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A Research Agenda for Tradespace Exploration and Analysis of Engineered Resilient Systems

Eric Spero[a]*, Christina L. Bloebaum[b], Brian J. German[c], Art Pyster[d], Adam M. Ross[e]

[a]*U.S. Army Research Laboratory, Aberdeen Proving Ground, MD 21005, USA*
[b]*Iowa State University, Ames, IA 50011, USA*
[c]*Georgia Institute of Technology, Atlanta, GA 30332, USA*
[d]*Stevens Institute of Technology, Washington, DC 20004, USA*
[e]*Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

Abstract

This paper describes the activity of a workshop on Data-Driven Tradespace Exploration and Analysis: A Key Technical Thrust of Engineered Resilient Systems (ERS). The workshop was attended by 40 academic, government, and industry researchers and practitioners involved in tradespace exploration for a variety of engineering domains. The one-and-one-half day workshop sought to develop near and far term tradespace technology research recommendations for the ERS Priority Steering Council (PSC) Lead. To determine promising research areas, workshop attendees were asked to describe desired tradespace capabilities, the associated current approach and its deficiencies, and gaps between the two states. These research areas were summarized in statements of need, supporting rationale, and investment timeframe. Resilience in the context of ERS is more than robustness; resilience implies that when the system is placed into an environment in which it was not originally intended to operate, after some degradation in performance, the system can be adapted or reconfigured to perform at its intended levels. To support design for resilience, more alternatives must be generated earlier, considered longer, explored over multiple, dynamic alternative futures, and searched exhaustively. The workshop described in this paper was organized to discuss current methods, process, and tools for performing these tradespace analysis related tasks and to better understand existing tradespace capabilities and their suitability for ERS.

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* Corresponding author. Tel.: +1-410-278-8743; fax: +1-410-278-2994.
  E-mail address: eric.spero.civ@mail.mil

1. Background and Motivation

In April of 2011, the Secretary of Defense released a memorandum describing seven priority Science and Technology (S&T) investment areas for Fiscal Years (FY) 2013-2017[1]. One of these investment areas was identified as ERS, defined as "engineering concepts, science, and design tools to protect against malicious compromise of weapon systems and to develop agile manufacturing for trusted and assured defense systems."[1] ERS intends to transform the engineering of complex systems to make the resulting systems more affordable, effective, and adaptable. The intent is to enable engineers and decision makers to focus on the 'right' things during system development such that the end-product system is: 1) effective in a wide range of operations and 2) effective across multiple alternative futures.

At the time this workshop was conducted, the ERS priority area consisted of five key technical thrusts, one of which was Data-Driven Tradespace Exploration and Analysis. Upon transfer of the ERS PSC Lead role from the Office of the Secretary of Defense (OSD) to the U.S. Army Engineer Research and Development Center (ERDC) in late 2012, the focus of the tradespace thrust shifted slightly, from supporting four other key technical thrusts, to being the foundation for ERS tradespace analytics and decision support[2]. Tradespace analysis for ERS initially was, and remains, concerned with the generation of large numbers of alternative designs, early in the design process, and the evaluation of these multi-attribute designs across multiple dimensions such that more informed decisions can be made. Resilience in the context of ERS is more than robustness; resilience implies that when the system is placed into an environment in which it was not originally intended to operate, after some degradation in performance, the system can be adapted or reconfigured to perform at its intended levels. To support design for resilience, more alternatives must be generated earlier, considered longer, explored over multiple, dynamic alternative futures, and searched exhaustively. In generating and evaluating these alternatives throughout the design process, the concept of resilience is critical.

The workshop described in this paper was organized to discuss current methods, process, and tools for performing these tradespace analysis related tasks and to better understand existing tradespace capabilities and their suitability for ERS. A summary of workshop outcomes and tradespace challenges has been previously presented to the systems engineering community[3]. The current document provides workshop outcomes and recommendations.

