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COMPUTATIONAL TRADESPACE EXPLORATION, ANALYSIS, AND DECISION-
MAKING: A PROPOSED FRAMEWORK FOR ORGANIZATIONAL SELF-
ASSESSMENT

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Department of Mechanical Engineering

by
Julia Daniels
August 2022

Accepted by:
Dr. Cameron Turner, Committee Chair
Dr. John Wagner
Dr. Gregory Mocko

ABSTRACT

The ability to assess technical feasibility, project risk, technical readiness, and realistic performance expectations in early-phase conceptual design is a challenging mission-critical task for large procurement projects. At present, there is not a well-defined framework for evaluating current practices of organizations performing computational trade studies. One such organization is the US Army Ground Vehicle Systems Center (GVSC). When defining requirements and priorities for the next-generation autonomy-enabled ground vehicle system, GVSC is faced with the challenge of an increasingly complex programmatic tradespace due to emerging complexities of ground vehicle systems. This thesis aims to document and evaluate tradespace processes, methods, and tools within GVSC. A systematic review of the literature was conducted to investigate existing gaps, limitations, and potential growth opportunities related to tradespace activities reflecting the greater body of knowledge observed in the literature. Following this review, an interview-based study was developed through which a series of interviews with GVSC personnel was conducted and subsequently benchmarked against the baseline established in the literature. In addition to characterizing the current practices of tradespace exploration and analysis within GVSC, the analysis of the collected interview data revealed current capability gaps, areas of excellence, and potential avenues for improvement within GVSC. Through this thesis, other organizations can perform similar self-assessments to improve internal capabilities with respect to tradespace studies.

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CHAPTER 1:

INTRODUCTION

1.1 Motivation and Challenges

The tradespace is a multi-variant, highly interdependent computational playspace represented by the feasible design space of possible design alternatives given a set of enumerated design variables [52]. It is used to explore trade-offs and inform decisions, especially during early phases of complex system design.

A system tradespace is driven by a set of quality attributes, or realized non-functional requirements, collectively referred to as ‘ilities.’ These quality attributes or ‘ilities,’ such as flexibility, scalability, or robustness, represent key drivers of system performance, and therefore critically impact the overall success of a project. In early-phase conceptual system design, ‘ilities’ are rarely well-defined or easily evaluated in isolation [39], which presents significant challenges when capturing, modeling, and communicating tradespace data. Determining the optimal solution of this space—that is, tradespace optimization—presents a highly complex multi-objective optimization problem which spans multiple domains and disciplines.

The ability to assess technical feasibility, project risk, technical readiness, and realistic performance expectations during early conceptualization of a project is a challenging mission critical task for large procurement projects. Trade studies enable development of a feasible design problem early in the design process using models with varying levels of fidelity, uncertainty, and technical robustness.

At present, there is not a well-defined framework for assessing tradespace practices across organizations. One such organization is the US Army Ground Vehicle Systems Center (GVSC) when defining requirements and priorities for the next-generation autonomy-enabled ground

vehicle system—as the emerging complexities of future ground vehicle systems have brought even greater complexity to the programmatic tradespace.

1.2 Research Objectives

This thesis aims to document and evaluate tradespace processes, methods, and tools within the US Army Ground Vehicle Systems Center (GVSC) to support the virtual prototyping of the next generation of autonomy-enabled ground vehicle systems.

A systematic literature review was conducted to explore existing gaps, limitations, and potential growth opportunities related to tradespace activities. The scope of these selected publications spanned across industry, government, and academic institutions. Ultimately, this literature review had two underlying objectives:

- (1) Develop a comprehensive understanding of the tradespace with respect to complex system design
- (2) Provide insight into existing trade study practices across industry, government, and academia.

Beyond these concrete objectives, this thesis aims to effectively capture not only what the current practices are, but also what they should be.

Using a series of interviews conducted with personnel working within (or adjacent to) the Operational and Trade Analytics Branch of GVSC, this work then proceeds to use the baseline established from the literature to reveal avenues for improvement and areas of excellence within GVSC. Through this thesis, other organizations can perform similar self-assessments to improve their capabilities with respect to tradespace studies.

1.3 Structure of Thesis

This thesis is structured into five chapters. Chapter 1 serves as an introductory chapter that provides background and motivation, defines the research aims and objectives, and then outlines the structure of the thesis.

Chapters 2 and 3 showcase two previous publications of which the candidate is the primary author. Chapter 2 includes a journal article titled “Designing the Design Space: Evaluating Best Practices in Tradespace Exploration, Analysis, and Decision-Making” from the *SAE International Journal of Advances and Current Practices in Mobility* [84], while Chapter 3 includes a paper titled “Tradespace Organizational Practices: A Case Study” submitted for publication to the *ASME 2022 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference* [84]. These chapters are similarly structured with introductory and conclusory sections serving as wrappers for the respective papers. The introductory sections 2.1 and 3.1 provide opening remarks and establish context, while the conclusory sections 2.3 and 3.3 summarize the findings and reflect on the objectives, significance, and contributions of each respective work.

Chapter 4 then proceeds to build on Chapters 1-3 and provide a more holistic analysis of the research representing the combined efforts of the previous publications presented in Chapters 2-3. Additionally, this chapter provides a more general discussion of the findings, significance, and overarching contributions of the research.

Chapter 5 serves as the conclusory chapter to summarize key findings and provide final remarks relating to the research. This final chapter concludes the thesis by outlining next steps, future directions, and potential applications of future work.

CHAPTER 2:

DESIGNING THE DESIGN SPACE

2.1 Introduction

The following journal article, titled “Designing the Design Space: Evaluating Best Practices in Tradespace Exploration, Analysis, and Decision-Making,” discusses the systematic literature review performed in the preliminary stages of the research. It also offers reflections on the current landscape of tradespace-related research and emergent themes.

This paper was selected for publication in the *SAE International Journal of Advances and Current Practices in Mobility*. The candidate was the primary author of this manuscript. All other authors contributed their expertise and revised the manuscripts for technical content and final approval for publication.

2.2 Manuscript of ‘Designing the Design Space: Evaluating Best Practices in Tradespace Exploration, Analysis, and Decision-Making’

The remainder of this chapter comprises the following manuscript:

Daniels, J., Turner, C., Wagner, J., Masoudi, N. et al., 2022, “Designing the Design Space:

Evaluating Best Practices in Tradespace Exploration, Analysis and Decision-Making,”

SAE Int. J. Adv. & Curr. Prac. in Mobility, <https://doi.org/10.4271/2022-01-0354>.

DESIGNING THE DESIGN SPACE: EVALUATING BEST PRACTICES IN TRADESPACE EXPLORATION, ANALYSIS AND DECISION-MAKING

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2.2.1 Abstract

Determining the validity of the design space early in the conceptualization of a project can make the difference between project success and failure. Early assessment of technical feasibility, project risk, technical readiness and realistic performance expectations based on models with different levels of fidelity, uncertainty, and technical robustness is a challenging mission critical task for large procurement projects. Tradespace exploration uses model-based engineering analysis, design exploration methods, and multi-objective optimization techniques to enable project stakeholders to make informed decisions and tradeoffs concerning the scope, schedule, budget, performance, and risk profile of a project. As the intersection with a number of project stakeholders, tradespace studies can provide a significant impact upon the direction and decision-making in a project. Yet, the act of studying the tradespace is data intensive, subject to variability,

uncertainty complexity and ambiguity (VUCA). These properties of the data in the tradespace present challenges in both conducting tradespace studies but also in presenting the results of tradespace studies to a variety of stakeholders. In this work, data collected from the literature concerning tradespace exploration, analysis and decision-making practices is reviewed and analyzed to identify the best practices and common pitfalls experienced by organizations conducting tradespace studies. Using a series of interviews conducted with members of a tradespace study group, the authors then proceed to use these best-practices and common issues to evaluate the tradespace study group to reveal avenues for improvement and areas of excellence within that group. Through this thesis, other organizations can perform similar self-assessments to improve their capabilities with respect to tradespace studies.

2.2.2 Introduction

Efforts to study the tradespace are a common step in an engineering project. Typically, these tradespace studies occur in multiple steps within the design process. Early in the design process, tradespace studies can be used to assess and develop a feasible design problem. In this scenario, the focus of a tradespace study is to examine the state of component technologies and determine a feasible set of requirements thresholds that achieve performance objectives while minimizing technical risk. We refer to this as pre-architectural tradespace analysis. However, tradespace analysis can also be a tool used later in the design process once a solution architecture is selected. In this case, the focus of the tradespace analysis is to size the components in the architecture to achieve an optimal vehicle design. This second scenario is referred to as post-architectural tradespace analysis.

Regardless of the phase in the design process where tradespace analysis is applied, the underlying methodologies are quite similar, and thus the challenges and obstacles to achieving a usable tradespace study are also similar. This work focuses on a comprehensive review of tradespace practices in multiple organizations that were studied to reveal common themes for challenges and best practices identified across organizations. This study allows for the development of an organizational self-assessment that can aid in the identification of internal strengths, weaknesses, and opportunities for improvement within tradespace analysis groups.

2.2.3 Literature Review of Tradespace Practices

A systematic literature review was conducted with two underlying objectives: (1) develop a comprehensive understanding of the tradespace with respect to complex system design, and (2) provide insight into existing trade study practices across industry, government, and academia.

Beyond these concrete objectives, this review aims to effectively capture not only what the current practices *are*, but also what they *should be*. As such, existing gaps, limitations, and potential growth opportunities related to tradespace activities were explored.

An initial search across industry, federal, and academic institutions identified 80 papers discussing the tradespace or greater trade study process [1]-[80]. For the complete summary of selected publications from the literature, see Appendix A. These publications are categorized with respect to publication type (i.e., journal, thesis/dissertation, conference, or technical report), sector (i.e., industry, government, or academia), field of study, primary goal (e.g., case study, gap analysis, or tool development), and relevant keywords. This data is summarized in Figure 2.1 provides a visualization of the distribution of publication types by year of publication.

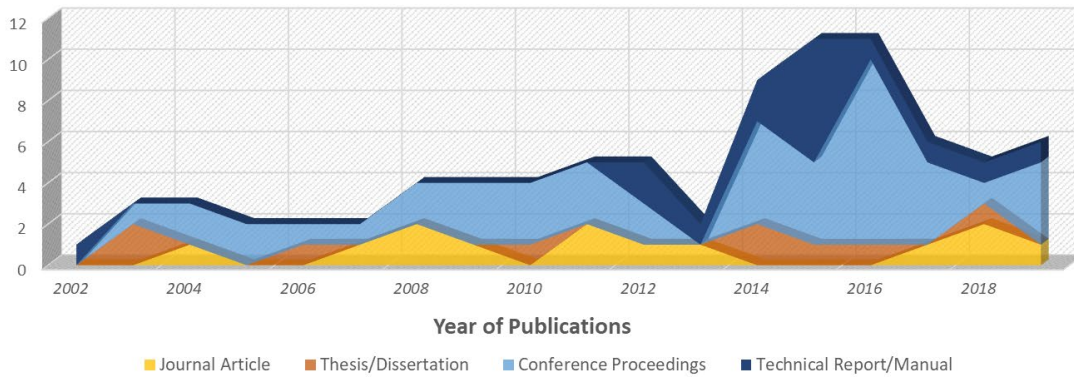


Figure 2.1: Distribution of surveyed publications by year and publication type

Following the initial literature search, an iterative thematic analysis approach was used to review the selected publications. After several iterations of annotations and meta tagging, distinct concepts, patterns, and themes emerged from the data. This content was then coded, arranged, and tabulated into an index of relevant keywords (or metatags). These metatags are listed in Table 2.1.

2.2.4 Emergent Themes

Data analysis and interpretation implemented both qualitative content analysis and thematic analysis approaches to reveal latent meaning and patterns within the data. A descriptive set of codes was inductively derived from the literature as an initial interpretation or “first impression” of the data. Iterative code clustering and comparison allowed further refinement and organization of emergent codes into more abstract themes and categories. Ultimately, this coding process is a qualitative data reduction technique used to transform raw data into a concise yet insightful story.

The following five emergent themes, shown in Figure 2.2, are informed by the literature: (1) System Modeling and Analysis, (2) Optimization and Decision Strategies, (3) Dataflow Architecture, (4) Software and Support Tools, and (5) Workplace Culture.

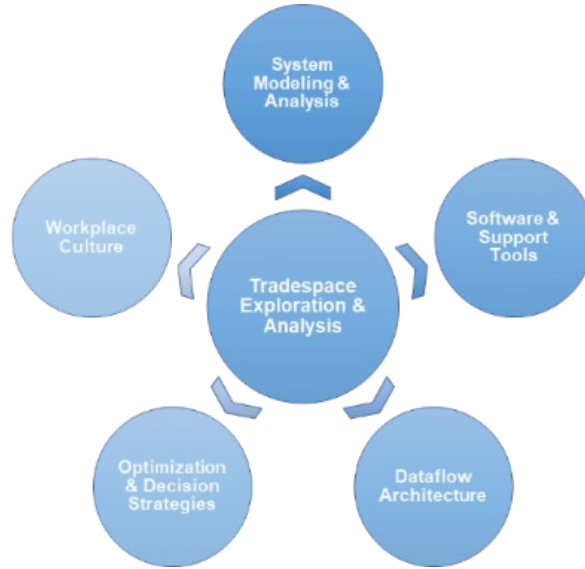


Figure 2.2: Five emergent themes of tradespace exploration, analysis, and decision-making

A thematic analysis was used to organize and structure the results of the literature review. The insights gained were critically analyzed and aggregated. The resulting hierarchy of themes and concepts review serve as a conceptual framework of the literature review.

