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THE ARCHITECTURE-BASED TECHNOLOGY EVALUATION AND CAPABILITY TRADEOFF METHOD FORMULATION AND INITIAL APPLICATION

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ABSTRACT

The Architecture-based Technology Evaluation and Capability Tradeoff Methodology has been formulated to aid pre-Milestone A decision-making by enabling users of the method to explore a large, diverse alternative space in a rigorous, quantitative, and traceable manner across the DOTMLPF spectrum. ARCHITECT uses key DoDAF products, a hierarchical modeling and simulation approach, and visual analytics to formulate the problem, identify key gaps and metrics, identify and evaluate a large number of alternatives, and support decision-making. The ARCHITECT methodology has been demonstrated on a simplified SEAD example problem.

INTRODUCTION

The use of architectures for the design, development, and documentation of system-of-systems engineering has become a common practice in recent years. This practice became mandatory in the defense industry in 2004 when the Department of Defense Architecture Framework (DoDAF) Promulgation Memo mandated that all Department of Defense (DoD) architectures must be DoDAF compliant. Despite this mandate, there has been significant confusion and a lack of consistency in the creation and the use of the architecture products. Products are typically created as static documents used for communication and documentation purposes that are difficult to change and do not support engineering design activities and acquisition decision making. At the same time, acquisition guidance has been recently reformed to move from the bottom-up approach of the Requirements Generation System (RGS) to the top-down approach mandated by the Joint Capabilities Integration and Development System (JCIDS), which requires the use of DoDAF to support acquisition. Defense agencies have had difficulty adjusting to this new policy, and are struggling to determine how to meet new acquisition requirements.

This research has developed the Architecture-based Technology Evaluation and Capability Tradeoff (ARCHITECT) Methodology to respond to these challenges and address concerns raised about the defense acquisition process, particularly the time required to implement parts of the process, the need to evaluate solutions across capability and mission areas, and the need to use a rigorous, traceable, repeatable method that utilizes modeling and simulation to better substantiate early-phase acquisition decisions. The objective is to create a capability-based systems engineering methodology for the early phases of design and acquisition (specifically Pre-Milestone A activities) which improves agility in defense acquisition by (1) streamlining the development of key elements of JCIDS and DoDAF, (2) moving the creation of DoDAF products forward in the defense acquisition process, and (3) using DoDAF products for more than documentation by integrating them into the problem definition and analysis of alternatives phases and applying executable architecting. This research proposes and demonstrates the plausibility of a prescriptive methodology for developing executable DoDAF products which will explicitly support decision-making in the early phases of JCIDS. A set of criteria by which CBAs should be judged is proposed, and the methodology is developed with these criteria in mind. The methodology integrates existing tools and techniques for systems engineering and system of systems engineering with several new modeling and simulation tools and techniques developed as part of this research to fill gaps noted in prior CBAs. The ARCHITECT method attempts to combine lessons learned and best practices from existing systems engineering approaches for requirements derivation, alternative generation, and alternative evaluation to improve the conceptual stage of the system of systems engineering.

A suppression of enemy air defenses (SEAD) mission is used to demonstrate the application of ARCHITECT and to show the plausibility of the approach. For the SEAD study, metrics are derived and a gap analysis is performed. The study then identifies and quantitatively compares system and operational architecture alternatives for performing SEAD. A series of down-selections is performed to identify promising architectures, and these promising solutions are subject to further analysis where the impacts of force structure and network structure are examined. While the numerical results of the SEAD study are notional and could not be applied to an actual SEAD CBA, the example served to highlight many of the salient features of the methodology. The SEAD study presented enabled pre-Milestone A tradeoffs to be performed quantitatively across a large number of architectural alternatives in a traceable and repeatable manner. The alternatives considered included variations on operations, systems, organizational responsibilities (through the assignment of systems to tasks), network (or collaboration) structure, interoperability level, and force structure. All of the information used in the study is preserved in the environment, which is dynamic and allows for on-the-fly analysis. The assumptions used were consistent, which was assured through the use of single file documenting all inputs, which was shared across all models. The work presented here is based on work previously presented by Griendling [1]. This paper will focus on the formulation of the methodology, using the SEAD example to demonstrate key results for each step of the process.

METHODOLOGY DEVELOPMENT

In order to develop the structure of the methodology, existing acquisition decision-making approaches from industry and government were studied to determine what general steps are generally taken in a strategic acquisition decision-making process, and what characterizes these processes. From literature, the following observations were made about strategic acquisition decision-making processes:

- Strategic acquisition decision-making is usually performed by large organizations with diverse stakeholders and many ``missions'' or lines of business [2]
- Organizational complexity is a characteristic of the acquisition process [2-4
- Decisions are typically made in face of ambiguity and uncertainty [3-5]
- In particular, there is a large amount of environmental uncertainty that cannot be minimized by organizational action [2, 3]
- In general, strategic decision-making involves several key activities, including goal formulation, problem identification, alternatives generation, and evaluation and selection. These are the same activities as take place in defense acquisition [3, 6]

The ARCHITECT Methodology is formulated around these basic decision-making steps, and the methods and tools selected to support each step have been selected with the overall characteristics of the decision environment in mind. In order to ensure that the resulting methodology appropriately met the needs of capabilities based analysis and pre-Milestone A acquisition and accounted for the characteristic acquisition landscape, a set of criteria was developed from literature. These criteria were then used to motivate the choice between competing tools and techniques to populate the steps of the ARCHTIECT Methodology. The criteria found are:

- The methodology should allow CBAs to be conducted more quickly (less than a year) [6]
- The methodology should result in a CBA which is transparent [6]
- The methodology should provide decision makers with an increased number and type of alternatives across the DOTMLPF spectrum [6]
- The methodology should allow materiel solutions to be evaluated with respect to multiple missions [6, 7]
- The methodology should leverage quantitative analyses when possible [6]
- The methodology should be rigorous and repeatable, but have enough flexibility to apply across a broad spectrum of problems [6]
- The resulting CBA should include a dynamic environment that allows decision makers to interact with results (similar to an interactive design review) [6]
- The methodology should result in a framework to support current and future decision making that preserves the results of previous analyses and can be easily updated and allows the CBA process to be repeated very quickly once updates are implemented and a new baseline is developed [8]
- Integration of information and data relevant to decision makers is important, and should not be done in an ad-hoc fashion [2, 5]
- Scenarios, assumptions, and baseline information should be consistent among all analyses conducted simultaneously [2, 5]