2. Tradespaces for Engineered Systems

A tradespace is a multidimensional solution space in which information about design alternatives is displayed in order to allow decision makers to investigate how much capability in one metric must be given up in exchange for a specified capability in another metric (i.e., tradeoff), and to understand how much capability must be forfeited in order to achieve a feasible solution (i.e., compromise). A tradespace is a repository of qualitative and quantitative information that can be queried, filtered, and visualized in order to help reveal information to a person making a decision[4]. By visualizing the information in different ways (e.g., through rotation, translation, coloring, and sizing of graphical representations), decision makers can identify trends and features that reveal the most advantageous design solutions in terms of the trades that may need to be made.

The ERS tradespace is not envisioned simply to be populated with more design alternatives and additional metrics as compared to a traditional tradespace; it is envisioned to be interactive, to be capable of being supplemented with new information in real-time as the design process proceeds, and to include criteria not traditionally used in early-phase design-decision making because of inherent uncertainty or insufficient knowledge. The ERS tradespace is envisioned to be collaborative, persistent, updated, and consulted throughout the system lifecycle. It is expected to be a common interface, between multiple decision makers at multiple levels and stages of the design and development process, that indicates possible alternative systems, the compromises required for achieving them, and the effects of decisions made.

Historically, many individuals and organizations have indicated that they perform "tradespace exploration" for different purposes and using different techniques. The term "tradespace" therefore has different meanings to

different people. From the technologists and engineers, to the program-level decision maker, and to the user, the amount of technical detail needed to inform a decision varies. The amount of information to be included in the tradespace therefore needs to be tailored based on the conditional and subjective perspectives of multiple decision makers[5]. A significant goal of the ERS tradespace workshop was to discuss tailoring tradespaces to the needs of different decision stakeholders.

3. Workshop Objectives

The primary workshop objective was to capture the state of the art and the gaps in tradespace exploration (TSE) and analysis capability (e.g., theory, methods, processes, tools). Participants were asked to consolidate the identified gaps into actionable technology research areas, which would be used to guide tradespace research in support of enabling ERS as by the PSC Lead. A secondary objective was to identify opportunities for collaborative research in the area of tradespace studies. Questions for discussion included:

- How are tradespace studies conducted with current methods, processes, and tools?
- What are the needs for improved tradespace studies that would enable ERS goals?
- How essential are each of these needs and how far are we from achieving each of them?
- Where, and when, should we be investing to achieve each of these needs?

4. Workshop Format

The invitation-only workshop was targeted for academia, government, and industry involvement, including experts in optimization, modeling and simulation (M&S), data visualization, value-focused thinking, decision making, and trade studies. Four Armed Services were represented amongst the 40 participants. The workshop was conducted at the Potomac Institute for Policy Studies in Arlington, VA, and the U.S. Army Research Laboratory (ARL) planned and moderated the workshop agenda.

The workshop was conducted over one-and-one-half days. Day 1 included introductory briefings from the ERS Priority Area Lead and the ARL Tradespace Technical Thrust Lead, as well as introductory briefings from breakout session chairs in order to provide a basis for discussion during subsequent breakout sessions. Day 1 concluded with preliminary reports from the breakout session chairs. Day 2 was dedicated to conducting breakout sessions, and concluded with briefings from each group and a workshop wrap-up discussion.

The workshop was held in conjunction with a Tradespace and Affordability Program (TAP) workshop sponsored by the Systems Engineering Research Center (SERC)[6]. The purpose of the TAP workshop was to bring together researchers from various SERC collaborator universities, Department of Defense (DoD) sponsors, potential transition partners, and other experts in the tradespace and affordability area, with the primary objective of establishing the near-term direction for the SERC's TAP initiative. The definition of the TAP tradespace was specific to exploring how to better create and analyze the tradespace of "ilities" (e.g., affordability, flexibility, reliability, usability, and interoperability). It was envisioned that the TAP and ERS tradespace efforts would inform each other and establish a basis for continued cooperation.