Table 2.1: Metatags used to code the surveyed publications with frequency of occurrence

Unique Keywords	Hits
Tradespace Exploration (TSE)	19
Uncertainty	17
Tradespace Visualization	13
Model-Based Systems Engineering (MBSE)	11
Multi-Attribute Tradespace Exploration (MATE)	11
System Attributes	11
Engineered Resilient System (ERS)	10
Multi-Attribute Utility Theory (MAUT)	9
Multi-Criteria Decision Analysis (MCDA)	7
Robustness	7
Set-Based Design (SBD)	7
Decision Analysis	6
Pareto Frontier	6
Sensitivity Analysis	6
Value-Driven Design (VDD)	6
Cognitive Bias	5

Decision Making	5
Epoch-Era Analysis (EEA)	5
Interoperability	5
Flexibility	4
Risk Assessment	4
Tool Integration	4
Traceability	4
User Interface	4
Analysis of Alternatives	3
Capability Maturity Model Integration (CMMI)	3
Cost-Benefit Analysis (CBA)	3
Design of Experiments (DoE)	3
Interactive Data Visualization	3
Modeling and Simulation (M&S)	3
Multi-Attribute Tradespace Exploration with Concurrent Design (MATE-CON)	3
Quality Function Deployment (QFD)	3
Stakeholder Analysis	3
Standards & Policies	3
Subject Matter Experts (SME)	3
<i>Bayesian Networks, INCOSE Decision Management Process, Monte Carlo Simulation (MCS), Multidisciplinary Design Optimization (MDO), Multi-objective Design Optimization (MODO), Stakeholder Communication, Whole System Trades Analysis Tool (WSTAT)</i>	2
<i>Capabilities-Based Planning (CBP), Collaborative Systems, Decision Support Tools, Distributed Decision Support, DMA, Enterprise Interoperability, ERS Cloud Computing Architecture (ECCA), Evaluation Criteria, Evolutionary Algorithms, JMP, Knowledge Base, Mission Tradespace Tool (MTT), Model Trading, Multidimensional Data Visualization, Multidisciplinary MBSD Environment, SAI Method, Sequential Design Process (SDP), Siemens NX HD3D Visual Reporting, Software Architecture, SoSTEM, Stakeholder Involvement, Standards, Surrogate Model-based Method, Tradeoff Index, TradeStudio Analytic Tools, TRIZ Framework, Utility Theory, Value Models</i>	1

Theme #1: System Modeling and Analysis

The first theme that emerged from the review was an emphasis on System Modeling and Analysis. This theme encompasses a number of modeling approaches as described in Table 2.2, ranging from limited fidelity descriptive models to probabilistic simulations.

Table 2.2: Organization of codes for Theme 1: System Modeling & Analysis

	CATEGORY	CODE
Theme #1: System Modeling & Analysis	1.1 Defining the Tradespace	
		<i>1.1-1 Tradespace Exploration (TSE)</i>
		<i>1.1-2 Tradespace Analysis</i>
		<i>1.1-3 Conceptual Distinction(s)</i>
		<i>1.1-4 Challenges of Trade Studies</i>
		<i>1.1-5 Recommended Practices for Trade Studies</i>
	1.2 Model-Based Systems	
	Engineering (MBSE)	<i>1.2-1 Cost Modeling</i>
		<i>1.2-2 Performance Modeling</i>
		<i>1.2-3 Value Model Trading</i>
	1.3 Deterministic Analysis	
	Methods	<i>1.3-1 Value-Focused Thinking (VFT)</i>
		<i>1.3-2 Capabilities Based Assessment</i>
	1.4 Probabilistic Analysis & Stochastic Modeling	
		<i>1.4-1 Design of Experiments (DOE)</i>
		<i>1.4-2 Exploratory Data Analysis (EDA)</i>
		<i>1.4-3 Uncertainty Characterization</i>
		<i>1.4-4 Sensitivity Analysis</i>
		<i>1.4-5 Risk Assessment</i>

Theme #2: Optimization and Decision Strategies

The second theme that emerged, described with Table 2.3, involves the incorporation of optimization and decision-making strategies.

Both formal mathematical programming and decision-making strategies are often employed, alongside Machine Learning and Evolutionary Computational approaches. The integration of these different approaches is not surprising given the size of the available datasets underlying tradespace exploration.

Table 2.3: Organization of codes for Theme 2: Optimization & Decision Strategies

	CATEGORY	CODE
Theme #2: Optimization & Decision Strategies	2.1 Logic-Based Models	
	2.2 Machine Learning/Data Minin	
		2.2-1 <i>Reinforcement Learning</i>
		2.2-2 <i>Artificial Neural Networks</i>
	2.3 Evolutionary Computation	
	2.4 Mathematical Programming	
	2.5 Evaluation Criteria	
		2.5-1 <i>Threshold Values</i>
		2.5-2 <i>Weighting Factors</i>
		2.5-3 <i>Normalization Scale</i>
		2.5-4 <i>Ranking</i>
		2.5-5 <i>Scoring</i>
	2.6 Decision Strategies	
		2.6-1 <i>Decision Analysis Methods</i>
		2.6-2 <i>Decision Mapping</i>
		2.6-3 <i>Predictive Analytics & Decision Modeling</i>
		2.6-4 <i>Decision Automation</i>

Theme #3: Dataflow Architecture

Table 2.4 describes the components of the third theme recognized in the literature survey, namely a concern for the management of the data within the tradespace analysis study.

Table 2.4: Organization of codes for Theme 3: Dataflow Architecture

Theme #3: Dataflow Architecture	CATEGORY	CODE
	3.1 Data Collection, Handling, & Management Plan	<i>3.1-1 Data Availability</i>
		<i>3.1-2 Data Interoperability</i>
		<i>3.1-3 Data Reliability</i>
		<i>3.1-4 Data Retrievability</i>
	3.2 Computational Methods	
	3.3 Tradespace Visualization	
		<i>3.3-1 Feasible Criterion & Decision Spaces</i>
		<i>3.3-2 Graphical Techniques</i>
		<i>3.3-3 Data Clustering Algorithms</i>
		<i>3.3-4 Network Layout Visualization</i>
		<i>3.3-5 Pareto-Optimal Solution Set</i>

The amount of data now available for tradespace analysis has risen dramatically in recent decades. Many organizations are facing challenges with the curation of the available datasets, models, and analysis records, as well as with the processing of such datasets to identify points of interest in the multi-dimensional tradespace such as pareto points, and the existence of and impacts resulting from hidden relationships between variables.

Theme #4: Software and Support Tools

Supporting the need for managing the dataflow of a tradespace analysis study is a suite of software packages. Software considerations are organized into a number of categories as shown in Table 2.5. These categories support a number of features necessary during the process of executing a tradespace study.

The system design and tradespace exploration tool presently implemented by the US Army Ground Vehicle Systems Center (GVSC) is the Whole System Trades Analysis Tool (WSTAT), which finds the optimal system configuration with respect to performance, cost, and risk using

multi-objective optimization [27]. This software is accompanied with ARIES, a decision support tool also developed by Sandia National Laboratory.

An additional tool currently under development through the US Army Engineer Research & Development Center (ERDC) is TradeStudio, an Engineering Resilient Systems (ERS) tool suite. This tool is developed with an emphasis on recursive workflow and the generalization of common tasks for conducting trade studies. At the time writing, this tool has been published under its fourth version, and the TradeAnalyzer v4.0 User Guide was included in the literature search for comparison to with the tools currently implemented by GVSC.

Other, more publicly available software tools are also widely implemented in trade studies conducted across industry and federally funded research. JMP, a visual statistical software tool is implemented in data analysis activities within several of the publications included in the initial literature survey, including the US Army Research Laboratory (ARL) [69], as well as decision support in studies involving ERS Architecture conducted by the Operations Research Center at the United States Military Academy and the Naval Postgraduate School.

Table 2.5: Organization of codes for Theme 4: Software & Support Tools

Theme #4: Software & Support Tools	CATEGORY	CODE
	4.1 Database Management System (DBMS)	<i>4.1-1 Data Collection</i> <i>4.1-2 Data Storage</i> <i>4.1-3 Data Transfer</i>
	4.2 Tradespace Exploration Tools	
	4.3 Tradespace Analysis Tools	
	4.4 SysML Tools	
	4.5 Post-Processing Features	<i>4.5-1 Visualization</i> <i>4.5-2 Reporting</i> <i>4.5-3 Decision Support</i>
	4.6 Limitations of Existing Tools	
	4.7 Advantages of Existing Tools	
	4.8 Software Evaluation Criteria	<i>4.8-1 Key Features</i> <i>4.8-2 Process & Tool Integration</i> <i>4.8-3 Operating System/Platform</i> <i>4.8-4 User Interface</i> <i>4.8-5 License Type</i> <i>4.8-6 Developer</i> <i>4.8-7 Supported File Formats</i> <i>4.8-8 Supported Programming Languages</i> <i>4.8-9 Technical Support & Maintenance</i>

Theme #5: Workplace Culture

The final theme identified relates to the Workplace Culture of the group responsible for tradespace analysis studies. Considerations with respect to the workplace culture are described in Table 2.6.

Like many organizations, workplace culture plays a role in the emergence of best-practices (and performance gaps) within tradespace groups. These issues can be further studied using semi-structured subject interviews.

Table 2.6: Organization of codes for Theme 5: Workplace Culture

	CATEGORY	CODE
Theme #5: Workplace Culture	5.1 Organizational Structure & Member Identify	<i>5.1-1 Roles & Responsibilities</i> <i>5.1-2 Professional Background</i> <i>5.1-3 Stakeholder Analysis & Management</i> <i>5.1-4 Project Workflow</i> <i>5.1-5 Subject Matter Experts (SMEs)</i> <i>5.1-6 Performance Orientation</i> <i>5.1-7 Project Timeline/Speed of Delivery</i>
	5.2 Communication Strategies	<i>5.2-1 Communication Channels & Tools</i> <i>5.2-2 Interpersonal Relationships & Trust</i> <i>5.2-3 Interdepartmental Collaboration</i>
	5.3 Change Control Systems	<i>5.3-1 Open-System Focus</i> <i>5.3-2 Project Documentation</i> <i>5.3-3 Feedback & Reporting</i>
	5.4 Standards & Procedures	<i>5.4-1 External Codes & Standards</i> <i>5.4-2 Internal Policies and Procedures</i> <i>5.4-3 Controlled Vocabulary</i> <i>5.4-4 Education & Training Programs</i>
	5.5 Strategic Assessment	<i>5.5-1 Current Gaps Relating To Workplace Culture</i> <i>5.5-2 Recommendations for Workplace Culture</i>

2.2.5 Summary of Best-Practices from the Literature

In addition to the five major themes identified as being common to tradespace study groups, several common best practices were identified from the literature survey. These best practices include:

- Use of Multi-Attribute Tradespace Exploration (MATE) techniques
- Structure an initial study activity for problem definition that involves all stakeholders

- Identify stakeholders early and arrange for participation at important stages (e.g., defining problem, constructing hierarchy, scoring alternatives)
- Involve subject matter experts (SMEs) and consider having a scoring review group
- Identify constraints early and keep separate from objectives
- Avoid reliance on easy to measure proxies and focus on one direct measure for each objective
 - Homogenized tradeoff index
 - Using an additive model when measures are not preferentially independent
 - Use multi-dimensional value measures to model dependencies when appropriate
 - Focus on clearly structuring levels and defining all objectives. Use 3-6 logically ordered objectives on the top layer
 - Focus on measures that will discriminate among alternatives; review model output to validate
 - Structure weight assessment using swing weight matrix or balance beam techniques
- Variable forms for input variables
 - Understand and review independence assumptions carefully
 - Assess upper, nominal, and lower bound measure response
- Incomplete use of probabilities as value measures
 - Use a decision tree to model probabilities that have outcomes with zero value

- Monte Carlo Simulation
- Consider emergent effects on the performance of the SoS during the evolutionary process
- Perform sensitivity analysis and assess the implications on your recommendation and further analysis. Avoid incomplete sensitivity analysis
- Continually search for better alternatives
 - TRIZ Trade Study Framework
 - Improve alternatives (feedback loop)
- Multiple Objective Decision Analysis (MODA)
 - Value-Focused Thinking (VFT)
 - Multi-Attribute Utility (MAU) Theory
 - Analytic Hierarchy Process (AHP)
 - Cost-Benefit Analysis (CBA)
 - Portfolio Theory

Because a tradespace study focuses on tradeoffs between multiple objectives (or attributes) techniques that consider multiple attributes are important [43],[41]. In addition, the complexity of the problem makes it very important to appropriately define the problem. A key aspect of this is to ensure that stakeholders in the project are identified early in the project and that their participation is incorporated throughout the project. Similarly, the involvement of Subject Matter Experts (SMEs) is important in determining viable representations of the design space [19],[67].

Defining the variables and objectives that comprise the mathematical foundation of the tradespace is also an important best-practice. While it is tempting to incorporate constraints into the objectives, this tends to be a poor practice. Instead, as is commonly done in optimization, it is

better to define the constraints independently from the objectives [43]. The preferred formulation for the objectives would be to define objectives that directly measure the desired properties of the system. These objectives should be homogenized so that they have comparable value ranges which enables multiple metrics to be additively combined in a meaningful manner [19]. When necessary, multi-dimensional metrics are appropriate, particularly when there are dependences inherent in the objectives. The goal is ultimately to develop a hierarchy of objectives that represent 3-6 top level objectives where weightings can be established. Perhaps most important is that the selected objectives should help discriminate between concepts and technologies [19],[67]. Objectives that do not facilitate meaningful decision-making are not particularly useful in the tradespace study process.

