WRT 1002: Approaches to Achieve Benefits of Modularity in Defense Acquisition – Part 2

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EXECUTIVE SUMMARY

Our efforts in WRT-1002 gathered the previous knowledge accumulated in RT-163 and RT-185 to conclude the investigation of how the DoD can support Program Managers in their development of systems that exploit modularity to enhance acquisitions and military capabilities. The work accounted for the guidelines and benefits associated with the implementation of a Modular Open System Approach (MOSA) ecosystem and sought to build a useful tool to provide analysis and insight to support informed choices for assembling capable and robust systems architectures.

The WRT-1002 effort was executed with a multi-prong approach. Data collection continued, expanding the work from previous projects, both with literature review and participation in conferences and workshops. These events also provided opportunities for collaborative exchanges with subject matter experts from DoD, the military, and academia, which resulted in valuable feedback about the approach followed in this research project. In order to demonstrate the applicability of this approach to diverse problems, we developed a synthetic case study based on a multi-domain battle scenario. Finally, our work completed the development of a Decision Support Framework (DSF) which integrates tools for the analysis and optimization of capabilities and cost in acquisition applications, generation and analysis of alternatives, evaluation of risks, and considerations about potential benefits of the application of MOSA principles.

BACKGROUND AND RESEARCH OBJECTIVES

The US Department of Defense (DoD) has many times recognized the need to transition to a culture of performance and affordability. This includes prioritization of speed of delivery, continuous adaptation, and frequent modular upgrades. These objectives are supported by various DoD initiatives, including the Modular Open System Approach (MOSA). – a defense acquisition initiative (and requirement in law for major programs) to encourage the adoption of modularization and of open architectures.

However, current MOSA guidelines provide limited insight into:

a) the "What": the specific potential benefits of modularity and openness, the conflicting priorities of the diverse set of stakeholders involved, and the complex interdependencies that exist between the technical and business elements of modular system acquisitions;
b) the "How": which levers to play, and decision problems to solve, to realize the benefits of modularity and openness throughout the "MOSA ecosystem";
c) the "Why": How can programs improve their evidence for specific MOSA implementations

A decision-support framework (DSF) would be useful for acquisition stakeholders in addressing the "What, How, and Why" in the MOSA ecosystem and thereby achieve desired program performance (cost, performance, schedule and risk) while accounting for stakeholder incentives in the ecosystem.

Previous research in RT-185, Approaches to Achieve Benefits of Modularity in Defense Acquisition, yielded:

- a prototype MOSA decision-support framework (DSF) based on case studies of key drivers in early state acquisition processes related to MOSA compliance; and
- a Program Manager Guidance Document to include insights for early stage acquisition decisions.

Findings from literature, workshops, and individual collaborator inputs provided key insights on how modularity is viewed, what are useful enablers of achieving the benefits of modularity, and, anecdotes/case studies of successful modular strategy implementations. The researchers' focus remained on the early stages of the defense acquisition lifecycle that include post Joint Capabilities Integration and Development System (JCIDS) process through Analysis of Alternatives (AoA). The focus on early stages of the defense acquisition lifecycle is consistent with collaborative exchange reports on the high impact that early stage requirements have on the successful adoption of MOSA in a program.

RESEARCH NEEDED

The execution of the prior RT-185 highlighted the need for a robust Decision Support Framework (DSF) that can assist relevant stakeholders in exploring tradeoffs while also understanding the technical and programmatic impacts that various strategies (modular/open) can have. The prototype DSF was based on a small application, dealt mainly with AoA, and did not include analysis of performance and risk. The WRT-1002 research has resulted in an expanded and refined MOSA DSF. Specific advancements include:

- Translate knowledge from specific programs into functional features of the decision support-framework in a manner that maximizes value to identified stakeholders (profiles), based on iterative feedback of users.
- Explore the nature of practically informed tradeoffs between and among common metrics of interest to partner programs (e.g. cost, schedule, risks) against various strategies for openness and modularization that are specific to each partner's objectives and interests.
- Demonstrate the prototype DSF effectiveness to guide software implementation of the framework to help rationalize MOSA decisions being made by programs.

WRT-1002 ACHIEVEMENTS

Based on the previously described objectives, the WRT-1002 research team identified a two-phase approach that focuses on extending and leveraging previous work in MOSA guidance. A summary of each phase is as follows:

1. Phase 1: Expand previous knowledge acquisition and gather feedback on research effort: In this phase, the research team performed additional MOSA and acquisition-related literature reviews, engaged relevant collaborators and participated in workshops and conferences to engage the community and receive feedback on research effort. More knowledge has been acquired on aspects of acquisition which benefit from the application of MOSA principles. The knowledge gained from this effort and the feedback received were considered when implementing the decision-support framework (DSF) in Phase 2.

2. Phase 2: Implement a MOSA decision support framework: In this phase, the research team took the start from the prototype decision support software environment developed in RT-185 to provide a fully functional and viable tool in support of decision-making for Program Managers. The functionality of the software has been extended to include tools from Purdue's System-of-Systems Analytic Workbench, which provide analysis and trade-off of multiple metrics of interest. This analysis goes in parallel with considerations about the application of MOSA principles and organizational requirements which derive from the studies in the previous efforts and in phase 1 of WRT-1002.

A description of the work completed during each phase is presented in the following subsections:

PHASE 1: EXPAND PREVIOUS KNOWLEDGE ACQUISITION AND GATHER FEEDBACK ON RESEARCH EFFORT

For Phase 1, the research team concentrated on the following key objectives:

- *Conduct further literature review and collaborative exchanges with key collaborators from industry, academia and government entities*
- *Receive feedback on research effort*
- *Map relevant knowledge artifacts to parts of the Decision Support Framework*
- *Develop a high-level architecture of the Decision Support Framework*

Extended literature review was conducted to further broaden the research team's knowledge of the application of modularity and openness in various programs. The review included study of military programs focusing on ground vehicles, such as VICTORY and FACE. Economic aspects were considered together with performance and timeliness of acquisition in the programs. The findings were leveraged in the design of the Decision Support Framework and the associated demonstrative case study. The literature review also included a thorough study of the MBSE effort and development of Integration Framework by Dr. Blackburn in Model-Centric Engineering with SERC. Like all thrusts intended to enhance DoD acquisition, MOSA goals can be accelerated when enabled by a Digital Engineering (DE) backbone and leveraging prime elements like Model-based Systems Engineering (MBSE).

The research team also executed a study of the US Navy's Open Architecture Assessment Tool (OAAT), a model with a set of scoring values and metrics that Program Managers use to assess compliance with Open Systems Architecture models. Some of the metrics are a useful tool to identify organizational requirements and to evaluate what type of systems and architectures can benefit from the application of MOSA principles.