5. Workshop Proceedings

5.1. Introductions

Dr. Robert Hummel, Chief Scientist, Potomac Institute for Policy Studies provided a welcome and overview to all attendees. He described the mission of the non-profit Potomac Institute for Policy Studies as public policy research that integrates business and government interests into meaningful options.

Dr. Robert Neches, Director, Advanced Engineering Initiatives, Office of the Deputy Assistant Secretary of Defense, Systems Engineering/ERS PSC Lead, provided an overview of the ERS priority area[7]. Although all of the attendees had received public release briefing materials on ERS and Tradespace Analysis with their invitations, not all attendees were intimately familiar with ERS. This briefing provided a succinct overview of the background,

motivation, end state description, and a possible development path for ERS. Dr. Neches explained that the ERS PSC has collected information on nearly 50 related research programs across DoD, however there are gaps that these programs are not addressing. Dr. Neches went on to state that TSE technology solutions need to be identified for the purpose of closing the gaps, in order to achieve the vision of ERS. He provided a list of major tenets of ERS: earlier, better-informed decision making; better data repositories, deeper analyses, and more options considered longer; a balance between performance, cost, and capability; using hardware and sensors to learn user needs; and implementing use cases that are generated from user interests and needs.[7]

Mr. Elias Rigas, Chief, Vehicle Applied Research Division, ARL/ERS Data-Driven Tradespace Exploration and Analysis Thrust Area Lead, provided an introduction to the ERS Tradespace thrust. The briefing discussed TSE within the context of ERS, as well as the workshop goals. Mr. Rigas stressed that the tradespace thrust of ERS must aid in communicating to decision makers what they are investing in, and where they should be investing. Additionally, the ERS tradespace needs to be expanded to include the tacit information that decision makers use, such as affordability, manufacturability, and reliability.

5.2. Breakout Groups

Attendees were assigned to individual break groups that were formed based on perceived functions of TSE. Prior to the workshop, the lead for each of the breakout groups was invited to prepare a 10-minute introduction of their breakout area. The intent was to give the breakout leads the ability to mold the breakout sessions around how they envisioned the problem, as well as provide an informal overview of each breakout area to all attendees. In this way, all attendees would be exposed to the background and main discussion points encountered by all groups. This also gave the attendees an opportunity to submit questions and topics for breakout sessions in which they were not scheduled to participate.

5.2.1. Broadening, Populating, and Managing the Tradespace
Dr. Art Pyster, Deputy Director of the SERC, provided his perspective on broadening the tradespace. Dr. Pyster posited that the premise of being able to select the "best" choice in a tradespace assumes that the tradespace contains a sufficient number of feasible/viable design alternatives as measured by the criteria against which the alternatives will be ranked, scored, or selected. An important question is whether sufficient information exists to adequately describe alternatives in the tradespace, and whether this information is stable, complete, robust, integrated, and even appropriate for quantitative or qualitative analysis. With multiple stakeholders, each with differing attribute preferences, there is a need to ensure that necessary and sufficient information is included in the tradespace. Dr. Pyster asked his group to think about qualitative data in a tradespace and what it 'looks like' (e.g., security, policy, safety). Although decision makers use this information in their decision making process, there are challenges pertaining to how these broad qualitative concepts can be included in the tradespace in a manner that would allow either humans or machines to evaluate.

5.2.2. Linking the Tradespace
Dr. Christina Bloebaum, Dennis and Rebecca Muilenburg Professor of Aerospace Engineering at Iowa State University, provided her perspective on linking the tradespace to the analysis/design environment and to the decision making environment. Although there is a desire to have the tradespace communicate bi-directionally with data-generating models and the decision making environment, there are technical and policy challenges to doing so. Some of these challenges include incomplete, inconsistent, and incompatible data provided from multiple sources at multiple times. Dr. Bloebaum asked her group to think about mechanisms for establishing links into and out of the tradespace, and how these links could enable more effective TSE.

