SYSTEMS ENGINEERING
Research Center

Engineered Resilient Systems – Systems Engineering: Knowledge Capture and Transfer

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PURPOSE OF RESEARCH

Engineered Resilient Systems (ERS) is one of the seven DoD Science and Technology (S&T) Priorities. The ERS program is evolving a framework and an integrated, trusted computational environment supporting all phases of acquisition and operational analyses. Resilient systems necessitate data-driven, richly informed decisions. Achieving resilience in the past has relied on expertise of experienced senior decision makers using deep knowledge of their systems within their context. In support of the ERS tradespace analysis goals, this research is motivated by the pressing concern in the defense-related industry and government of the aging workforce. The resulting wave of impending retirements of experienced personnel may lead to lost knowledge and inability to recreate past systems, let alone develop new ones of growing complexity. The concern over lost expertise, including both in-domain as well as systems-level thinking is a real one, and one that has received growing attention. Using a structured technique, it has been shown that novices can approach expert-like strategies in the use of visual tradespace exploration for decision-making. Additionally, tradespace exploration has been shown to be useful as a "boundary object" fostering cross-domain conversations, and facilitating decision making for complex systems. Such tradespace results are promising in representing a means for capturing and transferring expert knowledge and skills. In this project, the research team gathered expert knowledge and synthesized emerging ERS-related research, toward a goal enabling novices to have expert-like decision capability through encoded knowledge and data-driven tradespace analysis framework and integrated tool suite.

WORK ACCOMPLISHED

Task 1. Knowledge and Information Gathering. The research team investigated current and recent past briefings and literature related to engineered resilient systems, and specifically to tradespace exploration. Multiple discussions were held with government leaders, university researchers, practitioners. Given the importance of tradespace exploration (TSE), the team focused its efforts in this regard given the limitations of time and resources in this research project to date.

Task 2. Artifact and Knowledge Coding. Using the gathered information and insights, and the ongoing research of the team members, the key ERS-relevant artifacts were identified. The research team mapped these artifacts to the MPTs derived from the knowledge and information gathering performed in Task 1.

Task 3. Exploration Case Study. This task was initially intended to conduct an exploratory case study to identify tradespace exploration artifacts in practice and how they relate to knowledge goals within ERS. Unfortunately delays in data availability cut short the intended timeframe across which to perform this case study. As an alternative approach, the research team was able to generate some observations based on limited data availability to two Navy tradespace exploration activities conducted in concert with the ERS Program.

Task 4. Full Scale Case Study Design. Based on the results of the information gathering and observed exploration case studies, the research team developed some initial requirements for designing a larger full scale case study.

Task 5. Synthesize Preliminary Prescription for ERS Artifacts for Knowledge Capture/Transfer. Using the results of tasks 1 – 4, the research team enumerated some potential gaps and findings, along with suggested enablers for consideration in evolving the ERS framework and tool suite environment in support of the its tradespace analysis goals.

FINDINGS

A number of next steps were identified over the course of this research which would enhance and enable the ERS vision, specifically as related to tradespace exploration activities. These include:

- Efforts to begin compiling appropriate knowledge relative to the core constructs identified in this projects including past needs, contexts, constraints, design space, performance space, value space, performance model, value model, lessons learned, language, case examples, and tools.
- Research into effort vs. confidence tradeoffs so that projects can scale effort on various activities within the TSE process to match their needs subject to available resources.
- Development of fidelity tradeoff guidance and associated tools so that studies can scale TSE implementation appropriately.
- Explicit incorporation of resilience-related ilities evaluation into the ERS architecture, including model libraries and decision analyzer toolset.
- Inclusion of value models along with performance models in the model data store.
- Continued piloting of parts of the ERS associated TSE processes, as well as full end-to-end studies.
- Continued community building by the ERS program, including offices such as the various A9 (e.g. AF/A9, OAS, AFSPC/A9, etc.) and other entities with responsibilities overlapping with proposed ERS vision and capabilities
- Further research into supporting enabling methods, processes, and tools that can facilitate TSE knowledge capture and reuse, as well as resource-effective studies that can quantify and identify resilient, high value system solutions in diverse application.

RESEARCH RESULTS

The research team gathered expert knowledge and synthesized emerging ERS-related research, toward a goal enabling novices to have expert-like decision capability through encoded knowledge and data-driven tradespace analysis framework and integrated tool suite.

NEXT STEPS

- The research team will be using knowledge and information gained in this study to inform its work on RT-122, Interactive Model Centric Systems Engineering (IMCSE) and RT-113 Ilities Tradespace and Affordability (ITAP), and share with other relevant SERC projects.
- The research team will be using the results of this investigation toward the development of a publishable paper to transfer findings to the broader systems community.
- The specific findings will be shared with the ERS sponsor and its technical team and partners (see Figure 1) in appropriate discussions, workshops and research exchanges to potentially influence and extend the ongoing initiatives in support of the ERS vision.

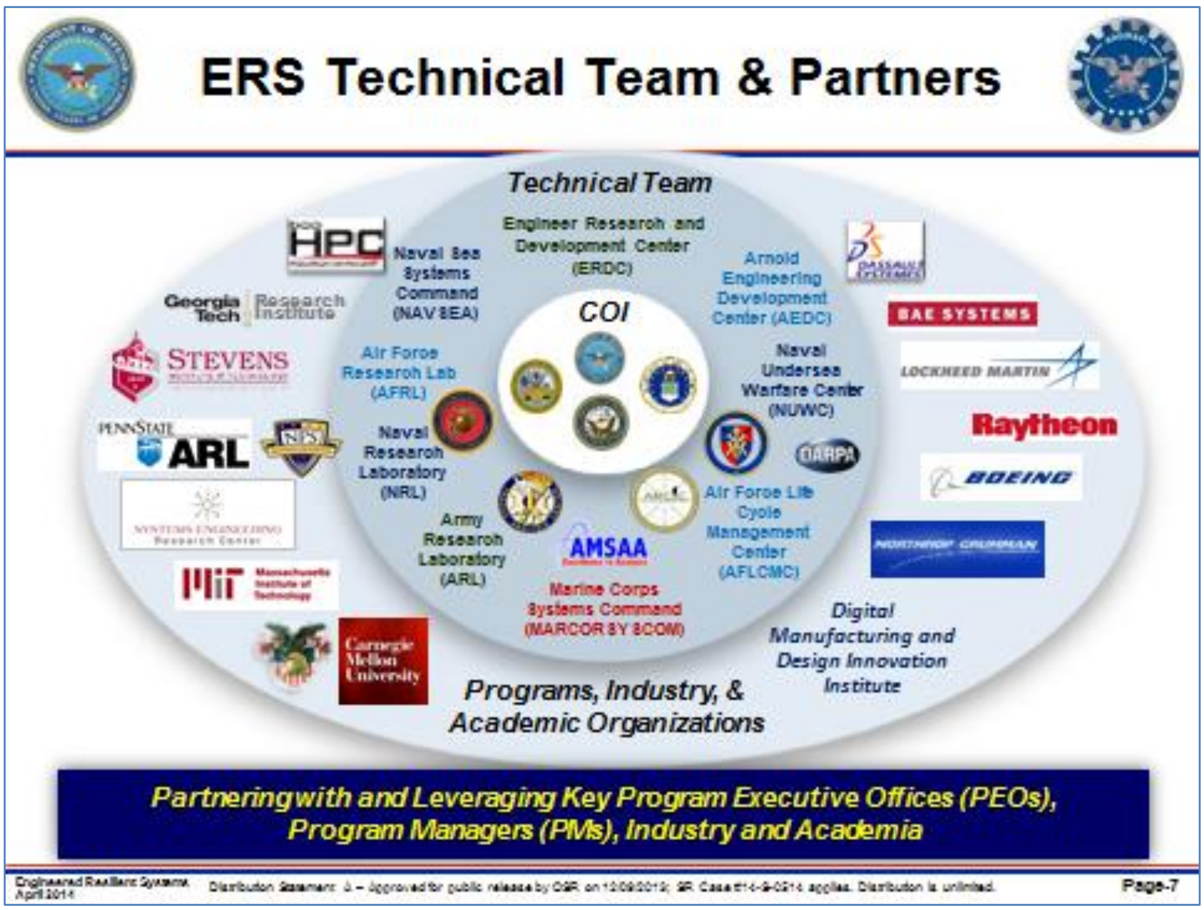

Figure 1: ERS Technical Team and Partners[1]

[1] Holland, J.P., Engineered Resilient Systems (ERS), Briefing, May 21st, 2014

INTRODUCTION

Engineered Resilient Systems (ERS) is one of the seven DoD Science and Technology (S&T) Priorities. The ERS program is evolving a framework and an integrated, trusted computational environment supporting all phases of acquisition and operational analyses. Resilient systems necessitate data-driven, richly informed decisions. This research is in support of ERS, and specifically focuses on tradespace exploration and its contribution to achieving the ERS vision.

MOTIVATION

Achieving resilience in the past has relied on expertise of experienced senior decision makers using deep knowledge of their systems within their context. In support of the ERS tradespace analysis goals, this research is motivated by the pressing concern in the defense-related industry and government of the aging workforce. The resulting wave of impending retirements of experienced personnel may lead to lost knowledge and inability to recreate past systems, let alone develop new ones of growing complexity. The concern over lost expertise, including both in-domain as well as systems-level thinking is a real one, and one that has received growing attention[2]. Using a structured technique, it has been shown that novices can approach expert-like strategies in the use of visual tradespace exploration for decision-making. Additionally, tradespace exploration has been shown to be useful as a "boundary object" fostering cross-domain conversations, and facilitating decision making for complex systems. Such tradespace results are promising in representing a means for capturing and transferring expert knowledge and skills.

Over time, the knowledge of a practicing engineer progresses across a spectrum, from factual to conceptual to procedural to meta-cognitive, with these levels reflecting a growing level of depth to the knowledge content. One of the key differences between novices and experts is the ability for "meta-cognitive" thinking. The "meta-cognitive" level encompasses a higher order knowledge of being "self-aware" of the knowledge itself (e.g. "thinking about thinking"). Experts develop this skill after years of experience, increasingly focusing on the deeper levels of knowledge, and requiring them to "question their assumptions" in order to understand the limits of their perceptions, cognitions, and conclusions.

Not all engineers can achieve this type of skill[3], and even if they did, it may take a long time to develop. As a consequence of time, complexity, and expertise constraints, often engineers must rely upon models, methods, processes, and tools (MPTs) to encapsulate, abstract, analyze, and synthesize solutions to their problems. Particularly attractive to resource-constrained practitioners are "tools," which appear to have an attractive ratio of effort to apply versus benefit obtained. In this context, a "tool" is something that codifies knowledge as an "automated or semi-automated" set of steps in a process, thereby "enhancing process performance efficiency"[4].

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[2] Lamb, C.M.T., *Collaborative Systems Thinking: An exploration of the mechanisms enabling team systems thinking*, Doctor of Philosophy Dissertation, Aeronautics and Astronautics, MIT, September 2009

[3] Rhodes, D.H., Lamb, C.T. and Nightingale, D.J., "Empirical Research on Systems Thinking and Practice in the Engineering Enterprise," 2nd Annual IEEE Systems Conference, Montreal, Canada, April 2008.

[4] Turner, R., Shull, F., Boehm, B., Carrigy, A., Clarke, L., Componation, P., Dagli, C., Lane, J., Layman, L., Miller, A., O'Brien, S., Osterweil, L., Sabados, D., and Wise, S., "Evaluation of Systems Engineering Methods, Processes and

The automation aspect is what appears to lead to reduced effort to apply, as opposed to the time required when working from first principles to solve problems, for example.

An example of tool use is in the area of tradespace exploration. Tradespace exploration is the quantitative comparison of large numbers of system alternatives to develop knowledge of costs and benefits, as well as their relative feasibility. Using a structured technique, it has been show that novices can approach expert-like strategies in the use of visual tradespace exploration for decision-making[5]. Additionally, tradespace exploration has been shown to be useful as a "boundary object" fostering cross-domain conversations, and facilitating decision making for complex systems[6 7]. Such tradespace results are promising in representing a means for capturing and transferring expert knowledge and skills.

In fact, "data-driven tradespace exploration" has been explicitly described as one of five key areas within the ERS program[8 9]. More generally, solutions that could deliver similar benefits, but at lower cost, would not only help to alleviate the financial challenges facing government today, but also increase the efficiency of US industry in an increasingly competitive global marketplace.

The US Department of Defense has recognized the potential benefits of tradespace exploration as strongly enabling "Data to Decisions" and "Engineered Resilient Systems" (ERS), two out of seven key OSD Science and Technology Priorities for Fiscal Years 2013-17 Planning[10].