Besides the collaborative exchange with the VICTORY program, the research team participated into multiple online meetings with the Modular Open Systems Working Group (MOSWG) and presented at the MOSWG session that gathered the military, industry, and academia. The meeting was held in Alexandria, VA, on July 17th, 2019. The team attended various presentations that yielded many learning points. The most relevant presentations and their outcomes are listed below:

- Mr. Nathaniel Barley presented about the *tiger teams* for implementation and guidance for MOSA.

- Dr. Kelly Alexander illustrated the US Army MOSA implementation plan, including army assessment criteria, which suggested some of the empirical rules used in the recommendations for MOSA benefits in the DSF.

- Mr. Steve Thelin of Raytheon listed recommendations by NDIA for MOSA strategy. Most of the recommendations reflect our previous findings included in the Program Manager Guidance Document. Some of the needs highlighted in this talk, such as necessity of support from Digital Engineering, need for engagement of industry, and creation of libraries of systems are echoed in the development of the DSF.

The team also presented a report of ongoing research at the SERC Sponsor Research Review and prepared a paper entitled "*Implementing a MOSA decision support tool in a model-based environment".* The paper, which describes the importance of MBSE in support of input and output representation for the DSF, has been accepted for the Conference on Systems Engineering Research. The collaborations produced good feedback which is reflected in the implementation of the Decision Support Framework. The acquired knowledge suggested two main modifications for the DSF framework:

1. The prototype version of the DSF relied on a series of cascading matrices, structured similarly to Quality Function Deployment (QFD) matrices, to help relate user inputs to relevant output, including available resources and organizational disposition. Many subject matter experts underlined the need to supplement the non-quantitative study of organizational requirements with quantitative study of cost, performance, and risk associated with different strategies. Therefore, the high-level architecture of the DSF has been updated as shown in Figure 1. The DSF can now produce and evaluate architectures

built upon different strategies, support trade-off between quantitative metrics of interest, including cost, performance, and risk, evaluated with SoS methods and tools, and indicate systems or architectures that can benefit from or require compliance with MOSA principles.

2. Since the knowledge gathered in this phase showed that the user needs can be very diverse, and the projects that could benefit from the DSF belong to many different fields, the research team decided not to use a small existing project as case study. Instead, the research team developed a synthetic case study based on a multi-domain battle scenario, considered under the lens of mission-based engineering (Figure 2).

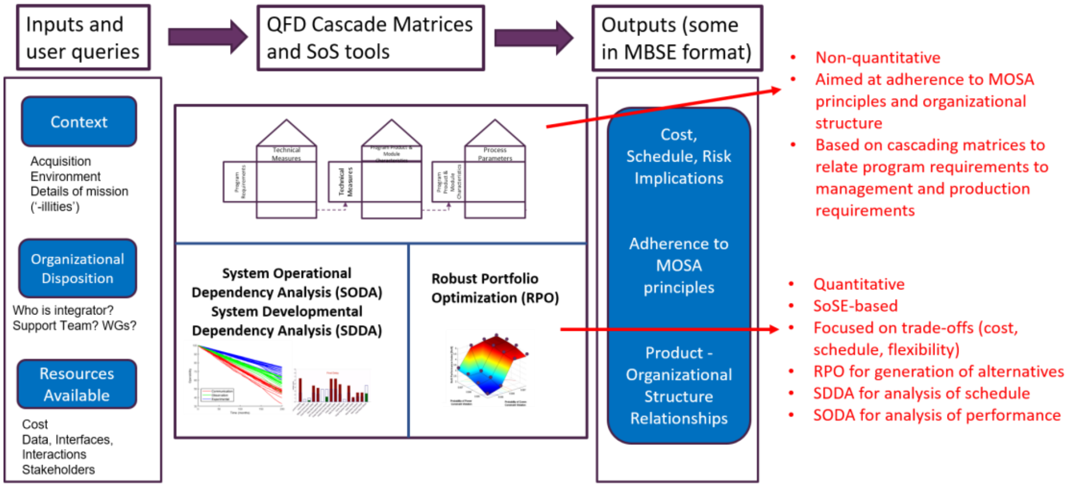


Figure 1. New concept for the Decision Support Framework. The non-quantitative analysis of organizational requirements is supplemented by SoSE-based quantitative analysis of cost, performance, risk implications.

Based on the user needs assessed in this phase, outputs from the DSF provide various information to Program Managers, listed in table 1.

Table 1. User needs and corresponding DSF outputs.

User Need	DSF Output
Rapid assessment of alternative systems architectures, modular and not modular	Generation of pareto-optimal architectures
Quantitative analysis of metrics of interest for comparison of architectures	Evaluation of cost, performance, and risk
Support to assess potential benefits of MOSA	Non-quantitative analysis of systems and sets of systems that can benefit from application of MOSA principles

The DSF structure permits the capture of elements caused by the possible complex interactions between the component systems, that are often not readily captured in complex programs. The

DSF also allows the user for comparison of systems architectures characterized by different strategies for modularity, including cases where it is imposed and cases where modular systems are not allowed.

The study of the Open Architecture Assessment Tool (OAAT) by the US Navy and engagement with other programs showed how the state-of-the-art approach to evaluation of "openness" is addressed with questionnaires that refer to the whole architecture from both a programmatic and a technical standpoint. The approach used by the WRT-1002 research team to combine this type of questionnaires with the generation and analysis of systems portfolios in the DSF is a set of empirical rules that, based on study of the technical questionnaires, suggest which systems and combination of systems is likely to benefit from the application of one or more MOSA principles (to meet new capability faster, evolve more easily, or even just to ensure proper functioning).

PHASE 2: IMPLEMENT A MOSA DECISION-SUPPORT FRAMEWORK

For Phase 2, the research team focused on the following research tasks:

- *Design a synthetic case study in a multi-domain battle scenario. This step included definition of required input for the DSF, and outputs of interest to the users.*
- *Develop the software of the DSF, including required interfaces with existing System-of-Systems analytical tools*
- *Design and test Graphic User Interfaces (GUI) for the DSF*

Design of Synthetic Case Study

The creation of a synthetic problem formed the foundation for developing the DSF software and interfaces with existing System-of-Systems (SoS) analytical tools. By executing each step of the framework using the synthetic problem, the team was able to expound on the specific steps in the process, validate the DSF, and improve extensibility to future usage of the DSF. The case study can also be used to illustrate the added value the DSF provides for Analysis of Alternatives and assessing adherence to MOSA principles.

The synthetic problem is an Amphibious Warfare Scenario, which was chosen since it is a multi-domain problem involving air, ground, naval, and space systems. The systems in Amphibious Warfare interact to provide logistical support and system-level capabilities to achieve certain SoS-level capabilities. This high-level operational concept is illustrated in Figure 2, a Department of Defense Architecture Framework (DoDAF) OV-1 representation. A case study was developed for the synthetic problem that specifically defined systems from a World War II Amphibious Warfare Scenario. Use of World War II systems and context was chosen since many measures of system capabilities from this time period are public knowledge, which allowed the research team to create a case study with adequate detail.