The variables used to define the tradespace are also important to consider. Careful consideration of the independence of variables should be practiced, and upper-, lower- and nominal-variable bounds should be determined. For some variables, their probabilistic nature should be incorporated into their formulation. [67] Decision Trees and Monte Carlo Simulations are primary tools that should be used to deal with probabilistic terms in the tradespace. As a result of the complex, multi-layered nature of tradespace simulations, emergent behaviors of System of System models are to be expected. Best practice is to ensure that emergent behaviors are expected and accounted for in modeling.

The results of a tradespace analysis should include a sensitivity analysis component to aid in the identification of correlations (both positive and negative) between variables and objectives in the study [67]. This type of information is particularly valuable for continuous improvement efforts. A tradespace study is rarely complete as new technologies and information are continually

emerging. Instead, a tradespace study is a snapshot in time. This continuous improvement via feedback and the use of generalized techniques such as TRIZ are recommended.

Ultimately, the goal of tradespace studies is to provide a robust, repeatable and defensible basis for decision-making. Use of techniques affiliates with Multiple Objective Decision Making (MODA) such as Value Focused Thinking (VFT), Multi-Attribute Utility Theory (MAU), Analytic Hierarchy Process (AHB) Theory, Cost-Benefit Analysis (CBA), and Portfolio Theory are widely utilized by different organizations. Best practices from practicing organizations are to adopt a set of consistent, compatible theories upon which to base the decision-making process.

2.2.6 Conclusions and Future Work

With the literature review defining a set of five themes and ten best practices, the next task for this project is to develop an assessment usable by a generic organization by which these themes and best practices can be identified and any gaps established.

The proposed tool for this is a semi-structured interview approach. This method was selected to guide the flow of the discussion while still allowing the participant the freedom to go into more detail or stray the conversation to other areas where they saw fit. The interview prompts shown in Table 2.7 represents the general structure each interview. As shown, the outlined objectives of the interviews sought to understand each participant's:

- (1) role or involvement in trade studies
- (2) perspectives on tradespace exploration and tradespace analysis
- (3) experiences and perceptions specific to trade study work within the organization
- (4) provide insight into the selection and communication of key attributes characterizing the tradespace

- (5) each participant's recommended practices, current gaps, and desired state of tradespace activities in their organization.

Table 2.7: Interview prompts used for interviews with GVSC personnel

No.	Interview Question	General Rationale
1	How long have you worked with this organization?	<i>Understand the participant's involvement with tradespace exploration and analysis in their organization</i>
2	What is your role? How do you execute this role?	
3	What is the overarching objective of a trade study?	<i>Understand the participant's perspective of tradespace exploration and analysis</i>
4	What is the typical process for performing a trade study?	
5	How, if at all, do you distinguish between tradespace exploration and tradespace analysis?	
6	Who is involved in executing trade studies in your organization?	<i>Understand participant's perception of work done by the organization</i>
7	What is typically needed before initiating a trade study?	
8	What tools are currently used when performing trade studies?	
9	What, if any, are challenges and capability gaps associated with these tools?	
10	What training did you receive for the tools?	
11	Typically, what is the result or deliverable of a trade study?	
12	How do the scopes of trade studies vary? Do all trade studies attempt to answer the same questions? What questions are being asked/answered?	
13	How else do trade studies vary? How would you classify these different 'types' of trade studies? How do these differences influence your approach?	
14	How many trade study requests are typically submitted to the organization per year?	<i>Provide insight on participant's perspective of how threshold values and priorities are established and communicated</i>
15	What steps are taken to establish threshold values in the trade study?	
16	How are these threshold values communicated to customers?	
17	What steps are taken by your organization to establish priorities?	
18	How are these priorities communicated to customers?	<i>Provides insight on into desired practices for tradespace exploration and analysis</i>
19	What would make information gathering for trade studies more effective?	

The next task is to conduct these interviews with GVSC personnel and to develop a robust coding procedure for the interviews that enables an assessment of the tradespace practices and gaps within an organization. Using this information, process and group improvement opportunities can be identified.

2.2.7 Acknowledgments

This work was supported by the Virtual Prototyping Ground Systems (VIPR-GS) Center at Clemson University and the Automotive Research Center (ARC), a US Army Center of Excellence for modeling and simulation of ground vehicles, under Cooperative Agreement W56HZV-19-2-0001 with the US Army DEVCOM Ground Vehicle Systems Center (GVSC). All opinions, conclusions and findings wherein are those of the authors and may not be those of the affiliated institutions. Distribution A. Approved for public release; distribution unlimited. (OPSEC 6706).

2.3 Concluding Remarks

This work seeks to perform a comprehensive literature review of tradespace practices across a variety of organizations observed in the literature. In this thesis, data collected from the literature is reviewed and analyzed with respect to the tradespace or greater trade study process. This literature review supports a foundational understanding of the tradespace in the context of complex system design with respect to implemented tools, processes, and methods.

The aim of this thesis is to provide insight into existing trade study practices across industry, government, and academia—ultimately, this thesis outlines two objectives of the research to ensure this underlying goal is realized. The first of these objectives is to identify emergent themes related to the tradespace. Five emergent themes were revealed through thematic analysis of the literature, including: (1) System Modeling & Analysis, (2) Optimization & Decision Strategies, (3) Dataflow Architecture, (4) Software & Support Tools, as well as (5) Workplace Culture

These themes served as the foundation from which an inductive coding process was implemented to capture common patterns, relationships, and trends across the data collected from the literature. Through this qualitative content analysis approach, a general code framework was developed to serve as a structured representation of the literature. This developed coding scheme provided a common ground through which to organize data collected across different organizations, industries, and disciplines observed in the literature.

The secondary objective of this thesis is to characterize the existing tradespace tools, processes, and methods observed across the literature—in particular, the thesis sought to capture the best practices and common pitfalls experienced by organizations spanning a broad range of industries and disciplines. The intention was to not only provide explicit documentation of various

tools, processes, and methods, but to also capture insights such as current challenges, common pitfalls, or future development strategies reported in the literature.

This work contributes to the greater body of research by capturing the current landscape of tradespace literature, specifically in the context of existing tools, processes, and methods. The findings of this thesis establish a framework of qualitative codes to describe an organizational trade study process. These codes were developed to organize and structure the collection of data as well as to provide insights into the general trade study process irrespective of the specific organization under consideration.

CHAPTER 3:

TRADESPACE ORGANIZATIONAL PRACTICES

3.1 Introduction

The following conference paper, titled “Tradespace Organizational Practices: A Case Study,” investigates the developed thematic codes through a qualitative case study on GVSC. These findings were then used to develop a set of best practices and recommendations for tradespace exploration, analysis, and decision-making strategies. This section goes on to identify five (5) capability gaps reflecting current practices of GVSC and the greater literature.

This work has been submitted to the *ASME 2022 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (IDETC/CIE 2022)* and is awaiting publication. The candidate was the primary author of this manuscript. All other authors contributed their expertise and revised the manuscripts for technical content and final approval for publication.

3.2 Manuscript of ‘Tradespace Organizational Practices: A Case Study’

The remainder of this chapter comprises the following manuscript:

Daniels, J., Wagner, J., Turner, C., Gorsich, D. et al., 2022 "Tradespace Organizational Practices: A Case Study," *Proc. of the ASME 2022 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, St. Louis, Missouri, USA, August 14–17, 2022.

TRADESPACE ORGANIZATIONAL PRACTICES: A CASE STUDY

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3.2.1 Abstract

Tradespace analysis capabilities are critical for organizations either selecting large programmatic efforts or those engaged in providing solutions to major program opportunities. The ability of an organization to effectively use the tradespace in their decision-making process had a substantial impact upon programmatic success. Poorly bounded tradespaces may lead to prototype vehicles (or any other system to be designed) that are ultimately unacceptable due to performance, cost, or technical risk issues. Tradespaces that are over-constrained can unduly limit design options and lead to stagnant designs that are unable to incorporate technical innovations. Most organizations find that tradespace analysis presents numerous challenges, so this research aims to

address the evaluation of strengths, weaknesses, and opportunities for improvement within an organization. In this study, we explain how an interview-based process was used to perform this analysis and make recommendations for opportunities for process improvement within an organization (Ground Vehicle Systems Center or GVSC). Similar approaches could be applied to other organizations to facilitate the development of an organizational self-assessment that can aid in the identification of internal strengths, weaknesses, and opportunities for improvement within organizations performing tradespace activities.

3.2.2 Introduction

Challenge of the Tradespace

Tradespace is a representation of the feasible design space of solutions to a design problem. The tradespace is bounded by the respective objective and threshold requirement levels. System Attributes characterize the tradespace and inform trade decisions. Early in the design process, tradespace studies can be used to assess and develop a feasible design problem. These attributes can be assessed and balanced with respect to performance, cost, and risk.

This space is often viewed in the objective space, where the axes of the space are defined by the Functional Objectives (or Performance Metrics) of the vehicle. The insight of Subject Matter Experts (SMEs) is commonly used to then make trades within the tradespace.

At present, there is not a well-defined framework for assessing tradespace practices across organizations. One such organization is the US Army Ground Vehicle Systems Center (GVSC). One of the roles of the GVSC is to assist the Army in defining the requirements and priorities for future ground vehicle programs. The emerging complexities of future ground vehicle systems,

which include relatively new technologies related to autonomy and electrification, have brought even greater complexity to the programmatic tradespace.

This study allows for the development of an organizational self-assessment that can aid in the identification of internal strengths, weaknesses, and opportunities for improvement within tradespace analysis groups.

Aims and Objectives

Trades effectively modify the requirements that bound the feasibility of the tradespace, and lead to a set of prioritized target requirement values that represent a satisfactory vehicle programmatic plan. These plans form the basis for a request for prototype vehicles from military contractors.

The aims and objectives of the research include the following:

- Understand the current practices of tradespace exploration and analysis across industry, government, and academia.
- Gain direct insight into trade study practices, methods, and tools implemented by GVSC.
- Establish areas of excellence and identify capability gaps, limitations, and needs regarding current tradespace practices at GVSC.

Research Plan

The project began with a benchmarking study of the area, covering industry, government, and academic aspects of tradespace studies. This review is discussed in Section 2.

Following this study, an interview study was designed to solicit information relevant to the findings from the benchmarking study for the GVSC. Targeted in this study were personnel within or adjacent to the Operational and Trade Analytics Branch. The goal of the interview process was to solicit information to identify current gaps and limitations in GVSC tradespace analysis capabilities.

Using the data collected, a set of best practices and recommendations for tradespace exploration, analysis, and decision-making strategies to enable gap-spanning solutions was developed. The interview and data analysis process could be applied to any organization seeking to improve their tradespace capabilities.

3.2.3 Best-Practice Benchmarking

Literature Survey

A systematic literature review was conducted in [84] with two underlying objectives: (1) develop a comprehensive understanding of the tradespace with respect to complex system design, and (2) provide insight into existing trade study practices across industry, government, and academia.

Beyond these concrete objectives, this review aims to effectively capture not only what the current practices are, but also what they should be. As such, existing gaps, limitations, and potential growth opportunities related to tradespace activities were explored.

Following an initial search across industry, federal, and academic institutions we have identified eighty [80] papers discussing the tradespace or greater trade study process [84]. These publications are categorized with respect to the publication type (i.e., journal, thesis/dissertation, conference, or technical report), sector (i.e., industry, government, or academia), field of study,

primary goal (e.g., case study, gap analysis, or tool development), and relevant keywords. This data is reported and discussed in [85]. The publications are selected based on their use of tradespace analysis tools and methods in different stages of the design and decision-making processes.

Developed Code Scheme

Following the initial literature search, an iterative thematic analysis approach was used to review the selected publications. After several iterations of annotations and meta tagging, distinct concepts, patterns, and themes emerged from the data. This content was then coded, arranged, and tabulated into an index of relevant keywords (or metatags) as listed in Table 2.2–Table 2.6.

Data analysis and interpretation implemented both qualitative content analysis and thematic analysis approaches to reveal latent meaning and patterns within the data. A descriptive set of codes was inductively derived from the literature as an initial interpretation or “first impression” of the data. Iterative code clustering and comparison allowed further refinement and organization of emergent codes into more abstract themes and categories. This coding process is a qualitative data reduction technique used to transform raw data into a concise yet insightful story.

Five emergent themes were identified from the literature and are shown in Figure 2.2. These emergent themes were identified through thematic content mapping of the literature and include: (1) System Modeling and Analysis, (2) Optimization and Decision Strategies, (3) Dataflow Architecture, (4) Software and Support Tools, and (5) Workplace Culture.

Emergent Themes

System Modeling and Analysis (Theme 1)

The first theme that emerged from the review was an emphasis on System Modeling and Analysis. This theme encompasses several modeling approaches as described in Table 2.2, ranging from limited fidelity descriptive models to probabilistic simulations.

Optimization and Decision Strategies (Theme 2)

The second theme that emerged, described with Table 2.3 involves the incorporation of optimization and decision-making strategies.

Both formal mathematical programming and decision-making strategies are often employed, alongside Machine Learning and Evolutionary Computational approaches. The integration of these different approaches is not surprising given the size of the available datasets underlying tradespace exploration.

Dataflow Architecture (Theme 3)

Table 2.4 describes the components of the third theme recognized in the literature survey, namely a concern for the management of the data within the tradespace analysis study.

Software and Support Tools (Theme 4)

Supporting the need for managing the dataflow of a tradespace analysis study is a suite of software packages. Software considerations are organized into several categories as shown in Table 2.5. These categories support a number of features necessary during the process of executing a tradespace study.

The system design and tradespace exploration tool presently implemented by GVSC is the Whole System Trades Analysis Tool (WSTAT), which finds the optimal system configuration with respect to performance, cost, and risk using multi-objective optimization [27]. This software is accompanied with ARIES, a decision support tool also developed by Sandia National Laboratory.