The benefits of an ERS approach go beyond finding potential solutions improving cost-benefit efficiency. In particular, an engineer must expand the space of considered alternative solutions to encompass not only technical aspects, but also the potential contexts in which they might operate. In their vision of what it means to be an Engineer of 2020, the National Academy of Engineering described engineering systems professionals with the knowledge and skills who can better confront significant societal problems, rife with the challenges of changing contexts (e.g., technologies, social conditions, and policies)[11]. In order to meet this vision, the set of ERS artifacts that could make up the Engineer 2020 repertoire must incorporate a diverse set of considerations that allow him to appropriately match methods to problem types and use cases of tomorrow.

The most significant benefits to accrue from the success of the proposed research is in mitigating or avoiding the risks identified earlier: "failure" due to solving the wrong problem, and "lost value" due to fixating on inferior solutions. Additionally, the ERS approach has the potential for

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Tools on Department of Defense and Intelligence Community Programs," Final Technical Report SERC-2009-TR-004, Systems Engineering Research Center: New Jersey, December 2009, p. 11.

[5] Wolf, D., An Assessment of Novice and Expert Users' Decision-Making Strategies during Visual Trade Space Exploration, MS Thesis, Mechanical Engineering, Penn State University, May 2009

[6] Ross, A.M., McManus, H.L., Rhodes, D.H., and Hastings, D.E., "Revisiting the Tradespace Exploration Paradigm: Structuring the Exploration Process," AIAA Space 2010, Anaheim, CA, September 2010

[7] Ross, A.M., McManus, H.L., Rhodes, D.H., and Hastings, D.E., "A Role for Interactive Tradespace Exploration in Multi-Stakeholder Negotiations," AIAA Space 2010, Anaheim, CA, September 2010

[8] Neches, R., "Engineered Resilient Systems: A DoD Science and Technology Priority Area, Overview Presentation," June 2012, p. 8

[9] Neches, R. and Madni, A. M., "Towards Affordably Adaptable and Effective Systems," Systems Engineering Journal, doi:10.1002/sys.21234, first published online 19 October 2012, pp. 1-11

[10] SECDEF Memorandum, Science and Technology (S&T) Priorities for Fiscal Years 2013-17 Planning, April 19, 2011. Washington, DC. OSD 02073-11

[11] National Academy of Engineering, "Engineer of 2020: Visions of Engineering in the New Century," Washington, DC: The National Academies Press, 2004, pp. 1-118

identifying more efficient allocation of resources across time and alternative solutions. ERS artifacts that effectively capture and transfer expert knowledge will enable less experienced engineers to be more “meta-cognitive” and therefore enable junior engineers to make better decisions, potentially mitigating the impact of a high skill workforce shortage.

One objective of this research project was to identify how ERS artifacts (and other supplemental knowledge management means) can act as an expertise transfer, enabling junior engineers to perform at the level of more experienced engineers. Tradespace exploration was selected as the specific focus of this study.

INSUFFICIENCIES IN CURRENT PRACTICE

Insufficient consideration of alternative solutions has been cited as a risk for “lost value” in the US Air Force.[12] In fact, the Government Accountability Office (GAO) has found that “programs that had a limited assessment of alternatives tended to have poorer outcomes than those that had more robust [analysis of alternatives]” [13]. In some cases, service sponsors are identifying a preferred solution or a narrow range of solutions early on. Some AoAs are conducted on compressed timeframe to meet planned milestones. As a result, this “short changes comprehensive assessment of risks and preclude effective cost, schedule, and performance trade-offs from taking place prior to beginning development” (quote?). AoA needs to occur early enough to inform decisions before program initiation. Findings indicate more specific AoA guidance may be necessary to ensure that AoAs meet their intended objectives and provide an in-depth assessment of alternatives.

The implication of these findings is that tradespace methods, which explicitly consider a large number of alternatives, are well-suited to address the risk of “poor outcomes” (e.g. “lost value), thereby increasing the likelihood of discovering superior solutions. Tradespace methods have been shown to be useful in identifying higher value efficient solutions, as well as exploring the impact of various contextual constraints, such as budget caps and changes in available technology.[14]

SCOPE: TRADESPACE EXPLORATION

Tradespace exploration is a technique for evaluating a large number of alternatives in order to generate knowledge and insights into tradeoffs, including costs and benefits. For a traditional system, key system design tradeoffs are made in the initial phase of the lifecycle, although tradespace exploration can be conducted throughout a system lifecycle. Researchers have demonstrated tradespace exploration methods as effective for gaining knowledge of the design space[15,16]. These methods enable enumeration of alternative concepts, and evaluation and

[12] National Research Council, “Pre-Milestone A and Early-Phase Systems Engineering: A Retrospective Review and Benefits for Future Air Force Acquisition,” The National Academies Press: Washington, DC, 2008, pp. 1-150

[13] GAO, “Defense Acquisitions: Many Analyses of Alternatives have not Provided a Robust Assessment of Weapon System Options,” GAO-09-665, September 2009, pp. 1-41.

[14] Ross, A.M. and Hastings, D.E., "The Tradespace Exploration Paradigm," INCOSE International Symposium 2005, Rochester, NY, July 2005, pp. 1-13

[15] Ibid.

[16] Ross, A.M., McManus, H.L., Rhodes, D.H., and Hastings, D.E., "Revisiting the Tradespace Exploration Paradigm:

selection of promising architectures that can be further investigated. Model-based tradespace exploration enables comparison of a much larger number of system designs than is possible with heuristics and qualitative approaches, or by using the traditional "point-based" approach in picking a design followed by successive refinement. By exploring the tradespace, in full or in part, one can gain knowledge of possible system performance, relative to stakeholder needs, often described as "value", or benefit at cost. Exploring tradespaces can reveal key tradeoffs as well as multi-stakeholder preference agreements and conflicts.

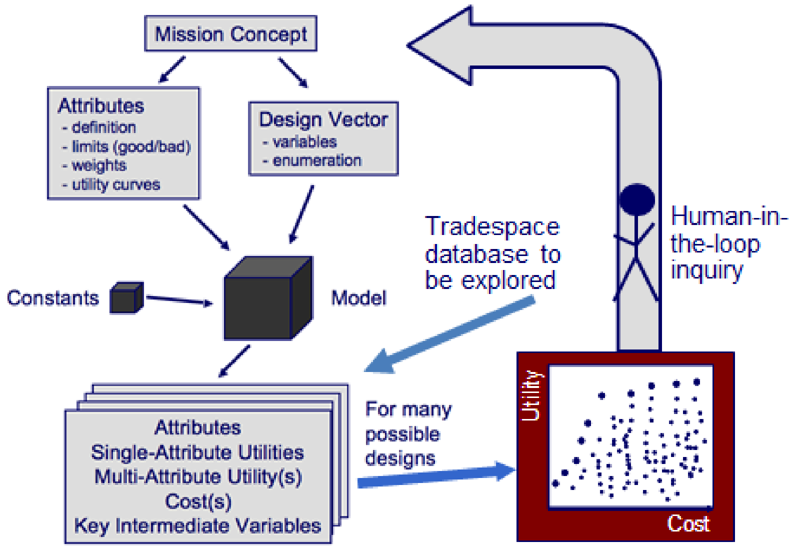

Figure 2 Notional tradespace exploration flow

Tradespace exploration leverages "models" in order to evaluate multiple alternative solutions (spanned by the design space) in terms of decision criteria (e.g. "attributes", KPPs, MOE, etc.) and other factors. In support of top level acquisition decisions, these can be codified as costs and benefits for orienting the decision maker to the evaluated alternative set. Tradespace exploration encourages "exploration" as opposed to optimization, explicitly empowering the human-in-the-loop analyst or decision maker to investigate the implications of the relationship between inputs and outputs (via the model and constraints/constants) as well as the definition of the problem (i.e. the proposed input/design space and the proposed output/value space). In spite of the apparent simplified representation of points on a two-dimensional scatterplot as seen above, the actual tradespace data set can be much larger and representing high dimensional tradeoffs of a large set (e.g. thousands, or millions, or more) of alternatives. Oftentimes tradespace exploration generates data through computer-based models, allowing for the automated assessment of the alternatives set and helping the analyst avoid the imposed limitations of focusing on a few point designs at a time.

Structuring the Exploration Process," AIAA Space 2010, Anaheim, CA, September 2010.

The key processes of tradespace exploration are illustrated in Figure 3 below[17]. These include:

- **Generation**: The definition of the design space (spanned by a design variable set, for example)
- **Enumeration**: The definition of particular alternatives from the design space
- **Sampling**: The definition of a particular subset of alternatives from the enumerated set intended for evaluation
- **Evaluation**: The evaluation of sampled alternatives via model(s) in terms of desired output metrics (e.g. benefits and costs as specified by stakeholders)
- **Exploration**: The intentional investigation of relationships and patterns between the input space and outputs space, resulting in knowledge and insights for the analyst/decision maker
- **Selection**: The decision on one or more alternatives as "answering the question" posed by the study, for example providing the "best" benefit at a given cost across considered use contexts

[17] Ross, A. and Rhodes, D.H., "A System of Systems Tradespace Exploration Method," Chapter 5 in *Modeling and Simulation Support for System of Systems Engineering*, ed. Rainey, L. and Tolk, A., Wiley and Sons, in press 2014.

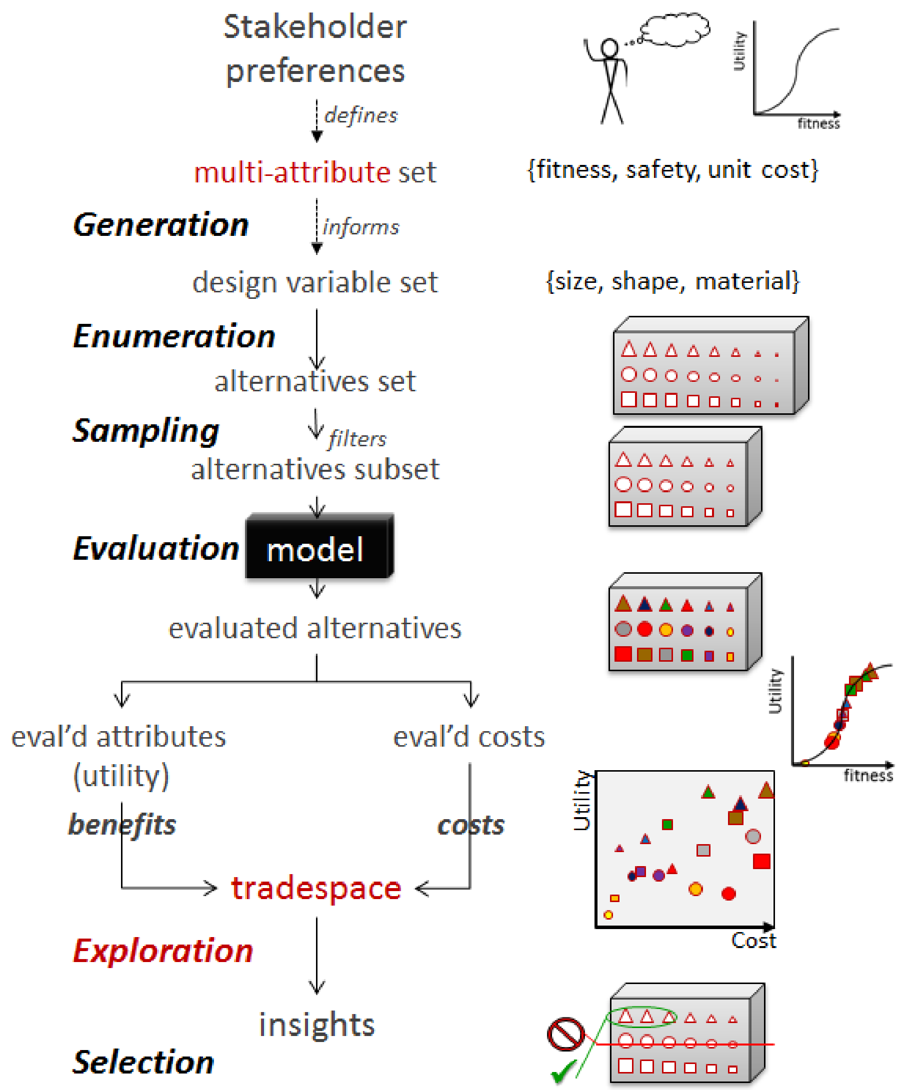

Figure 3 Key processes and constructs of tradespace exploration (from Ross and Rhodes 2014 in press)

These key processes are used in most tradespace exploration activities, although they may be referred to by different terms.

PHASE 1 RESEARCH

In phase 1 of the research, the team conducted knowledge and information gathering and collected key terms that form the basis of a preliminary lexicon for the ERS TSE community.

