ACQUISITION INNOVATION RESEARCH CENTER

Advanced Model-Based Tools for Portfolio Management and Analytic

EXECUTIVE SUMMARY AND REPORT

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ACRONYMS AND ABBREVIATIONS

A&S	Acquisition and Sustainment
AIRC	Acquisition Innovation Research Center
API	Application Programming Interface
AVDF	Acquisition Visibility Data Framework
AWB	Analytic Workbench
CAPE	Cost Assessment and Program Evaluation
CDF	Capability Development Framework
CPM	Capability Portfolio Management
CPMR	Capability Portfolio Management Review
CVaR	Conditional Value-at-Risk
DAVE	Defense Acquisition Visibility Environment
DE	Digital Engineering
DoD	Department of Defense
GMU	George Mason University
GTRI	Georgia Tech Research Institute
IAPR	Integrated Acquisition Portfolio Review
JWICS	Joint Worldwide Intelligence Communications System
LoA	Level of Autonomy
MADM	Multiple Attribute Decision Making
MATLAB	Matrix Laboratory (software)
MBSE	Model-Based Systems Engineering
MEG	Mission Engineering Guide
MET	Mission Engineering Thread
ML	Machine Learning
MoE	Measure of Effectiveness
MoP	Measure of Performance
MoS	Measure of Suitability
MTBF	Mean Time Between Failure
OUSD	Office of the Under Secretary of Defense
OUSD(A&S)	Office of the Under Secretary of Defense for Acquisition and Sustainment

OUSD(R&E)	Office of the Under Secretary of Defense for Research and Engineering
PBR	Program and Budget Review
PMRT	Project Management Resource Tools
RMVO	Robust Mean-Variance Optimization
RPO	Robust Portfolio Optimization
SAR	Search and Rescue
SERC	Systems Engineering Research Center
SIPRNet	Secret Internet Protocol Router Network
SoS	System of Systems
SPR	Strategic Portfolio Review
SysML	Systems Modeling Language
TMTR	Technology Modernization Transition Review
TPM	Technical Performance Measure
UAF	Unified Architecture Framework
USAF	United States Air Force

EXECUTIVE SUMMARY

Effective portfolio management is essential in defense acquisition to align investments with strategic goals, optimize resources, and enhance capabilities. It ensures that investments address emerging threats and budget constraints while maintaining technological superiority and readiness. The Department of Defense's (DoD) use of Integrated Acquisition Portfolio Review (IAPR) processes to conduct cross-functional reviews of acquisition portfolios is an important component in an overall Capabilities Portfolio Management (CPM) philosophy. The AIRC WRT-1081.7.5 team, consisting of Purdue University, Georgia Tech Research Institute (GTRI), and George Mason University (GMU), has collaborated to advance IAPR tools. Building on pilot tools developed in 2022 under AIRC WRT-1049.5 research, the team enhanced portfolio optimization algorithms and explored defense acquisition platforms like the Defense Acquisition Visibility Environment and Advana to improve transparency, with the ultimate goal of enhancing the effectiveness of the IAPR processes and tools.

Purdue's research has advanced a portfolio management tool for IAPRs. Key achievements include enhancing the Robust Portfolio Optimization (RPO) tool with new optimization algorithms to better evaluate complex mission design impacts on the System of Systems. Purdue successfully converted RPO scripts from MATLAB to Python, incorporating optimization methods such as Bertsimas-Sim, Conditional Value-at-Risk, and Robust Mean-Variance Optimization. These advancements are designed to provide decision-makers with robust IAPR tools for portfolio optimization.

GTRI's research focused on strengthening support for IAPRs by organizing human and technical data. The team analyzed existing documentation and data to create a comprehensive composite document that details the IAPR process and its alignment with mission engineering. GTRI developed an initial data model that integrates programmatic and mission engineering concepts and created a proof-of-concept tool called IAPR Data Exploration & Analysis Tool for data exploration, analysis, and visualization.

GMU's research explored integrating various levels of autonomy into Systems of Systems using a search and rescue (SAR) mission use case. GMU developed a framework to assess the effects of different levels of autonomy on SAR operations by using model-based systems engineering (MBSE). This approach demonstrated the potential for improved operational efficiency and highlighted significant enhancements in effectiveness through strategic integration of autonomy.

This report details the research findings that are considered Phase 1. A proposed second phase of research (Phase 2) would build on Phase 1's findings. Specifically, Purdue would propose to lead Track 1 (IAPR tool development), while GTRI would lead Track 2 (IAPR tool experimentation). In particular, Purdue would integrate RPO with MBSE software and explore hybrid RPO approaches in order to test applicability beyond IAPRs to other CPM activities. GTRI would experiment with the tools for IAPR support while working with stakeholders to understand needs and assess ontologies for future semantic technology adoption. GMU would refine the autonomy model, add operational data, and support a more model-based IAPR process.

1. INTRODUCTION

The AIRC WRT-1081.7.5 research project aims to advance portfolio management and analytics by developing advanced model-based tools. Building upon previous research conducted under AIRC WRT-1049.5 (DeLaurentis & Panchal, 2022; Tsutsui et al., 2023), the WRT-1081.7.5 initiative refines and adapts existing digital engineering (DE) tools as well as produces new DE tools. The initiative aims to enhance the prototype Robust Portfolio Optimization (RPO) originally developed by Purdue University (Guariniello et al., 2023), support the creation of the Integrated Acquisition Portfolio Reviews (IAPR) Data Exploration & Analysis Tool by Georgia Tech Research Institute (GTRI), and evaluate these DE tools using a use case developed by George Mason University (GMU).

The adaptation of tools developed from this research aims to create a sophisticated model-based portfolio assessment tool tailored to meet advanced engineering needs. These tools aim to enhance the Department of Defense's (DoD) IAPR process and support various analysis activities mandated by the Capability Portfolio Management (CPM) Directive (Hicks, 2023). IAPR is a portfolio review designed to identify and assess interdependencies and risks throughout the acquisition life cycle, strengthening the synchronization of warfighting concepts, technologies, requirements, program execution, and end-to-end mission performance (Hicks, 2023).

By establishing a DE environment and mission engineering methodology using RPO by Purdue and the IAPR Data Exploration & Analysis Tool, confirming their applications with and the use case by GMU, the current research effort seeks to assist the DoD in effectively implementing the IAPR process within the broader CPM framework. The current research effort under AIRC WRT-1081.7.5 focuses on Phase 1: Use Case Exploration and Data Model Definition, setting the stage for aligning these tools with the intricate demands of DoD IAPR to ensure their relevance and effectiveness. Further research is proposed in the "Proposed Future Work" section of the report.

2. ENHANCING DEFENSE ACQUISITION: PORTFOLIO MANAGEMENT AND ADVANCED TOOLS

2.1 ENHANCING DEFENSE ACQUISITION THROUGH PORTFOLIO MANAGEMENT

In defense acquisition, portfolio management is crucial by aligning strategic investments, optimizing resource allocation, and enhancing capabilities within the DoD (Driessnack & Johnson, 2023; Schultz, 2020). Portfolio management systematically evaluates and prioritizes investments to help the DoD respond to evolving threats and budget constraints, ensuring technological superiority and operational readiness in a complex defense landscape (DeLaurentis & Panchal, 2022; Schultz, 2020). The following paragraphs will address these three points: facilitating strategic investment alignment, optimizing resource allocation, and enhancing capability within the DoD.

Portfolio management aligns strategic investments within the DoD and ensures that financial resources focus on long-term objectives by adapting to evolving operational needs and technological advancements (Hicks, 2023). The systematic approach, associated with portfolio management, prioritizes investments across diverse programs and capabilities, optimizing resource allocation and bolstering defense strategy in response to changing threats and budgetary constraints (DeLaurentis & Panchal, 2022).

Efficient resource allocation is a significant advantage of portfolio management in defense acquisition. Strategically prioritizing funding across programs eliminates duplication and reduces unnecessary expenditures (Tremper, 2023). This comprehensive approach allows decision-makers to assess investments thoroughly, identifying synergies and potential redundancies across different programs and services. Effective risk management throughout the portfolio ensures a balanced mix of high-impact initiatives and essential programs, maximizing the utility of limited defense resources and enhancing overall defense capabilities (Hicks, 2023).

Furthermore, portfolio management enhances capability development within the DoD by fostering interoperability and integration across various systems (Tremper, 2023). It simplifies acquisition processes, facilitating faster delivery of capabilities to meet urgent operational needs. This streamlined approach provides robust oversight for ongoing development efforts, supporting agile and responsive acquisition strategies (DeLaurentis & Panchal, 2022). By promoting a coordinated approach to research and development, portfolio management ensures that new capabilities integrate seamlessly into a unified defense framework. This integrated capability development is essential for effectively addressing complex military challenges across different operational domains (Hicks, 2023).

2.2 IAPR AS A PART OF CPM

Although portfolio reviews in defense acquisition may have existed informally in the past, implementing IAPRs and formally adopting IAPRs within the CPM framework is a recent development. Introduced in 2021, IAPRs gather senior department leaders to collectively evaluate the programmatic status of interconnected systems within a portfolio, focusing on critical joint missions. According to the 2022 Acquisition and Sustainment (A&S) Year in Review document by the Office of the Under Secretary of Defense for Acquisition and Sustainment (OUSD(A&S)), dated January 17, 2023, 11 IAPRs were conducted in 2022, with 18 more planned for 2023 (OUSD(A&S), 2023). The updated DoD Directive 7045.20, issued on September 25, 2023, formalizes the policy for CPM, including IAPRs (Hicks, 2023). Furthermore, Dr. LaPlante's testimony to the Senate Appropriations Committee on May 15, 2024, describes IAPRs as "*holistic reviews that bring together stakeholders across the Office of the Secretary of Defense*" (LaPlante).

These developments from 2021 to 2024 underscore the DoD's active deployment and refinement of the IAPR process across various capability portfolios to enhance acquisition outcomes and align capabilities with strategic objectives. Our research focuses on developing decision-support tools to assist the DoD in effectively implementing the IAPR process within the broader CPM framework.

It is worth noting that although our current research activities focus on IAPRs, other reviews exist within the CPM framework, as shown below. These reviews collectively contribute to the comprehensive oversight and strategic alignment of defense capabilities.

- Program and Budget Review (PBR) by Comptroller and Cost Assessment and Program Evaluation (CAPE). PBR is a portfolio review to assess and align programs and budgets across the DoD (Hicks, 2023).

- Technology Modernization Transition Reviews (TMTR) by the Office of the Under Secretary of Defense for Research and Engineering (OUSD(R&E)). TMTR is a review to assess and manage the transition of technologies into acquisition programs and operational use (Hicks, 2023).

- Capability Portfolio Management Review (CPMR) by the Joint Staff. CPMR is a review to assess and manage capability portfolios across the DoD (Hicks, 2023).

2.3 ACTIVITIES LEADING TO ADVANCED MODEL-BASED IAPR TOOL DEVELOPMENT

This section highlights Purdue, GTRI, and GMU's collaborative efforts in advancing model-based defense acquisition tools. The section details establishing a strategic framework, integrating ontologies to enhance data interoperability within Model-Based Systems Engineering (MBSE), and exploring data platforms like DAVE and Advana to improve transparency and decision support. Significant progress includes migrating calculations from Matrix Laboratory (MATLAB) to Python and incorporating concepts such as Level of Autonomy (LoA) and Multiple Attribute Decision Making (MADM) to enhance decision-making and efficiency. This section illustrates the interrelationships among the research collaborators (i.e., Purdue, GTRI, and GMU) and how they worked together to achieve Phase 1 project goals. As such, some information will reappear in subsequent sections, where each institution's research contributions are presented in detail.

2.3.1 COLLABORATIVE FRAMEWORK AND STRATEGIC PLANNING

The collaborative efforts among Purdue, GTRI, and GMU have advanced our research initiative. The research team has engaged in meetings to foster discussions. The team outlined a comprehensive framework during these sessions, emphasizing a two-phase approach. Phase 1, which is WRT-1081.7.5, activities were identified as critical preparation for any future Phase 2 work. By establishing clear and realistic objectives during Phase 1, we ensured that any Phase 2 groundwork was robust and would support more complex tasks.

2.3.2 ONTOLOGY AND MBSE

Our discussions on ontology delved deeply into its role within System of Systems (SoS) tools and MBSE, recognizing its potential to overcome current limitations and enhance data interoperability. The team explored the applicability and practicality of ontologies, emphasizing their incremental scalability and diverse utility. By leveraging computational ontologies, we aim to provide a structured and scalable framework that can evolve with the project's needs. This approach ensures that our data models remain adaptable and integrate new information seamlessly.

Purdue, GTRI, and GMU have collaborated on integrating ontologies to enhance clarity and structure, translating academic language into practical terms for stakeholders. This effort includes developing analytical methods and visualizations to support future IAPRs, ensuring our tools are theoretically sound and practically applicable. Integrating ontologies with model-driven architectures is expected to prevent knowledge failures and enhance the robustness of our MBSE practices. By aligning our ontological framework with existing MBSE standards, we aim to create a comprehensive system supporting the project's long-term goals.

2.3.3 DATA MODELS AND CPM

A critical component of our research has been addressing the challenges of developing data models for CPM. Early identification and strategic planning around these challenges, such as scope, team expertise, and adoption likelihood, have contributed to a more informed and practical approach. By thoroughly examining these aspects, we have devised strategies that mitigate potential risks and enhance the robustness of our data models. This proactive approach has laid the groundwork for successful CPM implementation and, possibly, an accelerant to the use of ontologies more broadly across CPM activities.

GTRI has been pivotal in creating composite documents representing IAPR processes and proposing an initial data model that bridges the Acquisition Visibility Data Framework (AVDF) to mission engineering concepts. This model aims to enhance IAPR analytics integration with warfighting contexts, providing a more holistic view of capability management. By integrating AVDF with mission-based architecture data, we aim to overcome the challenges of standardizing mission engineering metadata within the DoD. This initiative improves data transparency and facilitates more informed decision-making in CPM.

2.3.4 DATA PLATFORMS AND TRANSPARENCY

The exploration of data platforms like Defense Acquisition Visibility Environment (DAVE) and Advana has been integral to our efforts to enhance data transparency and streamline business operations within defense acquisition. GTRI participated in a demonstration of these platforms, which serve as centralized hubs for accurate acquisition data and provide DoD users with common business data, decision support analytics, and data tools. These platforms are crucial for enhancing data transparency and facilitating more informed decision-making within the DoD.

Further investigation into the potential implementation of DAVE and Advana within our operations is underway, with GTRI leading this effort. By leveraging these platforms, we aim to gather accurate acquisition data and integrate it with our existing tools to support IAPR. This integration aims to streamline our data collection processes and enhance the overall efficiency of our research efforts. Additionally, these platforms will provide valuable insights into the DoD’s data transparency initiatives, helping us align our research objectives with broader organizational goals.

