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MEETING THE CHALLENGE OF SYSTEM OF SYSTEMS INTEROPERABILITY TO DELIVER COMBAT SYSTEM CAPABILITIES

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Abstract

Individual complex systems routinely operate with other complex systems (in a complex environment no less!) to achieve desired military capabilities; generally speaking, Lethality, Mobility and Survivability. While challenging in itself, this scenario is complicated by the fact that new systems are being deployed and retired which imposes training requirements and adaptation on the part of users and maintainers. The author will characterize the challenge and describe an approach to coping with the challenge and mitigating its impact. Specifically, ground combat vehicle capabilities are undergoing a transformation which can be accelerated by employing some of the techniques described and improve our soldiers' ability to meet and defeat rapidly changing threats. The technique is generically referred to as Capability Planning and it is supported by set of software tools and analytic techniques, commonly called a Decision Support Framework. This paper characterizes the techniques and generally demonstrates how engineers can better collaborate with program managers and customers though their use. Several examples of successful implementations will be described and clearly demonstrate the potential for the rapid fielding of increasingly effective military capabilities by interoperable complex systems, enabled by the use of these innovative engineering applications. This paper focuses on communications systems that enable Command and Control functions which are seen as key enablers for military capabilities such as lethality and survivability. The conclusions, however, generally apply to any systems that must interoperate.

Interoperability

Interoperability; the ability of systems, units, or forces to provide data, information, materiel, and services to and accept the same from other systems, units, or forces and to use data, information, materiel, and services so exchanged to enable them to operate effectively together. Source; Chairman, Joint Chiefs of Staff Instruction (CJCSI) 6212.01B, Interoperability and Supportability of National Security Systems and Information Technology Systems, May 8, 2000.

The Challenge

Interoperability is enabled by systems which permit operators and other systems to interact in a coordinated fashion. Specifically, interoperability is enabled by the interfaces between the systems that connect the operators and other systems… To work well, the systems must easily pass information and data specific to the task(s) at hand and within an acceptable period of time. Sounds simple enough, however, several factors currently complicate our ability to accomplish this feat either effectively or efficiently. When allowed to proceed independently, individual programs optimize a solution that meets their specific requirements and will implement what is deemed to be optimal within their scope. Those same requirements however are generally suboptimal when the systems are selected to be integrated as part of a System of Systems (SoS) solution. A typical response is to implement new and more complex interfaces between the systems. Sometimes, the participating systems are re-engineered or re-purposed. Engineering solutions are layered atop one another and foster complexity as well as complexity's by product; emergent behaviors. Additional complexity in SoS problems stems from the derivation of specific requirements in terms of generally vague desired capabilities. These capability statements are analyzed in order to derive and allocate requirements which can be in direct conflict with the requirements of other participating systems, but are nonetheless requirements. Shifting customer priorities, emerging mission needs, evolving threats, and uncertain budget priorities also contribute to the apparent complexity. While it is theoretically possible to develop a system of systems that can meet current interoperability challenges, we must contend with the fact that majority of the major constituents in an SoS construct are inherited and cannot be altered.

Capability Planning

Notionally speaking, Capability Planning (CP) is an analytic method which is intended to direct customers (military system acquisition professionals in this instance), engineers and managers towards adequate solutions with the least complexity. While CP helps Integrated Product Teams (IPTs) perform many other functions, this paper focuses specifically on CP's ability to highlight interoperability solutions. CP is founded upon a rigorous, systems engineering methodology at the enterprise (i.e., SoS) level to define capabilities and mission threads in a DoDAF compatible format. Originally, it was developed to support Joint Capabilities Integration & Development System (JCIDS) acquisitions. However, many of the utilities are useful in less complex acquisitions consistent with the "modify and upgrade" approach needed today to enhance fielded system capabilities. Essentially, CP compares complex families of systems (i.e., technical architectures) based on their contributions to operational mission performance and characterizes the interoperability of each potential system solution. It allows for interoperability to be characterized using metrics and measures deemed most appropriate by the IPT. CP differs from most common Analysis of Alternatives methods because it exercises an interoperability utility function to explicitly to measure synergy or harmony across a complex SoS construct.