An additional tool currently under development through the US Army Engineer Research & Development Center (ERDC) is TradeStudio, an Engineering Resilient Systems (ERS) tool suite. This tool is developed with an emphasis on recursive workflow and the generalization of common tasks for conducting trade studies. At the time writing, this tool has been published under its fourth version, and the TradeAnalyzer v4.0 User Guide was included in the literature search for comparison with the tools currently implemented by GVSC [40].

Other, more publicly available, software tools are also widely implemented in trade studies conducted across industry and federally funded research. JMP, a visual statistical software tool is implemented in data analysis activities within several of the publications included in the initial literature survey, including the US Army Research Laboratory (ARL) [69], as well as decision support in studies involving ERS Architecture conducted by the Operations Research Center at the United States Military Academy and the Naval Postgraduate School [33]. Further discussion on the purpose of decision making in tradespace studies can be found in [82],[83] where set-based design approaches are applied to the problem.

Workplace Culture (Theme 5)

The final theme identified relates to the Workplace Culture of the group responsible for tradespace analysis studies. Considerations with respect to the workplace culture are described in

Table 2.6. Like many organizations, workplace culture plays a role in the emergence of the best-practices (and performance gaps) within tradespace groups.

3.2.4 Methodology

Purpose of the Interview Study

This study implemented an interview style of qualitative research to facilitate direct contact with individuals involved in tradespace activities performed within GVSC. The interview study served as a technique to extract localized knowledge of GVSC personnel and characterize the organization-wide knowledge base. A secondary objective of the study was to obtain personal experiences of individual participants when relevant to the discussion.

The goal of this rating activity was to identify and extract responses within the interview transcripts that either (1) explicitly reflect current trade study practices at GVSC or (2) provide meaningful insight into tradespace activities and visualizations as relevant to the literature survey explained in [84].

Study Plan and Interview Design

Seven interviews were conducted with the personnel at GVSC working with (or in some cases, adjacent to) the Operational and Trade Space Analytics Branch between December of 2020 and January of 2021. The transcripts of these interview responses were then systematically categorized according to the established code frame and emergent themes in the literature.

A semi-structured interview approach was used in order to guide the flow of the discussion while still allowing each participant the freedom to go into more detail or stray the conversation to other

areas where they saw fit. The interview prompts shown in Table 2.7 represent the general structure of each interview.

As shown, the outlined objectives of the interviews sought to understand each participant's:

- Role or involvement in trade studies conducted by GVSC
- Perspectives on tradespace exploration and analysis
- Experiences and perceptions specific to trade study work within GVSC

as well as:

- Provide insight into the selection and communication of key attributes characterizing the tradespace
- Each participant's recommended practices, current gaps, and desired state of GVSC tradespace activities.

Conducting the Interviews

Each interview transcript was coded using a line-by-line process in responses that could be explicitly referenced. All potentially identifying information was redacted from the transcripts.

Interview Data Coding

During the coding process, preference was given to splitting data segments into smaller, more specific instances rather than lumping segments of data into broader codes. This preference was intended to help prevent the loss of contextual subtleties of participant responses and encourage more nuanced interpretations of the data.

Thematic analysis was performed using an exploratory or bottom-up approach to data collection and analysis. This included an inductive or open coding process to enable data-driven

exploration of the data and avoidance of unnecessary limitations or bounds on the findings and instead allow new themes to emerge. This systematic yet flexible approach served as a data reduction and normalization technique to classify and capture important aspects of the data while avoiding preconceived notions or bias.

Interrater Reliability

To establish the reliability of the developed coding scheme and reduce the risk of bias, the percent agreement between two coders were calculated for the first two interviews. The interrater reliability determined by calculating Cohen's Kappa κ defined in Equation (1).

$$\kappa = \frac{p_o - p_e}{1 - p_e} \quad (1)$$

where p_o and p_e are the observed and chance agreements, respectively. The contingency matrices and calculated inter-rater reliability indices for interviews with participant aliases *Taylor* and *Sam* are shown in Table 3.1 and Table 3.2, respectively.

Table 3.1: Rater agreement contingency matrices for the two-sample interview test

		<u>Rater A: n (%)</u>					
Rater B: n (%)	<i>(1) Present</i>			<i>(0) Absent</i>		<i>Total</i>	
	<i>(1) Present</i>	n ₁₁	p ₁₁	n ₁₂	p ₁₂	n ₁₊	p ₁₊
	<i>(0) Absent</i>	n ₂₁	p ₂₁	n ₂₂	p ₂₂	n ₂₊	p ₂₊
	<i>Total</i>	n ₊₁	p ₊₁	n ₊₂	p ₊₂	N	
Interview 1: Taylor							
<i>(1) Present</i>	40	(0.7547)	2	(0.0377)	42	(0.7925)	
<i>(0) Absent</i>	11	(0.2075)	0	(0)	11	(0.2075)	
<i>Total</i>	51	(0.9623)	2	(0.0377)	53		
Interview 2: Sam							
<i>(1) Present</i>	34	(0.6296)	8	(0.1481)	42	(0.7778)	
<i>(0) Absent</i>	12	(0.2222)	0	(0)	12	(0.2222)	
<i>Total</i>	46	(0.8519)	8	(0.1481)	54		
Normalized							
<i>(1) Present</i>	74	(0.6916)	10	(0.0935)	84	(0.7850)	
<i>(0) Absent</i>	23	(0.2150)	0	(0)	23	(0.2150)	
<i>Total</i>	97	(0.9065)	10	(0.0935)	107		

Table 3.2: Inter-rater reliability indices for the two-sample interview test

Interview ID	Level of Agreement (%)		Cohen's κ Coeff.	Interpretation
	<i>Observed, P_o</i>	<i>Expected, P_e</i>		
Taylor	0.7547	0.0323	0.7465	Substantial
Sam	0.6296	0.0333	0.6173	Substantial
Normalized	0.6916	0.0164	0.6810	Substantial

The Kappa coefficient calculates an adjusted level of agreement with respect to chance. The multivariate categorical data analysis methodology proposed by Landis and Koch [81] characterizes the strength of agreement with respect to this calculated Kappa statistic according to Table 3.3. As demonstrated in Table 3.2, the normalized Kappa statistic calculated for a set of interviews reviewed by two different raters indicate substantial reliability and thus supports the validity of the developed framework.

Table 3.3: Kappa statistic ranges and interpretations proposed by Landis and Koch [81]

Kappa Value	Interpretation
<0.00	Poor Agreement
0.00-0.20	Slight Agreement
0.21-0.40	Fair Agreement
0.41-0.60	Moderate Agreement
0.61-0.80	Substantial Agreement
0.81-1.00	Almost Perfect Agreement

3.2.5 Results

Keyword Analysis

This developed code frame was then used to analyze the data collected across all seven interviews. Appendix B provides a full summary of the codes assigned with respect to frequency. These clusters are highlighted in Figure 3.1 to Figure 3.5. As shown, above all else, topics concerning Communications Channels and Tools within Theme 5 (Workplace Culture) were perpetually relevant when discussing tradespace activities.