2.3.5 TOOL DEVELOPMENT AND IMPLEMENTATION

Significant progress has been made in developing and implementing various tools critical to our research initiative. Purdue has been at the forefront of improving the prototype SoS tool in Python, focusing on enhancing RPO. A key accomplishment was the migration of RPO Conditional Value-at-Risk (CVaR) calculations from MATLAB to Python, improving performance and facilitating greater integration with other tools and platforms. This migration represents a critical step in modernizing our toolset and ensuring compatibility with widely-used programming environments.

Additionally, Purdue has initiated the development of RPO using the Robust Mean-Variance Optimization (RMVO) approach. This approach aims to maximize SoS capability while minimizing costs, providing a balanced and efficient solution for portfolio optimization. Concurrently, GMU has explored integrating LoA and MADM into the existing SoS tool using a Search and Rescue (SAR) mission as a use case. LoA and MADM concepts are particularly relevant in defense acquisition, where autonomous systems and decision-making processes are crucial. By incorporating these concepts, the team aims to elevate our understanding and implementation of autonomous systems, enhancing decision-making capabilities within SoS operations.

3. DEVELOPMENT OF IAPR DECISION SUPPORT TOOL BY PURDUE UNIVERSITY

3.1 PORTFOLIO MANAGEMENT TOOLS AND METHODS

Purdue University's overarching goal within WRT-1081.7.5 was to develop and implement advanced portfolio management tools in collaboration with partners to study IAPR processes. The portfolio tools are designed to perform unique functions depending on the assessed items. Notably, Purdue has enhanced RPO, a decision tool integrated into the Analytic Workbench (AWB) developed under SERC-funded projects several years ago, to evaluate the impact of various mission design alternatives on the performance of complex systems.

RPO plays a crucial role in analyzing SoS and mission engineering problems, offering insights into how different mission design choices influence performance, thereby optimizing design strategies and enhancing systems' overall efficiency and effectiveness. Purdue has completed the development of RPO in the Bertsimas-Sim, CVaR, and RMVO approaches, successfully converting scripts from MATLAB to Python. Incorporating these three optimization methods enhances the performance and compatibility of our tools, providing a robust foundation for future development efforts. These methods offer decision-makers diverse "flavors" for portfolio optimization within RPO as follows:

- **Bertsimas-Sim**: This optimization method "*addresses parametric data uncertainty without excessively penalizing the objective function,*" offering a robust solution for handling uncertain data (DeLaurentis et al., 2022).

- **CVaR**: This optimization method considers risk and enables "*trade-offs between performance and anticipated worst-case scenario losses at the prescribed confidence level,*" making it ideal for risk-averse decision-making (DeLaurentis et al., 2022).

- **RMVO**: This optimization method balances "*SoS performance for a given variance in development time of a portfolio,*" allowing decision-makers to effectively manage and mitigate development time risks (DeLaurentis et al., 2022).

These three RPO flavors fall under the broader optimization umbrella, but each has its unique approach and focus. The term "flavors" aptly captures the idea that while they share the common goal of optimization, they each have distinct characteristics suited to different types of problems or decision-making preferences. Decision-makers can select the method that best fits their needs and potentially combine or adapt these methods to tackle complex optimization challenges. Further details on combined methodology applications will be discussed in the "Proposed Future Work" section.

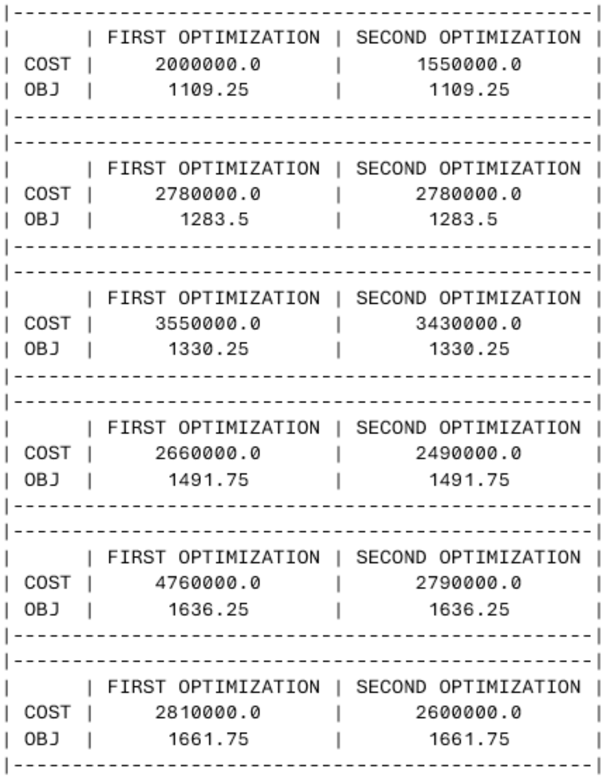
3.2 RESEARCH CONTRIBUTIONS AND TOOLS DEVELOPMENT

The primary contributions of Purdue University researchers toward achieving development goals included upgrading the CVaR toolset, adjusting the evaluation of performance metrics, and building the RMVO version of RPO. Elements of the research goals are outlined below with supporting text, figures, and a table where relevant. Additionally, Purdue University sees possible adaptations of the RPO toolset with GTRI and GMU, creating a process flow between RPO and MBSE tools.

Early phases of the contract were characterized by studying existing RPO codebases. Once requisite knowledge was obtained, the student researchers created an outline of tasking in conjunction with project leadership at each participating institution. The first task involved converting RPO's CVaR formulation from MATLAB to Python. The benefits of the converted tool include its rapid installation in RPO applications since MATLAB licensing is no longer required for the tool. The CVaR codebase could also be bundled into the AWB suite for future work.

The Purdue team also recognized an opportunity to improve cost and performance metric formulation (Figure 1). Completing the new optimization problem first involves minimizing an objective function under several constraints. Since the portfolio that results in the minimum cost may not be unique, a second optimization finds the lowest-cost portfolio that still achieves the optimal objective value. The benefits of this method include lower portfolio costs while achieving the same level of performance based on objective function values. An example of this sequential process is shown in Figure 1.

Researchers also developed a MATLAB-based version of the RMVO toolset (Figure 2 and Table 1). A previous formulation was available through NanoHub, but this version was not formulated using an objective-oriented software method. Additionally, integrating other tools would be nearly impossible using the prior version since the NanoHub version of RMVO incorporated a different data structure. The updated MATLAB version of RMVO successfully runs a case developed for RPO testing across multiple versions. The objective function is being evaluated, and constraints are utilized where required based on the mathematical approach underpinning RMVO. A Python version of RMVO is also under development and is currently in the prototype phase.



```
|-----------------------------------------------|
|      | FIRST OPTIMIZATION | SECOND OPTIMIZATION |
| COST |     2000000.0      |      1550000.0      |
| OBJ  |      1109.25       |       1109.25       |
|-----------------------------------------------|
|-----------------------------------------------|
|      | FIRST OPTIMIZATION | SECOND OPTIMIZATION |
| COST |     2780000.0      |      2780000.0      |
| OBJ  |       1283.5       |        1283.5       |
|-----------------------------------------------|
|-----------------------------------------------|
|      | FIRST OPTIMIZATION | SECOND OPTIMIZATION |
| COST |     3550000.0      |      3430000.0      |
| OBJ  |      1330.25       |       1330.25       |
|-----------------------------------------------|
|-----------------------------------------------|
|      | FIRST OPTIMIZATION | SECOND OPTIMIZATION |
| COST |     2660000.0      |      2490000.0      |
| OBJ  |      1491.75       |       1491.75       |
|-----------------------------------------------|
|-----------------------------------------------|
|      | FIRST OPTIMIZATION | SECOND OPTIMIZATION |
| COST |     4760000.0      |      2790000.0      |
| OBJ  |      1636.25       |       1636.25       |
|-----------------------------------------------|
|-----------------------------------------------|
|      | FIRST OPTIMIZATION | SECOND OPTIMIZATION |
| COST |     2810000.0      |      2600000.0      |
| OBJ  |      1661.75       |       1661.75       |
|-----------------------------------------------|
```

Figure 1. Illustration of Cost and Performance Updates from a new sequential approach to RPO via CVAR.

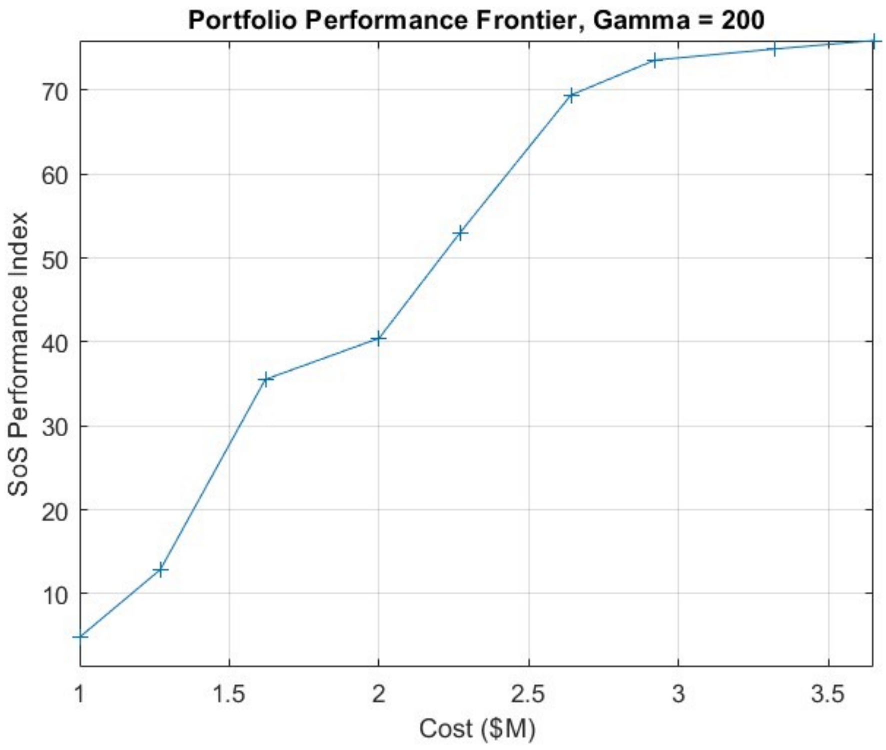
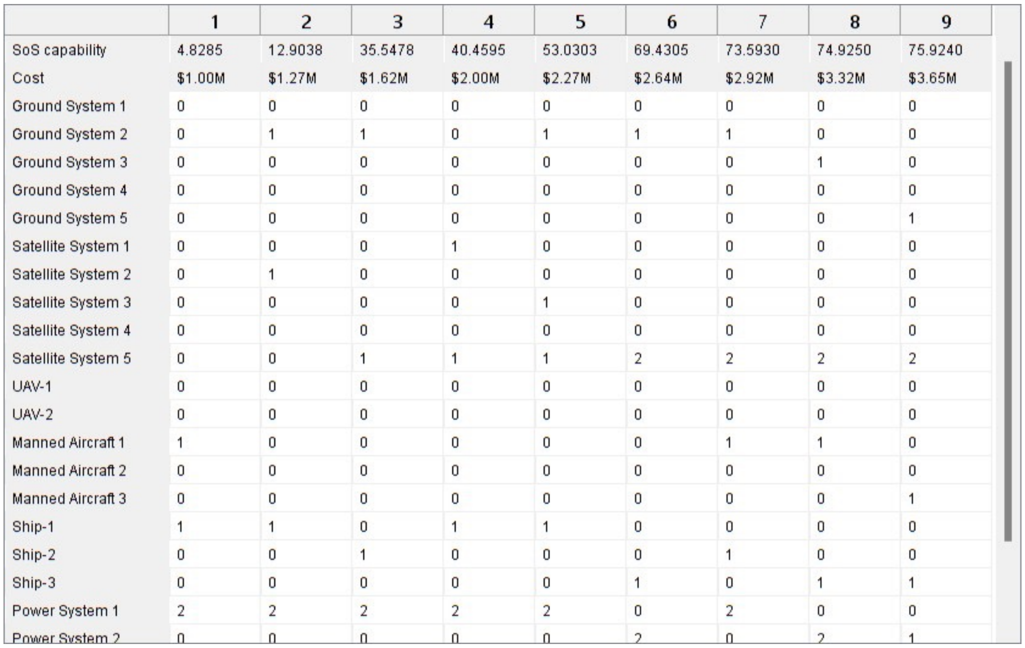


Figure 2. RMVO Results Plot

Table 1. RMVO Results Table



	1	2	3	4	5	6	7	8	9
SoS capability	4.8285	12.9038	35.5478	40.4595	53.0303	69.4305	73.5930	74.9250	75.9240
Cost	$1.00M	$1.27M	$1.62M	$2.00M	$2.27M	$2.64M	$2.92M	$3.32M	$3.65M
Ground System 1	0	0	0	0	0	0	0	0	0
Ground System 2	0	1	1	0	1	1	1	0	0
Ground System 3	0	0	0	0	0	0	0	1	0
Ground System 4	0	0	0	0	0	0	0	0	0
Ground System 5	0	0	0	0	0	0	0	0	1
Satellite System 1	0	0	0	1	0	0	0	0	0
Satellite System 2	0	1	0	0	0	0	0	0	0
Satellite System 3	0	0	0	0	1	0	0	0	0
Satellite System 4	0	0	0	0	0	0	0	0	0
Satellite System 5	0	0	1	1	1	2	2	2	2
UAV-1	0	0	0	0	0	0	0	0	0
UAV-2	0	0	0	0	0	0	0	0	0
Manned Aircraft 1	1	0	0	0	0	0	1	1	0
Manned Aircraft 2	0	0	0	0	0	0	0	0	0
Manned Aircraft 3	0	0	0	0	0	0	0	0	1
Ship-1	1	1	0	1	1	0	0	0	0
Ship-2	0	0	1	0	0	0	1	0	0
Ship-3	0	0	0	0	0	1	0	1	1
Power System 1	2	2	2	2	2	0	2	0	0
Power System 2	0	0	0	0	0	2	0	2	1

3.3 RESEARCH OUTCOME

The Purdue University team has developed a Python version of the CVaR methodology, refined a cost formulation, and completed an RMVO MATLAB implementation. Additionally, the team is completing a prototype of the RMVO Python implementation, which complements their efforts in Python CVaR methodology development and refined cost formulation alongside the completed RMVO MATLAB implementation.