KNOWLEDGE AND INFORMATION GATHERING FINDINGS

The research team gathered knowledge and information by several means. The current and recent past of ERS program was examined through discussions with leadership and review of recent briefing material. Tradespace exploration specific findings were gathered through informal interviews, literature review, and specific discussions with subject matter experts. Findings draw from a number of organizations, programs and projects involved in tradespace exploration policy/practice setting, research, and application of methods, processes and tools (MPTs). The constraints of this project did not allow for an exhaustive investigation, but did produce a number of key insights, observations and finding. The findings suggest directions for further study and investigation.

STAKEHOLDER PERSPECTIVES ON CHALLENGES, GAPS AND ISSUES

In order to enable the support of key decisions, especially ones that are resilient to dynamic uncertainties, it is important to frame the problem from the perspective of the decision makers. This research has taken a multi-prong approach to characterizing the challenges, gaps, and issues from a decision point of view. This includes leveraging recent research that has gathered stakeholder expectations and needs for the process of using tradespace exploration in decision making, to enable evidential reasoning. The mental model for decision-making using evidential reasoning is described below.

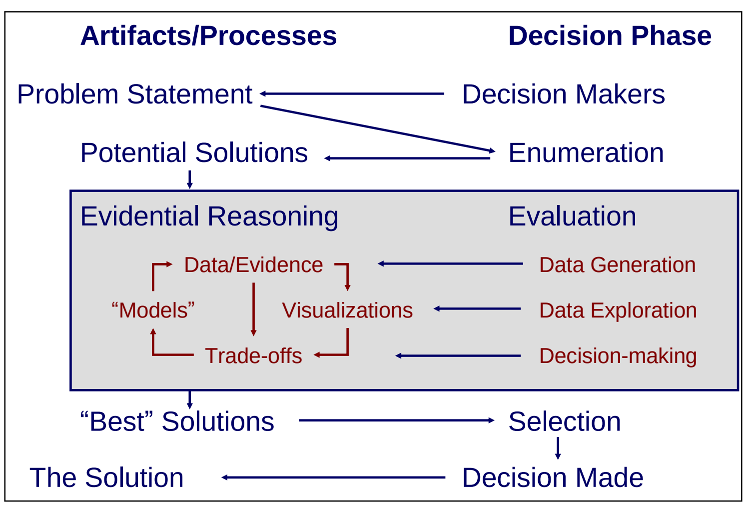

Figure 4. Mental model for decision making involving "evidential reasoning"

Figure 4 above attempts to capture the essence of the mental model for motivating the questions below. The left side of the figure lists the "tangible" artifacts and processes involved with making a decision, while the right side of the figure lists the principal phases for decision making: Enumeration, Evaluation, and Selection. The left side begins with a problem or needs statement that encapsulates what is trying to be solved (for example, the need for some system capability). Potential solutions are enumerated (by engineers, for example) through some formal or informal process. Evidential reasoning involves the use of models and/or data that form the basis of evidence that shows whether any or all of the potential solutions can solve the problem or meet the needs. Visualizations may be used to represent the data or evidence to help in uncovering the degree to which potential solutions meet the needs. Trade-offs may be necessary where solutions do not meet all needs and dominate all alternatives. The potential solutions that satisfactorily pass the trade-off and reasoning process become the "best" solutions from which a final solution is selected. Addressing these "decision phases" is important for ensuring ultimately good decisions will be made in the engineering of resilient systems. Current and emerging advances in tradespace exploration MPTs can enable the process across all phases including constructs for accelerating *evidential reasoning*.

Stakeholder Interviews: Expectations and Needs for TSE for Decision Support

A recent study involved the elicitation of expectations and needs. Stakeholder interviews were conducted within a large government agency to gather perspectives on the current practices and needs where TSE would potentially be applied. These are summarized below.

Decision makers

Q: Do you have a specific person, group, or type of decision maker in mind to benefit?

> A: *There is a need for having the ability to bridge the gap between the engineer and the decision makers. There are two types of "decision makers". There are internal and external decision makers. The internal decision makers are usually engineers and the external decision makers are usually non-engineers. The internal decision makers have a hard time communicating with the external decision makers and in vise-versa.*

Q: Are there different types of decision makers?

> A: *Yes, each of the decision makers (external) comes in with different needs and each can have different objectives which can range from cost, schedule, sustaining an industrial base, sustaining current capability, proposing a specific system which fits their needs, or any type of performance metric. The internal decision makers attempt to come up with a system which satisfies the external decision makers and convey the finding to the external decision makers.*

Q: How many decision makers typically decide on system selection?

> A: *The community can involve anywhere from 4 very senior decision makers to 100 lower level offices.*

Q: Do these decision makers work in parallel or sequence?

> A: *The external decision makers, for the most part work in parallel. They work on supporting the system they believe to be the best for their needs. The lower level decisions are made in sequence and the engineers work with the decision makers to come to a solution.*

Enumeration

Q: How are alternative solutions enumerated? (e.g., reuse of past systems, formal process, etc.)

A: *The initial stage of the design starts with prior domain knowledge and kicking off a study to consider multiple designs. The multiple designs are gradually weeded out through analysis, comparing the performance metrics the external decision makers would like to have. The multiple designs are carried through various studies until there are only a few designs left for the external decision makers to choose between. There tend to be problems with decision makers having a specific system they would like to have. No amount of analysis is able to steer them in a different direction from their system.*

Q: How many alternative systems are typically considered?

A: *At the beginning of the decision process, there are dozens of designs considered. After a down selection process, done internally, a few designs are presented to the external decision makers.*

Q: How many alternative scenarios are typically considered?

A: *Scenarios can be defined by user interests and can correspond to five or more scenarios.*

Evaluation

Q: What is the level of fidelity used for evaluating alternatives?

A: The models used are medium fidelity models and tend to be more precise than accurate. This is due to the assumptions going into the model so results are relative and not absolute.

Q: How does this vary based on technical phase of decision making (i.e., "Pre-phase A" vs. "CDR" vs. "PDR" level decisions)? How is the level of fidelity for modeling/simulation determined?

A: *As the design process progress, the fidelity of the model increases. This increase is for two main reasons: more is known about the system, assumptions are tightened up and more specifics of the system are known and start to get modeled.*

Q: Is the focus on "conceptual design"-level decision making appropriate?

A: *It is difficult to keep the decision maker at the right level of abstraction. We would like to keep the external decision makers focused on the performance metrics they value and the tradeoffs between the different performance metrics so the internal decision makers can help design a system specific to the external decision maker's needs. It is hard to keep the external decision makers from trying to offer engineering advice and attempting to design the system for the engineers.*

Q: What are the current representations in use for visualizing data?

A: *From engineer to engineer, the visualization of the data is through Excel data sheet, charts, and graphs in Power Point. The technical level of the data is not limited. As the data goes up the chain of the decision makers, all data is presented through Power Point and the amount of technical data presented is condensed and only the most pertinent data is presented. As the data goes up through the decision makers, the technical data is condensed and also attempted to put in a format which is hopefully conveyed to the decision maker with less technical background. If the decision makers have any questions, and cannot be answered then and there, the question travels down to the engineers to answer and then it goes back up the chain of decision makers.*

Q: What are the current tools used to represent data?

A: *The tool used to convey data are charts, graphs, and tables put in a Power Point presentation.*

Q: What are the current tools used to explore data?

A: *Charts, graphs, and tables are used to explore the data. If a question comes up not presented in the charts, graphs, or tables then the question is answered at a later time.*

Q: What are the current processes for exploring data?

A: *Charts, graphs, and tables with an iterative process on the decision maker getting together to get the question answered from the previous meeting. Sometimes the decision makers will ask the same question to different people to get a different opinion on the question.*

Q: What are the current processes for evaluating alternatives?

A: *The engineers attempt to consider different metrics and come up with figure of merit. The figure of merit is usually a performance versus cost chart. The main issue with evaluating alternatives is the different external decision makers comes in with an idea of which system they would like. Once the engineers propose their finding and their recommendation on the system/s there is usually a discrepancy with the external decision makers' system. This in turn causes many more iterations of analysis because the external decision maker believes their system was not evaluated properly.*

Selection

Q: How do decision makers ask questions?

A: *Questions are asked orally and by the time they are written down and given to the engineering, the question is distorted (the game phone call). The engineer will answer the question tersely.*

Q: To what degree do non-technical factors affect decisions?

A: *Many different factors affect the debate on what is motivating the external decision makers. At the end of the day it is usually performance metrics which can be measured discretely which wins the debate over a 'fuzzy' equation.*

Q: What are the current processes for communicating decisions?

A: *PowerPoint, word of mouth, and email.*

Q: Are there any major constraints about which we should be aware?

A: *Schedule is a fact of life and there seems to be politics which gets involved.*

Summary. Based on the results of the questions, there appears to be a need to provide a decision making framework that can be used across multiple decision makers, as well as continuously "up the chain" of detail from low level engineering up to senior, high level decision makers. Consistency and responsiveness to questions can accelerate "buy-in" and communication in order to facilitate decision making. The state of the practice involves the use of tables and Power Point, which is inherently static and not responsive if external decision makers introduce new questions during reviews and meetings. Quantitative metrics are preferred, as well as the ability to consistently aggregate data from low levels of analysis up to high level performance questions. Important, non-technical factors will tend to be under-considered if not represented in a concrete fashion.

Stakeholder feedback on benefits of using a TSE approach

A government user of the tradespace exploration approach discussed some of the problems and limitation with traditional trade-off analysis. This individual identified the following benefits of TSE as opposed to the more traditional process of design:

- Forces attention on value-driving design tradeoff decisions, rather than assumed technical factors (e.g. prior experience-derived design drivers, or reuse of design drivers from prior studies)
- Reveals design-value tradeoffs not apparent with assessing only a few point designs
  - By evaluating a large number of points, one can begin to see the patterns of relationships between different inputs (i.e. design choices) and outputs (i.e. performance and cost)
  - Interactive tradespace exploration allows decision makers to test their mental model and develop intuition of complex system tradeoffs
- Facilitates cross-domain communication on key system decision factors
  - The tradespace constructs are domain neutral (i.e. cost-benefit coordinates), which are mutually understandable and focus conversation on understanding "why" rather than "what"
- Provides an ability to discover compromise solutions
  - Fosters identification of "good" designs per decision maker, as well as highlighting tensions between decision makers
  - Experts often unable to find "suboptimal" solution that may be better compromise across stakeholders (i.e. each domain expert can propose an 80% good enough solution in their own domain, but impossible to guess if that is also 80% in other domains)
- Is a structured means for considering large array of possible futures for discovering robust systems and strategies
  - Explicit enumeration of design space and context space leads to conversations about possible variety of solutions within a possible variety of situations and provides structured analytic framework for quantifying the goodness over time

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STATE OF THE PRACTICE

Three broad areas of state of the practice for TSE (not exhaustive) were investigated by the research team, including (1) current TSE approaches and toolsets, (2) TSE related areas, and (3) open challenges for TSE.

Current Tradespace Exploration Approaches and Toolsets

The research team has interacted with other research groups involved in tradespace exploration research, and followed work in the literature and in technical exchanges.

Academia

Many tradespace exploration toolsets have been developed over the years within academia. For example, the ARL Trade Space Visualizer (ATSV)[18], a tradespace data visualization tool developed at Applied Research Laboratory at Penn State University. The ATSV toolset continues to evolve, using the concept of "visual steering" to drive human-directed optimization within a tradespace[19]. Additionally, the Penn State team has integrated the concept of "value robustness" into some of their work[20]. Other approaches and toolsets from various organizations were also reviewed to look for insights on how data was generated and displayed. These examples include work by Georgia Tech using GT-FAST for the DARPA F6 Program[21], as well as the Aerospace System Design Lab[22], and JPL[23]

There is a growing effort to use theory-based approaches to develop effective tradespace exploration constructs. The work of Stump et al. uses the design by shopping paradigm whereas user preferences on what makes a good design emerges through interaction with the possible alternatives represented in a multi-dimensional tradespace. Much of the existing work appears to extend from the operations research/optimization and decision analysis fields.

In the knowledge investigation an important area of tradespace exploration is in accommodating different types and levels of users. The work of Wolf et al. on novice vs. expert users is an example of this type of study[24]. Overall, there is a growing body of work in tradespace exploration that can be leveraged as the development of the ERS TSE architecture and toolsets move forward.

In particular, in recent years, there has been growing interest in using a "value-centric" perspective for framing and evaluating tradespaces[25],[26]. This is in contrast to a "cost versus performance" perspective and results in the ability to incorporate the impact of changing environments and uncertainty on the decision metrics. Depending on the case, the definition of

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[18] Stump, G., Yukish M., Martin J., and Simpson T. The ARL Trade Space Visualizer: An Engineering Decision-Making Tool. in 10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference. 2004. Albany, NY, Paper No. 2004-4568.

[19] Stump, G.M., Lego, S., Yukish, M., Simpson, T. W., Donndelinger, J. A. (2009), "Visual Steering Commands for Trade Space Exploration: User-Guided Sampling With Example," *Journal of Computing and Information Science in Engineering*, Vol. 9, No. 4, pp. 044501:1-10.