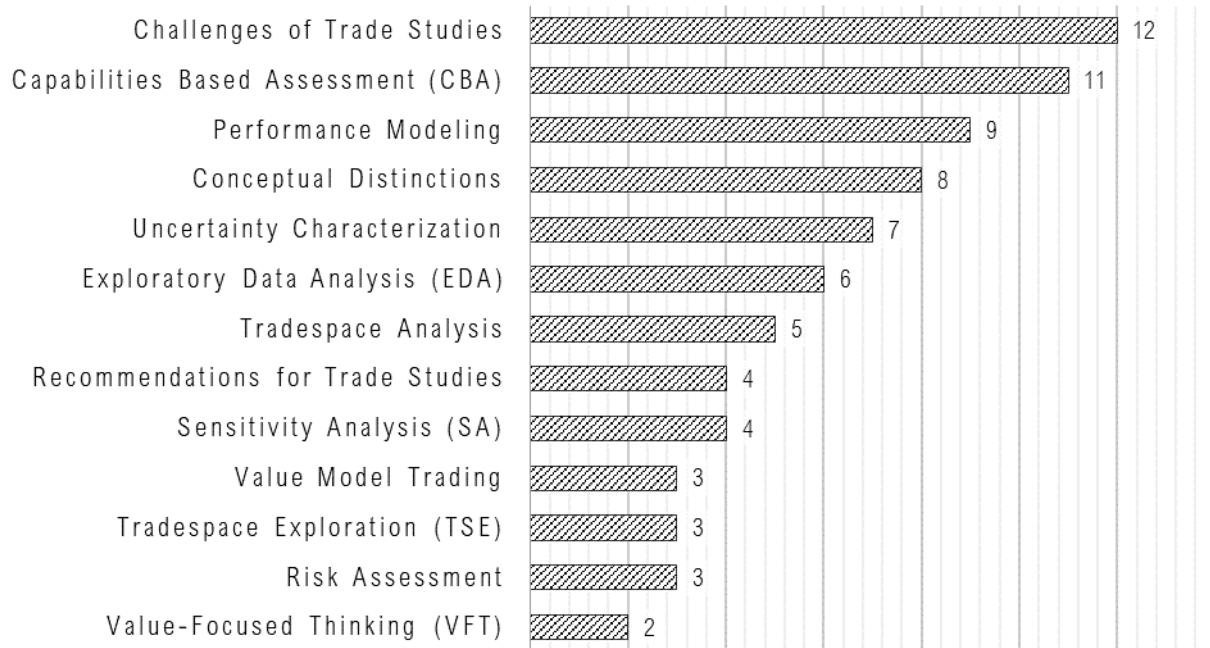


Figure 3.1: Categorical graph of codes assigned across Theme 1

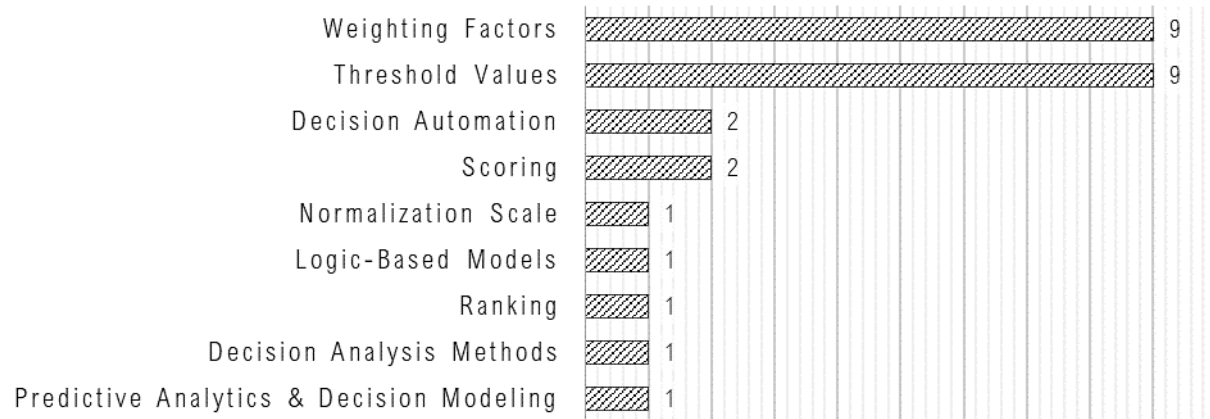


Figure 3.2: Categorical graph of codes assigned across Theme 2

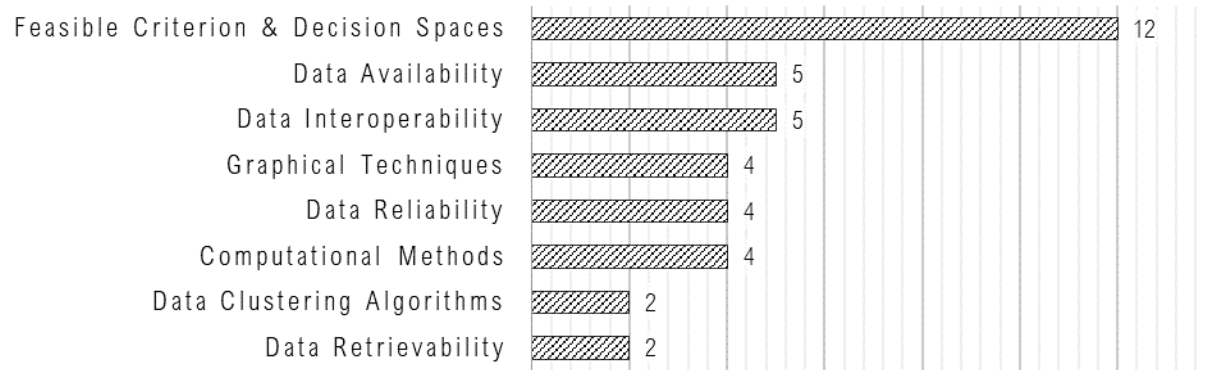


Figure 3.3: Categorical graph of codes assigned across Theme 3

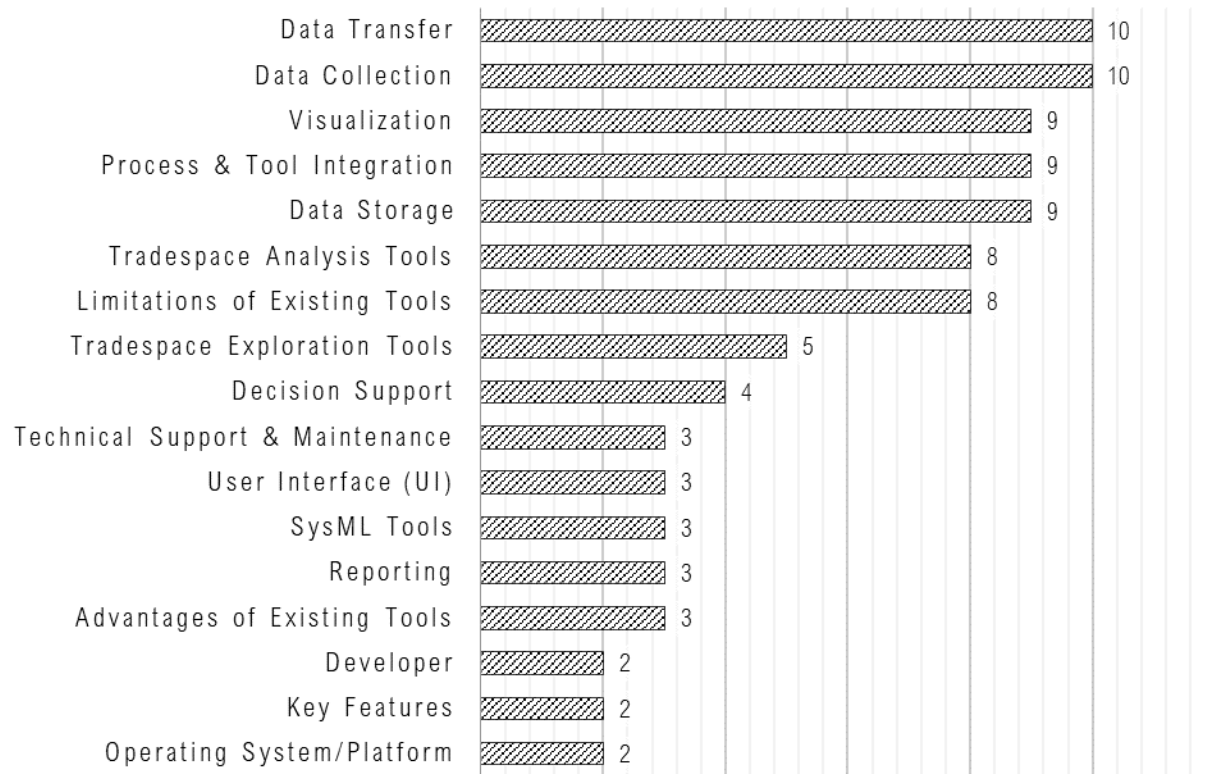


Figure 3.4: Categorical graph of codes assigned across Theme 4

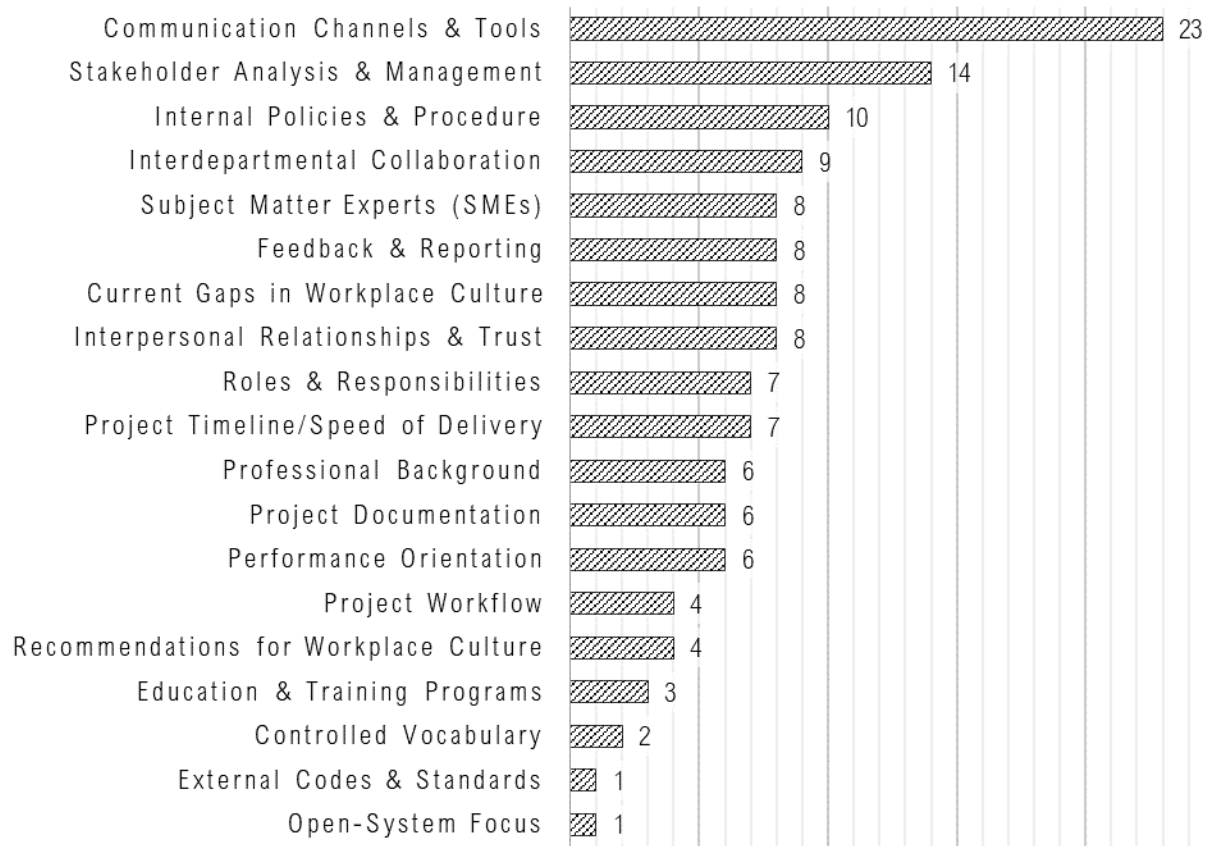


Figure 3.5: Categorical graph of codes assigned across Theme 5

Identifying Capability Gaps

In addition to characterizing GVSC trade study practices, current challenges, and capability gaps of tradespace activities conducted within GVSC were identified via categorical cluster analysis of the seven interview datasets in which categorical data was clustered by matching similarities between categorical objects with respect to a set of observable variable characteristics—or in the case of this research, visually grouping observed codes with respect to the five emergent themes identified from the literature.

These data clusters were then used to assess common trends across the datasets. Codes assigned to the data were grouped thematically and prioritized based on the frequency of occurrence.

Five major capability gaps emerged from the categorical clusters observed in [85]. These include:

- The Data Exploration-Exploitation Dilemma
- Lack of a Data Repository
- Information Silos
- Lack of Standardization
- Visualizing and Communicating the Tradespace

Gap 1: The Exploration-Exploitation Dilemma

A key challenge of the tradespace for GVSC and industry alike is finding the optimal balance between exploratory efforts and exploitation strategies. One interview participant stated: “it is difficult to balance out how much work we do versus how much information we need” when developing a project scope— “it is a learning process we are still in the middle of.”

The tradespace is essentially a highly complex multi-objective optimization problem across many domains. A combinatorial trade study, in essence, is a very large dimensional problem with as many as—and sometimes exceeding—a few hundred requirements. While performing an exhaustive search of the tradespace may yield a high-fidelity model of a system solution, a trade-off must be made between data exploration and computational demands. The challenge is identifying the point at which it is more advantageous to cease exploration efforts in favor of exploiting the best current information.

Another challenge surrounding the exploration-exploitation trade-off of combinatorial trade studies is the multi-relational nature of the system parameters. Early concept development is often limited by uncertainty surrounding the independent relationships of the trade-offs driving the

tradespace. For a given system, the tradespace is driven by a set of non-traditional design criteria, or “ilities” serving as critical system attributes such as accessibility, flexibility, or resilience.

Consequently, complex system’s design has historically been limited by the fidelity of the physics-based models and simulations. These tradeoffs are often intricately interconnected and cannot be performed in isolation. A framework developed by [39] suggests implementing Epoch/Era Analysis when incorporating “ilities” in complex system design [39].

In one interview, a participant suggested an exploratory data analysis (EDA) approach as another potential technique for rectifying the high complexity arising from system “ilities” within a tradespace. As explained by the participant, a significant aspect of tradespace exploration involves experimentally breaking a requirement and examining the effect on other areas— “and so, it is a great big design exploration where you are changing the constraints on your design space to [investigate] the payoff.”

Gap 2: Lack of Data Repository

As one participant stated, the lack of a data repository “is largely an infrastructure and data management problem.” Other data-centric challenges posited during the interviews included:

- How do we build databases that are maintainable?
- Who is responsible for maintaining these databases?
- How do we support workflow automation and integration?
- How do we document and communicate the assumptions and limitations of the data?

A current limitation of trade studies performed within GVSC is data accessibility. When asked about existing gaps, one participant responded that a lot of the work is accessing data for components or current vehicles; additionally, the participant reported that data management access

as well as tracking past and ongoing simulations are time-consuming and tedious. A potential remedy to this issue is a verification engine to synchronize and interchange data.

Developing the database architecture is not the only barrier to effective data exchange. It is also integral that the data is compatible and able to be integrated with other systems. As such, data interoperability and flexibility should be prioritized when developing future trade study databases. Current capability gaps regarding data interoperability include not only the technical aspects of data exchange, but also how well the system functions as an information sharing environment with respect to basic end-to-end operations.

At present, the Operational and Trade Space Analysis Branch of GVSC is collaborating with ERDC to develop a trades data warehouse. Development plans for this data warehouse include a library of functional directives and product structures. It was also noted during one interview that compatibility and integration with software presently used by GVSC, namely support for ARIES and WSTAT, would be ideal.

Gap 3: Information Silos

Workplace culture plays a crucial role in the degree to which information synthesized during a trade study is effectively communicated. A particular challenge reported by several participants was an organizational reluctance to share information. Trade studies involve many groups, either conducting their own simulations or the waterfall data in which one group feeds into another group. There is information spread-out across different organizations— “even within my own organization,” one participant noted—which must be effectively shared between GVSC, the SMEs and the stakeholders.

Information silos—in which information generated by an individual or group is not properly communicated, integrated, or aggregated into the collective knowledge of the organization—occur when organizational members or groups are either unable or unwilling to cooperate with adjacent parties. Information silos risk hindrance (or in some instances, a complete halt) of the communication process and therefore pose a significant threat to the success of a trade study. Ideally, information sharing should serve as a feedback loop between multiple agencies. Unfortunately, a common pitfall of trade studies is the communication process operating as a one-way passage of information between groups.

Poor personal relations between organization members may also severely limit the success of a trade study. One participant made the following statement regarding this dynamic and how it affects workplace culture within GVSC and other government agencies alike: “If you know someone, if you have names for the face, if you have a good relationship with the people, they are going to be more inclined to communicate better ... [sometimes], there are other groups that I [have not worked] with before, I can tell you that those are the groups we had the most issues with.” This sentiment was mirrored within several of the interviews. Another participant offered the following anecdote: “now that I [have gotten to know] some people better—and they know me— [there is] better communication ... and a better end product.”

Gap 4: Lack of Standardization

The lack of consensus or standardization for tradespace operations introduces ambiguity surrounding decision-making. This is amplified by the tendency for everyone to communicate differently. As stated by one participant, it is ideal for members within an organization to have differing professional backgrounds and areas of expertise, as this creates opportunity for differing

insights and methodologies. However, it is also crucial that all parties are on the same page, particularly regarding the goals and underlying assumptions of the project.

One participant expressed the potential value in developing a standard procedural framework for performing trade studies— “I realize [analyses are performed] in parallel, but in general, a one, two, three kind of a thing.” Although a more technical or detailed standard procedure is likely infeasible due to the broad scope of potential studies, a general guideline to tradespace exploration and analysis may provide a clearer path and improved organization, particularly when approaching a new study.

Another participant reported that a particularly challenging limitation arising from this gap is the inability to reuse models. Without standard data formats and interfaces, models typically require manipulation and updates with each new study. The ideal scenario, as reported by one participant, would be the ability to select a model from a library, make necessary updates, and meet a customer need quicker and faster. This could potentially be supplemented with standardized documentation. As noted by one participant, “a product structure for a ground combat vehicle is going to be the same” regardless of the specific model. As such, there is an opportunity to reuse those product structure elements and functional objectives across other ground combat vehicle tradespaces.

During the interviews, each participant was asked to describe their understanding of, and distinction between, tradespace exploration and tradespace analysis.

Gap 5: Visualizing and Communicating the Tradespace

Current practice at GVSC includes multiple innovation workshops with the soldiers, particularly during the initial phase of the trade study. As one participant explained, the reasoning

behind this approach is to “bring in soldiers to give feedback on different concepts or try to come up with ideas for new concepts for vehicles [and] get their ideas on their requirements.” Scheduling workshops and briefings to increase communication between GVSC, SMEs, and stakeholders is a favorable practice. However, an existing gap between existing data visualization capabilities and tradespace communication needs is the ability to interactively visualize and communicate the tradespace. As one participant noted, for “areas where you can only show plots,” it is more difficult for stakeholders to “wrap their minds around” or interpret the results. As stated during one of the interviews, “data visualization, telling the story, is the key.”

One participant described the following ideal scenario for relaying information between stakeholders and SMEs: “If our customer [specifies] the questions [they] want answered, we must make sure that we [accurately] explain [those questions] to the SMEs: “We are looking for [X] kind of data. [Reason Y] is why. We are looking for [a solution to issue Z]. We believe [X] is the data we need to solve [Z]. [Procedure V] is how we will use it.”

Effectively explaining a problem and current approach— and then reinforcing that understanding through visualization techniques—enables the SMEs to make better recommendations for capturing the correct data to use in the tradespace model, as opposed to just dictating what data is needed.

Another participant proposed that “data visualization is human in a loop data analysis ... [at least] certainly for physics-based modeling and simulation.” The ability to leverage tools and techniques to explore trades in real-time would enable rapid and effective stakeholder communication and prove invaluable to the overall communication process. Additionally, improving tradespace visualization tools and techniques presents an opportunity for stakeholders and SMEs to gain a more in-depth understanding of the trade-offs driving the tradespace.