How Capability Planning works

Here is a top-level description of Capability Planning methodology intended to shed light upon the typical input one must provide and decisions to be made during its use. Desired capabilities and the metrics used to measure them are defined through a traditional Enterprise Architecting Process. These top-level needs are often derived from doctrine and policy documents. Specific metrics are more easily developed once the needs are defined. The needs are also used to define mission "threads" and this can be done in a manner consistent with the DoDAF OV-5 nomenclature. The definitions can be documented and organized logically in commonly available architecting tools. However, Capability Planning uses the mission threads to perform an executable architecture analysis which is a significant distinction over traditional analytic methods that only use the OV-5 format to document architectural elements. Dependencies between functions are considered and weighted on a scale of 1-4 to account for the multiple ways a mission may be accomplished. Establishing the mission threads and weighting factors is the means by which IPT can account for one element of complexity: the operational complexity endemic to all SoS's. Equally as important, it is the means by which IPT members reconcile their understanding of the capabilities and threads being analyzed. When this "sense-making" is done, an algorithm is run to translate the threads and their weightings into a matrix of functional dependencies call the "Function-to-Function" matrix. An assessment of system performance at the functional capability scale is conducted to evaluate "how well a system performs a function" across one or more mission threads. This particular CP utility is simple yet powerful. It enables the comparison of very large numbers of functional threads – the kind of numbers inherent in the complex SoS constructs being integrated today. The assessment performed above can also produce a matrix called the "Function-to-Solution" matrix. This matrix enables the determination of how well the functions meet the requirements described in the capability need statements. Both of the assessments described above can incorporate qualitative (expert judgment) or quantitative (modeling and simulation) input. Figure 1 shows the typical products and benefits of Capability Planning. This graphic is included at this juncture to serve as the demarcation between the input products that constitute the data needed to populate CP and the output and visualization products it can deliver. This is where CP begins to "come into its own" so to speak.

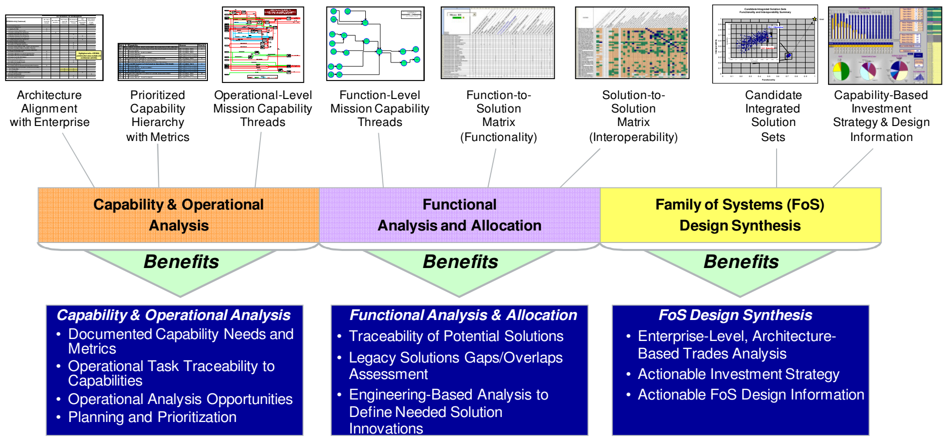

Figure 1. Typical Capability Planning Products and Benefits

CP treats interoperability explicitly and thus can enable the quantitative determination of how well systems work together in a candidate SoS concept. A typical product at this stage is the “Solution-to-Solution” matrix which delivers an empirical measure of how well one proposed solution can work with other candidates. Solution comparisons can be done using standards such as LISI, which stands for Levels of Information Systems Interoperability. LISI is a qualitative (0-4) scale and can be considered to be a Technology Readiness Level (TRL) for interoperability. LISI is currently one of the only real "standards" for assessing a system’s interoperability.

