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ALTERNATIVE DESIGNS FOR A JOINT COMMAND, CONTROL, COMMUNICATIONS, COMPUTERS, AND INTELLIGENCE (C4I) CAPABILITY CERTIFICATION MANAGEMENT (JC3M) SYSTEM

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by

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Alternative Designs for a Joint Command, Control, Communications, Computers, and Intelligence (C4I) Capability Certification Management (JC3M) System

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Abstract

The US DoD has tended to design Command & Control (C2) systems without consideration for them to interoperate for synergistic effects since each is designed for one warfighting function. As systems have grown biologically into a System of Systems, achievement of mission-level effects has disappointed. Architecting the C2 SoS as a whole is improbable. However, capabilities-based acquisition requires interoperability certification based on delivering a warfighter capability via SoS. Students at the Naval Postgraduate School examined this problem. Their result is the Joint Capability Command and Control Management (JC3M) system. This paper summarizes their efforts. A systems engineering process was applied to elicit requirements, create and simulate alternative solutions, and recommend a solution with lifecycle cost estimates. The simulation tools selected to support the project were CORE, to model function and data flow; Arena, for timing and resource utilization; and POW-ER (Project, Organization, Work for Edge Research), for organizational design and processes. The use of these tools to complement each other is unique. Results indicated that JTEM Capability Test Methodology (CTM) was projected to perform better than other alternatives, with the median LCC. The final recommendation is to monitor JTEM CTM for further maturation as it promises improvements in the utility of C4I SoS evaluations.

Keywords: interoperability assessment, modeling, systems engineering

Introduction

Across the US Department of Defense (DoD), early C4I systems were designed, acquired, and fielded independently. Each addressed a single warfighting function, such as logistics, fire support, or intelligence. Over time, warfighting has grown in complexity, tempo, and scope. Complex endeavors are characterized by participants from not only different services but also from different functional areas. They must respond with agility across a spectrum of action and across smeared boundaries between tradition levels of warfare. The current scenario requires a network-centric force, which in turn requires true C2 interoperability.

Individual C4I systems, most not designed, acquired, or managed as a collective enterprise, are being integrated as such and are forming an interdependent entity—a System of Systems (SoS)—in which emergent behavior dominates and capability delivery cuts across system boundaries. System-level acquisition and testing only result in individual systems meeting specific performance requirements. The Joint Interoperability Test Command (JITC) tests for end-to-end connections "in the most operationally realistic environment possible" (rather than delivery of desired capability) to assess interoperability. Successful information exchange results in "certification." This is the baseline system for DoD interoperability certification. However, complex interactions of effects drive changing configurations of C4I SoS with no formally established requirements for performance evaluation. Capability-based testing of a SoS is not well understood. However, the principle to ensure interoperability through testing during development (National Research Council) is still valid.

The baseline interoperability certification process is inadequate because it does not address how the actual SoS supports complex endeavors. Recent revision to the Joint Capabilities Integration and Development System emphasizes that true interoperability is characterized by "end-to-end operational effectiveness [...] for mission accomplishment" (CJCS, 2007). Guidance for writing Capability Development Documents (CDD) requires Net-Ready Key Performance Parameters that assess "the net-ready attributes required for both the technical exchange of information and the end-to-end operational effectiveness of that exchange" (DoD, 2004). This is consistent with the NATO definition of interoperability (NATO, 2002) and that proposed by the Software Engineering Institute (Kasunic & Anderson). Capability Portfolio Managers (DEPSECDEF, 2006, September) and Functional Capabilities Boards (CJCS, 2007) play a role in capabilities-based, cross-program interoperability. Even so, no system can assess the capability of a SoS requiring integration of functions and interfaces across multiple systems. Thus, a JC3M system is important because it provides a process for test planning to verify true interoperability. It documents traceability between capabilities and construction, and it provides confidence that the C4I SoS works.

In response to this need, the Joint Test Evaluation Methodology (JTEM) team is addressing Joint SoS interoperability testing at the Office of Secretary of Defense (OSD) level. Marine Corps Systems Command (MARCORSYSCOM), the acquisition organization for the Marine Corps, is approaching the issue from a service perspective. MARCORSYSCOM has tasked the Marine Corps Tactical Systems Support Activity (MCTSSA) to develop Marine Air Ground Task Force (MAGTF) C4I Capability Certification Testing (MC3T), a methodology for managing the MAGTF C4I SoS as a single system. MC3M will manage the MAGTF C4I SoS as a set of SoS-level capabilities, rather than as a fixed hardware or software baseline.

NPS students assigned to the JC3M project team adopted a systems engineering approach to the problem of architecting a C4I SoS assessment system that will identify desired effects-based capabilities and ensure that the system being tested meets those requirements. The JC3M project sought a lifecycle balanced solution for existing test organizations. The processes can be utilized by service and joint test agencies.

Approach Description

The student design team adapted several systems engineering process models (Acosta et al, 2007) and tailored them to this problem. As illustrated in Figure 1, it begins with identifying a customer's needs and proceeds through several phases until a final solution is recommended. One can see this is a modification of INCOSE's SIMILAR (state the problem, investigate alternatives, model the system, integrate, launch the system, assess performance, and re-evaluate) process model (INCOSE, 2007) that incorporates elements of the Systems Engineering and Design Process (Paulo, 2005) taught at USMA and at NPS.

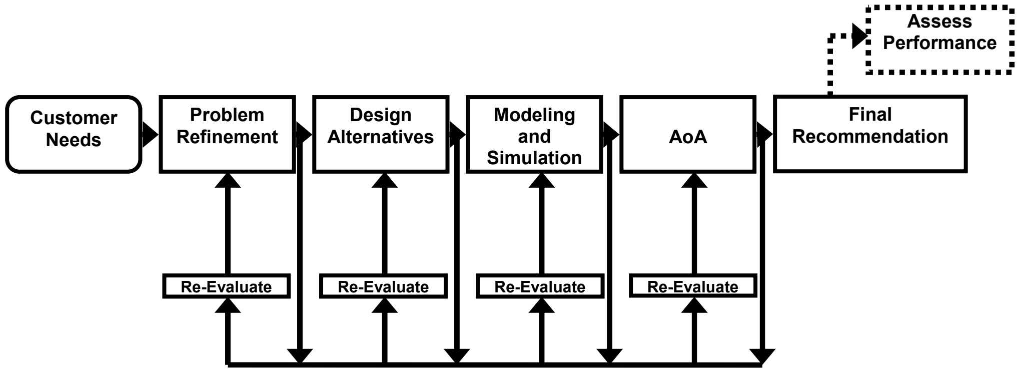

Figure 1. A Tailored Systems Engineering Process

During the problem refinement phase, research into the problem space was conducted, stakeholders were identified and interviewed, functional decomposition was started, and a value system was developed. Based on the preliminary functional analysis and value hierarchy, several alternatives were created. Those alternatives were screened, and ultimately, five alternatives entered the modeling and simulation phase. The predicted performance values generated by the models were used to objectively analyze those alternatives by comparing them to each other along with lifecycle cost estimates. The use of a LCCE as part of the analysis of alternatives in this problem domain is vital. Those testers and test planners must be paid for; it matters little if the final system provides the best solution if that solution is unaffordable. Finally, a solution was recommended, along with caveats. Both the JTEM project and MC3T project will make use of those recommendations.