The Mission System Library (MSL) was developed to be the key means to pass user inputs into the DSF. The MSL is created in an Excel workbook, where a series of eight sheets provide specific information on the problem:

1. Main Sheet: System names, support capabilities (i.e., internal logistic requirement), system capabilities, and capability uncertainties
2. SoS Capabilities: SoS capability names and sets of indices of the system capabilities that contribute to each SoS capability
3. Compatibility Constraints: matrices containing information on compatibility between systems, specification of maximum amount of specific systems allowed in a portfolio
4. Must Have Systems: the required systems in a portfolio
5. Conditional Must Have Systems: the systems that are required to operate other systems
6. Development Covariance (MISDP): for alternative linear programming solvers *(not active for this case study)*
7. Simulated Capabilities (CVaR): for alternative linear programming solvers *(not active for this case study)*
8. MOSA Principles: empirical rules, based on case studies and PM Guidance, indicating systems and sets of systems that can benefit from application of specific MOSA principles

Each of these sheets can be read automatically by the DSF software to run the SoS analysis tools and create the outputs of the DSF. A DSF user is expected to create their own Mission System Library for their specific problem. An example was created for the Amphibious Warfare Scenario (excerpts are shown in **Error! Reference source not found.** and Figure 4) and is provided as a product of this research project along with the DSF software. Additionally, the *User Guide to the Decision Support Framework* developed for this project provides detailed guidance for future users on creating an MSL and each following step in the DSF.

In the Amphibious Warfare case study, systems were defined in each of the domains, including air, ground, naval, and space, as well as human systems (e.g., operators). On the Main Sheet of the MSL, systems are listed in each row. In total, 26 systems were defined, though only an excerpt is provided in **Error! Reference source not found.** and Figure 4, and then each were evaluated for their support and system capabilities. Five support capabilities were defined for this case study: Transport Range (measured by range in miles), Transport Capacity (measured by capacity in pounds), Refuel (measured by fuel capacity in pounds), Communication Relay (measured using a constructed rating), and Operator (measured by number of operators). Each system might have one or more support input requirements, which must be fulfilled by a system that has a matching support output capability. Therefore, there are two sets of columns in the MSL for support capabilities: Support Input Requirement and Support Output Capability. It is worth mentioning that some systems might be only "support systems", if they only provide support output but do not provide system capabilities. Though the quantified SoS capabilities are evaluated using only the system capabilities, the Robust Portfolio Optimization tool is able to consider the support inputs and outputs by creating constraints that must be satisfied for any portfolio, making these interdependencies still critical to the architecture results.

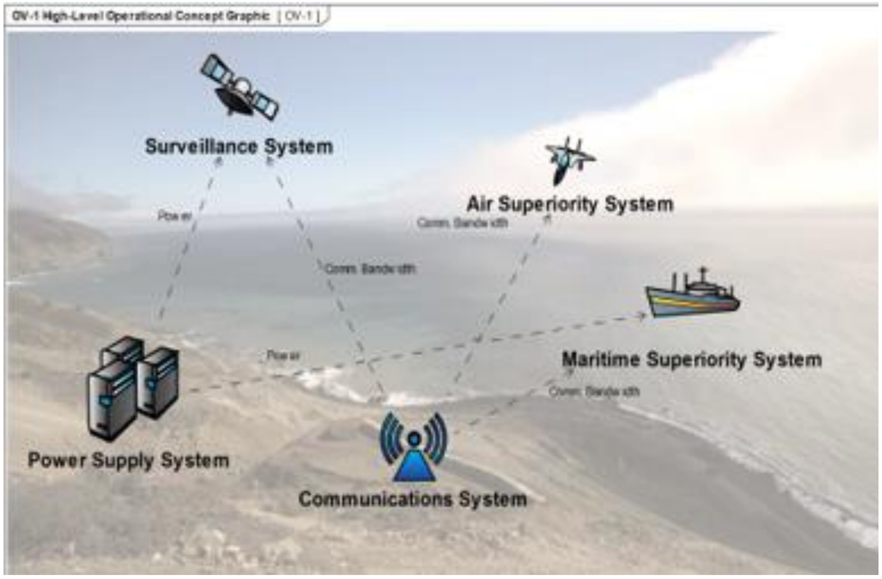


Figure 2. Concept of operations of a multi-domain Amphibious Warfare Scenario.

The system capabilities are evaluated next. In the Amphibious Warfare case study, 23 system capabilities were defined, and some capabilities were assessed with multiple measures. For example, the Attack Air-Air capability is measured by Weapons Range, in miles, and Stopping Power, using a constructed rating. In this case study, there are nine variations of "Attack" system capabilities to represent the different combinations of each domain (air, sea, ground), and each uses the same measures. Additionally, there are nine "Defend" system capabilities, which use the measures Weapons Range, Stopping Power, and also Robustness (a constructed rating). In several instances, constructed ratings were necessary where physical/natural measures were not possible or not consistent across types of technologies. For example, systems could receive a Stopping Power rating from zero to six, where zero indicated no stopping power and six indicated a high explosive weight appropriate for large bombs/missiles. This rating allowed the research team to compare different types of technologies, where natural measures of stopping power—such as caliber (in inches) or explosive weight (in pounds)—changed depending on the type of technology—such as guns or bombs. The rating options for stopping power are listed in Table 2. Other constructed ratings were defined for Detection, Communication, and Communication Relay, and more information on all the constructed ratings are provided in the *User Guide to the Decision Support Framework.*

Table 2. Constructed ratings for Stopping Power measure of "Attack" and "Defend" capabilities.

