligence, Surveillance, and Reconnaissance mission in order to exemplify multiple time-dependent analysis possibilities.

Acknowledgments

I would like to express my sincere appreciation to my faculty advisor, Lt Col Tom Ford, for his guidance and support throughout the course of this thesis effort. The insight and experience was certainly appreciated. I would also like to thank the Materiel Integration Division (XZI) from the Air Force Life Cycle Management Center for both the backing and latitude provided in support of using an exemplar mission. Special thanks to my wife and son for their love and support through this long endeavor. I would lastly like to dedicate this thesis to my lord and savior, Jesus Christ, through whom all things are possible.

Brian K. Scheller

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Notation

Notation	Name	Definition
ST_{Start}	Simulation Start Time	The initiation time of the simulation represented in the appropriate time format
ST_{End}	Simulation End Time	The end time of the simulation represented in the appropriate time format
FST	Full Simulation Time	The difference between simulation start time and simulation end time represented in the appropriate time format
$ST_{Reference}$	Simulation Reference Time	A reference time of the simulation represented in the appropriate time format
t	Epoch Time	The difference between simulation start time and simulation reference time
t_{Start}	Time Window Start	The initiation epoch time of a particular time window
t_{End}	Time Window End	The end epoch time of a particular time window
TW_m	Time Window	A time period of interest, with m being the numerical count of a particular time window
P_c	Operational Phase	An operational phase of battle, with c being the numerical count of a particular operational phase
n	Total Measures	The total number of value measures
$x_i(t)$	Value Measure Score	The ith value measure's time-dependent score
$v_{i,t}\left(x_i(t)\right)$	Value Measure Unweighted Value	The ith value measure's time-dependent, normalized, unweighted, single-dimensional value of a time-dependent score
$min_i(t)$	Value Measure Minimum Boundary	A value measure's time-dependent minimum boundary score, with i being a particular value measure
$max_i(t)$	Value Measure Maximum Boundary	A value measure's time-dependent maximum boundary score, with i being a particular value measure
$TL_i(t)$	Value Measure Threshold Level	The expected threshold level corresponding to the time-dependent score of the ith value measure
$v_{i,t}\left(TL_i(t)\right)$	Value Measure Unweighted Threshold Value	The unweighted, normalized single-dimensional threshold value of the ith value measure threshold level at t
$w_i(t)$	Value Measure Weight	The global swing weight of the ith value measure at t
$IV_i(t)$	Value Measure Instantaneous Value	The normalized, weighted value of the ith value measure at t
$ITV_i(t)$	Value Measure Instantaneous Threshold Value	The normalized, weighted threshold value of the ith value measure at t

Notation	Name	Definition
$IB_i(t)$	Value Measure Instantaneous Boolean Score	The Boolean solution to whether the ith value measure's instantaneous value is meeting or exceeding its respective instantaneous threshold value at t
$IB_n(t)$	Instantaneous Boolean Score	The sum of the Boolean scores across all n value measures at t
$IV(t)$	Instantaneous Value	The sum of each value measure's normalized, weighted instantaneous value at t
$ITV(t)$	Instantaneous Threshold Value	The sum of each value measure's normalized, weighted instantaneous threshold value at t
$IB_{IV}(t)$	Instantaneous Value Boolean Score	The Boolean solution to whether the instantaneous value is meeting or exceeding its respective instantaneous threshold value at t
PM_{IV}	Instantaneous Value Peak Maximum	The largest instantaneous value in a particular time window, m
PM_{ITV}	Instantaneous Threshold Value Peak Maximum	The largest instantaneous threshold value in a particular time window, m
$i(m)$	Mandatory Value Measure	A value measure whose Boolean score must be one for the calculation of mandatory instantaneous value occurring at t
$IV_M(t)$	Mandatory Instantaneous Value	The instantaneous value at t, only when all mandatory value measures' instantaneous values are meeting or exceeding their respective value measures' instantaneous threshold values
$IC_i(t)$	Instantaneous Constraint	The constraint of the ith value measure at t
$fm(t)$	Full Mandate	Ensures all mandatory value measures' instantaneous values are meeting or exceeding their respective value measures' instantaneous threshold values at t
$CV(t)$	Constraint Vector	A vector that captures each instantaneous constraint as an element, with the row number of the constraint vector corresponding to the value measure's number
T	Specific Time	The unchanging specific time of interest
$IV_{TB}(t)$	Instantaneous Value for Specific Time with Buffer	The instantaneous value at t, only while meeting or exceeding its instantaneous threshold value, across a particular time window, m, whose time range is determined by the specific time's buffer range
$LBuffer$	Specific Time Lower Buffer	Specific time's lower buffer time range
$UBuffer$	Specific Time Upper Buffer	Specific time's upper buffer time range

Notation	Name	Definition
$IV_C(t)$	Conditional Instantaneous Value	The instantaneous value at t based on the conditional influence that the required value measure has on the conditional value measure
$v_{i(c),t}\left(x_i(t)\right)$	Value Measure Unweighted Conditional Value	The conditional, time-dependent, single-dimensional value of a time-dependent score of $x_i(t)$
$i(r)$	Required Value Measure	A value measure at t whose Boolean score must be one in order to adjust the conditional value measure to its threshold value at t
$i(c)$	Conditional Value Measure	A value measure that experiences a conditional influence based on the performance of the required value measure at t
LT	Last Time	The last epoch time during a conditional time window where all mandated value measures are meeting or exceeding their respective value measures' threshold values

A TIME-VARIANT VALUE-FOCUSED METHODOLOGY FOR SUPPORTING PRE-AQUISITION

1. Introduction

1.1 Chapter Overview

Chapter 1 researches background information regarding the Analysis of Alternatives (AoA) and decision analysis techniques typically used to help down-select alternative options. Several issues are described to include why a pre-acquisition methodology does not exist, as well as concerns associated with not capturing time-dependent performance of alternatives. The pre-acquisition methodology is briefly introduced, along with materials and equipment needed to carry out such time-variant analysis. The research supporting a pre-acquisition methodology begins by looking at suggestions for improvement of the AoA within the acquisition process.

1.2 Background

An AoA performs assessment of those possible alternatives with the hopes of selecting the best value option (Office of Aerospace Studies, 2013). In a 2014 report to the Committee on Armed Services, the United States Government Accountability Office (GAO) identified 24 best practices for an AoA. One suggestion concluded that "the team creates a plan, including proposed methodologies, for identifying, analyzing, and selecting alternatives, before beginning the AoA process" (GAO, 2014). Likewise, Department of Defense Instruction (DoDI) 5000.02, *Operation of the Defense Acquisition System,* presents an opportunity for early analysis of desired alternatives prior to the Materiel Development Decision (MDD) (USD(AT&L), 2015). Both the GAO report and

DoDI 5000.02 allow for early architecture analysis, yet no pre-acquisition methodology exists that considers the time-variant performance of alternatives.

Traditional practice in military decision analysis techniques, such as Multi Objective Decision Analysis (MODA) or Multi-Criteria Decision Analysis, use value-focused thinking (VFT) to assess the performance of alternatives (Klimack, 2002). Military operations have a tendency to be drawn out over time, contributing differing levels of performance as time persists. The time-variance surrounding a military operation makes it difficult to label an alternative by any static performance value, making it even more difficult to accurately portray time-varying performance comparisons between alternatives.

Traditional VFT translates the dynamic nature of a military operation into a static value due to its reliance on a single, constant value model. It is unfair and inaccurate to use traditional VFT methods without capturing time-dependent performance changes in military operations. Value scoring should reflect expected changes in performance as time persists to more appropriately score, and ultimately compare alternatives. This research aims at capturing such a time-variant, value-focused methodology for comparison of an operational concept's architecture alternatives prior to Milestone A (MS A).

1.3 Problem/Issue

One reason a methodology for conducting analysis on pre-acquisition architecture alternatives does not exist is due to the diversity surrounding DoD-supported programs. Considering the wide range of support across vastly different United States Air Force (USAF) mission sets, the idea that a one-size-fits-all methodology could be applied across programs seems initially improbable. The latest publication of DoDI 5000.02 adjusted the acquisition models supporting diverse program types from one model in previous releases to six models in the 2015 release (USD(AT&L), 2015). While the DoDI 5000.02 adjustment acknowledges different types of acquisition organization, the listed pre-MDD phases surrounding any of the six acquisition models are consistent. The acknowledgement that DoD programs use regular steps during pre-acquisition implementation leads to the need for a methodology in support of architecture development and early alternative analysis.

Another reason a pre-acquisition methodology does not exist is due to the difficulty surrounding unknown or dynamic threats. Most DoD concepts are developed in anticipation of future threat scenarios, and thus require collections of intelligence and anticipated technology maturity to calculate threat estimations. Frank Kendall III, Under Secretary of Defense for Acquisition, Technology and Logistics (USD(AT&L)), acknowledged the difficulty in identifying constantly changing threats facing acquisition programs like the F-35 Joint Strike Fighter (Pellerin, 2015). There is no guarantee that the projected threat will ultimately transpire, which makes planning for that future threat difficult, especially during early stages of the acquisition process. Applying early concept analysis to an unknown threat scenario is problematic and therefore not typically performed until information can be gathered during the AoA. However, if a pre-acquisition methodology were established that could be adjusted later in response to updated threats and operational expectations, perhaps earlier architecture alternative analysis would be encouraged. The proposed methodology's early focus on modeling and simulation (M&S) presents the potential for rapid adjustments as threat scenarios evolve later in the acquisition process.

Space- and air-domain concepts require some level of periodicity in operation, whether that be from the operational specifications for space concepts (such as altitude and orbit parameters) or refueling and maintenance demands of air platforms. The time-variance of these relied upon military systems presents difficulties in assessing how well architecture alternatives meet the overall mission goal, whose expected performance could itself change with time. A snapshot in time of a space- or air-domain alternative might provide a high level of performance, while a snapshot only minutes later might equate a low performance level. Current military-employed decision analysis techniques do not focus on capturing the time-variant nature of military operations. The proposed pre-acquisition methodology will focus on how to best compare time-differing operational performance levels of architecture alternatives.

1.4 Justification/Need for Research

Current USAF guidance does not include a methodology for performing architecture alternative analysis prior to MS A. The proposed research will address the question of whether a pre-acquisition methodology in support of alternative analysis would benefit the USAF acquisition process. This study will capture a time-variant methodology that focuses on early architecture comparison that could contribute to both cost- and time-saving efforts for the DoD.

The Air Force does not operate in a world of unrestricted resources where every proposed alternative can be stringently analyzed in regards to a future threat. Instead only the most convincing architecture alternatives are considered for detailed analysis, modeling, and simulation; selecting too many alternatives for analysis is advised against due to the resource and time constraints of today's DoD-supporting environment (Office of Aerospace Studies, 2013). A pre-acquisition methodology could streamline down-selection of alternatives to be more stringently analyzed during the later phases.

A pre-acquisition methodology would additionally allow for an easier transition into the ever-important MS A, where acquisition is initiated and alternatives are further analyzed with updated information. While the *Analysis of Alternatives (AoA) Handbook* recommends using operational judgement and experience, AoA research teams tend to rely heavily on a dominant group of Major Command (MAJCOM) subject matter experts (SMEs) to support performance decisions of alternatives (Office of Aerospace Studies, 2013). Kendall advises against overreliance on "people's experience and intuition and their judgments" instead of policy-based reasoning (DoD News Briefing, 2012). With the military's future focus shifting towards operational agility of multi-domain systems, a pre-acquisition methodology is needed which abstracts higher strategic guidance into implementable alternatives, and tests the performance of those decisions rather than relying on SME experience (Department of Defense, 2015a).

Current VFT-centered decision analysis tools employed by the USAF and DoD focus on capturing the overall value for ranking of alternatives, but fail to include individual performance contribution details. Looking at value measure performance in support of the overall value provides additional assessment information that could contribute to a more valuable system. Performance can be more accurately analyzed early in the acquisition process using several time-dependent, value-focused variables to provide a more complete assessment picture for each alternative.

1.5 Approach/Methodology

In order to appreciate the benefits of a pre-acquisition methodology, it is first necessary to understand the current acquisition process, including the expectations for transitioning into the AoA. Once the process is described, an identification of what is missing and common practices will be addressed. The pre-acquisition methodology, which derives its steps from several in-place analysis processes commonly used throughout the Air Force, will next be explained. All underlying details of each methodology step are researched and explained in Chapter 2.

The pre-acquisition methodology's steps are described in detail in Chapter 3; these steps include identifying the purpose, defining the concept, creating a value hierarchy, developing system architectures, modeling and simulating those concept architectures, assessing alternatives' value, and providing recommendations. The methodology will focus on a comparison between current and future architecture alternatives using several different time-dependent variables. As systems are becoming more reliable on multi-domain application, special attention is given to multi-domain model-based systems engineering (MBSE) within the pre-acquisition timeframe (Department of Defense, 2015a; Piaszczyk, 2011).

Chapter 4 applies the pre-acquisition methodology to a project supported by the Air Force Life Cycle Management Center (AFLCMC) surrounding an Intelligence, Surveillance, and Reconnaissance (ISR) mission. The ISR mission will act as a pre-acquisition methodology exemplar by supporting time-variant analysis of a single architecture alternative. The entire pre-acquisition methodology will be applied to the ISR exemplar, to include all detailed steps, sub-steps, and analyses. Chapter 5 will review the pre-acquisition methodology's application by providing conclusions and recommendations.

1.6 Materials & Equipment

The sponsoring agency in support of this research is AFLCMC/Materiel Integration Division (XZI). Software used in the research includes Microsoft Word, Python XY, Systems Tool Kit (STK), and Enterprise Architect (EA). Transitions of data between these programs will be required to successfully implement the pre-acquisition methodology and perform the required analysis.

1.7 Introduction Summary

Chapter 1 introduced the purpose of this study, which included the development and implementation of a time-variant, value-focused pre-acquisition methodology to be used for architecture alternatives analysis in support of a specific government goal. Sustaining the need for a pre-acquisition methodology, this section used DoD leaders' expectations, government document guidance, and review agencies to provide the background, problems, and issues seen with current analysis leading up to MS A. The need for research was justified by the current absence of a DoD-wide pre-acquisition methodology. A brief methodology overview was provided, including the intended implementation of each step to an in-place ISR mission. A time-dependent focus was used throughout this chapter to express the vision of the methodology and the need to represent time-varying value for accurate architecture alternative comparisons.

2. Literature Review

2.1 Chapter Overview

The ideas used to represent the proposed pre-acquisition methodology are certainly not new steps. Many DoD programs already implement several of the steps, even if not represented as part of a specific methodology. This chapter aims at summarizing applicable past research upon which to build the methodology's steps and their associated sub-steps. Additionally, Chapter 2 captures current research gaps and builds justification behind choosing techniques as part of the pre-acquisition methodology to be explained in Chapter 3.

2.2 USAF Acquisition Process

An acquisition program is "a directed, funded effort that provides a new, improved, or continuing materiel, weapon, or information system or service capability in response to an approved need (USD(AT&L), 2007). Each acquisition program is developed through an acquisition process, also known as an acquisition strategy. An acquisition strategy is

> A business and technical management approach designed to achieve program objectives within the resource constraints imposed. It is the framework for planning, directing, contracting for, and managing a program. It provides a master schedule for research, development, test, production, fielding, modification, post-production management, and other activities essential for program success (Hagan, 2009).

Capability requirements drive the execution of an acquisition program through its designated acquisition process. An overarching diagram capturing the interaction between the capability requirements process and the entire acquisition process can be seen in Figure 1. The red box in Figure 1 indicates the focused acquisition phases of the pre-acquisition timeframe.

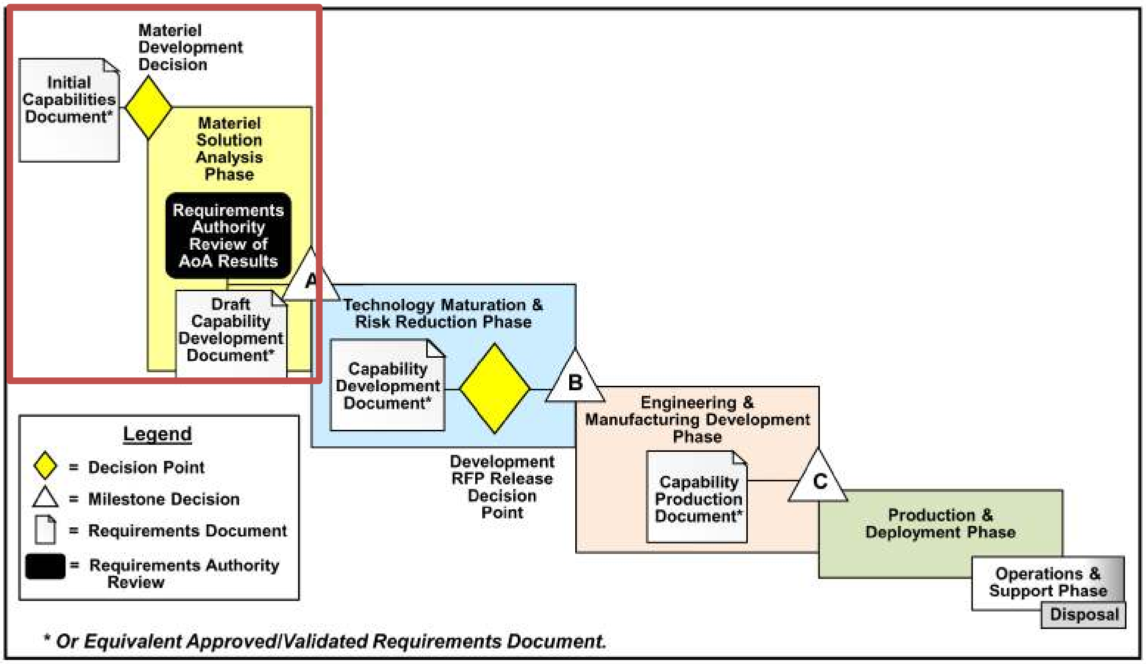


Figure 1 - Interaction between the Capability Requirements Process and the Acquisition Process (USD(AT&L), 2015)

Expanding the earliest phases of the acquisition process can be seen represented in Figure 2, which shows how strategic guidance and joint concepts influence the Capability Based Assessment (CBA) and Initial Capabilities Document (ICD). The Materiel Development Decision (MDD) is the formal decision to initiate an AoA, which includes Milestone Decision Authority (MDA) approval of the AoA study guidance and AoA study plan (Office of Aerospace Studies, 2013). Life-cycle events, such as the MDD and Milestone A Decision Review (represented as “A” in Figure 1 and “MS A” in Figure 2), are major decision points throughout the acquisition process.

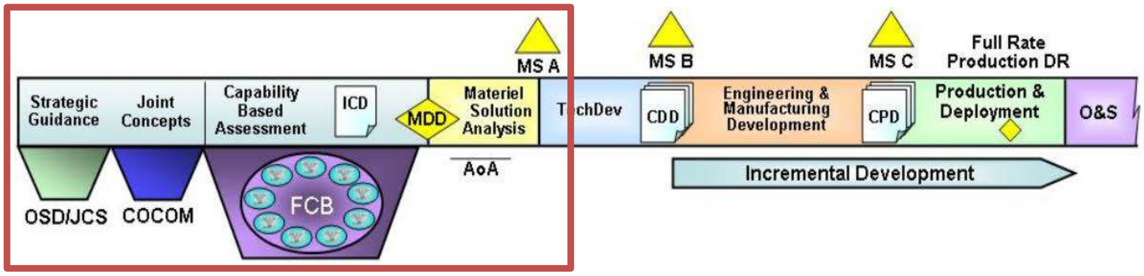


Figure 2 - MDD Review on DoD Acquisition Framework

(Office of Aerospace Studies, 2010)

"The AoA is an analytical comparison of the operational effectiveness, suitability, risk, and life cycle cost (or total ownership cost, if applicable) of alternatives that satisfy validated capability needs (usually stipulated in an approved Initial Capabilities Document (ICD))" (Office of Aerospace Studies, 2013). Traditionally occurring during the Materiel Solution Analysis (MSA), the AoA applies to all Acquisition Category (ACAT) initiatives. The AoA should stress decision-quality details given to stakeholders regarding the capabilities of alternatives in order to capture the military value of pursuing ACAT initiatives. "AoAs are essential elements of three Department of Defense (DoD) processes that work in concert to deliver the capabilities required by warfighters: the requirements process, the acquisition process, and the Planning, Programming, Budgeting, and Execution (PPBE) process" (Office of Aerospace Studies, 2013).

A pre-acquisition methodology should contribute to the already established acquisition process by providing later acquisition phases not only their required inputs, but initiating a positive impact on their expected outputs as well. The following sections will capture the expectations, inputs, and outputs that can be influenced by pre-acquisition actions. Table 1 summarizes senior leaders' and decision makers' expectations of an AoA.

Table 1 - AoA Expectations (Office of Aerospace Studies, 2013)

Senior Leaders And Decision Makers' Expectations Of An AoA
Unbiased inquiry into the costs and capabilities of options (identify the strengths and weaknesses of all options analyzed)
Identification of key trades among cost, schedule, and performance using the capability requirements (e.g., ICD and CDD gaps) as reference points
Identification of potential KPP/KSAs and an assessment of the consequence of not meeting them
Explanation of how key assumptions drive results, focused on the rationale for the assumption
Explanation of why alternatives do or do not meet requirements and close capability gaps
Identification of the best value alternatives based on results of sensitivity analysis
Increased emphasis on affordability assessments (conditions and assumptions under which a program may or may not be affordable)
Increased emphasis on legacy upgrades and non-developmental solutions versus new starts • Explore how to better use existing capabilities • Explore lower cost alternatives that sufficiently mitigate capability gaps but may not provide full capability
Increased emphasis on expanding cost analysis to focus beyond investment, for example, O&S across the force beyond the alternatives being analyzed
Explore the impact of a range of legacy and future force mixes on the alternatives
Increased emphasis on exploring an operationally realistic range of scenarios to determine impact on performance capabilities and affordability

Expectations from Table 1 should guide pre-acquisition development. Knowing what activities shape the AoA should additionally influence a pre-acquisition methodology, which can be seen in Table 2.

Table 2 - Activities that Shape the AoA (Office of Aerospace Studies, 2013)

Activities that Shape the AoA
Capability Based Planning (which includes the CBA)
Doctrine, Operations, Training, materiel, Leadership/Education, Personnel, Facilities, and Policy (DOTmLPF-P) Analysis
Early Systems Engineering and Development Planning (DP)
Materiel Development Decision (MDD)

The MSA Phase captures the AoA and occurs prior to MS A but after the MDD. Identified outputs of the MSA can be seen in Table 3.

Table 3 - Outputs of the MSA (Office of Aerospace Studies, 2010)

MSA Outputs
Scope of the AoA based on the refined problem definition
Range of alternatives for the AoA based on the identified viable, affordable materiel concepts/solutions
Scenarios and operational context
Analysis measures
Mission Tasks (MTs)
Measures of Effectiveness (MOEs)
Cost ground rules and assumptions
Definition of baseline capabilities
Definition of divestiture opportunities
Identifying whether the AoA is looking at a replacement capability or augmentation of existing capabilities
AoA core team members from ICD High Performance Team (HPT) membership
Initial Concept Characterization and Technical Descriptions (CCTDs)
Initial Requirements Correlation Table (RCT) (if developed)

The AoA has influence on much later acquisition phases than just those contained in MS A. For example, the AoA is the primary contributor for the Capability Development Document (CDD) and the Technology Development Strategy (TDS), both of which occur between MS A and MS B (Office of Aerospace Studies, 2013). The AoA is an important piece of not only early acquisition phases but also of all acquisition phases. Therefore, pre-acquisition tasks that develop the ever-important AoA should successfully follow the expectations of those later phases described previously by Table 1, Table 2, and Table 3.

2.3 Gold Standard Approach

Identified techniques for developing the value model include platinum, gold, and silver standards used in past MODA processes. The platinum standard focuses on interviews with stakeholders and senior leaders, the gold standard uses approved strategy or policy documents, and the silver standard uses data from stakeholder representatives (Parnell, Bresnick, Tani, & Johnson, 2013). Out of these options, the gold standard approach uses approved strategic documents as the foundation for the development and framework of decision objectives by examining the strategic vision and plan (Braziel, 2004; Parnell et al., 2013; Parnell, Conley, Jackson, Lehmkuhl, & Andrew, 1998). As long as policies are in line with current leadership goals, gold standard documents can be abstracted into a more complete understanding of the project purpose, can help define concepts, and can identify values and objectives (Parnell et al., 2013). Employing a gold standard-like approach in the early steps of the pre-acquisition methodology would benefit the overall process by ensuring policy and strategic abstraction to the mission at hand.

2.4 Operational Concepts

Air Force concepts influence plans in support of achieving national security and military objectives (DoD, 2012). Concepts help determine how the Air Force trains, equips, and organizes forces, to include how capabilities can respond to challenges and threats (DoD, 2012). An operational concept is part of the model itself; it is not just a document describing the "operations, functions, and activities" completed in response to future challenges (DoD, 2013). "The operational concept, whether institutional, functional, operational, or enabling, contributes the time horizon, assumptions, capabilities, sequences of actions, command relationships, desired end state, and other important elements to the model" (DoD, 2012; Ford, Meyer, Colombi, Scheller, & Palmer, 2015).

Concept white papers, talking papers, oral presentations, background papers, or bullet background papers are all USAF-employed techniques used to capture operational concept ideas (SAF/CIA A6SS, 2015). The background paper, for example, "is a multi-purpose communication instrument to transmit ideas or concepts from one office to another" (SAF/CIA A6SS, 2015). Regardless of the format used, enough detail should be included to accurately capture the intended concept. The continued development from initial ideas to informed, detailed concepts establishes guidance and information upon which to apply multi-criteria decision methods and eventually build the supporting system architectures.

2.5 Multi-Criteria Decision Methods

Assessing military value of operational concepts is intrinsically complex, especially in regards to DoD future projects and programs. This complexity spawns from an almost infinite solution space of competing alternatives and the subjective evaluation of competing objectives (Ford et al., 2015; Keeney & Raiffa, 1998). Problems as these are typically addressed using a multiple-objective or multi-criteria technique that considers impacts from each criterion. Specific to the DoD, multi-criteria decision methods have been used to assess military concepts for several decades, many including the use of a value hierarchy to make such assessments. The following section describes some past multi-criteria decision methods and their steps used to support DoD programs.

2.5.1 Past DoD Multi-Criteria Decision Examples

In 1997, Burk & Parnell used a value hierarchy in their multi-criteria decision methodology to identify probable technologies in support of future space operations. As a first step, Burk created a value model, or hierarchy, to evaluate qualities of alternatives.

For the goal of consistency, one can think of qualities as measures of effectiveness (MOEs), and alternatives can be interpreted as architecture options (Burk & Parnell, 1997). The hierarchy model used in this study was developed with a mission area, or singular goal represented at the top, and force qualities broken down beneath the overall goal. A measure of merit (MOM) was identified for the lowest, or leaf, force qualities. The previously identified alternatives were scored against each MOM and its corresponding benchmark levels. After those scores were assigned, normalized weights were established to the leaf-level force qualities on the value model. Each alternative's overall value was calculated by multiplying the quality weighted scores and summing those scores for each alternative. A sensitivity analysis was performed, and the alternatives with the best overall value were identified (Burk & Parnell, 1997). Burk's value model can be seen in Figure 3.

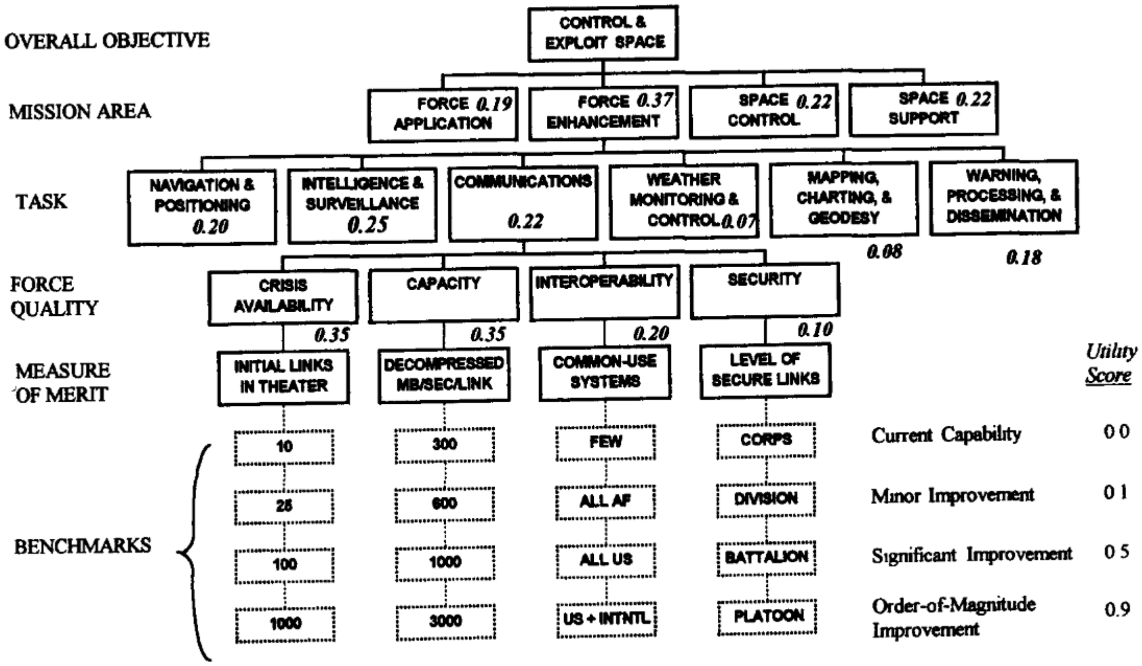


Figure 3 - Military Space Missions Value Matrix (Burk & Parnell, 1997)

Similar to Burk's article, "Foundations 2025: A Value Model for Evaluating Future Air and Space Forces," used concept analysis to help answer future Air Force needs (Parnell et al., 1998). Parnell's study followed an almost exact value hierarchy analysis methodology as Burk's. While analytical techniques have expanded over the years, the general steps of Burk's and Parnell's decision-making process in the 1990s can still be seen in more modern frameworks.

Several AFIT theses from the Operational Sciences department have used value hierarchies as part of employed multi-criteria decision methods to support past military problems. One 2005 thesis used a value-focused methodology to evaluate contingency construction methods. The methodology steps used by Tryon included problem identification, creation of a value hierarchy, development of evaluation measures, relation of value functions for scaling, application of weights to the value hierarchy, alternative generation, and alternative scoring (Tryon, 2005). In comparison to Burk's methodology, Tryon's initial step specifically identified the problem, whereas Burk's first step jumped straight to the value hierarchy. Additionally, Tryon's approach used value functions instead of just weighting and scoring concepts against the MOMs, as identified previously in Burk's method. Value functions convert each separate metric's raw scores into "values" scaled between a chosen range (Dorminey, Lasche, Santiago, & Washington, 2015). Developing accurate value functions provide a more scalable impact of each criterion for later concept comparisons (Ross & Hastings, 2005).

Another AFIT thesis examined MODA with prioritizing military engagements using VFT (Brine, 2012). Brine's methodology included all Tryon's previously identified phases, but adds alternative analysis and sensitivity analysis to the end of

Tryon's steps. Brine also chose to split his analysis steps into two sections, the first focusing specifically on the hierarchy model process and the second labeled as an analysis and results section (Brine, 2012). One notable precaution to these adjustments is that greater levels of analysis typically equate to greater resource commitments. For pre-acquisition inclusion, Brine's extra levels of analysis may not be implementable depending on project time and resource constraints.

The US Army Corps of Engineers' (USACE) *Trade-Off Analysis Planning and Procedures Guidebook* further expands upon multi-criteria decision-making (2002). This guidebook stresses an eight-component multi-criteria decision framework that fits most analysis methods. The multi-criteria decision framework links directly back to USACE's six-phase planning process, which can be seen in Figure 4. The traceable relationship in Figure 4 aligns each stage of the decision framework back to a specific phase of the established planning process, as seen by the arrows pointing down to the multi-criteria decision framework. As seen in Figure 4, no value hierarchy is mandated during this process (US Army Corps of Engineers, 2002).

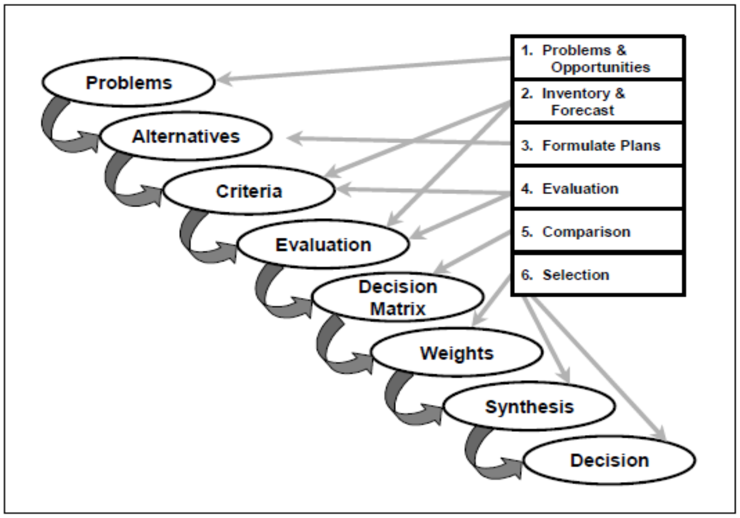


Figure 4 - USACE's Decision Framework (US Army Corps of Engineers, 2002)

USACE's framework differs from others by its reliance on a three-step decision matrix, which includes the matrix construction, pre-analysis, and matrix normalization. A preliminary decision matrix is used for structural review before undertaking the analysis. The pre-analysis simplifies the problem by removing non-discriminating criteria for a focus on only those criteria that have a direct impact on the decision. During post-normalization, the information in a decision matrix forms the foundation for recommendation to the decision-maker (US Army Corps of Engineers, 2002). The same three steps supporting USACE's decision matrix seem to align with traditional VFT procedures for constructing a value hierarchy.

While disparities have been noted between the five examples of DoD-supporting multi-criteria decision methods, the majority of steps are captured within all methodologies. Representation of those steps might be labeled or conducted differently, but most procedures are consistently performed throughout each process. Comparing Burk's and Parnell's process used in 1997-98 to Tryon's thesis in 2005, USACE's 2002 guidebook, and Brine's 2012 thesis shows much parallelism, despite the time separation between the establishment of these decision-making processes. Selecting best practices from different multi-criteria decision methods will ensure the pre-acquisition methodology implements all necessary steps for proper analysis of architecture alternatives.

2.5.2 AFT vs. VFT

Multi-criteria decision methods traditionally rely on one of two decision analysis techniques for comparisons between alternatives: alternative-focused thinking (AFT) or VFT. The AFT approach compares known alternatives by using the best alternative's value measure scoring as the value scale maximum and using the worst alternative's value measure scoring as the value scale minimum. AFT reduces the range of value measure scores to be used for comparison among alternatives. VFT instead starts with values and objectives prior to identifying possible alternatives. VFT uses a wide range of value measure scores to relate alternatives to the value measures' ideal scores, regardless of how other alternatives perform (Parnell et al., 2013).

A major problem with AFT's restricted value space is that alternative performance is not compared to expectations but rather to the performance of other alternatives. VFT encourages the development of new alternatives while AFT does not inspire the creation of new alternatives. However, a disadvantage of the VFT approach is that it usually leads to unused value when scoring alternatives, which can make differentiation between the performance of alternatives more difficult than AFT (Parnell et al., 2013). Decision-focused transformation (DFT) uses both approaches by beginning with VFT and transforming the value space to discriminate alternatives (Dees, Dabkowski, & Parnell, 2010; Parnell et al., 2013). While DFT might seem like the best analysis approach due to its VFT and AFT combination, the AFT transition to a constrained value space could still limit the decision frame and lead to missed alternatives.

Typically, a top-down, VFT approach is used if the decision-maker emphasizes the objectives over known alternatives, casting a wider hierarchy than AFT would contribute (Keeney, 1996; Parnell et al., 2013; Tryon, 2005). VFT helps to not only develop alternatives consistent with a concept, but also to evaluate alternatives based on those pre-established values (Parnell et al., 2013). The *Analysis of Alternatives (AoA)*

Handbook promotes VFT over AFT by recommending that, ”any method chosen… should map measure values in relation to the threshold value…not in relation to one another” (Office of Aerospace Studies, 2013).

2.5.3 10-Step VFT Process

The 10-step VFT process was developed at AFIT by Shoviak from MODA methodologies described previously (Cotton & Haase, 2009; Keeney & Raiffa, 1998; Kirkwood, 1997; Shoviak, 2001). Several previous authors have used the 10-step VFT process to drive value hierarchy development, scoring, and analysis (Braziel, 2004; Cotton & Haase, 2009; Shoviak, 2001; Springston, 2011). Each step of the 10-step VFT process is shown in Figure 5 and is described in the following sections.

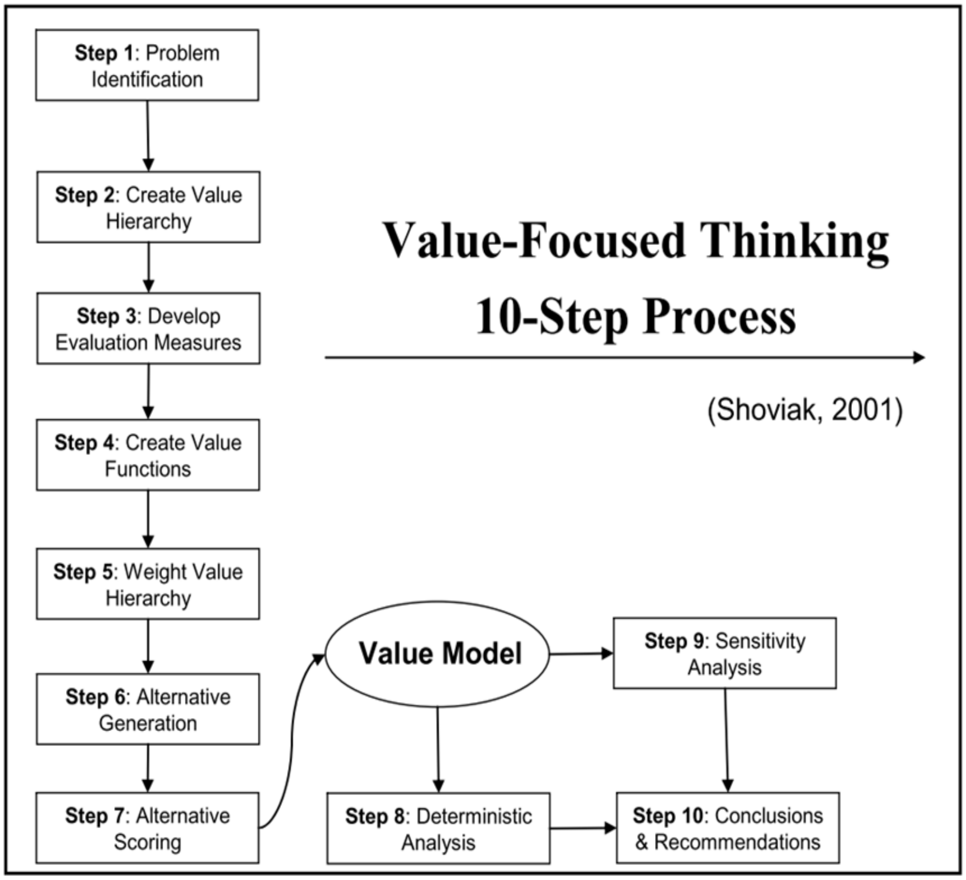


Figure 5 - 10-Step VFT Process (Shoviak, 2001)

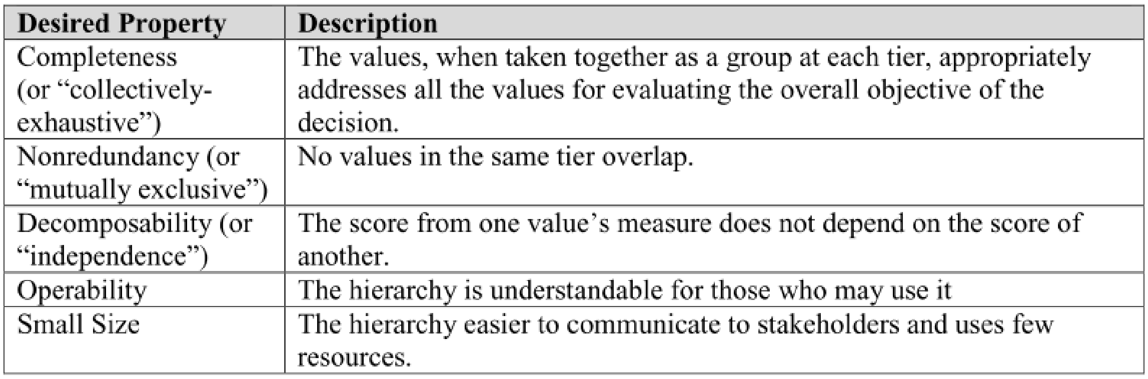
2.5.3.1 Step 1. Problem Identification

The beginning of the 10-step VFT process identifies the specific problem that stakeholders desire to solve, and should result in a well-defined problem statement (Shoviak, 2001).

2.5.3.2 Step 2. Create Value Hierarchy

The value hierarchy can be used to help constrain the solution space of possible alternatives and translate subjective objectives into objective values for analysis (Ford et al., 2015; Keeney & Raiffa, 1998). Examples of using value hierarchies were previously described in Chapter 2. A value hierarchy is typically used to evaluate how well each alternative achieves a range of functions, ultimately helping the decision-maker either narrow down options or select a best choice (Dorminey et al., 2015). A value hierarchy should be limited in complexity, and should include value functions and weighting to prioritize stakeholder requirements and alternative comparisons (Parnell et al., 2013). Value hierarchies should be complete, non-redundant, operational, decomposable, and contained to a small size, all of which can be seen in Table 4 (Keeney & Raiffa, 1998; Kirkwood, 1997; Sage & Rouse, 2014).

Table 4 - Value Hierarchy Desired Properties (Kirkwood, 1997)



Desired Property	Description
Completeness (or "collectively-exhaustive")	The values, when taken together as a group at each tier, appropriately addresses all the values for evaluating the overall objective of the decision.
Nonredundancy (or "mutually exclusive")	No values in the same tier overlap.
Decomposability (or "independence")	The score from one value's measure does not depend on the score of another.
Operability	The hierarchy is understandable for those who may use it
Small Size	The hierarchy easier to communicate to stakeholders and uses few resources.

While multiple-criteria decision methods utilize different analysis techniques, a value hierarchy is a visual representation tool that displays stakeholders' objectives to determine how well alternatives fit the respective goal or problem (Dorminey et al., 2015; Keeney & Raiffa, 1998). One purpose of VFT is the creation of a mutually-exclusive and collectively-exhaustive set of values representing stakeholder interests (Cotton & Haase, 2009; Kirkwood, 1997). A value hierarchy arranges system functions in a hierarchical structure in order to look at the full range of evaluation considerations, objectives, and measures surrounding an issue (Sage & Rouse, 2014). The goal of step two in the 10-step VFT process is to create "an objective or a functional value hierarchy that describes and organizes the objectives" (Parnell et al., 2013). Therefore, focusing only on the initial construction of the value hierarchy, with the goal on top and all values or objectives represented beneath, is acceptable for step two's creation of the value hierarchy. This step does not include applying value measures, value functions, or weighting to the value hierarchy, all of which are captured during later steps of the 10-step VFT process.

2.5.3.3 Step 3. Develop Value Evaluation Measures

"It's up to each study team to determine what data is important enough to be measured, and how all other data should/should not be used and reported" (Office of Aerospace Studies, 2013). A measure is "a device designed to convey information about an entity being addressed" (Office of Aerospace Studies, 2013). Evaluation measures, also known as value measures, are placed at the bottom of a value hierarchy for the purpose of quantifying each objective (Parnell et al., 2013). Value measures can be labeled as natural or constructed, and direct or proxy. A natural measure is widely understood while a constructed measure is created in response to an issue when a natural measures is not applicable or available (Cotton & Haase, 2009). A "direct scale directly measures the degree of attainment of an objective, while a proxy scale reflects the degree of attainment of its associated objective, but does not directly measure this" (Kirkwood, 1997). The preferred combination is to select natural and direct value measures.

2.5.3.3.1 Frequently Used USAF Evalutation Measures

While not considered part of the 10-step VFT process, capturing in-place USAF practices for identifying measures is important for implementation of the established acquisition process. Types of measures identified in the *Analysis of Alternatives (AoA) Handbook* and used to address performance concerns as part of the USAF acquisition process include Measures of Effectiveness (MOEs), Measures of Suitability (MOSs), and Measures of Performance (MOPs). Additionally, high interest measures are Key Performance Parameters (KPPs) and Key System Attributes (KSAs). One requirement of the AoA is to produce an initial set of possible KSAs and KPPs (Office of Aerospace Studies, 2013). Definitions of measure types according to the *Analysis of Alternatives (AoA) Handbook* can be seen in Table 5.

Table 5 - Measure Type Definitions (Office of Aerospace Studies, 2013)

Measure Type	Definition
Measure of Effectiveness	"A measure of operational success that must be closely related to the objective of the mission or operation being evaluated"
Measure of Suitability	"A measure of a system's ability to support mission/task accomplishment with respect to reliability, availability, maintainability, transportability, supportability, and training"
Measure of Performance	"A measure of the lowest level of physical performance (e.g., range, velocity, throughput, etc.) or physical characteristic (e.g., height, weight, volume, frequency, etc.)"
Key Performance Parameter	"Attributes or characteristics of a system that are considered critical or essential to the development of an effective military capability"
Key System Attribute	"System attributes considered critical or essential for an effective military capability but not selected as KPPs"

Minimum acceptable value of performance (threshold value) and a more demanding value (objective value) should be determined for measures to ensure performance value can be assessed (Office of Aerospace Studies, 2013). Table 6 lists measure development guidelines applicable for all measure types.

Table 6 - Measure Development Guidelines (Office of Aerospace Studies, 2013)

Measure Development Guidelines
Keep the measure as simple as possible – a simple measure requires only a single measurement
Develop measures that are important to understanding and assessing the alternatives as well as measures that enable discrimination among alternatives
Measures should not be listed more than once for a mission task, but the same measure may be listed under different mission tasks
Focus on the outputs, results of performance, or the process to achieve the activity
Check to ensure the units of the metric match the criteria values
Understand the type of data being collected and the appropriate statistics that can be used in the analysis
Do not apply weights to measures, although some measures may be more important than others

An attempt should be made as part of the pre-acquisition methodology to link USAF measure-defining practices described earlier to those VFT value measure techniques described as part of the 10-step VFT process.

2.5.3.4 Step 4. Create Value Functions

Many decision analysis methods use mathematical functions to evaluate the value of alternatives. A minimum acceptable level to a best possible level typically determines the ranges for each value measure (Parnell et al., 2013). Single-attribute value functions (SAVFs), also known as single-dimensional value functions (SDVFs), are used to constrain and control the normalized value resulting from a value measure's score. Each SAVF converts a value measure's score into a value unit normalized between zero and one. "The least preferred score being considered for a particular evaluation measure will have a single dimensional value of zero, and the most preferred score will have a single dimensional value of one" (Kirkwood, 1997). Value functions act as screening criteria for potential alternatives (Braziel, 2004).

The four primary shapes of SAVFs for value measures are linear, concave, convex, and S-curve (Kirkwood, 1997; Parnell et al., 2013). The linear SAVF captures constant estimation between the bounds of a value measure, the concave SAVF has decreasing marginal value, the convex shape has increasing bordering value, and the S-curve captures an early convex region with a later concave region (Colombi, Miller, Bohren, & Howard, 2015). The linear shape uses a linear function, while the other shapes utilize exponential curve fitting (Colombi et al., 2015). Regardless of the shape and interval scales chosen, a corresponding zero value does not mean that no value exists, but instead represents the minimum acceptable or achievable value (Parnell et al., 2013).