It should be noted that this team did an excellent job connecting values identified early by stakeholders, supported by a thorough functional analysis. They integrated, into the value hierarchy, the values resulting from modeling and simulation that drove the final decision process.

Problem Refinement & Functional Analysis

Developing a real problem, or effective need, in this situation proved more challenging than anticipated. Stating the central issue so that the stakeholders would receive some utility from the final solution proved slippery. In fact, just identifying the "right" stakeholders was a challenge. From the perspective of C4I system users, any process to certify a system is interoperable within a SoS adds value when that certification signifies the SoS' ability to support the complex endeavor. Verifying that it conforms to technical standards and that it can exchange data is a necessary, but not sufficient, prerequisite. Whereas, in the acquisition community, a program manager manages resources spent for certification. If test results are compared to criteria outside the scope of his or her program or are not explicitly stated in requirements documents, there is high risk with little gain. The test community, therefore, finds itself in the middle—being the honest broker representing users while still adding value to acquirers. The team focused on the test community, along with in-house testers inside the acquisition community, as primary stakeholders. The final list included the Joint Interoperability Test Command (JITC), Marine Corps Operational Test and Evaluation Activity (MCOTEA), Army Test and Evaluation Command, Navy Operational Test and Evaluation Force, Air Force Operational Test and Evaluation Center, MCTSSA, and the JTEM Project team under the

Director of Operational Test & Evaluation. As this team was mostly composed of MCTSSA employees, a major influence was the new MC3T project, which provided an initial primitive need for a "system that *defines* and *compares* System of Systems performance measures to warfighter needs in an objective and measurable way" (Finn, 2007). They needed a system that defined threshold values for C4I SoS performance in operational warfighting terms and then a way to obtain those performance measures.

The team examined the larger context of the problem to find the underlying need. The team researched the most up-to-date interoperability certification and the latest direction within the DoD that examines realizing desired capabilities. While the existing directives and instructions seem clear in identifying roles and responsibilities in a traditional sense, little light was shed on the root of the issue. All stakeholders were queried on how they plan a C4I SoS assessment, what resources they use to do so, how component systems under test are identified, how performance requirements are codified, how conflicts are resolved, and what metrics they use to assess their own performance (Acosta et al., 2007). The written questions sought to reveal how they knew they succeeded and what areas were most ripe for improvement. The responses from JTEM and JITC were professional, insightful and frank.

A basic functional hierarchy began to evolve around the three major functions: planning a C4I SoS evaluation, conducting the evaluation, and reporting results. The identification and definition of performance threshold values was of primary concern and all stakeholders seemed to be completely satisfied with their ability to execute and report on an evaluation event. Therefore, the problem scope was focused on the planning phases. Further decomposition resulted in a draft functional model, shown in Figure 2 (Acosta et al., 2007).

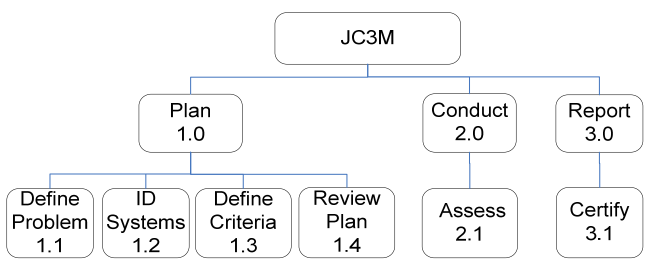

Figure 2. Initial JC3M Functional Decomposition

This project focused entirely on function 1.0, Plan a C4I SoS Evaluation. Further functional evaluation identified required inputs and outputs of the system, process activation and termination, and evaluation measures for each of the lowest level functions.

Eventually, several alternatives were to be compared objectively. The basis of that comparison was how well they achieved the functional and non-functional requirements. By combining a complete functional hierarchy with critical non-functional attributes and assigning evaluation measures to each, a value system was created. This classic systems engineering paradigm completed the initial requirements analysis work. A part of that value hierarchy—with only the critical evaluation measures that were eventually used in the final comparison of alternatives—is in Figure 3. This is a small sample of the information gained through the analysis. However, it is telling because it codifies how designers will know if we "got it right."