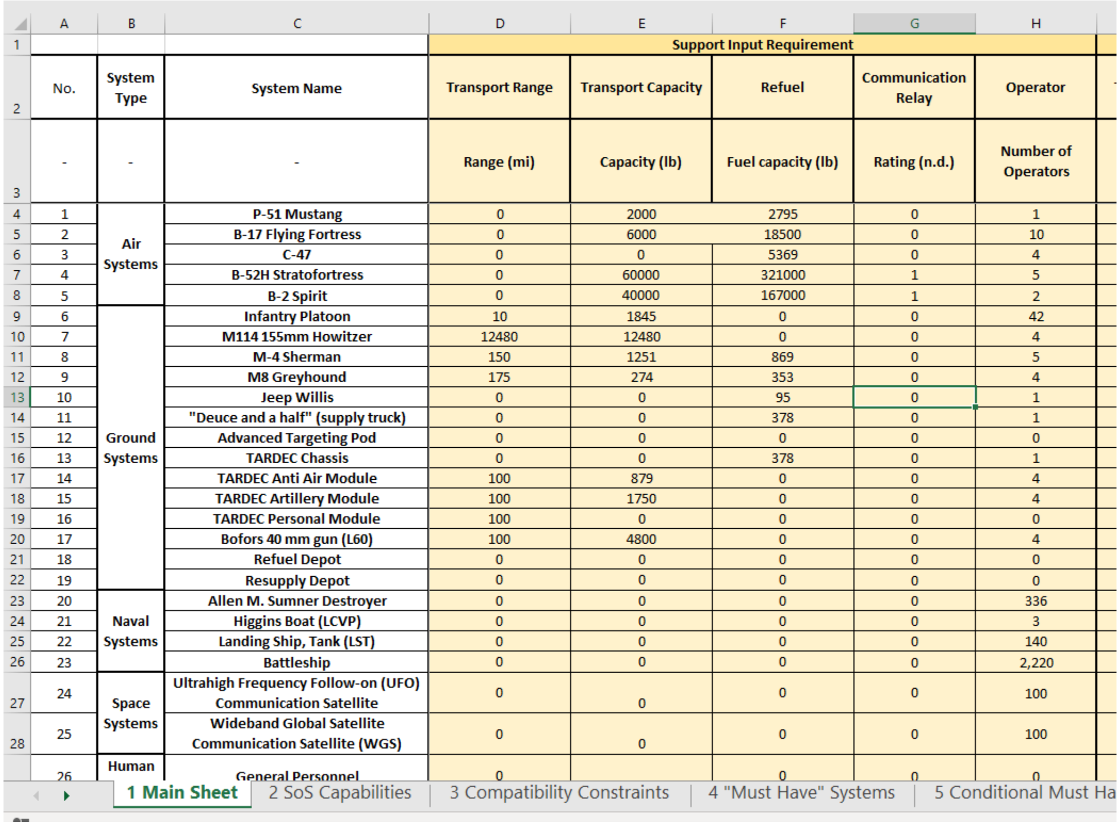
Rating Value	Natural Measure: Caliber or Explosive Weight Range	Notes
0	0	No stopping power
1	[0.10, 0.45] in	Dimension: Caliber Appropriate for guns
2	[0.50, 1.00] in	Dimension: Caliber Appropriate for guns
3	>1.0 in (but not explosive)	Cannons and other intermediate weapons
4	[500, 5,000] lb	Dimension: Explosive weight Appropriate for bombs/missiles
5	[5,000, 10,000] lb	Dimension: Explosive weight Appropriate for bombs/missiles
6	>10,000 lb	Dimension: Explosive weight Appropriate for bombs/missiles

Each support and system capability may also be evaluated for uncertainty, where the possible change in capability range is defined in individual columns on the Main Sheet of the MSL. The uncertainty values together with a variable representing the user's risk aversion are considered by the Robust Portfolio Optimization tool, which is discussed in a later section of this report. The last columns of the Main Sheet are system cost (USD$) and system modularity (yes/no).

Next, the SoS Capabilities sheet includes the names of all SoS Capabilities and the indices of the system capabilities that contribute to the SoS capability. The six SoS Capabilities for the case study are presented in Table 3. Each SoS capability is computed using a variation of the additive value model. Each of the subsequent sheets may optionally be filled out by the user to indicate desired strategies for the resulting portfolios (for example, whether certain systems are mandatory). For more information, please refer to the supplementary document, *User Guide to the Decision Support Framework.*

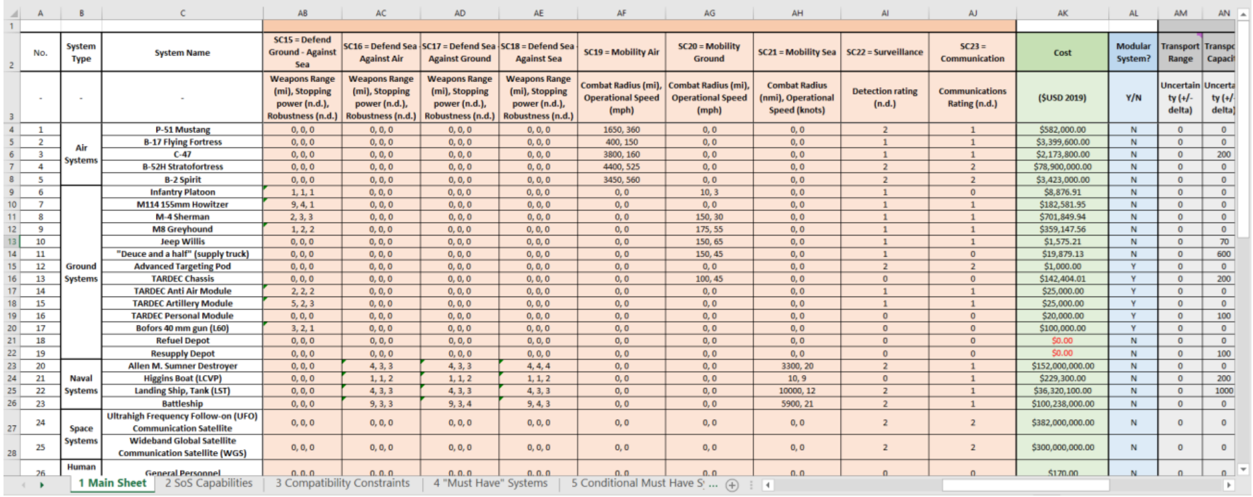
Table 3. SoS Capabilities for Amphibious Warfare case study, with system capability contributions.

No.	SoS-Capability	System-Capability Indices						
1	Air Superiority	1-6	19-27	46	47	52	53	
2	Naval Superiority	13-18	37-45	50-53				
3	Tactical Bombardment	3	4	46	47	52	53	
4	Land Seizure	3	4	9	10	15	16	46-53
5	Land Control	28-36	52	53				
6	Reconnaissance	46-53						



No.	System Type	System Name	Transport Range	Transport Capacity	Refuel	Communication Relay	Operator
-	-	-	Range (mi)	Capacity (lb)	Fuel capacity (lb)	Rating (n.d.)	Number of Operators
1	Air Systems	P-51 Mustang	0	2000	2795	0	1
2		B-17 Flying Fortress	0	6000	18500	0	10
3		C-47	0	0	5369	0	4
4		B-52H Stratofortress	0	60000	321000	1	5
5		B-2 Spirit	0	40000	167000	1	2
6	Ground Systems	Infantry Platoon	10	1845	0	0	42
7		M114 155mm Howitzer	12480	12480	0	0	4
8		M-4 Sherman	150	1251	869	0	5
9		M8 Greyhound	175	274	353	0	4
10		Jeep Willis	0	0	95	0	1
11		"Deuce and a half" (supply truck)	0	0	378	0	1
12		Advanced Targeting Pod	0	0	0	0	0
13		TARDEC Chassis	0	0	378	0	1
14		TARDEC Anti Air Module	100	879	0	0	4
15		TARDEC Artillery Module	100	1750	0	0	4
16		TARDEC Personal Module	100	0	0	0	0
17		Bofors 40 mm gun (L60)	100	4800	0	0	4
18		Refuel Depot	0	0	0	0	0
19		Resupply Depot	0	0	0	0	0
20	Naval Systems	Allen M. Sumner Destroyer	0	0	0	0	336
21		Higgins Boat (LCVP)	0	0	0	0	3
22		Landing Ship, Tank (LST)	0	0	0	0	140
23		Battleship	0	0	0	0	2,220
24	Space Systems	Ultrahigh Frequency Follow-on (UFO) Communication Satellite	0	0	0	0	100
25		Wideband Global Satellite Communication Satellite (WGS)	0	0	0	0	100
26	Human	General Personnel	0		0	0	0

Figure 3. List of available systems and support requirements.