[20] Private conversation with Professor Timothy Simpson, July 2008 and June 2009.

[21] Lafleur, J and Saleh, J., Exploring the F6 Fractionated Spacecraft Tradespace with GT-FAST, AIAA 2009-6802, 2009.

[22] Mavris, D. N., & Pinon, O. J. (2012). An Overview of Design Challenges and Methods in Aerospace Engineering. In *Complex Systems Design & Management* (pp. 1-25). Springer Berlin Heidelberg.

[23] Jones, M. and Chase, J., Conceptual Design Methods and the Application of a Tradespace Modeling Tool for Deep Space Missions, IEEE, 2008.

[24] Wolf, D., Simpson, T., and Zhang, X. "A Preliminary Study of Novice and Expert Users' Decision-Making Procedures During Visual Trade Space Exploration," Proceedings of the ASME 2009 Int'l Design Eng. and Tech. Conf., San Diego, CA, 2009.

[25] Ross, A.M., *Multi-Attribute Tradespace Exploration with Concurrent Design as a Value-centric Framework for Space System Architecture and Design*, Dual Master of Science Thesis, Aeronautics and Astronautics and Technology and Policy Program, MIT, June 2003.

[26] Brathwaite, J., and Saleh, J.H., "Beyond Cost and Performance, a Value-Centric Framework and Pareto Optimization for Communication Satellites," AIAA Space 2009, Pasadena, CA, September 2009.

"value" varies widely, from "net present value" to "multi-attribute utility"[27]. One example value-centric TSE approach is the Multi-Attribute Tradespace Exploration method, developed at MIT and expanded over 14 years of research[28, 29,30]

The following (not exhaustive) table illustrates some of the existing tradespace methods and tools in use at U.S. universities:

School	Method(s)	Tool(s)
Georgia Institute of Technology	CATE[33], IRMA[34]	RAVE[35,36], GTFAST[37]
Georgia Tech Research Institute		FACT[38]
Penn State / ARL	Design by shopping[39]	ATSV[40,41]
Massachusetts Institute of Technology	MATE[42], EEA[4344]	IVTea/VisLab[45],[46]
…		

Figure 5 Example academic methods and tools

Industry

Tradespace exploration has been employed in practice by various organizations for a number of years, including detailed design, across domains such as chip design[31]. The recent DARPA META Program wanted to leverage advancements in industry, especially those made by semiconductor manufacturers, in order to achieve drastic reductions in schedule and cost of development for complex DoD-class systems[32]. Specifically META aimed:

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33 Arruda, J., Gavrilowvski, A., Ahn, B., Chae, H., Spero, E., and Mavris, D.N., "The Capability Assessment and Tradeoff Environment (CATE) for Advanced Aerospace Vehicle and Technology Assessment," Conference on Systems Engineering Research (CSER) in Procedia Computer Science, Vol 28, pp. 583-590, March 2014.

34 Engler, W.O. III, Biltgen, P.T., Mavris, D.N., "Concept selection using an interactive reconfigurable matrix of alternatives (IRMA), 45th AIAA Aerospace Sciences Meeting and Exhibit, 2007.

35 Daskilewicz, M. and German, B., "RAVE: A Graphically Driven Framework for Agile Design-Decision Support" AIAA-2010-9033, in 13th AIAA/ISSMO Multidisciplinary Analysis Optimization Conference, Fort Worth, TX, Sep 2010.

36 http://www.rave.gatech.edu/

37 Lafleur, J and Saleh, J., Exploring the F6 Fractionated Spacecraft Tradespace with GT-FAST, AIAA 2009-6802, 2009

38 http://gtri.gatech.edu/casestudy/gtri-software-helps-systems-engineers-link-perform

39 Stump, G.M., Yukish, M., Simpson, T. W., and O'Hara, J. J. Trade Space Exploration of Satellite Datasets Using a Design By Shopping Paradigm. in IEEE Aerospace Conference. 2004. Big Sky, MT.

40 Stump, G., Yukish M., Martin J., and Simpson T., "The ARL Trade Space Visualizer: An Engineering Decision-Making Tool," in 10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference. 2004. Albany, NY, Paper No. 2004-4568.

41 http://www.atsv.psu.edu/

42 Ross, A.M., Hastings, D.E., Warmkessel, J.M., and Diller, N.P., "Multi-Attribute Tradespace Exploration as a Front-End for Effective Space System Design," *AIAA Journal of Spacecraft and Rockets*, pp. 20-28, Jan/Feb 2004

43 Ross, A.M., and Rhodes, D.H., "Using Natural Value-centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis," INCOSE International Symposium 2008, Utrecht, the Netherlands, June 2008.

44 Schaffner, M.A., Wu, M.S., Ross, A.M., and Rhodes, D.H., "Enabling Design for Affordability: An Epoch-Era Analysis Approach," Proceedings of the 10th Annual Acquisition Research Symposium- Acquisition Management, April 2013.

45 Ross, A.M., McManus, H.L., Rhodes, D.H., and Hastings, D.E., "A Role for Interactive Tradespace Exploration in Multi-Stakeholder Negotiations," AIAA Space 2010, Anaheim, CA, September 2010.

> to develop model-based design methods for cyber-physical systems far more complex and heterogeneous than those to which such methods are applied today; to combine these methods with a rigorous deployment of hierarchical abstractions throughout the system architecture; to optimize system design with respect to an observable, quantitative measure of complexity for entire cyber-physical systems; and to apply probabilistic formal methods to the system verification problem, thereby dramatically reducing the need for expensive real-world testing and design iteration.[47]

One of the outcomes of META was the development of a tool suite called "CyPhy" that ended up being spun off into a for-profit entity called CyDesign[48]. CyDesign aims to leverage cloud-based infrastructure to implement a CyPhy-derived software that enables scalable design space exploration by users. The company claims to enable users to "explore every design," although it is unclear how the design space is defined[49].

The United Technologies Research Center (UTRC) process for rapid design-space exploration called Architecture Enumeration and Evaluation (AEE) involves finding all feasible architectures within a design space, based on a set of design rules. Next, at each abstraction layer, AEE uses design rules to rapidly identify the sparse set of feasible architectures from within the combinatorically large design space at that layer, consisting of all the layer's available technology options and all the ways in which they can be interconnected.
Figure 6 show the visualization of the AEE algorithm searching the combinatorial space. According to Murray et al.[50], to ensure that ALL feasible architectures are found, "AEE considers every architecture in the design space, but does NOT actually build or visit every architecture. AEE builds only feasible architectures, and does so by building them one device or flow at a time, testing only the rules applicable to the added or deleted device or flow type. Once a partial

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[40] Stump, G., Yukish M., Martin J., and Simpson T., "The ARL Trade Space Visualizer: An Engineering Decision-Making Tool," in 10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference. 2004. Albany, NY, Paper No. 2004-4568.
[41] http://www.atsv.psu.edu/
[42] Ross, A.M., Hastings, D.E., Warmkessel, J.M., and Diller, N.P., "Multi-Attribute Tradespace Exploration as a Front-End for Effective Space System Design," *AIAA Journal of Spacecraft and Rockets*, pp. 20-28, Jan/Feb 2004
[43] Ross, A.M., and Rhodes, D.H., "Using Natural Value-centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis," INCOSE International Symposium 2008, Utrecht, the Netherlands, June 2008.
[44] Schaffner, M.A., Wu, M.S., Ross, A.M., and Rhodes, D.H., "Enabling Design for Affordability: An Epoch-Era Analysis Approach," Proceedings of the 10th Annual Acquisition Research Symposium- Acquisition Management, April 2013.
[45] Ross, A.M., McManus, H.L., Rhodes, D.H., and Hastings, D.E., "A Role for Interactive Tradespace Exploration in Multi-Stakeholder Negotiations," AIAA Space 2010, Anaheim, CA, September 2010.
[46] Ross, A.M., "Insights from a Multisensory Tradespace Exploration Laboratory for Complex System Selection," presented at MIT SEAri Research Summit, Cambridge, MA, Oct 2009. http://seari.mit.edu/documents/summit/2009/06-SEAriSummit09_RT_AMR.pdf
[47] http://cps-vo.org/group/avm/meta [accessed 8/1/2014]
[48] http://cydesign.com/
[49] http://cydesign.com/design-and-trade-space-exploration/
[50] Murray, B., et al., META II Complex Systems Design and Analysis (CODA), United Technologies Corporation, United Technologies Research Center, AFRL-RZ-WP-TR-2011-2102, August 2011.

architecture is found to be infeasible, an entire subtree within the overall design-space binary tree can be ruled out and avoided. The earlier that infeasibility can be detected, while an architecture is being built, the larger the subtree that can be avoided, speeding up the enumeration process. AEE not only enumerates the feasible architectures, but can also evaluate partial architectures quantitatively, and use their evaluation to reason about them, for example, enforcing quantitative design rules. AEE enables reasoning about network architectures, reaching through the network to compute necessary quantities to test whether requirements are met." Alternate AEE implementations have also been investigated.

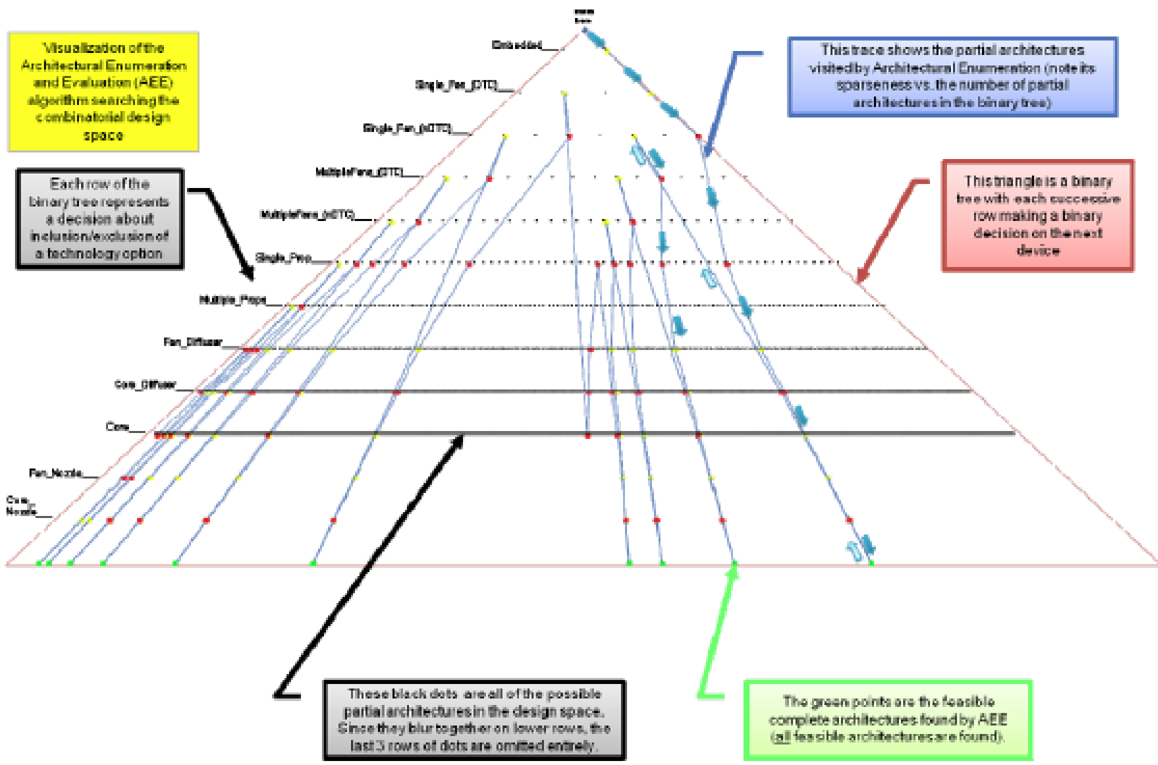

Figure 6. Visualization of UTRC's AEE Algorithm Trace through Design Space Binary Tree[50]

A set of TSE relevant tools were canvassed by Spero et al (2014), drawing upon surveys conducted by INFORMS[51],[52]. The results are not reproduced here, but can be readily found online.

Government/DoD

Tradespace exploration is conducted in different manners across government DoD. Analysis of Alternatives (AoA) are related, but not the same as a tradespace exploration study. One could conduct a TSE study to support an AoA, specifically when one desires addressing the gaps identified by GAO outlined earlier (i.e. insufficient consideration of alternatives and premature

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[51] Spero, E., Avera, M.P., Valdez, P.E., and Goerger, S.R., "Tradespace Exploration for the Engineering of Resilient Systems," Conference on Systems Engineering Research 2014, Redondo Beach, CA, March 2014.

