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A MODEL FOR COMMUNICATIONS SATELLITE SYSTEM ARCHITECTURE ASSESSMENT

by

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September 2011

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**A MODEL FOR COMMUNICATIONS SATELLITE SYSTEM ARCHITECTURE
ASSESSMENT**

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ABSTRACT

Communications satellite system architecture trades traditionally only consider the cost per unit of capacity provided. This selection method ignores the other requirements with which the system architectures were designed, and that are critical to providing a capability to the warfighter. A survey of communications satellite systems identified five common attributes that are incorporated in the design process: communications capacity, access, interoperability, commandability, and information assurance and protection. A mathematical model was implemented to enable the analysis of communications satellite system architectures based on multiple system attributes. Utilization of the model in a hypothetical test case demonstrated how variations in key performance attributes influences the choice of the preferred system in a selection process.

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EXECUTIVE SUMMARY

Communications satellite system architecture trades traditionally consider only the cost per unit of capacity provided. But a successful architecture has many critical attributes that meet documented and validated requirements. Making a decision based solely on cost per unit of capacity provided ignores critical requirements essential to providing a capability to the warfighter. To ensure these requirements are considered during trades, a method to account for additional system attributes in the execution of architecture trades was implemented.

A survey of communications satellites systems identified five common attributes that are incorporated in the system design process. These are communications capacity, access, interoperability, commandability, and information assurance and protection. Additional system specific attributes can be based on Technical Performance Measures (TPMs) and Key Performance Parameters (KPPs) for the actual system solutions to be analyzed.

A mathematical model was implemented to enable the analysis of communications satellite system architectures based on the performance of multiple system attributes. The mathematical model supports any number of attributes desired for analysis. All selected attributes are allowed to have a different relative importance based on the preference of the stakeholders. Utilization of the model in a hypothetical case indicated that a system selection considering additional key performance attributes can be different from the traditional solution of narrowly focusing on one parameter. Understanding the reasoning behind the difference will help ensure the best system is selected.

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I. INTRODUCTION

A. BACKGROUND

Satellite-based communications provide a crucial capability to the U.S. military in the execution of their missions. The need for a worldwide exchange of voice, video, and data during a military operation has resulted in the development and operation of satellite systems that provide a global communication capability. The operational benefits afforded by satellite-based communications were recognized from the beginning of the U.S. space program and continues to remain a fundamental mission area (Martin, 2001).

Satellite communications enable a level of pervasive coverage that is not possible by any other means. Satellite communications also provide coverage in remote areas that lack infrastructure, such as at sea, or in developed areas where communications infrastructure has been incapacitated by natural disasters, war, or other extreme circumstances. Additionally, demand for communications throughput continues to grow as more data is exchanged between operators and sensors in a theater of engagement and remotely located analysts, planners, and commanders.

In order to efficiently meet communications throughput demand, potential system architecture solutions are developed and then analyzed in trade studies. As the system designs are generated all requirements are included and balanced to meet specified needs. Traditionally the selection of a communications satellites systems architecture solution is based upon the evaluation of a single criterion: the cost per unit of system communication capacity, or throughput. This approach comes from the requirement to be compliant with the DoD 5000 Series Policy regarding cost analysis coupled with a comparison to commercial options (DoD Directive 5000.01, 2007 and DoD Instruction 5000.02, 2008].

Communications satellite system architecture selection based solely on the cost per unit of system communication capacity clearly omits documented and validated requirements from the decision making process. Examples of these requirements may include architecture robustness, the ability of the system design to operate in a variety of situations; and interoperability with other existing or planned equipment, tactics,

procedures, and systems. Thus, a method to assess communications satellite system architectures based on multiple attributes simultaneously is desired.

B. PURPOSE

The purpose of this thesis was to implement a mathematical model for assessing communications satellite system architectures based on the satisfaction of multiple performance attributes.

C. RESEARCH QUESTIONS

The following three questions are addressed.

1. What are the key quantifiable architectural attributes that contribute to meeting the users' requirements of a communications satellite?
2. What is an appropriate mathematical model for evaluating communications satellite architectures?
3. How can such a mathematical model be applied to the assessment of a communications satellite architecture?

D. SCOPE AND METHODOLOGY

The thesis proposes a methodology that can be utilized to perform system architecture trades on DoD satellite communications architectures that require multiple satellites to meet global communications needs. First, key communications satellite system architecture attributes were indentified. Next, a mathematical model to compare system architecture solutions was presented. Finally, the mathematical model was applied to evaluate a set of hypothetical communications satellite system architectures.

E. BENEFITS OF THIS STUDY

The outcome of this research could be used to support communications satellite system architecture trades. The application of this model may allow decision makers to be more informed during system architecture selection than if relying on the traditional approach that considers only system communications capacity and cost.

II. MODEL SELECTION

A. INTRODUCTION

This chapter discusses the mathematical model to be utilized to conduct trade studies on candidate communications satellite architectures. First, a survey of candidate system parameters upon which to base the mathematical model was conducted. Next, potential mathematical models were considered. Finally, a mathematic model was presented to assess the performance of the communications satellite system architectures.

B. IDENTIFICATION OF KEY SYSTEM ARCHITECTURE ATTRIBUTES

1. Survey of Common Technical Performance Measures, Key Performance Parameters, and System Requirements

A survey of open source literature identified key architecture attributes of military satellite communications systems. This set of attributes is not specific to an existing or planned satellite program, but is intended to be representative of multiple system design options. Some of the attributes may be applicable to non-military satellite communication systems, and should be highlighted when considering commercial solutions that support the current national space policy to “pursue potential opportunities for transferring routine, operational space functions to the commercial space sector where beneficial and cost-effective, except where the government has legal, security, or safety needs that would preclude commercialization” (Office of the President of the United States, 2010, p. 14).

The five key attributes are: communications capacity, access, interoperability, commandability, and information assurance and protection. The descriptions of these attributes follow.

a. Communications Capacity

Capacity is the most fundamental measure for a communications system and is common to both commercial and military satellite systems. This attribute measures the amount of data communicated per unit of time (Gigabits per second (Gbps) for

example). Alternatively, this parameter can also be expressed as the available frequency bandwidth per unit time. The frequency metric may be more useful if it is desirable to normalize a performance measure that is independent of signal modulation schemes. For the purposes of the mathematical model presented in this thesis, the choices of units for capacity are left to the expert analyzing the system. The only requirement is that the method utilized to predict capacity is applied in the same manner to all system solutions being considered (Kakavas, Ha, & Garcia, 1998, GAO 94-48).

b. Access

Access is the ability of the system to provide communication in a defined location when needed. The coverage area defines the global locations in which communications are expected to be provided. Commercial satellite communications systems have coverage areas generally limited to population centers to ensure sufficient revenue from operating the systems. Population centers are quite stable, essentially fixed over 5-15 years of a satellite's operational life. Military needs require communications capability in remote areas, be it sparsely inhabited land areas or open ocean. Additionally, the areas to be covered often change, whether simply from the movement of units or from new areas of operation; these new operational areas can arise from training operations, disaster relief, and armed conflict. The "when needed" part of access is not only the expected operational lifetime of the system, but also incorporates the need for a satellite system architecture to provide communications coverage in both nominal and stressed conditions. A nominal operating condition would include a complete satellite constellation supporting missions with concentrations and locations of users in accordance with system design scenarios. A stressed condition could be the loss of a satellite due to circumstances such as system failure, the inability to secure a commercial lease, or a distribution of users that was not envisioned in the system design process (Bradley 1997, Kakavas, Ha, & Garcia, 1998, GAO/NSIAD-93-216, GAO 94-48).

c. Interoperability

Interoperability is a capability requirement for DoD systems. For satellite communications architectures this includes the system's ability to work with both

existing and planned terminals. The set of terminals supported is likely to include all U.S. military services and allied systems used in a joint international effort. Quantifying the number of specified user terminals that a system architecture can support is one method to measure interoperability. Other interoperability metrics may also be defined specific to a system requirements set (Wickline 1998, pp. 5–10).

d. Commandability

Commandability refers to the operator’s ability to command the satellite per the system requirements. Commandability may be comprised of a number of factors including the level of protection of ground operations centers against threats both manmade and natural, the time necessary to switch between system configurations, autonomous operations, and system level planning functions (Bradley 1997, GAO 94–48). The ability of the system to comply with these requirements defines the performance for this attribute.

e. Information Assurance and Protection

The policy, requirements, and implementation of information assurance and information protection will be defined in the satellite system requirements documentation (DoD Instruction 5000.02, 2008). The ability of the system to comply with these requirements defines the performance for this attribute. The policies and regulations continue to evolve with the Defense Information Systems Agency (DISA) as the lead for the DoD. As system architectures are traded, it is important to consider not only compliance of the system at the time that the trades are executed, but also the ability of the system to evolve and adapt over its lifetime.