4. FOUNDATIONS FOR THE ANALYTICAL SUPPORT OF IAPRS BY GTRI

4.1 IAPR STUDY

The primary goal of this effort was to better understand and organize the necessary human and technical data associated with the performance of OUSD(A&S)'s IAPRs as a means to develop improved analytical tools to support IAPRs. This included, where possible, interacting with relevant available IAPR stakeholders and viewing available IAPR data. The project team could not view a live IAPR. Existing documentation and data were used to glean potential requirements for the IAPR process.

A large portion of this study was the identification, review, aggregation, and interpretation of all available documentation and reference material on IAPRs and CPM. GTRI worked with OUSD, SERC, and other team members to identify all openly available materials, of which the majority came from internal SharePoint sites, open literature, or directly from OUSD. This material was received throughout the period of performance, so the process of analyzing and mapping our understanding of IAPRs was highly iterative.

The result of this effort is a composite document that captures our latest understanding of IAPRs, the specifics of the review process, alignment with mission engineering concepts, and IAPRs' role within CPM. In addition, GTRI developed an initial data model to integrate the existing concepts of programmatics together with our understanding of relevant mission engineering concepts (in support of IAPRs) to better enable IAPRs to achieve their goals. To support the data collection effort, the team participated in several meetings with OUSD and its partners. Through these meetings, GTRI became aware of the importance of the AVDF as a data model for IAPR programmatics and its utilization within the DAVE. This triggered a full investigation into the AVDF, several efforts to analyze different versions of data dumps made available to the GTRI team (with subsets of the full data element catalog), and meetings with OUSD partners to understand how DAVE is used in support of program management.

In general, the discussions of IAPR objectives relative to other reviews within the larger CPM process was a key part of the literature review and heavily influenced the approach to aggregating the IAPR material into a common understanding of their purpose in the capture and assessment of aggregated program risk. Based on this work, it is our best estimate that the primary purpose of performing IAPRs is in their ability to directly inform portfolio design and investment decision-making. In particular, IAPRs are used to assess program risk in the context of mission engineering in order to reduce the likelihood of gaps in capability, overlap in program outcomes/objectives, and overall increase the effectiveness of portfolios within the context of the kill web. The specifics of the IAPR process, as dictated by the CPM, are shown in Figure 3.

GTRI understands that the exact nature of IAPRs and other critical CPM activities are evolving as OUSD(A&S) works towards implementing and supporting CPM. The exact nature of how IAPRs interact with various stakeholders, processes, and data remains somewhat in flux, and the process described is subject to change.

The IAPR process, as described by the CPM policy, outlines IAPRs as a portfolio analysis process wherein mission engineering strategies are applied to identify and mitigate critical risks associated with acquisition portfolios, with the overall goal of improving the delivery of integrated suites of capabilities across the DoD (Hicks, 2023). In this setting, critical risks may include the industrial base, supply chain, technology development and integration, interoperability, foreign military sales, and the workforce within each portfolio, with an initial focus on mission threads and priority portfolios (Integrated Acquisition Portfolio Review (IAPR) Charter, n.d.).

Individual IAPRs review a collection of portfolios that are related through some domain (JAC or A&S). These portfolios are made up of sub-portfolios, which consist of individual programs. The early description of the IAPR process centers around:

- Portfolio structure/alignment – capability vs. mission focused
- Strategic cross-cutting issues vs. details, program analytics, and metrics
- Scope of IAPR reviews vs. ongoing enterprise portfolio management
- Evolving processes on scoping, preparing, and executing IAPRs

This reinforces, in the near term, the need to align the IAPR process against mission engineering principles as defined in the Mission Engineering Guide (MEG). The provided IAPR template narrows the portfolio overview to a strategic view directly connected with a particular reference mission set, although the joint-services version of this may be more closely related to the concept of Mission Context from the MEG.

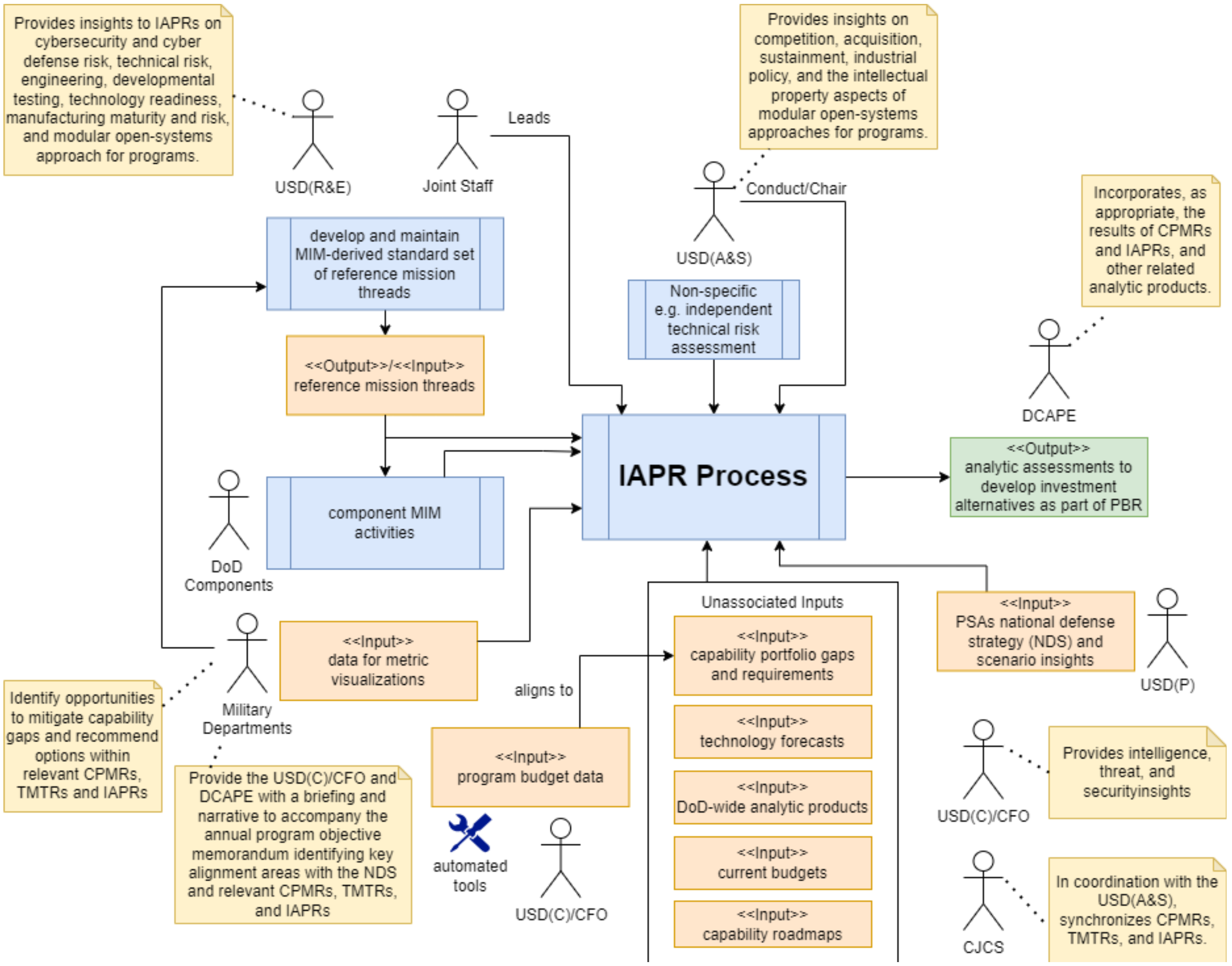


Figure 3. IAPR Process as Defined by the CPM Policy Document; Derived from Information in DoD Directive 7045.20 (Hicks, 2023)

The basic inputs to the IAPR in support of the process goals, as defined by the CPM, include capability portfolio gaps and requirements, technology forecasts, DoD-wide analytic products, and current program data (Hicks, 2023). While the CPM defined the output of the IAPRs as the analytical assessment that drives portfolio decision-making, a more granular output of the IAPRs is their assessment of program risk (i.e., cost and schedule) and how that risk affects the larger integrated risk picture across IAPRs, Strategic Portfolio Reviews (SPRs), TMTRs, CPMRs, and PBRs.

The information gathered has reinforced the notion that IAPRs' specific contributions to the larger integrated risk picture, their focus on program risk, and supporting analysis through mission engineering principles remain the primary areas of interest in immediate IAPR process support.

The results of this study were created in an effort to prepare for the potential of refining existing tools or developing new ones to support IAPRs. To address this need, GTRI was able to access and review the available AVDF, as well as develop an initial working data model that relates the AVDF to mission engineering. The data model is critical for contextualizing information in an IAPR. Finally, GTRI developed several proof-of-concept analytical and visualization tools to provide OUSD with a vision for what might be possible in an IAPR, given the underlying development and organization proposed. The following sections outline the identification of sources, perspectives on IAPR users, the approach taken to mission engineering modeling, and information on the initial set of developed IAPR tools.

4.1.1 IAPR SOURCES

Table 2 lists identified sources of information relevant to understanding IAPRs and summarizes their contribution/contents. Each of the documents or resources listed below was reviewed by the GTRI team, and a comprehensive document describing our internal understanding of IAPRs was produced.

Table 2. IAPR Resources

Resource	Description
DoD Directive 7045.20 - Capability Portfolio Management (Hicks, 2023)	• Discuss the role of major IAPR stakeholders and the relationship between IAPRs and other CPM reviews/tasks
(CUI) IAPR 101 – 16 March 2022 v2 (Abbott, 2022)	• High-level overview
(CUI) IAPR Process Flow v7	• Discussion of Portfolio-to-Mission alignment (incl. Mission Threads) • Mentions the desire to contextualize the program/system with the delivery of one or more Capabilities that enable missions
(CUI) IAPR Charter (Integrated Acquisition Portfolio Review (IAPR) Charter, n.d.)	• Explain the initial purpose, scope, schedule, and data requirements for IAPRs
(CUI) IAPR Template – Draft 3	• Provide a set of slides demonstrating how to decompose a portfolio into the structure needed to conduct an IAPR • Indicates the use of mission engineering in support of conducted analyses
(CUI) Cyberspace Operations – IAPR Scoping Working Group	• Demonstrate planning prior to IAPR • Background information

Resource	Description
(CUI) Cyberspace Operations – Analysis and Review Plan (ARP)	• Capture the scope and problem context for a specific IAPR • Demonstrate the type of domain and portfolio-specific contextual data needed to translate problem statements to portfolio integration needs • Outline IAPR objectives, deliverables, and analytical questions • Explicitly call out the value of mission engineering in support of IAPR effectiveness (task completion)
(CUI) Cyberspace Operations – IAPR Narrative	• A high-level outline describing initial considerations for IAPR planning • Identify links to mission engineering • Focus on domain-specific challenges
(CUI) Offensive/Defensive Cyberspace Operations IAPR Proposal	• Domain-specific overview (capability map) • Define current issues with portfolio management and concerns with ASD(A) oversight due to portfolio disparateness • Review previous alignment efforts • IAPR proposal overview
(CUI) Proposed Common Mission Framework – v5 (OUSD(A&S), n.d.)	• Review CPM and review processes with respect to integrated risk (kill web risk) • Define IAPRs as an activity to identify “Aggregated Program Risks” that result in “Integrated Acquisition Roadmaps • Capture the intercoupled relationship between IAPRs and TMTRs • Introduce the Joint Common Mission Framework and its proposed solution, the Capability Development Framework (CDF) • Describe the CDF and its ability to map capabilities and functions to mission engineering concepts in order to perform measurements (Measure of Performance (MoPs), Measure of Effectiveness (MoEs), Measure of Suitability (MoSs)) across portfolios

The following is a list of additional supporting sources/documents that indirectly link to concepts/relationships relevant to IAPRs.

- DoD Mission Engineering Guide - Version 2.0 (Browning, 2023)
- Universal Joint Task List (UJTL)
- Service task lists (e.g., Naval Task List (NTL))
- Joint Common System Functional List (JCSFL)
- Joint Capability Areas (JCAs)
- DAVE (*Defense Acquisition Visibility Environment (DAVE)*, 2024)
- AVDF (OUSD(A&S), 2024)

In general, there is very little openly available data to indicate what has/will support a *successful* IAPR in terms of portfolio integration. This is perhaps the most critical area for future support of IAPRs: working directly with stakeholders to model the IAPR process, data elements, and artifacts to support a more complete and thorough mission engineering analysis.

4.2 IAPR USER PERSPECTIVES

User perspectives define the intended interactions for specific users. In the context of early IAPR support, simplifying assumptions were made that the primary users are those participating in the review process. The proposed Cyber Operations IAPR defined a set of questions that translate nicely to the desired outcomes of any proposed analysis tools (OUSD(A&S), 2022):

- What are the fundamental Mission Scenarios, Vignettes, and Threads for the individual IAPR?
- What materiel solutions are currently used in these Mission Threads?
- Given the materiel solutions currently in use, what programs are responsible for acquiring/procuring and maintaining them?
- Of the materiel solutions, which ones are driven by Mission Threads? Which are driven by formal requirements? Which are driven in other ways, and how?
- For Programs, who is the single source of operational requirements?
- How are Mission Threads assessed/measured?
- How are Mission Elements assessed/measured?

These proposed questions are highly coupled with concepts from mission engineering, which requires understanding the relationship between IAPR programmatics and mission engineering assessments. To achieve this, a mission engineering data model will be needed to provide a relationship to the structured data provided by program acquisition databases/tools such as DAVE.

4.3 ACQUISITION VISIBILITY DATA FRAMEWORK

As part of the project, GTRI was able to access the AVDF through the DAVE. GTRI reviewed the available model for relevant fields to better understand how the AVDF was utilized. Further insight was gained through several meetings with the SERC and a chance to see how data was used in the Project Management Resource Tools (PMRT) by the United States Air Force (USAF). The ability to review relevant AVDF data fields on programs of interest during IAPRs is a critical capability any support tooling should provide.

4.4 PROPOSED MINIMAL MISSION ENGINEERING DATA MODEL

GTRI was provided with some context from OUSD(A&S) on the desire to build a CDF, a standardized metadata structure to capture mission engineering data related to CPM. GTRI understands the complexity of this effort and the continuing efforts surrounding developing metamodels and frameworks for mission engineering. Due to this project's limited scope and funding, GTRI developed a minimal mission engineering data model that provided just enough context for the proposed IAPR analysis. The focus of the metadata structure was to support analytics as a data model and not contribute to a wider ontological framework (e.g., Unified Architecture Framework (UAF)). If future efforts are undertaken to develop production quality analysis tooling to support IAPRs, this model could and should be revisited in the context of the continued OUSD(A&S) CDF effort. Significant work is being accomplished in the DoD and industry exploring broader frameworks; future work could leverage that effort.