[52] http://www.orms-today.org/surveys/das/das.html

focusing on preferred alternatives). The Air Force has provided an AoA Handbook[53] to help with the formulation and conduct of AoA, including AoA process, templates, and example metrics for alternatives evaluation. While not a full TSE study, this structure does provide a good starting point for conducting such as study. We found that in practice, AoAs often do not necessarily follow all of the proposed handbook advice.

In spite of this, there are a number of efforts in DoD that approach tradespace exploration in the broad sense. For example, the RDECOM "whole system trade approach" "multiple objective decision analysis," links together individual analyses with visualizations that enable "drill down capability" and "rapid and complete understanding of the trades available to stakeholders."[54] Public information on this approach is limited, so the researchers were unable to more fully evaluate its strengths and limitations vis a vis the current state of practice and art.

[53] Office of Aerospace Studies, "Analysis of Alternatives (AoA) Handbook: A Practical Guide to Analyses of Alternatives," AFMC OAS/A9, www.oas.kirtland.af.mil, July 2008.

[54] Chau, D., and Perriello, D., "Utilizing Model Based System Engineering to look at the Infantry Squad as a SoS architecture," RDECOM, 15 April 2014, http://www.acq.osd.mil/se/webinars/2014_04_15-SoCECIE-Chau-Perriello-brief.pdf

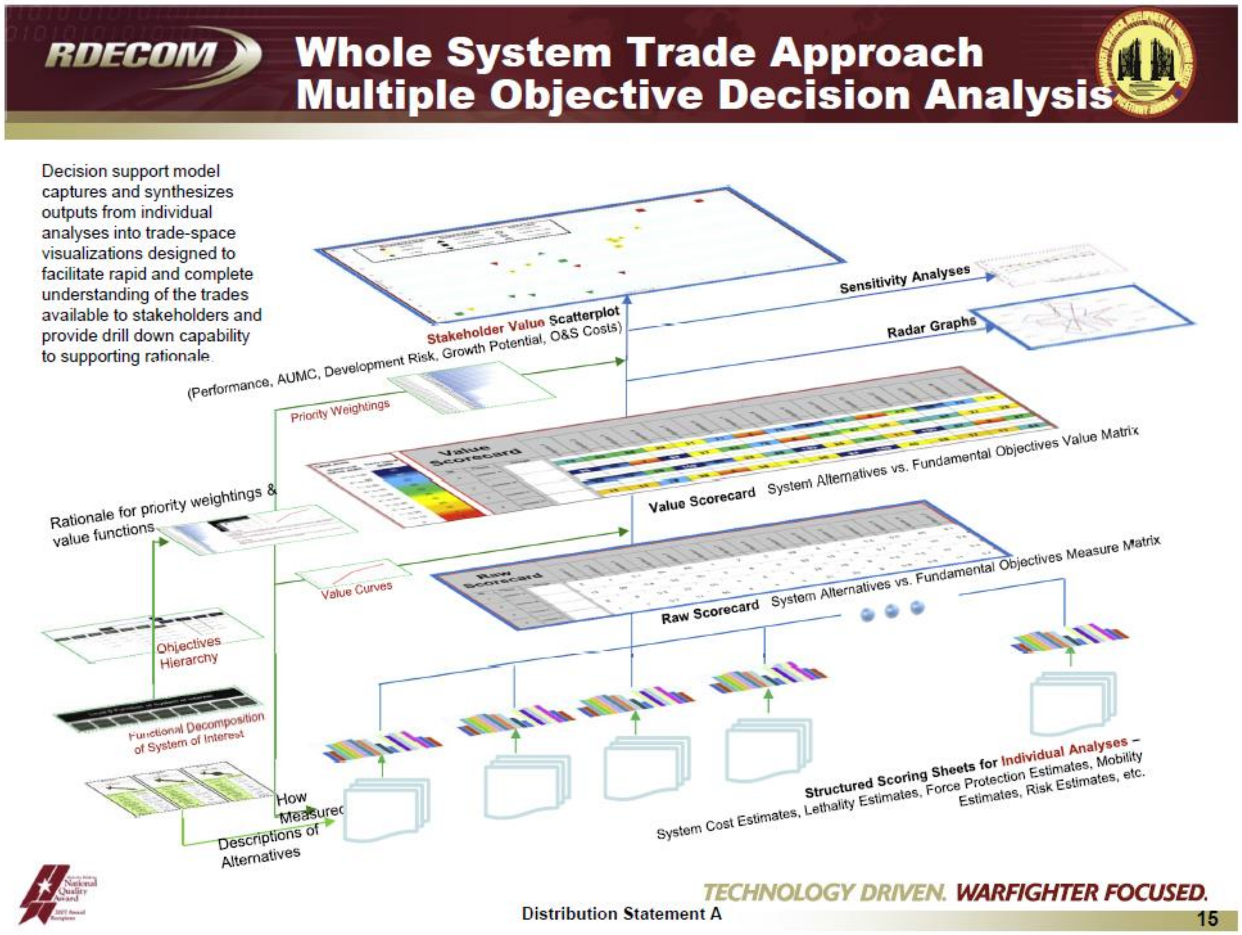

Figure 7 Army whole system trade approach (Chau and Perriello 2014)

Cross-cutting

As described in Spero et al.[100], TSE research activities across government and academia were investigated to look for commonality in process execution. Specific TSE projects within the government were also investigated. As a result, a set of twelve common process steps emerged in their work (noting that these were not tested), as shown in Figure 8. These authors describe the consolidation of processes and comparison to selected projects revealed the following: "1) TSE is commonly performed in steps, as assumed; 2) there exists no formal, singular, consistent process for performing TSE across the organizations investigated; 3) there exists no singular step within TSE processes that performs the action of "exploring" a tradespace – when such an action is performed it is done so using prerequisite inputs from multiple steps while simultaneously feeding back, and forward, exploration results to the decision analysis process; and 4) the ERS DPs both omitted steps 4 (subject matter expert measures) and 5 (stakeholder value)".

Step	Description
1	Determine mission scenario(s) and their requirements, and keep them open as long as possible
2	Identify set of operational performance characteristics and high level system design variables that impact operational requirements
3	Apply operational engagement models against various mission scenarios and threats to identify requirements, MOP, MOE, and other performance metrics
4	Expert knowledge teams determine values of measures for given mission scenarios and requirements
5	Break down stakeholder values into roles, attributes, and specific tasks
6	Generate alternatives that meet requirements and constraints, and map stakeholder values to system design variables using scalable multi-physics based modeling design tools
7	Create reduced-order surrogate models to show iterative ability of adjusting scenarios and requirements to physical feasibility
8	Qualitatively or quantitatively rank how alternatives meet measures
9	Perform a LCC estimate and lifecycle schedule analysis of the system
10	Perform an optimization study to determine the optimum feasible space that meets all constraints and for each course of action
11	Determine courses of action based on optimal feasible space and perform post-analysis studies (operational impact and gap analyses)
12	Perform case studies to test for robustness and to make sure that the alternative solutions are resilient in changing operational environments

Figure 8. TSE Best Common Practice Steps (source: Spero et al.[100])

The findings described in Spero et al.[100] also include results on tool functionality and tool attribute categories.

TSE Related Areas

The following are related areas to TSE and are not meant to be exhaustive or mutually exclusive, but merely to illustrate the existence of a vast relevant literature and knowledge base that should be leveraged in TSE. Each of these areas have their own conferences and journals, signifying their identities as distinct areas, even if their techniques are similar or complementary, especially in their application.

Systems Engineering

Trade studies are a key activity in the systems engineering process, and frameworks for conducting tradeoff studies continue to mature[55]. A trade study is an objective evaluation of alternative requirements, architectures, design approaches or solutions using identical ground rules and criteria. There are numerous variations of the trade study process, but have the basic steps of defining the objectives of the study, review inputs (including constraints and assumptions), choosing the evaluation criteria and their relative importance, identifying

[55] Cilli, M.V., and Parnell, G.S., "Systems engineering tradeoff study process framework," 24th INCOSE Int'l Symposium, Las Vegas, NV, June/July 2014.

alternatives, assessing performance of each using the criteria, comparing results and then choosing an option. The limitation of a trade study is that it involves the trade-off of several options, so it does not serve the same purpose as tradespace exploration. Trade studies are most effective when there are several viable options to consider and choose from. As such, once a tradespace exploration study identifies several good designs to consider in a more detailed study, a tradeoff study process can be applied.

Statistics and Data Science

The field of statistics is broad and there is no need to summarize it here. Suffice to say statistics is all about mathematical treatment of data analysis and is clearly relevant to any data-driven endeavor, including tradespace exploration. A big caveat, however, is that the data often used in early lifecycle phases for a system may be created via modeling and simulation, rather than through empirical testing. The consequence is that the data sets may be "artificial" (i.e. generated via human-made abstractions with ground truth unknown) and therefore statistical treatment must be done with appropriate caution (i.e. are the patterns being uncovered "real" or "artifacts", both challenges in analysis of natural data, but especially so in artificial data.)

The "new" field of data science merges techniques from statistics, computer science, math, machine learning, domain expertise, communication and presentation skills, and data visualization.[56] This field aims to leverage statistics and math techniques with a more "engineering" applied approach, grounded in making practical predictive models (e.g. recommendation engines) that may not be grounded in any one particular theory, but is "good enough" to generate useful results. Data science claims to be a response to managing the problem of "big data" (i.e. how to make sense from data sets that are large, diverse, dynamic, and of questionable quality?) Tradespace exploration activities could be considered to be a type of applied data science where the problem to be solved involves the design of technical systems.

Applied Decision Support

The area of decision analysis (DA) is fundamentally related to TSE in that decision analysis aims to apply rigorous quantitative techniques for representing stakeholder desires (i.e. preferences) and evaluating and ranking a set of alternatives. A key difference between decision analysis and TSE is that TSE often can have an open set of alternatives (that is, the set of evaluated alternatives can grow or shrink over time). This type of decision problem is considered "wicked" within the DA community since it is a very difficult problem to prove correctness for different ranking schemes. In a sense TSE is an application of decision analysis and one of the outcomes of TSE is to support decision making in different phases of the system lifecycle. Research and practice within the DA community should be relevant to TSE, especially relating to the evaluation and

[56] O'Neil, C., and Schutt, R., "Doing Data Science: Straight Talk from the Frontline," Cambride: O'Reilly, 2014, p. 11.

selection of alternatives[57,58,59]. It is worthwhile to note that it has been argued that existing decision methods within the engineering literature do not sufficiently adhere to the rigorously derived techniques from the DA community and that an opportunity exists to rectify this problem[60]. In particular, Hazelrigg argues that weighted sum of attributes, analytical hierarchy process, physical programming, Pugh matrix, quality function development, Taguchi loss function, Suh's axiomatic design, and six sigma, all suffer from undesirable qualities when used as selection methods in engineering design[61]. Ten "desirable properties" of a good engineering design selection method are proposed, which motivated the development of Multi-Attribute Tradespace Exploration, a TSE approach that merges techniques from DA with TSE[62].

Multi-Disciplinary Optimization and Robust Design

A variety of techniques from the operations research and optimization literature relate to concepts at the core of TSE. These include concepts such as decision parameters (i.e. "design variables"), objective functions, and constraints. Multi-disciplinary optimization (MDO) explicitly incorporates consideration of multiple domain/discipline specific evaluation techniques (i.e. models) to determine scores for alternatives, and potentially uses multiple objectives for evaluation as well. This version, multidisciplinary, multiple objective, optimization (MDMOO) bears a strong resemblance to techniques inherent in TSE, with the primary difference being emphasis on "optimization" versus "exploration." While this may appear to be only semantics, the difference is essential. Optimization has an inherent assumption of a "correct" answer, which hinges upon the definition of the objective set as well as a non-empty feasible region of alternatives for evaluation. In TSE, the objective functions themselves, as well as constraints, and definition of the alternatives set, are all open sets, that is, have membership that can change through intervention by the tradespace explorer/analyst. At its simplest, TSE can turn into an optimization exercise when the analyst is no longer "exploring" and instead locks down the objectives, constraints, evaluation models, and alternatives set. A great deal of research has gone into problem formulation and solution algorithms for optimization, and all of these can be leveraged for TSE. See for example, the use of one heuristic-based optimization technique (genetic algorithms) applied to the conceptual design of helicopters (in an automated fashion, as optimization has a tendency to pursue)[63].

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[57] Keeney, R.L., and Raiffa, H., "Decisions with Multiple Objectives: Preferences and Value Tradeoffs," Cambridge University Press: Cambridge, 1993.
[58] Parnell, G.S., Driscoll, P.J., and Henderson, D.L. ed., "Decision Making in Systems Engineering and Management," John Wiley and Sons: Hoboken, 2008.
[59] Watson, S.R., and Buede, D.M., "Decision Synthesis: The Principles and Practice of Decision Analysis," Cambridge University Press: Cambridge, 1987.
[60] Hazelrigg, G.A. (2003), "Validation of Engineering Design Alternative Selection Methods," Engineering Optimization, Vol. 35, No. 2, pp. 103-120.
[61] *Ibid*. p. 116.
[62] Ross, A.M., *Multi-Attribute Tradespace Exploration with Concurrent Design as a Value-centric Framework for Space System Architecture and Design*, Dual Master of Science Thesis, Aeronautics and Astronautics and Technology and Policy Program, MIT, June 2003.
[63] Crossley, W.A., and Laananen, D.H. (1997), "The Genetic Algorithm as an Automated Methodology for Helicopter Conceptual Design," Journal of Engineering Design, Vol. 8, No. 3, pp. 231-250.