- The process must include sufficient analysis and full consideration of the alternative space and be completed in a short time frame [2, 5]
- Clarifying requirements and reducing ambiguity is important to successful acquisition [2, 5]
- Emphasis should be placed on ease of integration of solutions into the SoS as well as performance and value [2, 5]
- It should be verified that a new solution can be integrated in such a way that expected benefits are realized prior to choosing that solution [2, 5]
- The process must help to reduce biases stemming from cognitive simplifications (the specific biases are unique to each step of the process) [3]

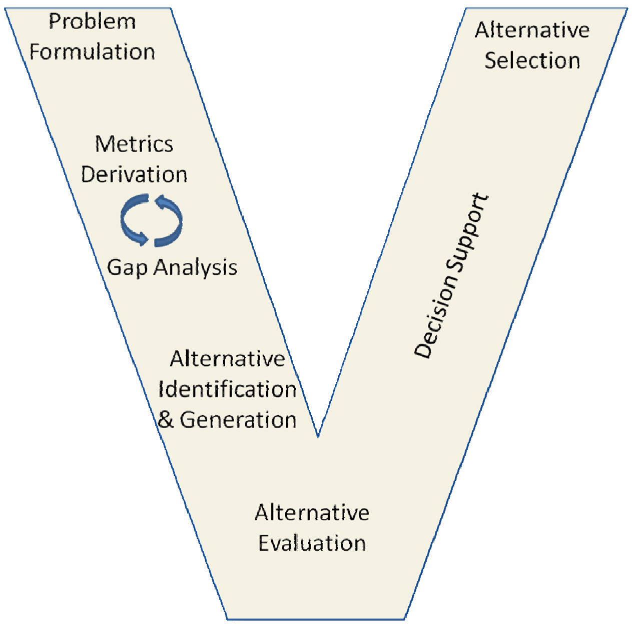


Figure 1: ARCHITECT Methodology represented in systems engineering vee structure

With these criteria in mind, each step of the ARCHITECT methodology was developed and populated with appropriate tools and techniques. Figure 1 shows an overall summary of the high-level steps of the methodology. The ARCHITECT methodology begins in the upper left-hand corner of the vee. First, missions of interest are identified and the baseline architectures are documented (or if existing, collected). This research makes the assumption that if a CBA is being conducted, it is because the person or organization requesting the study has identified a potential mission gap, or is interested in whether a proposed system can help fill capability gaps in a mission or set of missions. The methodology is designed to handle a multi-mission space, although it can be used equally well to consider only one mission. Although one mission may be selected as the focus for closing capability gaps, other missions that may be impacted by any proposed solution are also able to be included in the study. This is particularly applicable to large scale materiel solutions which will likely be employed across several missions if deployed operationally. Missions of interest are identified by those requesting the study, although it is anticipated that SMEs may later suggest additional missions to be included in the study. Again, it is assumed that the problem definition is supplied, as this is the standard procedure for kicking off CBA analysis. However, it is possible that additional missions are added by those performing the study, and these would be added via literature search and SME consultation. For each mission, the baseline architecture and mission performance should be established, again, either as part of the problem definition, with literature search, or by consulting SMEs.

Once the mission set is established, a set of metrics is then defined that provides a means through which mission success can be quantified. In the methodology, the relational-oriented systems engineering technology tradeoff analysis (ROSETTA) framework [9] has been chosen as a framework with which to perform the decomposition from the high-level mission needs to the MoE and MoPs. ROSETTA was inspired from the exploration of common techniques for qualitative and quantitative analysis in systems engineering and technology tradeoffs, and thus provides a natural framework for initially gathering SME-based information with the goal of migrating to quantitative analyses. ROSETTA is further used to eliminate redundant metrics and reduce data collection requirements. This is combined with the Practical Systems/Software Measurement (PSM) technique to ensure that the resulting set of metrics meet the criteria for good metrics. For the purposes of testing the method, the INCOSE criteria for good metrics are used, which are relevant, complete, timely, unambiguous, logical, simple, cost-effective, repeatable, and accurate. Additionally, for each metric, an aggregation function is identified for use in Rapid Architecture Alternative Modeling (RAAM). RAAM is a rapid, executable architecture analysis framework for the capability-based analysis of system of systems [10].

A literature search is combined with the use of subject matter experts (SMEs) to estimate the relationships in ROSETTA required for identifying, quantifying, and ranking capability gaps. Although it is possible with ROSETTA to project the gaps all the way up to the mission level, it may be more useful (and more in line with CBA guidance), to examine the gaps at the capability level, or even at the MoE level. This will provide a clear baseline for comparison of alternatives later in the process.

The scope of the alternative space is then defined by a combination of SMEs and decision-makers using the technique for the enumeration of system of systems alternatives (TESSA), previous presented in [1, 11], to clearly identify the boundaries of the alternative space that the decision-makers are willing to consider. This is done by first specifying the operational alternatives through the rules for variations on the activity sequences, and then specifying the list of alternative systems available to perform each activity, their compatibilities, and estimations on their performance against all metrics of interest. For each system and activity, the owning and responsible organizations are identified respectively, as well as whether the decision-maker is willing to consider a shift in organizational responsibilities. Finally, a minimum IOL is specified across all necessary interfaces. RAAM is used to automatically generate alternatives within this scope.

These alternatives are then analyzed and filtered using a multi-stage approach. First, RAAM is used to evaluate the alternatives against all metrics that can be evaluated using aggregation functions. Since it is infeasible to view, or even store, the full set of data that results from RAAM, several options are available to reduce the amount of data to be parsed for an initial down-selection. First, RAAM can be set to save only the top x performing alternatives, where x is user specified. Alternately, RAAM is able to group solutions by the system portfolio used in those alternatives, and then, for each portfolio, calculate the average and variance for each portfolio. This option is of interest in conducting a CBA, since the CBA is attempting to select between materiel and non-materiel alternatives. Using this approach, all of the system portfolios can be compared, and decision-makers can determine whether or not top-performing portfolios include new systems. Since the performance of these systems is uncertain, RAAM can use probability distributions in place of exact performance estimates. Since it is likely that the top performing alternatives will be statistically indistinguishable, the initial RAAM modeling is used to down-select to a smaller group of portfolios that will be carried forward to the next phase of analysis.

Once a smaller set of portfolios has been selected, these portfolios are re-run through RAAM, where each operational architecture associated with each portfolio is then recorded independently. This allows only the top performing operational architectures for each system portfolio to be carried forward to the higher-fidelity analysis.