2. Selection of Key Quantifiable System Architecture Attributes

Since the purpose of the model is to consider attributes that contribute to meeting vetted requirements, these five attributes appear to be at the core of communications systems architectures and should be included in the model as applicable. Thus, it is not necessary to use all five of the representative attributes in the mathematical model, but only those with significant requirements relevance. Of the five key attributes above, only

the communications capacity should be deemed required in the mathematical model to maintain traceability to the traditional modeling approach.

Beyond these five key attributes, there may be other requirements that are specific to the communications satellite system that lead to the inclusion of additional attributes in the mathematical model. Key Performance Parameters (KPPs), Technical Performance Measures (TPMs), and other system requirements should be assessed for relevance and utilized in the model as applicable. KPPs are a minimum set of performance parameters that guide a system development effort. KPPs are identified by users, approved by the requirements authority, and contained in the system Capability Description Document (CDD) (DoD Instruction 5000.02, 2008). TPMs are quantitative values that describe system performance (planned, predicted, or measured), and are often related to KPPs (Blanchard & Fabrycky, 2006, pp. 75–78; *The Defense Acquisition Guidebook*, <http://at.dod.mil/docs/DefenseAcquisitionGuidebook.pdf>, TPM definition and use).

The following three considerations should be employed in the selection of the key system architecture attributes for incorporation into the mathematical model.

First, a key attribute used in the mathematical model must be quantifiable with distinctly defined threshold, or minimum acceptable, and objective, or desired, levels. Qualitative assessments can be translated to numeric values; however, qualitative assessments should be avoided when possible. If the threshold and objective values are the same, or if all satellite system architectures provide the same level of performance, then the attribute will not be useful for distinguishing between architecture solutions, and therefore should not be included in the analysis.

Second, attributes that have a range of levels achievable between threshold and objective levels should be utilized in the mathematical model whenever possible. The range of capability will enable the mathematical model to more readily rank the various architectures. Extensive use of attributes that only meet or fail to meet objective performance may result in grouping of architectures into two categories. Attributes that do not have a range of levels achievable between the threshold and objective levels are discouraged but not precluded because there may be situations in which this ability to

provide objective performance is highly desirable. Examples may include an ability to survive a threat, or compatibility with other existing systems.

Third, attributes should be unique and not derived from each other. This can be done by avoiding the utilization of both primary and derived requirements. An example of a poor choice could be selecting both the Equivalent Isotropically Radiated Power (EIRP) and link data rate. Because the data rate is a function of the available power (Pritchard, Suyderhoud, & Nelson, 1993), they are interdependent. Remaining focused on high level system attributes avoids including dependent relationships in the model.

C. SELECTION OF A MATHEMATICAL MODEL TO ASSESS SYSTEM ARCHITECTURES

The mathematical model selected to assess system architectures is intended to replace the existing approach of calculating a cost per unit capacity. In order to have the new model accepted as a replacement it must incorporate the following elements. First, the model must be able to calculate a cost per capability provided to be compliant with DoD 5000 that requires system trades to be conducted in consideration of cost. Second, the model must be understandable by decision makers who use the data from the current cost per capacity method. To this end, it is desirable to have a method that can replicate the results of the traditional model for comparison. It is also necessary for the model approach and results to be clearly explainable to stakeholders or else the model will not be used.

1. Summary of Potential Mathematical Model Forms

Once a selection of key attributes is made it is necessary to have a methodology to implement for the assessment of the system architectures. A mathematical model incorporates multiple attributes and avoids subjectivity by quantifying system performance. It is expected that attributes used in the assessment of the architectures will have varying levels of importance. When system architecture trades are conducted on the system capacity attribute alone, the decision making process does not benefit from the careful consideration of other requirements-driven system architecture attributes.

One mathematical model that can be utilized in this analysis is termed the Weighting Method. In this approach, the attributes are first assigned a weight, with the sum of all the weights equal to one. A performance rating is then calculated for each attribute and the product of the weight and performance rating is computed. Finally, the sum of all weight and performance products for each communication satellite system architecture alternative is calculated. The resultant sum, or score, can be utilized to compare the scores from other communication satellite system architectures. The system architecture with the highest score is the most preferred (Blanchard & Fabrycky, 2006, pp. 178–180).

In a specific application of the Weighting Method, the attribute weights are given by the stakeholders. Next, the performance scores are assessed for each attribute and system based on the achieved performance normalized to the range defined by the threshold and objective levels. Specifically, the score achieved is a value between 0 and 1, where 0 represents achieving only the threshold level and 1 represents achieving the objective level. If a system under consideration does not meet the threshold performance value for an attribute, then a new threshold value must be specified and the model must be updated with the new value. Only when all systems meet the threshold for every key attribute can we ensure all systems are being assessed equally. The highest performance score is 1.0. No additional benefit is assessed for a system that exceeds the objective performance level. An overall score for each system architecture is calculated using the sum the products of the weight and score for each attribute. This value is called the Overall Measure Of Effectiveness (OMOE). The system selection is based on the highest OMOE (Laverghetta, 1998; Hootman & Whitcomb, 2005). This approach will be referred to as the OMOE Method.

Another mathematical modeling approach is the Analytical Hierarchy Process (AHP) developed by Thomas Saaty in the 1970s (Saaty, 1980). This process is another application of the Weighting Method, with the focus on the computation of a performance rating. Calculation of the performance rating is accomplished by comparing the performance between every system architecture pair for each performance attribute to determine which architecture is preferred and how strongly. The assessment of preference

can be done by group or individually. The AHP process is subjective and can be time consuming since the number of assessments grows geometrically as the product of the number of systems assessed and the number of key attributes selected (Ragsdale, 2008, pp. 777–784; Kaymaz & Dirı, 2008, Tsagdis, 2008).

Value Engineering is a technique that can be utilized to assess projects and identify opportunities for cost savings and cost avoidance while optimizing performance and productivity in a wide variety of applications including hardware, software, and infrastructure projects (Mandelbaum & Reed, 2006). Value Engineering is attributed to General Electric around 1948 when a process initially named Value Analysis was developed and applied to control production costs (Miles & Reger, 1958). This process has been updated over time and included in the United States Office of Management and Budget Circular A131 (Office of Management and Budget, 1993). The purpose of the Value Engineering technique is to provide best value system solution to both the customer and producer. The key principle of the Value Engineering technique is to consider all decisions and opportunities in light of the total system cost. The total system cost includes not only the cost to acquire the system that include development, manufacturing, and materials, but also costs to field, operate, maintain, upgrade, and dispose of the system. This approach can be used to account for the total cost of obtaining a level of performance that exceeds the threshold requirement as not every increase in capability is worth the cost to achieve the benefit.

2. Selection of Mathematical Model

The traditional system architecture selection process is a comparison of the cost per unit of system communication capacity. While this approach provides results that are easy to understand, it can also result in an architecture choice that ignores variation in other significant system requirements. Examples of key requirements that are ignored by this approach include, but are not limited to: access; interoperability; commandability; and information assurance and protection. In the traditional approach there is no way to consider tradeoffs between capacity and the other key system requirements. This could result in the preference and selection of an architecture that has significantly more

capacity in selected geographic areas over one that provides more uniform global coverage capability. Another example could be the selection of a system architecture that provides marginally more capacity over another that has more capability for information assurance and protection.