In the mechanical engineering design literature, the Method of Imprecision (MoI) was developed to treat uncertainty in choosing among alternatives. In particular, the method espouses that fuzzy set theory should be used to treat imprecision and not probabilistic approaches, as there is a fundamental difference in the nature of what is unknown[64]. The semantic differences between this distinction and the meaning of uncertainty in the context of design were not resolved in the literature. MoI is, however, complementary to other Robust Design methods in their objective to minimize the impact of unknown factors (e.g. noise or random fluctuation in the traditional probabilistic representation of uncertainty) on system design (e.g. form or function). Taguchi's Robust Design approach, for example, seeks to optimize a design by driving down the expected variation in a design's performance variables as a result of variance in inputs (i.e. a "robust design…[is one] that has minimum sensitivity to variations in uncontrollable factors[65].") The concept of robustness and minimizing sensitivity to changes has been expanded in recent years to include requirements sensitivity analysis[66].

Visual Analytics

According to the National Visualization and Analytics Center (NVAC) chartered by the US Department of Homeland Security, research on visual analytics is critical to facilitating advanced analytic insights. The NVAC defines the field of *visual analytics* as "the science of analytical reasoning facilitated by interactive visual interfaces." Focus areas in this field include analytic reasoning techniques, visual representations and interaction techniques, data representations and transformations, and techniques for production, presentation and dissemination of analysis results[67].

As a part of knowledge gathering, members of the research team participated in the IEEE Visual Analytics Conference held in October of 2009 to review research and talk with experts from the NVAC and research groups working on this topic. The conclusion is that there is a growing interest for this agenda, but as yet, there is little evidence of empirically-derived 'best practices' for visualizing complex tradespaces. The work to date is primarily a study on how various data has been generated and represented, most often in either text processing, geographic information or scientific graphics. The body of literature is challenging to follow, but it may offer some specific strategies, approaches and mechanisms that could be incorporated into tradespace visualization work.

To date, little significant work in this community is oriented toward or directly applicable to the challenges in visualizing complex tradespaces. Looking at others types of visualizations, however, may offer insights in the work. There is also emerging work in computational strategies that will

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[64] Antonsson, E.K., and Otto, K.N., "Imprecision in Engineering Design," ASME *Journal of Mechanical Design*, Vol. 117(B), pp. 25-32, 1995.

[65] Simpson, T.W., "Handout on Robustness" in IE 466 – Concurrent Engineering course at Penn State University, http://www.mne.psu.edu/simpson/courses/ie466/ie466.robust.handout.PDF

[66] Mavris, D. N., & Pinon, O. J. (2012). An Overview of Design Challenges and Methods in Aerospace Engineering. In *Complex Systems Design & Management* (pp. 1-25). Springer Berlin Heidelberg. http://link.springer.com/chapter/10.1007/978-3-642-25203-7_1

[67] National Visualization and Analytics Center, "Illuminating the Path: the R&D Agenda for Visual Analytics," 2004.

enable interactive data exploration that merits further investigation in support of an environment for running tradespace exploration sessions[68]. The role of value models in interactive visualization is an open area of investigation[69].

In the synthesis of prior tradespace exploration methods, topics such as differences in use between novice and experienced users[24] may have comparable papers in the visual analytics literature[70]. In this latter work from the field of financial analysis, common trends have been observed in tradespace exploration sessions and intend to study through experiments in the future (for example, Dou et al. observed "novices started to perform "random" explorations after they had exhausted the strategies that they learned during the training phase … for experts, however, 20 minutes were not enough for some to perform deeper and more complex investigations"). While preliminary knowledge is being generated at present, the current research is attempting to follow some of these common threads across fields and knowledge areas.

Open Challenges for TSE

Several open challenges were identified, which illuminate some of the potential boundaries between the "state of the practice" and the "state of the art."

Methods for Considering Context and Time

While there is much research and development of tools in fields related to tradespace exploration, much of the work involves the generation and exploration of design-performance data given a set of requirements and mission contexts. A key challenge identified by the ERS program is the fact that *circumstances change*. That is, factors beyond the system program may change, causing the perceived success of the system to change. ***The impact of these changing factors is the primary motivation to pursue resilient development processes and systems.*** Tradespace exploration must be expanded in scope to enable resilience in both the development process and systems and to support assessment of such resilience. To further bolster this concept, the literature review investigated how other fields incorporate context and time. This examination of literature from other domains serves to validate and to enrich areas of uncertainty characterization and the need to embed these considerations into TSE.

While dynamic quantitative analysis methods and tools exist in abundance (e.g. stochastic programming[71], time-expanded decision networks[72], etc.), in order for TSE to support high level

[68] Endert, A., North, C., Chang, R, Zhou, M., Position paper: Toward usable interactive analytics: Coupling cognition and computation, KDD Workshop on Interactive Data Exploration and Analytics (IDEA), 2014.

[69] Ricci, N., Schaffner, M.A., Ross, A.M., Rhodes, D.H., and Fitzgerald, M.E., "Exploring Stakeholder Value Models Via Interactive Visualization," 12th Conference on Systems Engineering Research, Redondo Beach, CA, March 2014.

[70] e.g., W Dou, D.H. Jeong, F. Stukes, W. Ribarsky, H.R. Lipford, R. Chang, "Comparing Usage Patterns of Domain Experts and Novices in Visual Analytical Tasks," ACM SIGCHI Sensemaking Workshop, 2009.

[71] Peter Kall and Stein W. Wallace, *Stochastic Programming*, John Wiley & Sons, Chichester, 1994.

[72] Silver, M.R., and de Weck, O.L., "Time-Expanded Decision Networks: A Framework for Designing Evolvable Complex Systems," *Systems Engineering*, Vol. 10, No. 2, pp. 167-186, 2007.

decision making (e.g. acquisition of systems) it must be both transparent and versatile. The transparency need is so that decision makers (and even analysts) without deep specialization in a particular technique, are able to interpret and trust results of analyses. While deep technical analysis may be essential in evaluating alternatives over time, the communication of the results must be transparent to the assumptions used in generating the data so that users understand how to, and feel comfortable with, incorporating the results into the larger set of considerations needed for making decisions. Additionally, related to this issue is the need for versatility in the dynamic method so that it can incorporate, or at least remain compatible with, a variety of metrics (and data types) so that decision makers are free to incorporate an appropriate mix of evidence for making their decisions. For example, economic climate might impact a decision and should be able to be included in the decision process even if the dynamic method is focused solely on evolution of technical systems and performance. It is for these reasons that TSE dynamic methods should draw upon both quantitative (e.g. operations research/optimization-based) methods, as well as more qualitative methods that may be more narratively satisfying for human decision makers

A number of anticipatory methods were investigated in this research effort. Many different fields use approaches to perform anticipatory practice. One example is *environmental scanning* in the field of management, involving the acquisition and use of information about events, trends, and relationships in an organization's external environment, the knowledge of which would assist management in planning the organization's future course of action[73]. Other examples include *morphological analysis*[74] which has been applied in military strategic planning, and *scenario planning*[75] used in business development and sustainable development planning. In general, it was observed that legacy methods are powerful as thinking approaches but are largely graphical or narrative, though some use quantitative approaches as well such as computational scenario planning (e.g. in the policy realm[76]). It was found that some researchers (e.g., Ritchey) are moving toward a model-based approach to scenario development, but the work has not progressed significantly.

In the TSE realm, research by Ross and Rhodes using an Epoch-Era Analysis (EEA) approach has demonstrated a means for encapsulating context and time into modular analysis blocks (called epochs and eras)[77]. EEA is a multi-step approach for identifying of the impact of changing contexts and needs on proposed systems. The approach combines two key concepts: “epochs” and “eras.” The “epochs” part refers to the short run possible futures that may be experienced

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[73] Choo, C., “Environmental scanning as information seeking and organizational learning”, *Information Research*, Vol. 7 No. 1, Oct. 2001.
[74] Ritchey, T., “Scenario development and risk management using morphological field analysis: research in progress,” *Proceedings of the 5th European Conference on Information Systems*, Vol. III, 1997, pp. 1053-1059.
[75] Kazman, J., Carriere, S. and Woods, S., “Toward a discipline of scenario-based architectural engineering,” *Annals of Software Engineering,* Vol. 9, No. 1-4, 2000.
[76] Lempert, R.J., S.W. Popper, and S.C. Bankes, Shaping the Next One Hundred Years--New Methods for Quantitative Long-Term Policy Analysis, 2003, Santa Monica, CA: RAND. pp. 187.
[77] Ross, A.M., and Rhodes, D.H., "Using Natural Value-centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis," INCOSE International Symposium 2008, Utrecht, the Netherlands, June 2008

by a system. Described as a pair of possible contexts and needs, the **epochs** encapsulate one possible environment, among many, within which a system may find itself. A technically sounds system may fail when confronted by unanticipated or harsh epochs. A particular time-ordered sequence of epochs is a possible system **era**. The path dependency of how epochs unfold over time may have a large impact on the time-varying success of a system. Strategies for delivering value over time will be considered for a system across possible eras. Along with Multi-Attribute Tradespace Exploration (MATE), EEA has been codified as the Responsive Systems Comparison Method and has been demonstrated on several case studies for evaluating the impact of changing contexts and needs over time on tradespaces[78],[79],

Additionally, there has been significant interest in developing solutions that are able to remain "good" in spite of changes, a quality sometimes called "robustness" or "flexibility" in a system. Robust design has been traditionally applied to the manufacturing of systems, but also increasingly upstream to the concept design as well[80]. Flexibility, likewise, has begun to be addressed as a system property that could be evaluated during tradespace exploration[81],[82].

Managing the Size of the Design and Uncertainty Spaces

Another key challenge facing the TSE community is that of managing the sizes of the evaluated spaces, which include both design space (potential alternatives) and context space (potential environments and use cases of the alternative). As has been noted in the literature, despite increases in computing performance and capabilities, gains in addressing the problem of evaluating large design spaces is offset by increases in the scope and scale of the input space, as well as the details of the evaluation models themselves. This problem is reflective of the inherently infinitely large possibility space confronted during open-ended design. The "art" of system design is in the abstraction of the actual potential system alternatives into a representation that is large enough to span a reasonable region of interest in the design space, while not being so large as to overwhelm our ability to effectively evaluate (with minimal bias) that space. Both the optimization[83] and TSE communities have faced this problem and have proposed a number of techniques for managing the "problem of size" including filtering/paring the design space through expert rules and abstraction[84], varying fidelity of the evaluation models,

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[78] Ross, A.M., McManus, H.L., Rhodes, D.H., Hastings, D.E., and Long, A.M., "Responsive Systems Comparison Method: Dynamic Insights into Designing a Satellite Radar System," AIAA Space 2009, Pasadena, CA, September 2009.

[79] Fitzgerald, M.E. and Ross, A.M., "Mitigating Contextual Uncertainties with Valuable Changeability Analysis in the Multi-Epoch Domain," 6th Annual IEEE Systems Conference, Vancouver, Canada, March 2012.

[80] Chen, W., Allen, J.K., Mavris, D.N., and Mistree, F., "A Concept Exploration Method for Determining Robust Top-Level Specifications" (1997), Engineering Optimization, Vol. 26, pp. 137-158.

[81] Ross, A.M. and Hastings, D.E., "Assessing Changeability in Aerospace Systems Architecting and Design Using Dynamic Multi-Attribute Tradespace Exploration," AIAA Space 2006, San Jose, CA, September 2006.

[82] Fitzgerald, M.E. and Ross, A.M., "Sustaining Lifecycle Value: Valuable Changeability Analysis with Era Simulation," 6th Annual IEEE Systems Conference, Vancouver, Canada, March 2012.

[83] Koch, P.N., Simson, T.W., Allen, J.K., and Mistree, F. (1999), "Statistical Approximations for Multidisciplinary Design Optimization: The Problem of Size," Journal of Aircraft, Vol. 36, No. 1, pp. 275-286.

[84] Murray, B., et al., META II Complex Systems Design and Analysis (CODA), United Technologies Corporation, United Technologies Research Center, AFRL-RZ-WP-TR-2011-2102, August 2011.

as well as the development of surrogate models, and aggregation techniques on the results, among other techniques[85].