5.2.3. Searching, Exploring, and Analyzing the Tradespace
Dr. Brian German, Assistant Professor in Aerospace Engineering and Associate Director of the Aerospace Systems Design Laboratory (ASDL) at the Georgia Institute of Technology, provided his perspective on searching the tradespace. Dr. German posed a question of how do humans, viewing a graphical representation of tradespace data, know when a feature or tradeoff worthy of further analysis has been discovered. There are fundamental

questions of what outcomes are being sought - an optimum (maximum/minimum), a single solution, a family of solutions, points of discussion, areas of compromise, or other features. Dr. German asked his group to think about how solutions such as search methods, novel graphics, and classification algorithms could be applied to TSE.

5.2.4. Acting on the Tradespace

Dr. Adam Ross, Lead Research Scientist in the Systems Engineering Advancement Research Initiative of the Massachusetts Institute of Technology, provided his perspective on acting on the tradespace. He pointed out that decision makers may come to consensus on the best design option, but that this decision is based on the current scenario. Dr. Ross asked his group to consider how changing operational contexts can affect the makeup of the tradespace, and ultimately the decision; changing operational contexts, lifecycle changes, and technology improvements can change a design currently described as 'bad' into a 'good' design. If it were possible to fully explore these possibilities, planning could then be tailored around them. Dr. Ross also presented his group with a challenge stemming from two types of decision makers involved in acting on the tradespace: technical leadership, who desire a holistic view of the system, and financial leadership, who desire highest cost-benefit and probability of success concepts.

5.2.5. Modeling and Simulation's Role in Generating Tradespace Data

Ms. Philomena Zimmerman, Deputy Director of Modeling, Simulation and Analysis in the Office of the Assistant Secretary of Defense, provided her perspective on an area pertinent to all four breakout areas (though was not a breakout area on its own): a common system description and design model. If such a common system model existed there could be consistency and re-use of data objects, which would create consistency across TSE. Rather than new, flat models being created to represent new instances of components and then linked across subsystems and domains, formal and rich models would be drawn from a repository (i.e., reused) to build a cohesive representation of what the system is and does. With this approach the system model would be dynamic and usable in simulations as opposed to just being a mechanism for generating static data points.

6. Breakout Group Summaries

The primary output of this workshop is the recommendations put forth by each breakout group, phrased as concise research areas of interest. Although the overall topic area name is necessarily an aggregate description, the supporting rationale and the observations together provide sufficient detail to define the research areas. It is expected that these recommendations will serve as reference points for the current ERS leadership to initiate tradespace research activities in the near and far term. The technology investments were binned into near- (1-3 years), mid- (3-5 years), and far- (5-7 years) term needs.

6.1.1. Broadening, Populating, and Managing the Tradespace

The Broadening, Populating, and Managing Breakout Group identified a total of six key technology investments, all of which are near-term needs. Each is discussed briefly here.

6.1.1.1. Characterizing the "ilities" (BPM1)

Data characterizing the "ilities" of tradespace options is often missing or inadequate, even though the quality of those ilities has a material impact on the relative value of the options to the stakeholders. Research is needed in: (a) methods and tools for integrating the analysis of physical, informational, and human characteristics of systems; (b) standardization of "ility" terminology and concepts to facilitate communication among stakeholders; and (c) languages and tools to express and analyze ilities in quantitative terms that can be understood by diverse stakeholders so they can state their preferences and understand the implications of those preferences. With such languages and tools, it would also be easier to establish incentives and monitor how well contractors are realizing ilities during system development. Developers need to hire staff with requisite skills, grow organically, or outsource. Researchers need to create more intuitive tools and methods, develop agreed upon terminology to express ilities, and build cross-impact models and relationships that quantitatively determine the impact of changing one ility on the other ilities.