A mathematical model that combines the principles of the Value Engineering technique and OMOE Method has been selected for use. Specifically, calculating the total system cost per OMOE per number of years at Full Operational Capability (FOC) for each system architecture. Including the number of years at FOC is critical for comparing system architecture solutions that may operate for different periods of time. This mathematical model meets the criteria presented in II.A.2 above. Use of Value Engineering technique establishes that the total system cost be utilized in the system architecture trades. The OMOE Method can be simplified to consider only the system capacity, or be expanded to incorporate any number of key attributes. The overall method that defines a cost per OMOE results in an understandable decision making approach where the lowest cost per OMOE solution is preferred.

The AHP method was not selected due to its complexity and inherent difficulty in tracing results back to cost per unit of capacity (Ragsdale, 2008, pp. 777–784; Kaymaz & Diri, 2008; Tsagdis, 2008). The AHP method could be still be utilized to determine the weighting factors of the attribute; however, that choice was omitted in this assessment approach.

a. Model Limitation

There is a limitation with the selected approach in the rare instance that one of the system architectures only provides the threshold performance levels for all key attributes. In this instance the OMOE would be zero, resulting in a divide by zero error in the computation of the final cost per capability calculation. To overcome this issue it is necessary to adjust the OMOE of the threshold only system to make it greater than zero.

It is suggested that initially the OMOE for the threshold-only system be set to half that of the next higher OMOE. Further investigation of the other system architectures will need to be conducted to determine if this is an appropriate adjustment.

For example, if the system with the next higher OMOE has only one of 10 key attributes that exceeds threshold performance by a small amount, then setting the threshold-only OMOE to half is appropriate. However, if the next higher OMOE comes from a system that has one or more of 10 key attributes that exceeds threshold performance by a significant amount then the OMOE for the threshold only system architecture should be less than half. A sensitivity analysis of the system trade off results will be necessary to assess the effects of the OMOE adjustment to the threshold only system.

3. Description of the mathematical model

Now that a mathematical model has been selected, the model will be described in greater detail. The discussion will first cover the inputs, followed by the output, and finally the mathematical operations that transforms the inputs to the output.

a. Model Inputs

The inputs to the mathematical model include the following six components:

(1) The key attributes used in the determining of the OMOE score. Quantifiable values for each attribute must be available for each system architecture being traded.

(2) Threshold and objective performance levels for each attribute utilized. These requirements must be the same for every system analyzed by the model to avoid biasing results that would lead to unfair comparisons. All systems must also provide at least threshold performance capability for every key attribute. A conditional check of the inputs with the modeling tool can be used to identify if there are any violations of the threshold. If any system architecture requires a waiver to a threshold performance level a waiver request will be processed through the program's formal system engineering process. If the waiver is accepted it must be applied to all communication satellite architectures and the new threshold value must be incorporated in the model. If the waiver is not accepted then the system or systems that do not meet the threshold level cannot be assessed using this method.

(3) Weighting factors for each attribute. The weights are determined by the stakeholders. The only requirement is the sum of the attribute weights must be equal to one.

(4) Performance levels achieved for each attribute of each system. When recording the performance levels it is important to be sure that units are consistent with those used for the threshold and objective performance levels. Mixing units will result in erroneous results.

(5) Total Cost for each communications satellite system architecture being analyzed. The methodology for computing total costs must be consistent across all systems. One might consider utilizing the time value of money to normalize varying funding profiles over multiple years. Utilizing the life cycle cost of the systems is encouraged as long as the computation across all systems is equivalent. For example, when comparing the expansion of an existing system to the development of a new system it may be necessary to exclude from the life cycle calculation funds that have previously been expended, or that were expended by other groups, such as venture capital.

(6) Time, in years, at full operational capability (FOC). This measure is necessary to normalize across potentially different time periods of FOC. The model will neglect to provide a value for any performance provided as the system architecture ramps up to FOC, or ramps down as the system is retired. Since the expectation is to provide full capability it is appropriate to neglect any partial capability for this trade.

b. Model Output

The output of the mathematical model is the “Cost per Year per OMOE” for each communications satellite system architecture evaluated. The lower the cost per year per OMOE per year, the more preferred the system architecture is. Final selection of the appropriate system architecture by decision makers is expected to be based on more than just the results of this mathematical model. Other factors outside of the model will need to be considered in the final satellite system architecture selection process. Such factors may include budget constraints, rapidly evolving threats and needs, and the level of program risk. However, the model output will provide objective data regarding

requirements satisfaction, which will help decision makers make an informed selection regarding which system architecture to develop, produce, or maintain.

Additional post processing of the cost per year per OMOE result can be performed for the display of the results or sensitivity analysis. The data post processing efforts are defined by the desires and expectations of the decision makers utilizing the data. The development of standard post processing efforts is beyond the scope of this thesis.

c. Model Calculations

The following is a description of how the inputs are transformed into an output in the mathematical model. The approach described can easily be implemented in Microsoft Excel, or any other calculation software. The number of key attributes, n , is a positive integer. For making a comparison, the number of system architectures is necessarily an integer greater than one. The steps demonstrated are for a given architecture and must be repeated for every system architecture under consideration.

The first step is to calculate a Raw Score that reflects the level of achieved performance for each key attribute. This is done by computing the ratio of achieved performance to the range as shown in Equation 1.

$$\text{Raw Score} = \frac{\text{Achieved Performance} - \text{Threshold Requirement}}{\text{Objective Requirement} - \text{Threshold Requirement}} \quad (1)$$

The achieved performance of all key attributes must be equal to or greater than the threshold performance level. As mentioned earlier, a system with an achieved performance below the threshold will only be considered if the decision maker sets a new threshold level for all architectures and the model is updated with the new threshold level. Otherwise, the architecture will be omitted from consideration.

Next, the Raw Score must be corrected so that the maximum value of the attribute Score is 1.0. This discourages obtaining greater than objective level performance

at the expense of other key attributes. Any Raw Score values that Equation 1 calculates higher than 1.0 are automatically assigned a value of 1.0 and represents the Corrected Score that is used for future calculations.

Once all Raw Score values are calculated and comply with the two rules, the Weighted Score for each attribute and system architecture is computed. This is done by calculating the product of the Corrected Performance Score and the input attribute weighting as shown in Equation 2.

$$\text{Weighted Score} = \text{Corrected Performance Score} \times \text{Attribute Weight} \quad (2)$$

With the Weighted Scores of all key attributes calculated, the OMOE score for each system architecture can be computed. For the number of key attributes, n , the OMOE score is the sum of all Weighted Scores of the system architecture as shown in Equation 3. There is an OMOE score for each system architecture.

$$\text{OMOE Score} = \sum_{n=1}^{\text{Number Key Attributes}} \text{Weighted Score}_n \quad (3)$$

Finally, the cost per year per OMOE is calculated for each communications satellite system architecture by dividing the total system architecture cost by number of years the system is planned to be FOC and the computed total OMOE score. This is shown in Equation 4. The total system cost includes all development, acquisition, fielding, operations, maintenance and upgrades, and system disposal costs paid by the Government or customer.

$$\text{Cost/year/OMOE} = \frac{\text{Cost}}{\text{FOC Years} \times \text{OMOE Score}} \quad (4)$$

D. CHAPTER SUMMARY

This chapter has presented a survey of candidate system parameters upon which to base a mathematical model that can be used to conduct trade studies on candidate communications satellite architectures. The five primary key attributes are: communication capacity, access, interoperability, commandability, and information assurance and protection. Only the capacity attribute should be considered necessary to all system architecture trade analyses, due to the commonality with current trade analyses and commercial leasing metrics. Including key attributes not identified in the primary list are encouraged but must be based on the specific requirements defined for the system and may include KPPs, TPMs, and overarching requirements.

Three mathematical model approaches were discussed. The selected approach is a combination of two of them and enables a comparison of the cost for achieved performance level. This approach leveraged three mathematical model benefits: 1) the ability for stakeholders to weight the relative importance of all key attributes utilized in the model; 2) a calculation of raw scores to measure the performance of each key attribute across system architectures; and 3) consideration of the total system cost for each system architecture.