The remaining architectures are then run through a higher fidelity modeling environment. The specific technique used in this environment is dependent on the problem at hand and the metrics being tracked. However, discrete event simulation, Markov chains, network models, and ARCNET paired with a simplified engagement model have been identified and tested as part of this research as techniques that can easily be incorporated into an executable framework and provide information that may of interest during the process. The Architecture Resource-based Collaborative Network Evaluation Tool (ARCNET) is a modeling tool created by Domercant [12] to evaluate and compare different alternatives for the information networks in an SoS.

Finally, an abbreviated list of alternatives that best fill capability gaps is analyzed using a decision support environment (DSE). The DSE provides an interactive, dynamic visualization environment of the relevant data and analyses to help decision makers choose the appropriate path forward. The DSE is also intended to guide additional analysis that may be required to increase confidence in the chosen solutions and to verify mission impact. Ultimately, the DSE is designed to aid decision makers in leveraging the entire method when addressing important pre-Milestone A specific concerns such as: *Should a new system acquisition program be launched, are there affordable architectural alternatives that best provide the needed capability, or are there any new methods of employing existing assets that can be leveraged to achieve the same desired effect?*

INITIAL DEMONSTRATION OF FEASIBILITY

In order to perform and initial demonstration of the feasibility of the method, a suppression of enemy air defenses mission will be used. SEAD is defined as any activity that neutralizes, destroys, or temporarily degrades enemy surface-based air defenses by destructive and/or disruptive means [13]. Systems such as Surface-to-Air Missile (SAM) sites, Anti-Aircraft Artillery (AAA), early warning and fire control radars, and Ground Control Intercept (GCI) sites can be combined by potential adversaries into an Integrated Air Defense System (IADS). Over time, IADS have become increasingly complex and can differ widely in terms of organization, sophistication, and operational procedures. The widespread proliferation of weapon systems and continual improvements in their speed, range, accuracy, stealth, and lethality require joint forces to be more responsive, flexible, and integrated. Since SEAD can be conducted jointly, a multitude of various system types can be included within the architecture. These range from sea, land, air, and space-based assets to manned and unmanned systems. Also, sophisticated communication systems are needed to enable and enhance Command and Control (C2) since enemy air defenses can be mobile or stationary and pose a significant threat to current military assets. Thus, SEAD presents an excellent SoS architecture design challenge and includes many of the aforementioned attributes including: managerial and operational independence as well as geographical distribution of elements, emergent behavior, and evolutionary development. For purposes of this study, a SEAD scenario that focuses on Area of Responsibility-/Joint Operating Area (AOR/JOA)-Wide Air Defense System Suppression provides the desired complexity for a military SoS architecture test case. This means that SEAD is conducted against specific enemy air defense systems throughout the AOR/JOA to degrade or destroy their major capabilities/effectiveness. The duration and level of disruption depends upon the mission objectives and the sophistication of the IADS [13]. In this case, it will be assumed that the SEAD mission is conducted in an area that is easily accessible by both an aircraft carrier and a forward operating base (FOB) in order to demonstrate joint and cross-service trades.

The study presented here is intended to demonstrate the plausibility of the ARCHITECT methodology. While the study presented in this paper is limited to a single mission area for ease of demonstration, the ARCHITECT methodology does allow for other SEAD mission types, such as localized and opportune suppression, as well as other mission types to be included for future analysis. The single mission focus allows a direct comparison with previous CBAs and can be used to more directly compare the ARCHITECT approach to previous studies. However, as was observed previously, one of the recommendations of ARCHITECT is to use a multi-mission focus on future CBAs. Data used in support of this study is notional and is not intended to reflect the actual performance of the real systems to mitigate export control concerns and to avoid the accidental production of potentially sensitive information.

Identification of Baseline

Prior to performing gap analysis, a baseline architecture must first be defined. In order to support this process, information in the form of documentation must be gathered. This documentation includes, but is not limited to documents that outline the appropriate doctrine, concept of operations (CONOPS), task lists, reports, etc. The use of this documentation is not limited to providing performance estimates of the baseline architecture, but also of the candidate alternative architectures for use in later modeling and simulation (M\&S) efforts as well. Because all aspects of the SoS architecture must be considered in the alternative space to make meaningful comparisons, a subset of DoDAF v2.0 models is used to document the baseline architecture, and to help identify the scope of alternatives to be considered. The OV-1 is used to document which missions are being considered and help capture any associated assumptions about the mission. It is also important to understand the organizational context of the roles and relationships amongst different stakeholders so the OV-4 is included as well. The OV-5a details the hierarchical structure of the activity sequences for the missions while the OV-5b (shown in Figure 2) provides contextual data to help depict the relationships among activities, inputs, outputs, performers, or other pertinent data. The OV-2 and OV-3 provide a description of the required resource flows exchanged between the operational activities. The SV-1 and SV-2 models provide the identification of systems, system items, and their interconnections as well as the resource flows exchanged between systems. The SV-5b is included to understand how the systems enable the activities shown in the OV-5, and to ensure that a set of systems selected for use in architecture is able to fully support the needs of the missions.

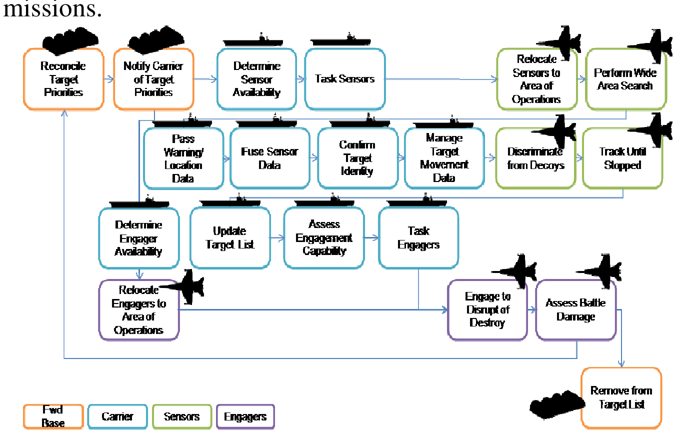


Figure 2: SEAD OV-5 with baseline system overlays

For the SEAD example, it should be noted that while the baseline was created to be representative, the data used is notional and not intended to reflect actual system performances. Any resemblance to actual performance data is coincidental. The OV-1, OV-2, OV-3, OV-4, OV-5, SV-1, SV-2, and SV-5b were created for the baseline case. Although not all views are depicted here, the OV-2 and OV-5b with system overlays are shown to provide description of the baseline assumed for this study. In addition to the architecture views, baseline SEAD JOA/AOR performance data is presented. The formulation of this data is based on a literature search and the best estimations of the author, and again should not necessarily be considered as an actual representation of real mission data. This data is only intended to allow for the utility of the method to be demonstrated.