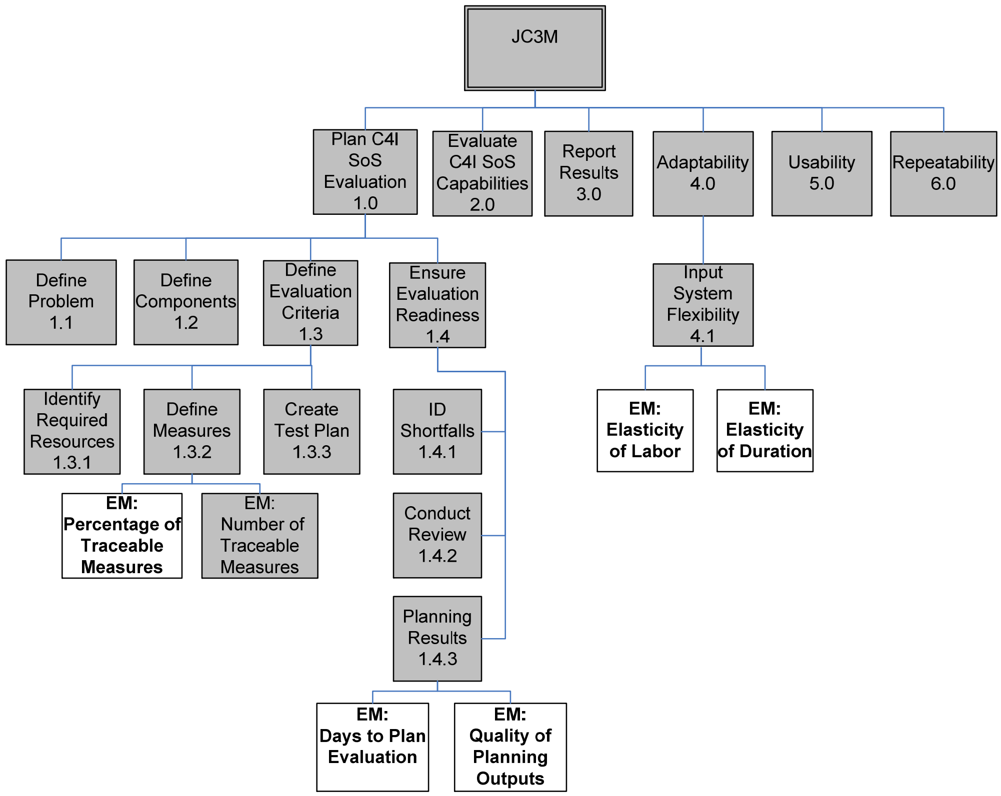

Figure 3. Part of JC3M Value Hierarchy
(Acosta et al., 2007)

The lighter-colored boxes indicate the evaluation measures that defined the needs for a set of modeling tools and that would drive the final analysis. A more complete definition for those elements is provided in Table 1.

Table 1. Evaluation Measure Details

	Percentage of Traceable Measures	**Days to Plan Evaluation**	**Quality of Planning Outputs**	**Elasticity of Labor**	**Elasticity of Duration**
JC3M Function	Define Measures 1.3.2	Planning Results 1.4.3	Planning Results 1.4.3	Input System Flexibility 4.1	Input System Flexibility 4.1
Definition	Alternative generated measures, traceable to stakeholder requirements, divided by the number of measures generated by the alternative. Ratio level data, from 0–100%	Elapsed time (in days) of planning for C4I SoS evaluation Integer count ≥ 0 days	Assign an overall quality level to the planning documents produced. Ordinal–Low, Medium, High	Divide percent change in labor hours to conduct planning phase of JC3M by the percent change in systems under test. Ratio level data from 0–∞	Divide percent change in duration to conduct planning phase of JC3M by the percent change in systems under test. Ratio level data from 0–∞
Rationale and Relevance	Identifies objectivity of performance measures. Performance measures traceable to doctrinal references will be perceived as objective, increasing the value of the evaluation.	Predicts SoS evaluations that can be conducted in a year. Alternatives that permit multiple SoS evaluations generate data to support fielding decisions sooner.	Identifies predicted utility of alternative. Quality of the planning products drives the overall value of the alternative.	Predicts changes in cost of SoS evaluation based on size. Can be used to determine most-effective alternative based on SoS size.	Predicts changes in duration of SoS evaluation based on size. Can be used to determine most-effective alternative based on SoS size.

Design Alternatives

There were three existing alternatives completed or in the final stages of development in response to the problem at hand. Additionally, the team sought to architect two additional systems. This would present the stakeholders a broad range of possibilities, while keeping the effort required for modeling and simulation manageable.

The first of the known alternatives was the Federation of Systems (FEDOS) system used at MCTSSA in 2005. FEDOS was designed to assess the performance of C4I systems when assembled into the MAGTF C4I SoS. FEDOS began at the order of the Deputy Commander for C4I Integration and Interoperability (C4II) at MARCORSYSCOM, that tasked MCTSSA to assess SoS and systems interoperability. A working group of stakeholders in the system developer community decided which systems would participate, which requirements were to be tested, and the schedule of events to include test planning, test conduct, and results reporting.

Because the MAGTF C4I SoS was not designed in compliance with an architecture, there were no overarching SoS performance measures or threshold criteria. This lack of doctrinal performance criteria meant that MCTSSA test personnel had to engage in long, and at times, inconclusive negotiations with stakeholders to define threshold values that were used to measure performance and determine if components passed or failed the test. The MARCORSYSCOM Product Groups, responsible for developing, fielding, and supporting C4I systems, were not ordered to participate in FEDOS, and a passing grade was not required for a milestone decision. It was perceived as a no-win situation for Product Groups: after a system had successfully passed Operational Tests by demonstrating compliance with system-level performance requirements in their respective CDD or equivalent, FEDOS tested component systems in ways they had not been designed for, but would be used in the field. The acquisition community's perception was that FEDOS was a risk with no off-setting benefit. Despite this shortcoming, FEDOS was relatively successful as the first USMC event specifically designed from the beginning as a SoS evaluation

Because FEDOS is the only alternative solution that has been used by a C4I test organization for a true SoS event, it was considered the "status quo" or baseline JC3M alternative solution. As with all good analyses of alternatives, the first option to consider is "do nothing," or, in this case, "do it like FEDOS."

The second alternative was MAGTF C4I Capability Certification Test (MC3T) developed at MCTSSA as a replacement for FEDOS. Other participants in MC3T development include the Space and Naval Warfare Center (SPAWAR) Systems Center in Charleston, S.C., and the Marine Corps Combat Development Command (MCCDC). More importantly, representatives of the MARCORSYSCOM Product Groups actively participated. Product Group representatives defined a "Capabilities Package" complete with system requirements and DoD Architecture Framework documents that depict the systems under their cognizance. MCTSSA analyzed the Capabilities Package and produced a Consolidated Requirements Assessment (CRA). The CRA was an agreement between the stakeholders on what needed to be tested, the required resources, and the Information Assurance compliance requirements. Once the CRA was approved, MCTSSA produced a Technical Proposal. The Technical Proposal defined the technical solution that the IPT proposed in order to meet the requirements in the Consolidated Requirements Assessment (CRA), including staffing, C4I systems architecture design, monitoring network architecture design, test cases, data capture and analysis plan, information assurance plan, and risk assessment. The Technical Proposal is confirmed, becoming the Technical Solution, which makes up nearly 90% of the Test Plan, includes detailed test procedures with reference documentation. The most promising aspect of MC3T is that MCCDC and MARCORSYSCOM have developed truly integrated architecture framework products. The operational activities doctrinally defined in the Marine Corps Task List are explicitly supported by specific systems working together. The idea that form should follow function in designing for network-centric effects-based operations is consistent with the latest direction for architectures (DoD, 2007).

The third alternative was JTEM's Capability Test Methodology (CTM). The purpose of JTEM is to "develop, test, and evaluate M&P (Methods and Processes) for defining and using a distributed LVC (Live, Virtual, and Constructive) joint test environment to evaluate system performance and joint mission effectiveness [...] focus on developing and enhancing M&P for designing and executing tests of SoS" (JTEM, 2007b). Figure 4 is an IDEF0 representation of the CTM process.