With the initial focus of IAPRs on reference mission sets and their connection to mission elements acquired by programs, the first iteration of the mission engineering data model focuses on the Mission Engineering Thread (MET), as it contributes to a "Kill Web" as the central concept. Program data exists as a limited placeholder in the initial data model but could be extended to support the entirety of the AVDF. The developed data model is heavily influenced by the framework outlined in the 2023 Mission Engineering Guide, version 2.0 (MEG 2.0) (Browning, 2023).

The proposed model, shown in Figure 4, connects Mission Tasks to Mission Elements through an allocation model as part of a MET. This means that METs are alternatives that prescribe different ways of completing a Mission Thread. An allocation may consist of one or more Mission Elements, each of which is associated with a given Program. METs identify the relationship between Mission Elements and Mission Threads, and thus programs and missions. This contrasts with a functional analysis of mission tasks, where data capturing the ability of a mission element (or group of elements) to complete a mission task (via capabilities/functions) would need to be defined explicitly. Due to the difficult and potentially classified nature of the data, this initial model did not consider a mapping between system-specific capabilities and the tasks to which they contribute.

IAPRs would likely target one or more reference mission sets, which could be defined as a subset of Mission Threads and potentially a subset of their METs based on specific mission contexts, containing a subset of Programs. These data definitions and linkages are the initial subset of knowledge necessary to begin building and iterating on decision-support tools for IAPRs. The linkage to existing program data via the AVDF and explicit support of concepts defined by the MEG 2.0 will help enable future integration with alternative analysis tools and data models (i.e., OUSD(A&S) proposed CDF).

4.4.1 RELATIONSHIP BETWEEN METS AND THE "KILL WEB"

The MEG 2.0 defines a Kill Web as "an inclusive set of multiple integrated Mission Threads and METs for the applicable scenario or vignette of interest." This, in addition to the definition of METs and Mission Context, indicates that a singular MET is independent of any specific context (i.e., scenario/vignette). The key implication is that a MET is an alternative way to satisfy some number of Mission Tasks without the ability to utilize measures that require Mission Context or Joint Conditions. This emphasizes MET curation on the "satisfiability" of applying Mission Elements to Mission Threads and the subsequent programmatic data analysis for those MET alternatives. While there may be future ways of measuring/comparing METs (distinct from measurements of the Kill Web), our analysis has been restricted to understanding their construction and relationship to programs. It is largely independent of any particular Mission Context.

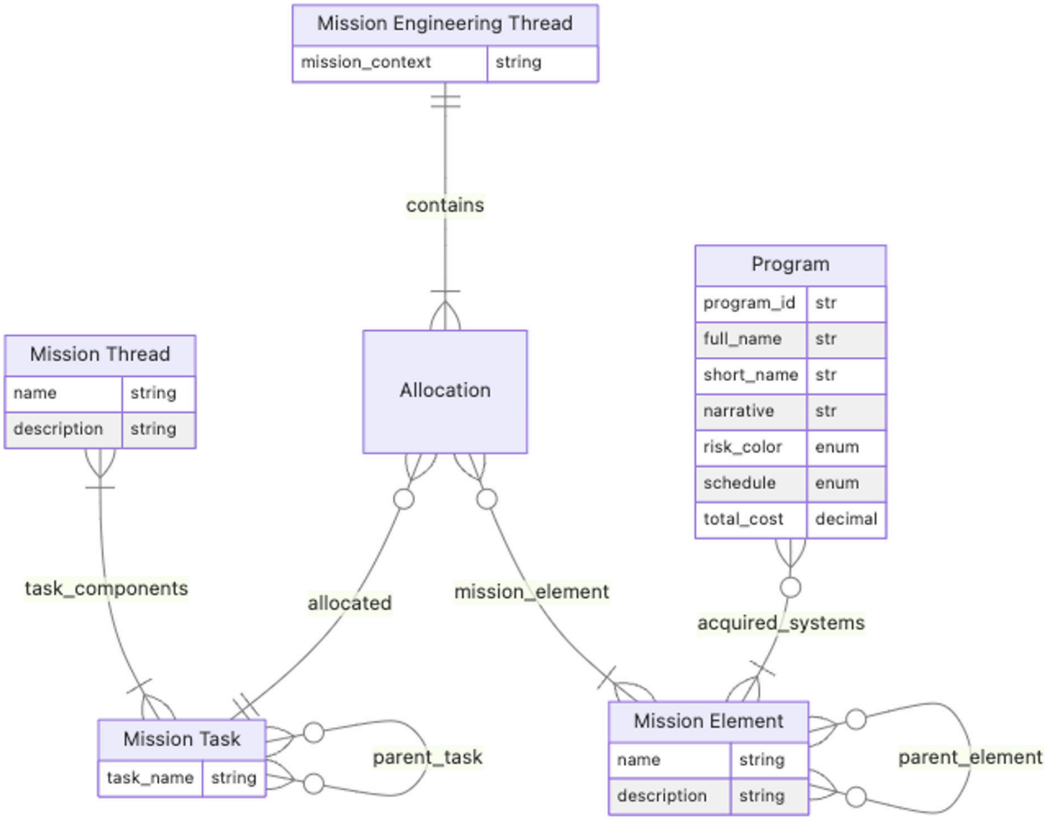


Figure 4. Proposed Initial ME Data Model

4.5 DATA GENERATION

GTRI was unable to secure full access to programmatic data due to the limited scope of this project. A data generation process was developed to create exemplar analysis capabilities for IAPRs using the mission engineering data model. This approach blends programmatic data available in DAVE with data synthesis techniques to create fake portfolios of METs, fake representative Mission Threads and Tasks, and fake Mission Elements. The goal is to demonstrate that programmatic data specifically can and should be sourced directly from the DAVE application or other DoD resources that conform to the AVDF. Our internal representation of data elements aligns directly with the AVDF for this exact purpose, and our mission engineering concepts align with the MEG 2.0 in an attempt to streamline integration with any mission engineering tools and/or enable compliant data capture with potential bespoke IAPR tools.

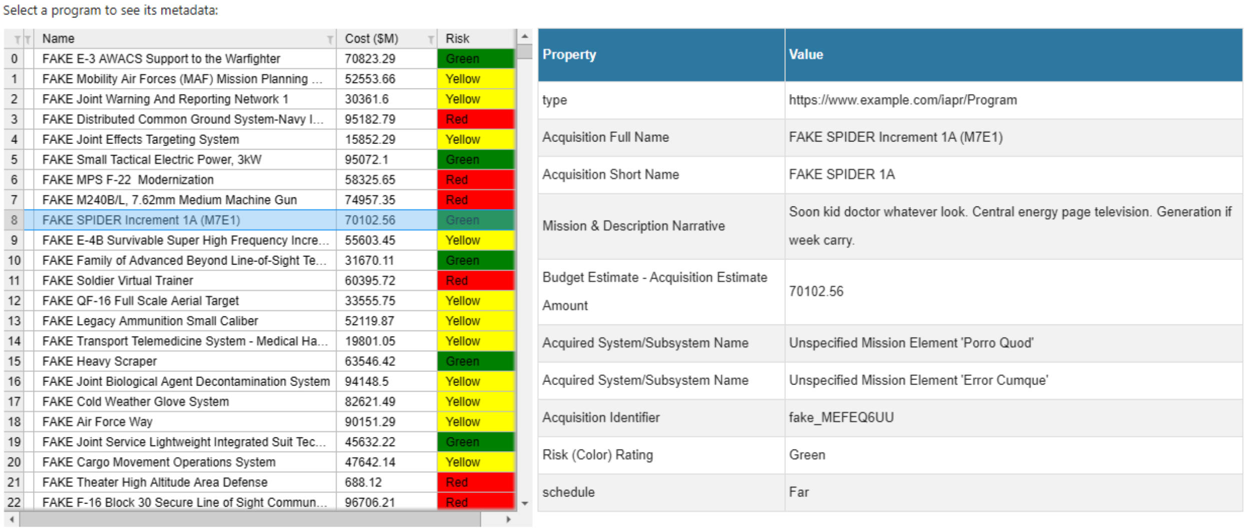
To indicate that the entirety of the programmatic data should not be considered accurate, the prefix “FAKE” is utilized for all program names and identifiers pulled from the DAVE platform. Additionally, unclassified program data was developed from publicly available DoD comptroller resources to avoid CUI concerns, with modifications to program and system names to further obfuscate any potentially sensitive data.

4.6 IAPR DATA EXPLORATION AND ANALYSIS TOOL

A number of proof-of-concept data explorations and decision analyses were developed in anticipation of IAPR needs. The prototype approaches were combined into an **IAPR Data Exploration & Analysis Tool**. These tools demonstrate the ability to access mission engineering and programmatic data via the mission engineering data model, as well as the ability to prototype and integrate individual components quickly. The hope is that these data exploration tools will serve as a starting point for discussions and help identify potential value during the IAPR process in order to aid decision-makers. With more direct access to IAPR stakeholders and analysts, GTRI could customize the analysis and visualizations to provide improved insights and better facilitate IAPRs.

4.6.1 PROGRAM ANALYSIS

For program analysis (external to DAVE), Figure 5 shows a program table and metadata preview tool that was developed. This visualizes the total cost and risk color for each program and, upon selection, will display the metadata available via the mission engineering data model (supported subset of the AVDF) relevant to the IAPR process. Of note is that the "Acquired System/Subsystem Name" is a link to the Mission Elements and would support such capabilities as direct linking to additional metadata about the elements. The metadata preview is dynamically created from the mission engineering data model. The metadata preview could support additional properties (supported by the AVDF) or alternative views based on individualized user needs (IAPR stakeholders). Programs can be sorted and filtered as needed, and states of the data table are exposed such that additional tools can hook into the information to drive other analyses.



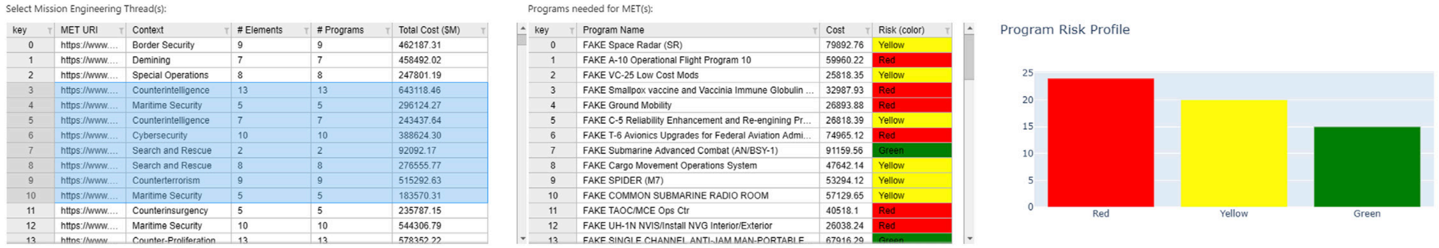
Select a program to see its metadata:

	Name	Cost ($M)	Risk
0	FAKE E-3 AWACS Support to the Warfighter	70823.29	Green
1	FAKE Mobility Air Forces (MAF) Mission Planning ...	52553.66	Yellow
2	FAKE Joint Warning And Reporting Network 1	30361.6	Yellow
3	FAKE Distributed Common Ground System-Navy I...	95182.79	Red
4	FAKE Joint Effects Targeting System	15852.29	Yellow
5	FAKE Small Tactical Electric Power, 3kW	95072.1	Green
6	FAKE MPS F-22 Modernization	58325.65	Red
7	FAKE M240B/L, 7.62mm Medium Machine Gun	74957.35	Red
8	FAKE SPIDER Increment 1A (M7E1)	70102.56	Green
9	FAKE E-4B Survivable Super High Frequency Incre...	55603.45	Yellow
10	FAKE Family of Advanced Beyond Line-of-Sight Te...	31670.11	Green
11	FAKE Soldier Virtual Trainer	60395.72	Red
12	FAKE QF-16 Full Scale Aerial Target	33555.75	Yellow
13	FAKE Legacy Ammunition Small Caliber	52119.87	Yellow
14	FAKE Transport Telemedicine System - Medical Ha...	19801.05	Yellow
15	FAKE Heavy Scraper	63546.42	Green
16	FAKE Joint Biological Agent Decontamination System	94148.5	Yellow
17	FAKE Cold Weather Glove System	82621.49	Yellow
18	FAKE Air Force Way	90151.29	Yellow
19	FAKE Joint Service Lightweight Integrated Suit Tec...	45632.22	Green
20	FAKE Cargo Movement Operations System	47642.14	Yellow
21	FAKE Theater High Altitude Area Defense	688.12	Red
22	FAKE F-16 Block 30 Secure Line of Sight Commun...	96706.21	Red

Property	Value
type	https://www.example.com/iapr/Program
Acquisition Full Name	FAKE SPIDER Increment 1A (M7E1)
Acquisition Short Name	FAKE SPIDER 1A
Mission & Description Narrative	Soon kid doctor whatever look. Central energy page television. Generation if week carry.
Budget Estimate - Acquisition Estimate Amount	70102.56
Acquired System/Subsystem Name	Unspecified Mission Element 'Porro Quod'
Acquired System/Subsystem Name	Unspecified Mission Element 'Error Cumque'
Acquisition Identifier	fake_MEFEQ6UU
Risk (Color) Rating	Green
schedule	Far

Figure 5. Program Ciew Showing Metadata based on User Selections

A MET summary dashboard was developed to demonstrate how the mission engineering data model links information across programmatic and mission engineering concepts. As shown in Figure 6, the MET summary view lists each MET, the related context, the number of allocated Mission Elements (therefore, required Programs), and the total program cost to “satisfy” the alternative. These METs can be filtered and sorted as needed. Upon selection of one or more METs (i.e., a portfolio), a program component (the same as for the program view) is shown to capture the Programs needed to achieve the portfolio, as well as a program risk profile that indicates the total portfolio risk for all included Programs.