The inputs, output, and calculation methodology of the selected mathematical model were presented. The output of the mathematical model is a cost per year per OMOE score. The OMOE score multiplied by the number of years at Full Operational Capability can be considered a unit of effectiveness. The higher the OMOE, the more effective the system architecture is at meeting requirement objectives. The longer a system can be at FOC, the more effective the system architecture is at providing communications capability. Thus, dividing the real cost of a system by a unit of effectiveness generates an “effective cost.” The result is an intuitive metric for decision makers to utilize in their system architecture selection. Namely, the most preferred system architecture will have the lowest cost per unit of effectiveness. We cannot claim “best,” as the decision makers will still have to consider these results in concert with other factors that are not quantitatively included in the model, such as how soon a system

can be fielded, budget constraints, and overall level of program risk before making a final communication satellite system architecture selection.

III. USE OF THE MATHEMATICAL MODEL

A mathematical model for conducting trade studies on candidate communications satellite architectures has been presented. In this chapter the mathematical model will be exercised to demonstrate the functionality. The satellite systems, requirements, and performance inputs used in this chapter are for illustrative purposes only, and do not represent real or planned satellite systems.

The system architecture envisioned in this example is intended to provide communications capability world-wide between 65° north and south latitude. The planned usage of the communications capability is described in a DoD generated scenario that includes details about terminal types, locations, and data needs in both nominal and stressed contingencies. This use of a scenario to quantify the capacity provided by the satellite communications architecture is the same process utilized traditionally for assessing systems. To provide worldwide coverage, the space system envisioned will utilize a minimum of four satellites in geosynchronous orbit. There is no restriction on the use of more satellites to meet system requirements.

A. DEFINITION OF THE SET OF KEY ATTRIBUTES FOR THE SATELLITE COMMUNICATIONS SYSTEM ARCHITECTURE

The first steps in creating the mathematical model are to select and weight the key attributes of the communications satellite system architecture. There is no upper limit to the number of attributes that the model can support; however, the list must be manageable and understandable to the stakeholders. For this exercise, all five of the primary attributes identified previously will be utilized in conjunction with six additional requirements. These attributes along with their threshold and objective values will be discussed below. All attributes are weighted equally, except for Communications Capacity and the Full Operational Capability date, which have double the weight of the other attributes. Assigning a different weight to these two attributes demonstrates the flexibility the user has in assigning priorities to the attributes under consideration.

1. Communications Capacity

Communications Capacity is the total throughput supported by the system architecture in a specified scenario that includes the global types, locations, and data needs. The units for this attribute are Gigabits per second (Gbps). The threshold value is 15 Gbps and the objective value is 50 Gbps.

2. Nominal Case Access

The Nominal Case Access attribute represents the percentage of terminals located globally that can be supported in the specified scenario that represents expected nominal usage. This would include all requirements for both operations and training exercises. This attribute is included in addition to the system capacity to limit biasing the performance score by choosing to support only a few high capacity terminals and abandoning the support of numerous smaller terminals. The units for the attribute are percent. The threshold value is 20% and the objective value is 100%.

3. Stressed Case Access

The Stressed Case Access attribute represents the percentage of terminals located globally that can be supported in a specified scenario that represents expected stressed usage. In a stressed situation the layout of terminals is expected to be different, including higher concentrations of terminals than the Nominal Case Access model in some geographically distinct areas. This attribute is included in addition to the system capacity to limit biasing the performance scores by choosing to support only a few high capacity terminals, and abandoning the support of numerous smaller terminals. The units for the attribute are percent. The threshold value is 30%, and the objective value is 100%.

4. Interoperability

Interoperability quantifies the extent to which different user terminal pairs can operate together. System requirements support communication in four distinct frequency bands, C, X, Ku, and Ka, for example. Communication between terminals of the same frequency band is automatically accomplished; however, it is highly desirable to have the ability to have unmatched frequency band terminals interface seamlessly. This means that

the satellite converts between bands, for example receiving a C band input from one terminal and linking that data stream to a receiving terminal in the Ku band. It is possible to support some of this capability on the ground with a multi band terminal, but if the functionality can be accommodated on the satellite at a reasonable price this would eliminate operations and maintenance constraints and costs to the terminals. This attribute is the count of the number of bands that can be converted from one to another. The threshold value is 0 and the objective value is 12. This input is an integer value.

5. Commandability

The Commandability attribute focuses on the autonomous response of each satellite in the constellation by quantifying how long the system will continue to provide communication service in the last commanded configuration. The configuration includes providing satellite station keeping, beam pointing, bandwidth allocations, and the system event logs that can be downloaded when ground control is restored. The threshold value is 5 days and the objective value is 20 days.

6. Information Protection

The Information Protection attribute will measure compliance with current information assurance and information protection policies. Waivers from the list of existing policies that must be complied with are possible but must be minimized. This attribute will count the number of waivers that must be obtained. The threshold value is 5 waivers and the objective is 0 waivers. This input is an integer value.

7. Initial Operational Capability Date

This attribute tracks when Initial Operational Capability (IOC) is expected to be achieved. The threshold value is 2025 and the objective is 2018. This input is an integer value.

8. Full Operational Capability Date

This attribute tracks when Full Operational Capability (FOC) is expected to be achieved. The threshold value is 2030 and the objective is 2024. This input is an integer value.

9. Constellation Restoration Time

The Constellation Restoration Time attribute quantifies how long it takes to restore FOC when a satellite in the constellation suffers a catastrophic loss. This allows a trade of constellation capability based on whether a spare is a) only manufactured and launched after a failure occurs; b) manufactured ahead of time and launched after the failure occurs; or c) maintained on-orbit and available to be repositioned after the failure occurs. The threshold value is 5 years and the objective value is 0.25 years.

10. Launch Vehicle Compatibility

This attribute addresses the flexibility in launch vehicles available for use. Flexibility in the launch vehicle used can enable a more robust fielding the system in the event of any production issues of the launch vehicle. The threshold value is 1 launch vehicle and the objective is 3 different launch vehicles. This value is an integer.

11. Anti-Jam Capability Level

The Anti-Jam Capability Level attribute indicates the combination of Anti-Jam capabilities provided by the communications satellite system architecture. The levels are integer values that indicate compliance with a variety of requirement levels including interference signals; interference nulling; geolocation identification and reporting; and the amount of power margin against an interference beam. Level 1 represents the most robust Anti-Jam capability required based on the combined performance of the constituent requirements. For example a Level 1 score would incorporate a high level of adaptive processing to isolate interference signals, nulling capability for the quantity and locations of interference sources, the ability to identify and report the location of interference sources to the required accuracy, and the ability to successfully transmit in the presence of interference. Level 2 would represent the next best Anti-Jam capability

achievement, and so forth to level 5, which would represent the minimum acceptable level of Anti-Jam capability. The threshold value is 5 and the objective value is 1. This value is an integer.

B. DEFINITION OF A SET OF ARCHITECTURES

For this example a set of nine fictitious communications satellite system architectures were analyzed. Each architecture represents a concept that meets the requirements through a different approach such as would be generated by multiple contractors. The range of system performance levels may result from varying: complexity and capability of the individual satellites; technology and production development times; satellite production rates; and levels of control and autonomy of the fielded system.

As with the key attributes, there is no limit to the number of system architectures that can be analyzed by the mathematical model. A set of nine architectures was selected to exercise the model in this example. The model and data have been input in a Microsoft Excel 2007 Workbook. This exercise is not based on a real system; therefore, values assigned for each key attribute were assigned by a random number generator. None of the performance inputs were allowed to be below the threshold value. Performance levels above the objective value were allowed when appropriate to verify that the Excel model properly corrects the attribute scores. Performance above the objective level is not realistic for the number of Information Protection waivers, Anti-Jam Capability Level, and the percentage of terminals supported attributes.

C. EVALUATION OF A SET OF ARCHITECTURES USING THE MATHEMATICAL MODEL

The mathematical model was implemented using an Excel spreadsheet with the defined inputs utilized in the model.

The weighting for the key attributes is shown in Table 1. A set of conditional formatting rules is applied to the Weighting Check value such that if the cell has a value of one the cell fill will be green. If the cell value is greater or less than 1 the Weighting Check box will turn red to indicate an erroneous input. This check is illustrated when the

Constellation Restoration Time weight is set to zero as shown in Table 2. The key attributes for Communications Capacity and FOC Date were selected to be more important than all other attributes, reflected by a weight that is twice the value of the other weights. Distributing the weights to the key attributes per this relative importance results in the distribution shown in Table 1.

Table 1. Mathematical Model Weighting Inputs.