No.	System Type	System Name	SC15 = Defend Ground - Against Sea	SC16 = Defend Sea Against Air	SC17 = Defend Sea Against Ground	SC18 = Defend Sea Against Sea	SC19 = Mobility Air	SC20 = Mobility Ground	SC21 = Mobility Sea	SC22 = Surveillance	SC23 = Communication	Cost	Modular System?	Transport Range	Transpo Capaci
-	-	-	Weapons Range (mi), Stopping power (n.d.), Robustness (n.d.)	Weapons Range (mi), Stopping power (n.d.), Robustness (n.d.)	Weapons Range (mi), Stopping power (n.d.), Robustness (n.d.)	Weapons Range (mi), Stopping power (n.d.), Robustness (n.d.)	Combat Radius (mi), Operational Speed (mph)	Combat Radius (mi), Operational Speed (mph)	Combat Radius (nmi), Operational Speed (knots)	Detection rating (n.d.)	Communications Rating (n.d.)	($USD 2019)	Y/N	Uncertainty (+/- delta)	Uncerta ty (+/- delta)
1	Air Systems	P-51 Mustang	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0	1650, 360	0, 0	0, 0	2	1	$582,000.00	N	0	0
2		B-17 Flying Fortress	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0	400, 150	0, 0	0, 0	1	1	$3,399,600.00	N	0	0
3		C-47	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0	3800, 160	0, 0	0, 0	1	1	$2,173,800.00	N	0	200
4		B-52H Stratofortress	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0	4400, 525	0, 0	0, 0	2	2	$78,900,000.00	N	0	0
5		B-2 Spirit	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0	3450, 560	0, 0	0, 0	2	2	$3,423,000.00	N	0	0
6	Ground Systems	Infantry Platoon	1, 1, 1	0, 0, 0	0, 0, 0	0, 0, 0	0, 0	10, 3	0, 0	1	0	$8,876.91	N	0	0
7		M114 155mm Howitzer	9, 4, 1	0, 0, 0	0, 0, 0	0, 0, 0	0, 0	0, 0	0, 0	1	1	$182,581.95	N	0	0
8		M-4 Sherman	2, 3, 3	0, 0, 0	0, 0, 0	0, 0, 0	0, 0	150, 30	0, 0	1	1	$701,849.94	N	0	0
9		M8 Greyhound	1, 2, 2	0, 0, 0	0, 0, 0	0, 0, 0	0, 0	175, 55	0, 0	1	1	$359,147.56	N	0	0
10		Jeep Willis	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0	0, 0	150, 65	0, 0	1	1	$1,575.21	N	0	70
11		"Deuce and a half" (supply truck)	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0	0, 0	150, 45	0, 0	1	0	$19,879.13	N	0	600
12		Advanced Targeting Pod	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0	0, 0	0, 0	0, 0	2	2	$1,000.00	Y	0	0
13		TARDEC Chassis	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0	0, 0	100, 45	0, 0	0	0	$142,404.01	Y	0	200
14		TARDEC Anti Air Module	2, 2, 2	0, 0, 0	0, 0, 0	0, 0, 0	0, 0	0, 0	0, 0	1	1	$25,000.00	Y	0	0
15		TARDEC Artillery Module	5, 2, 3	0, 0, 0	0, 0, 0	0, 0, 0	0, 0	0, 0	0, 0	1	1	$25,000.00	Y	0	0
16		TARDEC Personal Module	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0	0, 0	0, 0	0, 0	0	0	$20,000.00	Y	0	100
17		Bofors 40 mm gun (L60)	3, 2, 1	0, 0, 0	0, 0, 0	0, 0, 0	0, 0	0, 0	0, 0	0	0	$100,000.00	Y	0	0
18		Refuel Depot	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0	0, 0	0, 0	0, 0	0	0	$0.00	N	0	0
19		Resupply Depot	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0	0, 0	0, 0	0, 0	0	0	$0.00	N	0	100
20	Naval Systems	Allen M. Sumner Destroyer	0, 0, 0	4, 3, 3	4, 3, 3	4, 4, 4	0, 0	0, 0	3300, 20	2	1	$152,000,000.00	N	0	0
21		Higgins Boat (LCVP)	0, 0, 0	1, 1, 2	1, 1, 2	1, 1, 2	0, 0	0, 0	10, 9	0	1	$229,300.00	N	0	200
22		Landing Ship, Tank (LST)	0, 0, 0	4, 3, 3	4, 3, 3	4, 3, 3	0, 0	0, 0	10000, 12	2	1	$36,320,100.00	N	0	1000
23		Battleship	0, 0, 0	9, 3, 3	9, 3, 4	9, 4, 3	0, 0	0, 0	5900, 21	2	1	$100,238,000.00	N	0	0
24	Space Systems	Ultrahigh Frequency Follow-on (UFO) Communication Satellite	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0	0, 0	0, 0	0, 0	2	2	$382,000,000.00	N	0	0
25		Wideband Global Satellite Communication Satellite (WGS)	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0	0, 0	0, 0	0, 0	2	2	$300,000,000.00	N	0	0
26	Human	General Personnel	0, 0, 0	0, 0, 0	0, 0, 0	0, 0, 0	0, 0	0, 0	0, 0	0	0	$170.00	N	0	0

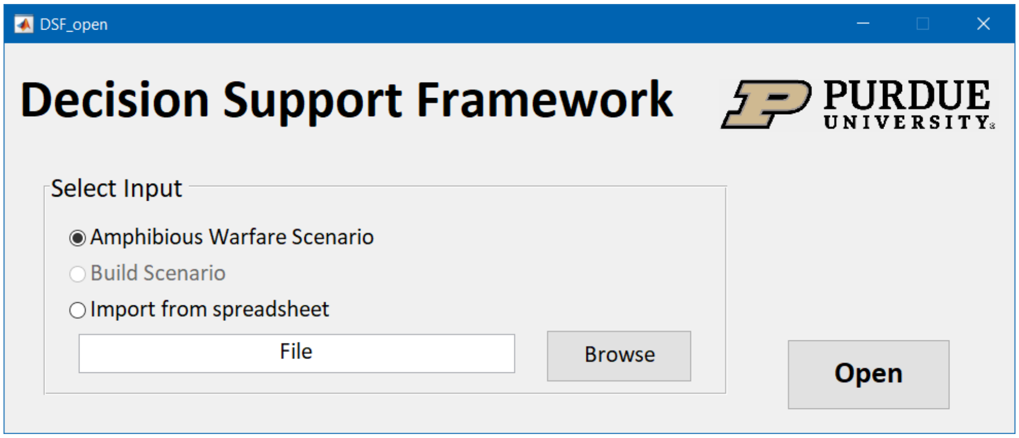
Figure 4. List of the same systems in Figure 3. Red columns are the provided system capabilities; green column is cost; blue column indicates modular or monolithic nature of the system; grey columns are uncertainties.