This traceability back to standards lends credibility to the results generated, but comes at a cost. For example, very specific measures (Timeliness, Accuracy, Reliability, Usability ... Visibility, Accessibility, Understandability, Traceability (TARU VAUT) can be specified to bring granularity to the analysis. These measures are used to quantify such attributes as “How does the system improve timeliness?” and “How much more accurate is it?”. These metrics are considered to be key attributes of interoperability and thus used in analyses where interoperability is a desirable system behavior. Ground vehicle and dismount system (communication) solutions typically impose the need to assess these "ilities". Ground vehicle solutions can also be assessed using "ilities" such as adaptability, flexibility, expandability, versatility, etc. These attributes can be used to measure how well the system can function in an SoS construct. While TARU VAUT assessments may be implemented to gain more granularity, this imposes the need for more data population, which can be cumbersome. The principle question the IPT must address as they proceed is “How much data/granularity is enough?” to answer the question(s) at hand. By way of explanation, if the analysis considers only one global metric (interoperability), then the analytic results are usually directly correlated to the input (you get back out only what you put in…). When you go to the TARU VAUT level, the assessment is more granular, but one needs 8 times as much data. Such granularity may be essential for one to understand where the system solution is not meeting expectations. The example above illustrates a tradeoff one must typically make when using CP. While daunting in one’s initial exposure, an experienced CP user can guide the team towards an appropriate level of data input. The granularity issue can become quite important as one necks down to a small number of competitive system solution candidates. Intuitively, with few parameters to judge by, proposed candidates are likely to all meet the requirements to one degree or another and the distinction becomes blurred when the results are aggregated as is normally done. CP offers the ability to include an appropriate number of "ilities" in combination with enough Mission Threads to gain the insight and justification needed to clearly distinguish a preferred solution. It is important to reinforce the fact that CP does not deliver “the answer”. Rather, it is highly effective at exposing the attributes that IPT members deem important in the discernment of and discrimination between viable solution candidates.

That said, SoS functionality and interoperability are clearly limited by a variety of constraints; most often, the budget and time available to obtain the desired capability. CP has the inherent functionality to associate cost and schedule data with proposed solution elements. This utility enables the creation of, for example, a “Solution-to-Cost” matrix. Matrices like these are the foundation for constrained optimization. CP can execute optimization routines based on genetic algorithms which can link, characterize and quantify the attributes of various system element combinations. These combinations can then be ordered in terms of their “goodness” according to metrics derived by the IPT. The metrics are specified as “objective functions” and are then used to differentiate those solutions that exceed the objective function from those which do not. Highly ranked candidates can be identified as potential integrated solution sets and be the subjects of further analysis.

The composite objective function described above is the basis for interoperability evaluation and can be used to discern between alternatives based on the interoperability metrics derived by the IPT. However, it is versatile and useful in other ways. Implementing the objective function with a 50/50 (balanced) weighting between alternatives will render solution candidates that generally meet the capability needs and are interoperable – if any exist. Varying the weighting will point towards potential solutions that favor the more heavily weighted parameter. Adding the cost matrices (constraint functions mentioned earlier) allows function-interoperability-cost(i) tradeoffs in 2+i dimensions. Essentially, these constraint functions are used to clarify and expose the presence of viable candidate solutions from among all contenders. In the example given, the (i) cost dimension is used to filter out non-compliant solutions. This aspect of CP (filtering after the optimization is executed) enables the IPT members to retain design freedom longer than most traditional methods might. Candidate solutions are carried further through the process as compared to such methods which tend to eliminate options as the evaluation process continues. Using a CP approach, one can vary constraints at will and explore “what-if” alternatives in response to questions posed by IPT members based on insight gained during discussion and data visualization. Data visualization is the forte of CPs companion application, generally referred to as a Decision Support Framework.

Figure 2. A Decision Support Framework display.

Decision Support Frameworks

Decision Support Frameworks, or DSFs, have been developed to provide a collaborative, interactive decision aid that can be used to enable engineers, military "operators" and program managers to collaborate so as to understand and resolve the issues caused by the inherent complexity of SoS solutions (Figure 2). Some DSFs rely on both qualitative and quantitative information to address these issues. These DSFs are now capable enough to cope with cost and schedule considerations in addition to engineering details. One such DSF originated at the Georgia Institute of Technology. Initially, it was developed to overcome some of the complexities of missile defense planning (Biltgen). This DSF was founded upon interactive Quality Functional Deployment (QFD) and Multi-Attribute Decision Making (MADM) techniques. The method was later extended to cope with challenges associated with strategic planning applications (Kirby and Raczynski) by incorporating the ability to display changes associated with specific parameters (cost and maturity of SoS elements) over time. The technique has since been matured and applied to resolve complexity issues for a wide variety of government and commercial applications. It has also been used to clarify issues associated with technology upgrades for individual systems (such as ground, air and seagoing vehicles) and combinations of their variants (1995, Schrage). As a complement to CP functionality, a DSF uses a large-format, interactive, graphical dashboard to display information that enables "what-if" studies in real-time.