Key Attributes	Weight
1. Capacity (Gbps)	0.15
2. Nominal Case Access (% terminals supported)	0.08
3. Stressed Case Access (% terminals supported)	0.08
4. Interoperability (# of cross band conversions)	0.08
5. Commandability (days of autonomous operations)	0.08
6. Information Protection (# of policy waivers)	0.08
7. IOC Date (year)	0.08
8. FOC date (year)	0.15
9. Constellation Restoration Time (years)	0.08
10. Launch Vehicle Flexibility	0.08
11. Anti Jam Capability Level	0.08
Weighting check	1.00

Table 2. Mathematical Model Weighting Check Error.

Key Attributes	Weight
1. Capacity (Gbps)	0.15
2. Nominal Case Access (% terminals supported)	0.08
3. Stressed Case Access (% terminals supported)	0.08
4. Interoperability (# of cross band conversions)	0.08
5. Commandability (days of autonomous operations)	0.08
6. Information Protection (# of policy waivers)	0.08
7. IOC Date (year)	0.08
8. FOC date (year)	0.15
9. Constellation Restoration Time (years)	0.00
10. Launch Vehicle Flexibility	0.08
11. Anti Jam Capability Level	0.08
Weighting check	0.92

The threshold and objective values for each key attribute are shown in Table 3. Additionally, the table shows whether an attribute is to be minimized or maximized. If the objective value is larger than the threshold value the attribute is to be maximized; otherwise, the attribute is to be minimized. The Criteria Type result is used to error check Table 4.

Table 3. Mathematical Model Threshold and Performance Inputs.

	1. Capacity (Gbps)	2. Nominal Case Access (% terminals supported)	3. Stressed Case Access (% terminals supported)	4. Interoperability (# of cross band conversions)	5. Commandability (days of autonomous operations)	6. Information Protection (# of policy waivers)	7. IOC Date (year)	8. FOC date (year)	9. Constellation Restoration Time (years)	10. Launch Vehicle Flexibility	11. Anti-Jam Capability Level
Threshold	15	0.2	0.3	0	5	5	2025	2030	5	1	5
Objective	50	1	1	12	20	0	2018	2024	0.25	3	1
Criteria Type	maximize	maximize	maximize	maximize	maximize	minimize	minimize	minimize	minimize	maximize	minimize

The performance inputs generated by the random number generator for each attribute are shown in Table 4. The green highlight in the cell for each performance input indicates the requirement for the value to meet or exceed the threshold requirement has been met. This is accomplished by first comparing the performance input value to the threshold requirement. If the key attribute value is to be maximized to meet objective performance, the input must be equal to or greater than the threshold value. If the key attribute value is to be minimized to meet objective performance, the input must be equal to or less than the threshold value. This check is accomplished in Excel by using the Excel IF function. The results of the performance check are indicated in a calculation section of the spreadsheet with a “Pass” or “Threshold Error.” Table 5 shows the results of this intermediate calculation for the model inputs. The highlight in the performance input cell is accomplished by utilizing two Excel conditional formatting rules, one that colors the cell green if the calculation sheet has a “Pass” in the corresponding system attribute cell, and the second to color the cell red if the calculation sheet has a “Threshold Error” in the corresponding system attribute cell. Calculations cannot continue until the threshold error is resolved by eliminating the system from consideration, adjusting the threshold value requirement so that all systems pass, or adjusting the system design so that the threshold requirement can be met.

Functionality of each cell's threshold check was verified. An example of this functionality check is illustrated in Tables 6 and 7 where System Concept 3 Capacity, System Concept 4 Commandability, and System Concept 7 Anti-Jam Capability Level were all set below the threshold level. These values were not used in further model calculations.

Table 4. Mathematical Model Performance Inputs.

	1. Capacity (Gbps)	2. Nominal Case Access (% terminals supported)	3. Stressed Case Access (% terminals supported)	4. Interoperability (# of cross band conversions)	5. Commandability (days of autonomous operations)	6. Information Protection (# of policy waivers)	7. IOC Date (year)	8. FOC date (year)	9. Constellation Restoration Time (years)	10. Launch Vehicle Flexibility	11. Anti-Jam Capability Level
System Concept 1	41.95	0.31	0.91	3	13	5	2021	2024	5	4	2
System Concept 2	20.35	0.95	0.77	14	20	5	2018	2027	0.75	2	3
System Concept 3	16.89	0.6	0.75	4	11	4	2019	2030	4	3	4
System Concept 4	17.16	0.72	0.89	8	22	2	2018	2024	1	2	1
System Concept 5	38.05	0.4	0.42	5	20	4	2018	2028	3.25	3	1
System Concept 6	24.24	0.33	0.37	3	10	1	2024	2029	1.25	3	1
System Concept 7	38.85	0.62	0.52	0	6	3	2023	2029	2.75	4	1
System Concept 8	28.34	0.96	0.63	4	18	5	2022	2029	1.25	4	4
System Concept 9	15.84	0.9	0.63	13	20	4	2018	2027	1.5	4	2

Table 5. Mathematical Model Threshold Error Check Intermediate Calculation.

	1. Capacity (Gbps)	2. Nominal Case Access (% terminals supported)	3. Stressed Case Access (% terminals supported)	4. Interoperability (# of cross band conversions)	5. Commandability (days of autonomous operations)	6. Information Protection (# of policy waivers)	7. IOC Date (year)	8. FOC date (year)	9. Constellation Restoration Time (years)	10. Launch Vehicle Flexibility	11. Anti-Jam Capability Level
System Concept 1	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
System Concept 2	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
System Concept 3	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
System Concept 4	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
System Concept 5	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
System Concept 6	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
System Concept 7	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
System Concept 8	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
System Concept 9	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass

Table 6. Mathematical Model Input Threshold Check Validation Example.

	1. Capacity (Gbps)	2. Nominal Case Access (% terminals supported)	3. Stressed Case Access (% terminals supported)	4. Interoperability (# of cross band conversions)	5. Commandability (days of autonomous operations)	6. Information Protection (# of policy waivers)	7. IOC Date (year)	8. FOC date (year)	9. Constellation Restoration Time (years)	10. Launch Vehicle Flexibility	11. Anti-Jam Capability Level
System Concept 1	41.95	0.31	0.91	3	13	5	2021	2024	5	4	2
System Concept 2	20.35	0.95	0.77	14	20	5	2018	2027	0.75	2	3
System Concept 3	10	0.6	0.75	4	11	4	2019	2030	4	3	4
System Concept 4	17.16	0.72	0.89	8	1	2	2018	2024	1	2	1
System Concept 5	38.05	0.4	0.42	5	20	4	2018	2028	3.25	3	1
System Concept 6	24.24	0.33	0.37	3	10	1	2024	2029	1.25	3	1
System Concept 7	38.85	0.62	0.52	0	6	3	2023	2029	2.75	4	6
System Concept 8	28.34	0.96	0.63	4	18	5	2022	2029	1.25	4	4
System Concept 9	15.84	0.9	0.63	13	20	4	2018	2027	1.5	4	2

Table 7. Mathematical Model Threshold Error Check Intermediate Calculation Validation Example.

	1. Capacity (Gbps)	2. Nominal Case Access (% terminals supported)	3. Stressed Case Access (% terminals supported)	4. Interoperability (# of cross band conversions)	5. Commandability (days of autonomous operations)	6. Information Protection (# of policy waivers)	7. IOC Date (year)	8. FOC date (year)	9. Constellation Restoration Time (years)	10. Launch Vehicle Flexibility	11. Anti-Jam Capability Level
System Concept 1	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
System Concept 2	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
System Concept 3	Threshold Error	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
System Concept 4	Pass	Pass	Pass	Pass	Threshold Error	Pass	Pass	Pass	Pass	Pass	Pass
System Concept 5	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
System Concept 6	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
System Concept 7	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Threshold Error
System Concept 8	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
System Concept 9	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass

The remaining inputs are the system cost and number of years at FOC. For the example all systems will be at FOC for 10 years. This fixed FOC period could represent a situation where the next generation system is required to be fielded. The total cost for each satellite communication system architecture was generated as a random number between \$3B and \$6B. The inputs for these parameters are shown in Table 8.