3.2.6 Conclusion & Future Work

The purpose of this research was to establish a tradespace analysis self-assessment framework to support the balance of new operational capabilities against cost and applied utility trades (i.e., risk, cost, and schedule) for tradespace activities performed within GVSC. Following a systematic literature study and based on the findings from that, personnel working with (or in some cases, adjacent to) the Operational and Trade Space Analytics Branch were interviewed in order to gain insight into current tradespace practices within GVSC. The interviews were then coded based on the emergent themes identified through the exhaustive literature survey. The themes identified through thematic content mapping of the literature include (1) System Modeling and Analysis, (2) Optimization and Decision Strategies, (3) Dataflow Architecture, (4) Software and Support Tools, and (5) Workplace Culture. The results of coding the interviews with respect to the frequency of keywords indicate that topics concerning Communications Channels and Tools that emerge in theme 5 were perpetually relevant when discussing tradespace activities.

These findings were then compared to the extant literature to develop a set of strategic development recommendations for future research priorities, resource allocation, and tool development. In addition to characterizing the current practices of tradespace exploration and analysis within GVSC, the analysis of the interview transcripts revealed five current capability gaps, including: (1) The Data Exploration-Exploitation Dilemma, (2) Lack of a Data Repository, (3) Information Silos, (4) Lack of Standardization, and (5) Visualizing and Communicating the Tradespace. In discussing these capability gaps, as the interviews were semi-structured and provided the freedom for participants to go into more detail or stray the conversation to other areas, some interviewees also stated recommendations to alleviate some capability gaps.

A potential application of the findings is the achievement of an interactive exploration and visualization of the tradespace via human-in-the-loop machine learning tools for multi-objective collaborative optimization. Additionally, potential future research directions include the development of a data-driven surrogate model-based Bayesian learning and optimization framework for adaptive and interpretable sequential engineering design decision-making. A secondary future direction includes the development of computational tools (e.g., software packages) for the proposed framework.

3.2.7 Acknowledgements

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3.3 Concluding Remarks

This study helped meet the dual objectives of gaining direct insight into trade study practices, methods, and tools implemented by GVSC and then establishing areas of excellence as well as identifying capability gaps, limitations, and needs concerning current tradespace practices at GVSC.

An interview-based process was used to achieve these outlined research objectives. A series of seven interviews were conducted with members working within (or adjacent to) the Operational and Trade Space Analytics Branch of GVSC. The thesis then proceeds to extract data related to tradespace-related tools, processes, and methods implemented by GVSC. The data extracted from these interviews are intended to serve as documentation for current tradespace practices at GVSC. These documented practices were then benchmarked against the baseline established in the literature to evaluate current GVSC practices.

In addition to contributing to the greater body of literature, this thesis aims to evaluate current tradespace practices at GVSC. Ultimately, this thesis seeks to provide significant revelations of internal organizational strengths, weaknesses, and opportunities for improvement related to the tradespace. Although this analysis is presented as a case study respective of GVSC, this thesis aims to provide a general framework for organizational self-assessment of internal practices related to the tradespace. This research contribution serves as a guide for other organizations to conduct similar self-assessments of their internal trade study process. Although this analysis is presented as a case study of GVSC to contribute to the greater body of tradespace literature, the findings of this thesis are extrapolated and considered in the context of other organizations external to GVSC. Thus, further contributions of this thesis are intended to support

research efforts toward the more generalized understanding of existing tools, processes, and methods related to the tradespace, independent of the organization performing the trade study.

CHAPTER 4:

DISCUSSION OF FINDINGS

4.1 Revisiting the Objectives

Building on the papers discussed in Chapters 2 and 3, these combined works represent efforts to build a fundamental understanding of tradespace existing tools, processes, and methods overlapping industry, academia, and government partners. The preliminary efforts represented in the “Designing the Design Space: Evaluating Best Practices in Tradespace Exploration, Analysis, and Decision-Making” [84] are predominantly aimed toward performing a comprehensive review of the literature regarding the tradespace or greater trade study process. In this thesis, the collection of data observed in the existing literature is reviewed and analyzed with respect to existing tradespace practices across a wide scope of organizations. The five themes emerging from this analysis (shown in Figure 2.2) fed efforts to represent the data through development of a qualitative coding. As detailed in Chapter 2, these emergent themes served as the foundations from which to organize and structured the collected literature data.

In Chapter 3, “Tradespace Organizational Practices: A Case Study” [85] discusses a case study of the US Army Ground Vehicle Systems Center (GVSC). The initial objective of these continued efforts explicitly sought to first design and then conduct an interview-based study to investigate current tradespace-related practices of GVSC. This research objective sought to thoroughly document current GVSC processes, methods, and tools for trade studies conducted within GVSC. Using the baseline established in Chapter 2, this thesis goes on to perform a benchmarking study of these documented GVSC practices to identify internal strengths, weaknesses, and potential avenues for improvement. From these benchmarks, this thesis uses these benchmarks to establish a set of capability gaps and strategic recommendations for GVSC—the

significance of which is to ultimately illuminate a practical, actionable forward path for strategic development.

The findings of the benchmarking study and subsequent strategic analysis identified five capability gaps which were reported to GVSC in December 2021. This report received positive feedback from GVSC personnel, who indicated the results accurately reflect the current and envisioned state of GVSC tradespace efforts.

4.2 Findings in Context

4.2.1 Systematic Review of the Literature

As discussed in Chapter 2, a literature review was performed to systematically search, identify, and analyze available literature relating to the tradespace and greater trade study process. An initial search was performed by searching keywords explicitly relevant to the project proposal. Search methods gradually evolved to include more specific search terms as well as a wider scope of implicit or related topics. Further search efforts were built around collaborative partnerships or other research relationships. A meta-analysis of the selected publications was performed to categorize each publication with respect to the type of publication, sector, field of study, primary goal, and relevant keywords. For the full summary of this meta-analysis, see Table A.1 of Appendix A.

Figure 4.1 provides a visualization of the publication type yearly distribution in context of programmatic funding decisions.

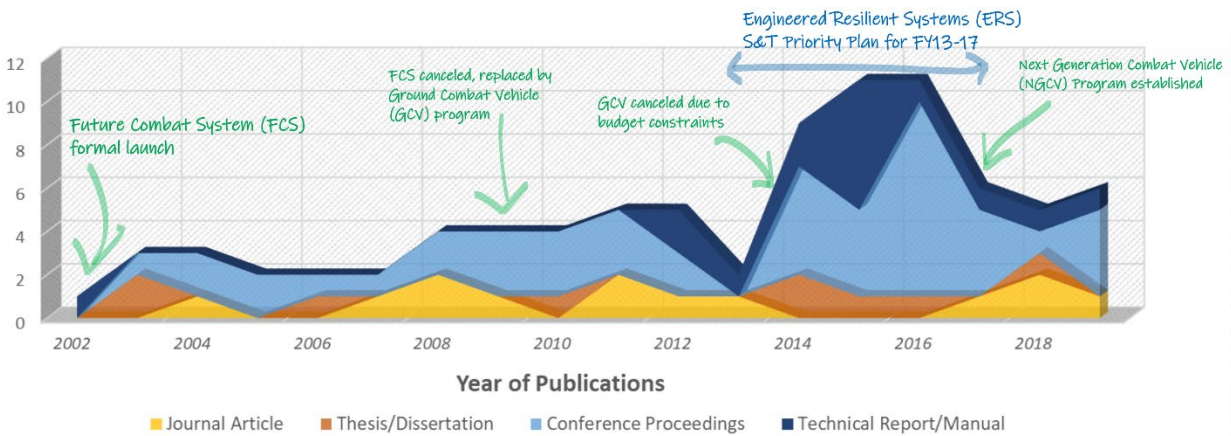


Figure 4.1: Distribution of the literature with respect to programmatic funding decisions

As shown in Figure 4.1, trends observed in the set of publications selected from the literature for inclusion in the survey align with programmatic funding decisions announced by the Department of Defense and Congress. A particularly significant fluctuation observed in the literature corresponds to the organized efforts toward the Engineered Resilient Systems (ERS) program outlined in the DoD-wide Science and Technology (S&T) Priority Plan for FY13-17 [86].

4.2.2 Development of the Interview Study

Findings of the literature review were used to develop an interview-based study to gather data from personnel working within (or adjacent to) the Operational and Trade Space Analytics Branch of GVSC. Ultimately, a series of seven semi-structured interviews were conducted with personnel representing a range of various roles and responsibilities regarding trade studies performed by GVSC. The interviews were designed with intentions to gain the insights described in Table 2.7. These insights include those explicitly related to the specific organization of interest, such as: each participant's role or involvement in trade studies within their organization, as well as organization-specific experiences. Beyond these insights explicit to organizational tradespace efforts, this interview study was also developed with the more general objectives of capturing

each participant's conceptual interpretations of tradespace exploration and analysis, perspectives on selection and communication of key drivers, as well as any participant anecdotes revealing personal recommendations, observed capability gaps, and ideal future state. The qualitative data obtained from these interviews were analyzed and framed using a bottom-up qualitative approach to drive reflexive exploration of trends, patterns, and relationships.

4.2.3 Data Analysis and Interpretation

Findings from the interviews were benchmarked against the baseline in hopes of facilitating development of a self-assessment framework. As indicated in Figure B.1, the results of coding the interviews with respect to the frequency of keywords indicate that topics concerning Communications Channels and Tools that emerge in Theme 5 were perpetually relevant when discussing tradespace activities.

Additionally, the findings revealed a strength of GVSC is the current practice of hosting a series of workshops during various phases of the trade study process to establish communication channels and mutual understanding between stakeholders—namely the soldiers. The tradespace is characterized by carving out the feasible design space driven by the needs and preferences of the soldiers (as well as other key stakeholders) and bounded by the technical constraints stipulated by the SMEs. As such, engagement between the soldiers (i.e., the primary end user of military ground vehicles) and the Subject Matter Experts (SMEs) is revealed to hold particular importance. This favorable GVSC practice encourages key stakeholders to take on more collaborative roles by facilitating initial and continued communication among a range of stakeholders.

4.3 Recommended Procedure for Organizational Self-Assessment

The set of steps outlined by the proposed framework first recommends the organization carefully examines their trade study process (as well as the system lifecycle) to identify all relevant stakeholders. An interview participant list should then be developed in which all relevant stakeholders are adequately represented. A set of recommended practices is provided in Table 4.1 to serve as a general guide from which organizations can adapt their own interview studies for the purpose of self-assessment.

Table 4.1: Interview prompts for the proposed framework

<i>Tool Integration & Data Interoperability</i>	
1	Describe the overall design approach of the organization.
2	What tools/methods/processes are currently used to support decision-making?
3	What is your personal approach to tradespace exploration and analysis?
4	What datatypes or formats are used across all parties throughout the system life cycle?
5	Are these datatypes/formats easily integrated using the current tools/software?
6	What data storage methods are currently implemented?
7	How is data transferred and updated across teams?
8	What methods are in place to ensure availability and retrievability of the current best data?
<i>Data Exploration vs. Exploitation</i>	
9	What is the current information gathering process?
10	How are assumptions documented and tracked?
11	How are you drawing the line between data gathering vs. proceeding with best available information?
<i>Data Visualization & Post-Processing</i>	
12	What tools and techniques are currently used for visualization and reporting?
13	Are there any observed capability gaps surrounding visualizing the tradespace or communicating trade-off decisions?
14	What is your personal approach to design decision-making?
15	What could be done to improve the organization-wide decision-making process?
<i>Standardization of Data & Documentation Practices</i>	
16	Are there any organization- or project-wide standardized documents or procedures used across teams?
17	Describe any current gaps or need for standardized documents or procedures.
18	Describe any opportunity areas for standardization efforts?
<i>Reporting & Feedback</i>	
19	How often are status updates communicated with sponsors and project leadership?

- 20 What communication channels and tools are currently implemented
 - 21 How are decisions and current approaches communicated across all individuals or teams to avoid creep?
 - 22 What methods are in place to ensure everyone is up to date and on the same page regarding current efforts?
 - 23 Who is the final decision-making authority?
 - 24 Who is responsible for communicating these decisions and/or disseminating information across all parties?"
 - 25 What is the current configuration management process?
 - 26 How are changes or revisions monitored, tracked, and communicated across parties?
-

Each transcript should be evaluated line-by-line in order to highlight segments of interest and tag relevant keywords. Each instance of an assigned code can be recorded and tracked using the location with the transcript as defined by the line number corresponding to each occurrence. The initial pass through each dataset may capture information as large ‘chunks’ of data (or long passages of text). Over subsequent iterations, these data chunks should be further broken down into text segments represented by individual keywords tags.

Keywords tagged across the interview datasets should be consolidated with respect to theme and category as outlined in the coding scheme defined in Table 2.2–Table 2.6. For example, the consolidated keywords collected across the GVSC interviews are shown in Table B.1.

Cluster analysis should then be applied to the findings in order to observe any trends or patterns within the data. These results can then be evaluated using SWOT analysis to identify organizational strengths, weaknesses, opportunities, and threats.

CHAPTER 5:

CONCLUSIONS AND FINAL REMARKS

5.1 Summary of Research Efforts

Thematic content mapping of the literature intersecting industry, academia, and government organizations revealed five emergent themes of organizational trade studies. Theme 1 (System Modeling and Analysis) and Theme 2 (Optimization and Decision Strategies) relate to the creation, exploration, and navigation of a system tradespace, while Theme 3 (Dataflow Architecture) encompasses the basic architecture and models of dataflow between and across organizations. Theme 4 (Software and Support Tools) captures various software and tools implemented by an organization, including any tool requirements, limitations, integrations, and future development efforts. Finally, Theme 5 (Workplace Culture) captured the atmosphere of the organization as a work environment—including the attitudes, beliefs, and behaviors of organizational members and teams.