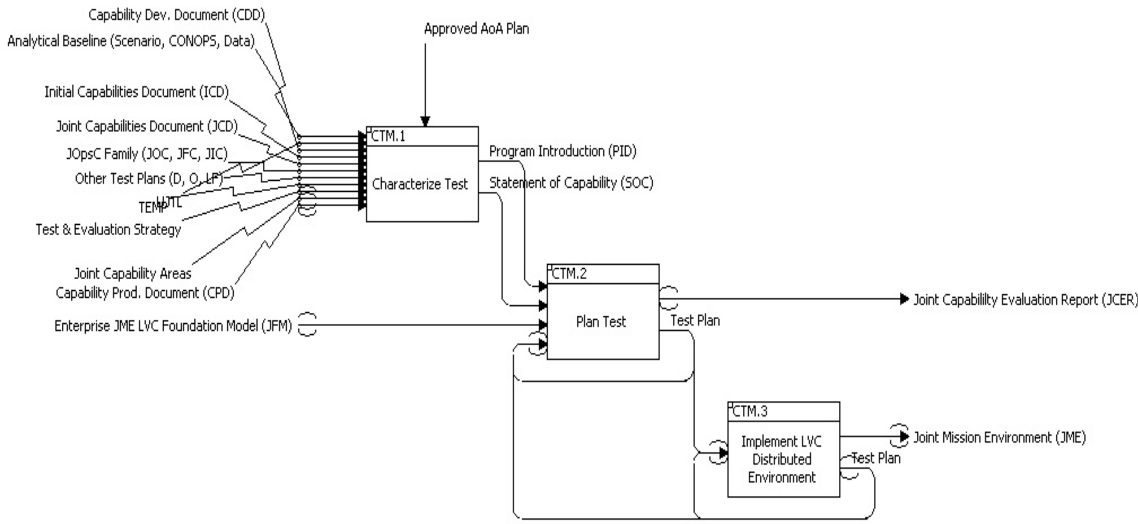

Figure 4. JTEM CTM in IDEF0
(Acosta et al., 2007)

One of the more promising aspects of JTEM's CTM is that test characterization explicitly examines requirements from families of CDDs in the context of missions based on the Universal Joint Task List (UJTL) (CJCS, 2002) and Combatant Command standing operations plans and orders. More detailed descriptions can be found in JTEM's *Joint Test and Evaluation (JT&E), Capability Test Methodology (CTM) Method and Process (M&P) Model Description* (JTEM, CTM, M&P). The complexity of scenarios developed for the LVC test environment reflects real-world complex military action involving disparate forces executing closely linked complicated tasks, including operations other than war.

Two new alternatives that offer significant differences from the existing systems were developed. The classic morphological box (Zwicky process) was applied and guided by the high-level functions identified earlier and then used, in part, to identify evaluation measures. Nine alternatives were initially defined. Through several screening iterations and re-evaluation against the root problem, only two remained: "Systems Capabilities Review" (SCR Alternative) and "Functional Capabilities Board" (FCB Alternative).

The Systems Capabilities Review (SCR) alternative combines two of the original nine alternatives. It is composed of a group of stakeholders: C4I SoS user representatives, test agency representatives, system developers and program managers. The test agency representative chairs the group, which meets, as required, to support a C4I SoS evaluation, at the Systems Command level. Inputs to SCR include source documents such as Capabilities Development Documents (CDD), Operational Requirements Documents, Test and Evaluation Master Plans (TEMP), Concept of Operations documents, Joint Integrating Concepts, Joint Operating Concepts, and system level metrics. First, the SCR reviews SoS capabilities specifications, examines the systems engineering artifacts already created (such as supporting DoD Architecture Framework documents and technical performance measures) and creates a list of implied and stated SoS capabilities. Next, the SCR reviews system-level documents and creates a system-level capabilities list. Third, the SCR maps system-level capabilities to SoS evaluation measures. The SCR identifies gaps in the evaluation measure list and creates the balance of evaluation measures necessary to evaluate the performance of the C4I SoS. Figure 5 illustrates how SCR performs the JC3M subfunction 1.3.2 "Define Measures."

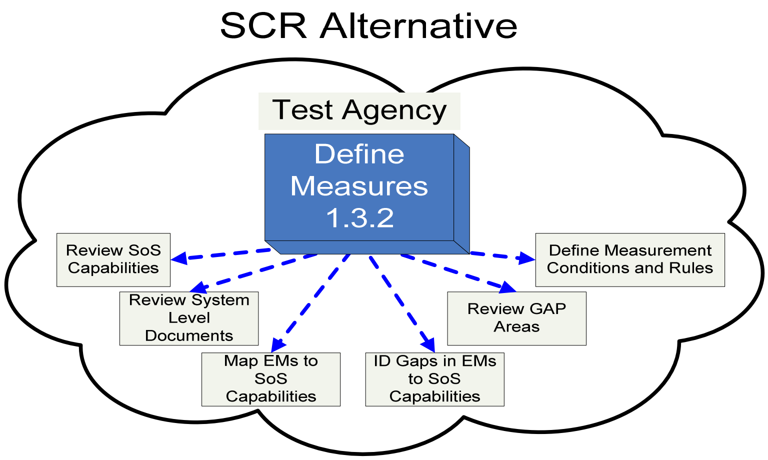

Figure 5. SCR Alternative Sub-functions
(Acosta et al., 2007)

The Functional Capabilities Board (FCB) alternative relies on an existing group—the JCIDS C2 Functional Capabilities Board—to define the performance measures of the SoS. The existing role of FCB is to perform "organization, analysis, and prioritization of joint warfighting capabilities within an assigned functional area" (CJCS, 2007). Inputs to the FCB Alternative include the UJTL and subsets, Concept of Operations (CONOPS) documentation, acquisition program documentation, and system trouble reports. The additional effort proposed in this alternative represents an increase in the work performed by the C2 FCB but is in the same functional area and engages in the similar tasks. Unlike the SCR, the FCB meets on demand, rather than as required, to support SoS evaluations. First, the FCB will identify the configuration of the SoS by determining the component systems. Next, the FCB will identify the SoS capabilities. SoS CONOPS are reviewed to determine evaluation measures. Finally, the FCB will generate the SoS evaluation measure list for use in C4I SoS evaluations. As the systems under the cognizance of the Joint Command & Control Capability Portfolio Manager are explicitly listed (DEPSECDEF, 2006, September), their participation in this alternative would be required. The FCB, under JCIDS, has a long-term mandate, and provides a short-term solution to the lack of SoS performance measures. The relationship between the FCB and C4I test organizations and the list of subtasks needed to complete the Define Measures task, is illustrated in Figure 6. Because the FCB is external to the test organization, some analysis of the performance measures generated by the FCB will be necessary. Additionally, it is understood that a working group within the FCB would perform the required analysis.