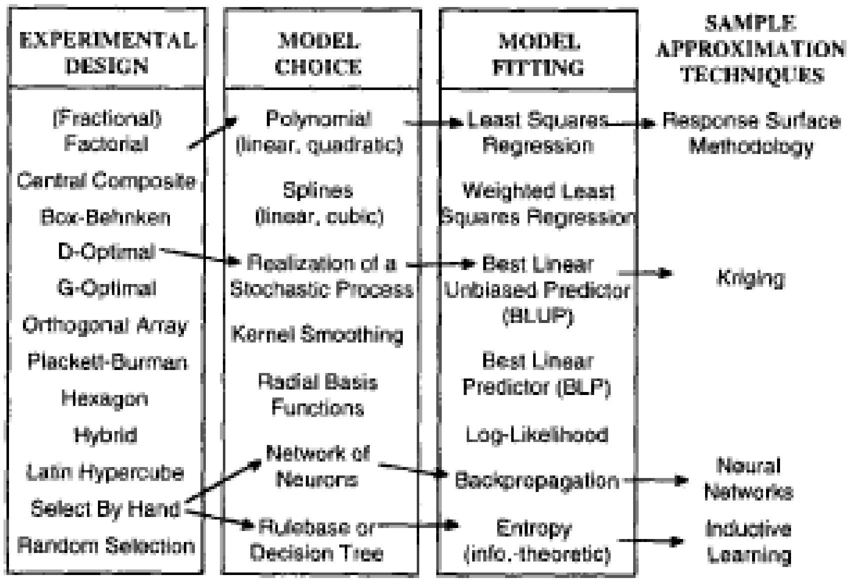

Figure 9 Techniques for building approximations in (Koch, Simpson, et al 1999, p. 276)

EMERGING STATE OF THE ART

Desire for a "new" TSE-based approach within DoD

There is increasing recognition within DoD of the need to increase knowledge earlier in the system lifecycle[86]. An underlying premise in making informed decisions is the concept that the *quality* of decisions we make is directly proportional to the *relevant* information and knowledge we have available at the time of the decision. A means to pull the information content we need to make high-value, high-confidence decisions ahead of the decision-making event itself would address many of the problems and challenges of early decisions. In Figure 10, the left-hand side you see the typical program as it relates to the degree of management leverage, cost committed, knowledge, and cost incurred on a program. Notice that the available information (or knowledge) early in the effort significantly lags early management decisions concerning program design architecture, scope, and specification. Perhaps just as importantly, at no point in the typical program does the knowledge needed for decisions arrive ahead of the cost commitment curve. The implication is that we consistently make decisions that significantly influence the cost of procurements without the knowledge needed to make them. The final point to make is that our information or knowledge in a typical program is usually a function of the incurred costs—the more we spend on the program, the more information we have available (although under the current approach, this usually means we have correspondingly less leverage over future

[85] Gries, M., "Methods for evaluating and covering the design space during early design development" INTEGRATION, the VLSI journal 38 (2004) 131-183.
[86] Cropsey, L., Informal correspondence with MIT researchers, 2013.

program direction). While this is perhaps a logical series of connections, it leaves us in the unenviable position of having to make decisions without the information needed to create high-value, high-confidence decisions.

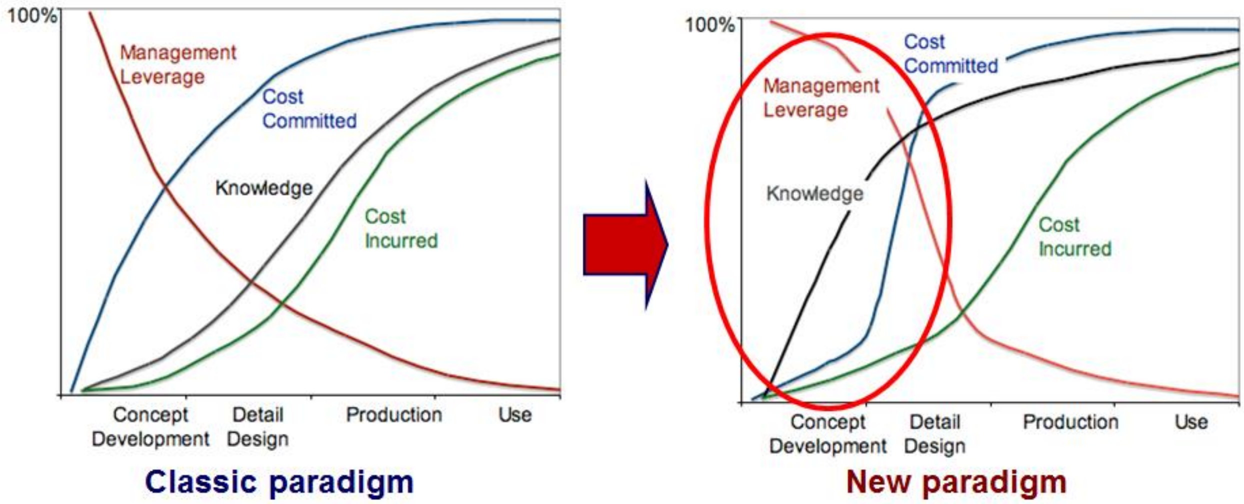

Figure 10 Changing the classical SE paradigm with earlier knowledge (adapted from Fabrycky and Blanchard 1991)

The single most effective way to pull knowledge ahead of decisions is to thoroughly explore the boundaries of the available tradespace at a low level of fidelity before selecting a specific set of alternative architectures to develop in more depth. Rather than attempting to drive out uncertainty and risk early in the materiel solution development process, these unknowns should be thoroughly explored in a way that facilitates a robust dialogue between the effect owner and the system provider to arrive at a common, shared understanding of the value of various design space considerations as they relate to the value attributes of the need space.

The essence behind a true tradespace exploration effort is the mental switch from thinking about specific design alternatives and their relative merits to instead decomposing the problem into desired attributes of a solution and the corresponding design vector that most impacts the delivery of those attributes. In this way, the number of potential solutions goes from just a few point designs to literally hundreds and even thousands of potential alternative solutions.

Government leaders have expressed the importance of “moving the knowledge curve up”. The thrust of the effort is to generate knowledge and insight into the system before needing to make decisions on significant life cycle cost and performance objectives. Tradespace exploration provides an effective way to do that by generating the broad, first-order effects between system design parameters at a relatively low-level of fidelity (and low cost in terms of both time and money) rather than choosing a few design points to model at high-fidelity (requiring more time and a lot of money). At the early stages of program definition, the insight available from exploring these low-fidelity, first-order relationships is much more important than making high-fidelity models of individual design points.

AFMC has expressed interest in pursuing a tradespace-based approach for generating the earlier knowledge as described above. In particular, they have worked with AFIT in performing a tradespace study on the trainer-x program. The research team could not find publically available information on this study beyond informal communication with the people involved. The interest in the work extends beyond cost versus capability to include utility as well. The inclusion of utility would serve to help with aggregating across multiple dimensions of capability, as well as to serve as a mechanism for exploring sensitivities “in the requirements” (i.e. the espoused utility functions on the capability attributes). There was additional interest in involving the AF/A9 organization in incorporating TSE-based approaches as they are responsible for integrating and coordinating studies across AF.

According to a memorandum from the Department of the Air Force, entitled “Implementation of Contractual Requirements Sufficiency,” dated November 16, 2012:

> **Presentation of Life Cycle Cost versus Capability Analysis.** AF requirements and acquisitions processes must be complimentary and aligned with fiscal realities. Affordability discussions must take place at all GO-level requirements and acquisition forums. Presentation of life cycle cost versus capability tradeoff analysis is required for all AFROCs, Air Force Requirements Review Groups (AFRRGs), Air force Review Boards (AFRBs), and Configuration Steering Boards (CSBs)., The Implementing Commands (AFMC and AFSPC) will support the requirements sponsor by providing cost and capability analysis for all analysis of alternatives (AoA) final reports, capability development documents (CDDs), an capability production documents (CPDs). This requirement for mandatory use of cost analysis is intended to ensure affordability is used to inform decisions throughout a program’s acquisition lifecycle.

This means that the tradespace resulting from an AoA must demonstrate “value” as the relationship between “what you pay” (cost) and “what you get” (capability, or benefit). At the least this requirement will force and opening of the tradespace to consider tradeoffs of what is possible for different budgets, one of the essential questions to investigate during a TSE study.

A recent article by Kane and Bartolomei makes the case that tradespace exploration and its representation can fundamentally change acquisition at the Air Force (and DoD more generally) by providing a boundary object for sharing knowledge within the acquisition decision support system and to provide top level synthesis of cost and benefit tradeoffs for the organization[87]. A top level illustration of a notional tradespace in
Figure 11 shows the essential concept within the article, where a situational awareness provided through a tradespace representation gives strategic insights for organization investments.

[87] Kane, R., and Bartolomei, J., “Taming the Tigers: Recapturing the Acquisition Excellence of Our Planning, Programming, and Acquisition Three-Ring Circus,” Senior Leader Perspective, Air and Space Power Journal, March-April 2013, pp. 4-27.

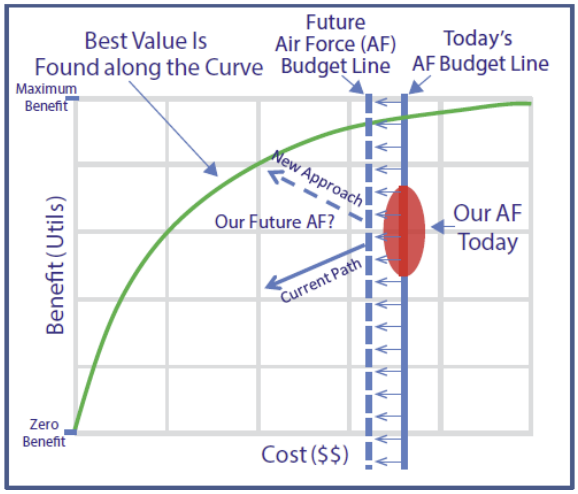

Figure 11 Value chart [tradespace] (benefit versus cost) from Kane and Bartolomei 2013 (p 6)

According to Kane and Bartolomei, the DoD, and the Air Force specifically, runs the risk of insufficient allocation of resources to meet national needs, due in part to information loss and poor decisions at the interface of the three intersecting decision support and acquisition processes of matching budget (AFCS or PPBE), requirements (CFLIs or JCIDS), and acquisition (AF Acq. or DAS), as seen in

Figure 12 below.

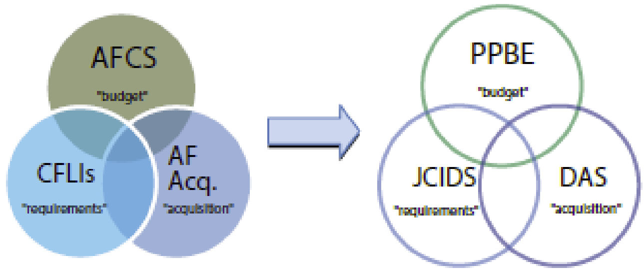

Figure 12 Air Force acquisition decision support systems (left) mirror those of the Department of Defense (right) from Kane and Bartolomei p. 8

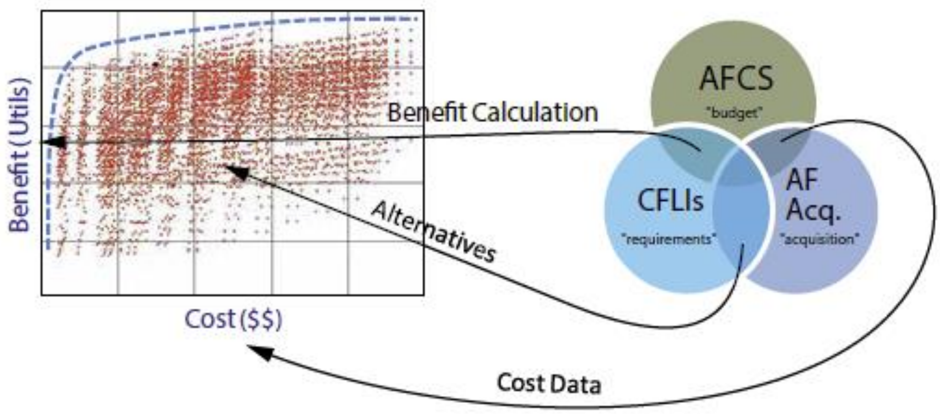

Figure 13 Inputs to the value trade space from Kane and Bartolomei 2013 p 23

Figure 13 illustrates how the tradespace construct can be used to synthesize information from the three parts of the acquisition decision support system in the Air Force.