Metrics Derivation and Gap Analysis

In order to derive the metrics, the high-level goals for SEAD JOA/AOR needed to be defined. The overall goal of SEAD is to effectively disable an enemy's air defenses in order to protect friendly aircraft flying over that area in a follow-up mission. Thus, the main goals are to effectively disable the air defenses, do so in a timely manner, do so with minimal friendly losses, and, of course, to do so in a cost-effective manner. While the first three can be measured by the percent of targets disabled, the probability of success, the time to complete mission, and the percent of friendly losses respectively, measuring the cost-effectiveness is more complicated. As there are many contributors to cost, and not all of them are likely to have available quantitative estimates during CBA, it will likely be necessary to use a mix of qualitative and quantitative assessments for cost. System acquisition costs are likely to be available for most systems, and estimates for new systems can most likely be obtained. The operations and support (O&S) costs are unlikely to be available, as well as the costs of integration into the SoS. However, based on the discussion in the literature search that complexity and cost are correlated in an SoS, the complexity measure developed by Domercant [12] will be used here as a surrogate for cost. Since this metric requires more information than is available early in the evaluation process, the complexity will need to be initially estimated qualitatively. However, as the evaluations progress and the architectures become more fully fleshed out, the complexity can be calculated using Domercant's metric. In addition, a qualitative estimation of maintainability can be obtained as well. This gives three metrics that will contribute to helping to assess the relative costs of the architectures, the acquisition costs of the systems, the complexity score, and the qualitative estimates of the maintainability. A summary of the high level metrics is shown in Table 1.

Table 1: Metrics Derivation for SEAD

	Probability of Success	% Targets Disabled	Combat Attrition (% Friendly Losses)	Time to Complete Mission	Ease of Maintainability	System Acquisition Cost	Complexity
Effectively disable air defenses	x	x					
Timely disablement of air defenses				x			
Reduce friendly losses			x				
Reduce mission costs					x	x	x

The metrics specified above are not unrelated. For example, the probability of success would be expected to increase if more targets are disabled, meaning that it may only be necessary to track one of these two metrics. It would also be expected that an increased probability of success would be correlated with fewer friendly losses. It also might be expected that there be some positive correlation between complexity and probability of success, as more complex architectures are sometimes expected to increase mission performance. It also would be expected that the time to complete mission would be correlated with both the percentage of targets disabled and the percentage of friendly losses. However, the direction of this correlation is not as obvious. It may be that performing the mission more quickly increases the probability of success because of the surprise factor, and because there would be less opportunity to lose assets. However, it may also be that when the mission is completed in a shorter time, less of the targets are successfully found and engaged, decreasing the probability of success. Taking these correlations into account, it is expected that architectures which perform well in probability of success will correspond to a high rate of target disablement and low combat attrition. Since the two metrics time and probability can be calculated without an engagement model, and combat attrition and percentage of targets disabled would most likely require an engagement model, time to complete mission and probability of success will be used in RAAM in the early phases of evaluation. The other two metrics will be considered later using a simplified engagement model on a selection of the downselected architectures. Ease of maintainability and complexity, and acquisition costs will be considered qualitatively in RAAM, but complexity will later be calculated quantitatively for the final architectures. System acquisition cost will be calculated quantitatively using RAAM.

Once the metrics were mapped to the requirements for SEAD, gap analysis was performed. For each metric, estimations on the gap size were developed based on information contained in [14]. Criticality estimates were assigned notionally to the requirements, and projected into the metrics space using the standard QFD approach. Each capability requirement was assigned an expected criticality on a one to five scale, and then given a minimum and maximum criticality as well. The gap sizes were then calculated on a metric basis, in order to enable a clear mapping between modeling results and gap closure. In order to do this, notional thresholds were set for each technical metric. Then, current performance was estimated by giving a mode value and range for each metric. The gap size was then calculated as the percent difference between the threshold value and the current performance. In cases where the current performance was better than the threshold, the gap size was set to zero, rather than having a negative gap size. This was done at the minimum value, the maximum value, and the mode value, giving the range of gap sizes. The criticalities were then mapped into the gap size space by projecting them through the mappings between the capabilities and metrics. It would have been equally possible to map the size of the gaps into the requirement space, and that may have been a more desirable approach for some problems. It should be noted that the cost-related metrics were not given an estimation of gap size. This is because it is assumed that decision-makers are most interested in the change in cost due to a proposed solution, and the effective benefit to cost ratio. Obviously once the costs are known solutions may be eliminated based on a cost threshold, but it is assumed that this will be determined later in the study and is not a focus of the initial gap analysis. The results of the application of the process are shown in Figure 3. The probability of success and the percentage of targets disabled were the top gaps, with time to complete mission being next in line followed by the combat attrition. However, because of the uncertainty, it is possible that these rankings would vary.

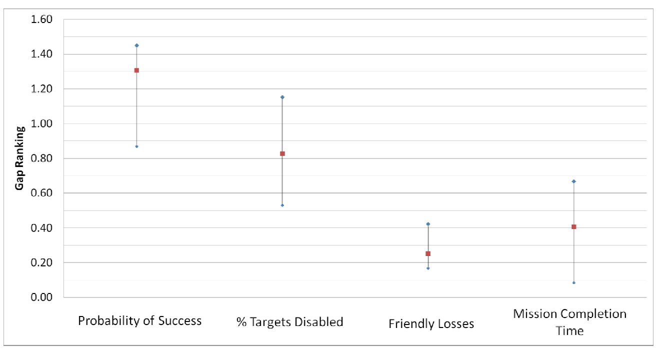
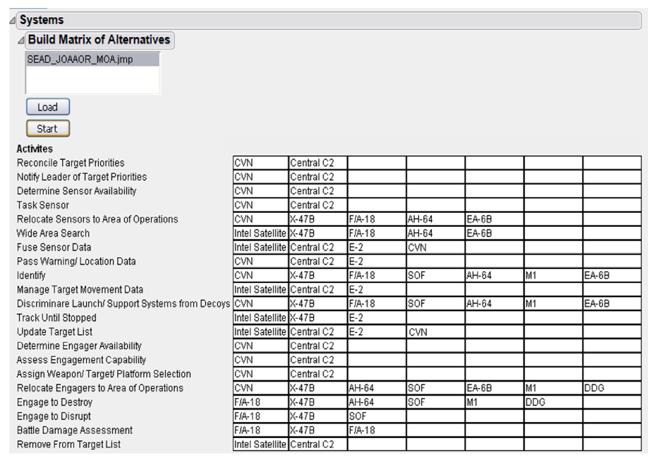