2.5.3.5 Step 5. Weight Value Hierarchy

Multiple-criteria methods assign weights to each objective in order to rank research subjects by composite scores. Local swing weights, occasionally referred to simply as weights, should be assigned over all objectives, not just value measures. The top of the hierarchy will always have a total weight of one (Cotton & Haase, 2009).

A highly important value measure should have an associated higher weight than a measure carrying less importance. However, weighting should also be representative of value measure score ranges. “The most common mistake is MODA is assessing weights without taking into account the specific range of value measure scores under consideration” (Parnell et al., 2013). Value measures with wide ranges should be weighted higher than those with smaller ranges (Parnell et al., 2013). A swing weight matrix is a tool developed to help stakeholders understand a value measure’s range on the total value of alternatives (Kirkwood, 1997; Parnell et al., 2013).

2.5.3.6 Step 6. Generate Alternatives

Parnell discusses the method of generating worthy alternatives as having two phases, the first being expansive and the second being reductive. The expansive phase generates as many alternatives as possible, relying on creative thinking over analytic thinking. The reductive phase instead uses analytic thinking and aims at converging the brainstormed alternatives during the expansive phase into those that will actually be evaluated against the value model (Parnell et al., 2013).

Special attention should be given to the placement of the alternative generation step, as the 10-step VFT process generates alternatives after value hierarchy construction, SAVF assignment, and weights are applied (Shoviak, 2001). Alternative generation is meant to best achieve those objectives represented in the value hierarchy, and one alternative can trigger the generation of several other alternatives (Cotton & Haase, 2009; Keeney, 1994). This method is proven to generate top alternative options that are perceived to score well against a permanently established value hierarchy.

The number of alternatives can be different depending on the supporting programs. Table 7 shows the minimum alternatives that must be included as part of the AoA.

Table 7 - Minimum Alternatives in an AoA (Office of Aerospace Studies, 2013)

Minimum Alternative Types in an AoA
The baseline, which represents the existing, currently programmed system funded and operated according to current plans
Alternatives based on potential, yet unfunded improvements to the baseline, generally referred to as the baseline+ or modified baseline. [Note: it is not always best to include all potential improvements to the baseline in one alternative, consider having multiple alternatives in this category.]
Alternatives identified in the AoA study guidance (for example, COTS/GOTS, allied systems, etc.)

Once alternatives are appropriately determined, scoring those alternatives is the following step in the 10-step VFT process.

2.5.3.7 Step 7. Score Alternatives

Those alternatives down-selected in step six of the 10-step VFT process are evaluated according to each value measure’s SAVF. Scoring alternatives can be a lengthy step depending on the number of value measures chosen (Cotton & Haase, 2009). The resulting score will be an unweighted, normalized (scale of zero to one) value for each individual value measure.

2.5.3.8 Step 8. Deterministic Analysis

With each value measure's unweighted value, the established weights are next applied to produce global weighted value for each value measure. An alternative's total value is calculated by multiplying each performance score's single-dimensional value (result from step seven of the 10-step VFT process) by its weight (from step five of the 10-step VFT process) and then summing (Parnell et al., 2013). Multiple additive value models have been developed to incorporate each value measure's SAVF and weighting to determine an overall value (Kirkwood, 1997; Parnell et al., 2013). While they use different variables for representation, all assume preferential independence between alternatives and between value measures (Shoviak, 2001). Deterministic analysis can lead to the ranked order of alternatives based on their resulting values.

2.5.3.9 Step 9. Sensitivity Analysis

Distribution of weights throughout the objectives in a value hierarchy is recognized as playing an important role in deciding alternatives (Parnell et al., 2013). Step nine of the 10-step VFT process analyzes the sensitivity of previously ranked alternatives by changing the weights. As weights are adjusted, alternatives' rankings based on their value can be tracked and compared to provide stakeholder insight on the weighting impacts (Cotton & Haase, 2009).

2.5.3.10 Step 10. Conclusion and Recommendations

The final step of the 10-step VFT process presents the results to the stakeholders or decision-makers, which typically includes the ranking of alternatives based on their scored value.

2.5.4 Additive Value Model

As previously mentioned in steps four and five of the 10-step VFT process, some form of value model is required to establish each alternative's total weighted value for comparison. Parnell's *Handbook of Decision Analysis* uses an additive value model to sum each value measure's weighted, normalized value in order to obtain an overall value for a particular alternative (Parnell et al., 2013). The additive value model equations 9.1 and 9.2 from his *Handbook of Decision Analysis*, along with Parnell's definitions of their variables, are represented in equations (1) and (2). In order to maintain consistency, these equations and variables will be continued with and expanded upon in Chapters 3 and 4 in support of the pre-acquisition methodology.

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

Where for a set of value measure levels given by vector x,

$v(x)$ is the alternative's value of x

$i = 1$ to n is the index of the value measure

x_i is the alternative's score of the ith value measure

$v_i(x_i) =$ is the single-dimensional y-axis value of an x-axis score of x_i

w_i is the swing weight of the ith value measure

and

$$\sum_{i=1}^{n} w_i = 1 \tag{2}$$

(all weights sum to one)

(Parnell et al., 2013)

Equation (1) assumes preferential independence, meaning that "the assessment of the value function on one value measure does not depend on the level of the other value measures" (Kirkwood, 1997; Parnell et al., 2013). Equation (1) says that an alternative's value of x is the summation of each value measure's normalized, unweighted, single-dimensional value of a score multiplied by that value measure's respective weight. Equation (2) mandates that all global value measure weights across a value hierarchy must sum to one.

Including the weighting of multiple performance criteria contributes to one overarching multi-attribute value function (MAVF) (Colombi et al., 2015). Parnell's additive model tends to focus on the summed total value of the MAVF instead of each value measure's individual contribution to an alternative's value of x. Notice in (1) how there is no established variable to represent a particular value measure's weighted value $\left(w_i v_i(x_i)\right)$. Consistent with the previously explained *Analysis of Alternatives (AoA) Handbook* analysis precautions, an attempt should be made to show individual value measure performance prior to weighting $\left(v_i(x_i)\right)$, after weighting $\left(w_i v_i(x_i)\right)$, and the eventual additive value of the MAVF $\left(v(x)\right)$ for full performance understanding of an alternative (Office of Aerospace Studies, 2013). The 10-step VFT process does designate step seven as scoring alternatives unweighted value prior to weighting, but based on Parnell's additive value equations (1) and (2), little attention is given to value measure results prior to summation.

2.5.5 Rolled-Up Technique Warning

"OAS discourages 'roll-up' and weighting schemes that tend to mask important information or potentially provide misleading results" (Office of Aerospace Studies, 2013). Air Force Materiel Command's *Analysis of Alternatives (AoA) Handbook* instead recommends that a direct performance analysis be made towards unweighted measures. While value hierarchies use weighting and their resulting additive value for alternative comparisons, the handbook's comment does not directly discredit using VFT methods. It instead discredits communicating only the "rolled up" weighted ranking results to stakeholders and senior leaders (Office of Aerospace Studies, 2013). Incorporating the *Analysis of Alternatives (AoA) Handbook*'s recommendation to assess performance directly against measures prior to incorporating weights should be an attempted inclusion of the pre-acquisition methodology.

2.5.6 Analytic Hierarchy Process

There are many analysis techniques used to rank possible alternatives. The US Army Corps of Engineers' *Trade-Off Analysis Planning and Procedures Guidebook* suggests that multi-criteria decision analysis techniques are most distinctive in the way they accomplish the latest steps of weighting, synthesis, and decision-making (2002). One of the most widely used approaches for multiple criteria decision-making is Analytic Hierarchy Process (AHP) (Xu & Yang, 2001). AHP is a commonly used method that derives ratio scales from paired comparisons (Alexander, 2012). AHP was developed in the 1970s by Professor Thomas L. Saaty as a decision support tool that formulates, measures, and analyzes complex problems, ultimately "allowing decision makers to organize and evaluate the significance of the criteria and alternative solutions of a decision" (Alexander, 2012; Alghamdi, 2009). AHP uses include ranking, choice, prioritization, benchmarking, resource allocation, and quality management (Alghamdi, 2009). Sections of AHP's model include a goal at the top, alternatives at the bottom, and criteria and sub criteria in the middle. AHP steps include: 1) selecting a goal, 2) listing criteria, 3) listing sub criteria, and 4) determining alternatives (Alghamdi, 2009). An example of the AHP hierarchy can be seen in Figure 6.

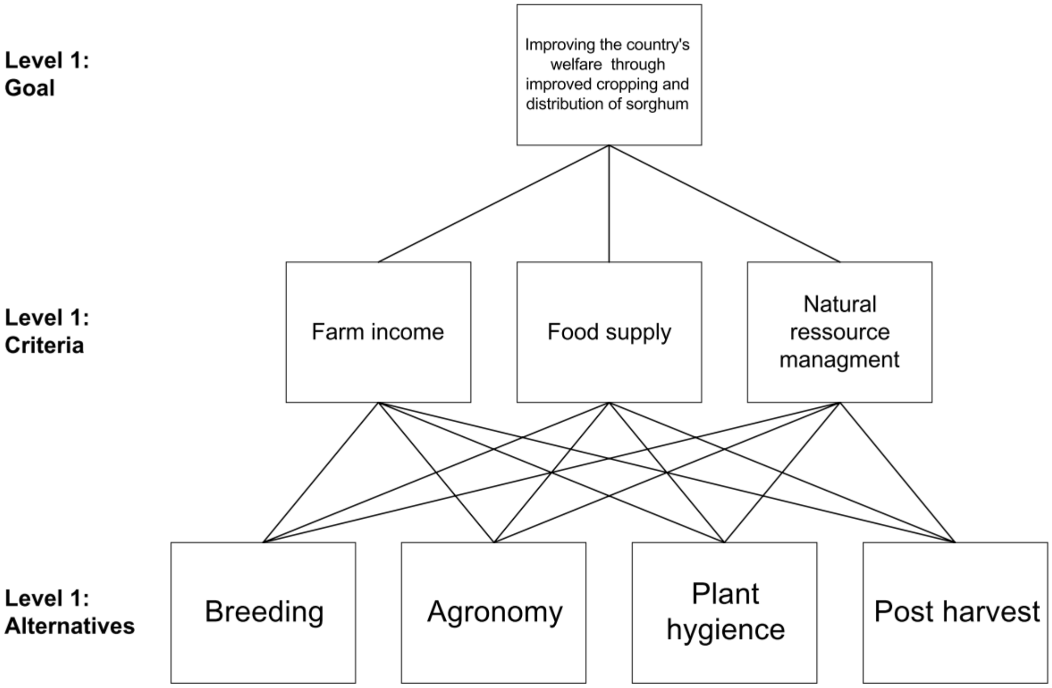


Figure 6 - AHP Structure for Weighting Agricultural Research (Hartwich, 1999)

AHP strengths include the use of logical decompositions to suppress personal preference. Another strength of AHP is its focus on goals (Hartwich, 1999). Similar to that of a value hierarchy, the hierarchical setup of the AHP ensures concordance between lower criteria levels derived from the overarching goal. Finally, AHP is useful for implementing rapid decision-making by a diverse team (Hartwich, 1999). For DoD programs, rarely does one person make the final decision as to which architecture alternative(s) to push forward in the acquisitions process. Instead, a team of decision-makers is more frequently responsible.

While AHPs have proven successful in various settings, major weaknesses or limitations are also associated with this method. Aggregation techniques are typically used for decisions with less complexity and less controversy, while pairwise comparison techniques, like AHP, demand that the decision-maker look at pairs of each criterion as matched against every other criterion. Because of the pairwise comparison's nature, an AHP with four criteria requires six comparisons. Increasing this total to seven criteria means 21 comparisons are needed, which is why decision criteria must be limited due to the overwhelming number of required comparisons (US Army Corps of Engineers, 2002). Pairwise comparison during an iterative methodology means accomplishing the pairwise comparison anytime a new criterion is added.

Another AHP limitation is the difficulty associated with comparing extremely different concepts (Hartwich, 1999). While the pre-acquisition methodology will initially compare alternatives across a single concept, eventually assessments will require cross-concept analysis. This limitation could impact the model's ability to contrast multi-domain concepts utilizing air, space, maritime, and land. The Office of the Assistant Secretary (OAS) does not endorse the use of the AHP as part of AoA effectiveness methodology (Office of Aerospace Studies, 2013).

2.6 Executable System Architectures

The Institute of Electrical and Electronics Engineers (IEEE) standard, ANSI/IEEE Std 1471-2000, defines an architecture as "the fundamental organization of a system, embodied in its components, their relationships to each other and the environment, and the principles governing its design and evolution" (Institute of Electrical and Electronics Engineers, 2000). The Open Group Architecture Framework (TOGAF) does not wholeheartedly agree with the software-intensive terminology used in the definition of ANSI/IEEE Std 1471-2000. TOGAF instead uses two definitions of architecture, the more applicable of the two being "the structure of components, their interrelationships, and the principles and guidelines governing their design and evolution over time" ("TOGAF, an Open Group standard," n.d.). Systems architecting is driven by the client, which takes on a holistic systems approach that links value judgements to design decisions. Architecting's inductive process is highly-abstract, being both and art and a science useful for creating unprecedented complex systems (Ford, 2015b; Maier & Rechtin, 2009). Some possible architecture frameworks include Department of Defense Architecture Framework (DoDAF), Ministry of Defense Architecture Framework (MODAF), TOGAF, Zachman, Integrated Architecture Framework (IAF), Federal Enterprise Architecture Framework (FEAF), and Business Process Model and Notation (BPMN) (Ford, 2015a; Maier & Rechtin, 2009).

The practice of systems architecture helps transform a vague concept into a satisfactory and feasible system concept (Maier & Rechtin, 2009). Turning a concept into system architecture alternatives can be performed after value hierarchy development just as represented in step six of the 10-step VFT process (Shoviak, 2001). Since alternative details should be captured in the form of system architectures, a methodology should attempt generation of a concept's architecture alternatives around the same time that system architecture is performed. Those generated alternatives should additionally be derived to an executable level using systems architecture best practices.

The transition from paper-based to MBSE produced new possibilities for implementation of executable architecture (Ge, Hipel, Yang, & Chen, 2014). Two main systems engineering approaches led to executable system models. The first of these approaches was the Structured Analysis Design Technique, which focused on fixed structures and sequential processes. The second approach is called the Object Oriented technique, which is best used in support of multiple independent events (Handley, Zaidi, & Levis, 1999).

Regardless of the approach used, methods such as Helle's and Levier's can be employed to ensure conversion from a traditionally integrated architecture into an executable architecture prior to modeling (Helle & Levier, 2010). Several examples exist that created executable architectures using in-place architecting frameworks, such as Unified Modeling Language (UML), Systems Modeling Language (SysML), or Colored Petri Nets (Ge et al., 2014). Other executable architecting methods that rely upon MBSE are tailored to a specific focus, such as architecting data-centric models or systems-of-systems (Ge et al., 2014; Li, Dou, Ge, Yang, & Chen, 2012). Referencing past successes of executable system architectures can be used during the pre-acquisition methodology to ensure system architecture views are developed correctly (Ford et al., 2015).

The three DoDAF views that might be helpful in developing an executable architecture for a pre-acquisition methodology include creating a Capability Taxonomy (CV-2), Operational Activities Decomposition Tree (OV-5a), and System Functionality Description (SV-4). Mapping the Joint Capability Areas (JCAs) to Universal Joint Task List (UJTL) tasks can help direct decomposition and ensure concordance with higher-level views (DoD CIO, 2010). Additional decomposition can be made to capture Ilities surrounding the architecture's intention (Boehm, 2013). Frameworks other than DoDAF have similar views that can be used capture operational performance decomposition to an executable systems architecture level.

2.7 Modeling & Simulation

"Whatever their complexity or form, there comes a point when the AoA team must decide which tools to use to generate measure data for alternative comparisons" (Office of Aerospace Studies, 2013). Incorporating an early M&S analysis technique into the value-based decision process can limit the reliance on qualitative performance assessments scored directly against criteria. Maier and Rechtin describe modeling as both the centerpiece and fabric of systems architecture (2009).

Executable architecting has been confirmed with M&S tools as a useful systems engineering practice throughout the past several decades (Ford et al., 2015). In 1999, executable architecting was used to generalize simulation models in experiments (Handley et al., 1999). Additionally, Wagenhals' 2002 research focused on manufacturing executable models of object oriented architectures, Shin's research keyed on validating the system behavior of design models initiating from UML-based models in 2003, and Wagenhals' research from 2009 centered on executable architectures to support evaluation later using Colored Petri Nets or agent-based simulations (Shin, Levis, & Wagenhals, 2003; L. W Wagenhals, Haider, & Levis, 2002; Lee W Wagenhals, Liles, & Levis, 2009).

The suggestions shown in Table 8 should be considered when selecting analysis tools, to include the potential of M&S implementation. Past successes of linking executable architecture to M&S tools should instill confidence in the possibility of M&S use in supporting the pre-acquisition methodology.

Table 8 - Analysis Tools Considerations (Office of Aerospace Studies, 2013)

Analysis Tools Considerations
Information or input data requirements and the quality of the data sources
Credibility and acceptance of the tool output or process results (e.g., SME assessments)
Who is available to run the M&S, develop/manipulate the spreadsheets or participate in SME assessments
Whether or not the tool can be applied to support the analysis within time and funding constraints
Cost of running M&S

2.7.1 Past M&S Uses with Executable Architectures

In 2008, Gregory Miller from the Naval Postgraduate School (NPS) proposed a systems engineering method that generated value-focused alternatives into system architectures supporting the Joint Capability Command and Control Management (JC3M), and using simulation was able to estimate the costs associated with the implementation of alternatives. Miller's method used objective analysis on performance criteria directly resulting from the simulation to estimate the life cycle cost of architecture solutions supporting the JC3M (Miller, 2008). While Miller's method incorporated simulation into cost estimations, the value-focused portions of his methodology did not capture time-dependent value as the pre-acquisition methodology intends to do.

A more recent example that used executable architectures with an M&S tool was seen in 2015, when an M&S program called Systems Tool Kit (STK) was utilized to support the planning of a manned mission to Mars (Colombi et al., 2015). This research recognized the influence of time on mission performance, and captured the changing values through discrete-event simulations. The example of mixing discrete-event simulation with value assessment presents optimization opportunities through iterations of an architectural design (Ford et al., 2015).

2.8 Capturing Time-Variant Value

> For the most part, decision analysis tools are often used for “static,” nonrecurring analyses, but often, there is additional value in their ability to be used dynamically to enhance the risk management process. As new information is gleaned, probabilities get updated; as events unfold, consequences become conditional and change over time. If we can build our models to accommodate these dynamic effects, their value-added is increased significantly as they are used through all phases of implementation. (Parnell et al., 2013)

The advantages described by Parnell of capturing dynamic value can be directly attributed to military operations. Military operations are time-dependent, meaning their performance can adjust with time as operational specifications or outside influences are imposed. Space systems are one type of military platform whose performance changes with time. Data collection missions are frequently performed from space, many of which rely on Low-Earth Orbit (LEO) to maximize data accuracy such as image resolution. While there are numerous benefits to operating at LEO, the reliance on such close-range space orbits presents the potential for periodic (non-constant) surveillance, depending on the amount of assets and their orbital placement. Similar to space-domain systems, air-domain systems are reliant upon their system design specifications (flight routes, maximum loiter time, maintenance schedule, etc.) that in turn produce periodic performance. Current military-employed decision analysis techniques choose to summarize the time-variant nature of such military operations into a static value, but the pre-acquisition methodology should attempt to account for the periodic performance of time-dependent systems.

2.9 Literature Review Summary

This chapter consisted of literature research surrounding different decision-making techniques, many of which contained a heavy emphasis on multi-criteria decision methods. The USAF acquisition process and AoA requirements were detailed, along with information supporting the gold standard approach and guidance for the creation of operational concepts. The major focus of Chapter 2 supported value hierarchy-based approaches, as the value hierarchy is a frequently used DoD tool for analysis of project alternatives having several different objectives. Common analysis techniques were reviewed, which included discussion of both the advantages and disadvantages of some leading practices, along with past examples of implementation. Executable systems architecture and its use with M&S practices were briefly touched upon, along with the importance of capturing time-variant performance of operational systems. The combined research from Chapter 2 drove the development of the pre-acquisition methodology and supporting analyses in the following chapters of this study.

3. Methodology

3.1 Chapter Overview

The purpose of this chapter is to present the proposed pre-acquisition methodology. Description of the methodology will first be explained holistically through the use of a waterfall diagram that utilizes proven Chapter 2 research areas, including a gold standard-like initiation in support of the purpose and concept development, all of the steps from the 10-step VFT process, executable systems architecture incorporation, best M&S practices, and a systems engineering focus throughout. Each methodology step will be explained in detail by touching on the sub-steps as well as their required outputs, a summary of which is captured in Table 10 at the end of Chapter 3.

3.2 Pre-Acquisition Methodology

Figure 7 captures a high-level representation of the pre-acquisition methodology, which shows the beginning-to-end process in support of analyzing any architecture.

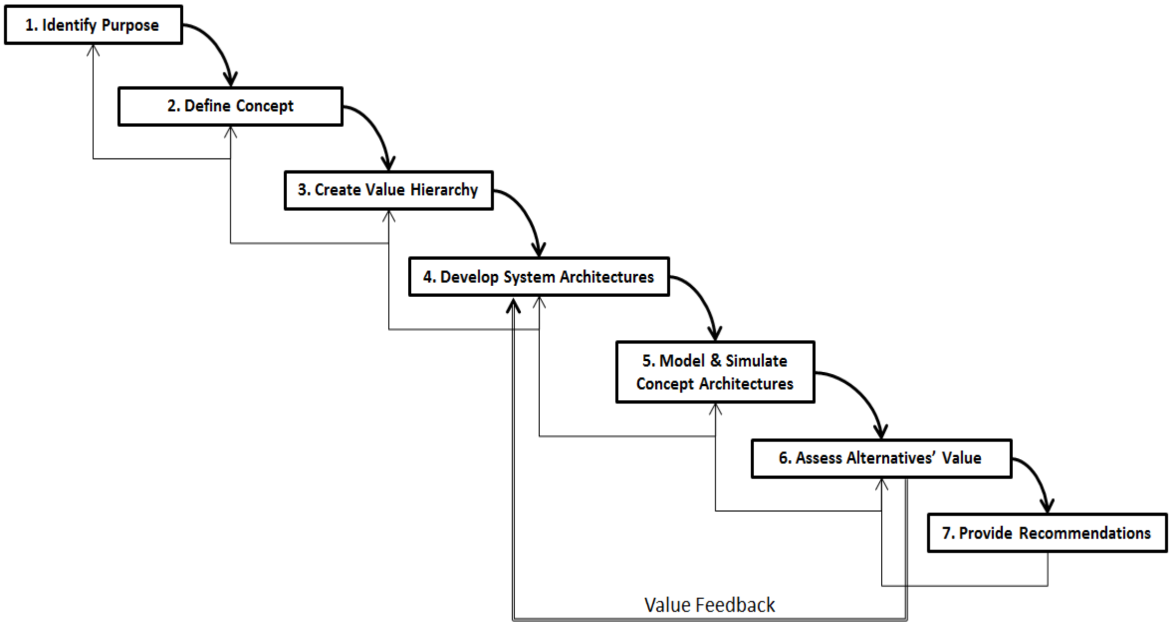


Figure 7 - Pre-Acquisition Methodology (Ford et al., 2015)

The steps in Figure 7 flow numerically from upper left to bottom right, as represented by the upper bold arrows bending from each previous step. The lower square arrows flowing upward and left indicate iterative transitions to earlier steps, which are permitted and expected at any point in the methodology. The double arrow from step six to step four represents improvement value feedback that should be provided after performing alternative analysis to update the architecture's specifications for improved performance. Although the methodology diagram does not explicitly show the reliance on time-dependence, each step should be performed with time adjustments in mind.

This process should attempt a numerical flow, but project constraints could impact the performance of all methodology steps. For example, step five requires modeling and simulating the different architectures to set up the retrieval of step seven's alternative value assessment. If an acquisition project does not have the programs, personnel, or time to model and simulate architecture alternatives prior to MS A, then a different analysis technique will be needed to accurately provide the time-variant value of each alternative. While substitutions can be made to relate specific DoD project constraints, each program should strive to best incorporate the steps as originally represented to ensure proper architecture development and a greater reliance on quantitative-based analysis.

Each of the methodology's steps is built from the information and outputs of earlier steps. Each high-level step in Figure 7 is comprised of sub-steps (see example in Figure 8). All sub-steps are collectively captured at the end of Chapter 3 in Table 10.

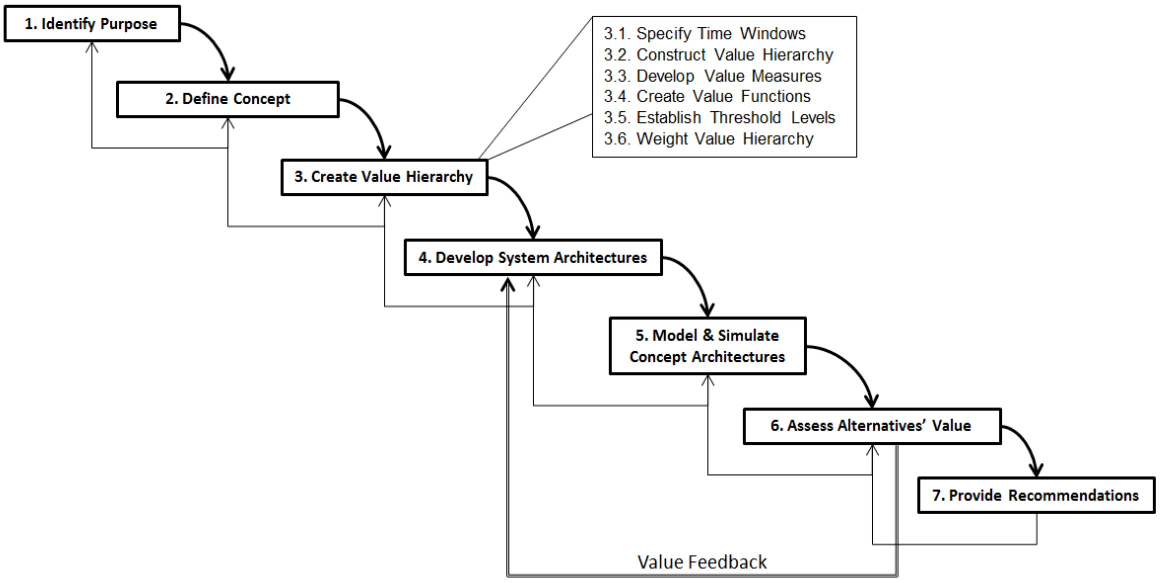


Figure 8 - Pre-Acquisition Methodology Showing Step 3 Sub-steps (Ford et al., 2015)

Now that the pre-acquisition methodology has been introduced, a breakdown of each step's intentions, lower sub-steps, and suggested sources will be examined.

3.3 Step 1 – Identify Purpose

Identification of the purpose and problem was recognized earlier in Chapter 2 as a crucial initial step used by several VFT processes to capture the strategic perspective of the project at hand. The only suggested sub-step of problem identification in the 10-step VFT process was the creation of a problem statement. AFIT's System Architecture course (SENG-640) includes the following problem identification sub-steps as part of the final project: project title, problem statement, architecture goal, scope, context, critical questions, and team experience (Ford, 2015b). Similar sub-steps should be incorporated as part of the pre-acquisition methodology to ensure the purpose is correctly identified.

3.4 Step 2 – Define Concept

Step two uses the details previously identified in step one to define the concept. Possible sub-steps in support of step two include establishing each concept title;

describing an executive summary, purpose, and background; establishing the anticipated future environment; listing the concept timeframe/scope; determining a military need statement and central idea; identifying risks; and creating a summary (Ford, 2015b). Any means of listing concepts is acceptable, to include Chapter 2's suggestions (white papers, talking papers, oral presentations, background papers, or bullet background papers).

Step two should encourage the capturing of concepts using both current and future systems of multi-domain employment, which is consistent with the *Air Force Future Operating Concept* guidance (Department of Defense, 2015a). Intelligence of the estimated performance of future concepts might be required to accurately realize performance expectations. Anytime a new concept is defined, that new concept should start at step two and use the later methodology steps to ensure proper development is employed. Attempted transformation from one concept into multiple new concepts without returning to step two is prohibited.

Traceability of the problem back to government and military policy is crucial to understanding the strategic implications of the project's purpose and proposed concepts. As the gold standard method attempts abstraction from higher policy-level guidance, so too should steps one and two of the pre-acquisition methodology.   Review of external policy documents required for steps one and two are the driving force for all remaining steps in the methodology. It is therefore important to start at the policy level and derive concepts based on senior leadership guidance. Starting with policy documents such as the National Security Strategy (NSS), National Military Strategy (NMS), and Quadrennial Defense Review (QDR) allows for abstraction down to strategic objectives using the JCA, UJTL, and applicable Illities to ensure top-level policy areas are abstracted to lower capabilities, operational activities, and system functions commonly represented in DoDAF (DoD CIO, 2010). This is not to say that strategic or policy guidance cannot be used for later steps, but rather simply means that all required support should pull from step one and step two deliverables.

3.5 Step 3 – Create Value Hierarchy

Step three is the overall creation of the value hierarchy. Its sub-steps have been previously shown in Figure 8, which include specification of time windows, initial construction of the value hierarchy, development of value measures, creation of value functions, establishment of threshold levels, and weighting of the value hierarchy. Step three relies heavily upon VFT, and therefore pulls much of its sub-step requirements from the 10-step VFT process described in Chapter 2. Unlike previously used VFT processes, step three's first sub-step is to specify time windows prior to initiating VFT requirements. All of step three's sub-steps will be expanded in the following paragraphs due to the uniqueness of incorporating time-variance into traditional VFT practice.

3.5.1 Sub-step 3.1: Specify Time Windows

Establishing time windows early on in the methodology provides accurate representation in the value hierarchy, system architectures, and M&S, which ultimately allows for time-based analysis during step six of those chosen time periods. Sub-step 3.1 produces those specified time windows that are referenced throughout the remainder of the methodology. Assignment of time windows can result from information described in steps one or two, or from surrounding intelligence gathered regarding the operation. Possible reasons for assigning time windows can be seen in Table 9.

Table 9 - Reasons for Assigning Time Windows

Time Window Assignment Reasons
Representation of the full simulation time
Representation of operational phases
Adjustments to SAVFs' boundaries or shapes
Changes in value hierarchy weights
Differing expected levels of performance (such as threshold levels)
Specific time with buffer periods
Conditional time periods
Any other particular time period of interest

The first task of sub-step 3.1 is to identify a time format that can be used consistently throughout the methodology. This time format should match that of the simulation output format in order to reduce complexity when analyzing data output. Once a consistent time format is selected, the following variables should be established during sub-step 3.1. These variables will be used in all later steps of the methodology, so capturing them correctly in step three is crucial to the success of later analysis. The iterative nature of the pre-acquisition methodology allows for redefining time windows at any needed point, but late time window adjustments or additions will have impacts on all following methodology steps and their sub-steps.

<u>Simulation Start Time</u> (ST_{Start}): The initiation time of the simulation represented in the appropriate time format.

<u>Simulation End Time</u> (ST_{End}): The end time of the simulation represented in the appropriate time format.

<u>Full Simulation Time</u> (FST): The difference between simulation start time and simulation end time represented in the appropriate time format.

$$FST = ST_{End} - ST_{Start}\ (in\ appropriate\ time\ format) \tag{3}$$

FST should stay constant as long as the simulation length does not change.

Simulation Reference Time $(ST_{Reference})$: A reference time of the simulation represented in the appropriate time format.

All variables defined thus far have relied upon an appropriate time format consistent with the simulation. The following variable transitions that time format into epoch time in order to accurately represent discrete simulation steps and capture data in a more implementable fashion.

Epoch Time (t): The difference between simulation start time and simulation reference time.

$$t = ST_{Reference} - ST_{Start}\ (in\ appropriate\ epoch\ step) \tag{4}$$

The variable t can be used to show an exact epoch time $(t = 4{,}250)$ or an epoch time range $(4{,}200 \leq t \leq 4{,}550)$. The epoch time can always be attributed back to an $ST_{Reference}$ by converting t into the original time format. Due to $ST_{Reference}$ and ST_{Start} being the same time at the beginning of a simulation, t will always be zero prior to starting the simulation. The epoch time should be aware of simulation time steps in order to ensure consistent representation of simulation outputs and data analysis.

The time-variant nature of the methodology allows for time windows to capture a range of specified epoch times. Time windows can be labeled using the following variables.

Time Window Start (t_{Start}): The initiation epoch time of a particular time window.

Time Window End (t_{End}): The end epoch time of a particular time window.

Time Window (TW_m): A time period of interest, with m being the numerical count of a particular time window.

$$TW_m = t_{Start} \leq t \leq t_{End} \tag{5}$$

The numerical count of the time window, m, is used to differentiate time windows from one another and to avoid confusion when several time windows are used throughout the simulation period. Figure 9 shows an example of relating an ST_{Start} of 10:00:00 UTC, an $ST_{Reference}$ of 10:30:00 UTC, and t (in seconds), along with t_{Start} and t_{End} supporting a one-hour TW_m.

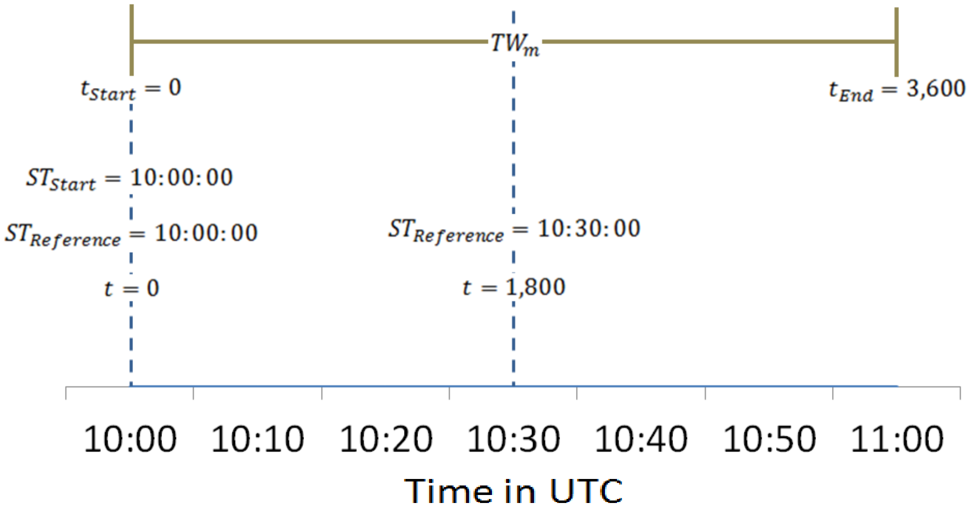


Figure 9 - Time Variable Relationship Example

Time windows can overlap as needed to signify the desired time period. When multiple time windows start at the same epoch time, the longer lasting time window should be assigned the smaller m number. One such example of distinguishing time windows from one another is the representation of different time-dependent operational phases. Separating military actions by time-dependent phases of battle is a commonly used tactic when planning military operations. Capturing these operational phases as a particular time window or set of time windows should be performed using (6).

Operational Phase (P_c): An operational phase of battle, with c being the numerical count of a particular operational phase.

$$P_c = TW_m = \{TW_a, TW_b \dots TW_d\} \quad \textbf{(6)}$$

Where a, b, and d represent different time windows contained within the operational phase, P_c.

Each operational phase count, c, can contain multiple time windows (6), or multiple operational phases can stretch over a single time window (i.e., the FST will be represented by a particular time window that contains all operational phases and all other time windows). Additionally, the entire range of a particular operational phase should be represented by a particular time window, in which case $P_c = TW_m$. Time windows represent more periods of interest than just operational phases, so the time window count, m, may or may not match the operational phase count, c. In order to perform accurate analysis of chosen time windows, anticipated operational impacts must first be captured in the form of value hierarchy adjustments. The value hierarchy is developed in sub-steps 3.2-3.6, which are described in the following paragraphs.

3.5.2 Sub-step 3.2: Construct Value Hierarchy

Sub-step 3.2 produces the initial construction of the value hierarchy. Value hierarchy construction should start with the goal on top and different levels of abstracted objectives (also referred to as force qualities, mission tasks, or values) below the goal. The goal on top of the value hierarchy should be consistent with that identified in sub-step 1.4. The mid-level objectives and eventual leaf-level objectives should be decomposed and representative of their respective higher-level objectives in the value hierarchy. All traditional VFT requirements are still valid for sub-step 3.2's value hierarchy construction, including the requirement that value measures be complete, non-redundant, operational, decomposable, and contained to a small size (Keeney & Raiffa, 1998; Sage & Rouse, 2014). An example value hierarchy construction can be seen in Figure 10, which takes a shape consistent with the simulation analyzed later in Chapter 4.

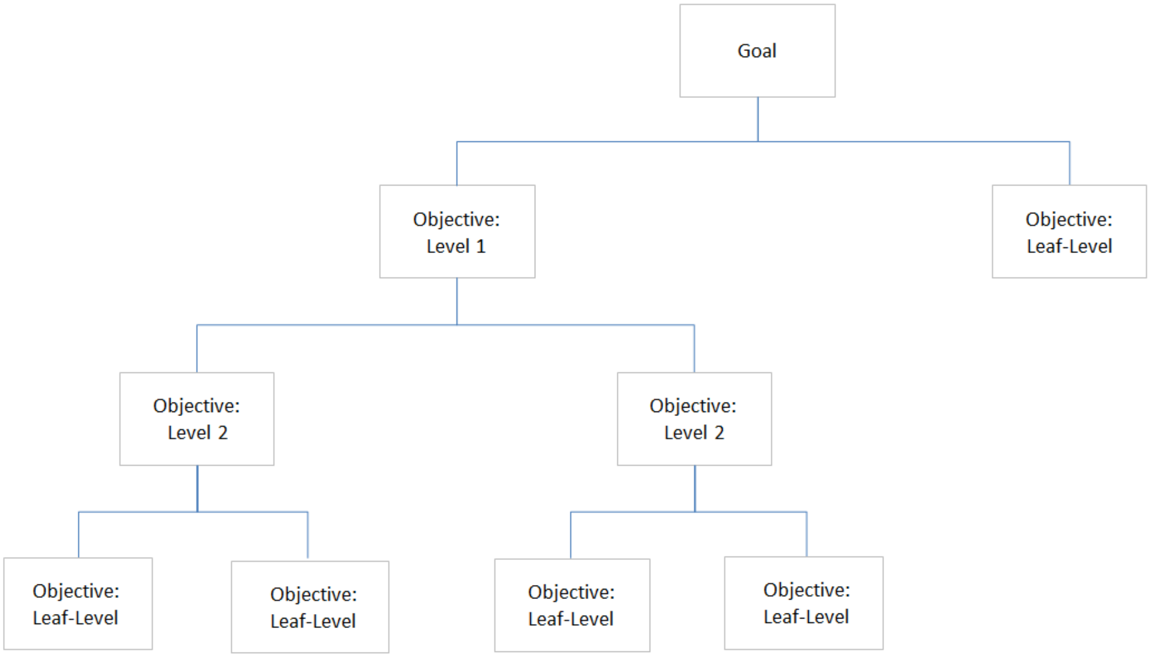


Figure 10 - Value Hierarchy Construction Example

3.5.3 Sub-step 3.3: Develop Value Measures

Sub-step 3.3 develops the value measures to be added to the previously constructed hierarchy from sub-step 3.2. Traditional VFT methods require each value measure to be representative of its determinate attribute value. Each leaf-level objective should be derived into value measures representative of MOEs, MOPs, MOSs, KSAs, or KPPs to maintain consistency with in-place USAF acquisition processes. Once appropriately selected, each value measure should be denoted by an oval and placed directly beneath its respective leaf-level objective on the value hierarchy. Figure 11 uses the continuing value hierarchy example to show how each leaf-level objective can be linked to its respective value measure. The value measure numbers will be referenced frequently for calculations later in the methodology, so maintaining consistency of value measure count and location is vital to the success of the pre-acquisition methodology.

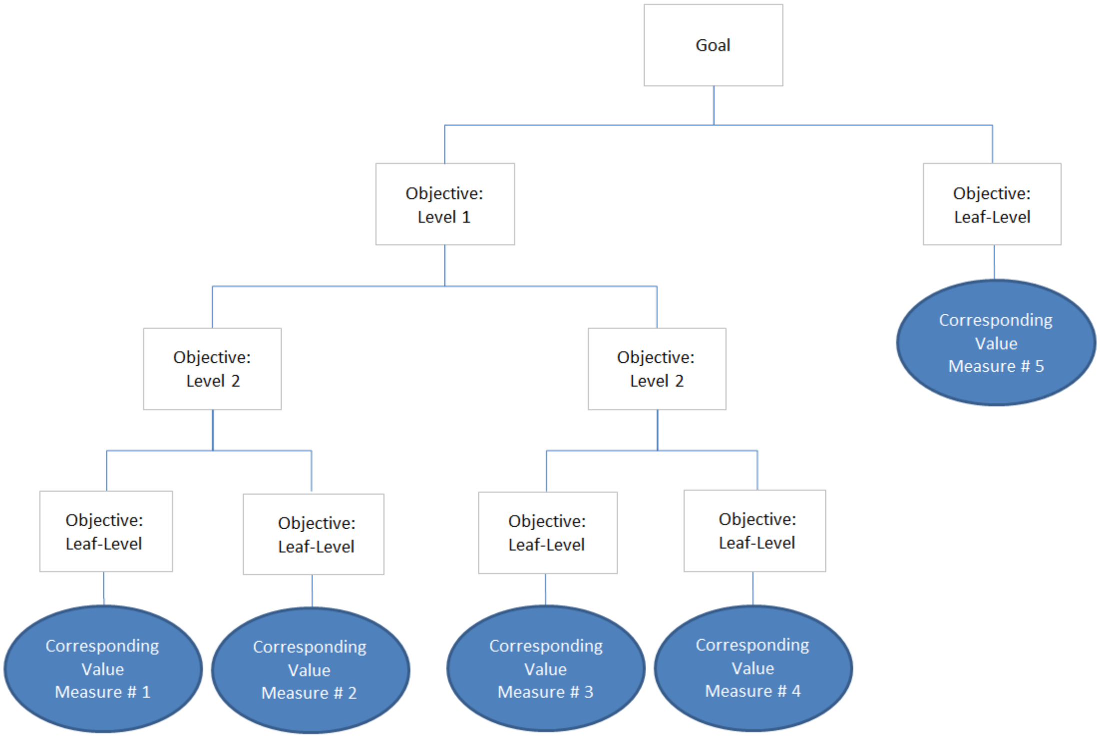


Figure 11 - Value Hierarchy with Value Measures Example

Sub-step 3.3 uses the same requirements as traditional VFT, but additionally recognizes that accurate, time-dependent performance of value measures may only be achievable using the architecture's simulation data. When applicable, simulation of each architecture alternative should produce time-dependent data that can be used to quantifiably assess a value measure's performance at each epoch time. Possible simulation outputs must be researched to first assess if the chosen value measures can be represented by the simulation tool to decide what simulation output data accurately embodies each value measure. If a simulation tool can accurately provide time-dependent data to drive a value measure, then an attempt should be made to use that tool's simulation output.

A simulation tool's availability or its listed outputs should not drive which value measures is chosen to represent leaf-level objectives (Office of Aerospace Studies, 2013). Simulation data may not be able to accurately capture every chosen value measure, in which case M&S should not be used to represent that particular time-variant value measure's performance. If M&S is not appropriate for a specific value measure, other analysis tools may include spreadsheets, methods, processes, or SMEs (Office of Aerospace Studies, 2013). Value measures should be chosen based upon the best representation of each leaf-level objective, whether or not that includes the use of simulation data.

3.5.4 Sub-step 3.4: Create Value Functions

Once all value measures are properly fit to their respective leaf-level objectives, sub-step 3.4 assigns time-dependent SAVFs to each value measure. Up to this sub-step of the methodology, the value hierarchy construction (sub-step 3.2) and value measures development (sub-step 3.3) have been held constant over time. Sub-step 3.4 is the first instance of capturing time variance by using time windows previously identified in sub-step 3.1. All remaining steps and sub-steps require a time window label to accurately describe what period of interest is under consideration.

Recall that (1) defines $v_i(x_i)$ as the single-dimensional value of the x_i score, and that (2) mandates all weights must sum to one (Parnell et al., 2013). Both (1) and (2) can be seen restated below.

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

$$\sum_{i=1}^{n} w_i = 1 \tag{2}$$

(Parnell et al., 2013)

As the methodology proposed in this thesis is time-variant, the variables used in (1) and (2) are each a function of time. Using similar notation to Parnell's variables in (1), sub-step 3.4 of the methodology creates time-dependent SAVFs to turn the ith value measure's time-dependent score $\left(x_i(t)\right)$ into a time-dependent, normalized, unweighted, single-dimensional value of a time-dependent score of $x_i(t)$, which can be represented as $v_{i,t}\left(x_i(t)\right)$.

Value Measure Score $\left(x_i(t)\right)$: The ith value measure's time-dependent score.

Value Measure Unweighted Value $\left(v_{i,t}\left(x_i(t)\right)\right)$: The ith value measure's time-dependent, normalized, unweighted, single-dimensional value of a time-dependent score.

The boundaries and SAVFs chosen for each value measure should be representative of time-dependent operational changes consistent with sub-step 3.1's time windows. In order for the value measures to provide acceptable calculations, an initial requirement of sub-step 3.4 is to develop time-dependent boundaries for each value measure. These time-dependent boundaries should be labeled as the minimum and a maximum for each value measure's score, and will be implemented with each SAVF. The minimum of a value measure's score equates to the normalized, unweighted value of zero $\left(v_{i,t}\left(x_i(t)\right) = 0\right)$ and a maximum score indicates a normalized, unweighted value of one $\left(v_{i,t}\left(x_i(t)\right) = 1\right)$.

Value Measure Minimum Boundary $(min_i(t))$: A value measure's time-dependent minimum boundary score, with i being a particular value measure.

Value Measure Maximum Boundary $(max_i(t))$: A value measure's time-dependent maximum boundary score, with i being a particular value measure.

Figure 12 displays a linear SAVF at an epoch time contained in a particular time window, as indicated by the t in all variables and the TW_m in the upper-left hand corner. Figure 12 shows that any score less than or equal to the ith value measure's minimum boundary should have a corresponding $v_{i,t}\left(x_i(t)\right) = 0$. Similarly, Figure 12 shows that any score greater than or equal to the ith value measure's maximum boundary should produce a $v_{i,t}\left(x_i(t)\right) = 1$. Any score falling between the minimum and maximum boundaries will be transitioned to its corresponding value using the appropriate time-dependent SAVF. Sub-step 3.4 only creates the SAVFs; it does not include actually scoring $x_i(t)$ using chosen SAVFs (this is performed later in step six).