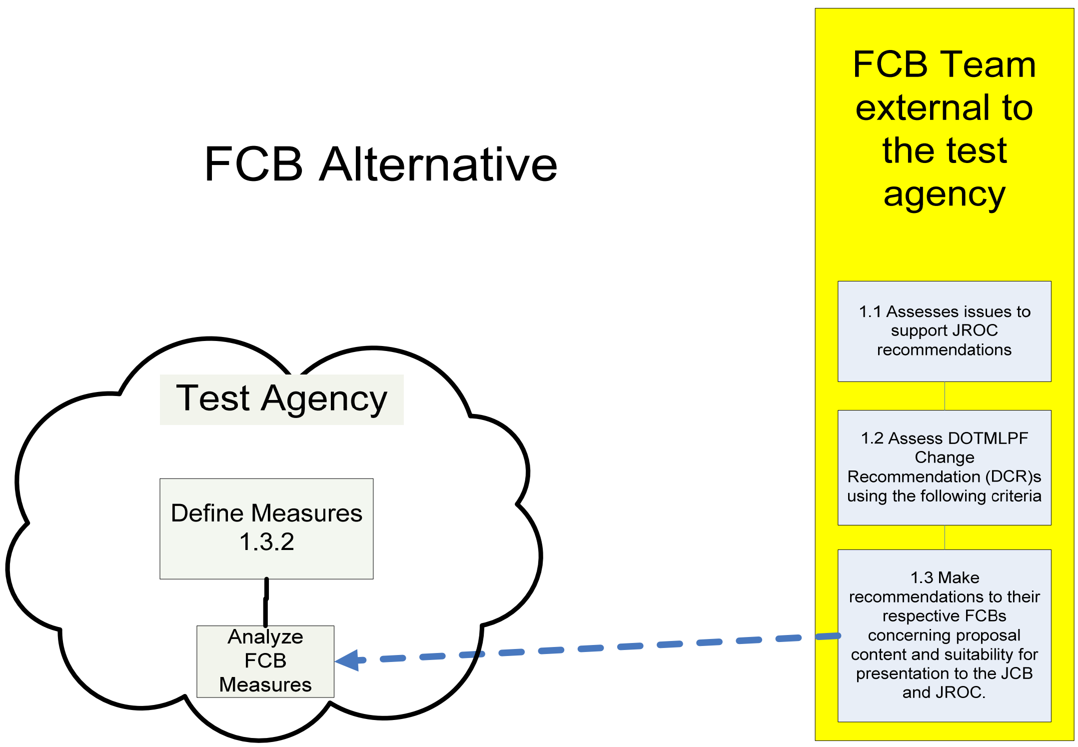

Figure 6. FCB Alternative Sub-functions
(Acosta et al., 2007)

Both of these new alternatives developed by the JC3M team rely on supporting integrated architectures and CONOPS documentation, in addition to documentation normally examined as part of C4I interoperability test preparation. The difference between these alternatives is in the approach taken to complete process 1.3.2 “Define Measures” in the JC3M Functional Hierarchy. The SCR alternative incorporates all tasks as part of the test planning process. The FCB Alternative utilizes an external team that meets year-round to provide capability measures to the test agency.

Five alternatives had now been defined in some detail, as well as evaluation measures to be used to compare those alternatives. Only determining the actual values or values obtained from simulation models for each alternative remained.

Modeling & Results

Modeling and simulation were used extensively in this project. With the exception of FEDOS, no other alternative under consideration existed. The only means to gather performance data in support of decision-making, short of “building” each alternative, was through simulation. It was the most cost-effective means to obtain the required evaluation measures in a repeatable and objective fashion. Several modeling tools were used to generate the necessary data. Figure 7 illustrates which tools were used to obtain the evaluation measures, which in turn supported later cost-benefit analysis.

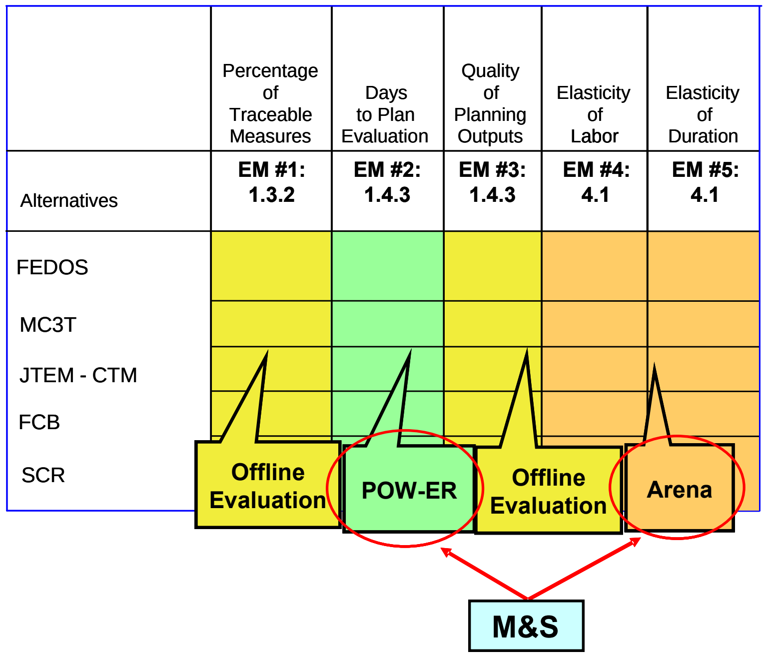

Figure 7. JC3M M&S Supporting Evaluation Measures
(Acosta et al., 2007)

Models of each alternative were built based on the functional architectures already created. Elements unique to their physical instantiations were added. In other words, complete functional models in IDEF0 were created with Vitech's CORE to support the simulation models built in Arena and POW-ER (Project, Organization, and Work for Edge Research). Within Arena and POW-ER, the attributes that differentiated the alternatives from each other— organizational structure, relationships with external systems, and processing of certain inputs—were included. The IDEF0 view of the systems actually proved insightful in terms of explicitly describing the relationship between the functions, at all levels of abstractions, in terms of their inputs and outputs. The models were executed by providing input to simulate a system under test along with its supporting information. The results of several iterations with variations in the input data sets were gathered and used to populate the table of evaluation measures with raw data. The "off-line evaluation" indicated the use of desk-top evaluation by test and development community representatives, similar to the JTEM Rock Drills. It could be considered a kind of human-in-the-loop simulation or just another kind of model or prototype that has been used successfully in this problem domain (JTEM, 2007b).