Figure 3: SEAD Gap Analysis Results

Alternative Identification

The first step in identifying alternatives is to define the operational/process variations. This requires use of the baseline OV-5b, such as the one previously presented in Figure 2, in order to identify dependencies between tasks. Tasks can be related in several ways. A task can be identified as 'must precede' or 'must secede' another task. Tasks can also be identified within the hierarchy as subtasks of other tasks. This occurs when a high level task is comprised of a set of other subtasks that can be mapped to individual systems. Tasks can also belong to a main sequence of events or to a bypass sequence that is executed in the event that specific conditions are met or not met. By adhering to these rules, alternate task sequences can be generated to represent variations in the overall manner in which the capability is accomplished. In this case, it is assumed that the OV-5 is fixed and there will be no process variations.

Once the task mappings are created, the system/technology alternatives for each task are defined. This step is performed using a matrix of alternatives. Each task is given a row in the matrix, and the baseline systems are identified for each task from the baseline architecture views. The user then defines a set of alternative architectures made up of different combinations of new and existing systems that will perform the various tasks. It is possible that the same system will map across multiple tasks. While the user is free to specify as many alternatives per task as desired, users must be cautioned that specifying more than five or six alternatives per task will result in a very large number of possible system portfolios since the alternative space is combinatorial in nature. The matrix of alternatives used for the SEAD example is shown in Figure 4. Once this is completed, the user then needs to specify the performance estimates for each system and system-task pair listed in the matrix of alternatives.



Activites							
Reconcile Target Priorities	CVN	Central C2					
Notify Leader of Target Priorities	CVN	Central C2					
Determine Sensor Availability	CVN	Central C2					
Task Sensor	CVN	Central C2					
Relocate Sensors to Area of Operations	CVN	X-47B	F/A-18	AH-64	EA-6B		
Wide Area Search	Intel Satellite	X-47B	F/A-18	AH-64	EA-6B		
Fuse Sensor Data	Intel Satellite	Central C2	E-2	CVN			
Pass Warning/ Location Data	CVN	Central C2	E-2				
Identify	CVN	X-47B	F/A-18	SOF	AH-64	M1	EA-6B
Manage Target Movement Data	Intel Satellite	Central C2	E-2				
Discriminare Launch/ Support Systems from Decoys	CVN	X-47B	F/A-18	SOF	AH-64	M1	EA-6B
Track Until Stopped	Intel Satellite	X-47B	E-2				
Update Target List	Intel Satellite	Central C2	E-2	CVN			
Determine Engager Availability	CVN	Central C2					
Assess Engagement Capability	CVN	Central C2					
Assign Weapon/ Target/ Platform Selection	CVN	Central C2					
Relocate Engagers to Area of Operations	CVN	X-47B	AH-64	SOF	EA-6B	M1	DDG
Engage to Destroy	F/A-18	X-47B	AH-64	SOF	M1	DDG	
Engage to Disrupt	F/A-18	X-47B	SOF				
Battle Damage Assessment	F/A-18	X-47B	F/A-18				
Remove From Target List	Intel Satellite	Central C2					

Figure 4: SEAD Matrix of System Alternatives

Next, the organizational alternative space is defined by designating the organization which owns and operates each system. For baseline systems, this will be known automatically from the baseline architecture, but will need to be user-supplied for systems not included in the baseline.

Alternative Evaluation

The first step of the Alternative Evaluation process is to collect estimates of systems performing tasks to use as an input to RAAM. Four metrics were identified as being compatible with the RAAM framework, and estimates were made for every system and every system-task pair. Next, RAAM was run to obtain first-order estimates of these four metrics, which included acquisition cost, risk, average time to execute the SEAD kill chain, and qualitative maintainability. Maintainability and complexity represent qualitative metrics, and time to complete and probability of success are representative of quantitative metrics. A summing aggregation function was used for time, a product function was used for probability of success, and a minimum function was used for maintainability. For complexity, a more complicated aggregation was used that calculated the complexity for each segment of the mission. Since the total alternative space had over 700,000,000 feasible architectures, it was decided to first group the alternatives by their system portfolios and eliminate portfolios with overall poor performance. In order to do this, a dynamic visualization environment was created to help understand the results of the data.

Upon implementing RAAM, 1,266 portfolios were found to be feasible and were evaluated against the four initial metrics. This data was then imported into the JMP® statistical software package for analysis. A visualization environment was created to help decision-makers determine which portfolios to eliminate from further consideration. Several different visualizations for analysis were created to allow decision-makers and engineers to work together, including a scatterplot matrix (shown inFigure 5), distributions of the results for every metric and an OEC which used an equal weighting scheme on all metrics, distributions for each system on how often each was included and excluded from portfolios, a data filter allowing filtering by any input or output variable, and a prediction profiler and Pareto plots to enable sensitivity analysis, as shown in Figure 6. The baseline performance is also included on the scatterplots, and is represented by the red star. There were several steps taken in the elimination of portfolios. It should be noted that decision-makers have the ability to change the weightings on the OEC on-the-fly.

The scatterplot matrix is a triangular matrix made up of scatterplots of every response against every other response. In each of the scatterplots, every portfolio is represented by a point, showing the average performance of that portfolio on one metric against the average performance of that portfolio on another metric. All 1,266 portfolios are represented in each of the scatterplots. Highlighting any one portfolio in one plot will cause that same portfolio to be highlighted in all other plot, thus giving the ability to visualize all of the dimensions of the problem simultaneously. Any changes made to a portfolio in one scatterplot (such as changing the point color or the marker shape) will be reflected in that portfolio across all other scatterplots as well. All of the information about each portfolio (i.e., which systems are included, the performance estimates for those systems that were input to the model, and the performance estimates for that portfolio across all metrics) is stored with each point, and can be easily pulled up if needed. Using the interactive visualization environment, a downselection decision process that might be taken was simulated, resulting in a total of 16 portfolios of interest.