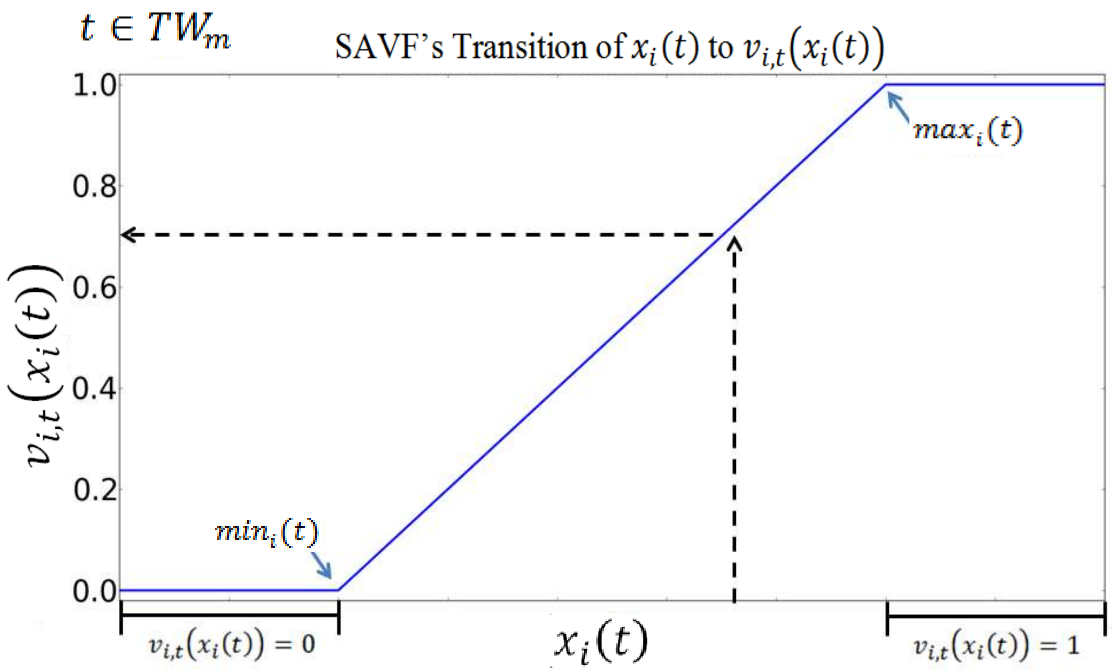


Figure 12 - Linear SAVF with Boundaries During a Particular Epoch Time

The t contained in the boundary variables represents the ability to adjust SAVF boundaries as time persists, but careful consideration should be given prior to doing so, as changing SAVF boundaries can lead to inconsistent comparisons over time. Adjusting SAVF boundaries is not the preferred approach of capturing differing performance levels of an operation, but these changes may be necessary depending on the operational environment. For this reason, Chapter 4's example architecture keeps all value measure boundaries constant over time. As researched in Chapter 2, the four most common SAVF shapes are linear, convex, concave, and s-curve. SAVF graphs should accommodate the developed functions to ensure the desired boundaries and shape characteristics are captured correctly.

3.5.5 Sub-step 3.5: Establish Threshold Levels

Consistent with Chapter 2's research of current USAF acquisition practice, threshold and objective levels of measures can be identified to assess performance against requirements (Office of Aerospace Studies, 2013). While some MODA practices recommend using threshold and objective levels as SAVF boundaries, the pre-acquisition methodology recognizes that there may be some value gained without necessarily meeting a threshold. Value measure threshold levels $\left(TL_i(t)\right)$ should be assigned for operationally changing time windows, meaning that for any anticipated performance adjustment at t_{start} of TW_m, the threshold level should correspond to the alternative's expected time-dependent score of the ith value measure.

<u>Value Measure Threshold Level</u> $\left(TL_i(t)\right)$: The expected threshold level corresponding to the time-dependent score of the ith value measure.

Placing $TL_i(t)$ through the ith value measure's time-dependent SAVF equates to an unweighted but normalized instantaneous threshold value for the ith value measure $\left(v_{i,t}\left(TL_i(t)\right)\right)$.

<u>Value Measure Unweighted Threshold Value</u> $\left(v_{i,t}\left(TL_i(t)\right)\right)$: The unweighted, normalized, single-dimensional threshold value of the ith value measure threshold level at t.

Establishing threshold levels between the sub-step 3.4 and 3.6 allows for time-dependent SAVFs to be known, but prevents the possibility of favoritism based on weighting, as weights have not yet been determined. $TL_i(t)$s should be determined by a decision-making team or group of stakeholders, along with the support of operation specialists who understand the threat environment and can provide input on anticipated performance changes consistent with adjusting time windows. Once weights are determined in the following sub-step 3.5, applying the appropriate value measure's time-variant weight produces the ith value measure's instantaneous threshold value $\left(ITV_i(t)\right)$. This process is more explicitly captured in step six of the methodology (9), but is introduced in now to account for determining $ITV_i(t)$ after weights are chosen in sub-step 3.6. Each time window does not require a new threshold level; only those time windows that equate to an operational performance adjustment need new threshold levels.

An incorrect approach to sub-step 3.4 is to attempt an estimated instantaneous threshold *value* for each value measure $\left(ITV_i(t)\right)$ instead of a threshold *level* $\left(TL_i(t)\right)$. The decision team should not attempt to guess time window-dependent threshold values without using the time-dependent SAVFs established in sub-step 3.4. For example, if a time-dependent threshold level for National Image Interpretability Rating Scale (NIIRS) were to be chosen by a decision team, only those NIIRS level's score should be provided by the stakeholders (the NIIRS level on a scale of zero to nine that is expected at each t). The value measure's threshold value over the time window should be determined by placing the agreed upon NIIRS threshold level's score through the appropriate time-dependent SAVF and eventual swing weight (not yet determined).

3.5.6 Sub-step 3.6: Weight Value Hierarchy

Sub-step 3.6 assigns local swing weights to each objective in the value hierarchy. The variable $w_i(t)$ represents the weight assigned to the ith value measure at a particular epoch time. Just as traditional VFT instructs, multiplying up the path from leaf-level objective to goal assigns the appropriate global weighting for each value measure.

Value Measure Weight $(w_i(t))$: The global swing weight of the ith value measure at t.

Stakeholders, decision-making teams, and operational experts should choose the time-variant weight of each value measure. Transitioning between operational phases typically incorporates differing levels of importance based on what is required to successfully perform the mission during a phase. The pre-acquisition methodology's time-variant weighting allows for more accurate representation of changing desires consistent with changing phase priorities. Local weights should only be adjusted over time if stakeholder preferences change with time or phase, and traditional VFT weighting requirements explained in Chapter 2 are still applicable.

Equation (2) mandates that the summation of the weighting across all value measures must be equal to one. The time-variance of this methodology similarly requires that for any epoch time, the summation of all value measure weights must equal one (7).

$$\sum_{i=1}^{n} w_i(t) = 1 \ , \forall t \tag{7}$$

Some time-variant adjustments, such as changing SAVF boundaries, have not been recommended due to potential inconsistencies over time. Time-dependent weighting adjustments, however, are recommended as long as they directly link to each epoch time's value measure priority and proper weighting relationships are used. Time-dependent weighting adjustments are typically easier for stakeholders and SMEs to accurately represent than adjusting SAVF boundaries or SAVF shapes. Additionally, the requirement from (7) that all time-dependent weights must sum to one places restrictions on the confines of collective value measure weighting, as opposed to a limitless possible range for some SAVF boundaries.

Continuing with the Chapter 3's value hierarchy example, Figure 13 shows how local value hierarchy weights should be assigned for a particular epoch time in TW_m. In order to meet the weighting requirements established in (7), each section of the hierarchy must have their section-restricted row's local weights sum to one in a fashion similar to that represented by each red oval in Figure 13. Keeping the red oval restrictions will ensure that the sum of each value measure's global weighting sums to one at each epoch time. The operational goal's top-level weight should be 1.00, indicating the total possible weight of one.

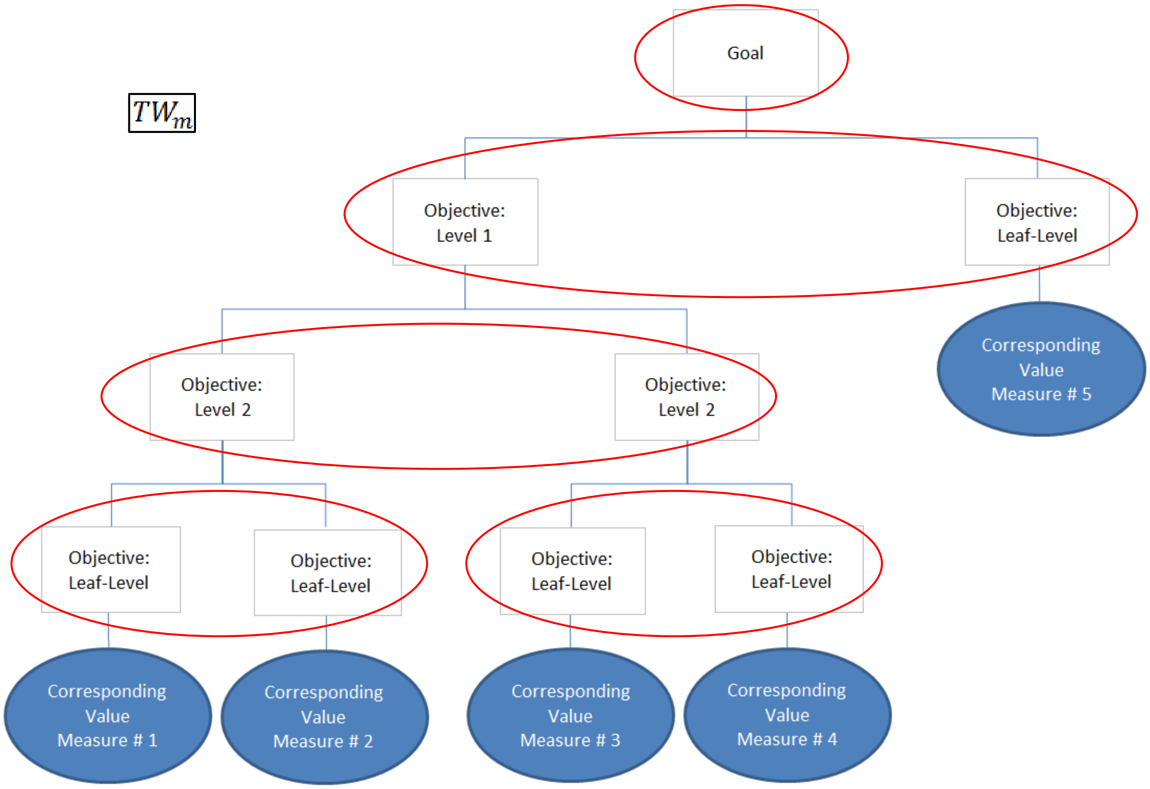


Figure 13 - Value Hierarchy with Weighting Example

3.5.7 Capturing Time-Variance in the Value Hierarchy

The focus on time-dependence is extremely important for sub-steps 3.1, 3.4, 3.5, and 3.6. Sub-steps 3.2 and 3.3 do not require adjustments with time, as the initial construction of the value hierarchy and the development of value measures should remain constant. Adjusting the SAVF shapes and/or their boundary levels over time can be accomplished during sub-step 3.4 to account for changing stakeholder preferences. Sub-step 3.5 establishes the time-variant threshold levels (and objective levels, if desired), which should accordingly match operational expectations. Adjusting the value hierarchy local weights in sub-step 3.6 is the preferred approach to account for stakeholders' changing desires over time.

It is recommended for stakeholders and SMEs to choose the time-differing adjustments as groups of time instead of referencing each individual epoch time. Using time windows to capture performance adjustments prevents wasted efforts that would be required if every single epoch time needed review. It is unlikely that all appropriate time windows will be captured correctly on the first attempt. Instead, multiple iterations will most likely be necessary to ensure the pre-acquisition methodology's time-variance specifications correctly represent all stakeholder intentions. Labeling of the value hierarchy and associated calculations using accurate time windows is key to the success of step three.

3.5.8 Step Three Summary

The sub-steps of step three cover the value hierarchy development (construction), pre-analysis (evaluation), and normalization using weights and value functions that can be seen in similar VFT methods (Brine, 2012; Burk & Parnell, 1997; Parnell et al., 1998;

Shoviak, 2001; Tryon, 2005; US Army Corps of Engineers, 2002). Capturing time-dependent adjustments is what separates the pre-acquisition methodology's step three from traditional VFT value hierarchy creation steps. Step three sets the stage for continued methodology development, beginning with system architectures development.

3.6 Step 4 – Develop System Architectures

System architectures use details from the purpose identified in step one and the concept defined in step two, and should be representative of the objectives chosen in the value hierarchy. The sub-steps of step four include generating alternatives from any single concept (sub-step 4.1), decomposing system architectures to an executable level (sub-step 4.2), and capturing timing impacts on system architectures (sub-step 4.3). Step four's combined sub-steps form the necessary detail to accurately represent an alternative's time-variance impact for later modeling of the executable architectures.

The transition from step three's emphasis on the value hierarchy to a focus on developing system architectures is an appropriate point to generate alternatives. The 10-step VFT process includes generating alternatives only after the entire development of the value hierarchy (see Chapter 2), which has similarly been accomplished at this point in the pre-acquisition methodology. Each alternative will need an applicable systems architecture, which can itself produce additional alternatives as details are discovered while capturing architecture views. Sub-step 4.1 is an appropriate point to generate alternatives as it falls between value hierarchy construction and systems architecture decomposition, both of which inspire new alternatives consistent with the concept. The pre-acquisition methodology's intention is to represent several different architecture alternatives from a single concept, a relationship which can be seen in Figure 14.

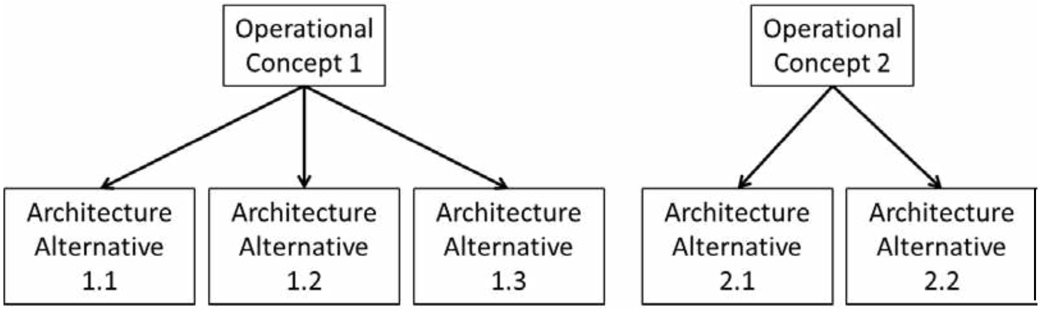


Figure 14 - Concept to Architecture Relationship

System architectures require transformation into executable architectures in order to capture alternative performance in a simulation (Ford et al., 2015). Regardless of the architecture framework used or amount of architecture views incorporated, sub-step 4.2 demands enough abstracted detail to meet an executable level. An executable architecture should include the system functions, such as the alternative's platforms and their associated performance specifications. An executable level should be decomposed from higher capabilities and operational activities, similar to those DoDAF requirements expressed in Chapter 2.

As the methodology is time-dependent, modifying system architectures with timing impacts should be performed as part of sub-step 4.3. Some systems architecting tools are static in nature and thus require a similar labeling scheme used in representing the value hierarchy. Most architecting tools allow for notes to be used when the architecture representation demands are outside of traditional functionality. A note should be used to represent a time period where part of the architecture changes, or to label certain time windows of performance, in order to capture time-variant impacts and ensure proper future modeling of the executable architectures.

3.7 Step 5 – Model and Simulate Concept Architectures

Traditional VFT processes researched in Chapter 2 use a permanently established value model to rank alternatives. However, a pre-acquisition phase will most likely only generate initial construction of a value model, functions, and associated weights that could be changed at a later time to reflect updated information. The pre-acquisition methodology allows for iterations to value models as perceived technologies are researched, performance updates realized, and strategic operational changes implemented. Performing several iterations of the value model and re-scoring alternatives in a timely manner requires reliance upon accurate M&S tools.

Step five takes the executable system architectures captured in step four and the value measures from step three, and incorporates these into a model representing the concept's operational environment from step two. The model outputs should feed applicable value measures identified as relying on simulation data to drive their time-variant value assessment. To model and simulate the architectures properly, one must model the threat environment (sub-step 5.1), model the concept architecture alternatives (sub-step 5.2), and establish applicable simulation parameters (sub-step 5.3) prior to running the simulation and collecting data (sub-step 5.4). Pushing forward time-variant output data that drives targeted value measures is the primary purpose of using M&S in the pre-acquisition methodology, so step five should focus on modeling accuracy to ensure useful, time-dependent data is provided.

Selecting the proper M&S tool is extremely important to the model's accuracy. The M&S tool must first meet the requirements set forth by earlier methodology steps. The required epoch time should match the simulation time step to ensure the discrete timing of data is coordinated across the value hierarchy. In the case a value measure is determined to be best represented by simulation data during sub-step 3.3, accessing that M&S tool is necessary in order to output the value measure's $x_i(t)$ for eventual placement through its time-dependent SAVF in step six. It is recommended to portray all simulation data output with corresponding epoch times to ensure timing is accurately kept.

Since architecture alternatives are anticipated to have similar details, it is advantageous to execute an M&S tool automatically using computer code. Driving an M&S engine from an internal or separate program presents the benefit of more efficiently simulating slightly adjusted alternatives and can help turn data output into implementable value measure performance scores more easily than other methods. Using code additionally allows for automated modeling of alternatives based on step four's architectures and the set of simulation parameters. Capturing time-variance of a simulation can also be performed by the use of computer code, which can establish changing model requirements and influence certain simulation parameters resulting from the iterations of earlier steps.

3.8 Step 6 – Assess Alternatives' Value

Step six initiates when the time-dependent simulation data output is provided from step five. While the value hierarchy shows several levels of interest, only the oval value measures located at the bottom of the value hierarchy should be associated with the simulation data. The sub-steps of step six include scoring alternatives from their simulation data (sub-step 6.1), performing deterministic analysis across all identified calculations (sub-step 6.2), and performing sensitivity analysis to account for weighting impacts on alternative rankings (sub-step 6.3), all of which are separate steps from the 10-step VFT process. The following step six paragraphs present several different equations by which to assess the time-dependent performance of alternatives. It is up to the stakeholders or decision-makers to determine the set of equations that are most reflective of the assessment types needed for their project.

Scoring alternatives turns the simulation data into time-dependent, unweighted, normalized value $\left(v_{i,t}\left(x_i(t)\right)\right)$ using each value measure's respective time-variant SAVF. As cautioned previously in Chapter 2 and again in sub-step 3.6, applying weights can hide value measure performance details (Office of Aerospace Studies, 2013). For this reason, sub-step 6.1 captures scoring a value measure's $v_{i,t}\left(x_i(t)\right)$, which should be analyzed prior to the influence of weighting. Once each value measure's unweighted performance is understood, applying $w_i(t)$ to $v_{i,t}\left(x_i(t)\right)$ can be done for deterministic analysis of each value measure in sub-step 6.2. Using each value measure and the respective time-based global weights previously established during step three, time-dependent, normalized, weighted value can be calculated for each value measure's time-dependent performance data using (8). Remaining consistent with Parnell's equations (1) and (2), the below variables account for time-variant value measure instantaneous value. Anytime the term "instantaneous" is used, it implies only a single epoch time (t) is referenced.

<u>Value Measure Instantaneous Value</u> $\left(IV_i(t)\right)$: The normalized, weighted value of the ith value measure at t.

$$IV_i(t) = w_i(t)v_{i,t}\big(x_i(t)\big) \qquad \textbf{(8)}$$

Where for a set of value measure levels given by vector x,

i is the numerical representation of a value measure between the $[1 \ldots n]$ index

$x_i(t)$ is the alternative's time-dependent score of the ith value measure

$v_{i,t}\big(x_i(t)\big)$ is the time-dependent, single-dimensional value of a time-dependent score of $x_i(t)$

$w_i(t)$ is the swing weight of the ith value measure at t

While Parnell's equations (1) and (2) started with summed value over all value measures, the pre-acquisition methodology instead starts with each value measure's time-dependent, unweighted value and its time-dependent, weighted value prior to summing all value measures into overall instantaneous value (12). Comparing each value measure's time-variant instantaneous value (8) provides feedback as to which value measures are producing acceptable performance value over time and which are not.

Since time-variant threshold levels were established previously for each value measure in sub-step 3.5, running them through their respective time-dependent SAVFs and weights produces a time-variant instantaneous threshold value for each value measure (9).

<u>Value Measure Instantaneous Threshold Value</u> $\big(ITV_i(t)\big)$: The normalized, weighted threshold value of the ith value measure at t.

$$ITV_i(t) = w_i(t)v_{i,t}\big(TL_i(t)\big) \qquad \textbf{(9)}$$

Where for a set of value measure threshold levels given at t,

$TL_i(t)$ is the expected threshold level corresponding to the time-dependent score of the ith value measure

$v_{i,t}(TL_i(t))$ is the unweighted, normalized single-dimensional threshold value of the ith value measure threshold level at t

It is beneficial to capture each value measure's performance compared to the preconceived instantaneous threshold levels determined by stakeholders and decision teams. Associating $IV_i(t)$ with $ITV_i(t)$ should provide comparisons for the ith value measure at any particular point in time. A direct comparison between the ith value measure's time-dependent performance and threshold value can be performed using (10).

Value Measure Instantaneous Boolean Score $(IB_i(t))$: The Boolean solution to whether the ith value measure's instantaneous value is meeting or exceeding its respective instantaneous threshold value at t.

$$IB_i(t) = \begin{cases} 0, & IV_i(t) < ITV_i(t) \\ 1, & IV_i(t) \geq ITV_i(t) \end{cases} \tag{10}$$

Using (10), a Boolean score of one is recorded for any epoch time where the ith value measure's instantaneous value is meeting or exceeding its respective value measure instantaneous threshold value. When $IV_i(t)$ is below $ITV_i(t)$, then a Boolean score of zero is recorded. Capturing the Boolean score is advantageous because it informs those performing the analysis of times when $IV_i(t)$ is outperforming $ITV_i(t)$, and allows for a summation of $IB_i(t)$ over time to represent a particular time window. A comparison can be made between $IV_i(t)$ and $ITV_i(t)$ due to them both using the same time-dependent and value measure-dependent swing weight, which conforms both variables to an equal scale from zero to $w_i(t)$.

The equations thus far have focused on a specifically considered value measure, i. The following equations transition to all value measures, beginning with (11).

Instantaneous Boolean Score $\left(IB_n(t)\right)$: The sum of the Boolean scores across all n value measures at t.

$$IB_n(t) = \sum_{i=1}^{n} IB_i(t) \tag{11}$$

Where for a set of Boolean scores given at t,

n is the total number of value measures

The maximum instantaneous Boolean score at any point in time is equivalent to the total number of value measures, n. When $IB_n(t) = n$, all value measures' instantaneous values are meeting or exceeding their respective time-dependent value measure instantaneous threshold values. When $IB_n(t) = 0$, no value measures' instantaneous values are meeting or exceeding their respective time-dependent value measure instantaneous threshold values.

Parnell's additive value model in (1) calculated overall value. Applying time-dependence to (1) produces instantaneous value, which can be seen represented in (12).

Instantaneous Value $\left(IV(t)\right)$: The sum of each value measure's normalized, weighted instantaneous value at t.

$$IV(t) = \sum_{i=1}^{n} IV_i(t) \tag{12}$$

The time-dependent weight summation requirement in (7) is valid for (12) and all remaining instantaneous value-based equations. Just as each value measure's $IV_i(t)$ was summed to produce $IV(t)$ in (12), so too should each value measure's instantaneous threshold value be summed to determine an overall time-dependent instantaneous threshold value (13).

<u>Instantaneous Threshold Value</u> (ITV): The sum of each value measure's normalized, weighted instantaneous threshold value at t.

$$ITV(t) = \sum_{i=1}^{n} ITV_i(t) \tag{13}$$

$IV_i(t)$ and $ITV_i(t)$ are recorded on a scale from zero to $w_i(t)$, which can vary based on time and across differing value measures. $IV(t)$ and $ITV(t)$ are instead always on a scale from zero to one, and therefore provide comparative performance feedback simply from looking at the time-dependent total. Figure 15 shows a hypothetical example of $IV(t)$ in red and $ITV(t)$ in black.

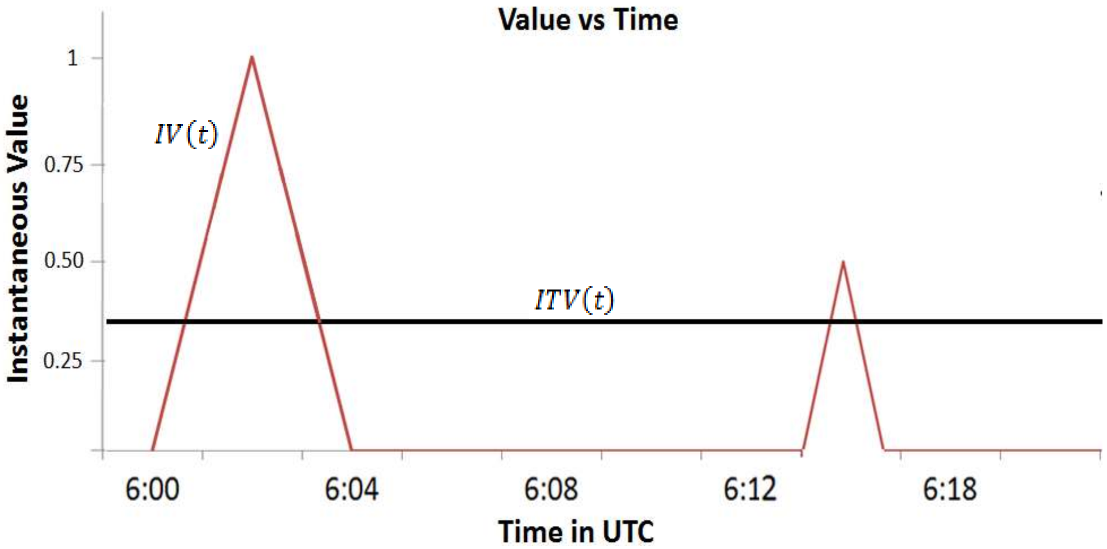


Figure 15 - Example of IV(t) & ITV(t)

Similar to the comparison between each value measure's $IV_i(t)$ and $IV_i(t)$, overall comparison between $IV(t)$ and $ITV(t)$ is also useful. Instantaneous value

Boolean score (14) compares the time-dependent performance between $IV(t)$ calculated in (12) and $ITV(t)$ from (13).

Instantaneous Value Boolean Score $\left(IB_{IV}(t)\right)$: The Boolean solution to whether the instantaneous value is meeting or exceeding its respective instantaneous threshold value at t.

$$IB_{IV}(t) = \begin{cases} 0, & IV(t) < ITV(t) \\ 1, & IV(t) \geq ITV(t) \end{cases} \tag{14}$$

Similar to the value measure-specific performance in (10), (14) instead looks at the combined totals for comparison. When $IV(t)$ is below $ITV(t)$ at a certain epoch time, then a Boolean score of zero is recorded. When $IV(t)$ is greater than or equal to $ITV(t)$ at a certain epoch time, then a Boolean score of one is recorded. Capturing the Boolean score is advantageous because it informs those performing the analysis of times when $IV(t)$ is outperforming $ITV(t)$, and allows for a summation of $IB_{IV}(t)$ over time to represent a particular time window. Figure 16 shows Figure 15's performance represented as instantaneous Boolean scores over time.

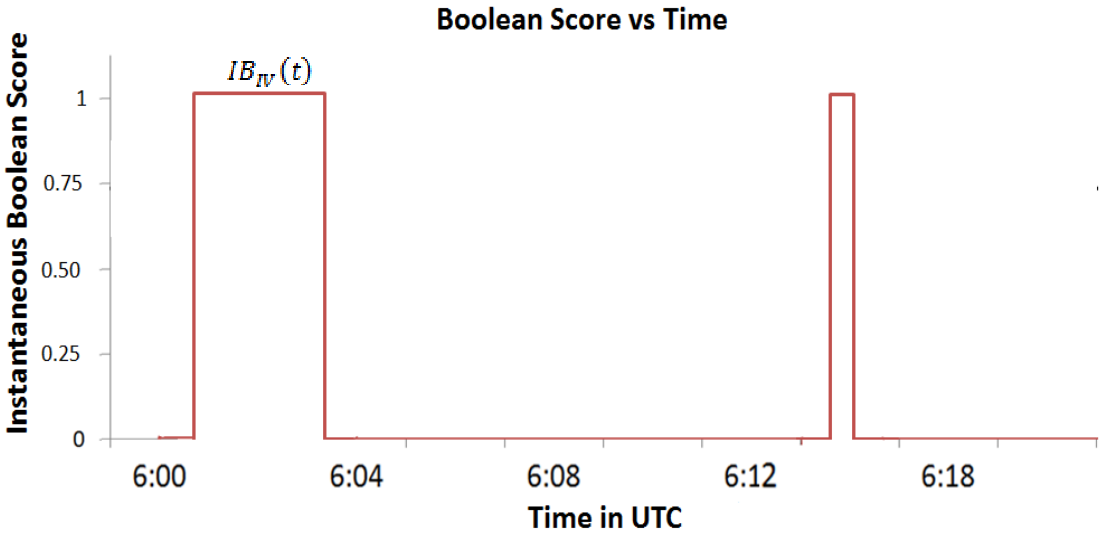


Figure 16 - Example of IB_IV(t)

Instantaneous objective value could be calculated much the same way threshold levels are placed through time-dependent SAVFs and applied to each value measure's time-based weighting. The only additional requirement needed for the pre-acquisition methodology would be the selection of time-dependent objective levels during sub-step 3.5 that are consistent with the project's expectations. Higher anticipated performance levels chosen by stakeholders or a decision team would be indicative of objective levels. For the purpose of conserving analysis demands in this research study, only $ITV(t)$ will be used for comparison in Chapter 4. The methodology recognizes the advantage of calculating instantaneous objective values from objective levels, if desired for analysis.

All types of instantaneous value equations shown thus far allow for comparable analysis over time. While analysis techniques over time can be used across an entire simulation to assess architectures, special focus on the earlier established time windows can provide additional analysis opportunities. Value occurring during a particular time window should indicate that some degree of stakeholders' needs is being met consistent with the chosen timeframe (i.e., some value measure performance is above its minimum SAVF boundary or threshold level). Being that the time window is simply a specific range of a simulation period, one should pay special attention to the comparison of architectures' values within these windows. Summation of instantaneous value types or Boolean scores is one way to perform analysis over time windows and, will be shown later in (24).

One such technique that identifies the maximum instantaneous value for any epoch time contained within a particular time window is called instantaneous value peak maximum. The simulation peak maximum can be calculated using (15).

Instantaneous Value Peak Maximum (PM_{IV}): The largest instantaneous value in a particular time window, m.

$$PM_{IV} = max[IV(t)]\,, \forall t \in\ TW_m \tag{15}$$

PM_{IV} is used to symbolize the relative maximum for each $IV(t)$ contained in a particular time window. Similar to the procedure above for obtaining types of threshold value, PM_{IV} can also be applied to $ITV(t)$ in (16).

Instantaneous Threshold Value Peak Maximum (PM_{ITV}): The largest instantaneous threshold value in a particular time window, m.

$$PM_{ITV} = max[ITV(t)]\,, \forall t \in\ TW_m \tag{16}$$

Capturing the peak maximum for $IV(t)$ and $ITV(t)$ across a time window provides a single, normalized value number on a scale from zero to one. Comparing PM_{IV} against PM_{ITV} indicates one form of performance assessment for an alternative across a particular time window. Figure 17 shows PM_{IV} against PM_{ITV} as dotted blue lines, with $IV(t)$ in red and $ITV(t)$ in black.

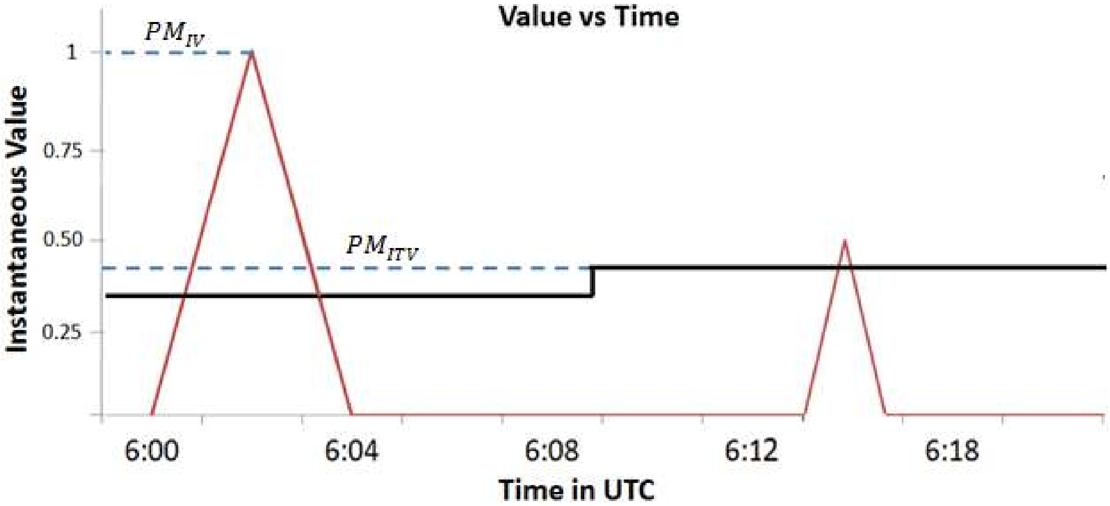


Figure 17 - Example of PM_IV(t) & PM_ITV(t)

The following calculations from this point forward are meant to show how the pre-acquisition methodology can provide additional types of instantaneous value based on simulation-specific requirements. The first of these is mandatory instantaneous value (17), which requires the identification of mandatory value measures $\left(i(m)\right)$ to identify when performance of those specified measures all meet the given standard.

Mandatory Value Measure $\left(i(m)\right)$: A value measure whose Boolean score must be one for the calculation of mandatory instantaneous value occurring at t.

Mandatory Instantaneous Value $\left(IV_M(t)\right)$: The instantaneous value at t, only when all mandatory value measures' instantaneous values are meeting or exceeding their respective value measures' instantaneous threshold values.

$$IV_M(t) = fm(t)\sum_{i=1}^{n} IC_i(t)IV_i(t) \tag{17}$$

Where for a set of value measures' instantaneous value given at t,

$IC_i(t)$ is the constraint of the ith value measure at t

$fm(t)$ is the full mandate that ensures all mandatory value measures' instantaneous values are meeting or exceeding their respective value measures' instantaneous threshold values at t.

Mandatory instantaneous value requires certain value measures to be labeled as mandatory $\left(i = i(m)\right)$. Anywhere from one to n value measures can be assigned the mandatory label for any t, but these should reflect a situation when instantaneous value feedback is only desired when all mandatory value measures' instantaneous values are meeting or exceeding their respective value measures' instantaneous threshold values.

Equation (17) starts by multiplying each $IV_i(t)$ by its corresponding value measure's instantaneous constraint $\left(IC_i(t)\right)$. $IC_i(t)$ can only be zero or one for the ith value measure at t $(IC_i(t) = \{0,1\})$. A value measure's time-dependent mandatory status places different requirements on $IC(t)$, those of which are shown in (18).

$$IC_i(t) = \begin{cases} 0, & \left(i = i(m)\right) \cap IB_i(t) = 0 \\ 1, & \left(i = i(m)\right) \cap IB_i(t) = 1 \\ 1, & \left(i \neq i(m)\right) \end{cases} \quad \textbf{(18)}$$

Summarizing (18) in words, if the ith value measure is a non-mandatory value measure $\left(i \neq i(m)\right)$, then the ith value measure's instantaneous constraint is a non-mandatory constraint $\left(IC_i(t) \neq IC_{i(m)}(t)\right)$. The resulting $IC_i(t)$ automatically equals one and provides no influence on $IV_i(t)$, due to the multiplicative relationship in (17). If the ith value measure is labeled as a mandatory value measure $\left(i = i(m)\right)$, then the resulting ith value measure's instantaneous constraint $\left(IC_i(t)\right)$ is labeled as a mandatory constraint $\left(IC_i(t) = IC_{i(m)}(t)\right)$ and that ith value measure's instantaneous Boolean score must be checked for performance against its value measure's instantaneous threshold value, as seen by the top two rows of (18) and shown previously in (10).

An organizational tool to keep track of the instantaneous constraint of each value measure $\left(IC_i(t)\right)$ is a constraint vector $\left(CV(t)\right)$. The equation relating each $IC_i(t)$ to $CV(t)$ can be seen in (19).

Constraint Vector $\left(CV(t)\right)$: A vector that captures each instantaneous constraint as an element, with the row number of the constraint vector corresponding to the value measure's number.

$$CV(t) = \begin{bmatrix} IC_i(t) \\ \dots \\ IC_n(t) \end{bmatrix} \tag{19}$$

The last variable in (17) is the full mandate $\left(fm(t)\right)$, which is multiplied against the resulting summation in (17). The full mandate at any time can only be zero or one $(fm(t) = \{0,1\})$. Circumstances that dictate requirements for $fm(t)$ can be seen in (20).

$$fm(t) = \begin{cases} 0, & \prod_{i=1}^{n} IC_i(t) = 0 \\ 1, & \prod_{i=1}^{n} IC_i(t) = 1 \end{cases} \tag{20}$$

The full mandate at any epoch time multiplies all instantaneous constraint values. Any time $IC_i(t) \neq 1$ for any value measure, the product of all instantaneous constraints equals zero and the full mandate becomes zero, as displayed by the top row in (20). A full mandate of zero produces an automatic $IV_M(t)$ of zero, since all mandatory value measures are not performing up to standard as represented in (18). The full mandate ensures that all mandatory value measures' $IV_i(t)$ are meeting or exceeding their respective $ITV_i(t)$ for any $IV_M(t)$ to be output. When all mandatory value measures' $IV_i(t)$ are meeting or exceeding their respective $ITV_i(t)$, then the resulting mandatory instantaneous value from (17) will equal instantaneous value calculated in (12). Mandatory instantaneous value helps decision makers by providing value only when all mandatory value measures are meeting or exceeding their value measures' instantaneous threshold values. The benefits of mandatory instantaneous value are only made possible if stakeholders feel obliged to label certain value measures as “mandatory” during particular time periods.

Another type of instantaneous value based on simulation-specific requirements is instantaneous value for a specific time with a buffer. Its purpose is linked to situations in which stakeholders need instantaneous value only if it meets or exceeds instantaneous threshold value during a specific epoch time $(t = T)$.

Specific Time (T): The unchanging specific time of interest.

T should represent a single epoch time of interest, and can be chosen based on intelligence or operational expectations (e.g., anticipated ground vehicle movement exactly at 22:00:00 UTC). The requirement should result in instantaneous value only if the architecture can support that exact specific epoch time to the threshold performance level. Figure 18 shows an example of specific time without a buffer, when the platform’s instantaneous value (red) is operating over its respective instantaneous threshold value (black), but not at the specific time (orange). The result of this example would be zero instantaneous value, as the alternative captured did not achieve suitable performance at T.

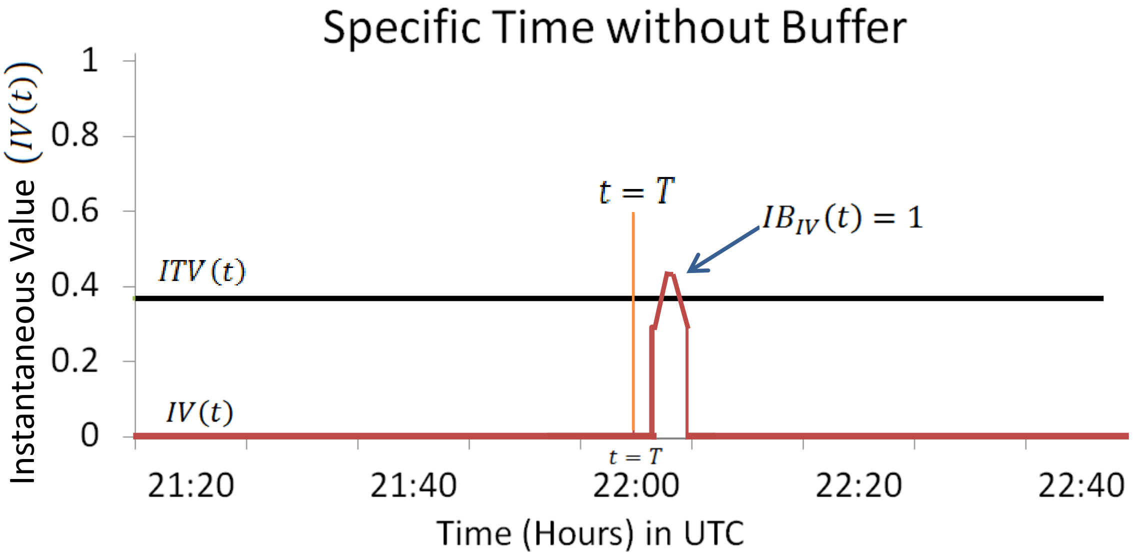


Figure 18 - Example of Specific Time without Buffer

Due to the periodicity of space and air platforms, there may be times when an alternative does not achieve high enough instantaneous value at the specific time, but would meet the performance requirements at a slightly earlier or later epoch time (Figure 18). Many targets are available for longer than a single epoch time, so the architecture's performance requirement can be extended (Figure 19). When operations are deemed suitable, a buffer range can be used to indicate whether instantaneous value meets performance requirements in a time window, as opposed to a single specific epoch time. Recording instantaneous value for a specific time with buffer is shown in (21).

<u>Instantaneous Value for Specific Time with Buffer</u> $(IV_{TB}(t))$: The instantaneous value at t, only while meeting or exceeding its instantaneous threshold value, across a particular time window, m, whose time range is determined by the specific time's buffer range.

$$IV_{TB}(t) = \begin{cases} IV(t), & IB_{IV}(t) = 1 \\ 0, & IB_{IV}(t) = 0 \end{cases} \quad \textbf{(21)}$$

for $TW_m = t_{Start} \leq t \leq t_{End}$,

where $t_{Start} = T - LBuffer$ and $t_{End} = T + UBuffer$

Where for a set of instantaneous value given at t,

T is the unchanging specific time of interest

$LBuffer$ is the specific time's lower buffer time range

$UBuffer$ is the specific time's upper buffer time range

When $IV(t) \geq ITV(t)$ within TW_m, capturing the time-dependent instantaneous value for a specific time with buffer is no different than capturing the time-dependent instantaneous value $\left(IV_{TB}(t) = IV(t)\right)$. However, when $IV(t) < ITV(t)$, equation (21) results in zero $IV_{TB}(t)$ for a particular epoch time. $IV_{TB}(t)$ only rewards those epoch times in which instantaneous value is performing up to standard. The buffer range $(LBuffer\colon UBuffer)$ is the time period containing T where stakeholders find it acceptable to track a time-dependent instantaneous value that meets or exceeds its time-dependent instantaneous threshold value. When $IV_{TB}(t)$ is provided in the time window, this may indicate to decision-makers that their needs are met to the same extent as if the value was provided exactly during T. Figure 19 shows Figure 18's example from earlier, but instead applies the buffer range (orange) to the specific time. Figure 19 shows an example where the provided platform's $IV_{TB}(t)$ will be equal to $IV(t)$, indicating performance needs are met in the buffer range.

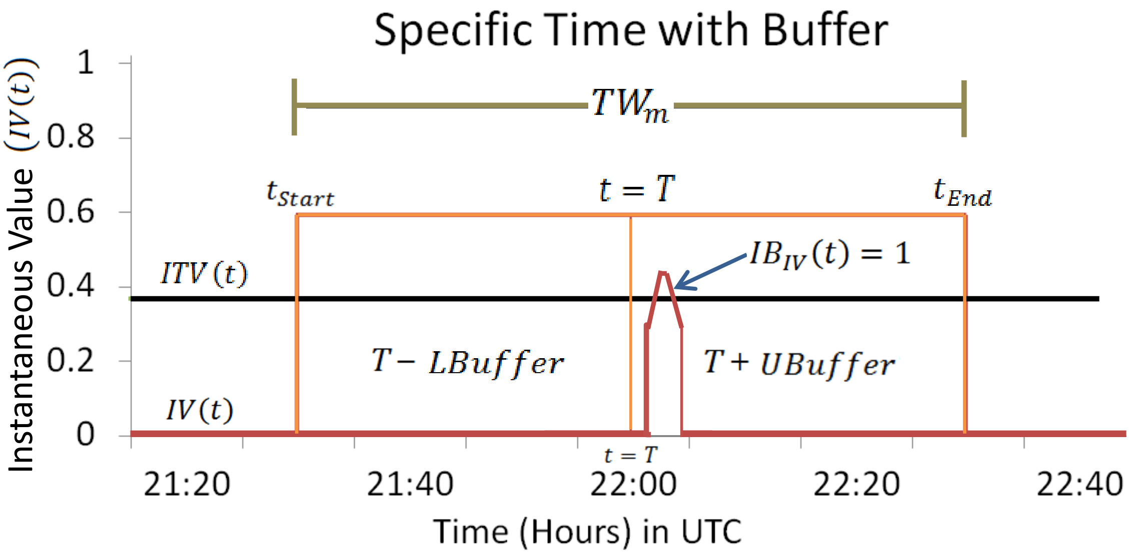


Figure 19 - Example of Specific Time with Buffer

Chapter 2 identified added benefits from capturing dynamic decision analysis practices. One of those benefits included the ability to apply conditional consequences and their adjustment with time (Parnell et al., 2013). The final type of instantaneous value based on simulation-specific requirements is called conditional instantaneous value. All value measures remain independent during a static VFT process, meaning that performance of one value measure does not impact the performance of another. However, certain operational time periods may require conditional performance of one value measure to influence the recorded value of a later value measure (e.g., identification of a target is just as valuable as target detection, provided the target has been identified in a certain prior time period). Conditional instantaneous value can be captured using (22) and (23).

<u>Conditional Instantaneous Value</u> $\left(IV_C(t)\right)$: The instantaneous value at t based on the conditional influence that the required value measure has on the conditional value measure.

$$IV_C(t) = \sum_{i=1}^{n} w_i(t) v_{i(c),t}\left(x_i(t)\right) \tag{22}$$

for TW_m where for $i = i(c)$:

$$v_{i(c),t}\left(x_i(t)\right) \tag{23}$$

$$= \begin{cases} v_{i,t}\left(TL_i(t)\right), \left(IB_{i(r)}(t) = 1 | fm(LT) = 1 \cap IB_{i(c)}(t) = 0\right) \\ v_{i,t}\left(x_i(t)\right),\ \ IB_{i(r)}(t) = 0 \\ v_{i,t}\left(x_i(t)\right),\ \ fm(LT) = 0 \\ v_{i,t}\left(x_i(t)\right),\ \ IB_{i(c)}(t) = 1 \end{cases}$$

Where for a set of value measure levels given by vector x,

$v_{i(c),t}\left(x_i(t)\right)$ is the conditional, time-dependent, single-dimensional value of a time-dependent score of $x_i(t)$

$i(r)$ is a value measure at t whose Boolean score must be one in order to adjust the conditional value measure to its threshold value at t

$i(c)$ is a value measure that experiences a conditional influence based on the performance of the required value measure at t

LT is the last epoch time during a conditional time window where all mandated value measures are meeting or exceeding their respective value measures' threshold values

It is suggested to reference Figure 20 and Figure 21 for a better understanding of equations (22) and (23), due to the difficulty surrounding explanation of such a dynamic influence during conditional instantaneous value.