POW-ER is a project organization modeling and simulation tool that integrates organizational and process views. POW-ER was developed via the Virtual Design Team (VDT) computational modeling research at Stanford University. POW-ER addresses organizational elements that impact the ability to work effectively, including policies and structures (culture, communication, decisions, meetings); staffing, hiring, and training needs for workforce plans. Using POW-ER, the team modeled the organizational structure, the relationship between individuals within those organizations, and individual task allocations. Use of CORE to support functional analysis proved most helpful as it allowed the modelers to represent the same functional architecture in the refined IDEF0 models as a functional flow in FFBD format. That allowed the creation of PERT-like sequencing of tasks required when modeling work processes in POW-ER. POW-ER's ability to predict and analyze backlogs proved useful designing and troubleshooting alternative models because it allowed the team to identify backlogs in the workflow of models. The analysis of backlogs in the workflow enabled the team to identify the optimized arrangement of tasks and personnel for FCB and SCR since they were created for this project. No such changes were made to the other alternatives. Based on modeler-defined parameters, such as the amount of effort required for each task, the number of full-time equivalents available with appropriate skills and number of hours in a work-week, the POW-ER simulation tool can calculate a project's duration based on simulated duration. Simulated duration factors the "hidden work" that traditional Critical Path Method does not. The "hidden work" associates an amount of rework that delays into each task based upon random variables described for each task by the modeler. The simulated duration provided the number of days to plan an evaluation for each alternative (Acosta et al., 2007).

Arena is a commercial tool available from Rockwell Automation. It provides a numerical evaluation of a system by imitating the system's operations or characteristics over time. Arena allowed the team to conduct numerical experiments in order to predict the behavior of an alternative, given a set of conditions. Two evaluation measures required assessing the changes in output as a function of the changes in inputs: Elasticity of Labor and Elasticity of Duration. Arena allowed the team to run simulations on the alternative models with varying sets of inputs. Those input data sets represent the number of systems with their associated documentation that a SoS test event would typically cover. The baseline data set was the group of systems used during the FEDOS event. It included over 90 systems, which included AFATDS, EPLRS, GCCS-J, SINCGARS and TBMCS. There were 14 SoS capabilities examined, including blue force common operational picture, call for fire, common logistics and theater ballistic missile tracking. Variation in the input data set was accomplished by changing the number of individual systems, the number of old SoS capabilities, and the number of new SoS capabilities under test for each data set. The same input data set was used for one run of each alternative, enabling a true head-to-head comparison. The model in Arena was designed so that the subprocess tasks would vary in duration, based on varying the input systems under test. Thus, Arena displayed the output changes of the entire alternative process that corresponded to each of the varying inputs. The output changes (as a percent of the baseline), compared to the percent change of the input became the values for elasticity of duration and elasticity of labor (Acosta et al., 2007).

The models were validated against actual data from the FEDOS event of 2005. Since the original labor hour timesheets for planning that event were available, validating the models was relatively simple. The FEDOS process model was built in CORE, which supported the more elaborate models in POW-ER and Arena. Then, the outputs were compared to the appropriate actual data from FEDOS. The number of labor hours and calendar day predictions from Arena and POW-ER were within 1% of the actual values (Acosta et al., 2007).

Figure 8 summarizes the entire simulation process, including inputs and output values.

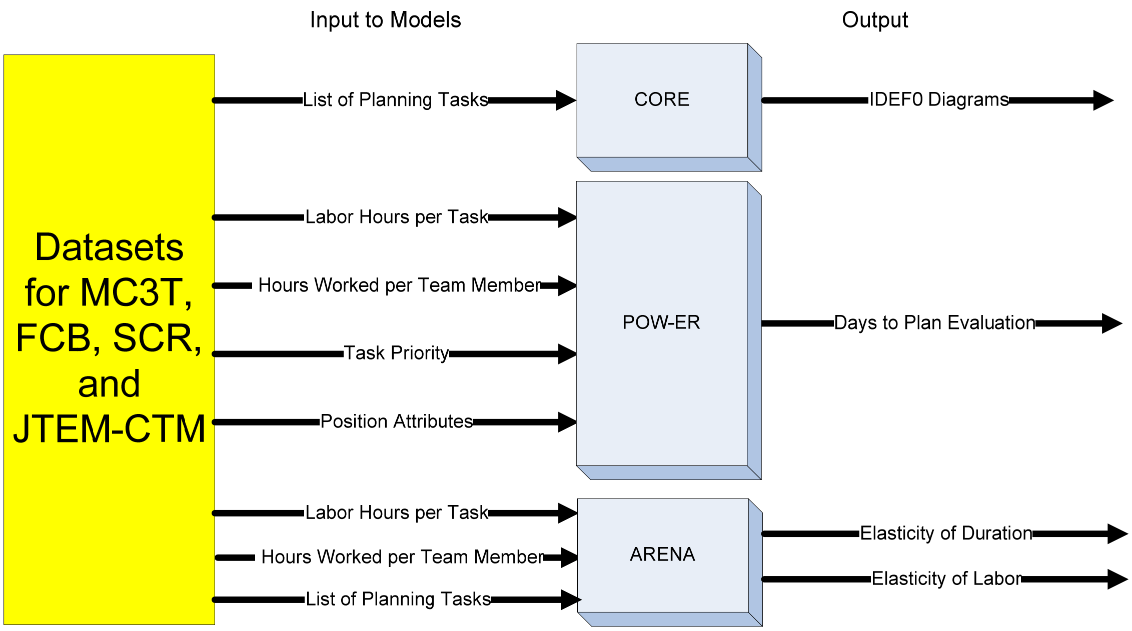

Figure 8. JC3M Modeling Overview
(Acosta et al., 2007)

This study represents the first time these modeling tools were used together to complement each other. The simulations predicted key parameters of each alternative design. Without such an approach, no objective or repeatable means to compare the alternatives against the requirements in those areas would have been possible. There is a high degree of confidence in the computer-based measures because the results for the FEDOS models were validated against known historical data and the other models used elements from the data, based on a task mapping from each alternative back to the FEDOS process.