Generally speaking, DSFs enable team members to localize on the most promising solution sets among competing alternatives. They aid teams by organizing and displaying the data associated with many different dimensions simultaneously. The dimensions (cost, time, effectiveness, complexity, etc.) are selected and defined by the participants. Generally, data is implemented as a "fact" and the combination of these facts in an agreed-to format renders insightful information. In doing so, the DSFs enable decision makers to see and better understand the interwoven tradeoffs across a system-of-systems solution as well as the key difference between competing solutions. This functionality is intended to make it easy for Integrated Product Team (IPT) members to see their unique areas of concern in a "big picture" context tailored to information and metrics most important to them. The effort of creating a DSF display also "socializes the decision making process." Typically, interaction between team members with different perspectives promotes the common definition and broad understanding of terminology and perspective between participants. These discussions frequently elicit new metrics that are not always intuitive to system designers or any individual team member. By making the decision space visible and navigable, the decision makers can quickly "see" non-optimal or infeasible solution sets. This allows the team to focus their efforts in areas which are feasible as well as enabling them to determine which solutions are most promising among the viable alternatives.

DSFs are a natural complement to physics-based models and simulations which are used to develop accurate and precise answers. They (DSFs) are powerful tools which, when used appropriately, guide teams towards the areas wherein further detailed analysis is needed to fully develop a robust point solution. In addition to providing an interactive experience to understand complex issues, the DSF also helps engineers and other participants set up the problem by using the interactive tradeoff environment to understand assumptions, sensitivities, and interactions. In conjunction with CP utilities, DSFs enable decision makers to eliminate non-viable alternatives or unimportant degrees of freedom. They expose the selected data and information which keeps the decision makers focused on impactful parameters. Likewise, a DSF construct helps organize results in a manner that can help the team convey their decision rationale more effectively. DSFs are an important System Engineering tool for this very reason.

The interactive dashboard is the visualization and reporting layer; the proverbial "tip of the iceberg". This is the visual display of the gauges designed to present metrics information to decision makers in an intuitive manner. The underlying database and methodologies by which data is related to produce information is where the true power of the DSF resides. Any number of analysis methodologies can be used to organize information, enable voting and maintain linkages between chosen parameters. QFD is popular and was the foundation for the Georgia Tech implementation described above. Voting methods are generally applied independently of the data and information organized in a DSF construct. Many such voting techniques can be traced back to the RAND Delphi method, which is also implemented in core elements of the AHP and ANP techniques used in readily available commercial software packages. Please note that commercial voting and "Decision Support" applications are generally limited in their capabilities with respect to mature and highly integrated CP and DSF applications. The integrated capabilities described in this paper are, by their design, more comprehensive and versatile. In sum, the methods described are key elements of an integrated decision support environment as depicted below. Inherently, they offer a robust method to understand the implications of system complexity as it relates to the interoperability of systems which interact as part of an SoS construct.

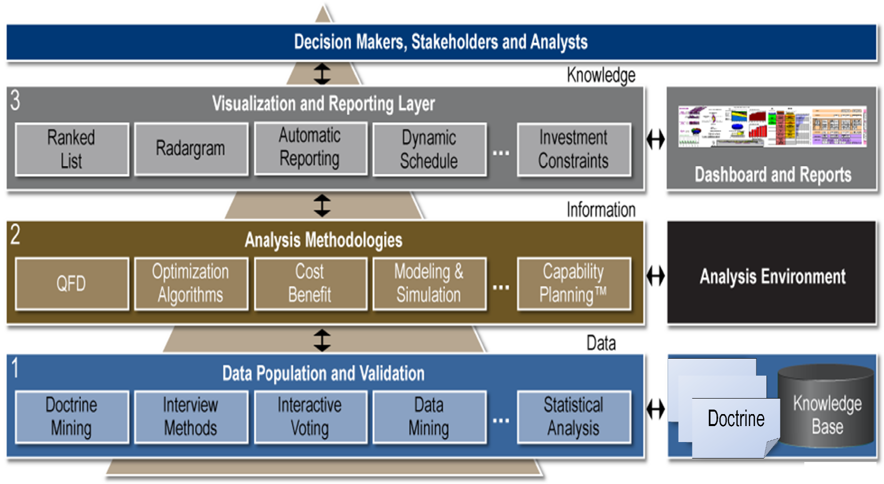

Figure 3. A Decision Support Framework with Capability Planning embedded.