Development of the DSF Software

In the second task of Phase 2, the research team translated the lessons learned in previous efforts and in Phase 1 into a viable executable software that implements the desired capability. The DSF performs quantitative AoA by generating portfolios of systems that provide both the SoS capabilities of interest and the necessary logistical support for the systems included in the portfolio. This capability is accomplished by integrating a Robust Portfolio Optimization (RPO) analysis tool for SoS which evaluates not only system- and SoS-level capabilities but also the interactions between systems (i.e., via support capability requirements). The DSF also performs qualitative analysis of each architecture by generating biographs and cascading matrices. These methods will be described in more detail in the following sections.

Starting the DSF Analysis and Providing User Inputs

Once the Mission System Library has been created in Excel, the user can use the Graphical User Interface (GUI) developed for the DSF. Figure 5 shows the opening GUI window, where the user can import the file for their MSL. The user is also given the option to run the synthetic case study (Amphibious Warfare Scenario), where the MSL has been provided with the software as an example. This GUI allows the MSL workbook to be automatically read by the DSF software, then opens the DSF Analysis GUI.



DSF_open

Decision Support Framework

Select Input

● Amphibious Warfare Scenario

○ Build Scenario

○ Import from spreadsheet

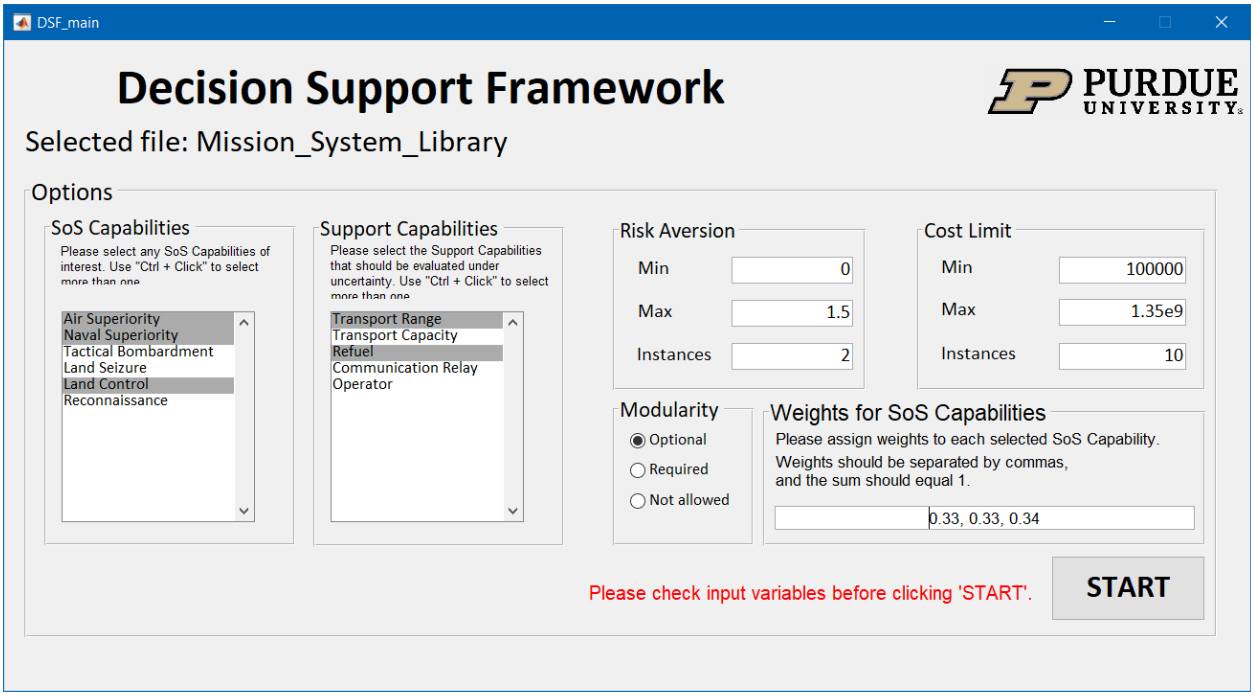
File

Figure 5. Opening GUI window of the DSF software.

Robust Portfolio Optimization

Robust Portfolio Optimization is a methodology to maximize the expected performance of a System-of-Systems and keep within acceptable levels of developmental risk and cost, while at the same time dealing with uncertain information. Implementation of RPO for a certain System-of-Systems design problem yields a set of Pareto optimal portfolios corresponding to a user-defined risk aversion factor. The optimization is based on a mixed integer programming technique and all the interdependency between component systems are depicted as constraints. In the DSF, RPO has been improved with an additional layer that includes support in addition to system and SoS capabilities. Initial quantitative architecture analysis of alternatives is performed in the DSF using the RPO method. RPO generates optimized portfolios of systems, and it creates Pareto graphs to display results for SoS-level performance vs. portfolio cost. Other tools can be added for further quantitative evaluation.

The DSF runs the RPO tool using as input the system information from the MSL. The user can modify the parameters of the analysis in the DSF Main GUI, shown in Figure 6. Based on the scenario loaded from the opening screen, the GUI will display the user's list of SoS capabilities that can be selected for optimization, as well as a list of support capabilities, from which the user can select whether uncertainty needs to be considered or not. These options implement concepts of Mission-Based design, where even the same set of available systems will generate different portfolios based on different mission requirements. On the right side of the GUI, the user can define levels of risk aversion and levels of available budget, which are used later for generating Pareto fronts. Other inputs include the importance weights for the selected SoS capabilities and the option to set the requirement (if any) to include modular systems.



Decision Support Framework

Selected file: Mission_System_Library

Options

SoS Capabilities

Please select any SoS Capabilities of interest. Use "Ctrl + Click" to select more than one

- Air Superiority
- Naval Superiority
- Tactical Bombardment
- Land Seizure
- Land Control
- Reconnaissance

Support Capabilities

Please select the Support Capabilities that should be evaluated under uncertainty. Use "Ctrl + Click" to select more than one

- Transport Range
- Transport Capacity
- Refuel
- Communication Relay
- Operator

Risk Aversion

Min	0
Max	1.5
Instances	2

Cost Limit

Min	100000
Max	1.35e9
Instances	10

Modularity

● Optional
○ Required
○ Not allowed

Weights for SoS Capabilities

Please assign weights to each selected SoS Capability. Weights should be separated by commas, and the sum should equal 1.