Select Mission Engineering Thread(s):

key	MET URI	Context	# Elements	# Programs	Total Cost ($M)
0	https://www....	Border Security	9	9	462187.31
1	https://www....	Demining	7	7	458492.02
2	https://www....	Special Operations	8	8	247801.19
3	https://www....	Counterintelligence	13	13	643118.46
4	https://www....	Maritime Security	5	5	296124.27
5	https://www....	Counterintelligence	7	7	243437.64
6	https://www....	Cybersecurity	10	10	388624.30
7	https://www....	Search and Rescue	2	2	92092.17
8	https://www....	Search and Rescue	8	8	276555.77
9	https://www....	Counterterrorism	9	9	515292.63
10	https://www....	Maritime Security	5	5	183570.31
11	https://www....	Counterinsurgency	5	5	235787.15
12	https://www....	Maritime Security	10	10	544306.79
13	https://www....	Counter-Proliferation	13	13	578352.22

Programs needed for MET(s):

key	Program Name	Cost	Risk (color)
0	FAKE Space Radar (SR)	79892.76	Yellow
1	FAKE A-10 Operational Flight Program 10	59960.22	Red
2	FAKE VC-25 Low Cost Mods	25818.35	Yellow
3	FAKE Smallpox vaccine and Vaccinia Immune Globulin ...	32987.93	Red
4	FAKE Ground Mobility	26893.88	Red
5	FAKE C-5 Reliability Enhancement and Re-engining Pr...	26818.39	Yellow
6	FAKE T-6 Avionics Upgrades for Federal Aviation Admi...	74965.12	Red
7	FAKE Submarine Advanced Combat (AN/BSY-1)	91159.56	Green
8	FAKE Cargo Movement Operations System	47642.14	Yellow
9	FAKE SPIDER (M7)	53294.12	Yellow
10	FAKE COMMON SUBMARINE RADIO ROOM	57129.65	Yellow
11	FAKE TAOC/MCE Ops Ctr	40518.1	Red
12	FAKE UH-1N NVIS/Install NVG Interior/Exterior	26038.24	Red
13	FAKE SINGLE CHANNEL ANTI-JAM MAN-PORTABLE...	67916.29	Green

Figure 6. MET Alternative Analysis Tool Showing Programs Required to Meet Allocations and the Associated Program Risk Profile

The goal is to identify potential groups of Programs based on METs and assess their viability against Cost/Risk. Additional degrees of comparison (i.e., specific mission task and context) could be used to modify the meaning of the analysis and assist in questioning and answering needs during IAPRs.

4.6.2 KILL WEB PROGRAM ANALYSIS

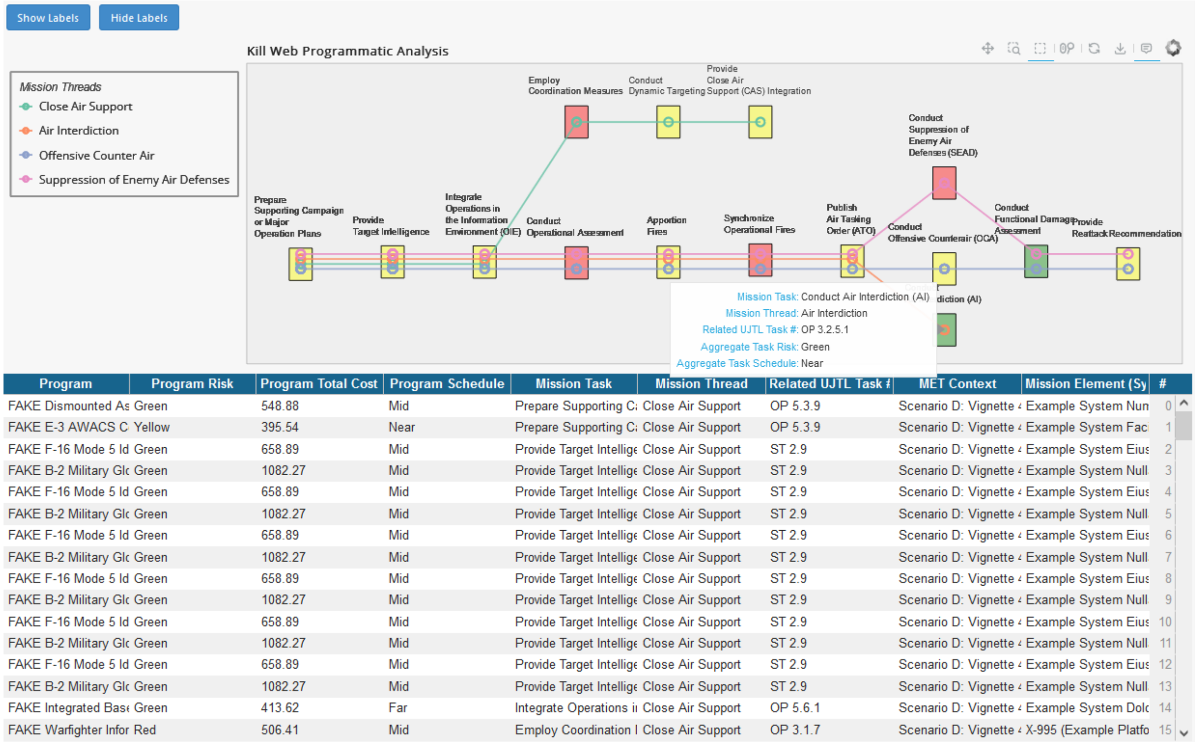
To represent programs in the context of a kill web, Figure 7 shows a visualization of four example mission threads across their constituent mission tasks. The mission threads are organized to indicate where various mission tasks are shared, with each task colored by an aggregate risk for accomplishing that task. Aggregate risk across each task is calculated by a weighted average and indicated by color in the task box around each mission task. Complete task data can be accessed via hover.

The visualization also provides a linked data table, where selected tasks are shown in the data table below. This allows for introspection of the METs, MET context, and associated programs for mission tasks of interest. Users can explore what programs contribute to risk (or schedule) across the kill web. A set of controls provided in the dashboard allows the user to select various mission threads to add or remove them from the kill web, which updates the underlying risk calculations.

4.6.3 MISSION ENGINEERING VISUALIZATION

The relationship between Mission Tasks and Mission Threads may have a high or low degree of interdependency, where Mission Tasks might be found among multiple Mission Threads or not very many. A visualization of the relationship between Tasks and Threads can be generated to provide a rapid way of grasping the scope of task and thread relationships. Figure 8 shows this visualization, where Mission Tasks are circles and Mission Threads are squares. They are colored by aggregated program risk based on the programs that are capable of performing a Mission Task. A square surrounded by circles shows a Mission Thread unrelated to others through Tasks (although it may be through Programs). More complicated relationships are seen where Mission Tasks are shared by multiple Threads, which may indicate sources of synergy or risk based on the programs that can complete the Tasks.

The visualization allows for changing the relationships being viewed between the combinations of Programs, Mission Tasks, and Mission Threads. Node coloring allows visual inspection of high and low risk and can be toggled to show cost information. Costs are aggregated to the Tasks and Threads through their dependencies on programs, where the programs contain the cost information.



Mission Task: Conduct Air Interdiction (AI)
Mission Thread: Air Interdiction
Related UJTL Task #: OP 3.2.5.1
Aggregate Task Risk: Green
Aggregate Task Schedule: Near

Program	Program Risk	Program Total Cost	Program Schedule	Mission Task	Mission Thread	Related UJTL Task #	MET Context	Mission Element (Sy	#
FAKE Dismounted As	Green	548.88	Mid	Prepare Supporting C	Close Air Support	OP 5.3.9	Scenario D: Vignette 4	Example System Nun	0
FAKE E-3 AWACS C	Yellow	395.54	Near	Prepare Supporting C	Close Air Support	OP 5.3.9	Scenario D: Vignette 4	Example System Faci	1
FAKE F-16 Mode 5 Id	Green	658.89	Mid	Provide Target Intellige	Close Air Support	ST 2.9	Scenario D: Vignette 4	Example System Eius	2
FAKE B-2 Military Glc	Green	1082.27	Mid	Provide Target Intellige	Close Air Support	ST 2.9	Scenario D: Vignette 4	Example System Null	3
FAKE F-16 Mode 5 Id	Green	658.89	Mid	Provide Target Intellige	Close Air Support	ST 2.9	Scenario D: Vignette 4	Example System Eius	4
FAKE B-2 Military Glc	Green	1082.27	Mid	Provide Target Intellige	Close Air Support	ST 2.9	Scenario D: Vignette 4	Example System Null	5
FAKE F-16 Mode 5 Id	Green	658.89	Mid	Provide Target Intellige	Close Air Support	ST 2.9	Scenario D: Vignette 4	Example System Eius	6
FAKE B-2 Military Glc	Green	1082.27	Mid	Provide Target Intellige	Close Air Support	ST 2.9	Scenario D: Vignette 4	Example System Null	7
FAKE F-16 Mode 5 Id	Green	658.89	Mid	Provide Target Intellige	Close Air Support	ST 2.9	Scenario D: Vignette 4	Example System Eius	8
FAKE B-2 Military Glc	Green	1082.27	Mid	Provide Target Intellige	Close Air Support	ST 2.9	Scenario D: Vignette 4	Example System Null	9
FAKE F-16 Mode 5 Id	Green	658.89	Mid	Provide Target Intellige	Close Air Support	ST 2.9	Scenario D: Vignette 4	Example System Eius	10
FAKE B-2 Military Glc	Green	1082.27	Mid	Provide Target Intellige	Close Air Support	ST 2.9	Scenario D: Vignette 4	Example System Null	11
FAKE F-16 Mode 5 Id	Green	658.89	Mid	Provide Target Intellige	Close Air Support	ST 2.9	Scenario D: Vignette 4	Example System Eius	12
FAKE B-2 Military Glc	Green	1082.27	Mid	Provide Target Intellige	Close Air Support	ST 2.9	Scenario D: Vignette 4	Example System Null	13
FAKE Integrated Base	Green	413.62	Far	Integrate Operations i	Close Air Support	OP 5.6.1	Scenario D: Vignette 4	Example System Dolc	14
FAKE Warfighter Infor	Red	506.41	Mid	Employ Coordination I	Close Air Support	OP 3.1.7	Scenario D: Vignette 4	X-995 (Example Platfo	15

Figure 7. Simple Example Kill Web Analysis and Visualization

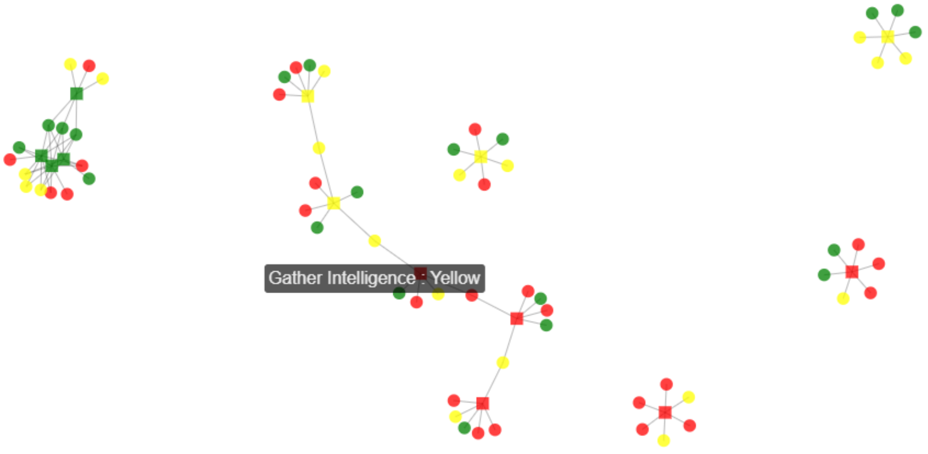


Figure 8. Mission Task to Mission Thread Relationships

4.7 OPTIMAL PORTFOLIOS

In addition to viewing, filtering, and summarizing the schedule, risk, and cost information for MET Programs, it is also possible to compute optimal portfolios. An optimization tool has the ability to search over the set of all Programs related to a mission, combine their risks into a cumulative risk to the MET of interest, and identify for the user the set (or sets) of Programs that minimize risk while staying within the specified budget. With an optimization tool, the user can examine the impact of multiple programs on the cumulative mission risk, as well as the total cost of all programs. The user can also add other objectives and constraints. Constraint values can be adjusted (e.g., maximum budget, minimum acceptable risk), and the various metrics can swap roles as objectives versus constraints (e.g., minimize cost with a risk constraint versus minimize risk with a cost constraint). In addition, the IAPR review board can compare multiple Program portfolios against one another or quickly identify mission threads that lack viable Program portfolios (all portfolios are too risky or expensive).

Figure 9 shows the output of an optimization tool that was developed to examine risk and cost using the aforementioned example data. A schedule optimization can be added as well. Figure 9 shows 5,000 portfolios (combinations of programs) that can all perform three missions: Maritime Interdiction, Anti-Piracy Operations, and Counterterrorism Operations. The probabilities are aggregated based on program choices, as are the costs. Therefore, if one program can perform tasks relevant to two missions, the overall cost of that portfolio can be lower than a portfolio of specialized programs.

Furthermore, the more programs a portfolio contains for a particular mission, the lower the overall mission-level risk will be (in exchange for higher cost). Finally, since there is often a trade-off between performance and cost, Figure 9 illustrates that a subset of the 5,000 portfolios can perform two of the missions at low risk and within budget but cannot perform Maritime Interdiction at low risk. This indicates that specialized programs may be needed for Maritime Interdiction (or additional funding may be needed). This example illustrates how data can be aggregated to facilitate the analysis of the benefits or costs of program alignments.

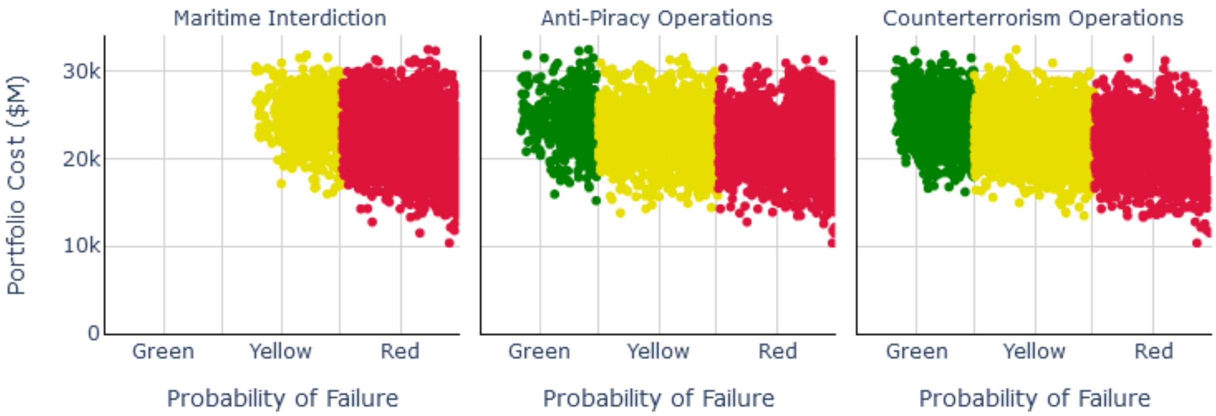


Figure 9. Minimum Risk within Budget for a MET Program Portfolio

4.8 LIMITATIONS AND CONSIDERATIONS

The goals of this effort were open-ended, with the primary objective being to “understand IAPRs and their needs.” With limited access to exemplar IAPRs or access to data from the systems that support IAPRs, efforts were primarily focused on identifying a subset of known programmatic data elements from the AVDF and exploring opportunities to link that information to mission engineering concepts. The result is this overview of IAPRs and their potential relationship to mission engineering. The tools developed in this effort are limited to simple cost/risk data available in DAVE. However, they could be expanded to include more granular information and additional data elements or integrated with additional data sources. Data modeling was restricted to the minimal subset necessary to demonstrate a potential way for IAPRs to leverage METs and achieve compliance. However, additional functional/performance data (i.e., from analytics, external systems, and simulation) could be included in order to evaluate against MoP/MoE/MoS and would be highly beneficial. As a general limitation, lack of access to more specific IAPR data/summaries/reports results in multiple unknowns regarding where the most value would be gained from development/analysis efforts.