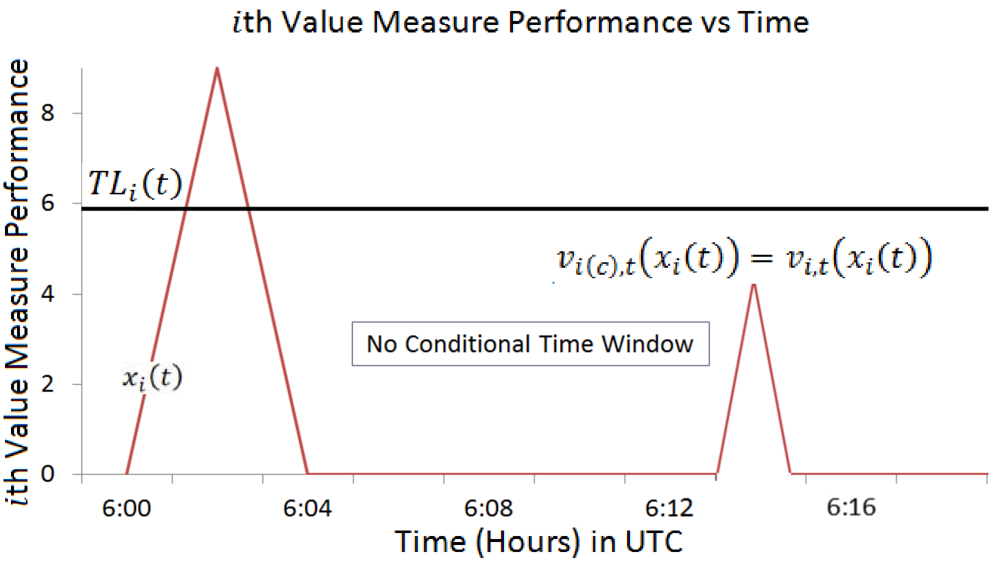


Figure 20 - Example of No Conditional Influence

Figure 20 shows an example of no conditional influence on the ith value measure. $x_i(t)$'s second performance peak occurring around 06:14 is well below the ith value measure's threshold level $\left(TL_i(t)\right)$, which can also be represented as $B_{i(c)}(t) = 0$. No conditional adjustment is made to the performance of the second peak, so the resulting ith value measure's conditional, time-dependent, single-dimensional value is equal to its time-dependent, single-dimensional value $\left(v_{i(c),t}(x_i(t)) = v_{i,t}(x_i(t))\right)$ as captured in (23).

Figure 21 shows the same example from Figure 20, but instead applies conditional influence on the ith value measure, which is assumed to be both the lone mandatory value measure $\left(i(m)\right)$ around 06:02 and the conditional value measure $\left(i(c)\right)$ around 06:14. The full mandate of the last epoch time in TW_m where all mandatory value measures are meeting or exceeding their respective value measures' threshold values $\left(fm(LT)\right)$ equals one because the mandatory value measure's $x_i(t)$ performance is above $TL_i(t)$ at LT = 06:03. Not shown in Figure 21 is the required value measure $\left(i(r)\right)$. It is assumed the required value measure's $IV_i(t)$ is outperforming its respective $ITV_i(t)$ from about 16:13 to 16:15.

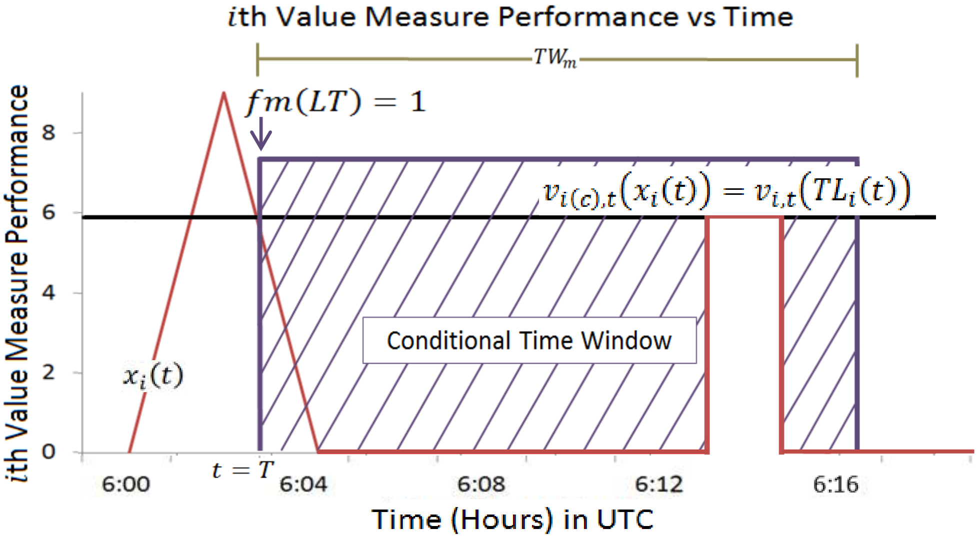


Figure 21 - Example of Conditional Influence

Due to the conditional influence (seen by the purple box in Figure 21) and the normal conditional Boolean score of zero on the second peak in Figure 20 $\left(B_{i(c)}(t) = 0\right)$, the resulting $v_{i(c),t}\left(x_i(t)\right) = v_{i,t}\left(TL_i(t)\right)$ while $IB_{i(r)}(t) = 1$ from 16:13 to 16:15. The implementation of the conditional adjustment can be seen by the rectangular shape of the second peak in Figure 21. Figure 20's $IV_C(t)$ will be the same as $IV(t)$ due to the lack of conditional impact, while Figure 21's resulting $IV_C(t)$ will be greater than the $IV(t)$ due to the conditional influence seen between 06:13 and 06:15. It should be noted that while a small peak was shown around 06:14 in Figure 20, the same conditional rectangular influence on $v_{i(c),t}\left(x_i(t)\right)$ in Figure 21 would have been seen even without any original $x_i(t)$ performance between 06:13-06:15 in Figure 20.

3.8.1 Step Six Assessment Tools

All of step six’s time-dependent variables were chosen for the specific reason of providing different assessment details for each alternative. However, simply having the ability to capture different forms of instantaneous value and Boolean scores at any point in time does not alone allow for comprehensive analysis. Time-dependent graphs, time window summations, and percentage comparisons using the identified variables are all analysis methods that provide valuable architecture performance information.

Looking at simulation output text files that show all of step six’s calculations across time can be a cumbersome task. It is instead recommended to show each desired calculation from step six in graphical form against time, allowing for analysis techniques to carry pictorial representation of architecture alternatives’ performance areas. Graphing those desired step six variables against time is advantageous in representing a large amount of time-dependent data in a visual fashion, and may identify capability gaps otherwise unnoticed. Matching later analysis comparisons with visually represented graphs also presents the benefit of briefing decision-makers with figures instead of numerical simulation data.

Summing each category over designated time windows initiates the next stage of detailed assessment. Variable summation should take advantage of coding programs to account for those needed step six’s variables. Using a computer program to determine Boolean scores or sum instantaneous value types over time windows is much more accurate and faster than relying on other forms of calculation. Comparing summed categories against one another can additionally capture performance details in the form of percentages. Time window percentage comparisons can store sums of multiple variables, a task easily accomplished by most computer programs. These desired step six summed variables can be used in certain combinations to produce time window percentage comparisons (24).

<u>Time Window Percentage Comparisons</u>: Any row-restricted combination from Table A:1 of numerator and denominator that leads to a percentage comparison of summed variables for analysis purposes.

$$\text{Percentage Comparison} = \frac{Numerator}{Denominator}(100) \tag{24}$$

Due to equivalent time windows, as well as consistent SAVF requirements and weighting in the value hierarchy regardless of the alternative being assessed, straightforward comparisons can be made between architectures using percentage comparisons. Depending on the needs of stakeholder, certain performance percentages might influence the decision more than others. Additionally, percentage comparisons across each time window can identify time-dependent performance gaps that may have been hidden if a traditional, static VFT process were used to output a single value for each alternative. Using (24) in correlation with Table A:1 is a powerful analysis tool that allows for direct comparison between alternatives, and is one of the added analysis tools associated with the pre-acquisition methodology.

After time window percentage comparisons are performed with the initial breakdown of weighting, sub-step 6.3 presents the opportunity to perform sensitivity analysis. Executing sensitivity analysis involves changing swing weights across the simulation time to discover the influence weighting has on architecture value and alternative rankings. Accomplishing instantaneous calculations (8)-(23) and percentage comparisons (24) after weights are adjusted will provide detail regarding the influence of chosen weights and their impact on the rank order of alternatives. Anytime swing weights are adjusted outside of an initially established time window, a methodology iteration back to sub-step 3.1 should occur to ensure the new time window's specifications are accurately accounted for during all methodology steps.

3.9 Value Feedback

While percentage comparisons can be useful analysis measures between architecture alternatives, they can also be used to update an ongoing architecture's specifications by providing value feedback. Updating architectures based on value feedback is an important piece of the pre-acquisition methodology, which is represented by the double-arrow from step six back to step four in Figure 7. One could think of this value feedback arrow as a way to iterate the current architecture's performance against the time-variant value model. Multiple iterations providing value feedback to the architecture under consideration could optimize the specifications until that architecture is the best representation possible. While early acquisition lifecycle time and resource constraints may prevent the optimization of architectures, this methodology's attempted reliance on M&S tools could prove useful in achieving such a task.

The pre-acquisition methodology stresses analysis of each value measure's instantaneous performance as opposed to just the overall value captured in most other VFT approaches. The reason for performing analysis in such a manner is to identify lacking value measures across time. Providing value feedback to the systems architecture as to which value measures are struggling during certain time windows can help identify architecture adjustments that improve performance of those lacking value measures.

Increasing the performance of struggling value measures increases comprehensive instantaneous value, Boolean scores, and time window percentage comparisons. Even adjusting the timing of architecture specifications from value feedback can lead to performance changes of the alternative.

Updating and optimizing alternatives' performances will result in a trend in which the platforms carrying the most powerful assets will typically provide the most successful analysis numbers. The AoA does not want to provide the best performing alternative, but instead wants the alternative with the best value (Office of Aerospace Studies, 2013). While cost is not considered part of the pre-acquisition methodology, constraints must be placed on concept architectures to ensure fair comparison. Perhaps identifying a maximum amount of platforms would provide a starting point for alternative regulations.

3.10 Step 7 – Provide Recommendations

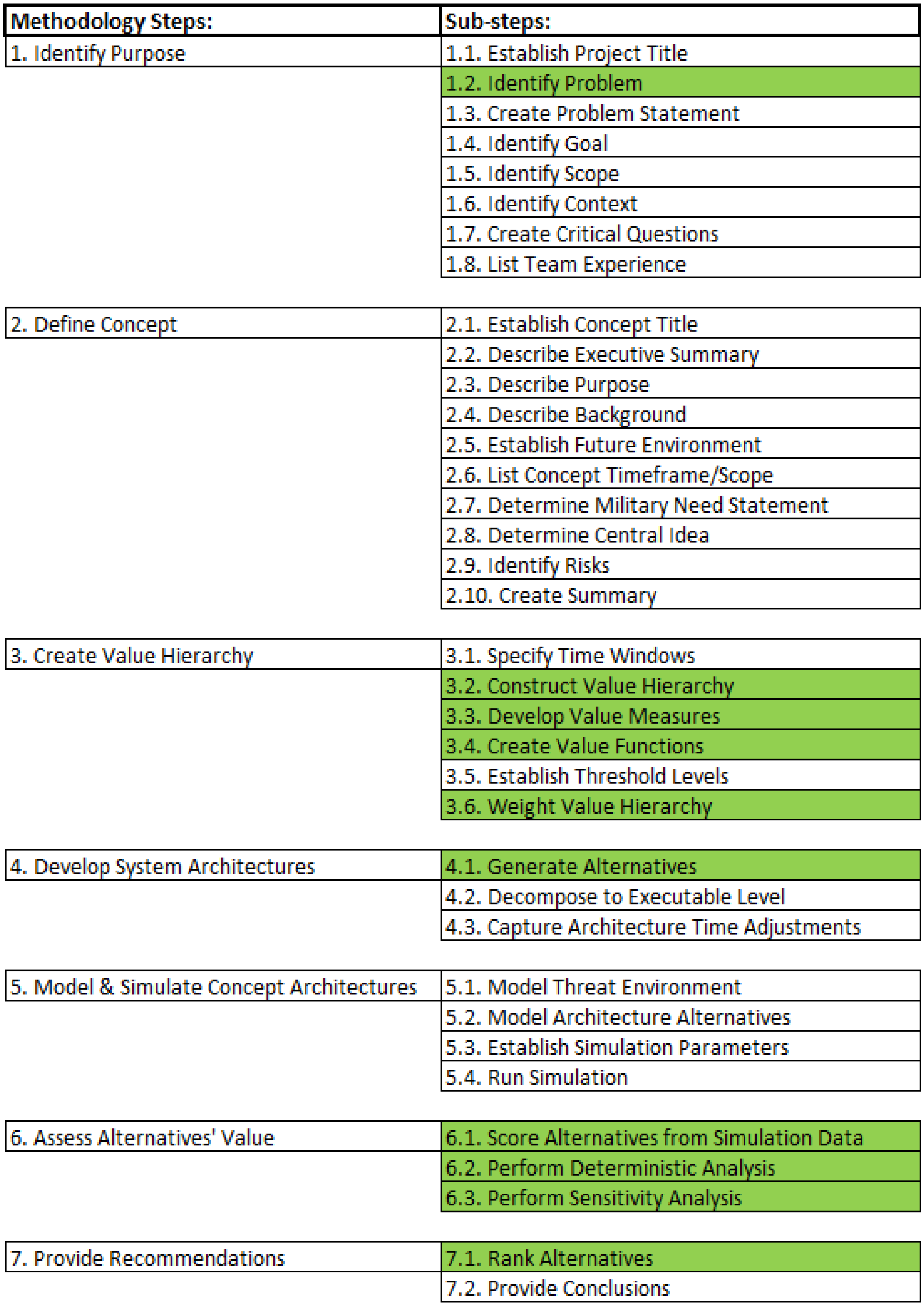
The final step of the methodology is to provide recommendations based on the alternatives analysis performed during step six. Providing recommendations during traditional VFT processes typically includes identification of a best alternative based on value rankings. Providing recommendations for the pre-acquisition methodology should go beyond the sole purpose of declaring a best architecture or ranking alternatives. Time-dependent conclusions can be made to distinguish performance successes among alternatives, time-based capability gaps, or struggling value measure performance.

Ranking alternatives (sub-step 7.1) should still be performed as part of step seven, but time-dependent analysis outside of simply stressing a winning architecture should occur. Providing conclusions (sub-step 7.2) should instead focus on time-dependent findings and beneficial analysis information leading up to MS A. Unlike traditional VFT processes that are finished with their assessment after providing recommendations, the possibility is likely that additional analysis still exists for the pre-acquisition methodology as it transitions into MS A. The intentions of step seven should therefore be to provide enough details for the continued assessment of alternatives through the AoA and into MS A.

3.11 Methodology Summary

Chapter 3 discussed each step of the pre-acquisition methodology by detailing the sub-step requirements and recommendations of use. The pre-acquisition methodology is kept generic enough to use with any DoD project in support of concept analysis prior to MS A. Chapter 4 will use Chapter 3's comprehensive explanation of the pre-acquisition methodology with an exemplar ISR mission, starting at step one and moving all the way through step seven with the intention of capturing a single architecture alternative's analysis. An exhaustive summary of the pre-acquisition methodology can be seen in Table 10, which includes all steps and their associated sub-steps, with the green-colored cells representing those parts of the 10-step VFT process captured as part of the pre-acquisition methodology.

Table 10 - Pre-Acquisition Methodology Summary



Methodology Steps:	Sub-steps:
1. Identify Purpose	1.1. Establish Project Title
	1.2. Identify Problem
	1.3. Create Problem Statement
	1.4. Identify Goal
	1.5. Identify Scope
	1.6. Identify Context
	1.7. Create Critical Questions
	1.8. List Team Experience
2. Define Concept	2.1. Establish Concept Title
	2.2. Describe Executive Summary
	2.3. Describe Purpose
	2.4. Describe Background
	2.5. Establish Future Environment
	2.6. List Concept Timeframe/Scope
	2.7. Determine Military Need Statement
	2.8. Determine Central Idea
	2.9. Identify Risks
	2.10. Create Summary
3. Create Value Hierarchy	3.1. Specify Time Windows
	3.2. Construct Value Hierarchy
	3.3. Develop Value Measures
	3.4. Create Value Functions
	3.5. Establish Threshold Levels
	3.6. Weight Value Hierarchy
4. Develop System Architectures	4.1. Generate Alternatives
	4.2. Decompose to Executable Level
	4.3. Capture Architecture Time Adjustments
5. Model & Simulate Concept Architectures	5.1. Model Threat Environment
	5.2. Model Architecture Alternatives
	5.3. Establish Simulation Parameters
	5.4. Run Simulation
6. Assess Alternatives' Value	6.1. Score Alternatives from Simulation Data
	6.2. Perform Deterministic Analysis
	6.3. Perform Sensitivity Analysis
7. Provide Recommendations	7.1. Rank Alternatives
	7.2. Provide Conclusions

4. Analysis and Results

4.1 Chapter Overview

Chapter 4 extends the pre-acquisition methodology detailed in Chapter 3 using an ISR mission exemplar. The specific details of the ISR mission were fictitious and simply intended to show how the pre-acquisition methodology was used to analyze a single architecture alternative developed from a multi-domain (space constellation and multiple UAV) concept. The steps and sub-steps were utilized to capture the usefulness of the methodology and to gather analytical data supporting the alternative's performance. Appendices should be frequently referenced for Chapter 4's pre-acquisition methodology's implementation with an ISR mission due to the many tables, graphs, figures, and lines of computer code supporting the time-variant analysis of the alternative.

4.2 Policy Abstraction

The pre-acquisition methodology was initiated by abstracting policy guidance for support towards identifying the ISR mission in step one and defining the concept in step two. A process similar to the gold standard approach was employed to capture policy and strategic intentions. A generic abstraction example can be seen using Table B:1 and Table B:2 with the rest of Appendix B, which used the NSS, NMS, QDR, JCA, UJTL, strategic USAF & DoD guidance, and identified Ilities to separate DoD areas of interest. Although the example in Appendix B was kept generic for supporting several different projects, abstraction should typically be tailored to incorporate operation details.

4.3 Step 1 – Identify Purpose

All step one suggested sub-steps from Chapter 3 were applied to the ISR mission, which can be seen represented in Appendix B.

4.4 Step 2 – Define Concept

All step two sub-steps were applied to the ISR mission, which can be seen represented in Appendix C. The multi-domain concept details captured in the sub-steps for both step one and step two were used to establish the foundation for all future pre-acquisition methodology steps.

4.5 Step 3 – Create Value Hierarchy

The complete value hierarchy was created in step three, but first time windows were specified in sub-step 3.1 to support time-dependent operational requirements.

4.5.1 Sub-step 3.1: Specify Time Windows:

Coordinated Universal Time (UTC) was chosen as the reference time, with the format being $hh:mm:ss$ on $Day\ Month\ Year$, with hh provided on a military-time scale of 0-24 hours. Time windows were next specified for all time periods of interest, beginning with the concept's four operational phases of anticipated mission impact.

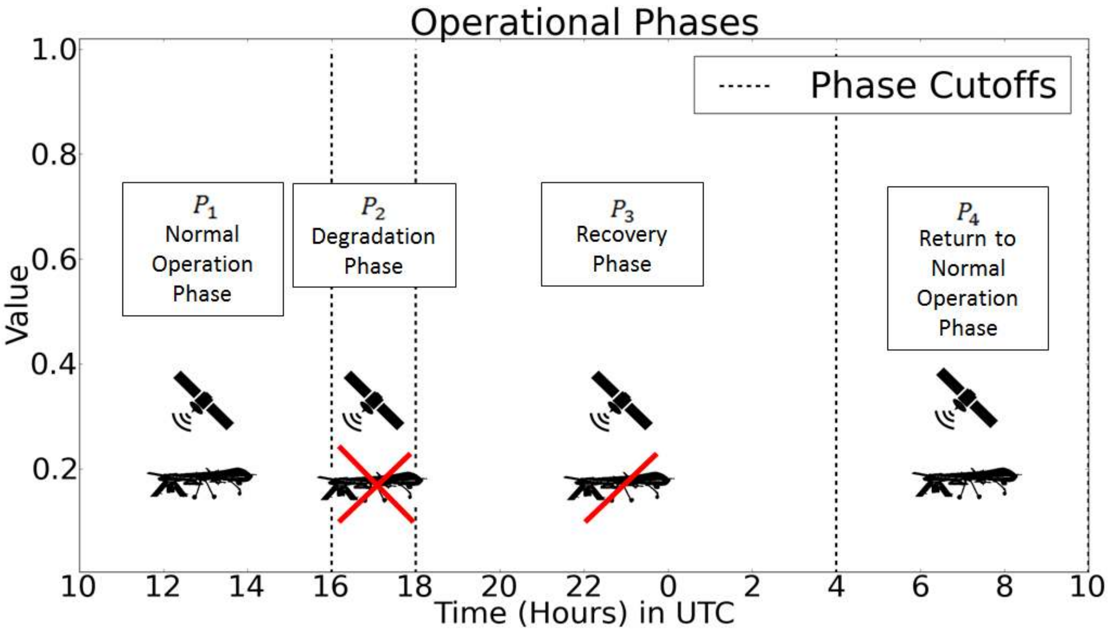


Figure 22 – ISR Mission Operational Phases

The operational phases defined in Figure 22 include Phase 1 representing the first six hours of anticipated normal operation, Phase 2 covering the next two hours of UAV performance degradation, Phase 3 covering the following ten-hour recovery from Phase 2's UAV performance impact, and Phase 4 covering the return to normal operations during the final six hours of the 24-hour FST. Phase 2's degradation was captured by turning off the UAV's fixed sensor in the STK model between 16:00:00 on 14 May to 17:59:59 on 14 May. All identified time windows along with their time range and reason for specification can be seen in Table D:1of Appendix D.

4.5.2 Sub-step 3.2: Construct Value Hierarchy

After time window specifications were established, construction of the value hierarchy was initiated based on objectives from step one's purpose and step two's concept. Initial value hierarchy construction for the ISR mission can be seen in Figure 23, which includes the goal on top and appropriate objectives underneath supporting the problem and concept.

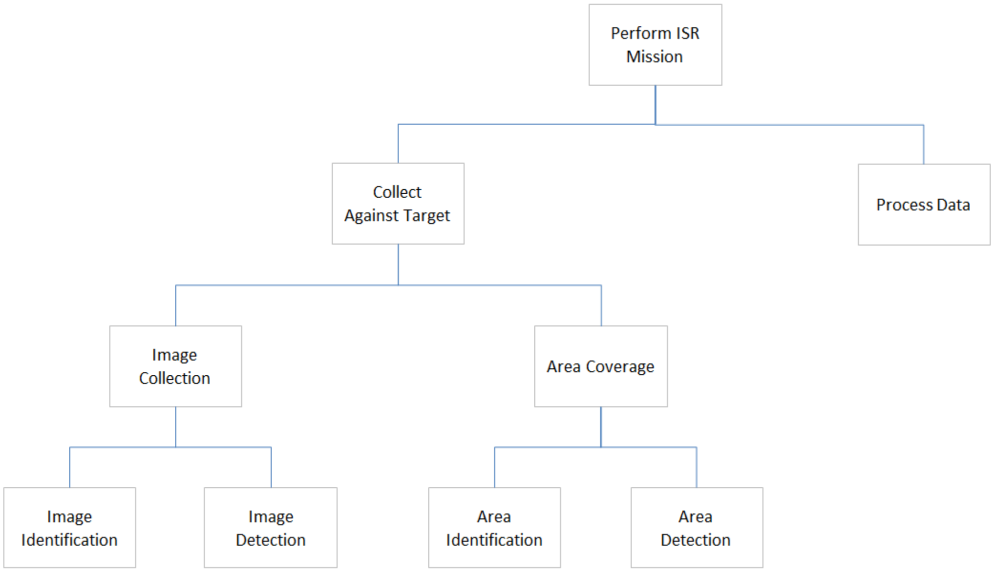


Figure 23 - ISR Mission Value Hierarchy Construction (Ford et al., 2014)

4.5.3 Sub-step 3.3: Develop Value Measures

After initial value hierarchy construction, value measures were developed in order to represent the leaf-level objectives of image identification, image detection, area identification, area detection, and process data. Image identification and image detection were defined as being separated by their image collection resolution quality. NIIRS was the decided measurement type to represent both leaf-level objectives, which is a scale from zero to nine expressive of image interpretability. The chosen value measures for image identification and image detection were NIIRS Identification ($NIIRS_{ID}$) and NIIRS Detection ($NIIRS_D$), respectively. The middle portion of the value hierarchy needed to represent the area of interest (AOI) coverage. Percent coverage was chosen as the measurement type, with percent coverage identification ($\%Cov_{ID}$) representing smaller area identification and percent coverage detection ($\%Cov_D$) used for larger area detection. The value measure chosen to represent the process data leaf-level objective was system response time (SRT) (Ford et al., 2014). Figure 24 shows the blue oval value measures applied to the constructed value hierarchy from Figure 23.

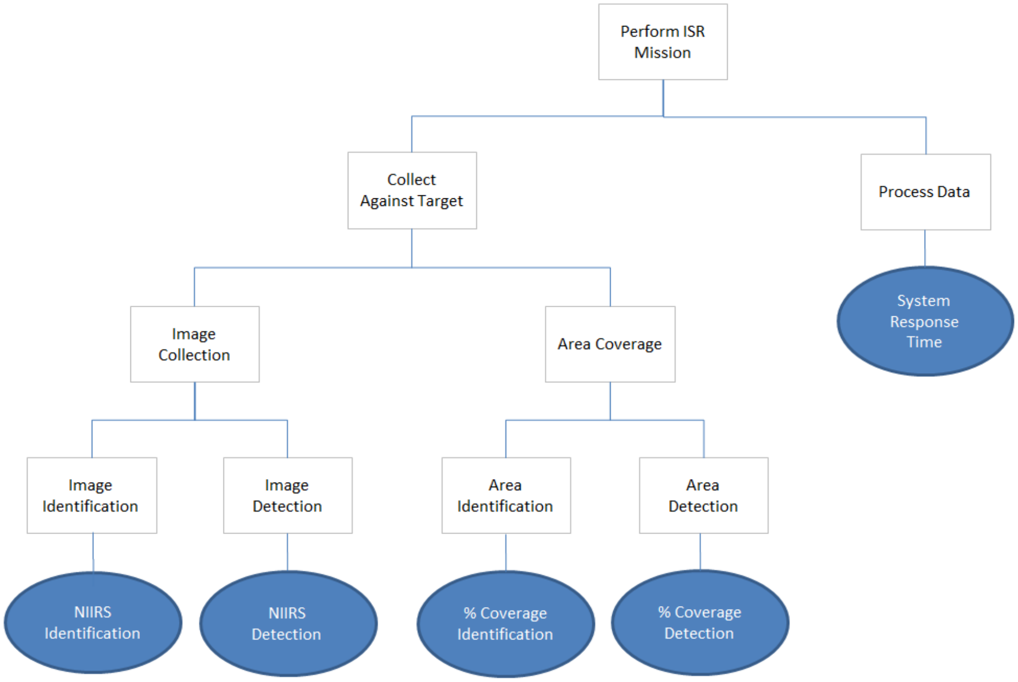


Figure 24 - ISR Mission Value Hierarchy with Value Measures (Ford et al., 2014)

Each value measure was distinguished by its unchanging position in the value hierarchy, with $NIIRS_{ID}$ being value measure number one and SRT being number five for a total of five value measures $(n = 5)$. Every leaf-level objective along with its representative value measure and appropriate identifier (i) can be seen in Table 11.

Table 11 – ISR Mission Leaf-Level Objectives & Corresponding Value Measures

Leaf-Level Objective	i	Corresponding Value Measure
Image Identification	1	$NIIRS\ Identification\ (NIIRS_{ID})$
Image Detection	2	$NIIRS\ Detection\ (NIIRS_D)$
Area Identification	3	$Percent\ Coverage\ Identification\ (\%Cov_{ID})$
Area Detection	4	$Percent\ Coverage\ Detection\ (\%Cov_D)$
Process Data	5	$System\ Response\ Time\ (SRT)$

While value measures were specifically chosen to represent each leaf-level objective, consideration was also given as to how each value measure would be scored. Matching M&S output data with some of the identified value measures would provide time-dependent scoring measurements, but the M&S tool had to fit each value measure's requirements. The possible outputs of simulation tools were researched to assess what output data could accurately represent each value measure, if applicable.

STK was identified as being able to output two figures of merit for each epoch time that could drive time-dependent value measure performance. The first data type that STK could generate was a time-dependent azimuth, elevation, and range (AER) output file for each platform (satellite or aircraft). While AER data did not match a NIIRS level, it was recognized that AER data could be placed through a function in Python to turn all three variables into usable time-dependent NIIRS levels for each platform (Palmer, Everson, & Meyer, 2015). The second STK figure of merit directly matched the required time-dependent percent coverage calculations for the AOI. System response time measurements were assumed to be a constant of 20 minutes, as too many assumptions were needed to accurately capture SRT, including ground station location and data processing rate.

4.5.4 Sub-step 3.4: Create Value Functions

Value functions were next needed for the identified value measures. Consistent with the pre-acquisition methodology's guidance from Chapter 3, sub-step 3.4 and later required representation of which time window was under consideration. $min_i(t)$ and $max_i(t)$ were first established for each value measure, which can be seen in columns two and three of Table 12. Matching the time windows in column five of Table 12 with columns two and three showed the unchanging SAVF boundaries throughout the FST. One observation from Table 12 was that the SRT SAVF boundaries were listed in reverse order when compared to the other four value measures. This was accurately captured, as a smaller SRT equated to more desirable value (boundary maximum) while a larger SRT was of less desirable value (boundary minimum).

After boundaries were determined, the next portion of sub-step 3.4 consisted of determining SAVF shapes and creating SAVF equations to turn $x_i(t)$ into $v_{i,t}\big(x_i(t)\big)$ for each value measure. Each value measure's time-dependent SAVF shape was represented in column four of Table 12, along with its corresponding time window in column five. All four SAVF shapes were used to exemplify at least one value measure. This was determined not by the best representation of each value measure, but instead chosen to show the implementation of all four SAVF shapes. Actual inclusion of the methodology should choose time-variant SAVF shapes most applicable to each value measure.

Table 12 – ISR Mission's Value Measure Boundaries and Shapes

Value Measure	$\boldsymbol{min_i(t)}$	$\boldsymbol{max_i(t)}$	**SAVF Shape**	**Time Window**
$NIIRS_{ID}$	5 NIIRS	9 NIIRS	Linear	$TW_1(0 \le t \le 86{,}400)$
$NIIRS_D$	1 NIIRS	5 NIIRS	Convex	$TW_2(0 \le t \le 46{,}799)$
$NIIRS_D$	1 NIIRS	5 NIIRS	Linear	$TW_{12}(46{,}800 \le t \le 86{,}400)$
$\%Cov_{ID}$	0.10 %	20 %	Concave	$TW_1(0 \le t \le 86{,}400)$
$\%Cov_D$	20 %	80 %	S-Curve	$TW_1(0 \le t \le 86{,}400)$
SRT	40 min	0 min	Concave	$TW_1(0 \le t \le 86{,}400)$

Each time-dependent SAVF was created to turn any $x_i(t)$ greater than or equal to its $max_i(t)$ into a $v_{i,t}\big(x_i(t)\big)$ of one, and any $x_i(t)$ less than or equal to its $min_i(t)$ into a

$v_{i,t}(x_i(t))$ of zero. Those $x_i(t)$ scores that fell between $min_i(t)$ and $max_i(t)$ would output appropriate $v_{i,t}(x_i(t))$ corresponding to their SAVF's intentions, but the actual scoring of alternatives would not take place until step six. Each value measure's time-variant SAVFs can be seen below, starting with the NIIRS_{ID} linear SAVF for TW_1 (25).

$$v_{1,t}(x_1(t)) = v_{NIIRS_{ID},t}(NIIRS(t)) \text{ for } TW_1 \qquad \textbf{(25)}$$

$$= \begin{cases} 0, & NIIRS(t) \le min_{NIIRS_{ID}}(t) \\ \dfrac{\left(NIIRS(t) - min_{NIIRS_{ID}}(t)\right)}{\left(max_{NIIRS_{ID}}(t) - min_{NIIRS_{ID}}(t)\right)}, & min_{NIIRS_{ID}}(t) < NIIRS(t) < max_{NIIRS_{ID}}(t) \\ 1, & NIIRS(t) \ge max_{NIIRS_{ID}}(t) \end{cases}$$

Equation (25)'s corresponding linear SAVF graph for $NIIRS_{ID}$ can be seen in Figure 25.

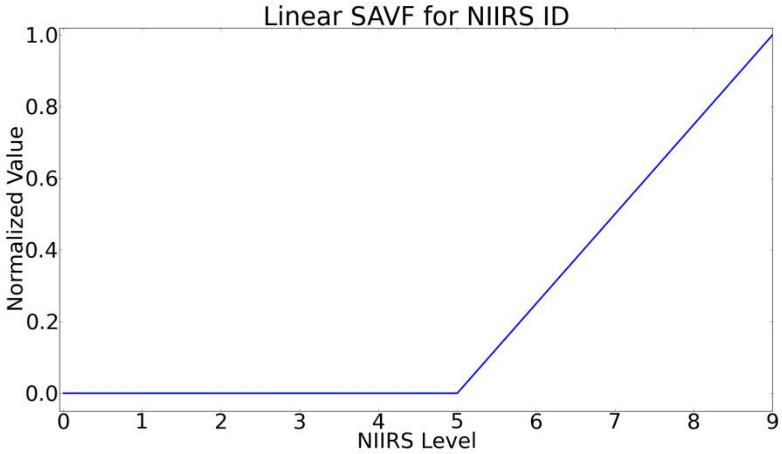


Figure 25 – ISR Mission's Linear (25) NIIRS ID SAVF for TW1

The $NIIRS_D$ convex SAVF for TW_2 can be seen in (26).

$$v_{2,t}\big(x_2(t)\big) = v_{NIIRS_D,t}\big(NIIRS(t)\big) \text{ for } TW_2 \tag{26}$$

$$= \begin{cases} 0, & NIIRS(t) \leq min_{NIIRS_D}(t) \\ \dfrac{e^{(NIIRS(t)\,\times\,2)}}{e^{(max_{NIIRS_D}(t)\,\times\,2)}}, & min_{NIIRS_D}(t) < NIIRS(t) < max_{NIIRS_D}(t) \\ 1, & NIIRS(t) \geq max_{NIIRS_D}(t) \end{cases}$$

Equation (26)'s corresponding convex SAVF graph for $NIIRS_D$ can be seen in Figure 26.

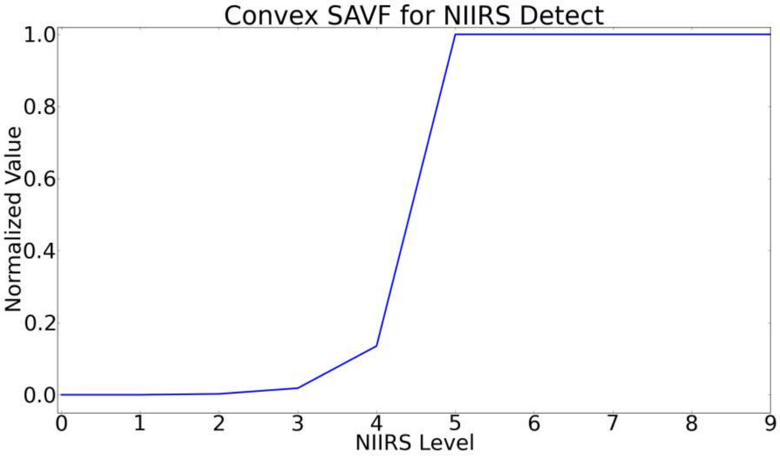


Figure 26 – ISR Mission's Convex (26) NIIRS Detection SAVF for TW2

$NIIRS_D$ relied on two different SAVF shapes, including a convex shape for TW_2 and a linear shape for TW_{12}. Equation (26)'s convex SAVF shape is only for TW_2 (not representative for FST), so a linear SAVF (27) was needed to represent TW_{12}.

$$v_{2,t}(x_2(t)) = v_{NIIRS_D,t}(NIIRS(t)) \text{ for } TW_{12} \tag{27}$$

$$= \begin{cases} 0, & NIIRS(t) \leq min_{NIIRS_D}(t) \\ \dfrac{\left(NIIRS(t) - min_{NIIRS_D}(t)\right)}{\left(max_{NIIRS_D}(t) - min_{NIIRS_D}(t)\right)}, & min_{NIIRS_D}(t) < NIIRS(t) < max_{NIIRS_D}(t) \\ 1, & NIIRS(t) \geq max_{NIIRS_D}(t) \end{cases}$$

Equation (27)'s corresponding linear SAVF graph for $NIIRS_D$ can be seen in Figure 27.

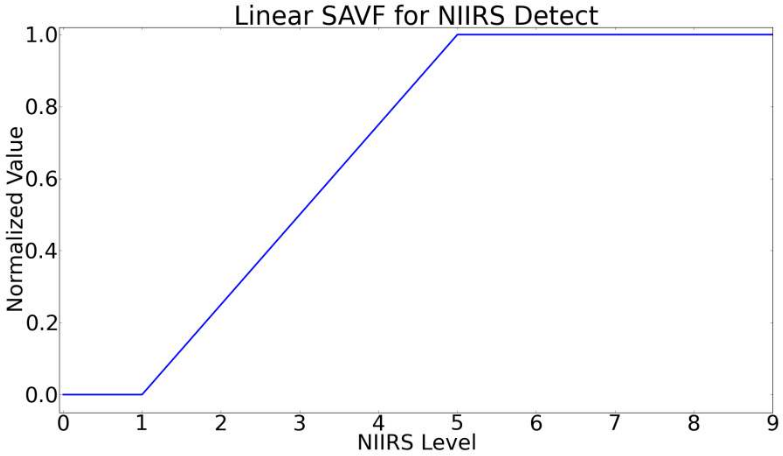


Figure 27 – ISR Mission's Linear (27) NIIRS Detection SAVF for TW12

The intention behind changing SAVF shapes for $NIIRS_D$ was to show how establishing time windows could help support the preferred change in performance. TW_2 ends and TW_{12} began midway through Phase 3 at 23:00:00 UTC on 14 May 2015, and switching from a convex shape to a linear shape showed stakeholders' desire to allow greater influence on smaller NIIRS levels that exceeded the $min_{NIIRS_D}(t)$. Comparing Figure 26 to Figure 27 shows the added influence on smaller NIIRS levels to $NIIRS_D$ created by switching to a linear SAVF shape for TW_{12}.

$\%Cov_{ID}$ was best represented by a concave shape throughout the FST, which can be seen in (28) for TW_1.

$$v_{3,t}\big(x_3(t)\big) = v_{\%Cov_{ID},t}\big(\%Cov(t)\big) \text{ for } TW_1 \tag{28}$$

$$= \begin{cases} 0, & \%Cov(t) \le min_{\%Cov_{ID}}(t) \\ \dfrac{\big(\ln\big(\%Cov(t)\big) + 2\big)}{\Big(\ln\Big(max_{\%Cov_{ID}}(t)\Big) + 2\Big)}, & min_{\%Cov_{ID}}(t) < \%Cov(t) < max_{\%Cov_{ID}}(t) \\ 1, & \%Cov(t) \ge max_{\%Cov_{ID}}(t) \end{cases}$$

Equation (28)'s concave SAVF graph for $\%Cov_{ID}$ can be seen in Figure 28.

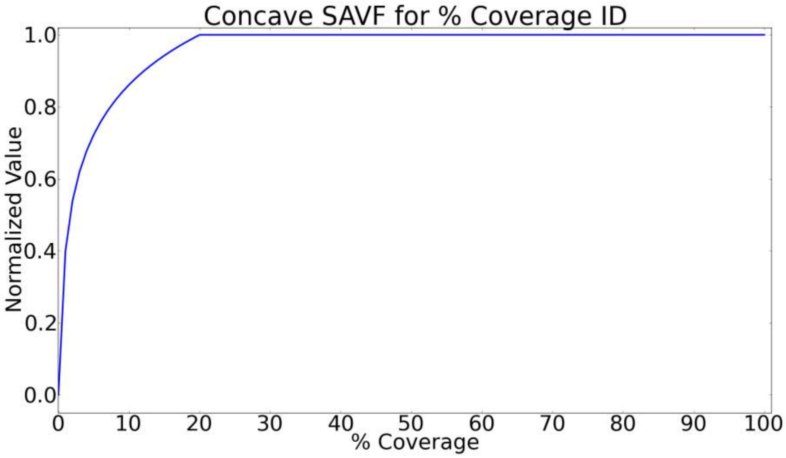


Figure 28 – ISR Mission's Concave (28) % Coverage ID SAVF for TW1

$\%Cov_D$ was best represented by an S-curve shape throughout the FST. The $\%Cov_D$ SAVF can be referenced in (29).

$$v_{4,t}\left(x_4(t)\right) = v_{\%Cov_D,t}\left(\%Cov(t)\right) \text{ for } TW_1 \tag{29}$$

$$= \begin{cases} 0, & \%Cov(t) \leq min_{\%Cov_D}(t) \\ \dfrac{1}{1+e^{\left[-\%Cov(t)+\left(max_{\%Cov_D}(t)-min_{\%Cov_D}(t)\right)\right]}}, & min_{\%Cov_D}(t) < \%Cov(t) < max_{\%Cov_D}(t) \\ 1, & \%Cov(t) \geq max_{\%Cov_D}(t) \end{cases}$$

Equation (29)'s S-curve SAVF graph for $\%Cov_D$ can be seen in Figure 29.

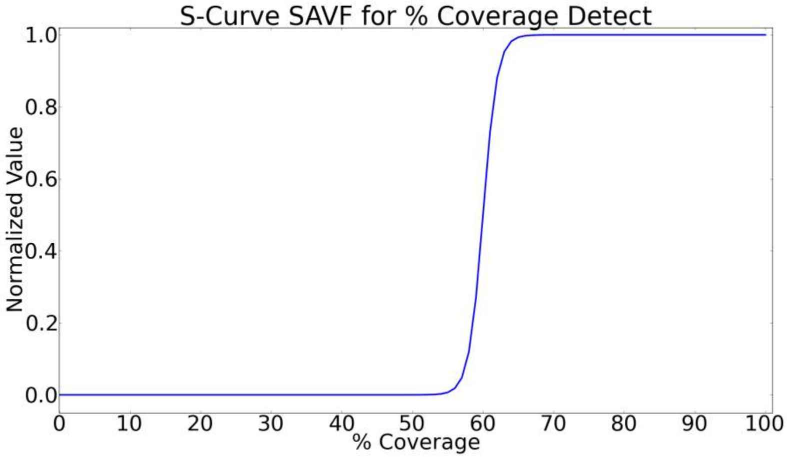


Figure 29 – ISR Mission's S-Curve (29) % Coverage Detection SAVF for TW1

The SAVF shape for SRT at any epoch time was best represented by a concave shape throughout the FST. The SRT SAVF for TW_1 can be seen in (30).

$$v_{5,t}\left(x_5(t)\right) = v_{SRT,t}\left(SRT(t)\right) \text{ for } TW_1 \tag{30}$$

$$= \begin{cases} 0, & SRT(t) \leq min_{SRT}(t) \\ 1-\dfrac{e^{\left(\frac{SRT(t)}{10}\right)}}{e^{\left(\frac{max_{SRT}(t)}{10}\right)}}, & min_{SRT}(t) < SRT(t) < max_{SRT}(t) \\ 1, & SRT(t) \geq max_{SRT}(t) \end{cases}$$

Equation (30)'s corresponding SAVF graph for SRT can be seen in Figure 30.

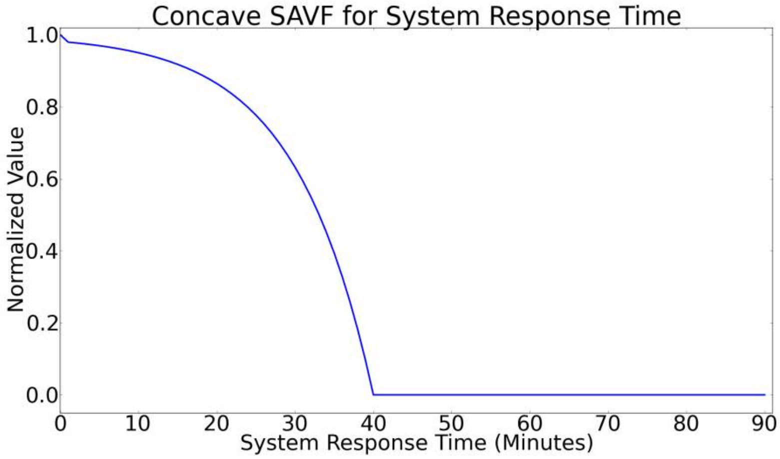


Figure 30 – ISR Mission's Concave (30) SRT SAVF for TW1

All time-dependent SAVFs and boundaries were transferred to Python computer code in order to be used for all threshold levels and eventual simulation output data, which concluded sub-step 3.4.

4.5.5 Sub-step 3.5: Establish Threshold Levels

Time-dependent threshold levels for each value measure $\left(TL_i(t)\right)$ were chosen based on their respective time windows, which can be seen in Table D:2. As stressed in Chapter 3, $TL_i(t)$ was chosen rather than $ITV_i(t)$. Each $TL_i(t)$ was transitioned into $v_{i,t}\left(TL_i(t)\right)$ using the time-dependent Python SAVFs from sub-step 3.4. Translating $TL_i(t)$ into $ITV_i(t)$ was delayed until $w_i(t)$ was determined in sub-step 3.6.

4.5.6 Sub-step 3.6: Weight Value Hierarchy

The final sub-step of step three was performed by determining value measure swing weights for each of Table D:1's time windows that represented the four operational phases. A TW_3 example of weighting the value hierarchy for the ISR mission can be seen in Figure 31.

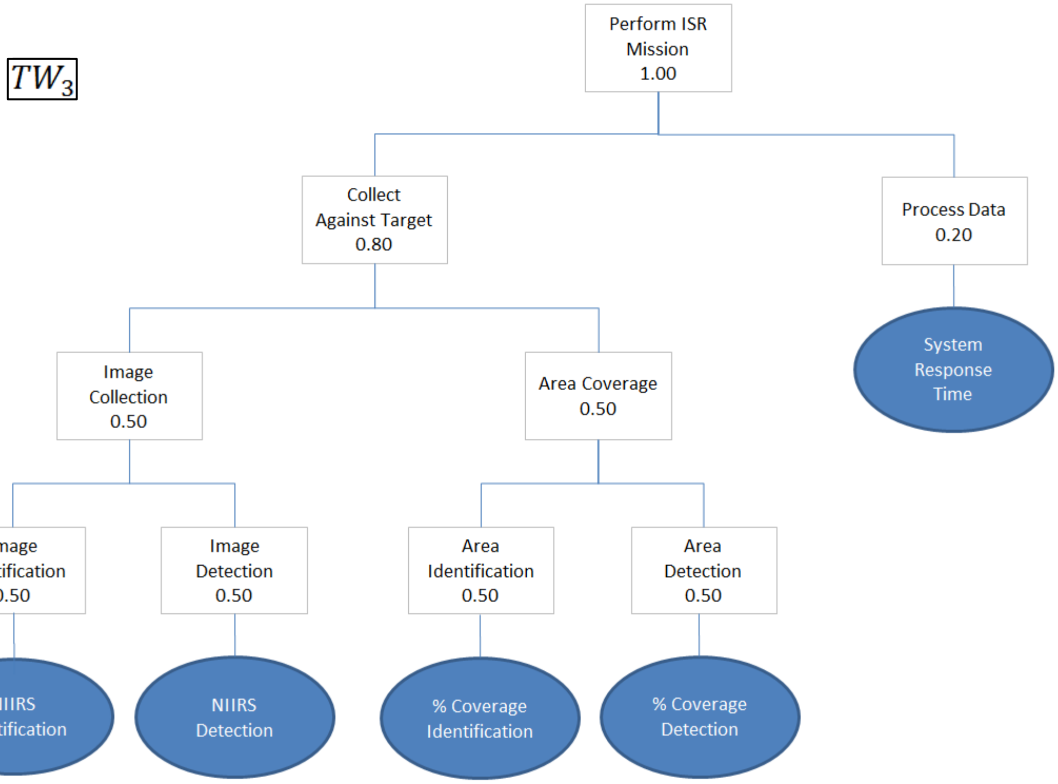


Figure 31 – ISR Mission Value Hierarchy with Weighting

Combining the local weights assigned for TW_3 (see Figure 31) produces global weights for each value measure (see below).

$$w_1(TW_3) = w_{NIIRS_{ID}}(0 \leq t \leq 21{,}599) = 0.50 \times 0.50 \times 0.80 \times 1.00 = 0.20$$

$$w_2(TW_3) = w_{NIIRS_D}(0 \leq t \leq 21{,}599) = 0.50 \times 0.50 \times 0.80 \times 1.00 = 0.20$$

$$w_3(TW_3) = w_{\%Cov_{ID}}(0 \leq t \leq 21{,}599) = 0.50 \times 0.50 \times 0.80 \times 1.00 = 0.20$$

$$w_4(TW_3) = w_{\%Cov_D}(0 \leq t \leq 21{,}599) = 0.50 \times 0.50 \times 0.80 \times 1.00 = 0.20$$

$$w_5(TW_3) = w_{SRT}(0 \leq t \leq 21{,}599) = 0.20 \times 1.00 = 0.20$$

The continued TW_3 example from Figure 31 can be seen calculated below as an extension of (7) to prove the summation of all five value measures was equal to one.