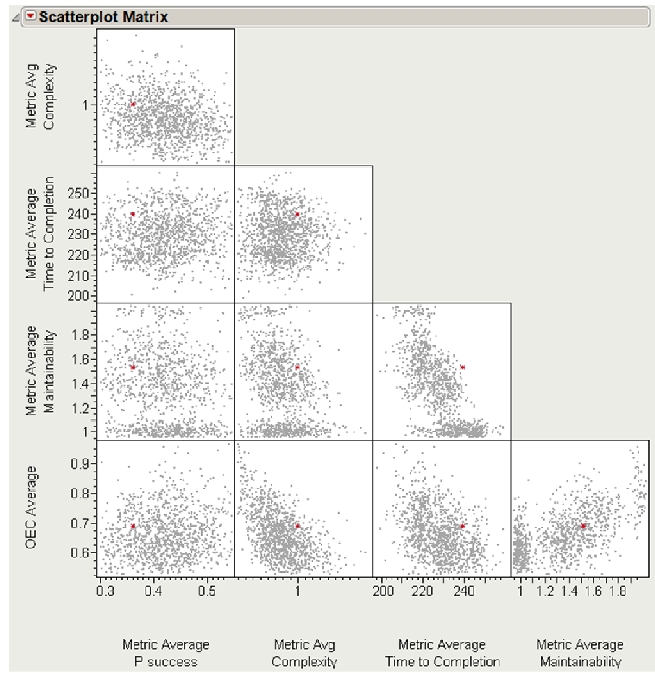


Figure 5: Portfolio Scatterplot Matrix

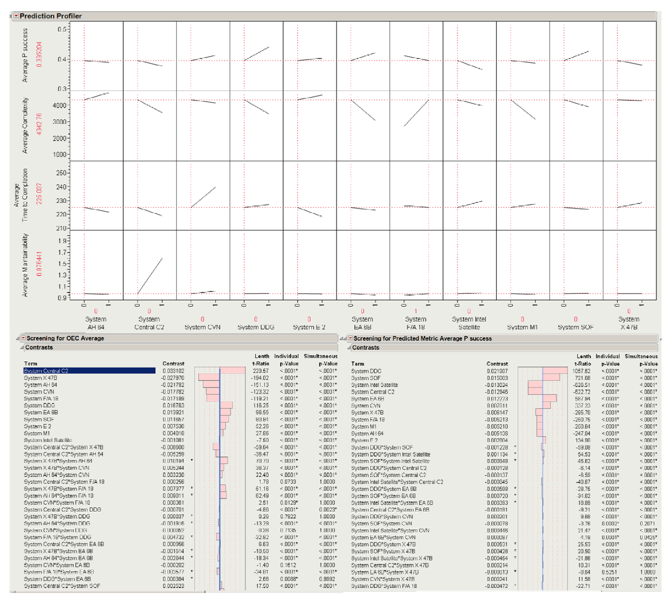


Figure 6: Prediction Profiler and Pareto Plots

Once these 16 portfolios were selected, the next step was to re-run them through RAAM and obtain all of the possible operational use cases of these portfolios in conducting the SEAD mission. This means that for each portfolio, every possible system-task mapping thread through the mission was run independently, and the results were not averaged across the portfolio. This allowed operational use cases that did not perform to be ruled out, leaving only a subset of the remaining operational-system alternative set to be evaluated using other modeling techniques. The downselection process used in this example implementation of ARCHITECT is described below; however, like the previous downselection, the choices and results will be dependent on the decision-maker and what is of interest. In addition to the other four metrics, acquisition cost (or value based on acquisition price) of each portfolio was also included in the calculations so as to give another way to differentiate between alternatives and further refine the downselection. The full results of this second round of runs are shown in Figure 7The baseline is shown using a black star. All of the alternatives within each portfolio are grouped by color. As can be seen in the figure, no single portfolio stands out as being necessarily superior. However there are some initial observations that can be made from this figure. First, some portfolios have a much greater variability than others when deployed using different system-task mappings. Some portfolios have a greater number of possible system-task mapping variations. The portfolios are grouped into bands with respect to both cost and maintainability, suggesting that certain systems are driving these metrics. Furthermore, portfolios 1 and 2 seem to have multi-modal behavior with respect to the probability of success, suggesting that certain system-task pairings are driving up (or down) the probability of success. All of these observations can be explored further using the visual environment to attempt to determine the causes of the observed behaviors and give insight to the decision-makers. Again, a downselction decision process was simulated, resulting in 11 finalists to be carried to the next level of modeling.

The next round of modeling leveraged the HADES model (developed by Bagdatli [15]) and the ARCNET model linked with a simple SEAD engagement model (both developed by Domercant [12]). For each of the 11 finalists and the baseline, variations on the force structure, the enabled interfaces between systems (also called collaboration structure), and the interoperability level were made using a design of experiments. For each of the 11 alternatives, a 2-level full factorial DoE was used for force structure. For each alternative with each force structure, a fractional factorial was used for the collaboration structure and a 2-level fractional factorial was used for the IOL. For the baseline case, a three-level full factorial was used for the force structure. The baseline was done with three levels because it included an F-18, which had a wider range of force structure than the other assets. Since the range was larger, it was decided that using a middle level would be necessary to better understand the impact of force structure. The red force structure (which included early-warning radars, surface-to-air missiles (SAMs), and anti-aircraft artillery (AAA), was varied using a three-level DoE. Since the engagement model is stochastic in nature, each case was repeated 100 times, and the average and standard deviation across these repetitions was recorded.

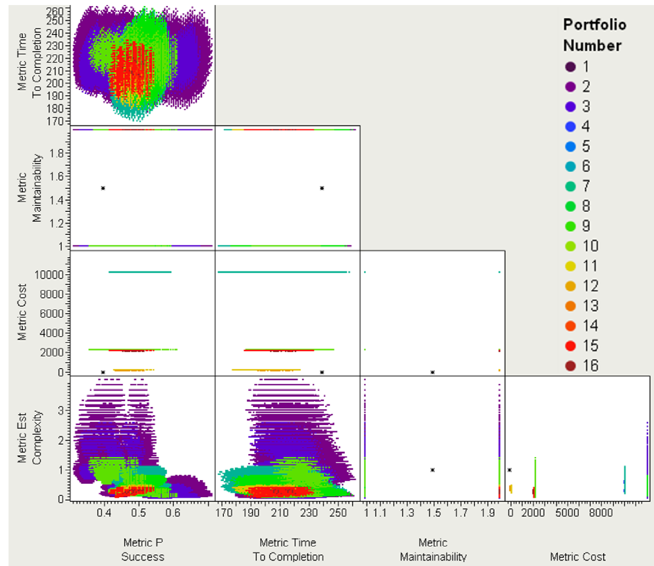


Figure 7: Results of second round, colored by portfolio

For the 11 alternatives that were carried through to this stage of the evaluation, the ARCNET and HADES results showed similar performance in the engagement. This was expected from the RAAM results, as the architectures selected to be carried forward for analysis all showed similar performance across all metrics in RAAM. Since the 11 alternatives show similar performance levels and trends, the first alternative will be discussed here to demonstrate how a decision-maker might use the results of ARCNET. The results for alternative 1 are shown in Figure 8.