5. TRADE STUDY ON INTEGRATING LEVELS OF AUTONOMY (LOA) IN SYSTEM OF SYSTEMS: A MODEL-BASED APPROACH WITH SEARCH AND RESCUE USE CASE BY GMU

5.1 INTRODUCTION

In many modern missions, reliance on manual processes and human decision-making often leads to slower response times and increased risks. The inherent complexity of these missions highlights the need for innovative approaches to enhance the effectiveness of portfolios assembled to execute them. This portion of the project seeks to address challenges faced in SoS operations by utilizing model-based techniques to study the effects of introducing varying Levels of Autonomy (LoAs). Studying these effects before implementation is crucial, as introducing autonomy can be expensive, have unexpected effects on other systems, and lead to the emergence of SoS. Our approach involves developing a framework, using MBSE and Systems Modeling Language (SysML) with Cameo Systems Modeler, for conducting a trade study that assesses SoS mission capabilities under different LoAs with the potential to “plug into” various CPM activities.

To demonstrate the effectiveness of our approach, we apply it to a SAR use case. SAR operations are critical for saving lives and involve multiple systems working together. Traditional SAR missions rely heavily on human decision-making and manual operations, which can be time-consuming and risky. However, advances in machine learning (ML) and autonomous systems present new opportunities to enhance SAR capabilities. SAR provides an ideal operation scenario to serve as a use case for implementing LoAs because of its well-established role as an SoS and the available opportunities for autonomy integration.

This project builds the SAR model in UAF using the MBSE tool Cameo Systems Modeler. The project conducts a trade study within the model to evaluate varying LoAs at the system level, ultimately providing insights into how these technologies can be effectively implemented to enhance complex operations. Figure 10 provides an Operational Concept of the SAR mission with an SoS, where there is an opportunity to investigate different system capabilities with increased LoA.

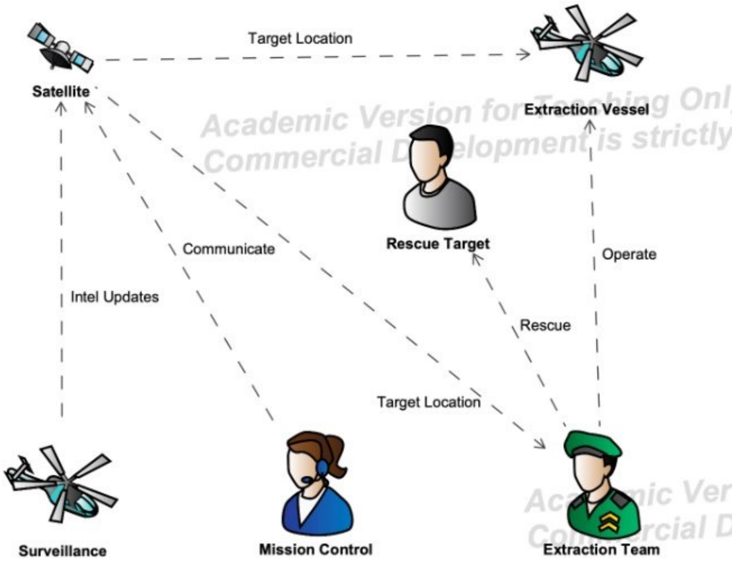


Figure 10. High-Level Operational Concept of SAR Mission

5.2 TRADE STUDY FRAMEWORK

To explore the effects of integrating LoAs into SAR operations, we employ MBSE and SysML to systematically decompose the SAR operational structure, as shown in Figure 11. This initial SAR architecture forms the basis for conducting the trade study by identifying different LoA for constituent systems of the SoS and assessing their impact on mission efficacy.

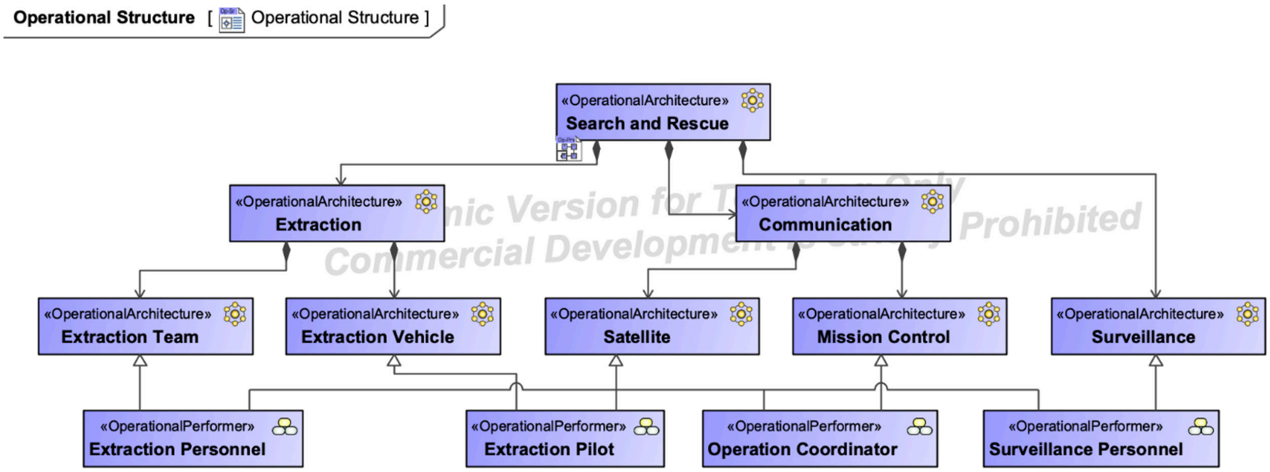


Figure 11. SAR Operational Structure

5.2.1 STEP 1. DEFINE CAPABILITIES

Capabilities and their corresponding mission-level MoEs are defined in the Strategic viewpoint of the UAF, Figure 12. These MoEs include transportation capacity, mean time between failure (MTBF), SoS cost, human lives at risk in the field, and intelligence response to evaluate overall SoS and mission effectiveness. In addition to capabilities, requirements were included to represent stakeholder preferences, as shown in Figure 13. These requirements are identified at a high abstraction level to demonstrate how requirements can be managed, traced, and evaluated within the MBSE environment.

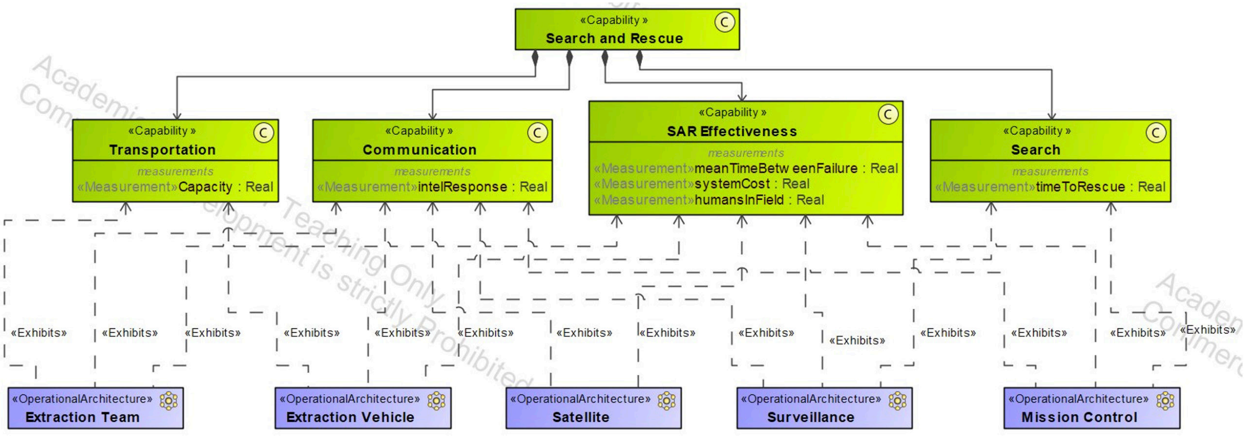
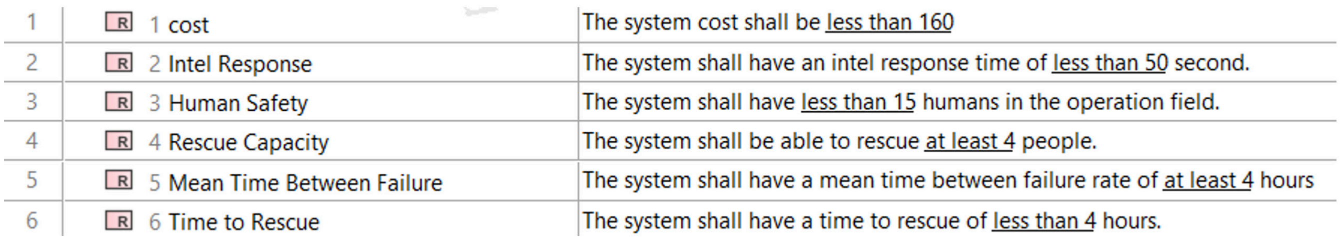


Figure 12. The Strategic Viewpoint of the SAR Mission Showing MoEs



1	R 1 cost	The system cost shall be less than 160
2	R 2 Intel Response	The system shall have an intel response time of less than 50 second.
3	R 3 Human Safety	The system shall have less than 15 humans in the operation field.
4	R 4 Rescue Capacity	The system shall be able to rescue at least 4 people.
5	R 5 Mean Time Between Failure	The system shall have a mean time between failure rate of at least 4 hours
6	R 6 Time to Rescue	The system shall have a time to rescue of less than 4 hours.

Figure 13. Example Requirement Table Accounting for Stakeholder Preference in MoEs

5.2.2 STEP 2. INTRODUCE LOAS

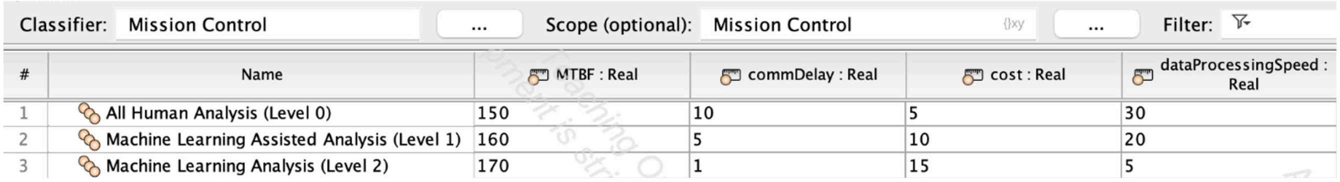
Different systems within the SAR operational structure can be replaced by different LoA-based technological advancements in autonomous systems and underlying AI/ML algorithms. For example, the Surveillance task can be accomplished by an autonomous drone instead of a piloted helicopter, or ML algorithms could assist in mission control. Table 3 identifies potential LoA that could be incorporated into different systems. Of the five systems that make up the SAR SoS, three of the systems have three different LoAs available, while the other two each have one. This shows the heterogeneity in LoA corresponding to different systems, while the MBSE approach can facilitate their integration at the SoS level.

Table 3. LoA for SAR Operations

Level of Autonomy	Mission Control	Surveillance	Extraction Vessel	Satellite	Extraction Team
LoA-0	All human intel analysis	Human operated helicopter – Blackhawk UH -60	Human operated helicopter – Blackhawk UH- 60	As-is operation	As-is human operation
LoA-1	Machine learning assisted intel analysis	Remote Controlled UAV – Gray Eagle MQ-1C	Reduced crew helicopter – Blackhawk UH- 60 with Pilot assist	N/A	N/A
LoA-2	Machine learning intel analysis	Autonomous UAV – Scan Eagle	Autonomous helicopter – Blackhawk UH- 60 with ALIAS	N/A	N/A

5.2.3 STEP 3. DEFINE TECHNICAL PERFORMANCE MEASURES FOR EACH LOA

Technical Performance Measures (TPMs) describe a measurable characteristic of a system, and each system can have a different set of TPMs based on its independent operation. Furthermore, each LoA can have a different value for the TPMs. For example, LoA-1 for mission control has a lower data processing speed than LoA-0. These TPMs are represented in the MBSE environment as instance tables for each system. Figure 14 shows the instance table for mission control, which holds the TPMs for each LoA. The figure highlights that increasing LoA may benefit certain TPMs (e.g., communication delay) but will have higher costs and MTBF.