Findings from the literature were then used to develop an interview study in which seven GVSC personnel within the Operational and Trade Space Analytics Branch were interviewed. The data collected from these interviews were then coded using the establish code framework and subsequently benchmarked against the baseline established in the literature. A gap analysis revealed five current capability gaps experienced by GVSC, including: The Data Exploration-Exploitation Dilemma, the lack of a data repository, data or information silos, a lack of standardization, and challenges related to tradespace visualization and communication.

5.2 Significance and Contributions

The combined research efforts within this thesis resulted in several research contributions that are of interest to organizations spanning the public and private sectors, including government departments and agencies, industry partners, and academic research institutions. Considering that a well-defined framework for assessing tradespace practices across organizations does not presently exist, the research efforts discussed in this thesis contribute to the greater body of tradespace-related research. Although this analysis is presented as a case study of GVSC, these findings were extrapolated where applicable to organizations external to GVSC—including other government departments or agencies, industry partners, and academic research institutions—for consideration within a more generalized context.

A particularly significant contribution of this research is the establishment of a general framework supporting the evaluation of an organization's internal trade study process. These research efforts facilitate self-guided support and improvement of an organization's trade study process as well as any other organization-wide tradespace-related research efforts. Through this framework, other organizations can perform similar in-house assessments to improve their respective trade study capabilities.

This thesis seeks to not only aid organizations in the performance of a trade study, but to also guide the capture and presentation of tradespace data. This includes the documentation, reporting, and communication of results to the wide variety of stakeholders involved in the trade study process. The significance of such efforts supports the success of large procurement projects, particularly regarding improvements toward the stakeholders' capacity for informed decision-making and tradeoff decisions impacting the scope, schedule, budget, performance, and risk profile of a project.

5.3 Avenues for Future Research

Future research is needed to validate the framework proposed within this thesis. It is recommended that a future study is conducted to apply the findings to a range of organizations external to GVSC to assess the efficacy of the proposed framework when used for self-assessment of non-GVSC organizations.

Additionally, the findings of this thesis could be furthered through the development of human-in-the-loop machine learning tools for multi-objective collaborative optimization. Future efforts in this area would help close the gaps related to interactive exploration and visualization. Application of the developed framework may be used to aid engineering design problems of interest to GVSC, such as the Deep Orange project currently being conducted at CU-ICAR. These collaborative efforts between VIPR-GS and Deep Orange will provide a foundation for continued tradespace research as well as support future performance studies and design decisions.

Another direction for future research includes the pursuit of adaptive and interpretable sequential engineering decision-making. A potential avenue for realization of this goal is the development of a data-driven surrogate model-based Bayesian learning and optimization framework. The metrics defined in the established framework can be incorporated into the model formulation process to further efforts toward modeling of technologies and technological development.

A final potential research focus is the development of computational tools (e.g., software packages) for the proposed framework. Realizations of current visualization capabilities may also enable future studies to develop a tradespace exploration process with integrated immersive reality. The established framework could be used to benchmark the proposed approach with traditional

analysis approaches using metrics developed to reflect current practices in tradespace exploration, analysis, and decision-making as observed in the tradespace literature.

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APPENDICES

Appendix A:

Summary of Surveyed Literature

Table A.1: Meta-analysis of surveyed literature

No	Author(s)	Year	Publication Type	Sector	Field of Study	Purpose	Keyword(s)
1	Beesemyer et al.	2012	Conference Paper	Industry	Decision Support Tools	Tool Development	<i>Decision Making, Evaluation Criteria, VDD</i>
2	Bertoni et al.	2013	Journal Article	Industry	Aero-Engine Systems	Case Study	<i>Color-Coding, SIEMENS NX HD3D Visual Reporting, Tradespace Visualization, VDD</i>
3	Bertoni et al.	2011	Conference Paper	Industry	Decision Support Tools	Tool Development	<i>Bayesian Network, DAGs, Distributed Decision Support, MAVT, MCDA, Robustness, SBR, Uncertainty</i>
4	Bhattacharya et al.	2017	Conference Paper	Government	Rotorcraft Systems	Case Study	<i>ERS, Stakeholder Communication, Stakeholder Involvement</i>
5	Blackburn et al.	2011	Journal Article	Industry	Pharmaceutical Development	Case Study	<i>QFD, TRIZ Framework</i>
6	Boehm et al.	2013	Technical Report	Government	Data Analysis and Optimization	Gap Analysis	<i>Collaborative Systems, System Attributes</i>
7	Bond et al.	2015	Technical Report	Industry	Decision Support Tools	Tool Development	<i>M&S, Risk Assessment</i>
8	Browne et al.	2016	Conference Paper	Government	Engineered Resilient Systems	Tool Development	<i>Decision Analysis, Decision Support Tools, ERS, Model Trading, Software Architecture</i>
9	Cataldo et al.	2014	Technical Report	Government	Space System Architectures	Tool Development	<i>Pareto Frontier, Sensitivity Analysis, Stakeholder Communication, TSE</i>
10	Chattopadhyay et al.	2009	Conference Paper	Academia	System of Systems Design	Gap Analysis	<i>MATE, SoSTEM</i>
11	Chattopadhyay et al.	2009	Conference Paper	Academia	System of Systems	Case Study	<i>EEA, MATE, TSE</i>
12	Chau & Patel	2016	Conference Paper	Academia	Engineered Resilient Systems	Tool Development	<i>Capability Gameboard, Collaborative Systems Engineering Tools, ERS, FACT, MBSE, SBD, Smart Mine Process, Tradespace Visualization, Trust</i>
13	Chhabra & Warn	2017	Conference Paper	Academia	Decision Support Tools	Tool Development	<i>Decision Making, ERS, M&S, Tradespace Visualization</i>
14	Cilli & Parnell	2014	Conference Paper	Academia	Data Visualization & Reporting	Gap Analysis	<i>INCOSE Decision Management Process, ISO/IEC 15288, Standards, Tradespace Visualization, Uncertainty</i>

No	Author(s)	Year	Publication Type	Sector	Field of Study	Purpose	Keyword(s)
15	Comes et al.	2011	Journal Article	Academia	Decision Support Tools	Tool Development	<i>Bayesian Networks, Causal Maps, Decision Maps, Decision Support Tools, Fuzzy Cognitive Maps, MAUT, MAVT, MCDA, Uncertainty, Uncertainty</i>
16	Comes et al.	2010	Journal Article	Government	Decision Support Tools	Tool Development	<i>Capabilities-Based Planning, MCDA, Stakeholder Analysis, Value-Focused Thinking</i>
17	Davenport et al.	2018	Conference Paper	Government	Data Visualization & Reporting	Tool Development	<i>Automatic Workflows, Bidirectional Integration, Digital Thread, Integrated Model Framework, Interoperability, MBSE, ModelCenter, SBD, Sensitivity Analysis, Tool Integration, Tradespace Visualizer, Visualization Tools</i>
18	Davison	2014	Thesis/Dissertation	Academia	Space System Architectures	Tool Development	<i>Decision Analysis, Decision Support Tools, M&S, Tradespace Visualization, TSE</i>
19	Dillon-Merrill et al.	2008	Journal Article	Academia	Decision Support Tools	Tool Development	<i>Decision Making, Mean-Risk Analysis, SBD, Sequential Design Process, Uncertainty</i>
20	Durbach & Stewart	2012	Journal Article	Academia	Decision Support Tools	Gap Analysis	<i>Decision Model, MAUT, Uncertainty</i>
21	Ender	2014	Technical Report	Government	Engineered Resilient Systems	Tool Development	<i>ERS, M&S, MBSE, Tool Integration, User Interface</i>
22	Ender	2016	Technical Report	Academia	SysML	Gap Analysis	<i>AoA, Software Architecture, SysML, TradeStudio, Uncertainty</i>
23	Ender & Goerger	2016	Conference Paper	Government	Engineered Resilient Systems	Tool Development	<i>Collaborative Systems, Decision Making, End-to-End Capabilities, ERS, Interoperability, MBSE, MCDM, MDAO, Scalability</i>
24	Felix	2004	Conference Paper	Industry	Decision Support Tools	Tool Development	<i>CMMI, Decision Analysis, DMA, Trade Study Matrix, Uncertainty, Weighting</i>
25	Fitzgerald & Ross	2019	Conference Paper	Industry	Artificial Intelligence	Tool Development	<i>Cluster Analysis, MATE, SBD</i>
26	Girerd	2005	Conference Paper	Government	Data Visualization & Reporting	Tool Development	<i>Mission Tradespace Tool, Tradespace Visualization, User Interface</i>
27	Henry et al.	2016	Conference Paper	Government	Ground Vehicle Systems	Case Study	<i>WSTAT</i>
28	Hitomi	2018	Thesis/Dissertation	Academia	Space System Architectures	Tool Development	<i>Evolutionary Algorithms, TSE</i>

No	Author(s)	Year	Publication Type	Sector	Field of Study	Purpose	Keyword(s)
29	Holland	2016	Conference Paper	Government	Computing and Information Technology	Tool Development	<i>Data Access, Design Repositories, ERS, ERS Cloud Computing Architecture, Interoperability, Scalability, Tool Access, Trust</i>
30	J. Le Moigne et al.	2017	Conference Paper	Government	Vehicle Management (Space/Air/Ground)	Tool Development	<i>Knowledge Base, User Interface</i>
31	Kelley et al.	2016	Conference Paper	Government	Engineered Resilient Systems	Gap Analysis	<i>Collaborative Web-Based Tools, Decision Analysis, ERS, MBSE, MCDA, MCDA, Measure of Performance, Traceability, Tradespace Visualization</i>
32	Lamassoure et al.	2004	Conference Paper	Academia	Modeling and Simulation	Case Study	<i>MBSE, Sensitivity Analysis, Traceability, Uncertainty</i>
33	MacCalman et al.	2015	Technical Report	Academia	Modeling and Simulation	Case Study	<i>M&S</i>
34	MacCalman et al.	2016	Conference Paper	Academia	Data Analysis and Optimization	Case Study	<i>DoE, JMP, Monte Carlo Simulation, User Interface</i>
35	Malan & Pretorius	2011	Conference Paper	Industry	Modeling and Simulation	Case Study	<i>Interoperability, MBSE, ModelCenter, Multidisciplinary MBSD Environment, SME, SysML, System Architecture Model, Tool Integration, Traceability</i>
36	Martin	2016	Conference Paper	Government	Computing and Information Technology	Guidebook	<i>Enterprise Configuration Manager, Enterprise Engineering Repositories, Enterprise Interoperability, Enterprise Linking Standard, Tool Integration</i>
37	McGowan & Lichty	2019	Conference Paper	Academia	Modeling and Simulation	Case Study	<i>Interoperability, MBSE</i>
38	McManus & Schuman	2003	Conference Paper	Government	Space System Architectures	Case Study	<i>Integrated Concurrent Engineering, MATE, System Attributes</i>
39	McManus et al.	2007	Conference Paper	Academia	Data Visualization & Reporting	Gap Analysis	<i>EEA, MATE, System Attributes, Tradespace Visualization</i>
40	Mixon et al.	2019	Technical Report	Government	Data Visualization & Reporting	Gap Analysis	<i>Decision Support Tools, ERS, Interactive Data Visualization, Tradespace Visualization, TradeStudio Analytic Tools</i>
41	Nickel	2010	Thesis/Dissertation	Academia	Transportation Systems	Tool Development	<i>CBA, MATE, Stakeholder Analysis, TSE</i>
42	Nickel et al.	2008	Conference Paper	Academia	Space and Transportation Systems	Gap Analysis	<i>Cognitive Bias, Stakeholder Analysis</i>
43	Nickel et al.	2009	Conference Paper	Academia	Project Management	Gap Analysis	<i>CBA, MATE, TSE</i>

No	Author(s)	Year	Publication Type	Sector	Field of Study	Purpose	Keyword(s)
44	Oster	2011	Conference Paper	Academia	Modeling and Simulation	Case Study	<i>Integrability, MATE, MAUT, Scalability, System Attributes, VDD</i>
45	Parnell et al.	2014	Conference Paper	Academia	Data Analysis and Optimization	Gap Analysis	<i>Cognitive Bias, INCOSE Decision Management Process, ISO/IEC 15288, Standards & Policies</i>
46	Pernin et al.	2012	Technical Report	Government	System of Systems	Gap Analysis	<i>Stakeholder Involvement, Standards & Policies</i>
47	Price	2016	Thesis/Dissertation	Academia	Space System Architecture	Gap Analysis	<i>CBA, MBSE, Robustness, TSE, VDD</i>
48	Qiao et al.	2017	Conference Paper	Academia	Data Visualization & Reporting	Tool Development	<i>Cluster Analysis, Decision Making, Interactive Data Visualization, Multi-dimensional Scaling Visualization, Principal Component Analysis, TSE</i>
49	Rader et al.	2010	Conference Paper	Academia	Decision Support Tools	Gap Analysis	<i>EEA, Monte Carlo Simulation, Risk Assessment, Uncertainty</i>
50	Ricci et al.	2014	Conference Paper	Academia	System of Systems	Tool Development	<i>SAI Method, System Attributes</i>
51	Rigas & Spero	2012	Conference Paper	Academia	Decision Support Tools	Tool Development	<i>Changeability, Cluster Analysis, Flexibility, System Attributes, Uncertainty</i>
52	Ross	2006	Thesis/Dissertation	Academia	Data Analysis and Optimization	Gap Analysis	<i>Adaptability, Data Reporting & Communication, DoE, EEA, Flexibility, MATE, MAUT, ModelCenter, Network Analysis, Pareto Frontier, Robustness, Scalability, Software Packages, Standards & Policies, Tradespace Visualization, TSE, Value Model</i>
53	Ross	2003	Thesis/Dissertation	Academia	Decision Support Tools	Tool Development	<i>Decision Analysis, Descriptive Models, MATE-CON, MAUT, Prescriptive Models, Sensitivity Analysis, Stakeholder Analysis, System Attributes</i>
54	Ross & Hastings	2005	Conference Paper	Academia	Space Systems	Case Study	<i>Flexibility, MATE-CON, Robustness, System Attributes, TSE, Uncertainty</i>
55	Ross & Hastings	2008	Conference Paper	Academia	System Architectures	Tool Development	<i>Latent Value, MATE, Robustness, TSE</i>
56	Ross et al.	2004	Journal Article	Government	Space Systems	Tool Development	<i>MATE-CON</i>
57	Ross et al.	2010	Conference Paper	Academia	Space System Architecture	Gap Analysis	<i>EEA, MATE, MAUT, Pareto Frontier, Risk Assessment, Sensitivity Analysis, System Attributes, Tradespace Visualization, TSE, Uncertainty</i>