For TW_3:

$$\sum_{i=1}^{n=5} w_i(t) = w_1(t) + w_2(t) + w_3(t) + w_4(t) + w_5(t)$$

$$= w_{NIIRS_{ID}}(t) + w_{NIIRS_D}(t) + w_{\%Cov_{ID}}(t) + w_{\%Cov_D}(t) + w_{SRT}(t)$$

$$= 0.20 + 0.20 + 0.20 + 0.20 + 0.20 = 1$$

This example proved that the value hierarchy was appropriately weighted for TW_3, which intended to have equal weighting across all value measures for normal operation during Phase 1. Time windows representative of other operational phases did not all have equal weighting. Phase 2 of the ISR mission heavily desired identification of a degradation threat and therefore $w_{NIIRS_{ID}}(t)$ was much higher than the other weights. Phase 3 instead desired detection in order to monitor the target during the recovery period, so $w_{NIIRS_D}(t)$ and $w_{\%Cov_D}(t)$ were weighted more heavily. Phase 4 returned to a normal operation with its weights equal as they were in Phase 1. Table D:3 summarizes all value measures' swing weights across all time windows.

After weights were established for all time windows, sub-step 3.5's resulting $v_{i,t}\big(TL_i(t)\big)$ was multiplied by its value measure's $w_i(t)$ to obtain $ITV_i(t)$ as seen in (9) from Chapter 3. The additive value model in (13) was applied to sum each $ITV_i(t)$ for overall calculation of $ITV(t)$ across each epoch time. In an effort to not show all 86,400 time-dependent instantaneous threshold values, Figure D:1 in Appendix D shows the graphical representation of $ITV(t)$ and Figure D:2 applies representation of Table D:1's longer time windows with $ITV(t)$. The $ITV(t)$ of each of the four operational phases and its appropriate time windows can similarly be viewed in Figure D:3 (Phase 1), Figure D:4 (Phase 2), Figure D:5 (Phase 3), and Figure D:6 (Phase 4). The purpose of capturing Figure D:1 through Figure D:6 was to create an easier visual understanding of the time window specification impacts on $ITV(t)$ and their relationships with the timing of operational phases.

Due to $NIIRS_D$ being the only value measure that included a SAVF shape adjustment between TW_2 and TW_{12}, special attention was given to the impact caused by that SAVF adjustment on $ITV_{NIIRS_D}(t)$. Figure 32 shows the large influence on $ITV_{NIIRS_D}(t)$ that resulted from a convex to linear SAVF and a small $TL_{NIIRS_D}(t)$ adjustment around 23:00:00 UTC on 14 May 2015.

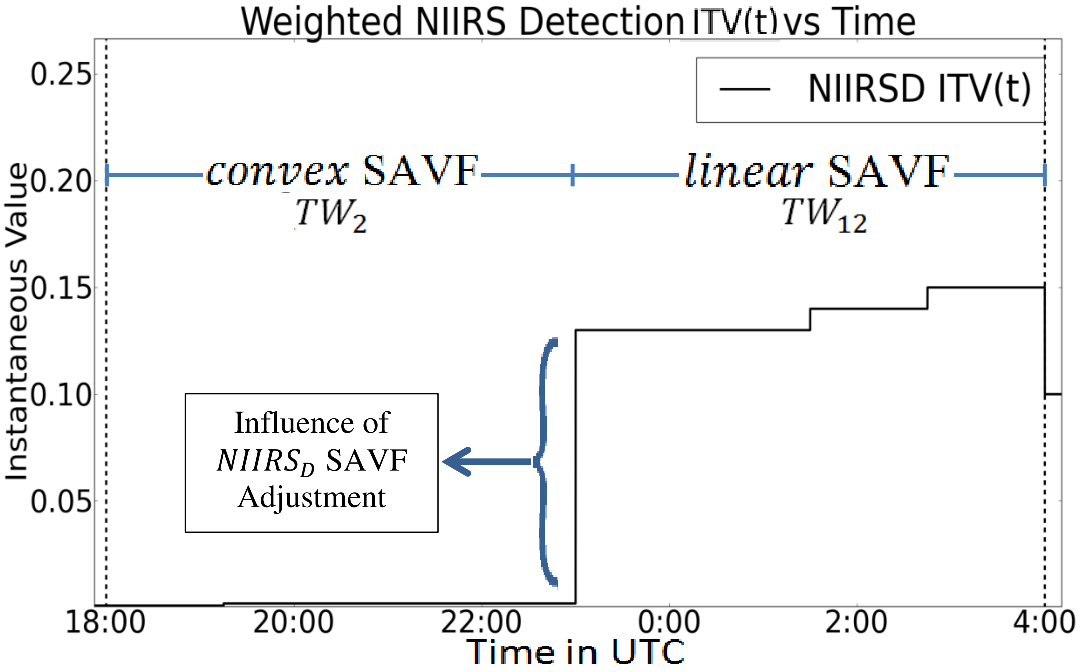


Figure 32 - NIIRS Detection SAVF Shape Change Influence on NIIRSD ITV(t)

4.6 Step 4 – Develop System Architectures

Development of a single alternative's executable systems architecture was generated to be consistent with the problem identified in step one, the concept from step two, the operational phases represented in Figure 22, Table D:1's time windows, and objectives specified in step three. Abstraction to an executable level for support of the ISR mission involved capturing both space-domain and air-domain assets' specifications. The number of orbits, number of satellites per orbit, each satellite's six classic orbital elements (COEs), and each satellite's sensor specifications were all required for an executable architecture of space-based ISR assets. The UAVs similarly required specifications such as each platform's speed, altitude, flight route, and sensor details in order to capture an executable level of architecture.

The specifications chosen for each domain's platforms were fictitious. The intention was to present a multi-domain alternative's systems architecture for use with the pre-acquisition methodology. The intention was not the representation of realistic space or UAV systems. Figure E:1 in Appendix E shows the single alternative's developed executable systems architecture. The architecture's time-variant performance adjustments that resulted from Phase 2's UAV fixed sensor degradation was captured in the architecture using a note attached to the UAV's fixed sensor specifications (seen in the bottom-left of Figure E:1).

4.7 Step 5 – Model and Simulate Concept Architectures

Python was used to automate the STK model of the architecture captured previously in step four. Step three of Chapter 4 discussed the reliance on STK and Python to obtain AER reports (turned into NIIRS levels using a Python function) and percent coverage reports output directly from STK. Other than STK's ability to match desired value measure outputs to its figures of merit, it was additionally chosen because of its proven accuracy in modeling air and space platforms. Python was chosen because of its ability to drive the STK engine and to perform the required post-simulation analysis.

Python code was created using five total scripts. The main architecture script created easy transfer of earlier methodology details to be automatically generated in the model. Some areas included time window impacts, weight adjustments, satellite and UAV M&S parameters from the executable architecture, specific scenario value details, and time window summation periods (Figure F:1, Figure F:2, Figure F:3). The other scripts were driven by the main architecture script, which generated the model in STK, created output text files, and computed the required analysis graphs and calculations (not shown due to script sizes). Loops were used frequently in the Python code to adjust the constellation spacing of satellites, apply consistent sensor parameters to multiple platforms, and automate the departure of UAVs without having to model each new platform and sensor combination as a separate entity. "If" statements were frequently used to account for differing time-dependent impacts on the simulation. Writing computer code in this manner saved time, resources, and allowed for value feedback towards the alternative discussed in later steps (Meyer, 2016).

The 24-hr simulation period was chosen from 10:00:00 on 14 May 2015 to 10:00:00 on 15 May 2015 UTC, which was consistent with earlier time windows (Table D:1). The threat environment was modeled by determining the AOI and target locations, which included Baghdad, Ramadi, a Red Outpost 1, a Red Outpost 2, and a non-moving

Ground Vehicle (GV1) that was the target for determining access (Palmer et al., 2015). The Python-driven model of the AOI threat environment can be seen in Figure F:5 of Appendix F.

The alternative's platforms were next modeled in STK using Python to capture the specifications outlined in step four's executable architecture. Figure F:6 shows one of the four STK-modeled UAVs over the AOI and Figure F:7 shows one of the nine modeled satellites approaching the AOI. As represented in the systems architecture, the time period between 16:00:00 on 14 May and 17:59:59 on 14 May was modeled to represent a jamming environment, when any UAV's fixed sensor would automatically capture 0% coverage during that time period. This degradation impact was modeled using an external Python script to turn off any UAV sensor deployed during that period.

The simulation time step was decided to account for every second, which meant the output text files produced second-by-second data (total of 86,400 data points). Once the threat environment and alternative were modeled in STK along with the simulation parameters, the STK simulation was automatically run using Python. The AER text files for each sensor were combined and transitioned into output text files that covered each epoch time's maximum NIIRS level using Python code (Meyer, 2016; Palmer et al., 2015). A portion of the NIIRS text file called Output.txt can be seen in Table F:1. The percent coverage data was generated directly from STK as a text file called Cov_Column.txt, a portion of which can similarly be seen in Table F: 2. Figure F:4 shows the simulation start time view of the alternative's full STK model.

4.8 Step 6 – Assess Alternatives' Value

Python was not only used to drive the STK engine, but additionally used to place time-dependent NIIRS and percent coverage data outputs into step three's requirements for value calculations. Step six from Chapter 3 identified several equations used to calculate differing forms of instantaneous value or instantaneous Boolean scores. Table G:1 shows a portion of the New_Outpout.txt, which converted the output NIIRS levels and percent coverage into $v_{i,t}(x_i(t))$ and $IV_i(t)$ for all value measures to ultimately calculate the combined $IV(t)$. Table G:2 represents a small portion of Threshold.txt, which converted each $TL_i(t)$ into $ITV_i(t)$; calculated $ITV_i(t)$, $IV_i(t)$, and $IB_i(t)$ across all value measures; calculated $ITV(t)$, $IV(t)$, and $IB_{IV}(t)$; recorded $IB_n(t)$; calculated $IV_M(t)$ for all five value measures and for three mandatory value measures ($NIIRS_{ID}$, $\%Cov_{ID}$, and SRT); calculated $IV_{TB}(t)$ for TW_{11}; and finally provided $IV_C(t)$ for TW_{18}. Each separate time-variant calculation was represented in a different column in the text file, which allowed for easy summation over different time periods using Python.

Due to the large amount of data contained in each output text file, equation (24) was used to perform row-restricting percentage comparisons from Table A:1. The alternative's percentage comparisons were calculated using Python to sum designated numerators and denominators in all specified time windows. The value measure-specific results from the percentage comparisons for all time windows can be seen in Table I:1. Value measure combined percentage comparisons can be seen in Table I:2. The percentage comparisons for those time windows that designated specific requirements (TW_{11} and TW_{18}) can be seen in Table I:3 for $IV_{TB}(t)$ and Table I:4 for $IV_C(t)$.

Accompanying time-dependent graphs were also created to show a visual depiction of each equation from step six in Chapter 3. Figure 33 shows the alternative's time-dependent $IV_i(t)$ of each value measure over the FST.

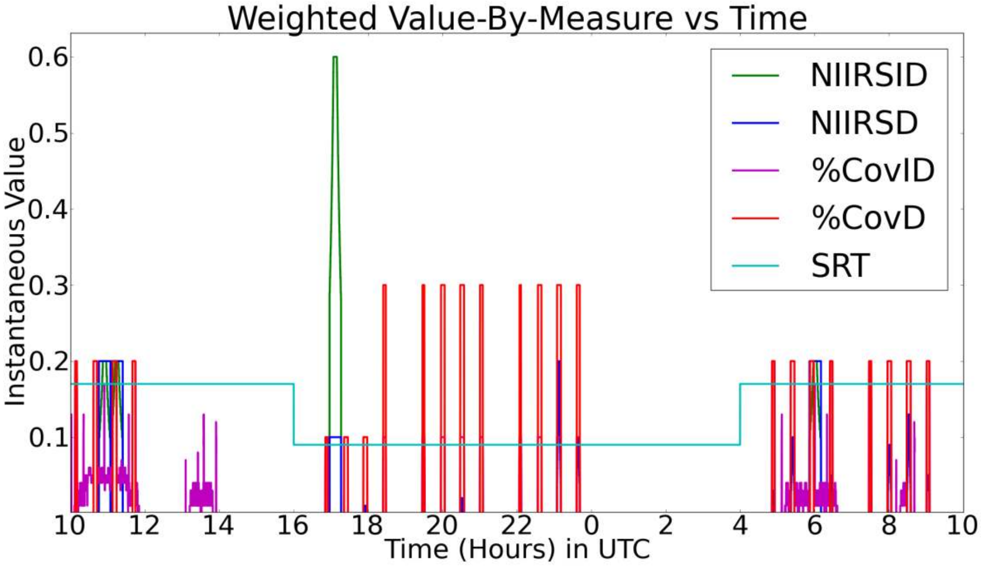


Figure 33 - Each Value Measure's IV_i(t) (Scale 0:0.62)

While effective in assigning emphasis to multiple objective value calculations, the additive value model can potentially result in only one or two strong performing, heavily weighted value measures that influence the overall $IV(t)$ without any input from other value measures. Figure 33 shows such a situation, where the green $NIIRS_{ID}$ peak reached 0.60 due to high $w_{NIIRS_{ID}}(t)$ during Phase 2. One can avoid the trap of assessing alternatives based solely on their $IV(t)$ by looking at each value measure's performance, which is a key attribute of the pre-acquisition methodology.

While Figure 33 provided time-dependent representation of the performance of all value measures, each measure was individually represented in Appendix G for the required level of value assessment. The simulation calculation graphs can be seen in Table 13 for quick reference.

Table 13 - Summary of Simulation Data Figures

Representation	Figures
NIIRS Levels vs Time	Figure G:1
Percent Coverage vs Time	Figure G:10
System Response Time vs Time	Figure G:19

Due to plotting tool text restrictions in Python, the variable used for each value measure-specific figure in Appendix G was represented as the "ith value measure $IV(t)$," which is equivalent to "$IV_i(t)$." Two examples include figure representation as "NIIRSID IV(t)" instead of $IV_{NIIRS_{ID}}(t)$, and representation as "NIIRSID V_t(x(t))" instead of $v_{NIIRS_{ID},t}\big(NIIRS(t)\big)$.

Each value measure's $v_{i,t}\big(x_i(t)\big)$, different scales for $IV_i(t)$, and $IB_i(t)$ were next captured vs time. The resulting Appendix G graphs for each value measure can be seen summarized in Table 14.

Table 14 - Summary of Value Measure Figures

Representation	$\boldsymbol{NIIRS_{ID}}$ **Figures**	$\boldsymbol{NIIRS_{D}}$ **Figures**	$\boldsymbol{\%Cov_{ID}}$ **Figures**	$\boldsymbol{\%Cov_{D}}$ **Figures**	$\boldsymbol{SRT}$ **Figures**
$v_{i,t}\big(x_i(t)\big)$	Figure G:2	Figure G:6	Figure G:11	Figure G:15	Figure G:20
$IV_i(t)$	Figure G:3 Figure G:4	Figure G:7 Figure G:8	Figure G:12 Figure G:13	Figure G:16 Figure G:17	Figure G:21 Figure G:22
$IB_i(t)$	Figure G:5	Figure G:9	Figure G:14	Figure G:18	Figure G:23

The following assessment was made for TW_1 to gather performance details of the FST, but any time window could provide similar analysis for value feedback. The examined areas of Table I:1 were bolded for easier identification. Table I:1 showed that during TW_1, $NIIRS_{ID}$ was the worst performing value measure, as its $\sum IV_{NIIRS_{ID}}(t)$ was only 13.70% of its $\sum ITV_{NIIRS_{ID}}(t)$ (visually captured in Figure G:3 and Figure G:4). Additionally, $NIIRS_{ID}$ only met or exceeded its threshold 4.32% of the time (visually captured as Figure G:5). Table I:1 also calculated that there was no $NIIRS_{ID}$ or $NIIRS_D$ capability during seven of the eight Phase 3 time windows (visually captured in Figure G:3, Figure G:4, Figure G:7, and Figure G:8). Table I:1 showed that the alternative did not generate any $IV_i(t)$ for any of the four simulated value measures during the last three time windows in Phase 3 (visually represented best as $IV(t)$ in Figure G:25).

The next set of graphs captured time-dependent data of all combined value measures, which can be seen in Table 15 and continues in figures from Appendix G figures.

Table 15 - Summary of Combined Figures

Representation	Figures
$IB_n(t)$	Figure G:24
$IV(t)$	Figure G:25
$IB_{IV}(t)$	Figure G:26
$IV_M(t)$ assuming three mandatory value measures ($i(m) = NIIRS_{ID}$, $\%Cov_{ID}$, and SRT)	Figure G:27
$IV_M(t)$ assuming all five mandatory value measures are mandatory	Figure G:28

Table I:2 showed combined (non-value measure-specific) percentage comparisons of the alternative's performance. Some analysis takeaways included a 42.78% of $\sum IV(t)$ compared to $\sum ITV(t)$ during FST (TW_1), although $\sum IV(t)$ only covered 18.91% of the possible value. Additionally, the alternative's $IV(t)$ outperformed its $ITV(t)$ 9.87% of the FST, which is equivalent to 2 hours, 22 minutes, and 7.68 seconds of the possible 24-

hour operation. Its PM_{IV} for TW_1 was 0.97 out of a potential 1.00 value, which was 160.33% compared to the PM_{ITV} for TW_1. The percent of value measures whose' $IV_i(t)$ met or exceeded their respective $ITV_i(t)$ was 25.50%. Mandatory value measures were chosen to ensure identification of the target, and percentage comparisons for those mandatory value measures ($NIIRS_{ID}$, $\%Cov_{ID}$, and SRT) included 4.04% of $\sum IV_M(t)$ compared to $\sum IV(t)$, 0.76% of $\sum IV_M(t)$ compared to $\sum ITV(t)$, and 0.84% of the time that the full mandate was one (percent of time all three mandatory value measures met or exceeded their respective $ITV_i(t)$). Only 8.49% of the time did $\sum fm(t) = 1$ compared to $\sum B_{IV}(t) = 1$, and 0.70% of the time all five value measures' $IV_i(t)$ met or exceeded their respective $ITV_i(t)$. Graphs corresponding with Table I:2's percentage comparisons can be seen throughout the last half of Appendix G.

The final set of graphs (see Table 16) captured specific requirements of only certain time windows, with the first being instantaneous value for a specific time with buffer in TW_{11} and the second covering conditional instantaneous value in TW_{18}.

Table 16 - Summary of Figures for Specific Time with Buffer & Conditional Time

Representation	Figures
$IV_{TB}(t)$ for TW_{11}	Figure H:1
$IV_M(t = LT)$ using $i(m) = NIIRS_{ID}$, $\%Cov_{ID}$, and SRT for TW_{18}	Figure H:2
$IB_{i(r)}(t) = 1$ using $i(r) = \%Cov_D$ for TW_{18}	Figure H:3
$v_{i(c),t}\big(x_i(t)\big) = v_{i,t}\big(TL_i(t)\big)$ using $i(c) = NIIRS_{ID}$ for TW_{18}	Figure H:4
$IV_C(t)$ influence on $IV(t)$ for TW_{18}	Figure H:5
$IV_C(t)$ influence on $IB_{IV}(t)$ for TW_{18}	Figure H:6
$IV(t)$ without $IV_C(t)$ influence against $IV(t)$ with $IV_C(t)$ influence for TW_{18}	Figure H:7

Specific time (T) was chosen in TW_{11} as 22:00:00 UTC on 14 May 2015, which was equivalent to $t = 43{,}200$ (43,200 seconds after ST_{Start} =10:00:00 UTC). A buffer was provided that captured ∓ 30 minutes on either side of the specific time, and the buffer range was set as TW_{11}. Code was developed in Python to first assess if the alternative's $IV(t = T)$ met or exceeded its $ITV(t = T)$ at the specific time, and to secondly assess if the alternative's $IV(LBuffer \leq t \leq UBuffer)$ met or exceeded its $ITV(LBuffer \leq t \leq UBuffer)$ during the specific time with buffer (Figure F:3). As shown in Figure H:1, instantaneous value for a specific time was not achieved ($IB_{IV}(t = T) = 0$), but instantaneous value for a specific time with buffer was achieved ($IB_{IV}(LBuffer \leq t \leq UBuffer) = 1$). The percentage comparison calculations equaled 0.00% without a buffer and 1.81% with a buffer (see Table I:3).

Conditional time was the most complex assessment to capture, as it involved multiple value measures, multiple time references, and performance adjustments based on conditional influence. It is recommended to follow the conditional figures in Appendix H as explanation is provided for the alternative's calculation of instantaneous conditional value.

A time window was first established (TW_{18}) to cover the time range where $IV_C(t)$ was desired. The mandatory value measures ($i(m) = NIIRS_{ID}, \%Cov_{ID}, \text{and } SRT$) were chosen with the intention of identifying the target, which set the precedence for calculating $IV_C(t)$. The last epoch time when all mandatory value measures were meeting or exceeding their respective $ITV_i(t)$ in TW_{18} can be seen below as an extension of (19) in Chapter 3 to show how using a constraint vector helped define when $t = LT$.

$$CV(t=72{,}035)=\begin{bmatrix} IC_1(t)\\ IC_2(t)\\ IC_3(t)\\ IC_4(t)\\ IC_5(t)\end{bmatrix}=\begin{bmatrix} IC_{NIIRS_{ID}}(t=72{,}035)\\ IC_{NIIRS_D}(t=72{,}035)\\ IC_{\%Cov_{ID}}(t=72{,}035)\\ IC_{\%Cov_D}(t=72{,}05)\\ IC_{SRT}(t=72{,}035)\end{bmatrix}=\begin{bmatrix}\mathbf{1}\\ 1\\ \mathbf{1}\\ 1\\ \mathbf{1}\end{bmatrix}$$

$$CV(t=72{,}036)=\begin{bmatrix} IC_1(t)\\ IC_2(t)\\ IC_3(t)\\ IC_4(t)\\ IC_5(t)\end{bmatrix}=\begin{bmatrix} IC_{NIIRS_{ID}}(t=72{,}036)\\ IC_{NIIRS_D}(t=72{,}036)\\ IC_{\%Cov_{ID}}(t=72{,}036)\\ IC_{\%Cov_D}(t=72{,}036)\\ IC_{SRT}(t=72{,}036)\end{bmatrix}=\begin{bmatrix}\mathbf{1}\\ 1\\ \mathbf{0}\\ 1\\ \mathbf{1}\end{bmatrix}$$

As captured above, when $t = 72{,}035$ all mandatory value measures' $IV_i(t)$ were outperforming their respective $ITV_i(t)$. One time step later, when $t = 72{,}036$, $\%Cov_{ID}$ was no longer performing up to expectations and therefore all mandatory value measures were not outperforming their respective $ITV_i(t)$. The last time that target identification was absolutely achieved $(fm(LT) = 1)$ was therefore determined as 6:00:35 on 15 May 2015 $(t = 72{,}035)$, which can be seen in Figure H:2.

The required value measure $\big(i(r)\big)$ chosen upon which to assign conditional value was percent coverage detection $(i(r) = \%Cov_D)$, meaning that whenever $\%Cov_D$ was operating up to standard any time after LT $\big(IB_{\%Cov_D}(t) = 1\big)$, a conditional influence would be placed on the conditional value measure $\big(i(c\ )\big)$ (see Figure H:3). The $i(c\ )$ was determined to be $NIIRS_{ID}$ because the collection of $\%Cov_D$ was determined to be just as advantageous as $NIIRS_{ID}$ due to the previous target identification during LT. Since $NIIRS_{ID}$ performance was zero $\big(IB_{NIIRS_{ID}}(t) = 0\big)$ during the same epoch times that $IB_{\%Cov_D}(t) = 1$, the conditional influence turned $v_{NIIRS_{ID},t}\big(NIIRS(t)\big)$ into $v_{NIIRS_{ID},t}\left(TL_{NIIRS_{ID}}(t)\right)$ (see Figure H:4), thus making $IV_{NIIRS_{ID}}(t) = ITV_{NIIRS_{ID}}(t)$ (see

Figure H:5 and Figure H:6). The conditional influence of $\%Cov_D$ on $NIIRS_{ID}$ produced a greater overall $IV_C(t)$ for those epoch times that met (23)'s requirements. The percentage comparison calculation can be seen in Table I:4, which shows a 2.32% increase in $IV(t)$ when conditional influence was used for the alternative analysis (see Figure H:7).

4.9 Value Feedback

The results from Table I:1 and Table I:2, along with their associated Appendix G graphs, formed the supporting analysis for value feedback and overall alternative value assessment that would have been used in comparison against another alternative. While only a single alternative was analyzed, it is easy to see how automatic production of Python-generated percentage comparisons could be used to assess the performance of alternatives or provide quick and easy value feedback. The following example shows how value feedback provided timing adjustments to the modeled architecture alternative.

The time period of interest from 11:00:00 to 11:45:00 (TW_4) was identified in step three due to desired awareness surrounding the performance of multiple UAVs, or Aircraft, operating along the same flight path. The alternative's departure time of the Aircraft 2 was 10:19:48 UTC (19 min, 48 seconds after Aircraft 1), just as represented in Figure E:1's systems architecture. Aircraft 2 happened to cover the GV1 target at the same time that a satellite was overhead, which contributed to a higher instantaneous value around 11:11:45 UTC ($IV(t = 4{,}305) = 0.96$) instead of lower $IV(t)$ during a lengthier time period. The dual-contribution of space and air platforms around 11:11:45 UTC on 14 May 2015 was captured in STK and can be seen in Figure 34 and Figure 35.

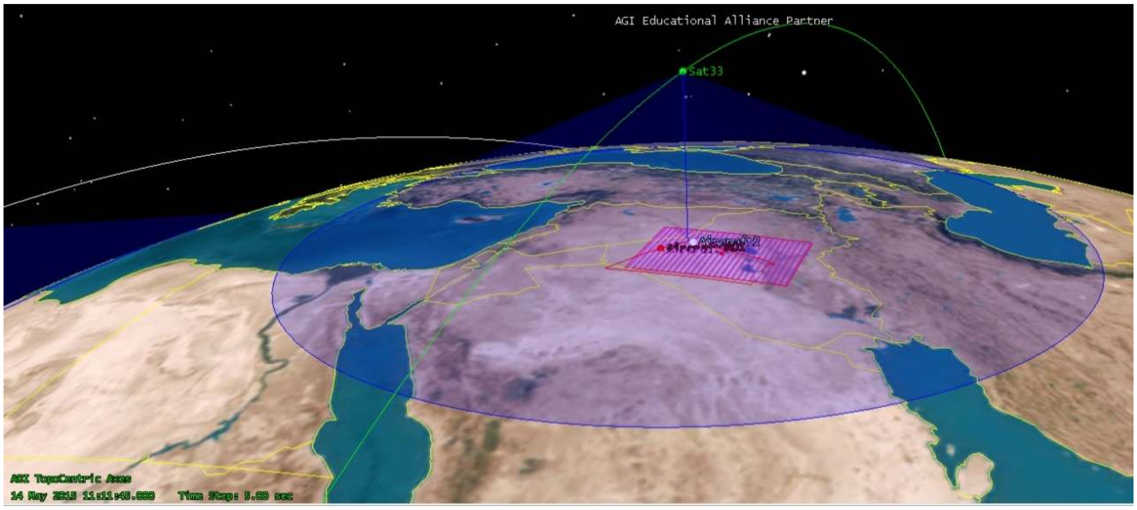


Figure 34 - Satellite Over Target at 11:11:45 UTC

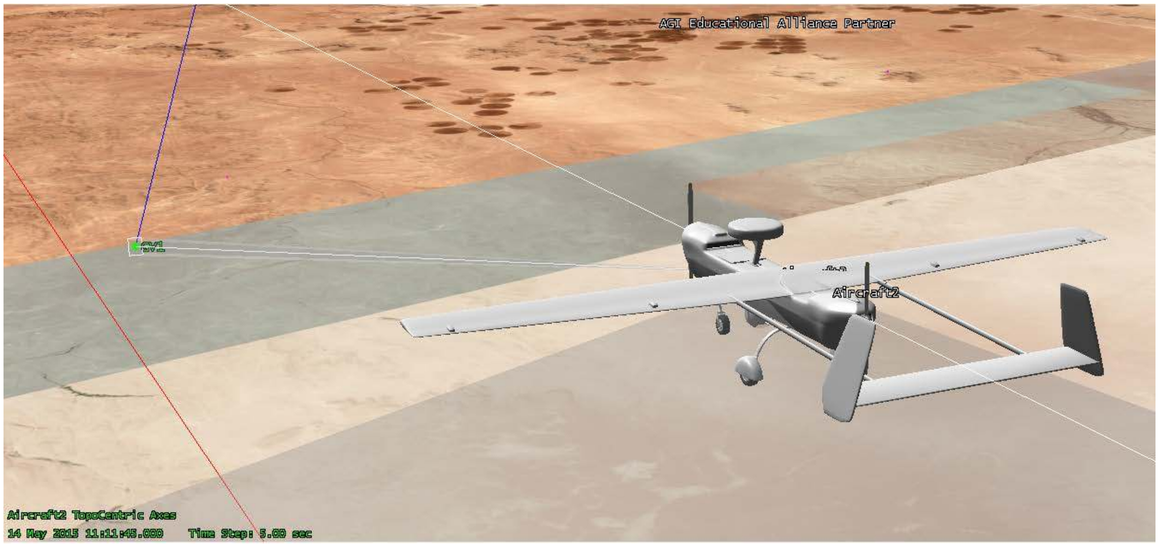


Figure 35 – Aircraft 2 Within Target Range at 11:11:45 UTC

ISR collection of the GV1 target was indicated by the blue access line from Sat 33 to GV1 in Figure 34 and by the white pointing sensor line from Aircraft 2 to GV1 in Figure 35. The normal alternative's percentage comparisons for TW_4 can be seen in Table I:1 and Table I:2.

The dual operation of the satellite and Aircraft 2 was provided as value feedback to the alternative under consideration, which resulted in delaying Aircraft 2's departure to the point where it was no longer collecting on GV1 at the same time as the satellite. The modeled departure time of Aircraft 2 was changed to 10:28:48 UTC on 14 May 2015 and the simulation was re-run. The STK simulation showed the GV1 target now out of range of the second UAV at 11:11:45 UTC on 14 May 2015, as seen by Figure 36's lack of pointing sensor line from the UAV to GV1 at that epoch time.

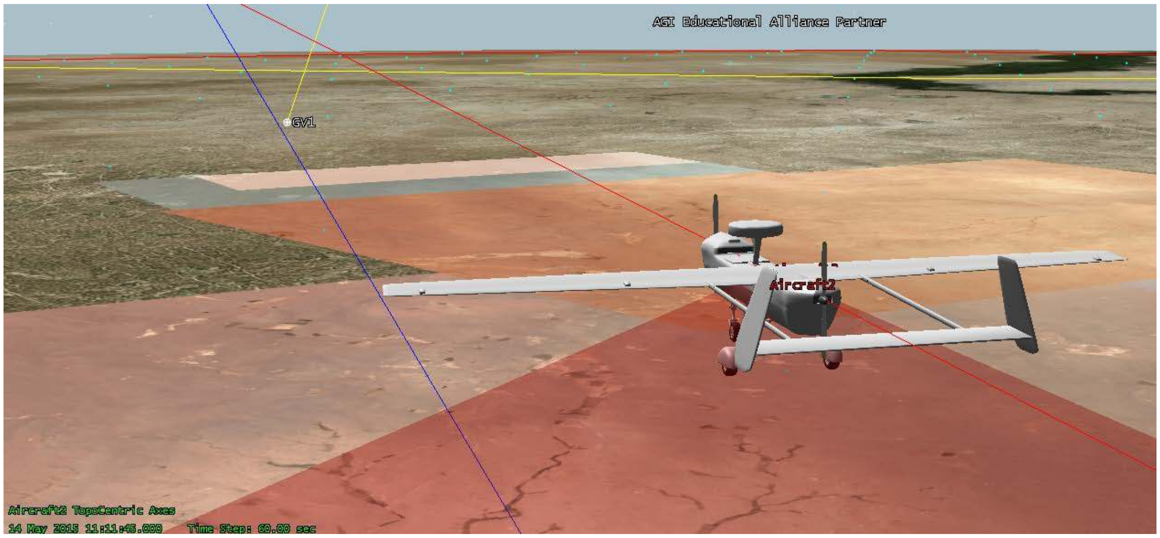


Figure 36 – Aircraft 2 Out of Target Range at 11:11:45 UTC

The timing adjustment that resulted from value feedback was as simple as changing Aircraft 2's departure time from 0.33 hours to 0.48 hours for its respective variable in the Python code in Figure F:3. Driving a new STK simulation from Python to account for Aircraft 2's adjusted departure time produced differences in corresponding TW_4 percentage comparisons, which can be seen in Table 17 and Table 18.

Table 17 - Delayed Aircraft 2 Value Measure Percentage Comparisons

Value Measure	$IV_{NIIRS_{ID}}(t)$	$IV_{NIIRS_{D}}(t)$	$IV_{\%Cov_{ID}}(t)$	$IV_{\%Cov_{D}}(t)$	$IV_{SRT}(t)$
Time Window	(24)1 (24)2	(24)1 (24)2	(24)1 (24)2	(24)1 (24)2	(24)1 (24)2
TW_4 UAV#2 Further Delayed	50.91% 24.33%	1,028.52% 55.11%	60.32% 26.96 %	47.64% 24.30%	130.77% 100.00%

Table 18 - Delayed Aircraft 2 Percentage Comparisons

Time Window	(24)3 (24)4 (24)5	(24)6 (24)7	(24)8	(24)9 (24)10 (24)11	(24)12 (24)13
TW_4 UAV#2 Further Delayed	79.61% 48.16% 13.56%	122.31% 74.00%	46.14%	1.07% 0.52% 0.70%	5.19% 0.00%

All green-colored text of Table 17 and Table 18 showed improved percentage performance for Aircraft 2's further delayed departure. All red text indicated a worse percentage than the original architecture during TW_4. The largest impact felt by further delay of the second aircraft was TW_4's PM_{IV} seen corresponding to (24)7 of Table 18. The initial architecture had a peak maximum percentage of 97.00% (see (24)7 of Table I:2). The further delayed Aircraft 2 produced a peak maximum percentage of only 74.00% due to lack of satellite and UAV contributions at the same time. While the decline was great in (24)7, peak maximum percentage is not the sole alternative assessment variable, as it only indicates the most value at a single point in time and not over an extended time period. The further delayed Aircraft 2 contributed to a higher

$\sum IV(t)$ and $\sum IB_{IV}(t)$ in TW_4 from the increased percentages seen in (24)3 and (24)4 of Table 18, which proved that Aircraft 2's delay led to more summed instantaneous value but a smaller percentage of time (13.56%) that it was operating above threshold. This example shows how providing value feedback for a specific alternative could lead to M&S adjustments that might improve or degrade the architecture analyzed, and could ultimately lead to an optimized alternative if enough iterations and value feedback were provided.

Sub-step 6.3's recommended sensitivity analysis was not performed due to the lack of there being other alternatives for comparison. The Python code was created for easy adjustment of time-dependent weights, so sensitivity analysis and automatic percentage comparisons could be performed easily if other alternatives existed against which to compare performance and rankings.

4.10 Step 7 – Provide Recommendations

Ranking alternatives was not performed due to only one alternative being used with the pre-acquisition methodology. As discussed in Chapter 3, recommendations other than just alternative rankings could be provided to enhance pre-acquisition assessment. Table 19's analysis-based recommendations would be provided to stakeholders supporting the assessed alternative resulting from the ISR mission.

Table 19 - Recommendations Provided Based on the Alternative's Assessments

Analysis Recommendations
The specific time with buffer range was supported by the alternative during TW_{11}
The conditional requirements were met and conditional influence was provided to increase instantaneous value of the alternative during TW_{18}
A capability gap existed between 0:00 on 15 May to 5:00 on 15 May (see Table I:1 and Table I:2)
Review of weighting or expected threshold levels should be performed (Phase 2's UAV drove $IV_{NIIRS_{ID}}(t)$ to 242.68% of $ITV_{NIIRS_{ID}}(t)$ due to the high $w_{NIIRS_{ID}}(t)$. However, $IV_{NIIRS_{ID}}(t)$ only outperformed $ITV_{NIIRS_{ID}}(t)$ 15.54% of TW_5's total 1 hour, 59 minute, 59 second time range)
The further delayed alternative platforms contributed to a greater $IV(t)$ during TW_4 than a UAV and satellite overhead at the same time. Further analysis should be done on separating the timing of platform performance over the target.
The alternative had no $NIIRS_{ID}$ or $NIIRS_D$ capability during seven of the eight Phase 3 time windows
$IV_i(t)$ was not obtained by the alternative for any of the four simulated value measures during the last three time windows in Phase 3

4.11 Analysis and Results Summary

The pre-acquisition methodology described in Chapter 3 was put into practice by supporting an exemplar ISR mission during Chapter 4. All methodology steps were shown as a multi-domain alternative's performance was assessed in support of the hypothetical ISR mission. Each form of instantaneous value and instantaneous Boolean score was calculated to influence initially generated time-dependent simulation data. Percentage comparisons and corresponding graphs were used as analysis tools to capture the time-variant performance of the single alternative under review. Lastly, a value feedback example and time-based recommendations were provided that resulted from the single alternative's assessment.

5. Conclusions and Recommendations

5.1 Chapter Overview

The AoA and MS A have many purposes, one of which is to down-select top architecture alternatives and identify those with the best value. A pre-acquisition methodology that initiates value analysis of different alternatives could help provide time-variant performance assessments to be carried into MS A for continued use. Chapter 5 discusses the conclusions of research behind incorporating time-variance into a VFT-based pre-acquisition methodology. The research significance is also expressed, as realized during the methodology's implementation with the ISR mission from Chapter 4. Additionally, Chapter 5 provides recommendations for action particular to the exemplar implementation, recommendations for future research, and a summary of research.

5.2 Conclusions of Research

The pre-acquisition methodology was created as a combination of multi-criteria decision analysis and VFT processes traditionally seen in the operational science field. It additionally relied on physics-based M&S tools to generate realistic performance calculations for air- and space-based systems. The methodology also included representation of an architecture alternative using executable systems architecture as traditionally performed in the systems engineering field (Ford et al., 2015). A holistic integration of those fields' best practices combined to provide the overarching steps and sub-steps of the pre-acquisition methodology. Analysis equations supporting the methodology were displayed in Chapter 3 to provide different assessment tools for comparing alternatives. The pre-acquisition methodology was successfully implemented with an exemplar ISR mission and was able to perform time-variant analysis of the represented alternative.

5.3 Significance of Research

The pre-acquisition methodology was unique in that it performed value-focused, multi-criteria decision assessment on every epoch time's output simulation data, which was modeled from an executable systems architecture representing a specific operational concept. While many VFT methods use M&S tools to produce simulation data for inclusion towards an alternative's assessment (several were discussed in Chapter 2), performing analysis on all time-dependent simulation data is exclusive to this process. Doing so provided the opportunity to sum different types of performance over particular time windows for an overall breakdown of the results of different operational time periods.

Time-dependent analysis contributions resulting from the pre-acquisition methodology were the numerous forms of instantaneous value and instantaneous Boolean score equations that were identified in Chapter 3 and exemplified in Chapter 4. A focus on value measure-specific, time-variant performance is one area that the pre-acquisition methodology stressed that most VFT practices disregard. Concentrating on each value measure's performance provided assessment details for early inclusion of the acquisition process and identification of those areas lacking in their contributing value to the overall system value.

5.4 Recommendations for Action

The methodology initially focused on pre-AoA timeframe implementation, but after execution using Chapter 4's ISR mission exemplar, it was soon realized that the methodology included many actions typically performed as part of the actual AoA and beyond. While the methodology may not perform all senior leader AoA expectations, Table 20 shows those Table 1 applicable sections that the pre-acquisition methodology anticipates capturing using underlined text.

Table 20 - AoA Expectations Applicable to the Pre-Acquisition Methodology

(Office of Aerospace Studies, 2013)

Senior Leaders And Decision Makers' Expectations Of An AoA
Unbiased inquiry into the costs and capabilities of options (identify the strengths and weaknesses of all options analyzed)
Identification of key trades among cost, schedule, and performance using the capability requirements (e.g., ICD and CDD gaps) as reference points
Identification of potential KPP/KSAs and an assessment of the consequence of not meeting them
Explanation of how key assumptions drive results, focused on the rationale for the assumption
Explanation of why alternatives do or do not meet requirements and close capability gaps
Identification of the best value alternatives based on results of sensitivity analysis
Increased emphasis on affordability assessments (conditions and assumptions under which a program may or may not be affordable)
Increased emphasis on legacy upgrades and non-developmental solutions versus new starts • Explore how to better use existing capabilities • Explore lower cost alternatives that sufficiently mitigate capability gaps but may not provide full capability
Increased emphasis on expanding cost analysis to focus beyond investment, for example, O&S across the force beyond the alternatives being analyzed
Explore the impact of a range of legacy and future force mixes on the alternatives
Increased emphasis on exploring an operationally realistic range of scenarios to determine impact on performance capabilities and affordability

Many of those lacking AoA expectations (non-underlined text) dealt with cost or schedule analysis, which the pre-acquisition methodology did not attempt to capture. A recommended action resulting from the realization that the methodology could be equally attributed to the AoA and beyond is that cost analysis elements should be applied to alternatives under consideration.

5.5 Recommendations for Future Research

The most logical continuation of the pre-acquisition methodology is its application to a realistic military operation in which the performance of several architecture alternatives can be assessed against one other. Chapter 4 involved using the pre-acquisition methodology with a single alternative supporting a generic ISR mission. The follow-on step to Chapter 4 is the more detailed analysis of several architectures attempting a time-dependent mission, ranking of those alternatives based on their percentage comparison calculations, and the application of sensitivity analysis to see if changing swing weights impacts alternatives' rankings or comparisons against one another.

The pre-acquisition methodology's success would be more accurately judged if alternatives' time-dependent performance could be optimized with value feedback. The problem with optimization in supporting several modeled architectures is the sheer number of simulations required, along with their data, time, and supporting resources to perform such analyses. Incorporating the use of supercomputers to optimize each architecture alternative's time-variant performance would allow several iterations to be performed in minutes instead of hours or days. Lt Col Tom Ford and Mr. Dave Meyer at AFIT have recently proven the capability of running several different STK windows on Wright-Patterson Air Force Base supercomputers. Creating small adjustments in Python code and STK simulation windows, loading them on a supercomputer, and collecting the resulting percentage comparisons could lead to an optimized architecture alternative for each concept within a reasonable amount of time.

As alternative options increase, an automated analysis process will be needed to evaluate percentage comparisons among alternatives. Chapter 4 showed a visual evaluation between the resulting percentage comparisons for the original alternative and the slightly delayed second UAV option. Visual comparison of many alternatives' percentage calculations would not be efficient or accurate enough to support the methodology. Instead, an automated process would be needed to assess differences between several alternatives and point out which alternative performs best in certain areas.

An example from Chapter 4's implemented alternative showed the next recommendation of future research. Phase 3's recovery period consisted of a new time window every 75 minutes to represent eight evenly-spaced threshold level adjustments over the 10-hour time period (see Figure D:5). While these time windows accurately showed steady increases in $ITV(t)$ during the recovery phase, they were not chosen based on any other detail except for even distribution during Phase 3. It would instead be beneficial to match operational influence with threshold level adjustments to capture different expectations over differing time windows. For example, matching changing time windows to satellites' orbital periods might indicate expected performance adjustments based on each satellite's potential pass. Setting time windows to alternatives' operational characteristics might lead to more accurate expected performance changes.

Specific to (15) listed in Chapter 3 and applied in Chapter 4, $PM_{IV}(t)$ accounted for the relative maximum instantaneous value for any epoch time contained in a particular time window. While calculating $PM_{IV}(t)$ was a useful assessment tool, calculating the average $IV(t)$ or minimum (worst case) $IV(t)$ in a time window would provide additional details on architecture performance. Future implementation of an average or minimum calculation similar to $PM_{IV}(t)$ would allow for two additional means of analysis between architectures, and could easily be included in time window calculations by adjusting Python calculation code.

An identified area of concern with applying the pre-acquisition methodology is its reliance on a set operational environment with known time windows, degradation periods, and operational phases. The methodology's intended use during pre-MS A causes a concern for unknown timing of events. The methodology would instead be more applicable if it incorporated stochastic operational states to account for probabilistic occurrences. Future application of a stochastic nature would allow for multiple iterations of a simulation to gather architecture assessment details over several different timed scenarios. Incorporating dynamic operational states might force reliance on different M&S tools, as some programs, such as STK, struggle with incorporating stochastic application to scenarios.

The final future research recommendation surrounds the idea that each alternative could reach a decision point to either continue with a mission or scratch the mission based on value obtained up to that point. Research would be needed to dictate at what point the go/no-go decision would be made for an operation, to include detailed support for which calculation would be of most use for that decision. As discovered in this research, time-dependent performance of an alternative can vary depending on when implementation is required. A go/no-go decision point would need to take into account whether the required levels of success could be met by each alternative based on performance up to that decision point.

5.6 Conclusions and Recommendations Summary

This chapter provided research conclusions and significance surrounding the developed pre-acquisition methodology, which included the influence of time-variant, value-focused assessment of an alternative. Recommendations for action were provided stressing the implementation of the pre-acquisition methodology in support of pre-acquisition activities of a real project. Finally, several future research recommendations were provided upon which to grow this initial research on a time-variant value focused pre-acquisition methodology for architecture alternative assessment.