There were still two evaluation measures that could not be determined by computer-based simulation: percent traceable measures and quality of planning outputs. The team was able to engage SMEs from several NAVSEA and NAVAIR field activities to participate in assigning a value for quality of planning products. The team assembled and then presented with all five alternatives. They were then allowed to ask questions in order to ensure clear understanding of how each process worked along with built-in limitations. Each SME responded to specific questions about the predicted quality of planning products coming from each process, with regard to their effectiveness in examining interoperability within a SoS, conformance to standards, and usability. The responses were based on a 4-point Likert scale for each alternative. Percent of traceable measures was more simple to determine once a key assumption was accepted. A proxy was defined as the number of authoritative sources considered, divided by the total number of authoritative sources available. This assumption is valid if there is a linear relationship (as a set) between the number of measures created and the number of sources used in creating those measures.

The final listing of the raw scores is provided in Table 2.

Table 2. Raw Evaluation Measures

	Percentage of Traceable Measures (%)	Days to Plan Evaluation (Days)	Quality of Planning Outputs (1-4 Likert Scale)	Elasticity of Labor (unit less)	Elasticity of Duration (unit less)
Ideal Value	**100%**	**Less is better**	**4 is Ideal**	**Less is better**	**Less is better**
FEDOS	0	140	3.17	0.87	0.87
MC3T	72	121	3.25	0.78	0.78
JTEM CTM	92	73	3.42	1.04	0.83
SCR	92	158	3.00	0.98	0.98
FCB	88	127	2.75	0.72	0.72

The extremely short duration to plan an event for the JTEM CTM process should be noted. This is to be expected because of that system's reliance on SMEs in so many different fields, which minimizes cross-checking with multiple stakeholders. On the other hand, the JTEM CTM elasticity of labor was the worst.

Considering so many measures, how could a single "best" alternative be found? The team chose to apply classic multi-attribute utility theory (MAUT). While MAUT has its well-documented limitations, it presents a means to compare the alternatives on a single weighted sum of utilities associated with each evaluation measure. Raw scores are converted to a value or utility score; that value is then multiplied by its global weight, and the resulting weighted values are summed to an overall value. The same SMEs who participated in the process to obtain planning, product-quality figures also participated in the process to determined value functions and swing weights. It should be noted that this team used the mathematically rigorous Wymorian standard scoring functions for value curves to convert raw scores to utility. Additionally, they were very precise about their application of swing weights and rigor of the analytical hierarchy process to obtain weights (Acosta et al., 2007). So, the weaknesses inherent in MAUT were minimized via these tools and techniques. The final total scores are shown in Table 3.

Table 3. Overall Utility of the Alternatives

	Percentage of Traceable Measures	Days to Plan Evaluation	Quality of Planning Outputs	Elasticity of Labor	Elasticity of Duration	Overall Utility (0 – 1)
FEDOS	0.00	0.04	0.39	0.06	0.14	0.63
MC3T	0.02	0.05	0.39	0.07	0.16	0.71
JTEM CTM	0.24	0.06	0.40	0.04	0.15	0.89
SCR	0.24	0.02	0.37	0.05	0.10	0.79
FCB	0.22	0.05	0.34	0.08	0.18	0.87

The last step in the process to consolidate the elements of the alternatives was to create a lifecycle cost estimate (LCCE) for each alternative. All costs associated with development, implementation, operations and support through disposal and transition were estimated. Actual data from the FEDOS event, to-date actual costs and to-completion estimates (directly from their respective project managers) for development of JTEM CTM and for development of MC3T were relatively easy to capture, once complete definitions for those phases and cost-breakdown structures were developed. Because the SCR and FCB alternatives were similar to MC3T in scope and effort, development costs were based on the MC3T numbers. As operations and support for such a system is dominated by labor costs, the annual cost for each alternative was based on applying the prevailing man-hour rates to the labor hour counts from the POW-ER models. Disposal and transition costs were assumed to be the same for each alternative because those efforts were practically identical in terms of level of effort and duration. Table 4 summarizes the LCCE for each alternative.

Table 4. LCCE Summary

Alternatives	Lifecycle Year					Total Cost ($)
	1	2	3	4…9	10	
FEDOS						
Development	0	0	0	0	0	0
Implementation	1,052,527	0	0	0	0	1,052,527
Operational & Maint.	0	419,497	419,497	419,497	2,200	3,908,178
Transition and Disposal	0	0	0	0	50,000	50,000
Total Cost	1,052,527	419,497	419,497	419,497	52,200	**5,010,706**
MC3T						
Development	0	0	0	0	0	0
Implementation	1,169,414	0	0	0	0	1,169,414
Operational & Maint.	0	525,537	525,537	525,537	2,200	4,756,500
Transition and Disposal	0	0	0	0	50,000	50,000
Total Cost	1,169,414	525,537	525,537	525,537	52,200	**5,975,913**
JTEM CTM						
Development	1,030,000	2,470,000	0	0	0	3,500,000
Implementation	0	0	1,169,414	0	0	1,169,414
Operational & Maint.	0	0	0	558,535	2,200	2,253,410
Transition and Disposal	0	0	0	0	50,000	50,000
Total Cost	1,030,000	2,470,000	1,169,414	558,535	52,200	**6,972,824**
FCB						
Development	1,021,835	0	0	0	0	1,021,835
Implementation	1,301,282	0	0	0	0	1,301,282
Operational & Maint.	0	650,223	650,223	650,223	2,200	5,753,985
Transition and Disposal	0	0	0	0	50,000	50,000
Total Cost	2,323,117	650,223	650,223	650,223	52,200	**8,127,101**
SCR						
Development	952,007	0	0	0	0	952,007
Implementation	1,169,414	0	0	0	0	1,169,414
Operational & Maint.	0	624,451	624,451	624,451	2,200	5,547,811
Transition and Disposal	0	0	0	0	50,000	50,000
Total Cost	2,121,421	624,451	624,451	624,451	52,200	**7,719,232**

The JC3M team determined the most expensive alternative was the FCB Alternative, at a cost of $8.13 million over the 10-year projected lifecycle. The team calculated the cost of FCB as a cost to the DoD. While the senior SMEs who generate the performance measures do not charge their efforts directly to a C4I test organizations, their time and effort is a cost to the DoD. The team determined that MC3T was estimated to cost approximately $960,000 more than FEDOS, which it replaced. While this is nearly a 20% difference, the increase can be directly attributed to the increase in scope, duration, and level of effort involved in MC3T, which anecdotally supported the increased cost of MC3T (Acosta et al., 2007). More importantly, the development cost for JTEM-CTM is the largest (its development is spread over several years). However, the O&S costs are the lowest. This result is significant because a test agency (or test branch within a development agency) deciding between these options would incur only the costs to implement such an option and then would reap the benefit of keeping annual costs very low.