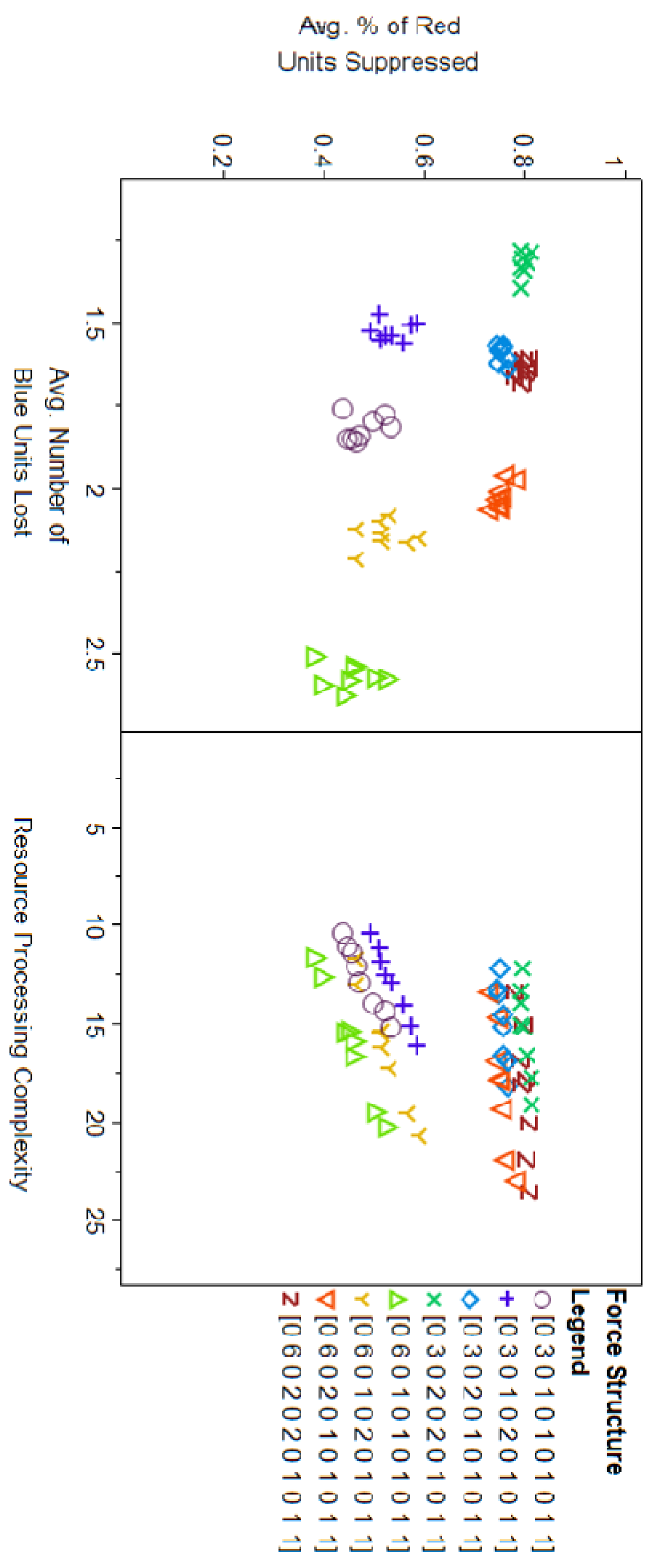


Figure 8: Alternative 1 ARCNET results

The results show groupings in performance according to the force structure. The legend can be interpreted as a vector of all the possible systems included in the study with the integer value representing the number of that system included. The order of the systems is: F/A-18, AH-64, X-47B, EA-6B, Mortar, DDG, SOF, E-2, Intel Satellite, Central C2, and CVN. The relevant systems (those with a non-zero value) to this case are, in order: AH-64, EA-6B, DDG, E-2, Central C2, and CVN. These systems are used according to the alternative 1 system-task mappings shown in Table 2. While this alternative behaves similarly to the baseline with respect to the force structure groupings, the impact of IOL and collaboration structure is not as obvious. In fact, there is almost no noticeable impact from either one on blue losses, although for small force structures there is still a noticeable impact on the number of red suppressions. It is hypothesized that the reason for this is that the systems chosen to perform engagement (both disruptive and destructive, the DDG and EA-6B) are able to act against multiple targets at once, and are not at risk to be shot down during the engagement process. Thus, unlike the baseline where the F-18s rely on each other to obtain needed information to both locate targets and avoid detection, the set of systems used here does not need to rely on the networked effects as heavily.

There are two clear bands of force structures with respect to the average percentage of successful suppressions. The top band corresponds to those cases which include 2 (rather than 1) DDGs. This occurs because this doubles the rate at which tomahawk missiles can be fired, and thus greatly improves the performance against the targets. The best performing alternative uses a maximum number (2) of DDGs and EA-6Bs, which makes sense because it is able to most quickly find and engage targets. What is interesting to note however, is that it uses the lower number (3, as opposed to 6) AH-64s. Since these are the assets flying into the engagement zone and at risk of being shot down, it makes sense that the less there are, the less that will be hit. However, it is of great interest that having less of these assets does not result in a depredation in performance with respect to the number of targets suppressed. This implies that for the tasks being done by the AH-64 (battle damage assessment and decoy discrimination), 3 is enough and having more of this asset is unnecessary.

Looking at the second plot in Figure 8, it can be seen that for the top performing alternatives, increasing the complexity through increases to IOL and collaboration structure has very little effect on the ability to suppress targets. This is observed by the way each force structure alternative shows an almost flat line as RPC increases. In the cases where there are fewer DDGs, there is a greater effect from increasing the level of net-centricity. As the RPC increases, there is roughly a twenty percent improvement in the average percentage of red units suppressed.