Table 8. Mathematical Model Cost and FOC Duration Inputs.

System Architecture	Cost (\$B)	Years at FOC
System Concept 1	3.6	10
System Concept 2	3.3	10
System Concept 3	4.5	10
System Concept 4	6.0	10
System Concept 5	5.7	10
System Concept 6	3.8	10
System Concept 7	5.1	10
System Concept 8	4.7	10
System Concept 9	4.7	10

The calculation of the OMOE score occurs in three steps in the spreadsheet. First, an uncorrected raw performance score is computed for each attribute using Equation 1. The results of this computation are shown in Table 9. This example problem included

some performance inputs that exceeded the objective level, resulting in a raw performance score that is greater than 1.0, such as the Interoperability for System 2 and the Commandability for System 4.

Table 9. Raw Performance Calculation Results.

	1. Capacity (Gbps)	2. Nominal Case Access (% terminals supported)	3. Stressed Case Access (% terminals supported)	4. Interoperability (# of cross band conversions)	5. Commandability (days of autonomous operations)	6. Information Protection (# of policy waivers)	7. IOC Date (year)	8. FOC date (year)	9. Constellation Restoration Time (years)	10. Launch Vehicle Flexibility	11. Anti-Jam Capability Level
System Concept 1	0.77	0.14	0.87	0.25	0.53	0.00	0.57	1.00	0.00	1.50	0.75
System Concept 2	0.15	0.94	0.67	1.17	1.00	0.00	1.00	0.50	0.89	0.50	0.50
System Concept 3	0.05	0.50	0.64	0.33	0.40	0.20	0.86	0.00	0.21	1.00	0.25
System Concept 4	0.06	0.65	0.84	0.67	1.13	0.60	1.00	1.00	0.84	0.50	1.00
System Concept 5	0.66	0.25	0.17	0.42	1.00	0.20	1.00	0.33	0.37	1.00	1.00
System Concept 6	0.26	0.16	0.10	0.25	0.33	0.80	0.14	0.17	0.79	1.00	1.00
System Concept 7	0.68	0.53	0.31	0.00	0.07	0.40	0.29	0.17	0.47	1.50	1.00
System Concept 8	0.38	0.95	0.47	0.33	0.87	0.00	0.43	0.17	0.79	1.50	0.25
System Concept 9	0.02	0.88	0.47	1.08	1.00	0.20	1.00	0.50	0.74	1.50	0.75

The next calculation step is the correction of the raw performance scores to limit the score to a maximum of one. If the raw performance score is greater than 1, it is automatically reset to 1 to prohibit systems from benefiting from exceeding objective performance. The result of this correction is shown in Table 10.

Table 10. Corrected Performance Score Calculation Results.

	1. Capacity (Gbps)	2. Nominal Case Access (% terminals supported)	3. Stressed Case Access (% terminals supported)	4. Interoperability (# of cross band conversions)	5. Commandability (days of autonomous operations)	6. Information Protection (# of policy waivers)	7. IOC Date (year)	8. FOC date (year)	9. Constellation Restoration Time (years)	10. Launch Vehicle Flexibility	11. Anti-Jam Capability Level
System Concept 1	0.77	0.14	0.87	0.25	0.53	0.00	0.57	1.00	0.00	1.00	0.75
System Concept 2	0.15	0.94	0.67	1.00	1.00	0.00	1.00	0.50	0.89	0.50	0.50
System Concept 3	0.05	0.50	0.64	0.33	0.40	0.20	0.86	0.00	0.21	1.00	0.25
System Concept 4	0.06	0.65	0.84	0.67	1.00	0.60	1.00	1.00	0.84	0.50	1.00
System Concept 5	0.66	0.25	0.17	0.42	1.00	0.20	1.00	0.33	0.37	1.00	1.00
System Concept 6	0.26	0.16	0.10	0.25	0.33	0.80	0.14	0.17	0.79	1.00	1.00
System Concept 7	0.68	0.53	0.31	0.00	0.07	0.40	0.29	0.17	0.47	1.00	1.00
System Concept 8	0.38	0.95	0.47	0.33	0.87	0.00	0.43	0.17	0.79	1.00	0.25
System Concept 9	0.02	0.88	0.47	1.00	1.00	0.20	1.00	0.50	0.74	1.00	0.75

The weighted score for each performance input is calculated by applying Equation 2. The OMOE score is calculated by applying Equation 3. The results of both these calculations are shown in Table 11. The OMOE score is highlighted in blue.

Table 11. Weighted Performance Scores and OMOE Calculation Results.

	1. Capacity (Gbps)	2. Nominal Case Access (% terminals supported)	3. Stressed Case Access (% terminals supported)	4. Interoperability (# of cross band conversions)	5. Commandability (days of autonomous operations)	6. Information Protection (# of policy waivers)	7. IOC Date (year)	8. FOC date (year)	9. Constellation Restoration Time (years)	10. Launch Vehicle Flexibility	11. Anti-Jam Capability Level	OMOEE Score
System Concept 1	0.12	0.01	0.07	0.02	0.04	0.00	0.04	0.15	0.00	0.08	0.06	0.59
System Concept 2	0.02	0.07	0.05	0.08	0.08	0.00	0.08	0.08	0.07	0.04	0.04	0.60
System Concept 3	0.01	0.04	0.05	0.03	0.03	0.02	0.07	0.00	0.02	0.08	0.02	0.35
System Concept 4	0.01	0.05	0.06	0.05	0.08	0.05	0.08	0.15	0.06	0.04	0.08	0.71
System Concept 5	0.10	0.02	0.01	0.03	0.08	0.02	0.08	0.05	0.03	0.08	0.08	0.57
System Concept 6	0.04	0.01	0.01	0.02	0.03	0.06	0.01	0.03	0.06	0.08	0.08	0.42
System Concept 7	0.10	0.04	0.02	0.00	0.01	0.03	0.02	0.03	0.04	0.08	0.08	0.44
System Concept 8	0.06	0.07	0.04	0.03	0.07	0.00	0.03	0.03	0.06	0.08	0.02	0.48
System Concept 9	0.00	0.07	0.04	0.08	0.08	0.02	0.08	0.08	0.06	0.08	0.06	0.62

Applying Equation 4, the Cost per OMOE per year at FOC is calculated using the OMOE score and the values in Table 8. The Excel “Rank” function is applied to this result to graphically show the results, with the highest rank associated with the lowest Cost per year at FOC per OMOE and indicated in the Excel generated graded color scale where the most preferred system is highlighted in green and least preferred is highlighted in red. The results of these calculations are shown in Table 12.

Table 12. Cost per OMOE per year at FOC Calculation and Ranking Results.

System Architecture	Cost (\$B)	Years at FOC	OMOEE Score	Cost/OMOEE/FOCyear	Rank
System Concept 1	3.6	10	0.59	0.61	2
System Concept 2	3.3	10	0.60	0.55	1
System Concept 3	4.5	10	0.35	1.30	9
System Concept 4	6.0	10	0.71	0.85	4
System Concept 5	5.7	10	0.57	1.00	7
System Concept 6	3.8	10	0.42	0.91	5
System Concept 7	5.1	10	0.44	1.15	8
System Concept 8	4.7	10	0.48	0.99	6
System Concept 9	4.7	10	0.62	0.76	3

Example Demonstrating Threshold-Only Performance Handling

As mentioned previously, there is one special case that may arise from a given set of inputs. In the unlikely event a system achieves only threshold levels for all key attributes, an OMOE of zero would result and cause a divide by zero error. To avoid this, the model replaces the zero value with an OMOE of one half the lowest OMOE of all other system architectures being considered.

To demonstrate how the model handles this special case, an additional system is added to the previous example. The cost of the Threshold Only system architecture was generated in the same manner as for the other system architectures, as a random number between \$3.0B and \$6.0B. In this example, the cost of the Threshold Only system architecture is \$3.9B. Years at FOC matches the others at 10 years. Table 13 shows the revised rankings. In this case the Threshold Only option is least preferred.

Table 13. Cost per OMOE per year at FOC Calculation and Updated Ranking Results.