Appendices

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Appendix A: Percent Comparison Equation Table

Table A:1 - Equation (24) Percentage Comparison Chart

Percentage Comparison Definition	Numerator	Denominator	Sub-Eq. #
Percentage of the ith value measure's summed instantaneous value against the ith value measure's summed instantaneous threshold value	$\sum_{t=t_{Start}}^{t=t_{End}} IV_i\,(t)$	$\sum_{t=t_{Start}}^{t=t_{End}} ITV_i\,(t)$	**1**
Percentage of time the ith value measure's Boolean score is one	$\sum_{t=t_{Start}}^{t=t_{End}} IB_i(t)$	$(t_{End} - t_{Start})$	**2**
Percentage of summed instantaneous value against summed instantaneous threshold value	$\sum_{t=t_{Start}}^{t=t_{End}} IV(t)$	$\sum_{t=t_{Start}}^{t=t_{End}} ITV(t)$	**3**
Percentage of summed instantaneous value against summed instantaneous possible value	$\sum_{t=t_{Start}}^{t=t_{End}} IV(t)$	$(t_{End} - t_{Start})$	**4**
Percentage of time instantaneous value Boolean score is one	$\sum_{t=t_{Start}}^{t=t_{End}} IB_{IV}(t)$	$(t_{End} - t_{Start})$	**5**
Percentage of instantaneous value peak maximum against instantaneous threshold value peak maximum	PM_{IV}	PM_{ITV}	**6**
Percentage of Instantaneous value peak maximum against maximum possible peak maximum	PM_{IV}	1	**7**
Percentage of Instantaneous Boolean scores against the total number of value measures possible	$\sum_{t=t_{Start}}^{t=t_{End}} IB_n(t)$	$n \cdot (t_{End} - t_{Start})$	**8**

Percentage Comparison Definition	Numerator	Denominator	Sub-Eq. #
Percentage of summed mandatory instantaneous value against summed instantaneous value	$\sum_{t=t_{Start}}^{t=t_{End}} IV_M(t)$	$\sum_{t=t_{Start}}^{t=t_{End}} IV(t)$	**9**
Percentage of summed mandatory instantaneous value against summed instantaneous possible value	$\sum_{t=t_{Start}}^{t=t_{End}} IV_M(t)$	$(t_{End} - t_{Start})$	**10**
Percentage of time the full mandate is one	$\sum_{t=t_{Start}}^{t=t_{End}} fm(t)$	$(t_{End} - t_{Start})$	**11**
Percentage of the summed full mandate occurrences against the summed instantaneous value Boolean scores	$\sum_{t=t_{Start}}^{t=t_{End}} fm(t)$	$\sum_{t=t_{Start}}^{t=t_{End}} B_{IV}(t)$	**12**
Percentage of time all n value measures are meeting or exceeding their respective value measure instantaneous threshold value	$\sum_{t=t_{Start}}^{t=t_{End}} fm_{i(m)=n}(t)$	$(t_{End} - t_{Start})$	**13**
* Percentage of summed instantaneous value for specific time without buffer when $t = T$ against summed possible value	$IV_{TB}(t = T)$	$(t_{End} - t_{Start})$	**14**
* Percentage of summed instantaneous value for specific time with buffer when $(T - LBuffer \leq t \leq T + UBuffer)$ against summed possible value	$\sum_{t=T-LBuffer}^{t=T+UBuffer} IV_{TB}(t)$	$(t_{End} - t_{Start})$	**15**
* Percentage of summed conditional instantaneous value against the summed instantaneous value	$\sum_{t=t_{Start}}^{t=t_{End}} IV_C(t)$	$\sum_{t=t_{Start}}^{t=t_{End}} IV(t)$	**16**

* Implies that the percent comparison calculation is only applied to applicable time windows containing the numerator or denominator of interest

Appendix B: Example Alternative Pre-Acquisition Methodology (Step 1)

Generic Abstraction of Policy and Strategic Guidance

Table B:1 - Example Abstraction of Policy and Strategic Guidance (Department of Defense, 2014, 2015b, 2015c)

U.S. Enduring National Interests (NSS 2015)	National Military Objectives (NMS 2015)	National Security Interests (QDR 2014)	Joint Force Prioritized Missions (QDR 2014 & NMS 2015)	Top-Level Capabilities (JCA)
National Security	Deter, Deny, and Defeat State Adversaries	Survival of the Nation	Maintain a secure and effective nuclear deterrent	Force Application
			Provide for military defense of the homeland	Force Support
			Counter weapons of mass destruction	Battlespace Awareness
	Disrupt, Degrade, and Defeat Violent Extremeist Organizations	Prevention of Catastophic Attack against U.S.	Defeat an Adversary	Protection
			Deny an adversary's objectives	
			Combat Terrorism	
Strong U.S. Economy	Resourcing the Strategy	Security of Global Economic System	Provide support to civil authorities	Corporate Management and Support
Respect for Universal Values	Advance Globally Integrated Operations	Preservation and Extension of Universal Values	Conduct humanitarian assistance and disaster response	Building Partnerships
			Respond to crisis and conduct limited contingency operations	Net-Centric
Rules-Based International Order to Meet Global Challenges	Strengthen Our Global Network of Allies and Partners	Security, confidence, and reliability of allies	Conduct military engagement and security cooperation	Logistics
			Provide a global, stabilizing presence	Command and Control
		Protection of American citizens abroad	Conduct stability and counterinsurgency operations	

* Note: Some abstracted levels could be matched into several higher-level categories

Table B:2 - Continued Abstraction to Ilities (Boehm, 2013)

UJTL

Strategic USAF & DoD Guidance

Top-Level Ilities (Boehm)	Effect on Operational System (Boehm)
Mission Effectiveness	Stakeholders-satisfactory balance of Speed, Delivery Capability, Endurability, Maneuverability, Accuracy, Usability, Scalability, and Versatility
Speed	Distance or work accomplished per unit of time
Physical Capability	Amount of needed platform range, payload weight, capacity, energy, etc. provided
Cyber Capability	Amount of needed bandwidth, memory capacity, execution cycles, etc. provided
Accuracy	Closeness of estimate to actual state
Impact	Ability to change system state
Endurability	Ability to withstand physical attacks or extreme environmental conditions
Maneuverability	Ability to rapidly and controllably change course
Usability	Ease of learning, ease of use, difficulty of misuse
Scalability	Sustainability of system capability across a range of system or environmental scales
Versatility	Range of functions provided
Resource Utilization	Ability to deliver other ilities within constraints on limited resources
Cost	Amount of funding to complete delivery
Duration	Amount of calendar time to complete delivery
Key Personnel	Amount of available personnel with needed skills
Other Scarce Resources	Amount of scarce resources needed to satisfy Mission Effectiveness
Manufacturability*	Amount of resources needed to produce desired quantities
Sustainability*	Amount of resources needed to sustain Mission Effectiveness across life cycle
Protection	Ability to protect stakeholders' personnel and assets
Security	Ability to protect stakeholders' personnel and assets vs. adversary threats
Safety	Ability to protect stakeholders' personnel and assets vs. environmental extremes
Robustness	Ability of the system to continue to deliver stakeholder-desired capabilities
Reliability	Probability that the system will continue to deliver stakeholder-desired capabilities
Availability	Fraction of the time that the system will deliver stakeholder-desired capabilities
Maintainability	Expected amount of time required to restore stakeholder-desired capabilities
Survivability	Ability of the system to continue to deliver partial stakeholder-desired capabilities
Flexibility	Ability of the system to be rapidly and cost-effectively changed
Modifiability	Flexibility via external reconfiguration
Tailorability	Flexibility via parameter setting, configuration directives, or services interfaces
Adaptability	Flexibility via internal reconfiguration
Composability	Ability of the system to be rapidly and cost-effectively composed with other systems
Interoperability	Composability via continuing negotiation and evolution of interfaces
Openness	Composability via open standards compliance
Service-Orientation	Composability via published-service interfaces and assumptions
Composite ilities	
Comprehensiveness	All of the above
Resilience	Protection, Robustness, Flexibility
Dependability	Mission Effectiveness, Protection, Robustness
Affordability	Mission Effectiveness, Resource Utilization

Purpose

1. Project Title: ISR Mission

2. Problem: The ISR mission involves collection against a designated target in which an adversary has the ability to jam or degrade an ISR sensor's performance. Differing performance emphasis is placed on the ISR mission depending on time-variant events and impacts on the ISR systems. An alternative is needed in response to intelligence showing anticipated location of the degradation system and its aftereffects on ISR capability. An alternative that meets time-dependent needs of the operation is required to perform the ISR mission. Top mission objectives include target identification and detection, AOI coverage, and the transfer of data in a timely manner.

3. Problem Statement: ISR is desired to support a 24-hour operational mission against potential emerging threats, to include electronic warfare (EW) jamming on platform's sensor(s) during collection timeframes. This degradation threatens to compromise US military leaders from maintaining strategic situational awareness and removes their capability to convey their intent to joint combatant commanders (AFDD 3-14, pg. 31-32).

4. Goal: The proposed alternative should optimize the ISR collection capability without the use of legacy space systems. The proposed alternative shall include means to identify and detect the target, perform surveillance over the entire AOI, and maintain the timeliness of global space data transfer.

5. Scope: This proposed alternative shall improve ISR capability by 2035. This scope was chosen based on the foreseen timeline of anticipated future threats identified in the Air Force Future Operating Concept (Department of Defense, 2015a).

6. Context: Governing documents for the use of this ISR mission include:
    - National Space Policy of the United States of America – June, 2010
    - National Security Space Strategy – January, 2011
    - Department of Defense Directive 3100.10 – October, 2012
    - Joint Publication 3-14, Space Operations – May, 2013
    - Air Force Doctrine Document 3-14, Space Operations – June, 2012
    - Air Force Instruction 10-1201, Space Operations
    - Joint Electromagnetic Spectrum Management Operations Joint Publication 6-01 (dated 20 March 2012)

    Potential organizations include: The Office of the Secretary of Defense (OSD), Air Force Space Command (AFSPC), Defense Intelligence Agency (DIA), National Geospatial-Intelligence Agency (NGA), National Security Agency (NSA), National Reconnaissance Office (NRO), Air Force Global Strike (AFGS), Air Combat

Command (ACC), Air Force Special Operations Command (AFSOC), Strategic Command (STRATCOM), United States Transportation Command (USTRANSCOM), Special Operations Command (SOCOM), and Naval Sea Systems Command (NAVSEA).

7. Critical Questions:
   a. What are current alternatives capable of addressing the need?
   b. What are possible current and potential future threats to ISR collection against the area of interest?
   c. What are the capability gaps?
   d. What technology is expected to be available during ISR mission threats?

8. Team Experience: Not applicable for this thesis.

(Ford, 2015b; Watson, Everson, & Scheller, 2015)

Appendix C: Example Alternative Pre-Acquisition Methodology (Step 2)

Concept

1. Concept Title: LEO Space Constellation and Multiple UAV Concept

2. Executive Summary: The following concept document details the primary implementation of a multi-domain architecture using both satellites and UAVs to gather ISR collection against anticipated threats. The concept document includes basic information pertaining to the potential operating environment, scope, and background information regarding the military need for a resilient ISR system.

3. Purpose: The alternative chosen is intended to enhance the legacy space architecture by identifying vulnerable areas and mitigating the impacts of an attack on ISR systems. The architecture shall include means to identify the source and type of threat while maintaining the reliability of global space ISR.

4. Background: Current ISR systems are not robust to emerging operational threats. Legacy satellite and UAV systems threaten to compromise US leaders from maintaining strategic situational awareness and removes their capability to convey their intent to joint combatant commanders (AFDD 3-14, pg. 31-32).

5. Future Environment: In order to maintain intelligence superiority, ISR systems must utilize operation around time-dependent events. A Middle East environment is anticipated, in which future ISR systems will need to identify threats, transmit information against degradation influence, and continue operations in a contested environment for a 24-hr time period.

6. Concept Time Frame/Scope: The alternative will needed to be complete by 2035.

7. Military Need Statement: In the 2010 National Space Policy, the president directed that the U.S. shall enhance the protection and resilience of space-enabled mission-essential functions to ensure continuity of services. The Secretary of Defense translates this directive in his National Security Space Strategy. The Chairman of the Joint Chiefs of Staff outlines five mission areas in Joint Publication 3-14 of which US military space operations are composed. Space Force Enhancement is one such mission area which increases joint force effectiveness and resiliency by providing ISR. Air Force Doctrine Document 3-14 and Air Force Instruction 10-1201 detail the required operational capabilities that the ISR system must support.

8. Central Idea: The ISR alternative will rely on sensors in both the benign and contested space/terrestrial environment to identify a target. Once a threat has been identified, the system will transmit information about the target back to US ground stations in a timely manner for the benefits of trusted intelligence communities.

Continued coverage will be performed against the AOI to ensure no other targets can degrade sensor collection capability.

9. Capabilities: The following is a list of the capabilities that the ISR system will need to support by the identified initial operational capabilities (IOC) date (Note this list is not exhaustive):
   - Detect/Identify Target
   - Perform Resilient Operations Against Threats (such as):
     - Directed energy attack
   - Collect against target during a specific time period of interest
   - Collect against target based on conditional objectives

10. Risks: To be developed at a later date.

11. Summary: The ISR mission alternative will provide global, reliable, and high quality information sharing capability to maintain strategic situational awareness for U.S. and allied nation military leaders (JP 3-14). The future space- and air-based systems alternative will rely on advanced optimization techniques in order to evade threats and their impact on ISR collection.

12. The following documents were used as references for the multi-domain concept described above:

    a. National Space Policy of the United States of America – June, 2010
    b. National Security Space Strategy – January, 2011
    c. Department of Defense Directive 3100.10 – October, 2012
    d. Joint Publication 3-14, Space Operations – May, 2013
    e. Air Force Doctrine Document 3-14, Space Operations – June, 2012
    f. Air Force Instruction 10-1201, Space Operations
    g. Joint Electromagnetic Spectrum Management Operations Joint Publication 6-01 (dated 20 March 2012)

(Ford, 2015b; Watson et al., 2015)

Appendix D: Example Alternative Pre-Acquisition Methodology (Step 3)

Table D:1 - ISR Mission's Time Window Specifications

Time Window	Time Range	Reason
TW_1	10:00:00 on 14 May, 2015 to 10:00:00 on 15 May, 2015 ($0 \leq t \leq 86{,}400$)	FST
TW_2	10:00:00 on 14 May, 2015 to 22:59:59 on 14 May, 2015 ($0 \leq t \leq 46{,}799$)	$NIIRS_D$ SAVF Original
TW_3	10:00:00 on 14 May, 2015 to 16:00:00 on 14 May, 2015 ($0 \leq t \leq 21{,}599$)	P_1
TW_4	11:00:00 on 14 May, 2015 to 11:45:00 on 14 May, 2015 ($3{,}600 \leq t \leq 6{,}300$)	Time Period of Interest
TW_5	16:00:00 on 14 May, 2015 to 17:59:59 on 14 May, 2015 ($21{,}600 \leq t \leq 28{,}799$)	P_2 & $w_i(t)$ Adjustment
TW_6	18:00:00 on 14 May, 2015 to 3:59:59 on 15 May, 2015 ($28{,}800 \leq t \leq 64{,}799$)	P_3 & $w_i(t)$ Adjustment
TW_7	18:00:00 on 14 May, 2015 to 19:14:59 on 14 May, 2015 ($28{,}800 \leq t \leq 33{,}299$)	$TL_i(t)$ Adjustment
TW_8	19:15:00 on 14 May, 2015 to 20:29:59 on 14 May, 2015 ($33{,}300 \leq t \leq 37{,}799$)	$TL_i(t)$ Adjustment
TW_9	20:30:00 on 14 May, 2015 to 21:44:59 on 14 May, 2015 ($38{,}800 \leq t \leq 42{,}299$)	$TL_i(t)$ Adjustment
TW_{10}	21:45:00 on 14 May, 2015 to 22:59:59 on 14 May, 2015 ($42{,}300 \leq t \leq 46{,}799$)	$TL_i(t)$ Adjustment
TW_{11}	22:00:00 on 14 May, 2015 to 23:00:00 on 14 May, 2015 ($43{,}200 \leq t \leq 46{,}800$)	Specific Time Buffer Range
TW_{12}	23:00:00 on 14 May, 2015 to 10:00:00 on 15 May, 2015 ($46{,}800 \leq t \leq 86{,}400$)	$NIIRS_D$ SAVF Adjustment
TW_{13}	23:00:00 on 14 May, 2015 to 0:14:59 on 15 May, 2015 ($46{,}800 \leq t \leq 51{,}299$)	$TL_i(t)$ Adjustment
TW_{14}	0:15:00 on 15 May, 2015 to 1:29:59 on 15 May, 2015 ($51{,}300 \leq t \leq 55{,}799$)	$TL_i(t)$ Adjustment
TW_{15}	1:30:00 on 15 May, 2015 to 2:44:59 on 15 May, 2015 ($55{,}800 \leq t \leq 60{,}299$)	$TL_i(t)$ Adjustment
TW_{16}	2:45:00 on 15 May, 2015 to 3:59:59 on 15 May, 2015 ($60{,}300 \leq t \leq 64{,}799$)	$TL_i(t)$ Adjustment
TW_{17}	4:00:00 on 15 May, 2015 to 10:00:00 on 15 May, 2015 ($64{,}800 \leq t \leq 86{,}400$)	P_4 & $w_i(t)$ Adjustment
TW_{18}	6:00:00 on 15 May, 2015 to 7:00:00 on 15 May, 2015 ($72{,}000 \leq t \leq 75{,}600$)	Conditional Period

Table D:2 - ISR Mission’s Threshold Levels

Value Measure Threshold Levels Across Time Windows					
Time Window	$TL_{NIIRS_{ID}}(t)$ (NIIRS)	$TL_{NIIRS_{D}}(t)$ (NIIRS)	$TL_{\%Cov_{ID}}(t)$ (%)	$TL_{\%Cov_{D}}(t)$ (%)	$TL_{SRT}(t)$ (minutes)
TW_1	N/A	N/A	N/A	N/A	30
TW_2	N/A	N/A	N/A	N/A	30
TW_3	8	3.5	8	52	30
TW_4	8	3.5	8	52	30
TW_5	5.2	2.4	2	47	30
TW_6	N/A	N/A	N/A	N/A	30
TW_7	5.4	2.3	4	47	30
TW_8	5.5	2.4	4	48	30
TW_9	5.7	2.5	4	48	30
TW_{10}	6.0	2.6	4	49	30
TW_{11}	6.0	2.6	4	49	30
TW_{12}	N/A	N/A	N/A	N/A	30
TW_{13}	6.3	2.7	4	49	30
TW_{14}	6.7	2.8	4	50	30
TW_{15}	7.0	2.9	4	50	30
TW_{16}	7.1	3.0	4	51	30
TW_{17}	7.1	3.0	4	51	30
TW_{18}	7.1	3.0	4	51	30

* N/A implies that multiple threshold levels are used across the particular time window. The multiple threshold levels not shown in the table are accounted for in the simulation.

Table D:3 - ISR Mission's Weights

Value Measure Weights Across Time Windows					
Time Window	$w_{NIIRS_{ID}}(t)$	$w_{NIIRS_D}(t)$	$w_{\%Cov_{ID}}(t)$	$w_{\%Cov_D}(t)$	$w_{SRT}(t)$
TW_1	N/A	N/A	N/A	N/A	N/A
TW_2	N/A	N/A	N/A	N/A	N/A
TW_3	0.20	0.20	0.20	0.20	0.20
TW_4	0.20	0.20	0.20	0.20	0.20
TW_5	0.60	0.10	0.10	0.10	0.10
TW_6	0.20	0.30	0.10	0.30	0.10
TW_7	0.20	0.30	0.10	0.30	0.10
TW_8	0.20	0.30	0.10	0.30	0.10
TW_9	0.20	0.30	0.10	0.30	0.10
TW_{10}	0.20	0.30	0.10	0.30	0.10
TW_{11}	0.20	0.30	0.10	0.30	0.10
TW_{12}	0.20	N/A	N/A	N/A	N/A
TW_{13}	0.20	0.30	0.10	0.30	0.10
TW_{14}	0.20	0.30	0.10	0.30	0.10
TW_{15}	0.20	0.30	0.10	0.30	0.10
TW_{16}	0.20	0.30	0.10	0.30	0.10
TW_{17}	0.20	0.20	0.20	0.20	0.20
TW_{18}	0.20	0.20	0.20	0.20	0.20

* N/A implies that multiple weights are used across the particular time window.

The multiple weights not shown in the table are accounted for in the simulation.

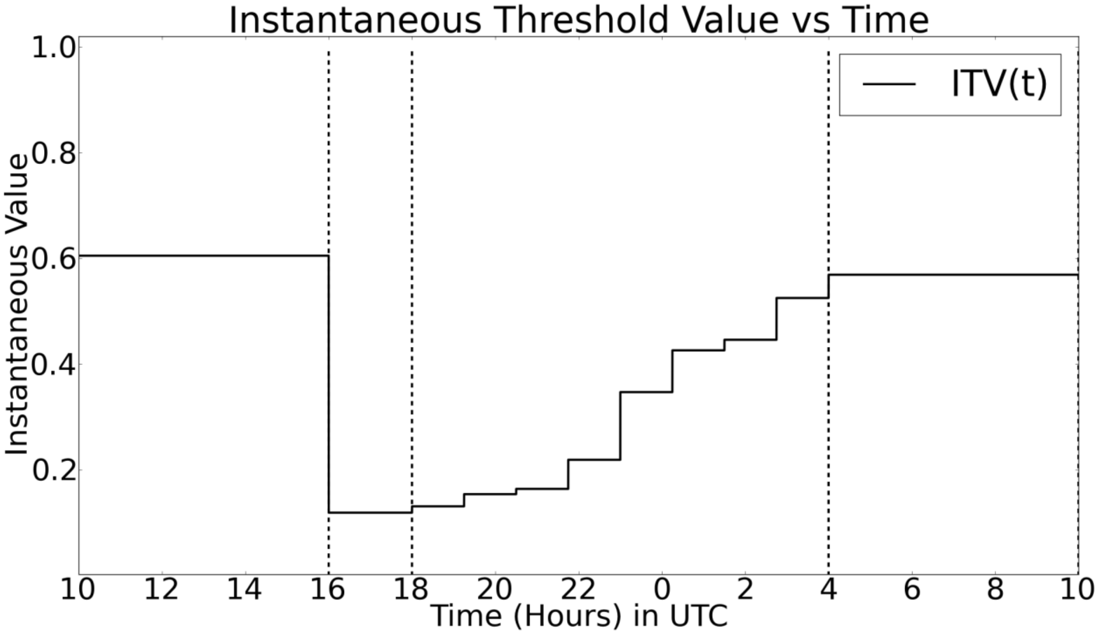

Figure D:1 - ISR Mission's Instantaneous Threshold Value vs Time

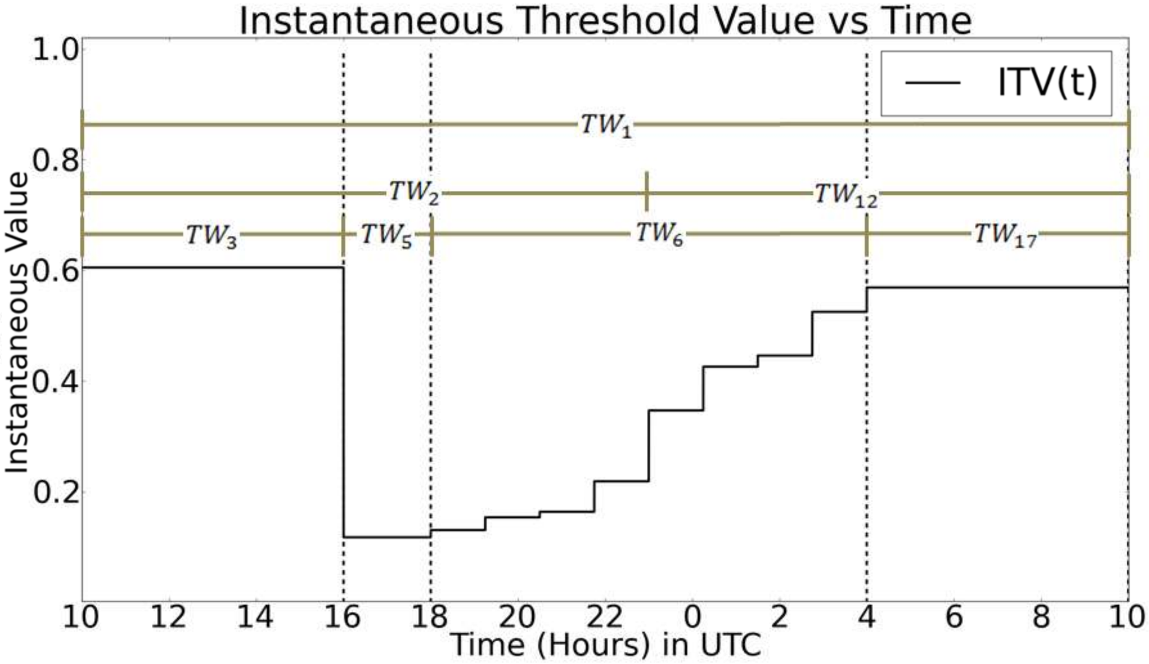

Figure D:2 - ISR Mission's Time Windows with ITV(t) (Full Simulation Time)

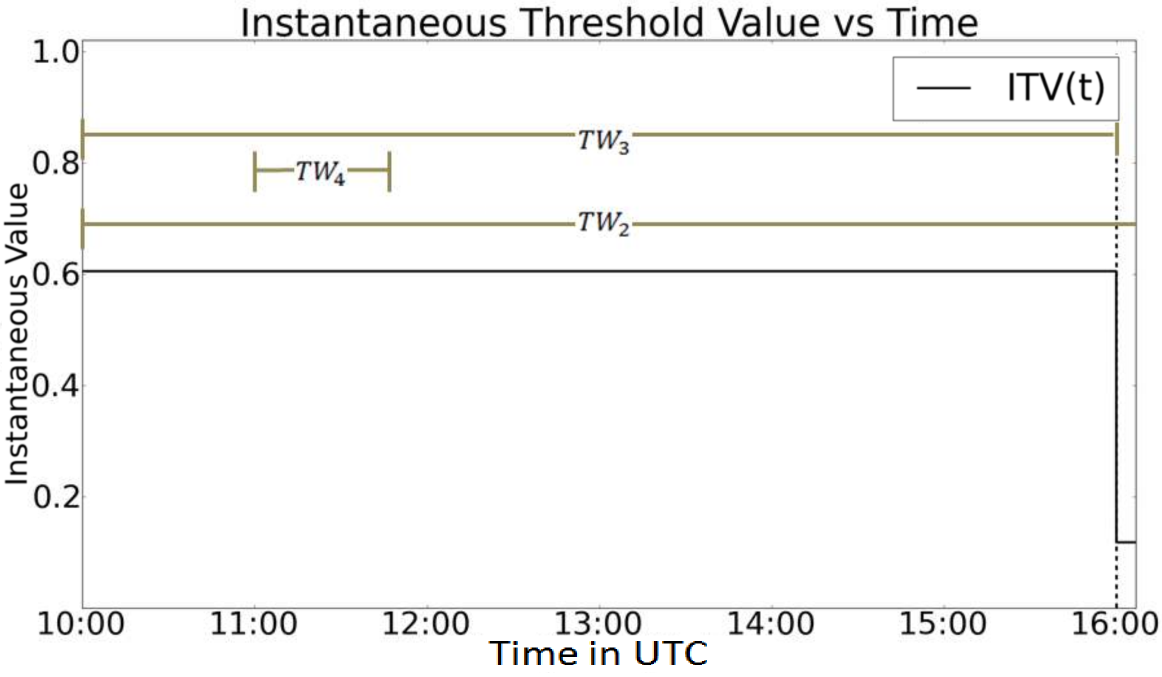

Figure D:3 - ISR Mission's Time Windows with ITV(t) (Phase 1)

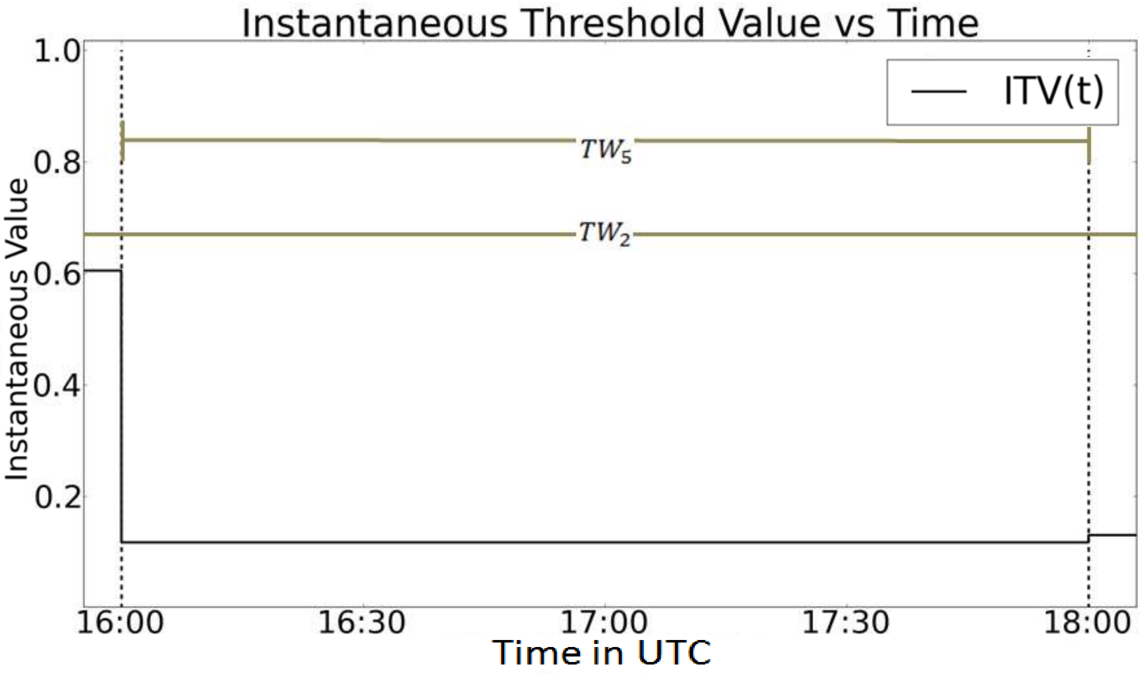

Figure D:4 - ISR Mission's Time Windows with ITV(t) (Phase 2)

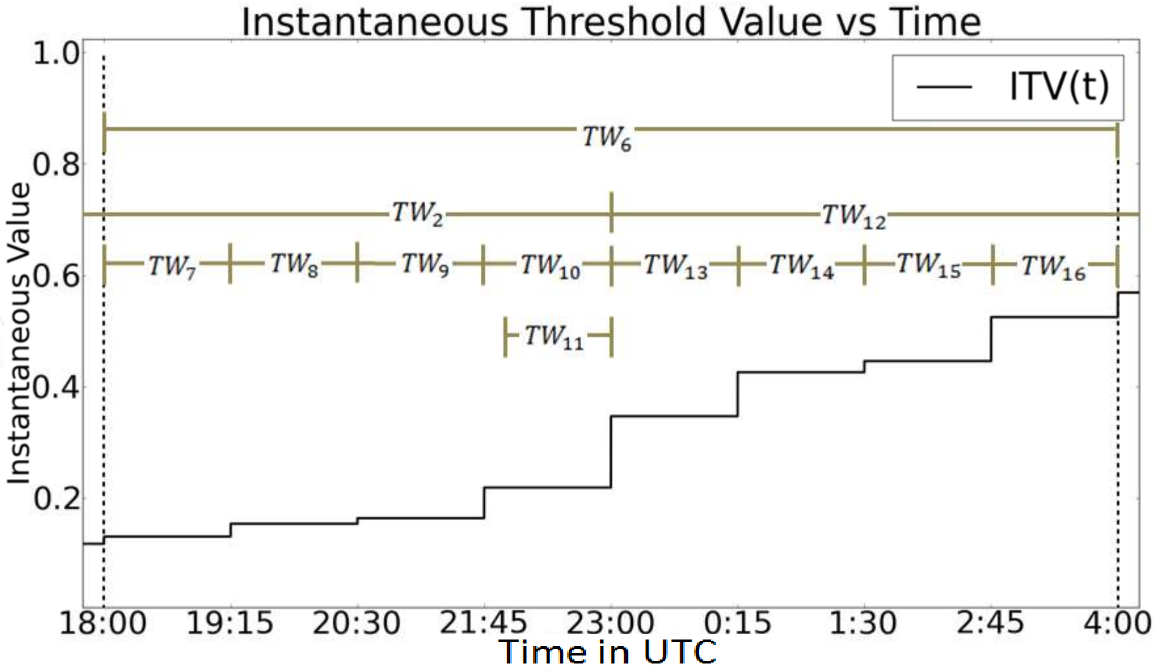

Figure D:5 - ISR Mission’s Time Windows with ITV(t) (Phase 3)

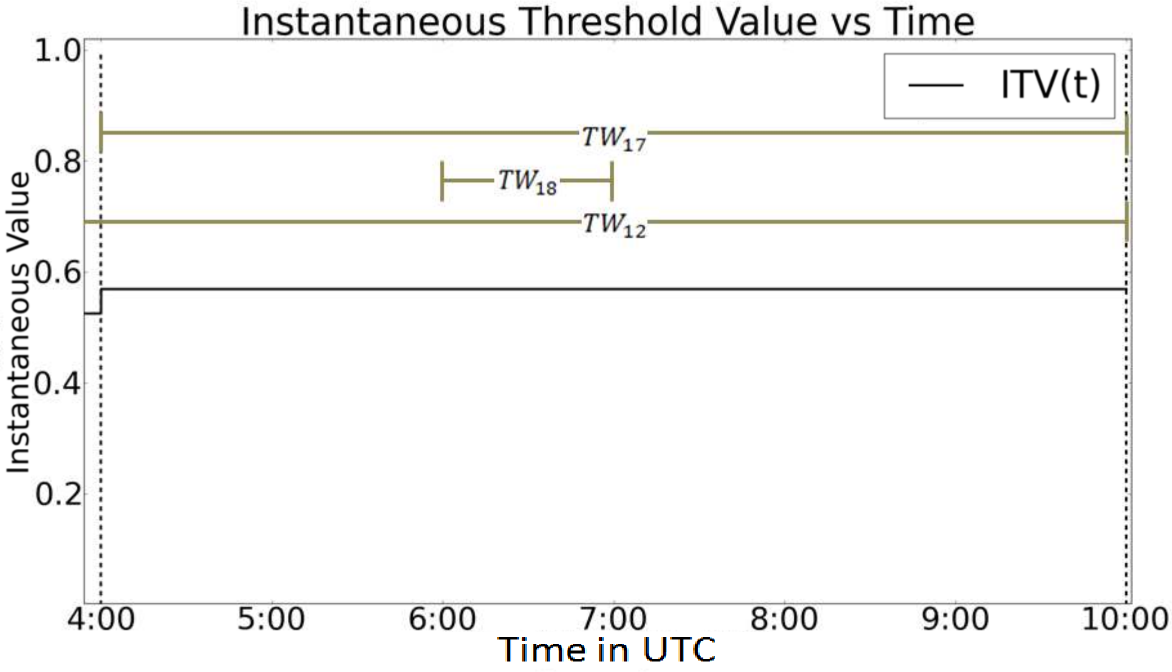

Figure D:6 - ISR Mission’s Time Windows with ITV(t) (Phase 4)

Appendix E: Example Alternative Pre-Acquisition Methodology (Step 4)

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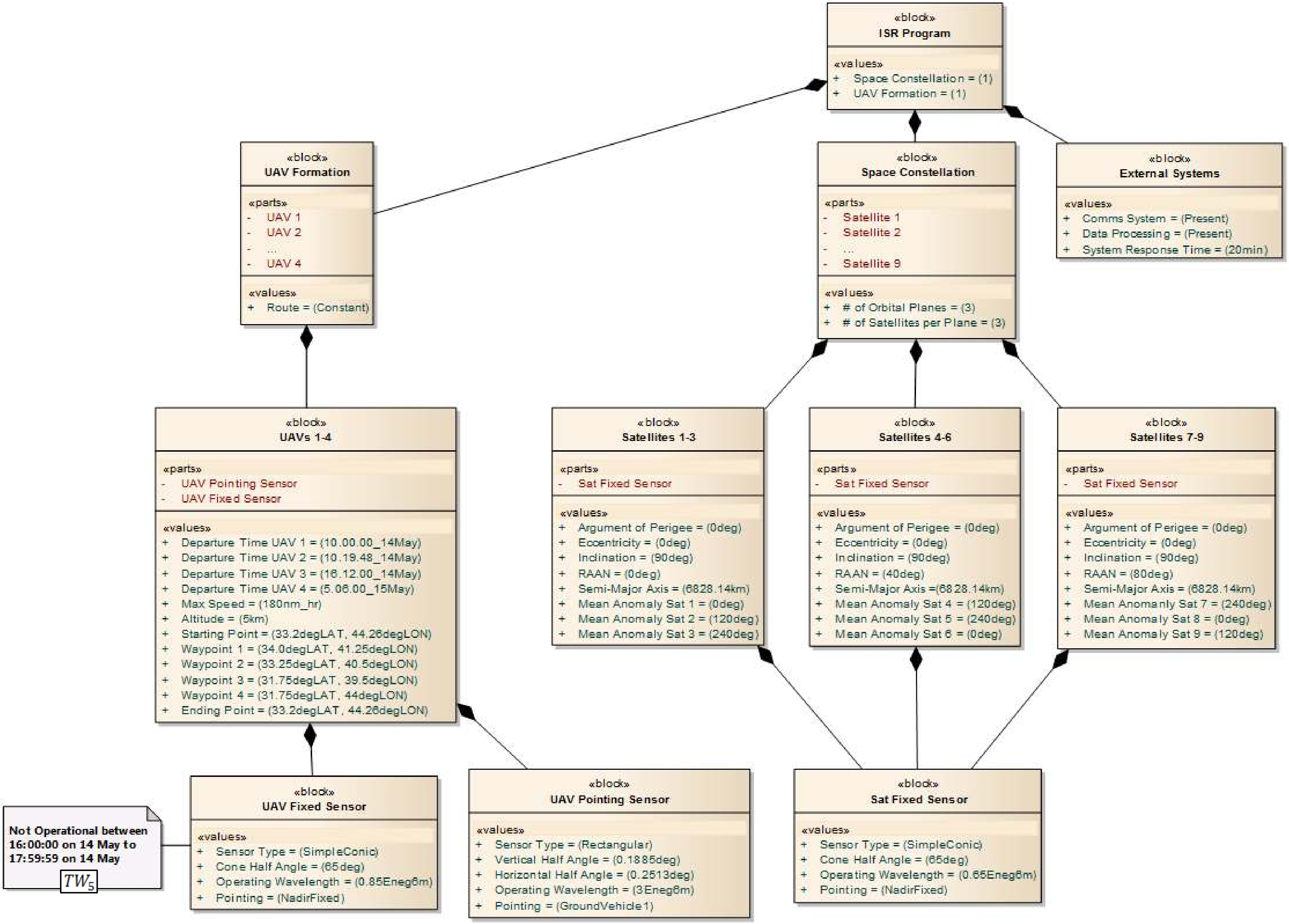


Figure E:1 - Alternative's Executable Systems Architecture (Ford et al., 2015)

Appendix F: Example Alternative Pre-Acquisition Methodology (Step 5)

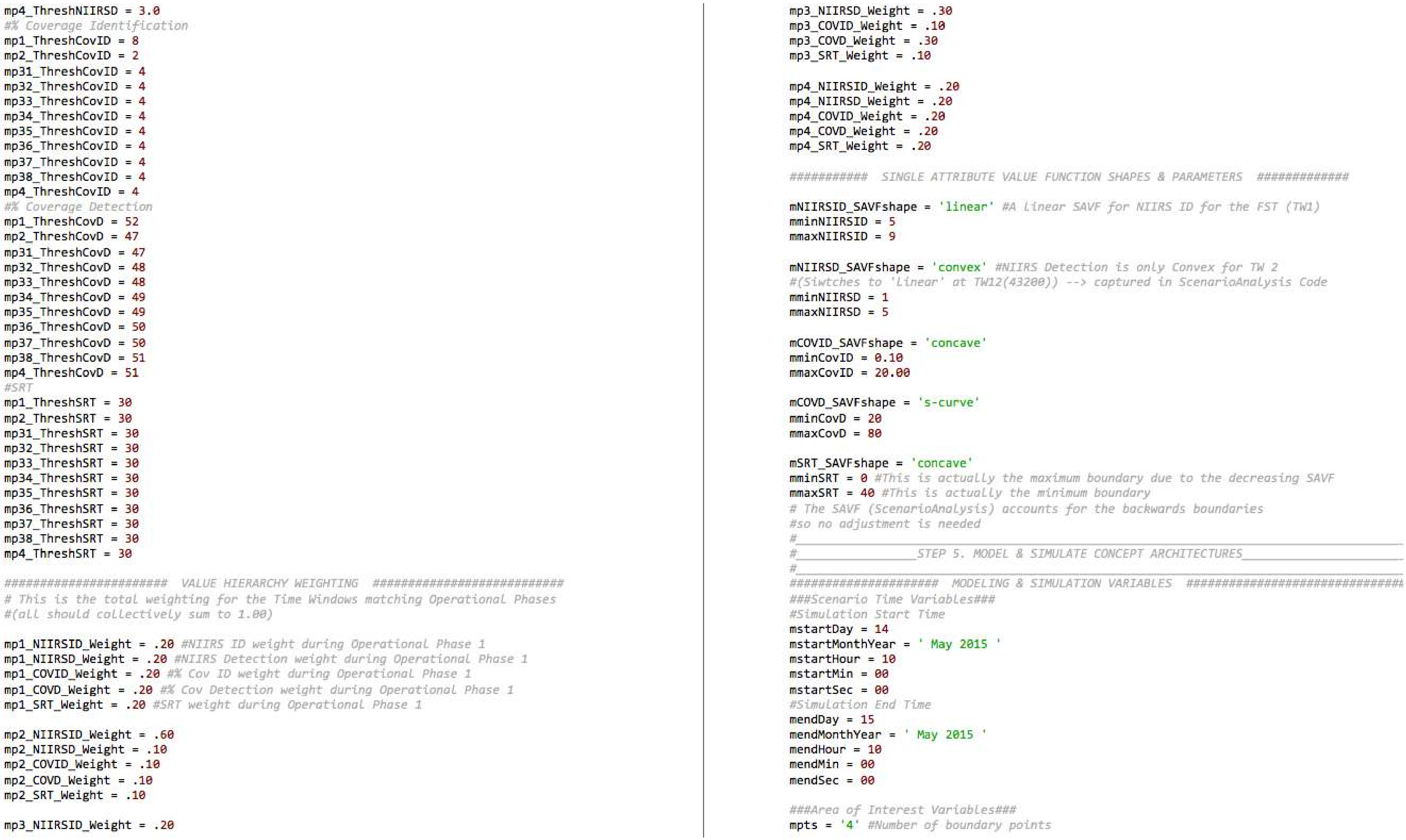
```
# -*- coding: utf-8 -*-
#Main_ArchitectureSpecs.py
"""
@author: Capt Brian Scheller
(Used platform detail code originally represented as part of SENG-699 course)
"""
### This file is intended at capturing M&S specifications decided by time
#window specifications (Step 3) &  the executable systems architecture (Step 4)
#______________________________________________________________________________________
#_____________________STEP 3. CREATE VALUE HIERARCHY______________________________
#______________________________________________________________________________________
##################  SEPARATION OF OPERATIONAL PHASES  #########################

mphase1_endHR = 6 #The number of hours after simulation start time that
#operational phase 1 should end
mphase2_endHR = 8 #The number of hours after simulation start time that
#operational phase 2 should end
mphase3_endHR = 18 #The number of hours after simulation start time that
#operational phase 3 should end
mphase4_endHR = 24 #The number of hours after simulation start time that
#operational phase 4 should end

mphase1_endSEC = mphase1_endHR * 3600.00 #Converts mphase1_endHR into seconds
#for simulation use
mphase2_endSEC = mphase2_endHR * 3600.00 #Converts mphase2_endHR into seconds
#for simulation use
mphase3_endSEC = mphase3_endHR * 3600.00 #Converts mphase3_endHR into seconds
#for simulation use
mphase4_endSEC = mphase4_endHR * 3600.00 #Converts mphase4_endHR into seconds
#for simulation use

###############  THRESHOLD LEVELS BY APPROPRIATE TIME WINDOWS  ################
#NIIRS Identification
mp1_ThreshNIIRSID = 8 #For Operational Phase 1 (TW3)
mp2_ThreshNIIRSID = 5.2 #For Operational Phase 2 (TW5)
mp31_ThreshNIIRSID = 5.4 #The 1st 1hr, 15 minutes of Operational Phase 2 (TW7)
mp32_ThreshNIIRSID = 5.5 #The 2nd 1hr, 15 minutes of Operational Phase 2 (TW8)
mp33_ThreshNIIRSID = 5.7 #The 3rd 1hr, 15 minutes of Operational Phase 2 (TW9)
mp34_ThreshNIIRSID = 6.0 #The 4th 1hr, 15 minutes of Operational Phase 2 (TW10)
mp35_ThreshNIIRSID = 6.3 #The 5th 1hr, 15 minutes of Operational Phase 2 (TW13)
mp36_ThreshNIIRSID = 6.7 #The 6th 1hr, 15 minutes of Operational Phase 2 (TW14)
mp37_ThreshNIIRSID = 7.0 #The 7th 1hr, 15 minutes of Operational Phase 2 (TW15)
mp38_ThreshNIIRSID = 7.1 #The 8th 1hr, 15 minutes of Operational Phase 2 (TW16)
mp4_ThreshNIIRSID = 7.1 #For Operational Phase 4 (TW17)
#NIIRS Detection
mp1_ThreshNIIRSD = 3.5
mp2_ThreshNIIRSD = 2.4
mp31_ThreshNIIRSD = 2.3
mp32_ThreshNIIRSD = 2.4
mp33_ThreshNIIRSD = 2.5
mp34_ThreshNIIRSD = 2.6
mp35_ThreshNIIRSD = 2.7
mp36_ThreshNIIRSD = 2.8
mp37_ThreshNIIRSD = 2.9
mp38_ThreshNIIRSD = 3.0
```