Table 2: System-Task Pairings for 11 Finalists

ID Number	Assess Engagement Capability	Assign Weapon And Platform	Battle Damage Assessment	Determine Sensor Availability	Discriminate Decoys	Engage To Destroy	Engage To Disrupt	Fuse Sensor Data	Wide Area Search
1	CVN	CVN	AH-64	Central C2	AH-64	DDG	EA-6B	E-2	EA-6B
2	CVN	CVN	AH-64	CVN	AH-64	DDG	EA-6B	E-2	EA-6B
3	CVN	CVN	AH-64	Central C2	AH-64	DDG	EA-6B	E-2	EA-6B
4	CVN	CVN	AH-64	CVN	AH-64	DDG	EA-6B	E-2	EA-6B
5	CVN	CVN	AH-64	Central C2	AH-64	DDG	EA-6B	E-2	EA-6B
6	CVN	CVN	AH-64	CVN	AH-64	DDG	EA-6B	E-2	EA-6B
7	CVN	Central C2	AH-64	Central C2	AH-64	DDG	EA-6B	E-2	EA-6B
8	CVN	Central C2	AH-64	CVN	AH-64	DDG	EA-6B	E-2	EA-6B
9	CVN	Central C2	AH-64	Central C2	AH-64	DDG	EA-6B	E-2	EA-6B
10	CVN	Central C2	AH-64	CVN	AH-64	DDG	EA-6B	E-2	EA-6B
11	CVN	CVN	AH-64	Central C2	AH-64	DDG	EA-6B	E-2	EA-6B

Decision Support

In the case of the SEAD example presented here, it is not necessary to employ additional decision support techniques to choose between potential new technologies or systems because the remaining options do not include any new acquisitions. Thus, in this case, it would be recommended to decision-makers that for SEAD, it is unnecessary to invest in new systems when existing systems can be used in a new way to perform the mission. Decision-makers would be advised to verify that the life-cycle of the selected systems is long enough that they will not have to be replaced in the near future, otherwise, it may again be necessary to explore new materiel solutions. However, if the decision is made to move down a materiel path for reasons other than performance, it would be suggested that alternate materiel solutions be suggested beyond the ones chosen for this study, and that the analysis be repeated with these other systems. This is because the materiel solutions selected for study here did not perform adequately for the SEAD mission. However, the results from this study can advise what the characteristics should be included for a new materiel solution for SEAD. It was observed that long-range, stand-off type engagement systems are more effective in this mission, and thus future materiel solutions should perhaps be of this type. This insight can be used to develop the requirements for a new research effort. Furthermore, it is suggested to decision-makers that tactics for SEAD should focus on effectiveness through numbers rather than through networked effects. In the case of this mission, it was shown that the number of forces, and in particular the number of engaging and sensing assets has the largest impact on mission success. It should be noted that the type of results given by this study are not typically included in previous CBA studies to date, which are typically heavily focused on materiel solutions, and the use of the ARCHITECT method enabled a much more thorough CBA analysis than is traditionally done. However, it should not be forgotten that this method is helping to prune down the very large alternative space into a more manageable set of alternatives. To complete the CBA, more detailed analysis of these alternatives will be required to better study the implementation into the existing SoS and to better verify the expected performance outcomes predicted here.

SUMMARY AND CONCLUDING REMARKS

The research conducted here developed a capability-based systems engineering methodology for the early phases of design and acquisition. In particular, this method targets the CBA phase of the acquisition process, and works to improve the overall quality of information available for conducting CBA by implementing more rigorous metrics derivation and gap analysis, providing a comprehensive process for developing architectural alternatives, providing more a more quantitative and complete analysis process, and including sound decision support principles. The selection of techniques for each step of the methodology was done by mapping the set of criteria as to what is needed for a acquisition against the steps in the ARCHITECT method, and choosing the technique which best met this criteria. In the absence of a technique to meet these criteria, a new technique was developed that was better able to meet the criteria. As techniques for each step were chosen and developed, an assessment of each of these techniques against the relevant criteria was performed. The SEAD study presented demonstrated the overall plausibility of the ARCHITECT methodology, showing that the techniques selected for each step can not only be used individually to enable each step of the methodology, but can also be used together in a complementary way to execute the methodology as a whole, gathering or creating the needed information at each step to support the next one. The SEAD study also demonstrated the ability of the methodology to perform high-level architectural trades that allow for generalizations regarding how certain characteristics of an architecture drive the overall performance. These generalizations included generalizations about which systems were more effective, which system-to-task mappings had the greatest impact on success, and the trade between using force-by-numbers versus smaller forces with networked effects. These generalizations could be mapped to quantitative performance increases. The assumptions, baseline, models, data, and architecture alternatives are all stored in a reusable framework for future use. To complete the analysis for a Milestone A decision, more detailed modeling for the final alternative set would be required to study the integration effects for the SoS and refine the performance estimates from the initial ARCHITECT analysis. Although it is expected that the ARCHITECT methodology will apply to early-phase systems engineering for a broader class of problems, this has not been tested.

While the ARCHITECT methodology creates a solid initial foundation for conducting CBA, there are many areas of future work which could further improve the ARCHITECT methodology and could help to extend the applicability. There is room for improvement in the area of uncertainty, and a more formal treatment of uncertainty would act to increase confidence in the results. Additionally, guidance on the verification and validation of models used in support of the ARCHITECT method would be beneficial to users and would also help to increase the confidence in the results of the ARCHITECT method. Another area of future work is to further explore how the input parameters for ARCHITECT can be estimated. Several ideas for the estimation are proposed in the methodology, but a formal comparison of these approaches as well as other ideas on how he estimates of the required inputs can be obtained with increasing confidence would be a beneficial next step. Furthermore, exploring more of the ideas used by strategic decision-makers in corporate acquisitions may hold much promise for improving the ARCHITECT methodology. In particular, strategic decision-making research has heavily researched when in the design and development process down selections should be made, and the application of the research to explore the timeline associated with the ARCHITECT method would be of interest. While some steps have been taken to identify and reduce decision-maker biases, further research in this area could help to uncover and address even more potential biases. A more thorough exploration of existing decision-support techniques and principles would benefit the ARCHITECT method. A better treatment of both the consideration of the ease of integration of solutions into the existing SoS and exploration of verification are both also areas which would benefit greatly from further research. A more detailed study of interoperability, the complexities it adds to the decision-space, and how to better capture interoperability trades during early-phase systems engineering is of interest. A study comparing the results of each step of the methodology using qualitative and quantitative data may provide additional guidance as to when each is necessary. This could be aided by further implementation of the ROSETTA framework within the ARCHITECT methodology as the data structure to capture and store both qualitative and quantitative information. Implementation of ROSETTA in this way would add structure to the methodology. Finally, only time and a broader range of applications can fully demonstrate the utility of the methodology and its ability to apply for multi-mission analysis, and this is the most obvious and necessary next step in the research.

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