Classifier: Mission Control

Scope (optional): Mission Control

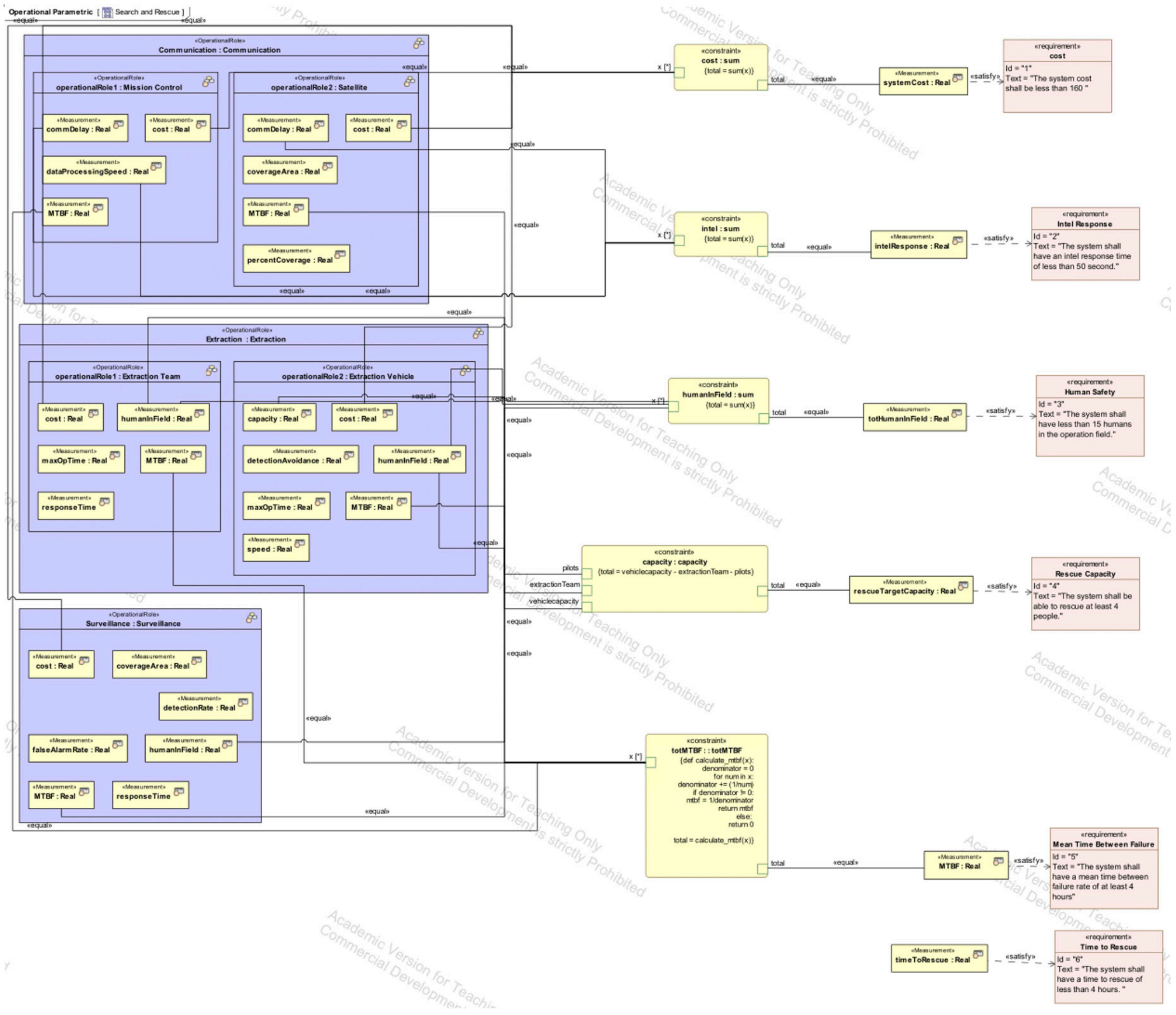
Filter:

#	Name	MTBF : Real	commDelay : Real	cost : Real	dataProcessingSpeed : Real
1	All Human Analysis (Level 0)	150	10	5	30
2	Machine Learning Assisted Analysis (Level 1)	160	5	10	20
3	Machine Learning Analysis (Level 2)	170	1	15	5

Figure 14. Instance Table of Mission Control TPMs

5.2.4 STEP 4. CALCULATE MOES

The MoEs reflect how different TPMs interact to affect the overall mission effectiveness and the SoS performance. Since different LoAs have different TPM values for similar systems, it is important to assess how the integration of LoA changes the overall SoS performance. Within this trade study framework, the MoEs are calculated using constraint blocks within the SAR parametric diagrams that connect the TPMs of all SAR systems, as shown in Figure 15. Moreover, the MoEs are connected to requirements with a “satisfy” relationship in the parametric diagram showing traceability to stakeholder preferences for the SAR mission.



```
{def calculate_mtbf(x):
denominator = 0
for num in x:
denominator += (1/num)
if denominator != 0:
mtbf = 1/denominator
return mtbf
else:
return 0

total = calculate_mtbf(x)}
```

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Text = "The system cost shall be less than 160 "

Id = "2"
Text = "The system shall have an intel response time of less than 50 second."

Id = "3"
Text = "The system shall have less than 15 humans in the operation field."

Id = "4"
Text = "The system shall be able to rescue at least 4 people."

Id = "5"
Text = "The system shall have a mean time between failure rate of at least 4 hours"

Id = "6"
Text = "The system shall have a time to rescue of less than 4 hours. "

Figure 15. Parametric Diagram of the SAR Block with MoEs Connected to Requirement Blocks

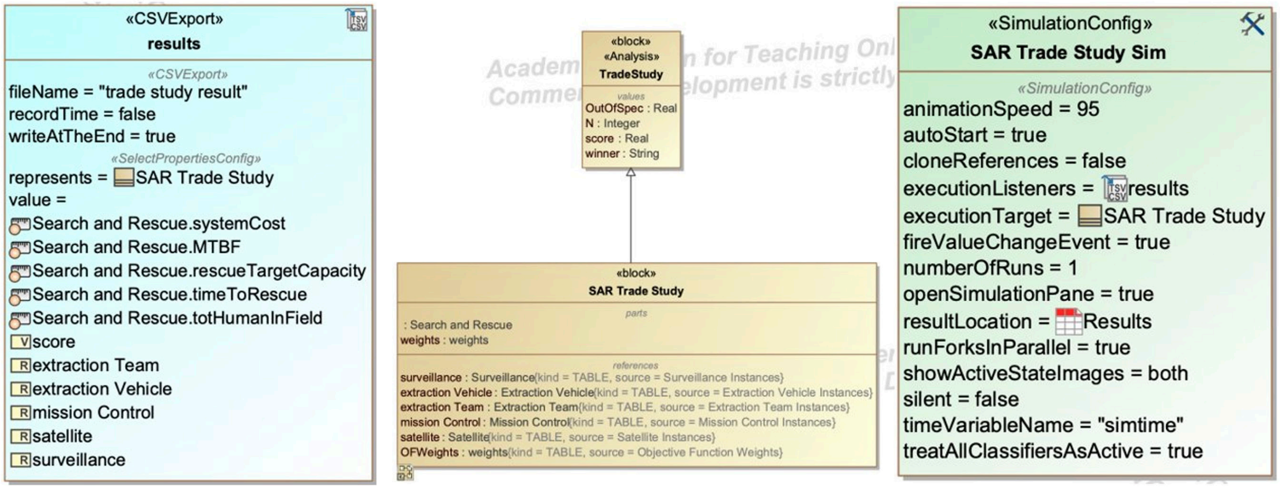
5.2.5 STEP 5. CALCULATE THE OVERALL SCORE OF SOS

Different LoAs can be combined to create feasible SoS architectures by configuring each SAR system with varying degrees of autonomy. For instance, the mission control system might be set to a higher LoA, where ML algorithms handle most data processing. In comparison, the extraction vehicle operates at a lower LoA, relying primarily on manual input. These combinations result in multiple SoS architectures with distinct performance characteristics derived from the TPMs corresponding to their LoAs. As each architecture has varying overall performance, there is a need for an approach to compare these SoS architectures.

A weighted metric is employed to evaluate and compare the SoS architectures, where all MoEs are normalized, weighted, and summed to produce a single score (Equation 1). Normalizing the MoEs ensures they are on a comparable scale, facilitating an objective comparison of different SoS architectures. The weights are another avenue for stakeholder preference to be considered when evaluating LoA integration.

$$Score = \sum_{i=1}^{n} w_i \cdot \frac{MoE_i - \min(MoE_i)}{\max(MoE_i) - \min(MoE_i)} \qquad \textbf{Equation 1}$$

This evaluation process uses a simulation configuration in Cameo with a trade study block and parametric diagrams within the model-based framework. The SAR Trade Study block (Figure 16) serves as the executable component of the simulation. When executed, the SAR Trade Study block parametric diagram (Figure 17) accesses the TPM instance tables as alternatives for each system, which are used to calculate MoEs for each configuration. The MoEs are normalized and weighted within the parametric diagram to give a score for each SoS architecture. Once all architectures are evaluated, the architecture with the highest score while remaining within requirements is selected as the winner and reported to a results table.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«SelectPropertiesConfig»
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Search and Rescue.systemCost
Search and Rescue.MTBF
Search and Rescue.rescueTargetCapacity
Search and Rescue.timeToRescue
Search and Rescue.totHumanInField
score
extraction Team
extraction Vehicle
mission Control
satellite
surveillance

«block»
«Analysis»
TradeStudy
values
OutOfSpec : Real
N : Integer
score : Real
winner : String

«block»
SAR Trade Study
parts
: Search and Rescue
weights : weights
references
surveillance : Surveillance{kind = TABLE, source = Surveillance Instances}
extraction Vehicle : Extraction Vehicle{kind = TABLE, source = Extraction Vehicle Instances}
extraction Team : Extraction Team{kind = TABLE, source = Extraction Team Instances}
mission Control : Mission Control{kind = TABLE, source = Mission Control Instances}
satellite : Satellite{kind = TABLE, source = Satellite Instances}
OFWeights : weights{kind = TABLE, source = Objective Function Weights}

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«SimulationConfig»
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executionTarget = SAR Trade Study
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openSimulationPane = true
resultLocation = Results
runForksInParallel = true
showActiveStateImages = both
silent = false
timeVariableName = "simtime"
treatAllClassifiersAsActive = true

Figure 16. Simulation Configuration (Left), SAR Trade Study Block (Middle), and Results CSV File Capturing MoEs (Right)

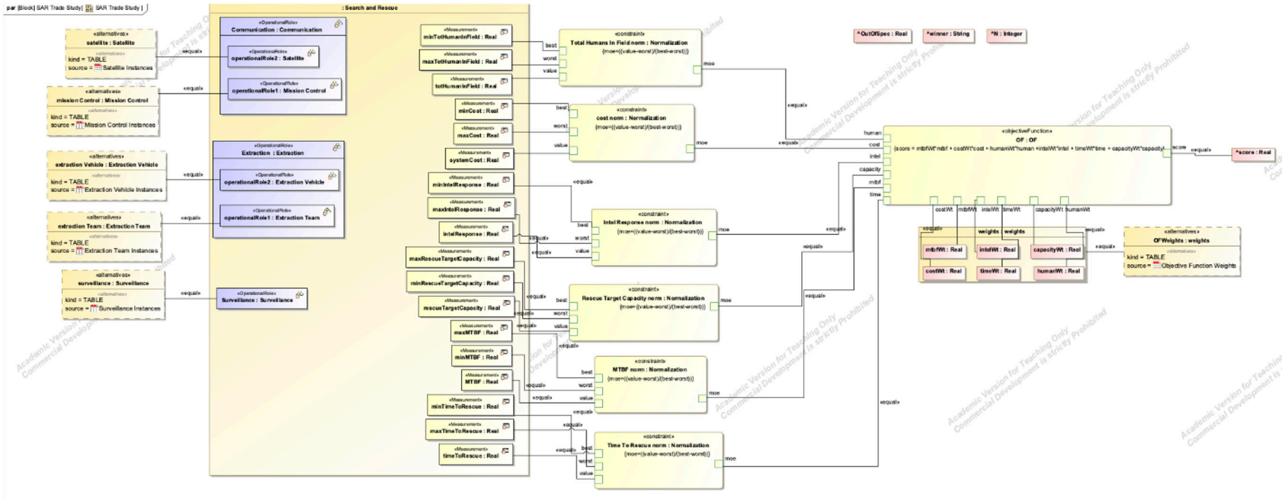
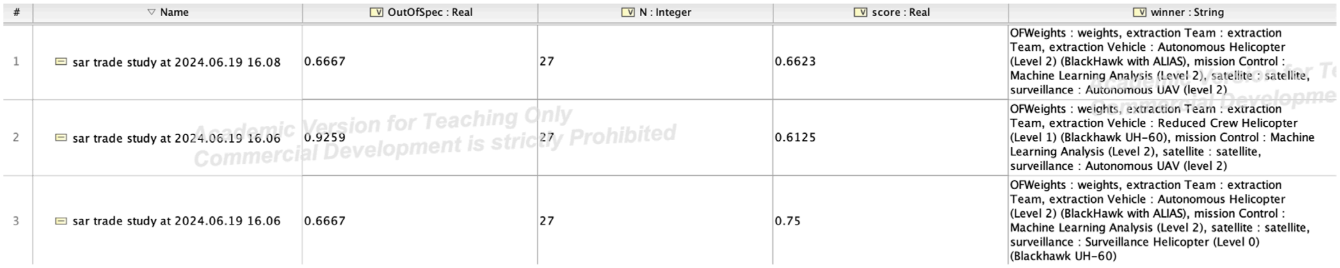


Figure 17. Parametric Diagram of the SAR Trade Study Block

5.3 RESULTS

A simulated performance of each SoS architecture containing different LoA systems is obtained. The different SoS architectures are compared against each other to find the highest score. Once executed, the simulation creates an entry in the report table with Cameo (Figure 18). The report includes the simulation instance (Name), the percent of architectures that did not meet requirements (OutOfSpec), the number of combinations tried (N), the winning score (Score), and the combination that achieved the winning score (winner).



#	Name	OutOfSpec : Real	N : Integer	score : Real	winner : String
1	sar trade study at 2024.06.19 16.08	0.6667	27	0.6623	OFWeights : weights, extraction Team : extraction Team, extraction Vehicle : Autonomous Helicopter (Level 2) (BlackHawk with ALIAS), mission Control : Machine Learning Analysis (Level 2), satellite : satellite, surveillance : Autonomous UAV (level 2)
2	sar trade study at 2024.06.19 16.06	0.9259	27	0.6125	OFWeights : weights, extraction Team : extraction Team, extraction Vehicle : Reduced Crew Helicopter (Level 1) (Blackhawk UH-60), mission Control : Machine Learning Analysis (Level 2), satellite : satellite, surveillance : Autonomous UAV (level 2)
3	sar trade study at 2024.06.19 16.06	0.6667	27	0.75	OFWeights : weights, extraction Team : extraction Team, extraction Vehicle : Autonomous Helicopter (Level 2) (BlackHawk with ALIAS), mission Control : Machine Learning Analysis (Level 2), satellite : satellite, surveillance : Surveillance Helicopter (Level 0) (Blackhawk UH-60)

Figure 18. Example Report Table Stored within the Model

Capturing raw MoE data allows for further analysis of LoA implementation from which meaningful insights regarding the LoA impact can be derived. For example, Figure 19 shows the relationship between System Cost and the MTBF, where each light blue circle represents a valid SoS architecture with different LoA of constituent systems. The following observations are noted as an exemplar of analysis that can be conducted with this framework:

- The winning configuration (circled in red)
    - Mission control: LoA-2,
    - Extraction Vehicle: LoA-2
    - Surveillance: LoA-2
    - Extraction Team: LoA-0
    - Satellite: LoA-0

- Highest MTBF configuration (circled in black)
    - Mission control: LoA-2
    - Extraction Vehicle: LoA-2
    - Surveillance: LoA-0
    - Extraction Team: LoA-0
    - Satellite: LoA-0

- Lowest cost configuration (circled in blue)
    - Mission control: LoA-0
    - Extraction Vehicle: LoA-0
    - Surveillance: LoA-2
    - Extraction Team: LoA-0
    - Satellite: LoA-0

The winning configuration represents the highest performing architecture, considering all MoEs, including those not shown in Figure 19, and their corresponding weight in the objective function, Equation 1. The three distinct groups indicated in green in Figure 19 are due to the surveillance system having a larger MTBF difference between its LoAs when compared to extraction vehicle and mission control systems. This trend indicates that surveillance has the largest impact on MTBF and cost when implementing different LoAs.