Figure F:1 - Python Architecture Code (Page 1) (Meyer, 2016)



```
mp4_ThreshNIIRSD = 3.0
#% Coverage Identification
mp1_ThreshCovID = 8
mp2_ThreshCovID = 2
mp31_ThreshCovID = 4
mp32_ThreshCovID = 4
mp33_ThreshCovID = 4
mp34_ThreshCovID = 4
mp35_ThreshCovID = 4
mp36_ThreshCovID = 4
mp37_ThreshCovID = 4
mp38_ThreshCovID = 4
mp4_ThreshCovID = 4
#% Coverage Detection
mp1_ThreshCovD = 52
mp2_ThreshCovD = 47
mp31_ThreshCovD = 47
mp32_ThreshCovD = 48
mp33_ThreshCovD = 48
mp34_ThreshCovD = 49
mp35_ThreshCovD = 49
mp36_ThreshCovD = 50
mp37_ThreshCovD = 50
mp38_ThreshCovD = 51
mp4_ThreshCovD = 51
#SRT
mp1_ThreshSRT = 30
mp2_ThreshSRT = 30
mp31_ThreshSRT = 30
mp32_ThreshSRT = 30
mp33_ThreshSRT = 30
mp34_ThreshSRT = 30
mp35_ThreshSRT = 30
mp36_ThreshSRT = 30
mp37_ThreshSRT = 30
mp38_ThreshSRT = 30
mp4_ThreshSRT = 30

#######################  VALUE HIERARCHY WEIGHTING  ###########################
# This is the total weighting for the Time Windows matching Operational Phases
#(all should collectively sum to 1.00)

mp1_NIIRSID_Weight = .20 #NIIRS ID weight during Operational Phase 1
mp1_NIIRSD_Weight = .20 #NIIRS Detection weight during Operational Phase 1
mp1_COVID_Weight = .20 #% Cov ID weight during Operational Phase 1
mp1_COVD_Weight = .20 #% Cov Detection weight during Operational Phase 1
mp1_SRT_Weight = .20 #SRT weight during Operational Phase 1

mp2_NIIRSID_Weight = .60
mp2_NIIRSD_Weight = .10
mp2_COVID_Weight = .10
mp2_COVD_Weight = .10
mp2_SRT_Weight = .10

mp3_NIIRSID_Weight = .20
```

```
mp3_NIIRSD_Weight = .30
mp3_COVID_Weight = .10
mp3_COVD_Weight = .30
mp3_SRT_Weight = .10

mp4_NIIRSID_Weight = .20
mp4_NIIRSD_Weight = .20
mp4_COVID_Weight = .20
mp4_COVD_Weight = .20
mp4_SRT_Weight = .20

###########  SINGLE ATTRIBUTE VALUE FUNCTION SHAPES & PARAMETERS  #############

mNIIRSID_SAVFshape = 'linear' #A Linear SAVF for NIIRS ID for the FST (TW1)
mminNIIRSID = 5
mmaxNIIRSID = 9

mNIIRSD_SAVFshape = 'convex' #NIIRS Detection is only Convex for TW 2
#(Siwtches to 'Linear' at TW12(43200)) --> captured in ScenarioAnalysis Code
mminNIIRSD = 1
mmaxNIIRSD = 5

mCOVID_SAVFshape = 'concave'
mminCovID = 0.10
mmaxCovID = 20.00

mCOVD_SAVFshape = 's-curve'
mminCovD = 20
mmaxCovD = 80

mSRT_SAVFshape = 'concave'
mminSRT = 0 #This is actually the maximum boundary due to the decreasing SAVF
mmaxSRT = 40 #This is actually the minimum boundary
# The SAVF (ScenarioAnalysis) accounts for the backwards boundaries
#so no adjustment is needed
#________________________________________________________________________________
#_________________STEP 5. MODEL & SIMULATE CONCEPT ARCHITECTURES_________________
#________________________________________________________________________________
#####################  MODELING & SIMULATION VARIABLES  ##############################
###Scenario Time Variables###
#Simulation Start Time
mstartDay = 14
mstartMonthYear = ' May 2015 '
mstartHour = 10
mstartMin = 00
mstartSec = 00
#Simulation End Time
mendDay = 15
mendMonthYear = ' May 2015 '
mendHour = 10
mendMin = 00
mendSec = 00

###Area of Interest Variables###
mpts = '4' #Number of boundary points
```

Figure F:2 - Python Architecture Code (Pages 2 & 3) (Meyer, 2016)

```
mAOI = '32 40 32 45 35 45 35 40' #Lat/Lon Boundary points

###Sensor Variables###
#Pointing Sensor (UAVs Only)
msen1_Param = 'Rectangular 0.1885 0.2513'

#Fixed Sensor (Satellites and UAVs)
msen2_Param = 'SimpleCone 65'

###Satellite Variables###
#Satellite 1 Parameters
msat1_Alt = (450 + 6378.137)*1000.0 #STK expects meters for altitude
msat1_E = 0 #Satellite eccentricity
msat1_inc = 90 #Satellite inclination
msat1_AoP = 0 #Satellite Arguement of perigee
msat1_RAAN = 0 #Right accession of ascending node
msat1_M = 0 #Mean anomaly

###Constellation Parameters###
#ScenarioExecte uses Satellite 1 Parameters (above) as a starting point
#Constellation Parameters to create the constellation
mconstel = 1 # 0 = no constellation, 1 = constellation
mNum_Sats = 3 #Number of satellites in each orbital plane
mNum_Planes = 3 #Total number of orbital planes
mTrueAnom = 120 #True anomaly difference b/t satellites (impacts mean anomaly)
mRAANSpread = 40 #RAAN difference between satellites

###Aircraft Varibles###
mNum_AC_actual = 4 #Total number of UAVs
mNum_AC = mNum_AC_actual - 2 #Accounts for the two automatic UAVs (next line)
mUAV_freq = 0.33 #Delay time (in hours) b/t UAV#1 & UAV#2
#(1st UAV departs upon simulation start time)
mAC_alt = 5 # Cruising altitude in km
#NOTE: UAV waypoints are accounted for in the ScenarioExecute code

###Target Varibles###
mTgt_Set = ['Bagdad', 'Ramadi', 'RedOutPost1', 'RedOutPost2'] #Target names
mTgt_Pos = ['33.2 44.26', '33.5 43.25','34 41.25', '33.25 40.5'] #Corresponding
#target locations
#____________________________________________________________________________________
#_____________________STEP 6. ASSESS ALTERNATIVES' VALUE______________________________
#____________________________________________________________________________________
##########################  TEXT FILE/GRAPH CREATIONS  ##############################
#Different output text files created
ma = '\\OUTPUT.txt'
mb = '\\NEW_Output.txt'
mc = '\\Cov.txt'
md = '\\Cov_Column.txt'
mg = '\\ThresholdR.txt'
mh = '\\Threshold.txt'

######  VALUE MEASURE TOTAL & MANDATORY VALUE MEASURE IDENTIFICATION  ################

mTotVMcount_n = 5 # Total number of value measures (n)
mMandatoryVM1 = 'NIIRSID' # Mandatory value measure 1
```

```
mMandatoryVM2 = '%CovID' # Mandatory value measure 2
mMandatoryVM3 = 'SRT' # Mandatory value measure 3

#################  SPECIFIC TIME WITH BUFFER SPECIFICATIONS  ########################
mSpecificTime = 43200 # The Specific Time Stp to be used with buffer (sec).
#43200 is 22:00:00 on 14 May 2015
mBuffer = 1800 # Should be 1/2 of Buffer Range
#(Covers both the positive time and negative time of buffer range)
#NOTE: This scenario used the same lower buffer as upper buffer (30 min each)
#Separate variables would need to be created if LBuffer did not equal UBuffer

####################  CONDITIONAL VALUE SPECIFICATIONS  #############################

mConditionalValueStart = 72000 # Starting time step (sec) of Time Window 17
mPostConditionPoint = 72036 # Last Time (LT) step (in seconds) of the mandatory
# value measures meeting/exceeding their respective threshold.
mConditionalValueDuration = 3600 # Duration time step (sec) of Time Window 17

#######################  TIME WINDOW SUMMATION RANGE  ###############################

mtstart = 0 #Starting time step of the summation period
#(Should match whatever time window start time step is)
mtend = 86400 #Ending time step of the summation period
#(Should match whatever time window end time step is)

####################################################################################
###############################  FUNCTIONS ##########################################
####################################################################################
#Imports the above variables to other scripts via functions
#___________________________________________________________________________________
#This creates SAVF graphs for all value measures
from SAVFAnalysis import SAVFGraphs
SAVFGraphs(mNIIRSD_SAVFshape, mminNIIRSD, mmaxNIIRSD, mNIIRSID_SAVFshape, mminNIIRSID,
#____________________________________________________________3______________________
#Mods/sims architecture in STK and genenrates an OUTPUT.txt & Cov_Column.txt
#
from ScenarioExecute import RunSimulation
RunSimulation(mUAV_freq, mstartDay, mstartMonthYear, mstartHour, mstartMin, mstartSec,
#___________________________________________________________________________________
#Creates a NEW_Output.txt applying SAVF and weight requirements
from ScenarioAnalysis import NEW_OutputAnalysis
NEW_OutputAnalysis(mphase1_endSEC, mphase2_endSEC, mphase3_endSEC, mphase4_endSEC, mp1_
#___________________________________________________________________________________
#Creates creates performance graphs from the NEW_Output.txt file
#Produces graphs af unweighted & weighted impacts of all value measures
from ScenarioAnalysis import GraphAnalysis
GraphAnalysis(mstartDay, mstartMonthYear, mstartHour, mstartMin, mstartSec, mendDay, me
#___________________________________________________________________________________
#Creates threshold value & creates Threshold.txt for all step 6 equations
#Sums Variables in the defined Time Window and plots all desired analysis
#Calculates % Comparison for all 16 options
from Thresh_Obj import Thresh_ObjAnalysis
Thresh_ObjAnalysis(mh, mtstart, mtend, mPostConditionPoint, mConditionalValueStart, mCc
#___________________________________________________________________________________
```

Figure F:3 - Python Architecture Code (Pages 4 & 5) (Meyer, 2016)

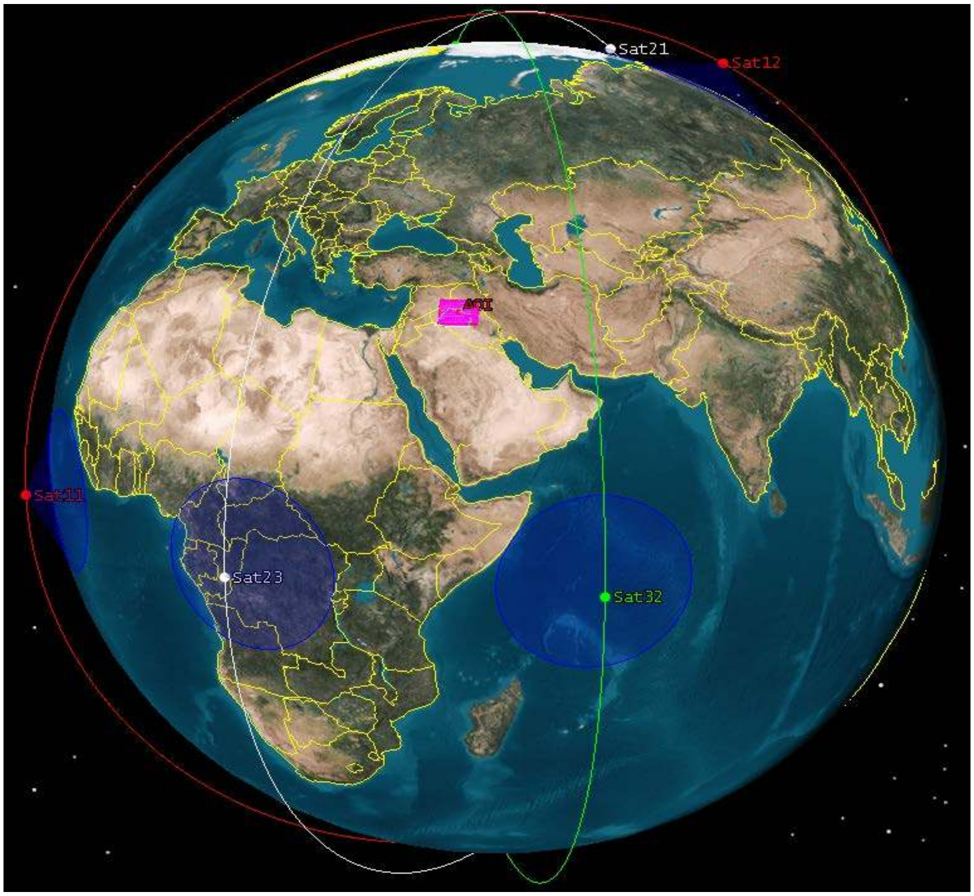


Figure F:4 - Alternative’s STK Model

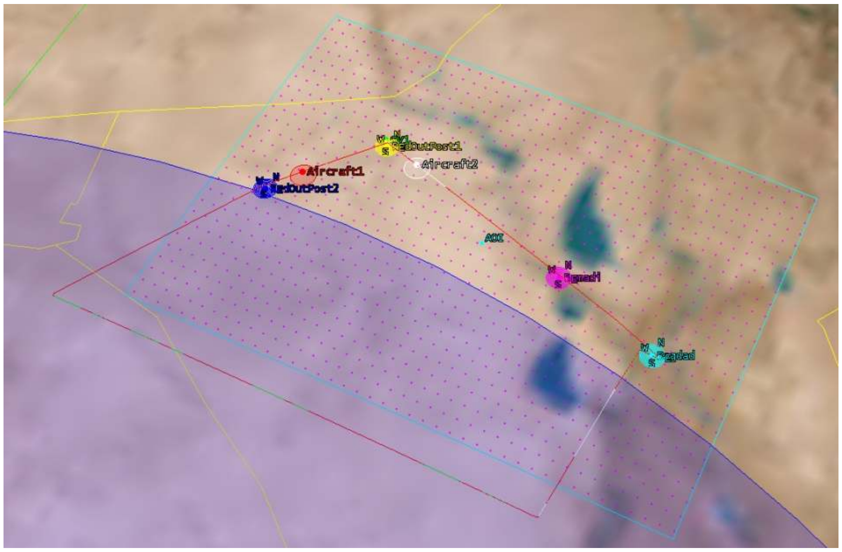


Figure F:5 - Alternative’s STK Model Area of Interest

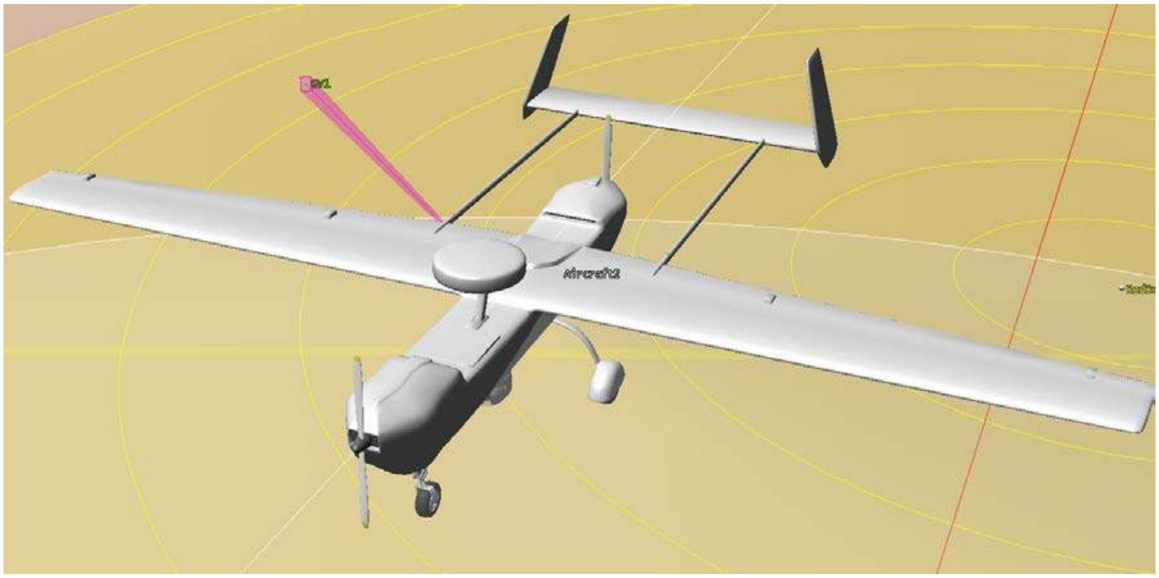


Figure F:6 - Alternative's STK Model UAV

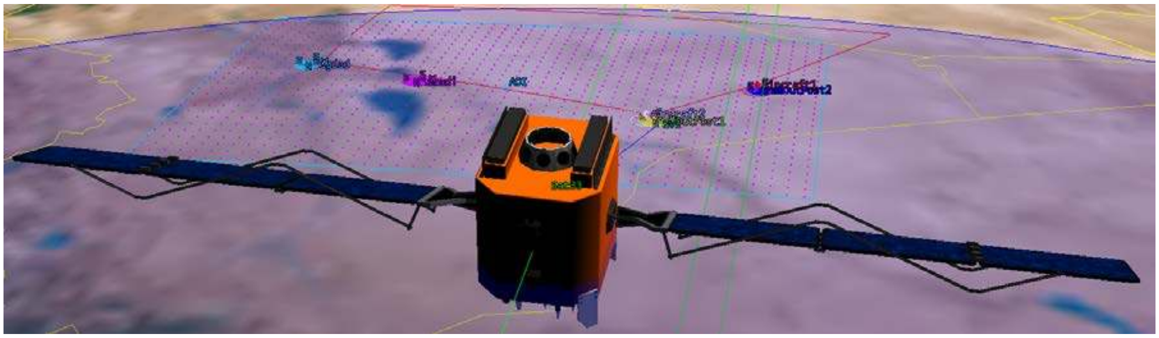
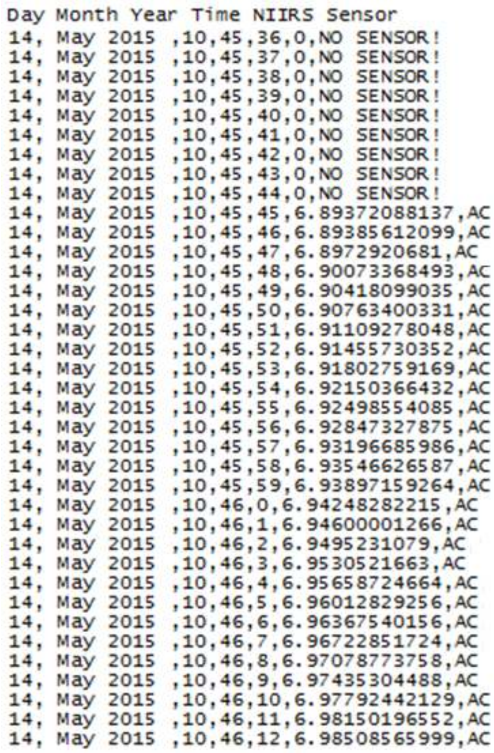


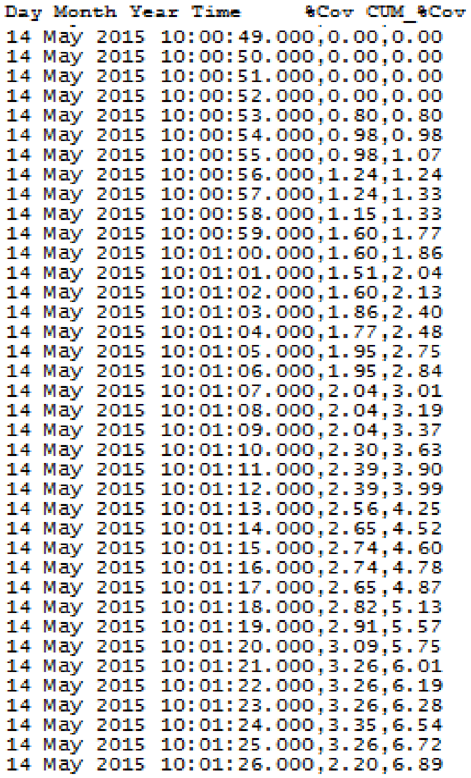
Figure F:7 - Alternative's STK Model Satellite

Table F:1 - Alternative’s Combined NIIRS Levels



```
Day Month Year Time NIIRS Sensor
14, May 2015 ,10,45,36,0,NO SENSOR!
14, May 2015 ,10,45,37,0,NO SENSOR!
14, May 2015 ,10,45,38,0,NO SENSOR!
14, May 2015 ,10,45,39,0,NO SENSOR!
14, May 2015 ,10,45,40,0,NO SENSOR!
14, May 2015 ,10,45,41,0,NO SENSOR!
14, May 2015 ,10,45,42,0,NO SENSOR!
14, May 2015 ,10,45,43,0,NO SENSOR!
14, May 2015 ,10,45,44,0,NO SENSOR!
14, May 2015 ,10,45,45,6.89372088137,AC
14, May 2015 ,10,45,46,6.89385612099,AC
14, May 2015 ,10,45,47,6.8972920681,AC
14, May 2015 ,10,45,48,6.90073368493,AC
14, May 2015 ,10,45,49,6.90418099035,AC
14, May 2015 ,10,45,50,6.90763400331,AC
14, May 2015 ,10,45,51,6.91109278048,AC
14, May 2015 ,10,45,52,6.91455730352,AC
14, May 2015 ,10,45,53,6.91802759169,AC
14, May 2015 ,10,45,54,6.92150366432,AC
14, May 2015 ,10,45,55,6.92498554085,AC
14, May 2015 ,10,45,56,6.92847327875,AC
14, May 2015 ,10,45,57,6.93196685986,AC
14, May 2015 ,10,45,58,6.93546626587,AC
14, May 2015 ,10,45,59,6.93897159264,AC
14, May 2015 ,10,46,0,6.94248282215,AC
14, May 2015 ,10,46,1,6.94600001266,AC
14, May 2015 ,10,46,2,6.9495231079,AC
14, May 2015 ,10,46,3,6.9530521663,AC
14, May 2015 ,10,46,4,6.95658724664,AC
14, May 2015 ,10,46,5,6.96012829256,AC
14, May 2015 ,10,46,6,6.96367540156,AC
14, May 2015 ,10,46,7,6.96722851724,AC
14, May 2015 ,10,46,8,6.97078773758,AC
14, May 2015 ,10,46,9,6.97435304488,AC
14, May 2015 ,10,46,10,6.97792442129,AC
14, May 2015 ,10,46,11,6.98150196552,AC
14, May 2015 ,10,46,12,6.98508565999,AC
```

Table F:2 - Alternative's Percent Coverage



```
Day Month Year Time      %Cov CUM_%Cov
14 May 2015 10:00:49.000,0.00,0.00
14 May 2015 10:00:50.000,0.00,0.00
14 May 2015 10:00:51.000,0.00,0.00
14 May 2015 10:00:52.000,0.00,0.00
14 May 2015 10:00:53.000,0.80,0.80
14 May 2015 10:00:54.000,0.98,0.98
14 May 2015 10:00:55.000,0.98,1.07
14 May 2015 10:00:56.000,1.24,1.24
14 May 2015 10:00:57.000,1.24,1.33
14 May 2015 10:00:58.000,1.15,1.33
14 May 2015 10:00:59.000,1.60,1.77
14 May 2015 10:01:00.000,1.60,1.86
14 May 2015 10:01:01.000,1.51,2.04
14 May 2015 10:01:02.000,1.60,2.13
14 May 2015 10:01:03.000,1.86,2.40
14 May 2015 10:01:04.000,1.77,2.48
14 May 2015 10:01:05.000,1.95,2.75
14 May 2015 10:01:06.000,1.95,2.84
14 May 2015 10:01:07.000,2.04,3.01
14 May 2015 10:01:08.000,2.04,3.19
14 May 2015 10:01:09.000,2.04,3.37
14 May 2015 10:01:10.000,2.30,3.63
14 May 2015 10:01:11.000,2.39,3.90
14 May 2015 10:01:12.000,2.39,3.99
14 May 2015 10:01:13.000,2.56,4.25
14 May 2015 10:01:14.000,2.65,4.52
14 May 2015 10:01:15.000,2.74,4.60
14 May 2015 10:01:16.000,2.74,4.78
14 May 2015 10:01:17.000,2.65,4.87
14 May 2015 10:01:18.000,2.82,5.13
14 May 2015 10:01:19.000,2.91,5.57
14 May 2015 10:01:20.000,3.09,5.75
14 May 2015 10:01:21.000,3.26,6.01
14 May 2015 10:01:22.000,3.26,6.19
14 May 2015 10:01:23.000,3.26,6.28
14 May 2015 10:01:24.000,3.35,6.54
14 May 2015 10:01:25.000,3.26,6.72
14 May 2015 10:01:26.000,2.20,6.89
```

Appendix G: Example Alternative Pre-Acquisition Methodology (Step 6)

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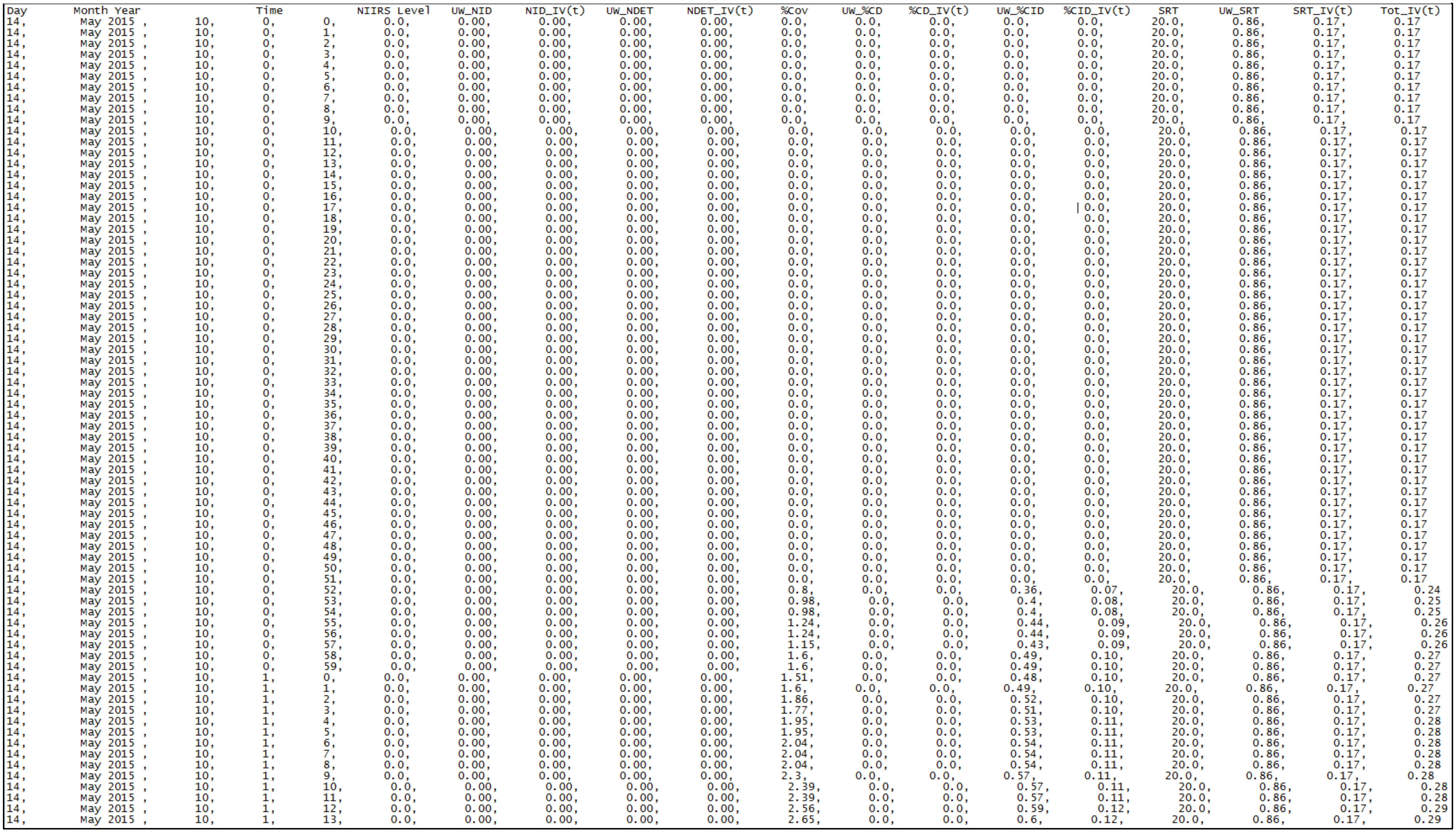
Table G:1 - Alternative’s Simulation Output Text File Example #1



```
Day      Month Year            Time          NIIRS Level  UW_NID   NID_IV(t)  UW_NDET  NDET_IV(t)  %Cov   UW_%CD  %CD_IV(t)  UW_%CID  %CID_IV(t)  SRT    UW_SRT  SRT_IV(t)  Tot_IV(t)
14,      May 2015 ,    10,     0,     0,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     1,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     2,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     3,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     4,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     5,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     6,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     7,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     8,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     9,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     10,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     11,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     12,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     13,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     14,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     15,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     16,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     17,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,    |0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     18,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     19,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     20,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     21,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     22,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     23,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     24,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     25,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     26,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     27,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     28,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     29,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     30,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     31,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     32,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     33,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     34,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     35,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     36,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     37,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     38,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     39,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     40,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     41,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     42,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     43,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     44,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     45,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     46,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     47,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     48,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     49,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     50,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     51,     0.0,     0.00,    0.00,      0.00,    0.00,       0.0,   0.0,    0.0,       0.0,     0.0,        20.0,  0.86,   0.17,      0.17
14,      May 2015 ,    10,     0,     52,     0.0,     0.00,    0.00,      0.00,    0.00,       0.8,   0.0,    0.0,       0.36,    0.07,       20.0,  0.86,   0.17,      0.24
14,      May 2015 ,    10,     0,     53,     0.0,     0.00,    0.00,      0.00,    0.00,       0.98,  0.0,    0.0,       0.4,     0.08,       20.0,  0.86,   0.17,      0.25
14,      May 2015 ,    10,     0,     54,     0.0,     0.00,    0.00,      0.00,    0.00,       0.98,  0.0,    0.0,       0.4,     0.08,       20.0,  0.86,   0.17,      0.25
14,      May 2015 ,    10,     0,     55,     0.0,     0.00,    0.00,      0.00,    0.00,       1.24,  0.0,    0.0,       0.44,    0.09,       20.0,  0.86,   0.17,      0.26
14,      May 2015 ,    10,     0,     56,     0.0,     0.00,    0.00,      0.00,    0.00,       1.24,  0.0,    0.0,       0.44,    0.09,       20.0,  0.86,   0.17,      0.26
14,      May 2015 ,    10,     0,     57,     0.0,     0.00,    0.00,      0.00,    0.00,       1.15,  0.0,    0.0,       0.43,    0.09,       20.0,  0.86,   0.17,      0.26
14,      May 2015 ,    10,     0,     58,     0.0,     0.00,    0.00,      0.00,    0.00,       1.6,   0.0,    0.0,       0.49,    0.10,       20.0,  0.86,   0.17,      0.27
14,      May 2015 ,    10,     0,     59,     0.0,     0.00,    0.00,      0.00,    0.00,       1.6,   0.0,    0.0,       0.49,    0.10,       20.0,  0.86,   0.17,      0.27
14,      May 2015 ,    10,     1,     0,     0.0,     0.00,    0.00,      0.00,    0.00,       1.51,  0.0,    0.0,       0.48,    0.10,       20.0,  0.86,   0.17,      0.27
14,      May 2015 ,    10,     1,     1,     0.0,     0.00,    0.00,      0.00,    0.00,       1.6,   0.0,    0.0,       0.49,    0.10,       20.0,  0.86,   0.17,      0.27
14,      May 2015 ,    10,     1,     2,     0.0,     0.00,    0.00,      0.00,    0.00,       1.86,  0.0,    0.0,       0.52,    0.10,       20.0,  0.86,   0.17,      0.27
14,      May 2015 ,    10,     1,     3,     0.0,     0.00,    0.00,      0.00,    0.00,       1.77,  0.0,    0.0,       0.51,    0.10,       20.0,  0.86,   0.17,      0.27
14,      May 2015 ,    10,     1,     4,     0.0,     0.00,    0.00,      0.00,    0.00,       1.95,  0.0,    0.0,       0.53,    0.11,       20.0,  0.86,   0.17,      0.28
14,      May 2015 ,    10,     1,     5,     0.0,     0.00,    0.00,      0.00,    0.00,       1.95,  0.0,    0.0,       0.53,    0.11,       20.0,  0.86,   0.17,      0.28
14,      May 2015 ,    10,     1,     6,     0.0,     0.00,    0.00,      0.00,    0.00,       2.04,  0.0,    0.0,       0.54,    0.11,       20.0,  0.86,   0.17,      0.28
14,      May 2015 ,    10,     1,     7,     0.0,     0.00,    0.00,      0.00,    0.00,       2.04,  0.0,    0.0,       0.54,    0.11,       20.0,  0.86,   0.17,      0.28
14,      May 2015 ,    10,     1,     8,     0.0,     0.00,    0.00,      0.00,    0.00,       2.04,  0.0,    0.0,       0.54,    0.11,       20.0,  0.86,   0.17,      0.28
14,      May 2015 ,    10,     1,     9,     0.0,     0.00,    0.00,      0.00,    0.00,       2.3,   0.0,    0.0,       0.57,    0.11,       20.0,  0.86,   0.17,      0.28
14,      May 2015 ,    10,     1,     10,     0.0,     0.00,    0.00,      0.00,    0.00,       2.39,  0.0,    0.0,       0.57,    0.11,       20.0,  0.86,   0.17,      0.28
14,      May 2015 ,    10,     1,     11,     0.0,     0.00,    0.00,      0.00,    0.00,       2.39,  0.0,    0.0,       0.57,    0.11,       20.0,  0.86,   0.17,      0.28
14,      May 2015 ,    10,     1,     12,     0.0,     0.00,    0.00,      0.00,    0.00,       2.56,  0.0,    0.0,       0.59,    0.12,       20.0,  0.86,   0.17,      0.29
14,      May 2015 ,    10,     1,     13,     0.0,     0.00,    0.00,      0.00,    0.00,       2.65,  0.0,    0.0,       0.6,     0.12,       20.0,  0.86,   0.17,      0.29
```

Table G:2 - Alternative’s Simulation Output Text File Example #2

```
Day   Month Year          Time        NID_ITV  NID_IV  NID_IB  ND_ITV  ND_IV  ND_IB  %CID_ITV  %CID_IV %CID_IB %CD_ITV %CD_IV %CD_IB  SRT_ITV  SRT_IV SRT_IB Tot_IB_i P(IB_n)  ITV     IV   IB_IV IV_M=n IV_M=3 IV_TB IV_C Zero IV_NoC NID_IV_NoC
14,   May 2015 ,   10,   0,   0,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,   1,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,   2,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,   3,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,   4,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,   5,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,   6,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,   7,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,   8,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,   9,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  10,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  11,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  12,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  13,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  14,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  15,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  16,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  17,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  18,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  19,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  20,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  21,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  22,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  23,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  24,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  25,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  26,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  27,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  28,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  29,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  30,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  31,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  32,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  33,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  34,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  35,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  36,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  37,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  38,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  39,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  40,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  41,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  42,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  43,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  44,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  45,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  46,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  47,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  48,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  49,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  50,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  51,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
14,   May 2015 ,   10,   0,  52,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.07,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.24,   0,   0,   0,   0,   0,   0,   0.24,   0.0
14,   May 2015 ,   10,   0,  53,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.08,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.25,   0,   0,   0,   0,   0,   0,   0.25,   0.0
14,   May 2015 ,   10,   0,  54,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.08,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.25,   0,   0,   0,   0,   0,   0,   0.25,   0.0
14,   May 2015 ,   10,   0,  55,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.09,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.26,   0,   0,   0,   0,   0,   0,   0.26,   0.0
14,   May 2015 ,   10,   0,  56,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.09,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.26,   0,   0,   0,   0,   0,   0,   0.26,   0.0
14,   May 2015 ,   10,   0,  57,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.09,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.26,   0,   0,   0,   0,   0,   0,   0.26,   0.0
14,   May 2015 ,   10,   0,  58,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.1,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.27,   0,   0,   0,   0,   0,   0,   0.27,   0.0
14,   May 2015 ,   10,   0,  59,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.1,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.27,   0,   0,   0,   0,   0,   0,   0.27,   0.0
14,   May 2015 ,   10,   1,   0,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.1,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.27,   0,   0,   0,   0,   0,   0,   0.27,   0.0
14,   May 2015 ,   10,   1,   1,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.1,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.27,   0,   0,   0,   0,   0,   0,   0.27,   0.0
14,   May 2015 ,   10,   1,   2,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.1,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.27,   0,   0,   0,   0,   0,   0,   0.27,   0.0
14,   May 2015 ,   10,   1,   3,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.1,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.27,   0,   0,   0,   0,   0,   0,   0.27,   0.0
14,   May 2015 ,   10,   1,   4,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.11,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.28,   0,   0,   0,   0,   0,   0,   0.28,   0.0
14,   May 2015 ,   10,   1,   5,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.11,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.28,   0,   0,   0,   0,   0,   0,   0.28,   0.0
14,   May 2015 ,   10,   1,   6,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.11,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.28,   0,   0,   0,   0,   0,   0,   0.28,   0.0
14,   May 2015 ,   10,   1,   7,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.11,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.28,   0,   0,   0,   0,   0,   0,   0.28,   0.0
14,   May 2015 ,   10,   1,   8,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.11,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.28,   0,   0,   0,   0,   0,   0,   0.28,   0.0
14,   May 2015 ,   10,   1,   9,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.11,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.28,   0,   0,   0,   0,   0,   0,   0.28,   0.0
14,   May 2015 ,   10,   1,  10,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.11,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.28,   0,   0,   0,   0,   0,   0,   0.28,   0.0
14,   May 2015 ,   10,   1,  11,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.11,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.28,   0,   0,   0,   0,   0,   0,   0.28,   0.0
14,   May 2015 ,   10,   1,  12,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.12,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.29,   0,   0,   0,   0,   0,   0,   0.29,   0.0
14,   May 2015 ,   10,   1,  13,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.12,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.29,   0,   0,   0,   0,   0,   0,   0.29,   0.0
14,   May 2015 ,   10,   1,  14,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.12,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.29,   0,   0,   0,   0,   0,   0,   0.29,   0.0
14,   May 2015 ,   10,   1,  15,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.12,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.29,   0,   0,   0,   0,   0,   0,   0.29,   0.0
14,   May 2015 ,   10,   1,  16,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.12,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.29,   0,   0,   0,   0,   0,   0,   0.29,   0.0
14,   May 2015 ,   10,   1,  17,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.12,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.29,   0,   0,   0,   0,   0,   0,   0.29,   0.0
14,   May 2015 ,   10,   1,  18,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.12,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.29,   0,   0,   0,   0,   0,   0,   0.29,   0.0
14,   May 2015 ,   10,   1,  19,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.13,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.3,    0,   0,   0,   0,   0,   0,   0.3,    0.0
14,   May 2015 ,   10,   1,  20,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.13,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.3,    0,   0,   0,   0,   0,   0,   0.3,    0.0
14,   May 2015 ,   10,   1,  21,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.13,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.3,    0,   0,   0,   0,   0,   0,   0.3,    0.0
14,   May 2015 ,   10,   1,  22,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.13,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.3,    0,   0,   0,   0,   0,   0,   0.3,    0.0
14,   May 2015 ,   10,   1,  23,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.13,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.3,    0,   0,   0,   0,   0,   0,   0.3,    0.0
14,   May 2015 ,   10,   1,  24,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.13,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.3,    0,   0,   0,   0,   0,   0,   0.3,    0.0
14,   May 2015 ,   10,   1,  25,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.11,   0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.28,   0,   0,   0,   0,   0,   0,   0.28,   0.0
14,   May 2015 ,   10,   1,  26,   0.15,   0.0,   0,   0.010,   0.0,   0,   0.139,   0.0,    0,   0.176,   0.0,   0,   0.13,   0.17,   1,   1.0,   0.2,   0.605,   0.17,   0,   0,   0,   0,   0,   0,   0.17,   0.0
```

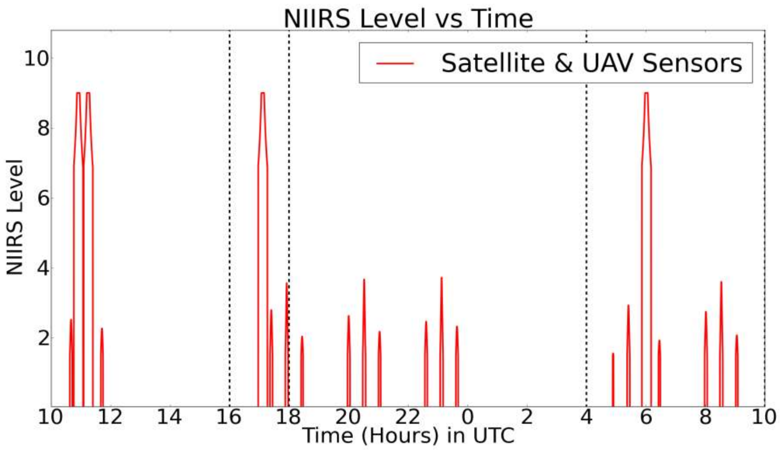


Figure G:1 - Alternative's NIIRS Level

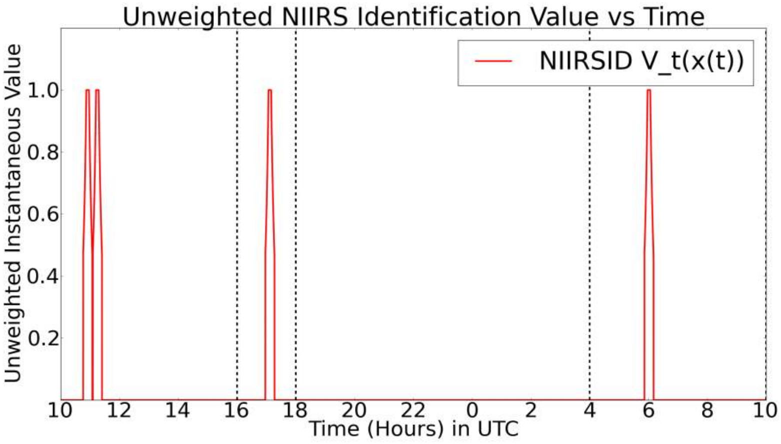


Figure G:2 - Alternative's Unweighted, Normalized NIIRS Identification Value

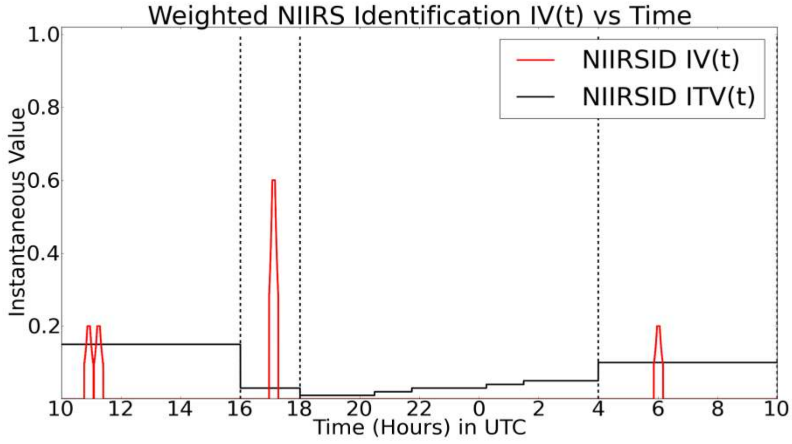


Figure G:3 - Alternative's Weighted NIIRS Identification IV(t) (Scale 0:1)

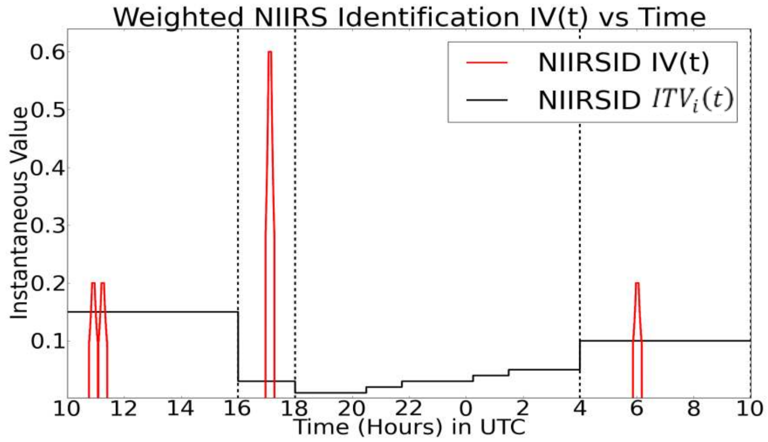


Figure G:4 - Alternative's Weighted NIIRS Identification IV(t) (Scale 0:0.65)

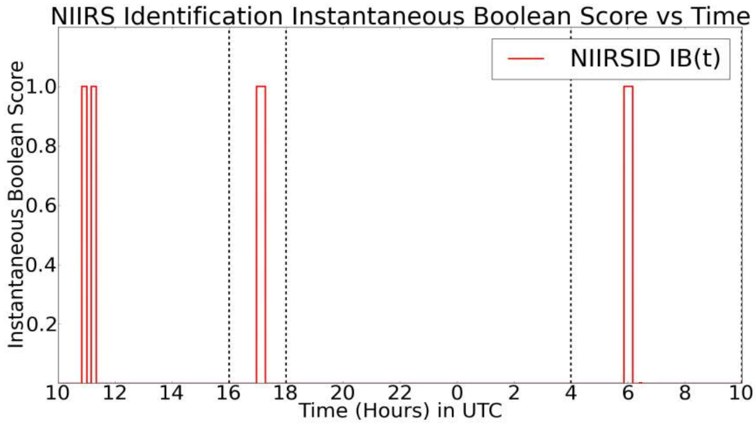


Figure G:5 - Alternative's NIIRS Identification IB(t)

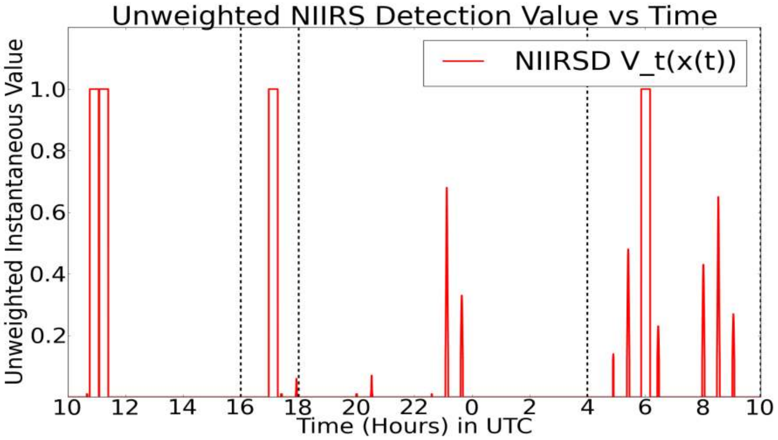


Figure G:6 - Alternative's Unweighted, Normalized NIIRS Detection Value

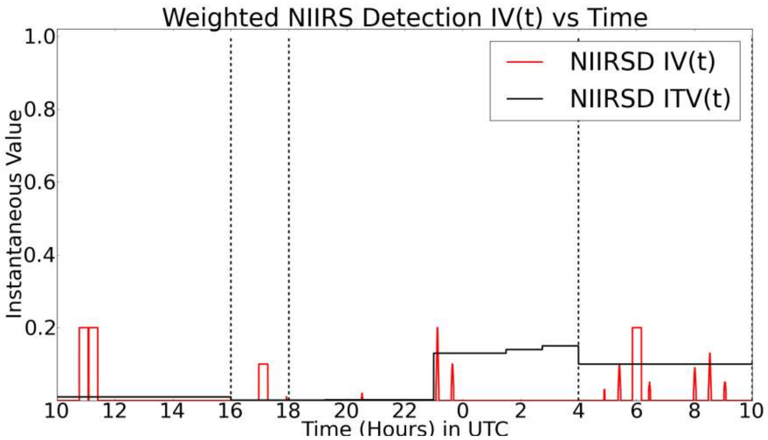


Figure G:7 - Alternative's Weighted NIIRS Detection IV(t) (Scale 0:1)

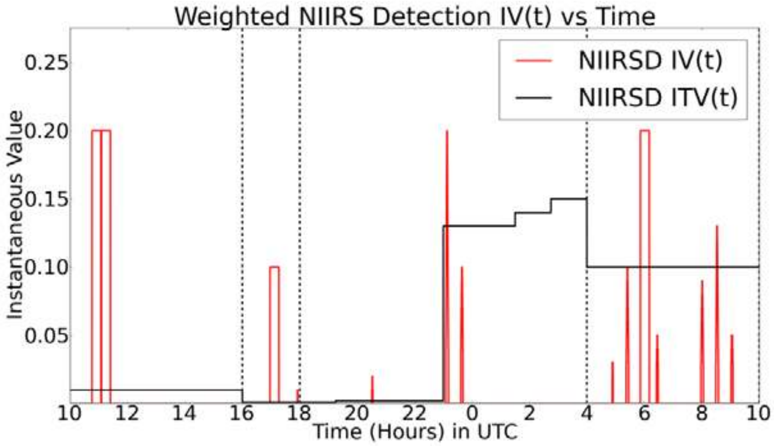


Figure G:8 - Alternative's Weighted NIIRS Detection IV(t) (Scale 0:0.28)