The intent of the methods described is to enable (in this instance) interoperability related analyses by virtue of being able to perform "what-if" studies in real-time utilizing customized metrics traceable back to established standards. Specifically, CP can be used to support Enterprise Architecting, gap analyses, Analysis of Alternatives, System Design and Optimization and Portfolio generation, programming, and budgeting. As depicted, CP and DSF can be combined to form the analytic layer of a DSF to provide a capability and interoperability-optimized assessment of candidate system architectures.

Here is a generic representation of a dashboard which can be produced.

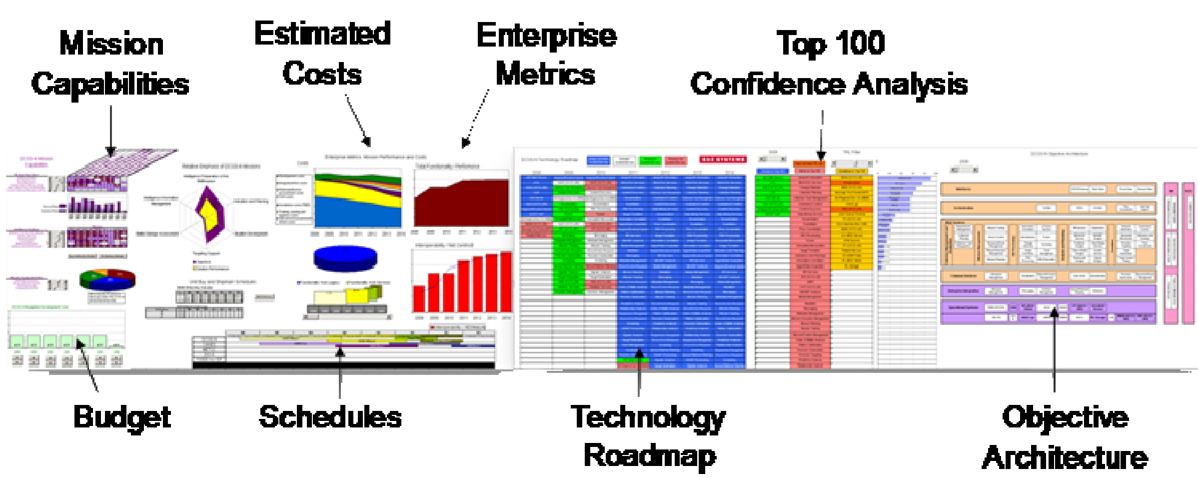

Figure 4. An example of a Decision Support Framework Dashboard.

Inputs on the left typically contain degrees of freedom, for example, cost and schedule. Various metrics are displayed in the middle. The metrics can depict either the reality of some of the constraints applied or the visualization of some future state under consideration (e.g., altered funding profile impact on system(s) under consideration). The middle right generally displays the parameters that distinguish the solution under consideration from the current reality or other contenders. The right most panel may be used to display a desired end state (in terms of capabilities or architectures). The power of the implementation is the ability to toggle between candidate constructs and immediately see the potential impact of implementing the alternative being considered. In this example, a technology roadmap occupies the central panels. A very useful byproduct of CP/DSF optimization analyses is that there are typically three "zones" within a given set of solution components. Some components are always part of the candidate solution and some never are. By removing these components from further consideration, one can focus more effectively on the components that "make the difference" in the selection of the preferred alternative. Thus, the integrated construct can guide the IPT explicitly and specifically to the heart of the information that matters for the degrees of freedom being explored. The results are compelling and sometimes counter-intuitive.

Conclusion

Capability Planning and Decision Support Framework implementations deliver the ability to investigate interoperability opportunities, concerns and issues at the enterprise or System of Systems level. Such implementations are robust and informative and serve to align the understanding of decision makers working with Integrated Product Teams. Given that industry-accepted standards are applied during the metrics derivation part of the analysis process, the solutions exposed through the use of these tools are considered traceable back to meaningful benchmarks. Such benchmarks exist with respect to system interoperability and have been successfully implemented in CP/DSF constructs. In fact, these environments have now routinely demonstrated the ability to expose adequate and achievable cross-domain interoperability solutions in complex SoS constructs where no solutions were even remotely apparent to the analysts and IPT members at the onset of an analytic effort.

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