0.33, 0.33, 0.34

Please check input variables before clicking 'START'.

Figure 6. Main GUI window of the DSF software.

As a result of running the DSF Main GUI, Pareto front charts are displayed, such as the one shown in Figure 7, and the user will have access to the optimized portfolios. This is the first part of the data that can be used for decision support. To perform further analysis, the DSF Analysis GUI is opened next. In this GUI, shown in Figure 8, the user has the option to create graphical representation of the network of systems and dependencies in a portfolio, display cascading matrices that expand the analysis from the prototype DSF in previous efforts (SoS requirements to SoS capabilities, SoS capabilities to systems capabilities, systems to MOSA principles that cause benefits), perform further quantitative analysis, and assess potential benefits of the selected portfolio from applying MOSA principles.

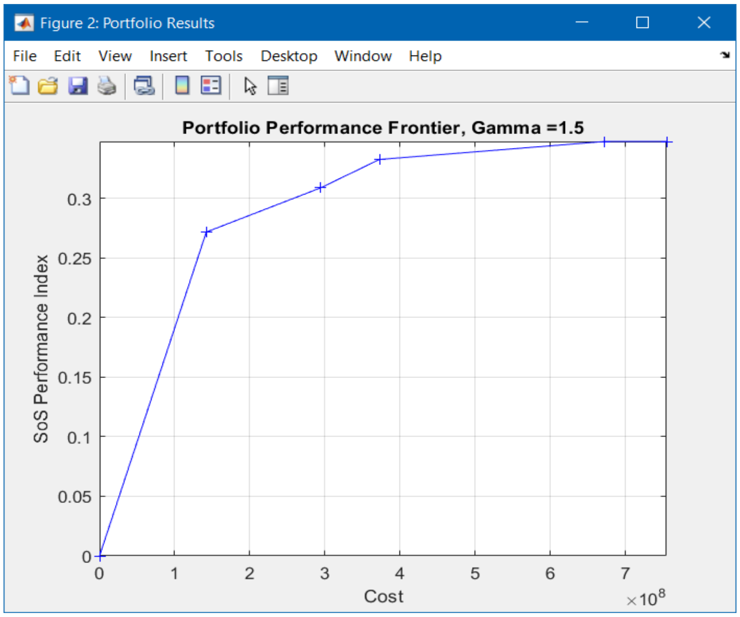
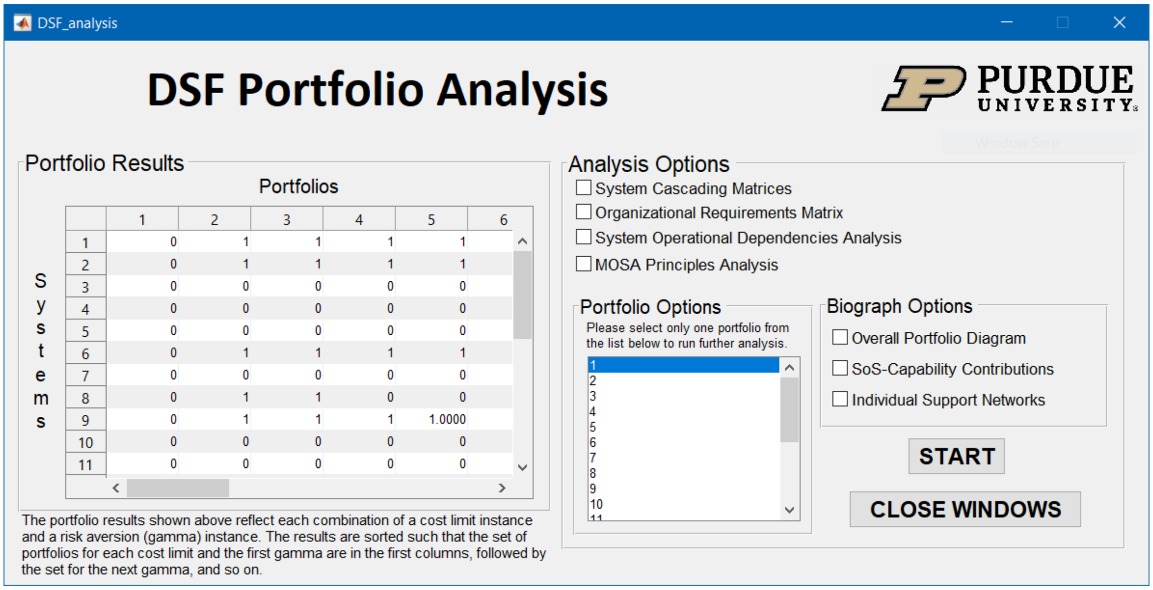


Figure 7. Cost vs. SoS performance Pareto chart with Pareto-optimal portfolios, which are subject to different budget constraints at a given level of risk aversion.



	1	2	3	4	5	6
1	0	1	1	1	1	
2	0	1	1	1	1	
3	0	0	0	0	0	
4	0	0	0	0	0	
5	0	0	0	0	0	
6	0	1	1	1	1	
7	0	0	0	0	0	
8	0	1	1	0	0	
9	0	1	1	1	1.0000	
10	0	0	0	0	0	
11	0	0	0	0	0	

The portfolio results shown above reflect each combination of a cost limit instance and a risk aversion (gamma) instance. The results are sorted such that the set of portfolios for each cost limit and the first gamma are in the first columns, followed by the set for the next gamma, and so on.

Please select only one portfolio from the list below to run further analysis.

1
2
3
4
5
6
7
8
9
10

Figure 8. DSF Analysis GUI with initial portfolios and selection of options for further analysis.

Biographs

Biographs are a way to represent networks in Matlab as a graph of nodes and links. In this effort, they have been used to represent portfolios, including systems and their logistics connectivity, as well as the systems capabilities produced by each system or set of systems. The user can also decide to visualize the dependency of SoS capabilities on systems capabilities.

Cascading Matrices

Part of the non-quantitative outputs of the DSF, the "QFD-like" cascading matrices related to a portfolio provide a matrix representation of the relations between systems in a portfolio, system capabilities, and SoS capabilities. One matrix shows the relationship between systems or sets of systems in a portfolio and MOSA principles they can benefit from. The user can also obtain further analysis of beneficial or necessary application of MOSA principles.

Adherence to MOSA Principles

Besides one of the matrices, the user can elect to visualize graphical representations of advice for MOSA, based on the empirical rules built based on case studies. For example, Figure 9Figure 9 shows a bar plot indicating what systems or combination of systems (horizontal axis) can benefit from the application of a certain number of MOSA principles (height of the bar). MOSA principles include establish an enabling environment, employ modular design, designate key interfaces, use open standards, and certify conformance.