6.1.1.2. Future Environments and Scenarios (BPM2)

Anticipated and possible future operational environments and user scenarios are usually not stated in sufficient detail to support tradespace evaluation. Research is needed to create general toolkits to rapidly assemble concepts of operations in multiple domains in a way that vividly communicates to diverse stakeholders and can be translated into parameters for a model of the system. Milestone decision authorities should insist on exploring possible future scenarios. Systems Engineering practice should be involved in very early phases of the lifecycle, in parallel with S&T activities. For example, applying holistic system cost models to justify greater expenditures early in lifecycle for the purpose of reducing total cost of ownership (TOC). Research should be conducted to develop better ways to understand which constraints drive the value of the system, measuring robustness at the scenario level, and diversifying those who evaluate scenarios.

6.1.1.3. Affordability (BPM3)

Affordability, an ility worthy of special note, is often not addressed during trade studies (which often focus on technical aspects of trades apart from the cost implications across the full lifecycle, including manufacturing, operations, and maintenance). Better TOC methods and tools are needed that account for system of systems, avoid suboptimization on colors of money across the lifecycle, and avoid suboptimization around different phases of the lifecycle such as S&T, development and manufacturing, and support. As these methods and tools emerge, they should be applied in contracts.

6.1.1.4. Missing Data (BPM4)

The government often doesn't require contractor data to be submitted in formats that facilitate analysis or comparisons across alternative designs (e.g., using standard formats or engineering models). The government should require submission in standard formats that are amenable to automated analysis and include more intellectual property (IP) clauses into contracts.

6.1.1.5. Tradeoffs Not Considered (BPM5)

The tradeoff of greater risk vs. greater performance, lifecycle cost, or another desirable system characteristic is often not properly considered. The government and developers should: (a) provide technology maturation funds to advance lower readiness level technology up to levels 6 and 7; (b) recognize that technology readiness levels (TRL) are system dependent; and (c) compare alternative technologies using effectiveness models at the mission level such that systems are simulated in their intended operational environments.

6.1.1.6. Historical Knowledge (BPM6)

Historical knowledge that could inform the creation and/or evaluation of options is often not captured and made readily accessible at the enterprise level, making it difficult to recognize and apply that knowledge when needed. Limited access to previously developed knowledge and other artifacts such as engineering models and system architectures result in regeneration of data rather than reuse of existing data.

6.1.2. Linking the Tradespace

The Linking Breakout Group identified a total of six key technology investments, with four near-term (L1-L4) and two mid-term needs (L5-L6).

6.1.2.1. Standard Interchange Methodology (L1)

The participants recognized that the need to link the tradespace capability to design and decision-making environments should be bi-directional. Not only should these environments inform the tradespace, but the tradespace should inform the environments. In order for this to become practical, however, it is recognized that a standard interchange methodology must exist to provide for the greatest inclusion of externally provided or available tools, as well as data. Such a methodology should be scalable to address any size of tradespace, as well as the needs of the different stakeholders and decision makers. It is critical that such an interchange methodology be platform independent, enabling the greatest breadth of tools to be supported.

6.1.2.2. Knowledge Management Infrastructure (L2)

Separate from the Interchange Methodology listed in L1 is the need for an infrastructure that will provide for rigorous treatment of data storage, interchange and reuse for knowledge being generated as well as used. The needed knowledge management infrastructure should facilitate the ability to link across tools and environments. Such an infrastructure would provide for longevity of data and knowledge, which would, given trust and confidence factors as well as uncertainty representations, enable use of the data over the long term despite any changes in personnel or organizational reorganization. Additionally, such a knowledge management infrastructure will enable the linking of the elements supporting a decision to the actual decision being made.