System Architecture	Cost (\$B)	Years at FOC	OMOE Score	Cost/OMOE/FOCyear	Rank
System Concept 1	3.6	10	0.59	0.61	2
System Concept 2	3.3	10	0.60	0.55	1
System Concept 3	4.5	10	0.35	1.30	9
System Concept 4	6.0	10	0.71	0.85	4
System Concept 5	5.7	10	0.57	1.00	7
System Concept 6	3.8	10	0.42	0.91	5
System Concept 7	5.1	10	0.44	1.15	8
System Concept 8	4.7	10	0.48	0.99	6
System Concept 9	4.7	10	0.62	0.76	3
Threshold Only	3.9	10	0.17	2.25	10

D. DISCUSSION OF RESULTS

It is acknowledged that decision makers will still have to consider the results of the model in concert with other factors that do not lend themselves to incorporation into a mathematical model, such as budget constraints, rapidly evolving threats and needs, and

the level of program risk. An analysis of the results will be necessary to support the final decision, with the approach and focus to be defined by the needs of the decision makers.

While this analysis is based upon fictional inputs, some interesting observations can be made about the results.

1. Comparison to Cost per Capacity Approach

For comparison to the generally accepted current approach of calculating a cost per capacity, the cost was divided by the capacity defined in the performance input for each system. This calculation results in a significantly different preference ranking of the system architectures as shown in Table 14. The preference from System Concept 2 changed from 1st to 6th place. System Concept 7 changed from 8th to 2nd place. The Threshold Only system moved up from 8th to 3rd place. This result indicates that when a satellite communications system architecture has additional requirements beyond the system capacity, these other key attributes must be factored into the decision to avoid eliminating critical capabilities defined by the users.

This biasing can be quantifying by varying the cost and capacity to identify when the preference ranking changes. System Concept 1 is strongly preferred in the Cost per Capacity method. The capacity must drop from 42 Gbps to less than 28 Gbps, 33%; or the cost must increase from \$3.6B to more than \$5.5B, 55%, before System Concept 7 becomes the most preferred system architecture. Decreasing the capacity of System Concept 1 to less than 28Gbps does not change the 2nd place preference in the Cost per OMOE per year at FOC Calculation. Increasing the cost of System Concept 1 to \$5.6B changes the preference from 2nd to 5th place. This biasing is significant, and again ignores the benefits of all other key system requirements, resulting in the likely selection of a system architecture solution that is not optimized for either cost or performance.

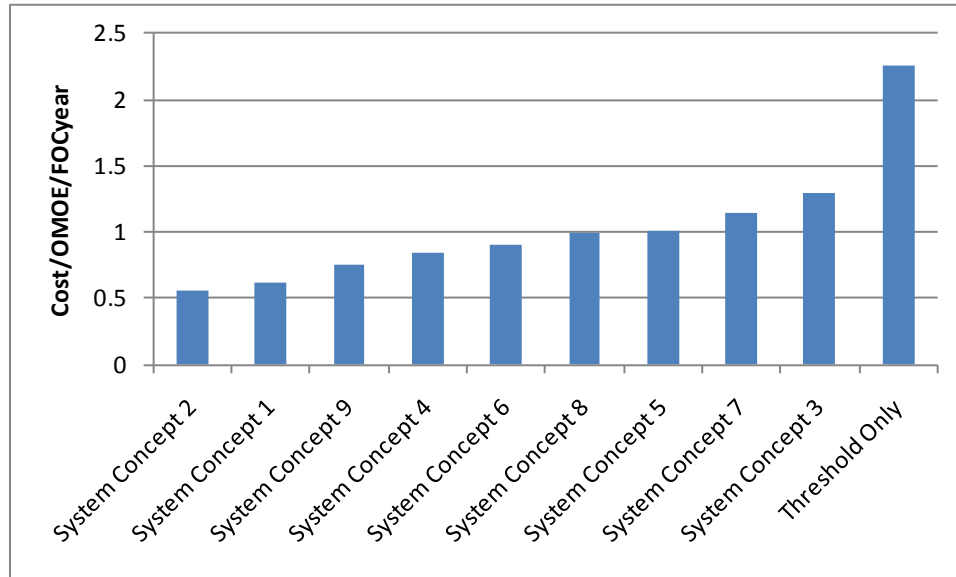
Table 14. Cost per Capacity Calculation and Ranking Results.

System Architecture	Cost/Capacity	Cost/Capacity Rank
System Concept 1	0.08582	1
System Concept 2	0.16216	5
System Concept 3	0.26643	8
System Concept 4	0.34965	10
System Concept 5	0.14980	3
System Concept 6	0.15677	4
System Concept 7	0.13127	2
System Concept 8	0.16584	6
System Concept 9	0.29672	9
Threshold Only	0.26000	7

2. Threshold Only Concept Addition

The addition of the Threshold Only system concept does not affect the ranking of any other system architecture. All other systems are more preferred. Adjustment of the Threshold Only system OMOE shows that the rankings do not change until the Threshold Only OMOE is at least 87% of the lowest OMOE score, that of System Concept 3. If the Threshold Only system OMOE is made equal to that of System Concept 3 the ranking of the Threshold Only system will increase to 8th place which remains well out of range of the most preferred system concepts. None of the system concepts in this example have more than one key attribute that is at the threshold performance level, and as such there is relevant benefit to achievement of performance above the threshold level. In light of this it would be more appropriate to decrease the OMOE score of the threshold only system relative to System Concept 3. A comparison of all Cost per OMOE per year at FOC arranged from lowest to highest is shown in Figure 1.

Figure 1. Cost per OMOE per year at FOC Summary.



3. Performance Score and Cost Comparisons

The preference rankings clearly show that more performance at any cost is not the best value solution. Cost is considered as independent variable and accounted for in the system trades. In this example, we see how system cost is the dominating factor in determining the preferred solution. The small cost or OMOE changes don't influence the rankings significantly.

The highest OMOE score belongs to System Concept 4, the system that is ranked 4th in preference, and is 0.11, or 18%, higher than the score for System Concept 2. System Concept 4 is also the most expensive system and \$2.7B, or 82%, more than System Concept 2. The 82% cost difference dominates the 18% performance benefit. Similarly, for comparing System Concept 9 to System Concept 2, the 2% OMOE performance benefit is dominated by the 42% higher cost of System Concept 9. In both instances cost will need to be decreased for this solution to become competitive with System Concept 2.

The OMOE score for System Concept 2 is 0.02, or 2%, higher than for System Concept 1, the system ranked 2nd in preference. Additionally, System Concept 1, the

system ranked 2nd in preference, is \$0.3B, or 9%, more than System Concept 2. System Concept 2 has more capability at a lower cost, thus it makes sense it is preferred over system Concept 1.

4. Performance Score and Cost Variation

A simple sensitivity analysis of the cost input indicates that for System Concept 2 cost must increase by \$0.4B (12%) to \$3.7B, or the OMOE score must decrease by 0.07 (12%) to 0.53 to change the preference rank from first to second place. This variation is consistent with the differences described in the previous section. Similarly, a net change in cost and performance between System Concepts 2 and 9 of at least 40% would need to be accomplished for System Concept 9 to become the most preferred.

In an actual system the cost and OMOE score are likely to be related and decreased cost will result in decreased capability. These relative changes, while outside the scope of this thesis, must be considered in the detailed sensitivity analysis for real application.

It is possible that the system architecture threshold requirements are based on existing systems, and because these systems would have little to no development cost, a Threshold Only solution would be one that has significantly lower cost than the other system architectures. In order to be the most preferred solution the maximum cost of the Threshold Only system is \$0.9B, or 73% lower than the cost of System Concept 2.

The Threshold Only system is not competitive with eight of the nine system concepts. This is despite having a cost that is already 40% lower than the next least expensive concept. To become the most preferred concept the cost would have to decrease an additional \$1.1 (55%), down to \$0.9B, or the OMOE score would have to be increased to 0.37 (206%). It must be noted that an OMOE score of 0.38 would exceed the score achieved by System Concept 2 which had performance above threshold in 10 of the 11 key performance attributes.

5. Attribute Weighting Effect

To check the effect of the selected attribute weighting an analysis was run with all attributes weighted equally at 1/11. The results are shown in Table 15, with the most preferred concept remaining unchanged (System Concept 2). The cost per OMOE per year at FOC for System Concept 1 increased significantly from 0.61 to 0.78 (27%) and fell in preference to 3rd place, indicating the benefit gained with the emphasis on Capacity and the year FOC is achieved through their increased weighting.