No	Author(s)	Year	Publication Type	Sector	Field of Study	Purpose	Keyword(s)
58	Ross et al.	2015	Conference Paper	Government	Data Analysis and Optimization	Gap Analysis	<i>AHP, CBA, MAUT, MBSE, Robustness, Value Models</i>
59	Salado	2018	Technical Report	Government	Decision Support Tools	Tool Development	<i>ERS Cloud Computing Architecture, TSE</i>
60	Simpson et al.	2017	Journal Article	Academia	Data Visualization & Reporting	Gap Analysis	<i>Interactive Data Visualization, MDO, Multi-dimensional Data Visualization, Pareto Frontier, TSE, VDD</i>
61	Sitterle et al.	2015	Conference Paper	Government	Engineered Resilient Systems	Tool Development	<i>AoA, ERS, Flexibility, MAUT, Robustness, TSE</i>
62	Smead	2015	Technical Report	Government	Data Visualization & Reporting	Guidebook	<i>Capability Portfolio Analysis Tool, Communication, DoE, FACT, MCDA, Model Trading, QFD, Reporting, System Attributes, Tradespace Visualization, WSTAT</i>
63	Smead	2015	Technical Report	Government	Decision Support Tools	Tool Development	<i>Dashboards User Interface, Decision Support Tools, QFD, Tradespace Visualization</i>
64	Smith et al.	2007	Journal Article	Academia	Cognitive and Human Factors	Gap Analysis	<i>CMMI, Cognitive Bias, Decision Analysis, Preferences, Sensitivity Analysis, Uncertainty, Weighting</i>
65	Smith et al.	2008	Journal Article	Academia	Cognitive and Human Factors	Gap Analysis	<i>CMMI, Cognitive Bias</i>
66	Spaulding	2003	Thesis/Dissertation	Academia	Data Analysis and Optimization	Gap Analysis	<i>MATE, Pareto Frontier, Utility Theory</i>
67	Specking et al.	2018	Journal Article	Government	Unmanned Aerial Vehicle (UAV)	Case Study	<i>Decision Analysis, MBSE, SBD, TSE</i>
68	Specking et al.	2019	Conference Paper	Government	Unmanned Aerial Vehicle (UAV)	Case Study	<i>Model Validation, SBD, TSE</i>
69	Spero et al.	2015	Technical Report	Government	Engineered Resilient Systems	Gap Analysis	<i>Additive Value Model, Decision Analysis, ERS, TSE, Value-Focused Thinking</i>
70	Spero et al.	2014	Conference Paper	Government	Engineered Resilient Systems	Tool Development	<i>Data Reporting & Communication, ERS, M&S, Standard Interchange Methodology, System Attributes, Traceability, TSE</i>
71	Stump et al.	2009	Journal Article	Academia	Human-Machine Systems	Case Study	<i>Interactive Data Visualization, Tradespace Visualization, TSE</i>
72	NOAA	2012	Technical Report	Government	Decision Support Tools	Guidebook	<i>Documentation & Reporting, Risk Assessment, Sensitivity Analysis, SME, Stakeholder Communication, Uncertainty</i>

No	Author(s)	Year	Publication Type	Sector	Field of Study	Purpose	Keyword(s)
73	Pilato, J.	2019	Conference Paper	Government	Computing and Information Technology	Tool Development	<i>AoA, Architectural Integration, CCE, Computational Notebooks, CPE, CREATE-GV, Data Analytics, Data Visualization, Industry Partners, Integrated Capability & Workflow, Knowledge Management, MoP, Reduced Order Modeling, SME, Standards & Policies, SysML, TradeStudio Analytic Tools, Virtual Prototyping, VPG, Workflow Automation</i>
74	Tibor	2014	Thesis/Dissertation	Academia	Satellite Systems	Tool Development	<i>Interactive Data Visualization, MDO, ModeFrontier, TSE, Uncertainty, VDD</i>
75	Ullman & Spiegel	2006	Conference Paper	Government	Data Analysis and Optimization	Gap Analysis	<i>AHP, Belief Map, MAUT, Uncertainty</i>
76	Unal et al.	2015	Conference Paper	Academia	Cognitive and Human Factors	Case Study	<i>Cognitive Bias, Pareto Frontier, Scalability, Tradeoff Index, Tradespace Visualization</i>
77	Unal et al.	2018	Journal Article	Academia	Data Analysis and Optimization	Gap Analysis	<i>MODO, Pareto Frontier, TSE</i>
78	Witus & Bryzik	2015	Conference Paper	Government	Ground Vehicle Systems	Tool Development	<i>SBD, System Attributes</i>
79	Xiong et al.	2019	Journal Article	Academia	Additive Manufacturing	Tool Development	<i>Bayesian Networks, Data-Driven Approach, Gaussian Process Regression, Surrogate Model-based Method, TSE</i>
80	Yoe	2002	Technical Report	Industry	Data Analysis and Optimization	Gap Analysis	<i>Decision Analysis, Decision Support Tools, MCDA, Sensitivity Analysis, Tradeoff Index, Uncertainty, Utility Theory</i>

Appendix B:

Summary of Assigned Codes

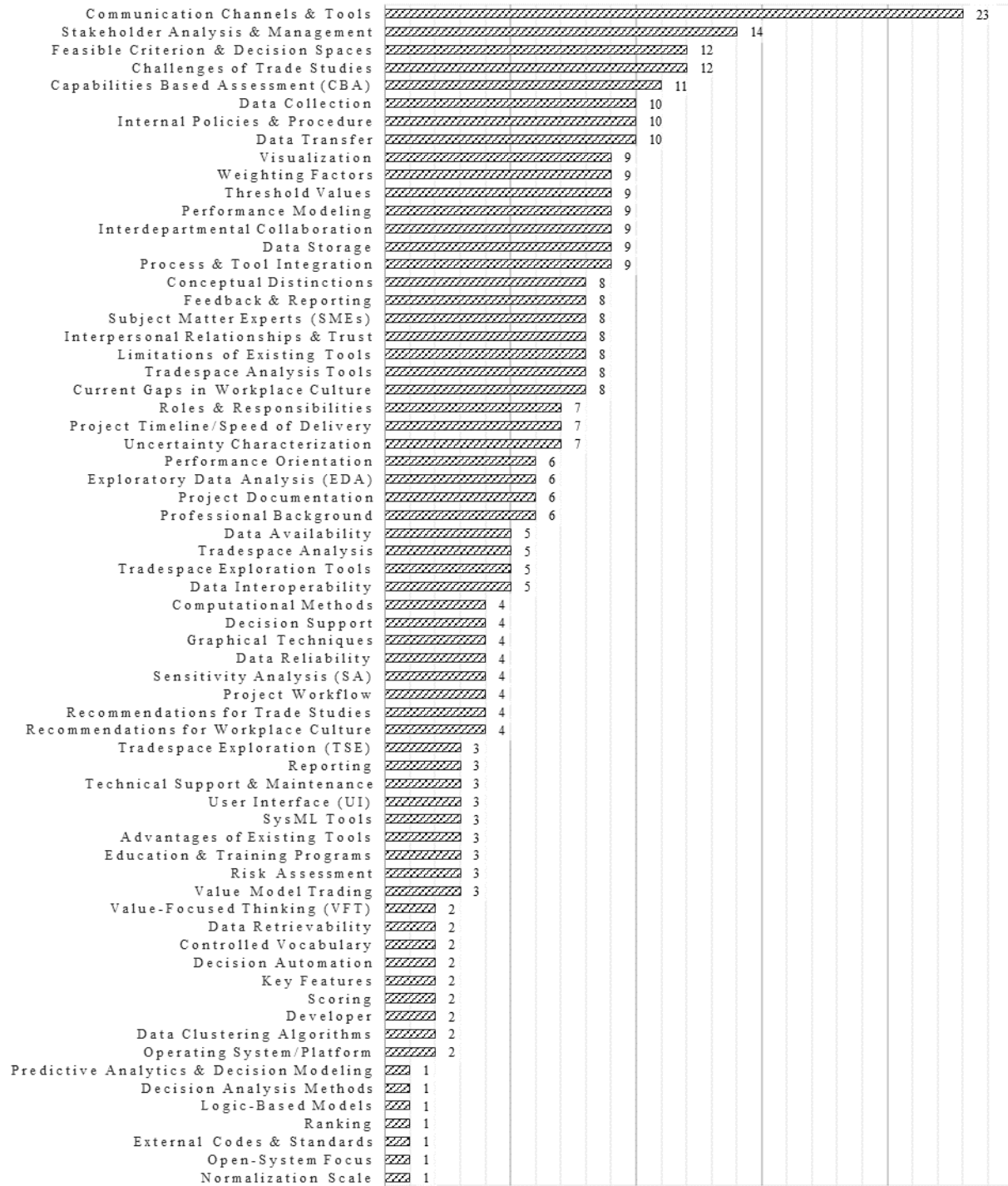


Figure B.1: Summary of codes from the interview data sorted by frequency

Table B.1: Example of keyword consolidation for coded interview data

Theme	Category	Unique Keywords	Hits
1	Defining the Tradespace	Conceptual Challenges	12
1	Defining the Tradespace	Conceptual Distinctions	8
1	Defining the Tradespace	Tradespace Analysis	5
1	Defining the Tradespace	Recommendations for Trade Studies	4
1	Defining the Tradespace	Tradespace Exploration (TSE)	3
1	Deterministic Methods	Capabilities Based Assessment (CBA)	11
1	Deterministic Methods	Value-Focused Thinking (VFT)	2
1	Model-Based Systems Engineering (MBSE)	Performance Modeling	9
1	Model-Based Systems Engineering (MBSE)	Value Model Trading	3
1	Probabilistic/Stochastic Methods	Uncertainty Characterization	7
1	Probabilistic/Stochastic Methods	Exploratory Data Analysis (EDA)	6
1	Probabilistic/Stochastic Methods	Sensitivity Analysis (SA)	4
1	Probabilistic/Stochastic Methods	Risk Assessment	3
2	Decision Strategies	Decision Automation	2
2	Decision Strategies	Decision Analysis Methods	1
2	Decision Strategies	Predictive Analytics & Decision Modeling	1
2	Evaluation Criteria	Threshold Values	9
2	Evaluation Criteria	Weighting Factors	9
2	Evaluation Criteria	Scoring	2
2	Evaluation Criteria	Normalization Scale	1
2	Evaluation Criteria	Ranking	1
2	Logic-Based Models	Logic-Based Models	1
3	Computational Methods	Computational Methods	4
3	Data Management	Data Availability	5
3	Data Management	Data Interoperability	5
3	Data Management	Data Reliability	4
3	Data Management	Data Retrievability	2
3	Tradespace Visualization	Feasible Criterion & Decision Spaces	12
3	Tradespace Visualization	Graphical Techniques	4
3	Tradespace Visualization	Data Clustering Algorithms	2
4	Advantages of Existing Tools	Advantages of Existing Tools	3
4	Database Management System	Data Collection	10
4	Database Management System	Data Transfer	10
4	Database Management System	Data Storage	9
4	Limitations of Existing Tools	Limitations of Existing Tools	8
4	Post-Processing Features	Visualization	9
4	Post-Processing Features	Decision Support	4
4	Post-Processing Features	Reporting	3
4	Software Evaluation Criteria	Process & Tool Integration	9
4	Software Evaluation Criteria	Technical Support & Maintenance	3
4	Software Evaluation Criteria	User Interface (UI)	3
4	Software Evaluation Criteria	Developer	2
4	Software Evaluation Criteria	Key Features	2
4	Software Evaluation Criteria	Operating System/Platform	2
4	SysML Tools	SysML Tools	3
4	Tradespace Analysis Tools	Tradespace Analysis Tools	8
4	Tradespace Exploration Tools	Tradespace Exploration Tools	5
5	Change Control Systems	Feedback & Reporting	8

5	Change Control Systems	Project Documentation	6
5	Change Control Systems	Open-System Focus	1
5	Communication Strategies	Communication Channels & Tools	23
5	Communication Strategies	Interdepartmental Collaboration	9
5	Communication Strategies	Interpersonal Relationships & Trust	8
5	Organizational Structure	Stakeholder Analysis & Management	14
5	Organizational Structure	Subject Matter Experts (SMEs)	8
5	Organizational Structure	Project Timeline/Speed of Delivery	7
5	Organizational Structure	Roles & Responsibilities	7
5	Organizational Structure	Performance Orientation	6
5	Organizational Structure	Professional Background	6
5	Organizational Structure	Project Workflow	4
5	Standards & Procedures	Internal Policies & Procedure	10
5	Standards & Procedures	Education & Training Programs	3
5	Standards & Procedures	Controlled Vocabulary	2
5	Standards & Procedures	External Codes & Standards	1
5	Strategic Assessment	Current Gaps in Workplace Culture	8
5	Strategic Assessment	Recommendations for Workplace Culture	4