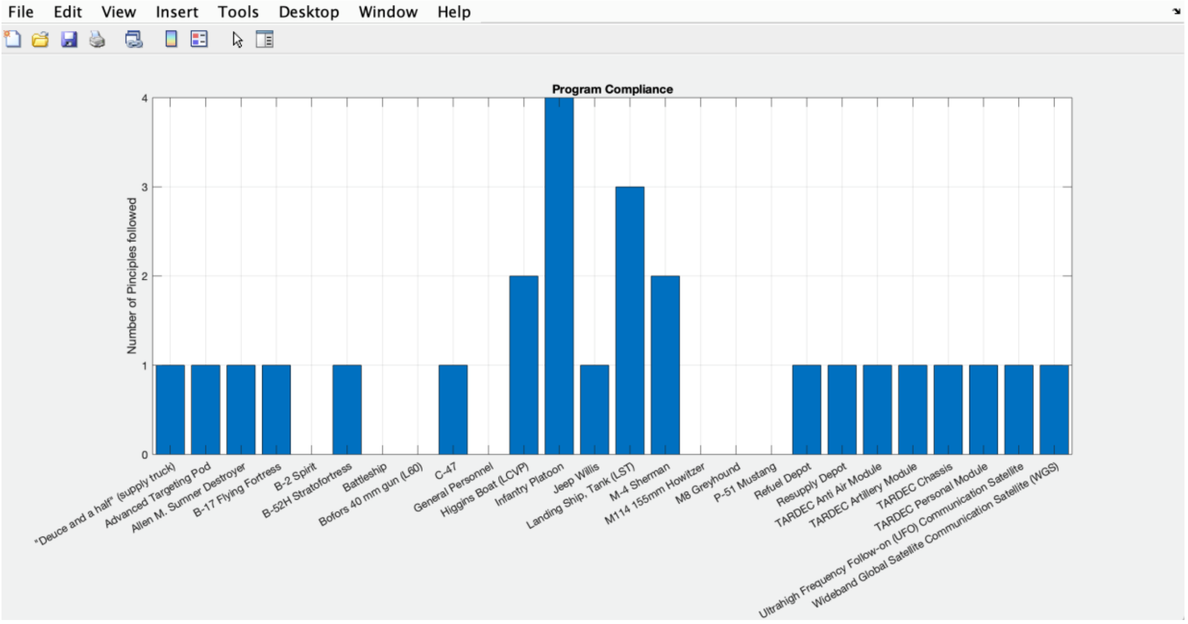


Figure 9. Number of MOSA principles that can benefit certain systems selected in a portfolio.

The DSF software is now a rich and viable tool for the generation and analysis of architectures for a variety of problems in acquisition. Based on mission engineering considerations, SoS analysis techniques, and the large amount of knowledge acquired in this research effort, the DSF provides support to Program Managers decision-making processes, as well as traceability to instances of resource availability, generation of capability, and logistic support. Documentation of the design of the synthetic problem and a *User Guide to the Decision Support Framework* are provided as further deliverables in this project.

SUMMARY AND TRANSITION PLANS

This research task has extended prior RT-163 and RT-185 research towards developing a useful tool in support of Program Managers for decision-making in acquisition problems, accounting for the guidelines suggested from a Modular Open System Approach. The research team has expanded the literature review and collaborative exchanges with stakeholders and subject matter experts and used the acquired knowledge to implement a Decision Support Framework which includes a software tool for generation and analysis of systems architectures using different strategies.

Table 4 lists the Transition Action Plan for WRT-1002 and for the previous effort RT-163 and RT-185, identified in the Tech Management Work Plan. Research in WRT-1002 expanded the engagement with the community and focused on actions 3 and 4: the design and implementation of the DSF followed the SERC principle of productizing and piloting continuously. This task was supported by the engagement and feedback received from the community. Collaboration with the MOSWG and the VICTORY program have helped the research team to identify important user needs. However, there has not been a single program identified as a partner for tailored MOSA decision-support tool and pilot use of the DSF. A positive outcome is that the DSF has been built as a problem-agnostic framework, open to a variety of applications. Further transition actions to increase the use of the DSF include the distribution of the final version of the DSF to groups working with MOSWG (military, industry) and to the Defense Acquisition University.

Table 4. Approaches to Achieve Benefits of Modularity in Defense Acquisition Project Transition Action Plan

#	Transition Action	Principles Implemented
1	Began project with SERC Workshop on MOSA to engage community from the beginning and build network of partners.	• Engage Community • Plan Early
2	Developed a “Program Manager’s Guide to Achieving benefits to MOSA and Program Success”; current version is 2.0.	• Engage Community • Pilot Continuously • Productize
3	Develop a MOSA decision-support framework (DSF) and associated computational tools for PM’s to use for learning and exposing key program metric tradeoffs as impacted by modularity and openness	• Plan Early • Pilot Continuously • Productize
4	Leverage partnerships with programs to developed specific relationships with them to produced tailored MOSA decision-support tools that are effective and trusted.	• Productize • Engage Community

Appropriate characteristics of the transition, identified in the Tech and Management Work Plan and listed in Table 5, have been adequately followed throughout the effort. The DSF has been promptly modeled and modified based on the feedback received in phase 1 and in the engagement with the community. Progress of the research has been showcased in presentations and publications, generating valuable interactions.

Table 5. Approaches to Achieve Benefits of Modularity in Defense Acquisition Project Transition Characteristics

Characteristic	Evidence
Readiness (relevance, practicality)	• Responsiveness to feedback from programs on usefulness of MOSA guidance and decision-support tools, especially as the law and policy on MOSA shifts and the emphasis from DOD leadership increases • Adoption, enhancement, and tailoring by programs to reap maximum benefit.
Progress (approval, adoption)	• Conference papers, journal publications, and presentations to establish validation with academic / research community • Feedback from programs that have adopted and enhanced products • Suggested project follow-on activities requested, especially for targeting Mission Engineering applications and use for “new” acquisitions like AI and Autonomy

APPENDIX A: LIST OF PRESENTATIONS AND PUBLICATIONS

DeLaurentis, D., Domercant, C., Guariniello, C., McDermott, T., Witus, G., Dai, M., Approaches to achieve benefits of modularity in defense acquisition, *Modular Open Systems Working Group (MOSWG) meeting,* Alexandria, VA, 17 July 2019.

Guariniello, C., DeLaurentis, D., Domercant, C., McDermott, T., Witus, G., Report on WRT-1002, *11th annual SERC Sponsor Research Review (SSRR),* Washington, DC, 19 November 2019.

Dai, M., Guariniello, C., DeLaurentis, D., Implementing a MOSA decision support tool in a model-based environment, *Conference on Systems Engineering Research,* Redondo Beach, CA, 20 March 2020.