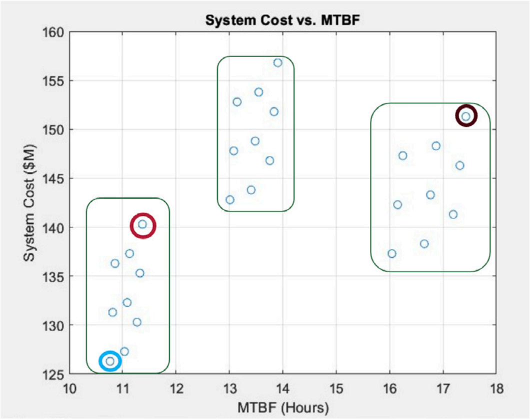


Figure 19. System Cost vs. MTBF

5.4 CONCLUSIONS ON THE LOA INTEGRATION INTO SAR OPERATIONS

This portion of the overall WRT-1081.7.5 research demonstrates the potential of using model-based techniques to explore the integration of LoAs in SoS. LoAs describe the extent to which tasks within a system are automated, with higher LoAs indicating greater autonomy involvement in completing tasks. Identifying and evaluating different LoA configurations within the MBSE environment makes it possible to assess their impact on overall SoS performance.

Modeling a SAR use case, an initial SAR architecture was established to develop a framework for conducting a trade study within the MBSE tool Cameo. This trade study evaluated the impact of different LoA configurations on mission-level MoEs. LoAs were identified for each system, and TPMs were given for each LoA. This approach allowed for comprehensive analysis, including assessing the overall SoS performance, cost, and risk factors of various configurations to determine the impact of autonomy integration in SoS architecture based on stakeholder requirements and preferences.

6. PROPOSED FUTURE WORK

6.1 OVERALL DISCUSSIONS

Proposed Phase 2 work would build upon Phase 1's research effort by implementing a two-track SoS development and experimentation approach. In collaboration with GTRI and GMU, Purdue would lead Track 1, focusing on advancing the development of AWB tools. Concurrently, GTRI would lead Track 2 with support from Purdue and GMU, concentrating on rigorous testing and validation of these tools using real-world DoD IAPR data. This phase would address challenges in developing tailored data models for CPM, aiming to expand tool functionality, enhance team expertise, and foster adoption within the DoD framework. Further elaboration will be provided in this report's subsequent sections, emphasizing theoretical exploration and practical application to ensure robust research outcomes.

The team engaged in comprehensive discussions regarding future research directions, emphasizing the importance of articulating a clear path forward with input from various DoD stakeholders. Consideration was given to tailoring analytical tools to meet the diverse needs of IAPRs while addressing challenges related to data modeling within budget constraints. This forward-looking approach ensures that our research remains relevant and adaptable to the evolving needs of our stakeholders. By continuously engaging with DoD stakeholders, we aim to align our research objectives with their priorities and ensure that our outcomes are practically applicable.

Future plans were outlined to articulate a coherent path forward, integrating program requirements and potential demonstrations to underscore capabilities and demonstrate value to sponsors. This includes exploring potential funding opportunities to expand our research endeavors and develop proof-of-concept analytics to support IAPRs. By demonstrating the practical applications of our research through well-planned demonstrations, we aim to showcase the value and impact of our work to sponsors and stakeholders. This proactive engagement strategy will foster stronger partnerships and secure ongoing support for our research initiatives.

6.2 INSTITUTION-SPECIFIC DISCUSSIONS

6.2.1 FUTURE WORK BY PURDUE

Purdue would find potential future work with partner institutions to link RPO with MBSE software. A preliminary version of such linkage was demonstrated several years ago, relying on multiple third-party tools for links. A more streamlined version would utilize the same inputs required by each flavor of RPO. Therefore, a future proposal would include three methods linking RPO to SysML, one for each tool version. If both MATLAB and Python links were desired, then a total of six linking methods would be required. There are also opportunities to utilize Python Application Programming Interface (API) frameworks provided by SysML V2, assuming MBSE tool vendors implement these solutions before a potential future contract (Gomes, n.d.; Object Management Group, n.d.)

Another potential enhancement would be combining different RPO versions based on specific situations and run points. For example, integrating the three objectives could offer mission designers greater control over situational effects and mitigate portfolio differences arising from the three methods. Creating a hybrid approach by combining elements from each RPO flavor could enhance portfolio optimization and better address varying mission needs. Further research into these hybrid methods may reveal new strategies for improving decision-making and performance. This exploration includes exploring pairings of objectives, such as the combination of two RPO flavors (i.e., weighted application using two of the following: Bertsimas-Sim, CVaR, and RMVO) and three RPO Flavors (i.e., weighted application of the three: Bertsimas-Sim, CVaR, and RMVO). The following section details potential use cases that illustrate the application of the hybrid RPO approach.

Potential Use Cases: Combination of two RPO flavors

The weighting method in the following scenarios assumes that the objective function is normalized relative to other objective function values.

Example 1: (Bertsimas-Sim, CvaR, RMVO) = (0.5, 0.5, 0)
Potential use cases:

- Variations in system support and capabilities, alongside limited intelligence into adversary's equipment.

Example 2: (Bertsimas-Sim, CvaR, RMVO) = (0, 0.5, 0.5)
Potential use cases:

- Limited intelligence into the adversary's equipment, while the ally's equipment to counter the adversary is still in development.

Example 3: (Bertsimas-Sim, CvaR, RMVO) = (0.5, 0, 0.5)
Potential use cases:

- Variation in system support and capabilities, while the ally's equipment to counter the adversary is still in development.

Potential Use Cases: Combination of three RPO flavors

Example 4: (Bertsimas-Sim, CvaR, RMVO) = (0.2, 0.4, 0.4)
Potential use cases:

- Well-defined systems support parameters and capabilities for the nation and its allies.
- Intelligence about the adversary for upcoming battles is limited.
- Equipment being specifically developed to counter the adversary is early in the development cycle.

Example 5: (Bertsimas-Sim, CvaR, RMVO) = (0.4, 0.2, 0.4)
Potential use cases:

- Wide range of system support and capability uncertainty.
- Already have significant intelligence about adversary's equipment.
- Equipment being specifically developed to counter the adversary is early in the development cycle.

Example 6: (Bertsimas-Sim, CvaR, RMVO) = (0.4, 0.4, 0.2)
Potential use cases:

- Wide range of system and support capability uncertainty.
- Intelligence about the adversary for upcoming battles is limited.
- Equipment being specifically developed to counter the adversary is late in the development cycle.

6.2.2 FUTURE WORK BY GTRI

6.2.2.1 IAPR Analytical Support

A continued effort could refine methods, models, and tools that could expand and facilitate IAPRs (and other CPM processes). The resulting support for data-driven decision-making could be used to expand stakeholders, improve insights and data flow, and support better long-term decisions.

The initial development of tools was aimed at demonstrating that some form of IAPR analysis leveraging mission engineering concepts *could* be done. However, due to the limited scope of this effort and the lack of appropriate contractual security mechanisms, the specific needs of IAPRs have not been fully determined. Ideally, GTRI would work with IAPR stakeholders to develop data analysis tools to better understand their questions and needs. Additionally, supporting mission engineering data modeling and ontological work would be best accomplished in coordination with ongoing efforts across OUSD, with a deeper understanding of how, when, where, and by whom actual mission engineering data is created.

In order to develop a toolset to support IAPRs successfully, GTRI recommends future planning with the following general outline:

1. Directly interface with OUSD(A&S) and other stakeholders to refine a clear understanding of the specific needs of IAPRs.
2. Collaborate with OUSD(A&S) and other OUSD entities (e.g., Research & Engineering) to better understand the state of Mission Engineering data engineering. Support the development and adoption of mission engineering data models that meet the needs of CPM and can support desired analytic methods.
3. Access and understand real mission data, constructing missions and related entities in prescribed structures as necessary.
4. Iterative with OUSD(A&S) and other stakeholders as necessary to propose and develop the necessary analytic and visualization toolset. Care should be taken to understand and build the necessary infrastructure available to support real IAPRs (e.g., Secret Internet Protocol Router Network (SIPRNet) or Joint Worldwide Intelligence Communications System (JWICS) deployable).
5. Apply real mission and program data (i.e., AVDF) to the developed analytic toolset for stakeholder review. Review and assess how well the developed toolsets perform in a representative IAPR environment.

6.2.2.2 Ontologies for IAPRs

During the contract period, one notable achievement was a study into the value of ontologies and semantic technologies in support of IAPRs, specifically regarding mission engineering and portfolio analysis tools. This assessment weighed the pros and cons of formal ontological definitions. The conclusion was that a simple approach to concept definitions would be more appropriate while the IAPR process is still being defined. Avoiding specific commitments to ontologies or ontological frameworks will help with early iterations while still laying a solid foundation for adopting advanced semantic technologies in the future.

In general, the proposed data model is sufficient for capturing data in support of mission engineering analysis. However, implementing this data model will likely require schemas and/or ontologies to enable software applications to process the information. While ontologies can define the semantics of data and relationships between concepts, they are not the only method, and we are not specifically proposing them as a recommended solution. The formal curation of an ontology for the AVDF or IAPRs would require significant additional work. Alternative approaches may be more beneficial for future implementations of IAPR analysis tools, including mission engineering tools in support of IAPRs.

6.2.3 FUTURE WORK BY GMU

GMU's proposed future work would refine the model to enhance its sophistication and precision. This effort would incorporate an expanded and more detailed operational data set, providing a richer analytical context. GMU would support Purdue and GTRI in exploring the integration of MBSE LoA analytical capabilities with the IAPR toolsets. This integration aims to significantly enhance the accuracy and applicability of trade study results, broadening their relevance to a diverse array of SoS challenges. By addressing these complex problem sets with advanced tools and comprehensive data, the project seeks to deliver more profound, actionable insights for defense acquisition and system design. In collaboration with Purdue and GTRI, the GMU team would address a critical area of need for developing model-based practices for autonomy acquisition in future defense systems.

7. CONCLUSIONS

In enhancing defense acquisition, portfolio management is vital by aligning investments with strategic goals, optimizing resource allocation, and boosting DoD capabilities. Portfolio management systematically evaluates and prioritizes investments to address evolving threats and budget constraints, thus ensuring technological superiority and operational readiness. Recent developments include adopting IAPRs to integrate senior leaders' evaluations to enhance acquisition outcomes and align capabilities with strategic objectives. Purdue, GTRI, and GMU's collaborative efforts have advanced IAPR support tools, including developing data models for IAPR and exploring defense acquisition platforms like DAVE and Advana for enhanced transparency. These efforts collectively aim to optimize decision-making and streamline acquisition processes, fostering a more effective defense acquisition strategy.

The Purdue research focused on advancing portfolio management tools for analyzing IAPRs. Key achievements include enhancing the RPO tool by adding several flavors of optimization algorithms to evaluate complex mission design impacts on the SoS. Purdue successfully converted RPO scripts from MATLAB to Python, incorporating three optimization methods: Bertsimas-Sim, CVaR, and RMVO, each offering unique approaches to handling data uncertainty, risk, and development time variance. Contributions also include improving cost and performance metric formulations and a new RMVO tool with a Python version. These developments aim to provide decision-makers with versatile and practical tools for portfolio optimization and integration with MBSE tools.

The GTRI research aimed to enhance the support for IAPRs by organizing human and technical data related to OUSD(A&S)'s IAPRs. The team analyzed available documentation and data, creating a composite document detailing the IAPR process, alignment with mission engineering, and programmatic integration. They developed an initial data model integrating programmatic and mission engineering concepts, emphasizing the role of AVDF and mission engineering in IAPRs. GTRI also crafted proof-of-concept tools for data exploration and analysis, including program risk and portfolio optimization visualizations. The study highlighted that while the tools were foundational, more detailed data and further development are needed to fully support IAPRs and refine decision-making processes.

The GMU research explored integrating varying LoAs into SoS to improve operational efficiency, using a SAR mission as a case study. By employing MBSE and SysML with Cameo Systems Modeler, the project developed a framework to evaluate how different LoAs affected SAR operations. The approach involved defining system capabilities and requirements, introducing different autonomous technologies, and assessing their impact through TPMs and MoEs. A weighted scoring metric compared various SoS architectures, identifying optimal configurations that balanced performance, cost, and risk. The results highlighted the potential for enhanced efficiency and effectiveness in complex operations through strategic autonomy integration.

The research findings reported in this report have detailed Phase 1 of this effort. A proposed Phase 2 effort would build on Phase 1's research, with Purdue, GTRI, and GMU continuing to collaborate to advance the development and experimentation of IAPR tools. To this end, a Phase 2 effort would have a simultaneous two-track approach: Purdue would lead Track 1 (i.e., IAPR tool development), while GTRI would lead Track 2 (i.e., IAPR tool experimentation).

Purdue would advance the integration of RPO with MBSE software by developing streamlined linking methods. Purdue's activities would also involve hybrid RPO approaches, combining different RPO versions (Bertsimas-Sim, CVaR, and RMVO) to address varied mission needs. GTRI would conduct experiments with IAPR tools while collaborating with DoD stakeholders to understand the needs of the IAPR data analysis tools. GTRI would also assess the use of ontologies, recommending more straightforward definitions while preparing for the future adoption of advanced semantic technologies. GMU would refine the model, incorporate detailed operational data, and support Purdue and GTRI in integrating MBSE LoA capabilities with IAPR tools, aiming to augment the precision and relevance of trade study results across a broader spectrum of SoS challenges.

8. APPENDIX

APPENDIX A. LIST OF PUBLICATIONS RESULTED

Building on the research conducted under WRT-1049.5, the predecessor to WRT-1081.7.5, the following conference paper was published:

Tsutsui, W., Guariniello, C., Mall, K., Patterson, F., Balestrini, S., Panchal, J., & DeLaurentis, D. (2023). Model-based Approach in Defense Portfolio Management: Data Preparation, Analysis, and Visualization of Decision Spaces. 2023 Annual Acquisition Research Symposium, Monterey, CA.

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Tremper, D. (2023). Portfolio-Focused Acquisition for the 21st Century Battlespace. *Defense Acquisition*, *52*(4), 16–19.

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