Table 15. Cost per OMOE per year at FOC Calculation and Ranking Results with Equally Weighted Performance Attributes.

System Architecture	Cost (\$B)	Years at FOC	OMOE Score	Cost/OMOE/FOCyear	Rank
System Concept 1	3.6	10	0.53	0.78	3
System Concept 2	3.3	10	0.65	0.50	1
System Concept 3	4.5	10	0.40	1.28	9
System Concept 4	6.0	10	0.74	0.80	4
System Concept 5	5.7	10	0.58	1.08	7
System Concept 6	3.8	10	0.46	0.94	5
System Concept 7	5.1	10	0.45	1.36	10
System Concept 8	4.7	10	0.51	1.07	6
System Concept 9	4.7	10	0.69	0.76	2
Threshold Only	2	10	0.20	1.14	8

6. Variation of the FOC Period

The time at FOC for the model has been set to a constant of 10 years. To analyze the effect of making varying this input new values for all concepts have been replaced with a random value between 8 and 11. The results are shown in Table 16. While there are some changes in ranking, System Concept 2 remains the most preferred, even with the increased cost per OMOE per year at FOC.

7. Range of Variation of the Cost

It may be argued that the cost variation in the example at a factor of 2 is too large and biasing the results. To address this concern the existing cost variations were mapped from the \$3–6B range over to a \$3–4B range. This would maintain the cost comparisons

between system concepts, but decrease the total input cost, and as such the ratio of cost to OMOE. The results are shown in Table 17.

This change in range does have an effect on the ranking of the third through seventh place concepts, it is still not sufficient to change the results for the two most preferred solutions. This result shows that the smaller the range of variation is on the cost, the more meaningful the variation of the OMOE will become in the decision making process.

Table 16. Revised Ranking With a Variable FOC Period.

System Architecture	Cost (\$B)	Years at FOC	OMOE Score	Cost/OMOE/FOCyear	Rank
System Concept 1	3.6	8	0.59	0.76	3
System Concept 2	3.3	8	0.60	0.69	1
System Concept 3	4.5	9	0.35	1.44	9
System Concept 4	6.0	10	0.71	0.85	4
System Concept 5	5.7	11	0.57	0.91	6
System Concept 6	3.8	10	0.42	0.91	5
System Concept 7	5.1	10	0.44	1.15	8
System Concept 8	4.7	9	0.48	1.10	7
System Concept 9	4.7	10	0.62	0.76	2
Threshold Only	3.9	10	0.17	2.25	10

Table 17. Revised Ranking With a Reduced Cost Variation Range.

System Architecture	Cost (\$B)	Years at FOC	OMOE Score	Cost/OMOE/FOCyear	Rank
System Concept 1	3.2	10	0.59	0.54	2
System Concept 2	3.1	10	0.60	0.52	1
System Concept 3	3.5	10	0.35	1.01	9
System Concept 4	4.0	10	0.71	0.56	3
System Concept 5	3.9	10	0.57	0.69	5
System Concept 6	3.3	10	0.42	0.78	7
System Concept 7	3.7	10	0.44	0.83	8
System Concept 8	3.6	10	0.48	0.75	6
System Concept 9	3.6	10	0.62	0.58	4
Threshold Only	3.3	10	0.17	1.91	10

E. CHAPTER SUMMARY

This chapter has discussed the application of the mathematical model in an example communications satellite system architecture trade study. A set of nine different system architectures and eleven key attributes were investigated. The model was implemented in an Excel workbook. Performance values were created by a random number generator, and the calculation results were presented and discussed. A comparison of the mathematical model results to the traditional cost per capacity calculation shows that there can be different recommended solutions for the two approaches. This difference in results shows that if other key system attributes are ignored it is likely that a system architecture solution will be selected that is not optimized for either cost or performance.

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IV. CONCLUSIONS AND RECOMMENDATIONS

This chapter presents a summary of the work described in this thesis and identifies areas for further research.

A. CONCLUSIONS AND RECOMMENDATIONS

The purpose of this thesis was to implement a mathematical model for assessing communications satellite system architectures based on the satisfaction of multiple performance attributes. To this end the following three questions have been addressed:

1. What are the key quantifiable architectural attributes that contribute to meeting the users' requirements of a communications satellite?
2. What is an appropriate mathematical model for evaluating communications satellite architectures?
3. How can such a mathematical model be applied to the assessment of a communications satellite architecture?

Satellite based communications provide a crucial capability to the U.S. military in the execution of their many missions. System architectures are developed based on a set of requirements that define the capabilities needs. Traditionally the selection of a communications satellite systems architecture solution is based upon the evaluation of a single criterion: the cost per unit of system communication capacity. This selection approach disregards the other key system design requirements and can result in the selection of an architectural solution that does not reflect other system attributes the stakeholders may consider significant. To address this shortcoming, a mathematical model to assess multiple attributes simultaneously was implemented.

A survey of candidate system parameters for inclusion into a mathematical model for trade study analysis of candidate communications satellite architectures was conducted. The five identified potential key attributes are: communications capacity; access; interoperability; commandability; and information assurance and protection. Due to the commonality with current trade analyses and commercial leasing metrics, the

communications capacity attribute should be considered applicable to all system architecture trade analyses. Additional key attributes should be utilized in the mathematical model based on the defined requirements for the system, such as KPPs, TPMs, and overarching requirements.

Three mathematical model approaches were discussed. The selected approach is a combination of two of them and enables a comparison of the cost for achieved performance level. This approach leveraged three mathematical model benefits: 1) the ability for stakeholders to weight the relative importance of all key attributes utilized in the model; 2) a calculation of raw scores to measure the performance of each key attribute across system architectures; and 3) consideration of the total system cost for each system architecture.

The inputs, output, and calculation methodology of the selected mathematical model were presented. The output of the mathematical model is a cost per year at FOC per Overall Measure of Effectiveness (OMOE) score. The lower the cost per OMOE score, the more preferred the system architecture is relative to the others under consideration. This results in a metric for decision makers to utilize in their system architecture selection where the annualized cost per unit of performance is minimized.

The mathematical model was applied to an example communications satellite system architecture trade study. A set of nine different system architectures and eleven key attributes were investigated. The model was implemented in an Excel workbook and performance values were created by a random number generator within the bounds of expected values for a fictitious system. The output of the mathematical model showed the lowest cost per capability can be lower than the cost per capacity. The difference in results supports applying the crucial step of accounting for additional key system attributes when selecting a communications satellite system architecture.

This model is intended to aid decision makers in a system architecture selection process. Decision makers will still have to consider the results of the model in concert with other factors that do not lend themselves to incorporation into a mathematical model, such as budget constraints, rapidly evolving threats and needs, and overall level of

program risk. An analysis of the results will be necessary to support the final decision, with the approach and focus to be defined by the needs of the decision makers. It is also possible that the results of this approach may yield a result that is not different from that produced by the traditional cost per capacity approach. In this case, this approach would be a validation of the traditional approach.

B. AREAS FOR FURTHER RESEARCH

There are a number of areas where this research could be expanded in further research as a result of this effort. Three possibilities are suggested.

The mathematical model could be applied to existing or proposed system architecture to determine if there is any difference between the system selected by the traditional cost per capacity method and this multi-attribute mathematical model. This effort would include identification of the key attributes, determination of appropriate weightings based on inputs from stakeholders, execution of the mathematical model, and an analysis of the results. This research could help to demonstrate the utility of the mathematical modeling approach.

Another potential research area would be the expansion of the model to accommodate more complex types of functionalities between the satellites in the system architecture and the user terminals. This would enable the modeling of a more complex solution that includes a variety of different elements assembled to create an integrated system architecture solution. Examples of such an architectural solution include: satellites of differing capabilities and in different orbits to provide full earth coverage; a mix of military satellites and commercially leased capacity; and the inclusion of atmospheric assets such as balloons and aircraft.

The mathematical model can be expanded to handle time-varying values, such as the time value of money, or even statistically varying inputs. This type of analysis could provide an even more relevant outcome for use by the stakeholders.

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