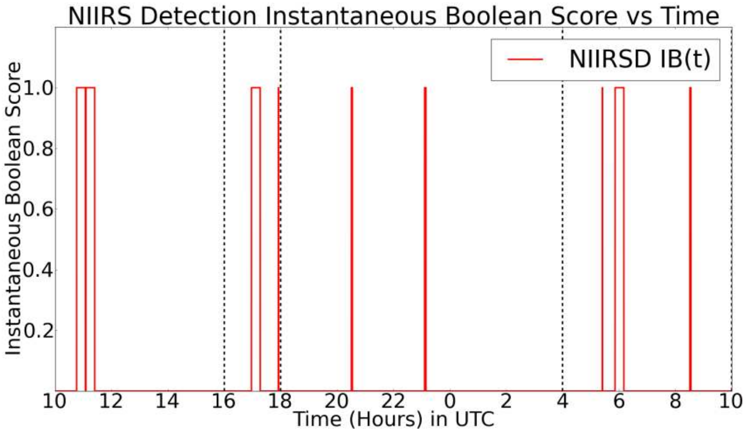


Figure G:9 - Alternative's NIIRS Detection IB(t)

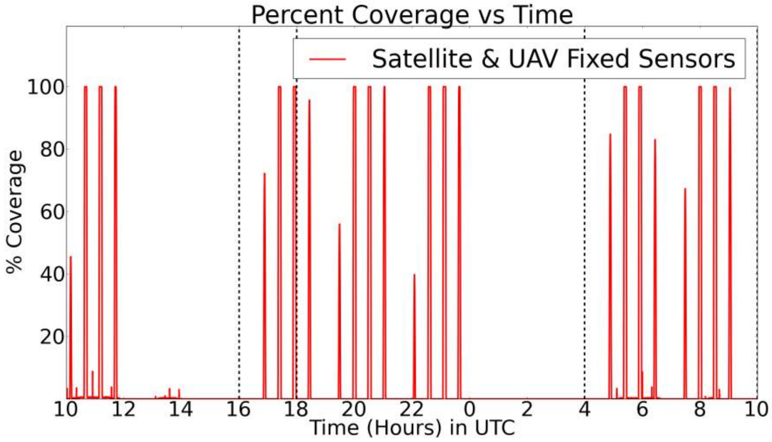


Figure G:10 - Alternative's Percent Coverage

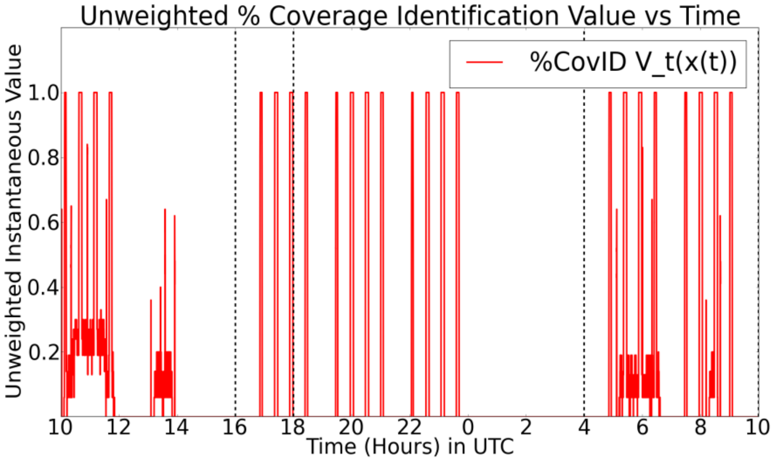


Figure G:11 - Alternative's Unweighted, Normalized % Coverage Identification Value

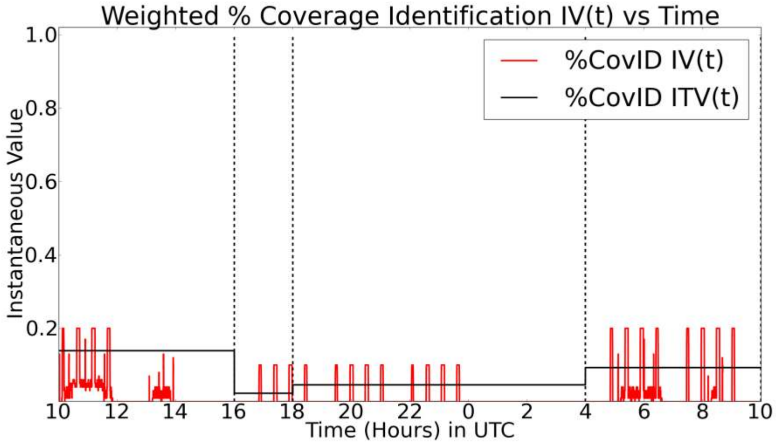


Figure G:12 - Alternative's Weighted % Coverage Identification IV(t) (Scale 0:1)

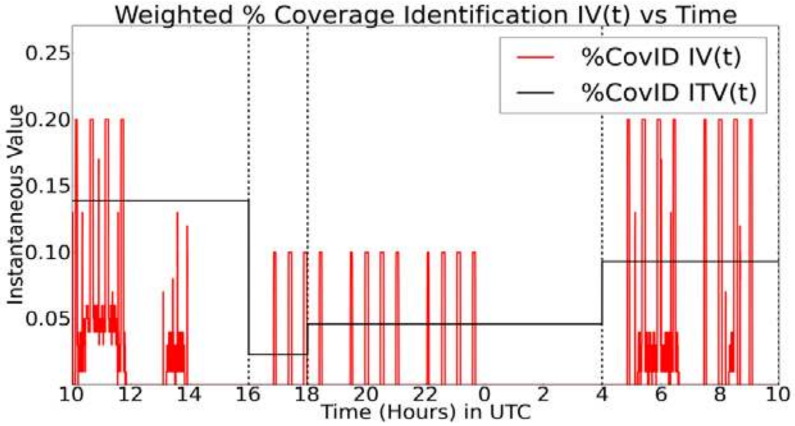


Figure G:13 - Alternative's Weighted % Coverage Identification IV(t) (Scale 0:0.27)

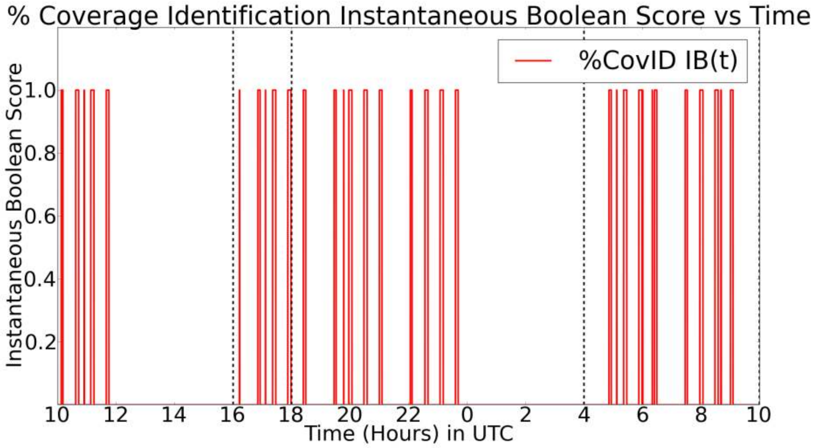


Figure G:14 - Alternative's % Coverage Identification IB(t)

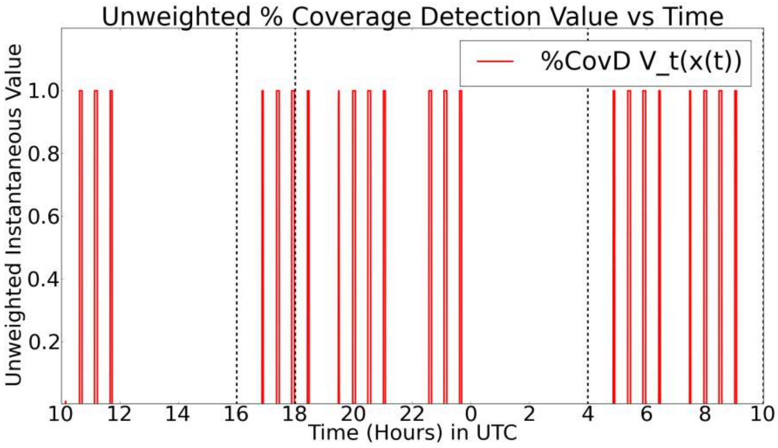


Figure G:15 - Alternative's Unweighted, Normalized % Coverage Detection Value

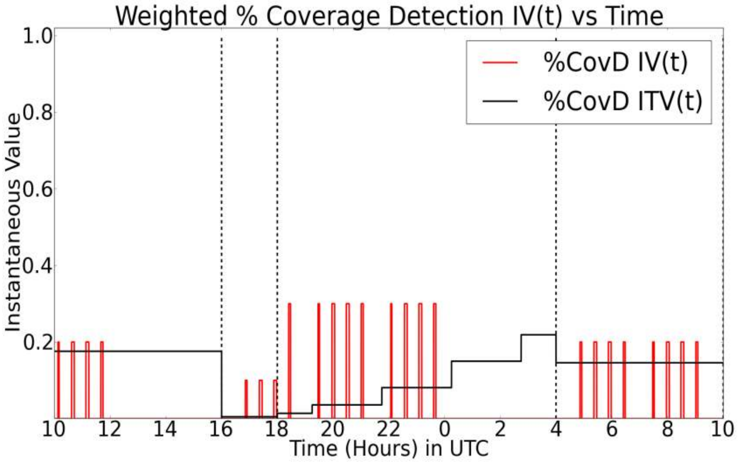


Figure G:16 - Alternative’s Weighted % Coverage Detection IV(t) (Scale 0:1)

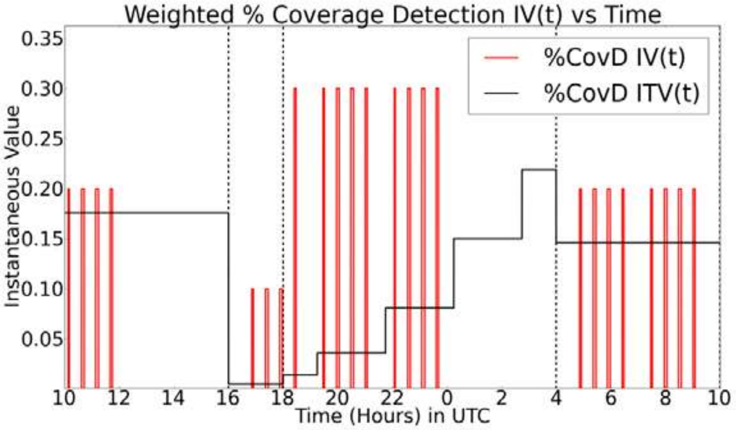


Figure G:17 - Alternative’s Weighted % Coverage Detection IV(t) (Scale 0:0.36)

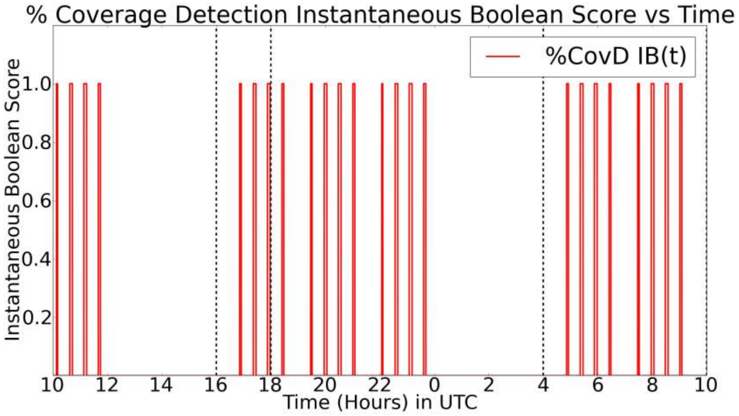


Figure G:18 - Alternative's % Coverage Detection IB(t)

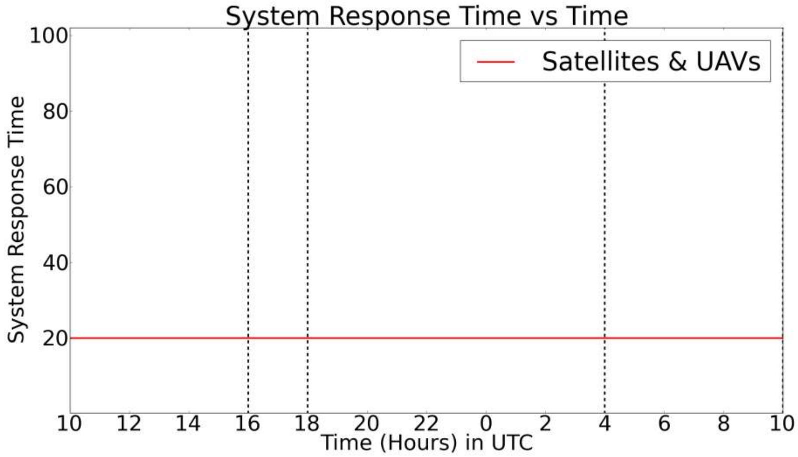


Figure G:19 - Alternative’s System Response Time

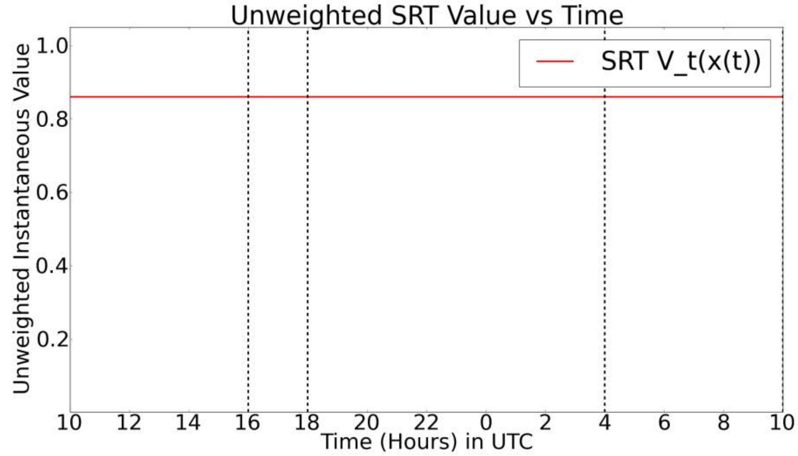


Figure G:20 - Alternative's Unweighted, Normalized SRT Value

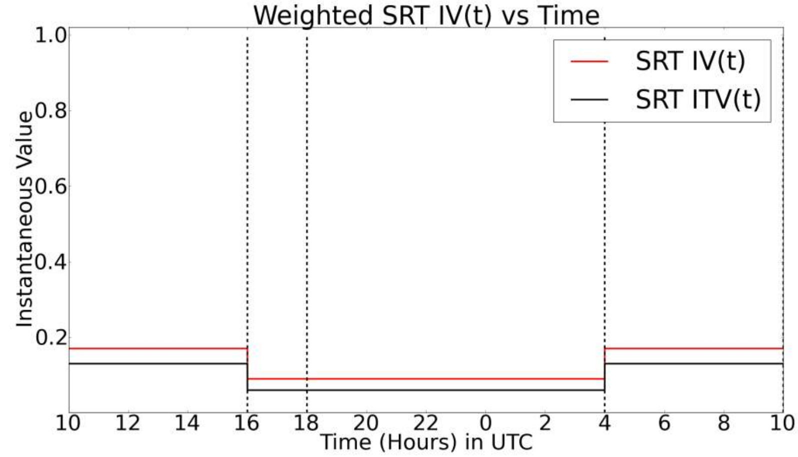


Figure G:21 - Alternative’s Weighted SRT IV(t) (Scale 0:1)

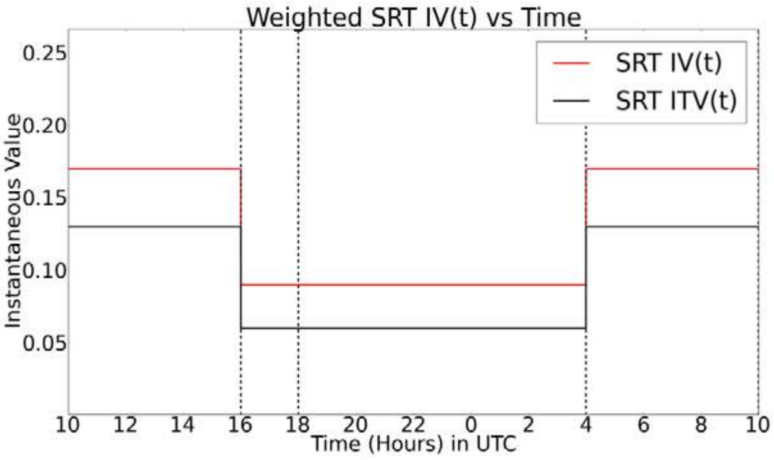


Figure G:22 - Alternative's Weighted SRT IV(t) (Scale 0:0.27)

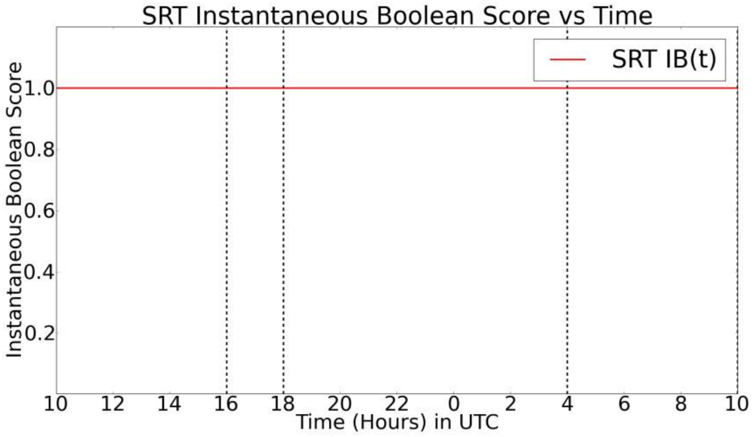


Figure G:23 - Alternative's SRT IB(t)

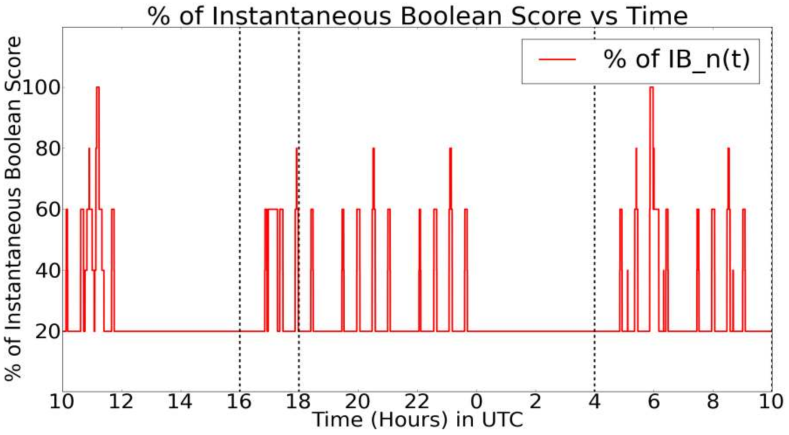


Figure G:24 - Alternative's Percent of IB_n(t)

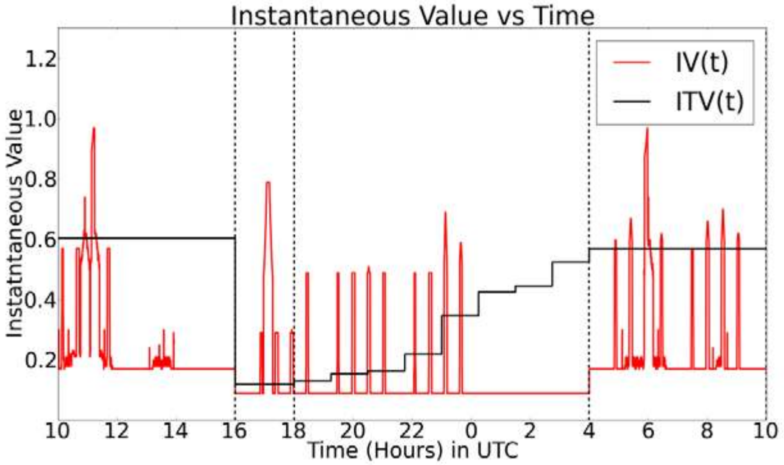


Figure G:25 - Alternative's IV(t)

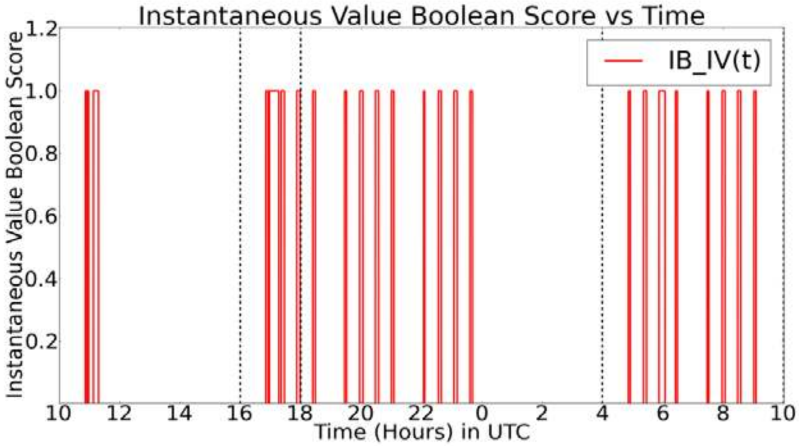


Figure G:26 - Alternative's IB_IV(t)

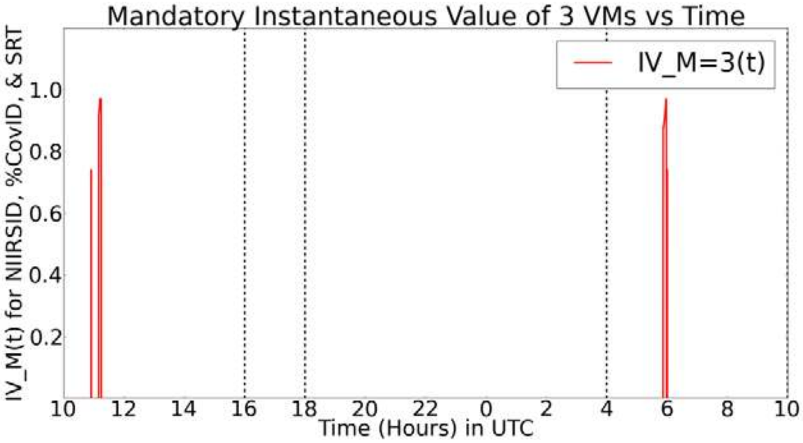


Figure G:27 - Alternative's IV_M(t) for NIIRSID, %CovID, and SRT

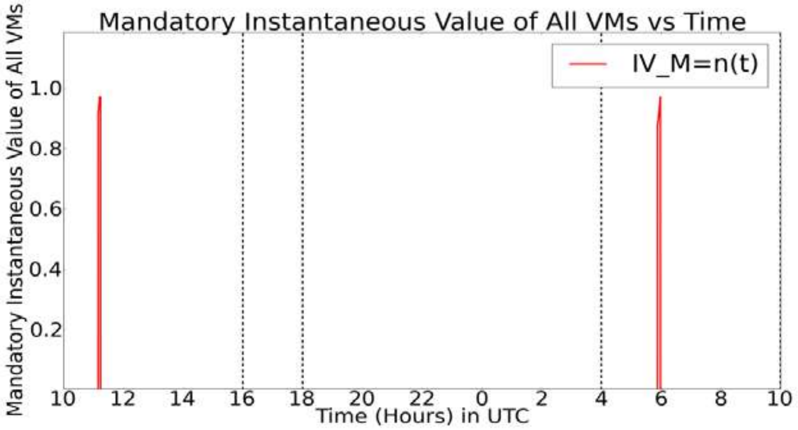


Figure G:28 - Alternative's IV_M(t) for All Value Measures

Appendix H: Example Alternative's Specific Requirements

Specific Time with Buffer

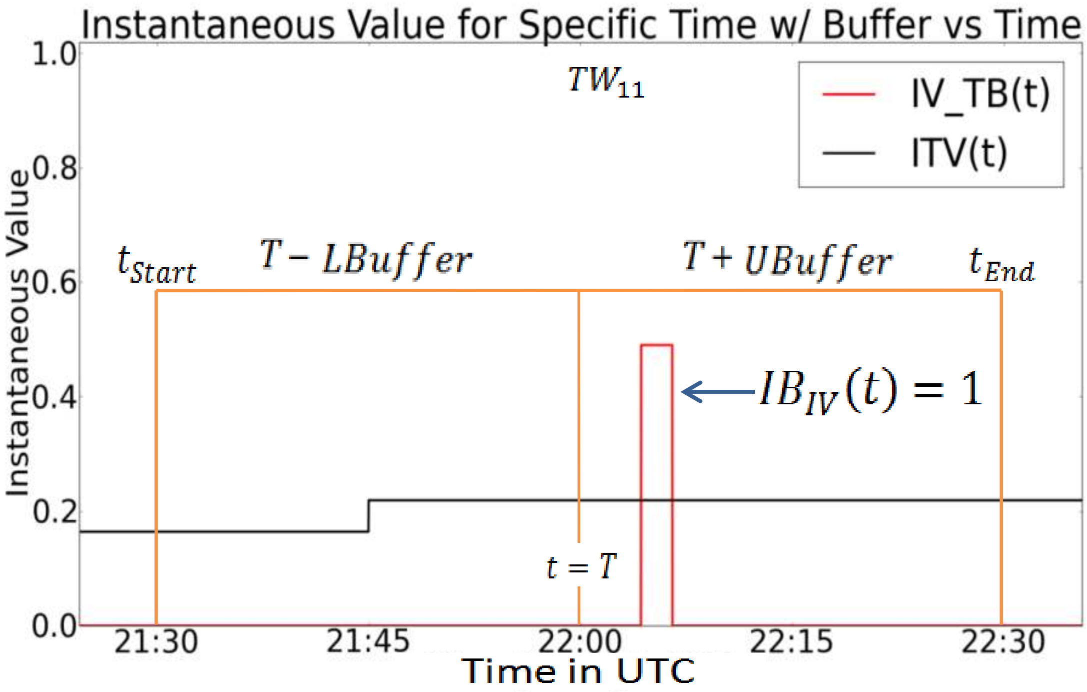


Figure H:1 – Instantaneous Value for Specific Time with Buffer

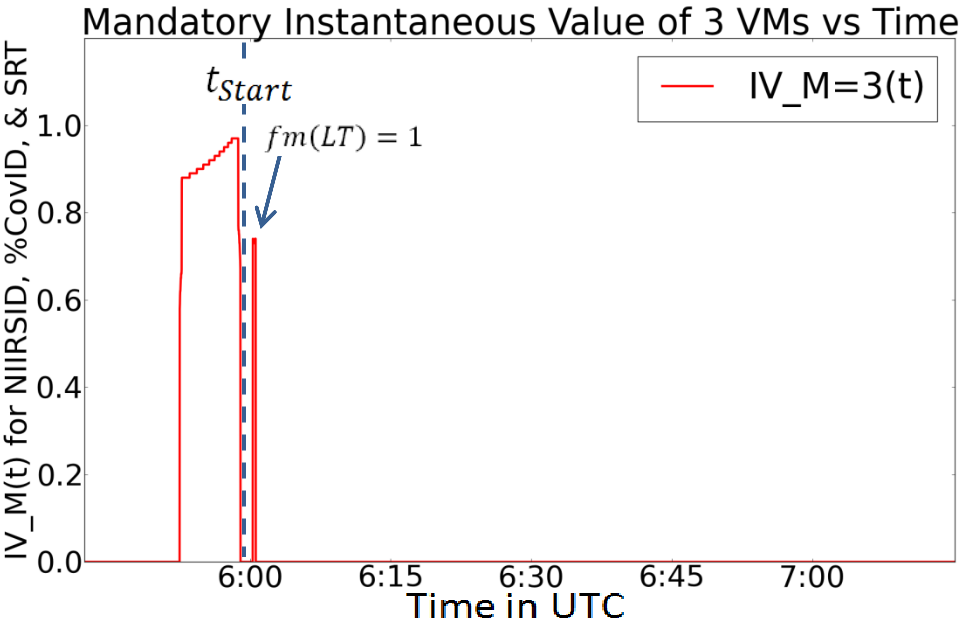


Figure H:2 - Alternative's Last Epoch Time for All 3 Mandatory Value Measures' Full Mandate

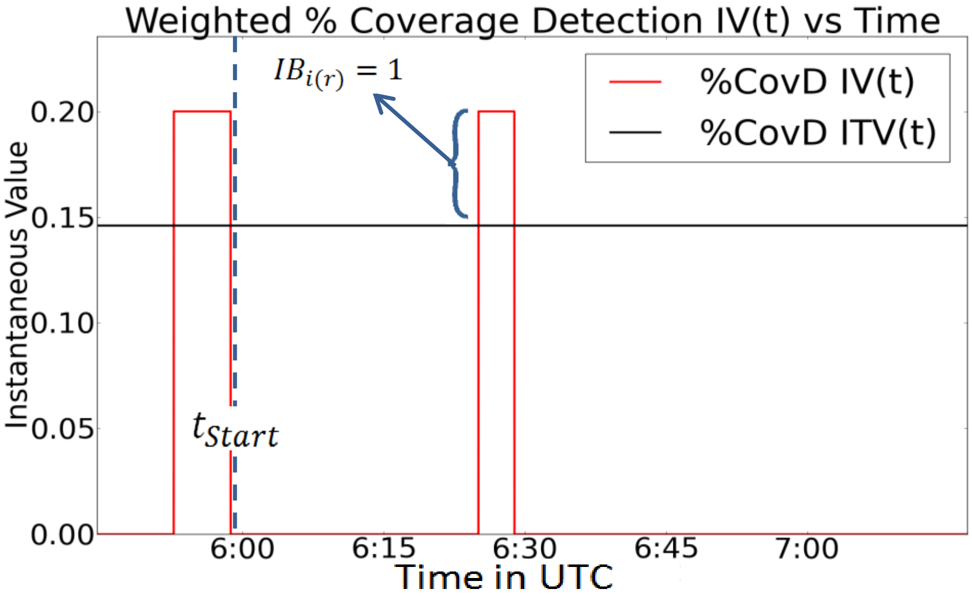


Figure H:3 - Alternative's Required Value Measure Outperforming ITV_i(t)

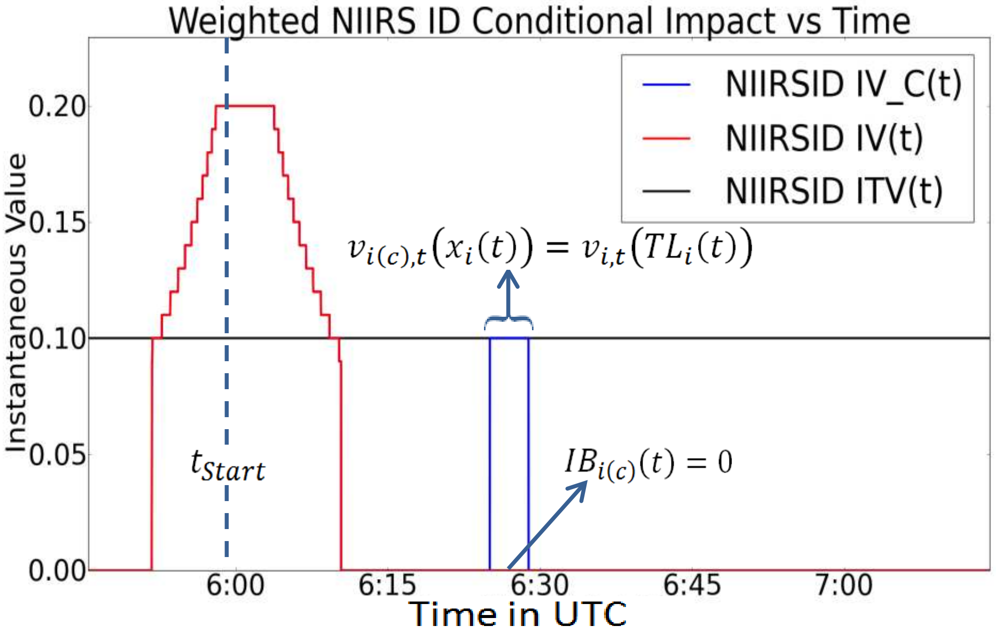


Figure H:4 - Alternative's Influence of a Required Value Measure on a Conditional Value Measure

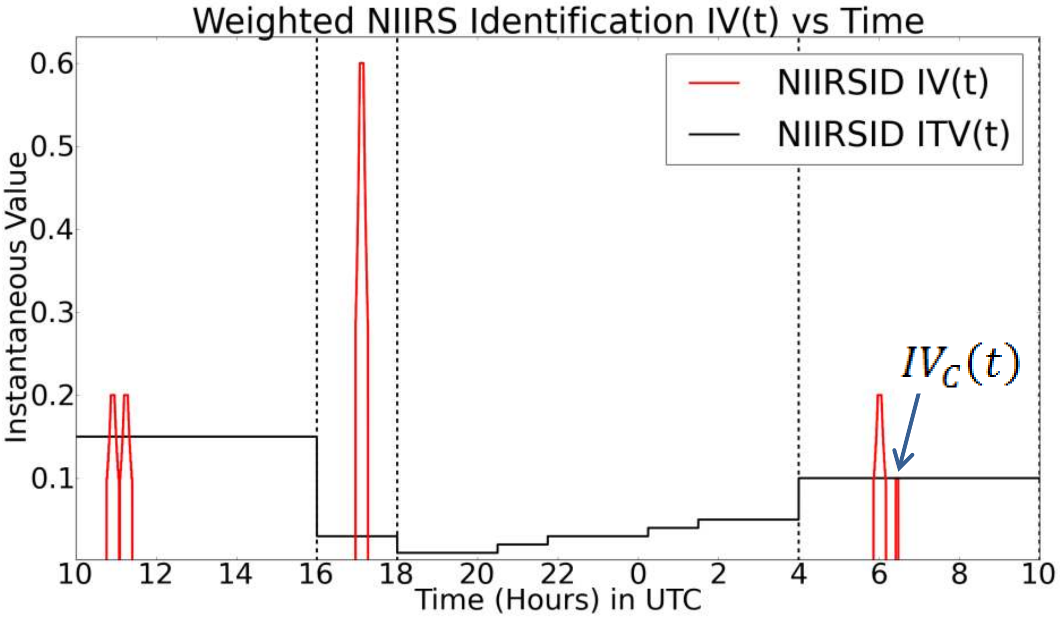


Figure H:5 - Alternative's Conditional Impact on Conditional Value Measure’s IV(t)

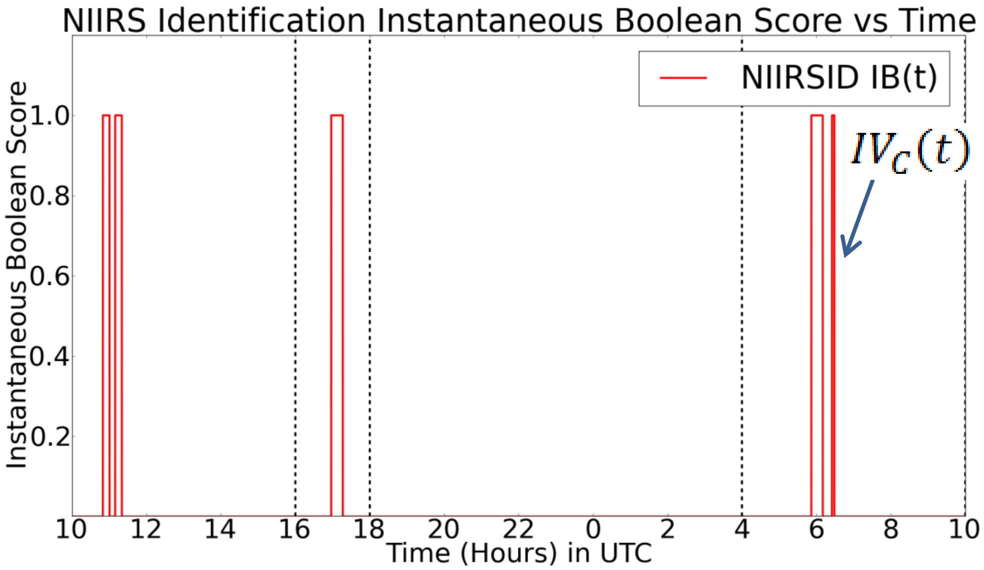


Figure H:6 - Alternative's Conditional Impact on Conditional Value Measure's IB(t)

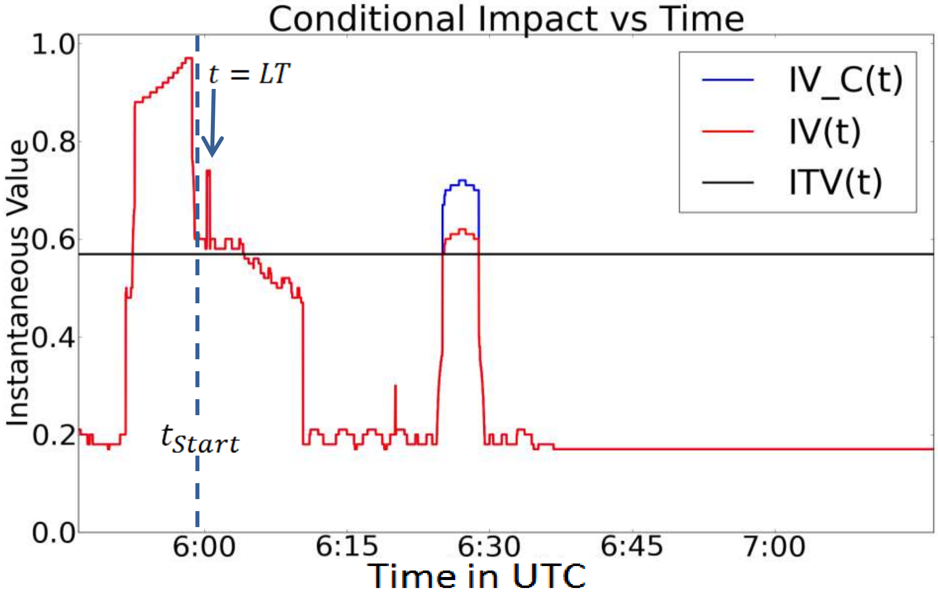


Figure H:7 - Alternative's Non-Conditional Impact IV(t) Against Conditional Impact IV_C(t)

Appendix I: Example Alternative’s Percentage Comparisons

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Table I:1 - Alternative's Value Measure Percentage Comparisons

(Table A:1 & (24))

Value Measure	$\boldsymbol{IV_{NIIRS_{ID}}(t)}$	$\boldsymbol{IV_{NIIRS_{D}}(t)}$	$\boldsymbol{IV_{\%Cov_{ID}}(t)}$	$\boldsymbol{IV_{\%Cov_{D}}(t)}$	$\boldsymbol{IV_{SRT}(t)}$
Time Window	(24)1 (24)2	(24)1 (24)2	(24)1 (24)2	(24)1 (24)2	(24)1 (24)2
TW_1	**13.70%** **4.32%**	19.18% 5.76%	22.57% 9.34%	14.77% 8.08%	136.84% 100.00%
TW_2	21.38% 5.12%	220.54% 7.55%	20.89% 9.81%	18.19% 8.47%	137.50% 100.00%
TW_3	10.79% 5.92%	207.22% 10.36%	17.13% 6.04%	13.53% 5.31%	130.77% 100.00%
TW_4	50.91% 24.33%	1,024.44% 51.22%	60.04% 26.30%	47.42% 24.30%	130.77% 100.00%
TW_5	**242.68%** **15.54%**	1,560.63% 16.17%	62.30% 14.77%	286.60% 12.95%	150.00% 100.00%
TW_6	0.00% 0.00%	2.60% 0.83%	17.44% 8.20%	8.40% 7.06%	150.00% 100.00%
TW_7	**0.00%** **0.00%**	**0.00%** **0.00%**	14.04% 6.62%	46.12% 5.45%	150.00% 100.00%
TW_8	**0.00%** **0.00%**	**0.00%** **0.00%**	34.12% 16.07%	43.60% 13.60%	150.00% 100.00%
TW_9	**0.00%** **0.00%**	**0.00%** **0.00%**	19.15% 9.03%	24.48% 7.63%	150.00% 100.00%
TW_{10}	**0.00%** **0.00%**	**0.00%** **0.00%**	27.62% 13.07%	15.68% 10.56%	150.00% 100.00%
TW_{11}	0.00% 0.00%	0.00% 0.00%	34.51% 16.33%	19.60% 13.19%	150.00% 100.00%
TW_{12}	5.29% 3.37%	8.12% 3.64%	24.95% 8.80%	12.09% 7.62%	136.11% 100.0%
TW_{13}	0.00% 0.00%	10.82% 3.69%	34.55% 16.14%	19.62% 14.63%	150.00% 100.00%
TW_{14}	**0.00%** **0.00%**	**0.00%** **0.00%**	**0.00%** **0.00%**	**0.00%** **0.00%**	150.00% 100.00%
TW_{15}	**0.00%** **0.00%**	**0.00%** **0.00%**	**0.00%** **0.00%**	**0.00%** **0.00%**	150.00% 100.00%
TW_{16}	**0.00%** **0.00%**	**0.00%** **0.00%**	**0.00%** **0.00%**	**0.00%** **0.00%**	150.00% 100.00%
TW_{17}	9.15% 6.17%	14.49% 5.91%	31.67% 12.76%	20.17% 10.92%	130.77% 100.00%
TW_{18}	34.03% 23.36%	37.04% 17.33%	29.20% 8.56%	18.60% 6.36%	130.77% 100.00%

Table I:2 - Alternative's Percentage Comparisons (Table A:1 & (24))

Time Window	(24)3 (24)4 (24)5	(24)6 (24)7	(24)8	(24)9 (24)10 (24)11	(24)12 (24)13
TW_1	**42.78%** **18.91%** **9.87%**	**160.33%** **97.00%**	**25.50%**	**4.04%** **0.76%** **0.84%**	**8.49%** **0.70%**
TW_2	52.75% 19.44% 11.05%	160.33% 97.00%	26.19%	3.25% 0.63% 0.68%	6.11% 0.59%
TW_3	39.89% 24.13% 4.60%	160.33% 97.00%	25.53%	5.66% 1.37% 1.46%	31.79% 1.27%
TW_4	79.48% 48.09% 22.52%	160.33% 97.00%	45.23%	21.67% 10.42% 11.00%	48.85% 10.14%
TW_5	172.84% 20.57% 30.31%	663.87% 79.00%	31.88%	0.00% 0.00% 0.00%	0.00% 0.00%
TW_6	36.37% 12.10% 7.37%	120.00% 69.00%	23.22%	0.00% 0.00% 0.00%	0.00% 0.00%
TW_7	79.99% 11.28% 6.53%	374.52% 49.00%	22.41%	0.00% 0.00% 0.00%	0.00% 0.00%
TW_8	84.20% 14.65% 14.74%	281.61% 49.00%	25.93%	0.00% 0.00% 0.00%	0.00% 0.00%
TW_9	66.14% 12.17% 7.86%	266.30% 49.00%	23.33%	0.00% 0.00% 0.00%	0.00% 0.00%
TW_{10}	56.22% 13.44% 10.56%	205.02% 49.00%	24.73%	0.00% 0.00% 0.00%	0.00% 0.00%
TW_{11}	60.86% 14.55% 13.19%	205.02% 49.00%	25.91%	0.00% 0.00% 0.00%	0.00% 0.00%
TW_{12}	34.57% 18.29% 8.48%	168.70% 97.00%	24.68%	5.05% 0.92% 1.03%	12.15% 0.84%
TW_{13}	43.46% 16.38% 14.63%	183.02% 69.00%	26.89%	0.00% 0.00% 0.00%	0.00% 0.00%

Time Window	(24)3 (24)4 (24)5	(24)6 (24)7	(24)8	(24)9 (24)10 (24)11	(24)12 (24)13
TW_{14}	18.91% 9.00% 0.00%	18.91% 9.00%	20.00%	0.00% 0.00% 0.00%	0.00% 0.00%
TW_{15}	18.15% 9.00% 0.00%	18.15% 9.00%	20.00%	0.00% 0.00% 0.00%	0.00% 0.00%
TW_{16}	15.65% 9.0% 0.0%	15.65% 9.00%	20.00%	0.00% 0.00% 0.00%	0.00% 0.00%
TW_{17}	43.04% 24.49% 12.50%	170.47% 97.00%	27.15%	6.91% 1.69% 1.89%	15.11% 1.54%
TW_{18}	49.38% 28.09% 13.42%	130.05% 74.00%	31.12%	1.38% 0.39% 0.53%	3.93% 0.00%

Table I:3 - Specific Time with Buffer Percentage Comparison

(Table A:1 & (24))

Time Window	(24)14 (24)15
TW_{11}	0.00% 1.81%

Table I:4 - Conditional Instantaneous Value Percentage Comparison

(Table A:1 & (24))

Time Window	(24)16
TW_{18}	102.32%

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 074-0188

1. REPORT DATE *(DD-MM-YYYY)* 24-03-2016	**2. REPORT TYPE** Master's Thesis	**3. DATES COVERED** *(From – To)* September 2014 – March 2016

TITLE AND SUBTITLE A Time-Variant Value-Focused Methodology for Supporting Pre-Acquisition	**5a. CONTRACT NUMBER** **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) Scheller, Brian, K, Captain, USAF	**5d. PROJECT NUMBER** **5e. TASK NUMBER** **5f. WORK UNIT NUMBER**

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S)
Air Force Institute of Technology
Graduate School of Engineering and Management (AFIT/EN)
2950 Hobson Way, Building 640
WPAFB OH 45433-7765

8. PERFORMING ORGANIZATION REPORT NUMBER
AFIT-ENY-MS-16-M-236

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
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10. SPONSOR/MONITOR'S ACRONYM(S)
AFLCMC/XZI

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRUBTION STATEMENT A. APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES
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14. ABSTRACT

Military operations are dynamic in nature, as time-dependent requirements or adversary actions can contribute to differing levels of mission performance among systems. Future military operations commonly use multi-criteria decision analysis techniques that rely on value-focused thinking (VFT) to analyze and ultimately rank alternatives during the Analysis of Alternatives phase of the acquisition process. Traditional VFT approaches are not typically employed with the intention of analyzing time-variant performance of alternatives. In this research, a holistic approach towards integrating fundamental practices such as VFT, systems architecture, and modeling and simulation is used to analyze time-dependent data outputs of an alternative's performance within an operational environment. Incorporating this approach prior to Milestone A of the acquisition process allows for the identification of time-based capability gaps and additional dynamic analysis of possible alternatives that can be implemented as a flexible means of assessment. As part of this research, the pre-acquisition methodology is implemented with a hypothetical multi-domain Intelligence, Surveillance, and Reconnaissance mission in order to exemplify multiple time-dependent analysis possibilities.

15. SUBJECT TERMS
Value-Focused Thinking, Multi-Objective Decision Analysis, Analysis of Alternatives, Systems Architecture, Modeling & Simulation

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Lt Col Thomas C. Ford, AFIT/ENV
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(Include area code)*
U	U	U	UU	193	(937) 255-6565 x4747 thomas.ford@afit.edu

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18