6.1.2.3. An Engineering Modeling Framework (L3)

At present, there is no formal mechanism for ensuring information integrity from the earliest stages of the design process through to the later stages, and then back again. In order to achieve the desired bi-directional linking of design and decision environments to the tradespace environment, a framework must exist to provide for a unifying approach that is used across all participating groups in the process.

6.1.2.4. Conceptual Design Toolbox (L4)

At present, the conceptual design stage of a large-scale engineered system development process relies heavily on a tradespace capability. It is at this stage that the greatest flexibility exists to make meaningful trades in a system's context. Yet, there are no standardized methods or tools to support the trades necessary. The common tools used today are often discipline-specific and rarely enable an understanding of how decisions will impact the larger system preference. Having a mechanism to enable quick assessment of 'goodness', with an ability to scale to large systems, would be extremely advantageous. Having the ability to link these modeling capabilities to those that would be used in detailed design stages is also critical. This would better enable a seamless propagation of modeling and simulation from early stages in the process through to the later stages, and vice versa.

6.1.2.5. System Architecture Representation (L5)

It is recognized that organizational structure often drives the system architecture, resulting in an undue influence on the outcomes of a system product. Hence, a need exists for a system architecture that will maintain the representation of the system regardless of organizational structure. Such an architecture should then enable bi-directional trades for all decision makers in the process (across all levels of stakeholders) as well as across the lifecycle of the system.

6.1.2.6. Tradespace Consistency (L6)

Different stakeholders will require different information at different times in the lifecycle of a system. Hence, the tradespace environment should provide a seamless consistency and continuity across all stakeholders, with the appropriate level of fidelity being automatically identified and supplied. This consistency is particularly important to enable the bi-directional linking desired for the tradespace.

6.1.3. Searching, Exploring, and Analyzing the Tradespace

The Searching, Exploring, and Analyzing Breakout Group identified a total of 10 key technology investments, with three near-term (SEA3, SEA7, SEA9), two near-to-mid-term (SEA1, SEA8), one mid-term (SEA5), one mid-to-far-term (SEA10), two far-term (SEA4, SEA6), and one need spanning the near-far spectrum (SEA2).

6.1.3.1. Communicating Tradespace Data (SEA1)

Guided TSE with decision makers in the loop. Capabilities are needed to illustrate design decisions and the impact of constraints/objectives in interactive sessions. This interaction capability should be able to queue analyses with linked tools on demand and in near real-time based on questions by decision makers. Desire interactive scenarios and storylines that anticipate the interests of decision makers, show traceability in previous tradespace analysis, and indicate how recommended designs were found by design engineers and technologists. Approaches to design and automatically produce effective summary graphics/reports for decision makers.

6.1.3.2. Interactive Visualization (SEA2)

Effective visual representations of time series data for dynamics in the physical system and for changes in the tradespace over time. Graphics that efficiently and effectively present n-D tradespace data by going beyond the state-of-the-art in current 2-D and 3-D views. Innovative interaction paradigms that can identify and manipulate sampled designs within the tradespace more holistically than traditional control paradigms such as slide bars and brushing. Intuitive visualizations must be readily internalized by the viewer, efficiently communicating meaning.

6.1.3.3. Preserving Tradespace Search Decisions and Rationale (SEA3)

Customizable and automated features to record the tradespace search activity (e.g., paths taken by the user through the tradespace, time stamps and user annotations, audio/video recording). Ideally, these features should allow users to record tradespace sessions in a way similar to screen video capture software, but with much richer tradespace-specific features. Post-processing algorithms and interfaces would allow a user to refine these recordings into a presentation format for documenting the design process. Additionally, the capability could be used to develop recordings to educate engineers on best practices in TSE.

6.1.3.4. Incorporating the "ilities" (SEA4)

Methods to facilitate TSE and valid decision making when metrics such as "ilities" are involved. The ability to understand the impact of, or characterize the uncertainty in, using such "ilities" in the design process could aid in streamlining, potentially reducing the risk of over-designing only to have an "ility" invalidate previous decisions.