Recommendations

A complete analysis of the alternatives based on the preceding data was conducted to determine the "best" alternative. That is, which alternative is projected to provide the greatest utility for the cost? Figure 9 summarizes the results. Again, the utility is a weighted sum of several different attributes, all tied directly to the overall goal of ensuring testing for true interoperability, which is a pre-requisite for any C2 SoS supporting a disparate networked force.

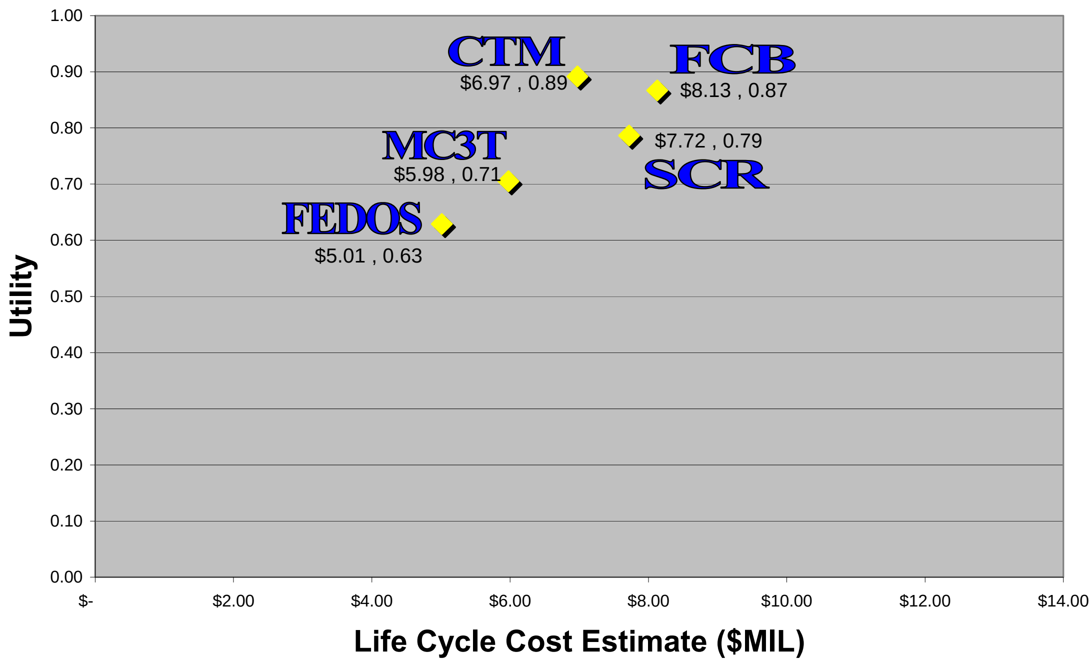

Figure 9. Utility versus LCC
(Acosta et al., 2007)

The JTEM CTM process is projected to perform slightly better than the other options and maintains a LCCE less than the two other alternatives with the closest utility scores. The attributes that drive this performance are the number of days to plan an evaluation, the quality of planning products and the percentage of traceable measures. It should also be noted that a nearly straight line could be drawn between FEDOS, MC3T and FCB. That leaves the SCR

Alternative below the line and JTEM CTM above it. However, the better way to examine this figure is to consider an efficient frontier of utility for every cost value. A linear frontier is formed by a line connecting the points for FEDOS, MC3T, and CTM. Thus, the FCB and SCR points are "below" that line—meaning they are less efficient and dominated by CTM.

It must be noted that there is some difference in the confidence we have in the performance measures. Because FEDOS and MC3T were used in actual full-scale SoS test events, their performance is based on historical documentation. JTEM CTM's performance measures are based on desk-top simulations called "rock drills," in which test community personnel exercised certain aspects of the system in an artificial scenario. Additionally, members of the JTEM team participated in this study, which validates nearly every aspect of JTEM CTM that was considered and confirms the expected simulation output. The results from the SCR and FCB alternatives were purely from the simulation. However, the simulation was based on modifying parts of models validated through FEDOS data.

With regard to cost, similar logic can be applied. Those numbers from FEDOS and MC3T are based on actual costs. The cost estimates for the other alternatives, dominated by the labor of annual operations, were driven by the simulation output for number of labor hours.

In spite of the differences in confidence levels, the overall results should be considered valid. The JTEM CTM had the median LCCE, with the lowest O&S cost. This is significant because O&S is a recurring cost, borne by every C4I test organization that implements one of the alternatives. Development costs of JTEM CTM are the largest portion of its LCCE—a nonrecurring cost borne by OSD and not borne by any single C4I test organization.

Summary & Next Steps

This team was the first to apply a disciplined systems engineering process to the problem of re-engineering the business of testing for C4I interoperability certification. The JTEM project is the only other organization to examine this issue from the perspective of optimizing a lifecycle-balanced solution to meet explicitly stated and quantifiable needs. No group has applied an integrated set of computer-based simulation tools to quantitatively predict the performance of competing options and compare that performance to lifecycle cost. Knowing that C4I systems never perform in a vacuum, but always interoperate as part of a larger SoS, developers and testers will benefit from the results of this study. Ensuring interoperability across services and between civil authorities and multinational organizations begins with an effects-based approach. Only by testing for interoperability against performance measures that are linked to desired effects in the battle-space can C2 SoS support warfighters engaged in complex endeavors.

Based on the insights into the problem domain and potential solutions, there are areas that need further study. The team believed the C4I acquisition and testing communities would benefit from a dedicated Joint C4I SoS manager to provide consistency in an evolving environment. Their role could include documenting C4I SoS capabilities, long-range SoS capabilities planning, and testing requirements management; supporting developmental and operational testing; and addressing ad hoc SoS configuration, resulting from new threats and concepts (Acosta et al., 2007). These roles represent overlap between the acquisition community and those responsible for communicating needed capabilities to them. It is hoped that codifying the relationship between the Joint C2 Capability Portfolio Manager and the C2 FCB will be a move in this direction.

Next, as changes to the SoS configuration are made, the likelihood of capability failures increases. The JC3M team believes risk management strategies should be developed and applied to the C4I SoS. The JC3M team's preliminary list of risks includes the lack of a single entity responsible for SoS performance; the lack of an objective, repeatable, and methodical approach to address individual system problems impacting SoS functionality; varied levels of maturity of systems within the C4I SoS architecture; and varied interfaces between individual systems.

Finally, systems that are components of the C4I SoS have their capabilities defined as if they exist in a vacuum, and their impact on C4I SoS capabilities is generally not considered. The DoD C4I SoS acquisition process should require component system sponsors to define C4I SoS level effects; establish a funding line for SoS testing; and include SoS effectiveness testing as part of operational testing (Acosta et al., 2007).

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