6.1.3.5. Search and Sampling Algorithms (SEA5)

Effective and efficient search and sampling methods that better span the space and/or zoom to particular regions at a specified or pragmatic computational cost. Multi-fidelity search approaches to leverage more rapid analysis tools while tracking and managing error with higher fidelity tools. Dynamic emulation and identification of primary processes to inform search and bridge the gap between fidelity tiers. Mechanisms are needed to guide searches based on selective dimensions, while still tracking other dimensions.

6.1.3.6. Identification of Tradespace Features (SEA6)

Approaches to filter and/or identify interesting areas of large tradespaces prior to or during interactive exploration. Novel classification and pattern recognition algorithms that allow humans to identify abstract and previously unknown objectives and constraints by interaction with tradespace graphics. Similar algorithms could help to guide search to interesting regions based on observations of past search behavior by the designer and/or a more informal specification of the search objectives than with classical optimization approaches.

6.1.3.7. Applying Uncertainty to the Tradespace (SEA7)

Formal understanding of the relevant types of uncertainty that are involved in the tradespace problem and systematic approaches to model and mitigate these uncertainties. Identification, attribution, and characterization of sources of uncertainty are crucial to this process. Uncertainties also imply additional tradeoffs (e.g., one may pay more to achieve less variability in system performance through additional expenditures during the design process or by designing additional robustness into the system). There is a need for research into paradigms for representing and managing tradeoffs based on uncertainty.

6.1.3.8. Applying Formal Decision Making Models to TSE (SEA8)

Descriptive, prescriptive, and normative decision making models for TSE activities. Formal processes that seek to drive irrationality and misalignment of incentives out of the decision making process. Characterization of how TSE leads to decision making in the engineering of complex systems.

6.1.3.9. Characterizing and Trading Resilience, Robustness, Flexibility, and Adaptability (SEA9)

Formal domain-specific and domain-independent metrics to define and assess resilience, robustness, flexibility, and adaptability of engineered systems for use in TSE and decision making. Models to evaluate and trade these

metrics relative to the overall system requirements and value proposition; if a goal of ERS is the design of resilient systems, then resiliency must be quantified, modeled, and included in the system tradespace.

6.1.3.10. Systematic Appending and Reduction of the Tradespace (SEA10)

Multi-step approaches to manage the propagation of design decisions and the tradespace itself over time during system development. Specific desired capabilities include: (a) archiving tradespaces at each phase in the systems engineering process; (b) systematically narrowing the set of designs under consideration using new knowledge; (c) identifying optimal recourse actions and points of reversion to prior decision points; (d) systematically quantifying and reducing uncertainty at each phase; (e) illustrating the reduction of the available tradespace as decisions are incrementally locked in and/or as requirements change; and (f) valuation and options pricing formulations as an aid to decision making at each phase in the development process.

6.1.4. Acting on the Tradespace

The Acting Breakout Group identified a total of 14 key technology investments, grouped here into four areas, with two near-term (ACT1, ACT3), one near-to-mid-term (ACT4), and one spanning the near-far spectrum (ACT2). The individual investment area components developed at the workshop are indicated with an "A#".

6.1.4.1. TSE Foundations (ACT1; A1, A2, A12, A16)

TSE Foundations seeks to establish foundations for purposefully conducting TSE to support decision making. A1: If tradespaces are expected to be the basis for design decisions, then it is critical to understand what these key decisions are. A set of key decisions should be developed that allow for focused, purposeful execution and continuous improvement of TSE. A2: Previously conducted TSE can provide insights and lessons as leverage towards understanding how TSE actions and decisions have impacted historical systems. Understanding these links can reveal the impact that formal, consistent TSE can have on a system. A12: Build upon, rather than reinvent, knowledge gained from early phase TSE. Apply the knowledge gained from prior decisions by using formal/informal codification of lessons and insights, and use this as leverage throughout the lifecycle and across different programs. A16: As tradespaces are to be the foundation for decisions, as well as the repository for decision rationale, then fundamentals must be established for conducting TSE. Further, there must be advocacy for the development of TSE education and training; rather than continued dependence on portions of TSE research and knowledge scattered across multiple domains, fuse this content into its own core capability.

6.1.4.2. TSE Process (ACT2; A4, A5, A6, A9, A15)

TSE Process seeks to establish best practice for TSE. A4: Interrogate and update tradespaces within the context of a seminar or workshop to develop group decision maker buy-in. Interactive sessions with real-time feedback are expected to increase trust of the tradespace and therefore increase confidence in TSE-based decisions. A5: Desire the ability for TSE to be useful even with incomplete information. Nontechnical factors and unarticulated objectives are often omitted from the tradespace, but are influential in decision making. A6: Guidelines are needed for knowing when one has performed "best practice" TSE. Varied formalism in TSE tools, processes, and execution due to lifecycle phase and system complexity must be overcome. A9: Desire a mechanism for conferring legitimacy/accountability to TSE to allow for incorporation in existing acquisition process. A15: Desire a formalized, iterative, sequential TSE process to avoid decisions based on trial-and-error TSE.

6.1.4.3. TSE for Resilience (ACT3; A7, A11)

TSE for Resilience seeks to establish ways to explicitly consider system resilience in the tradespace. A resilient system solution is no longer just materiel – it includes strategies for sustainment. A7: Evaluate system alternatives across appropriate types and quantities of alternative futures, and discover which scenarios "break" the system. A11: Means for generating, evaluating, and valuating a set of adaptability approaches with designs to deliver value robustness and resiliency across alternative futures.

6.1.4.4. TSE Throughout the Lifecycle (ACT4; A3, A8, A10, A13, A14)

TSE Throughout the Lifecycle seeks to establish the tradespace as a decision enabler. A3: Consistency and compatibility of TSE activities throughout the lifecycle, eliminating inconsistent assumptions and making previous tradeoff insights both transparent and capable of being revisited. A8: Trace preferences and decisions across the lifecycle and the system hierarchy. Understand how sequential TSE-based decision making limits the system value achievable. A10: Counter increasingly large tradespaces by using human expertise and metrics as appropriate "filters" for effective decision making. A13: Use TSE-based decisions to help set requirements and also understand how requirements drive system value. A14: Desire for TSE to support multi-stakeholder collaboration, creating the ability to quickly identify and focus on conflicts and confluence among decision makers.

7. Workshop Conclusions and Next Steps

Many methods, processes, and tools have been developed to generate, store, manipulate, search, and act upon data in a decision making environment. However, the process of performing tradespace analysis for exploring the realm of feasibility, and demonstrating that sufficient knowledge of the system has been generated for decision making, is inconsistent and has little reuse across multiple tradespace explorers. Issues of uncertainty propagation, subjective data, high-dimensional spaces, static and flat visualizations, combinatorial what-if scenarios, feature identification, and retention of data throughout a lifecycle have not been sufficiently addressed. These and other gaps partially exist because there appears to be interchangeability in the lexicon of related terms such as trade-off study, optimization, alternative analysis, and value-focused thinking. The breakout group results presented here show that there is necessarily some amount of overlap in the defined breakout group functions, evident by repetition in needs. This bolsters assumptions that TSE is a collaborative effort in support of the decision making process throughout a system's lifecycle, there is no independent function of "perform tradespace exploration", and the responsibility to support decision making is shared across those who generate, store, search, and act on data.

The research agenda presented here is intended to illuminate gaps and challenges, for the purpose of advancing research in tradespace analysis methods, processes, and tools from their current capability to that desired for realizing the ERS vision. It is expected that government, industry, and academic research organizations will refer to these gaps and challenges to purposefully align their tradespace exploration research efforts.

Acknowledgements

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