Ongoing research and development

The academic work cited in the "state of the practice" section is a bit misleading in that universities are constantly striving to push the "state of the art" and yet their work, once published, becomes part of the past. Each of the universities discussed previously have continued their work in evolving their methods, processes, and tools, especially with expanded considerations of issues such as downstream (e.g. manufacturability and sustainment) and upstream challenges (e.g. requirements volatility and context shifts). For example, Penn State ARL has expanded its tradespace research to incorporate manufacturability through their work with DARPA's "instant foundry through adaptive bits" project[88]. MIT has expanded its tradespace

[88] http://news.psu.edu/story/147150/2012/08/30/penn-state-arl-lead-defense-manufacturing-research-project

work into applications to Systems of Systems (SoS)[89], survivability[90], affordability[91], and multi-stakeholder negotiation[92].

Within the Systems Engineering Research Center (SERC), Wayne State University is leading a small team of collaborating universities, including Penn State and GTRI, in finding opportunities to support NAVSEA in conducting set-based design activities for ship design.

ERS PROGRAM

Engineered Resilient Systems (ERS) is one of the seven DoD Science and Technology (S&T) Priorities derived from a comprehensive analysis of recommendations resulting from the Quadrennial Defense Review mission architecture studies[93]. Over the past several years, several government briefings have shared the goals and vision for ERS.[94] [95] [96] [97]

The ERS priority area initially consisted of five key technical thrusts, one of which was Data-Driven Tradespace Exploration and Analysis. Upon transfer of the ERS Priority Steering Council (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[96].

In a recent issue of Defense AT&L Magazine[98], Mr. Shaffer highlights the focus of ERS program's contribution to the strategic objective to affordably enable new or extended capabilities, as follows:

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[89] Ricci, N., Fitzgerald, M.E., Ross, A.M., and Rhodes, D.H., "Architecting Systems of Systems with Ilities: An Overview of the SAI Method," 12th Conference on Systems Engineering Research, Redondo Beach, CA, March 2014.

[90] Ross, A.M., Stein, D.B., and Hastings, D.E., "Multi-Attribute Tradespace Exploration for Survivability," Journal of Spacecraft and Rockets, accessed April 03, 2014. doi: http://arc.aiaa.org/doi/abs/10.2514/1.A32789

[91] Wu, M.S., Ross, A.M., and Rhodes, D.H., "Design for Affordability in Complex Systems and Programs Using Tradespace-Based Affordability Analysis," 12th Conference on Systems Engineering Research, Redondo Beach, CA, March 2014

[92] Fitzgerald, M.E., and Ross, A.M., "Controlling for Framing Effects in Multi-Stakeholder Tradespace Exploration," 12th Conference on Systems Engineering Research, Redondo Beach, CA, March 2014

[93] SECDEF Memorandum, Science and Technology (S&T) Priorities for Fiscal Years 2013-17 Planning, April 19, 2011. Washington, DC. OSD 02073-11

[94] Neches, R., Engineered Resilient Systems (ERS): Insights and Achievements within the ERS Secretary of Defense Science and Technology (S&T) Priority, October 25, 2012

[95] Holland, J.P., Engineered Resilient Systems (ERS): A DoD Science and Technology Priority Area, Overview Presentation, Feb 28, 2013

[96] Holland J. P. ERS PSC Lead. Engineered Resilient Systems (ERS) – A DoD Science and Technology Priority Area. Overview Presentation, Feb. 28, 2013. Director, U.S. Army Engineer Research and Development Center (ERDC). Director, Research and Development U.S. Army Corps of Engineers.

[97] Goerger, S., Engineered Resilient Systems (ERS) Overview for Model-Based Enterprise Summit 2013, December 18, 2013

[98] Shaffer, A., Concepts for Change: DoD's 2014 Research and Engineering Strategy, Defense AT&L Magazine, January-February 2014

Engineered Resilient Systems (ERS): Our focus in ERS is to develop engineering concepts, science, and design tools to protect against malicious compromise of weapon systems and to greatly enhance the manufacturability of trusted and assured defense systems across the acquisition life cycle. Through the ERS initiative, the department is developing an integrated suite of computational modeling and simulation capabilities and systems engineering tools, complete with an open-reference architecture, directly aligned to acquisition and operational business processes. The R&D investment in ERS focuses on infrastructure, information, design support, highly robust tradespace analytics, decision support tools and knowledge environments to increase the speed and efficiency of system development, improve the effectiveness of fielded systems and provide life-cycle costs for decision making. The tools and procedures of ERS will produce more comprehensive and robust requirements suitable for many more alternative mission scenarios very early in the design process or pre-Milestone A. The reuse of data and models, distributed databases that are searched jointly, virtual collaboration environments and open architectures that encourage partnering will lead to better-informed acquisition decisions. The engineering design process is streamlined, and the manufacturability of a proposed design is explicitly investigated from both engineering and cost perspectives before design commitment. Finally, we are developing robust tools to stress systems against new mission contexts, tactics, techniques and procedures or emerging requirements, to permit precise measurement and understanding of their impact on all design and production factors.

ERS Tradespace Exploration

According to ERS Program overview briefings, ERS technology anchors include "ERS Framework and Open Architecture" and "Tradespace Analysis."[99] The purported benefits of tradespace analysis include, "enables informed decisions," "empowers AoA and Requirements Generation," and "'visualizes' trades of many more designs in far less time." The implied benefit of the last item is the discovery of "better" solutions in terms of cost and capability than would be the case in investigating fewer designs. The inputs into tradespace analysis in the ERS vision include both the mission context and the design elements to be traded, considered throughout the "product lifecycle" from "design to disposal" and which also consider sensitivity and confidence analysis of the results.

[99] Holland, J., "Engineered Resilient Systems (ERS)", ERS overview briefing, May 21, 2014

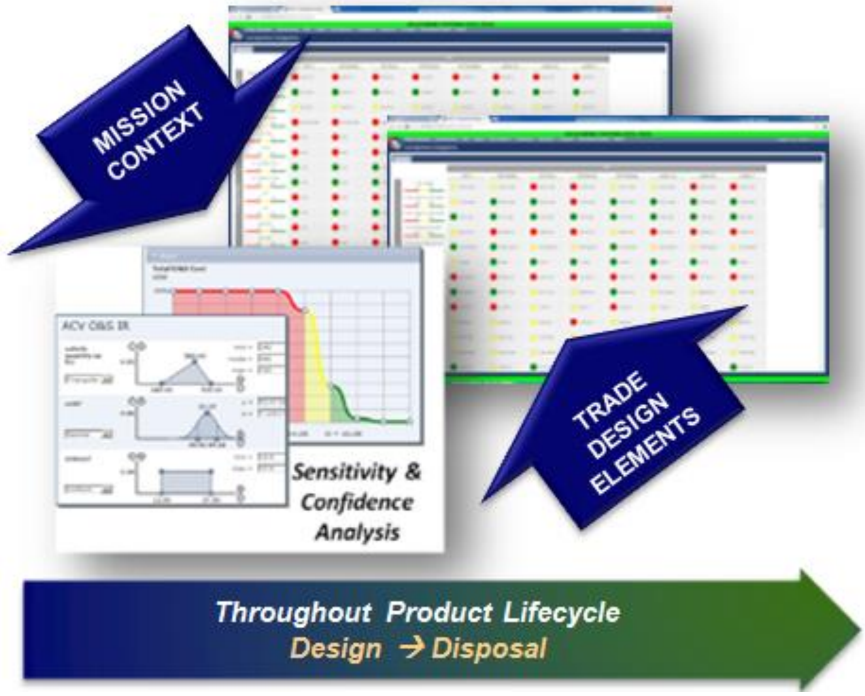

Figure 14 ERS tradespace analysis for informing decisions through visualizing trades of many design in less time (from Holland 2014)

Due to its essential role within ERS, this research project investigated tradespace exploration in context of the ERS program and its objectives. Spero et al.[100] say "tradespace exploration for ERS is envisioned to coalesce pertinent information tuned to specific decision makers, at the appropriate time, presenting a holistic view of decision impacts on required system capabilities."

As summarized in Spero et al.[102], "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."

The ERS TSE ***desired capabilities***, while not exhaustive, include the following capabilities extracted from multiple briefings and recent papers.

- Ability to readily identify both physical and preference constraints on feasible solutions

[100] Spero, E., Avera, M., Valdez, P., Goerger, S., "Tradespace Exploration for the Engineering of Resilient Systems," Conference on Systems Engineering Research (CSER), March 2014

- Ability to link tradespace tool with combat simulations(s) for inclusion of mission analysis
- Ability to perform analysis across alternative futures
- Ability to assess policy robustness of alternative solutions
- Auto-analysis of design elements
- Comparing point designs to alternatives in a tradespace
- Computation for tradespace calculation in SysML
- Data visualization – visualizes models (graphs, charts, 3_D objects)
- Differentiation of alternatives in terms of their ability to change state (i.e., "flexibility")
- Exploration of alternatives robust to requirements shifts
- Evaluating sets of alternatives against preferences on outcomes
- Performing portfolio analysis
- Representation to illustrate the differential impact of uncertainty across a tradespace of
- alternatives
- Reusing data from prior studies
- Seeing the immediate effects of changing needs
- Sensitivity & confidence analysis
- Supports set-based design
- Tradespace visualization of multiple parameters

A recent study (see Spero et al.[100)] provides an ERS view of tradespace exploration, noting that having a valid set of attributes, and an understanding of how a cross-section of tools can satisfy them, is presently insufficient. The authors discuss the need for a deeper understanding of how these tools are used and how they can be used when performing tradespace exploration in support decision analysis. The study identified 81 candidate tradespace exploration tools (and also recognized more exist). It assembled a "best common practice" process for their requirements, identified a set of attributes for an ideal tradespace exploration tool, and surveyed existing tools that satisfy these attributes.

Desired outcomes, as a result of achieving the goals of ERS TSE, are enumerated in various briefings and publications. While not an exhaustive list, the following desired outcomes have been articulated.

- Accelerate requirements analysis via surrogate response surfaces
- Affect feedback between manufacturability and capability
- Consider (100x) number of parameters and scenarios in setting requirements
- Capabilities for handling a broader range of solutions in tradespace analysis
- Data and lessons learned retained for rework
- Empowers AoA and requirements generation
- Enables larger tradespaces, keep alternative design options open longer
- Generate requirements that consider more alternative scenarios
- Identification of risk-reducing technologies
- Integration of tradespace analysis into single architecture
- Integration into tool with Plug-and-Play Modules and Tool Orchestrator
- Make much more informed decisions early in acquisition process

- SoS insights more deeply understood and utilized
- Supporting mission context analysis
- Tradespace analysis support for cost, schedule, and performance risk analysis
- Tradespace analytics thrust - support collaborative analyses, tools incorporating risk and cost, and user-friendly control of distributed systems
- Visualization of quantified assessment of feasibility/affordability
- “Visualizes” trades of many more designs in far less time

There are various enablers that have been identified supporting these outcomes. These include ample data storage, multi-physics based modeling design tools, ontologies describing system and trades, and toolsets linking mission context to tradespace tools. Other enablers include enhanced visualization in the toolsets and reduced order surrogate models with iterative ability of adjusting scenarios and requirements to physical capability.

Toward an ERS TSE Research Agenda

A research agenda for ERS TSE has been emerging as a result of several recent workshops and ongoing research programs in universities and government. The U.S. Army Research Laboratory's Vehicle Technology Directorate (VTD), in collaboration with the Office of the Deputy Assistant Secretary of Defense for Systems Engineering, held an invitation-only workshop on Data-Driven Tradespace Exploration and Analysis on July 17-18, 2012. The output from this workshop served as input to a workshop on tradespace and affordability that was hosted the following day by the SERC, for which a report was published[101].

Attendees in these workshops view resilience in the context of ERS as 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. Current TSE practice and toolsets are inadequate.

The Data-Driven Tradespace Exploration and Analysis 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. It 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. 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.

[101] Tradespace & Affordability Program (TAP) Workshop Report, Stevens Institute of Technology, Washington, DC. July 18-19, 2012. v1.0

The results of the workshop have been summarized in a publication, providing a foundational research agenda[102]. The research agenda was elaborated by break-out groups for five perceived functions of TSE:

1. Broadening, Populating, and Managing the Tradespace
2. Linking the Tradespace
3. Searching, Exploring, and Analyzing the Tradespace
4. Acting on the Tradespace
5. Modeling and Simulation's Role in Generating Tradespace Data
6.

Spero et al.[102] highlight their important assumption 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".

PROGRESS TOWARD AN ERS TRADESPACE EXPLORATION LEXICON

A vocabulary for tradespace exploration has informally been emerging in the community, but there has been limited effort to establish a common lexicon. As the tradespace exploration community expands to a diverse set of practitioners and is used in discussions with various stakeholders, a lexicon is necessary to ensure there is no ambiguity of terms. Further, the lexicon will be important to developing and transferring MPTs across the community. This research gathered an initial set of terms, and can serve as the basis for evolving a standard lexicon for the ERS community.

The list below show the set of terms gathered during this research project. It should not be considered as complete, nor does it represent a community consensus.

Preliminary Lexicon of elements/constructs used in tradespace exploration

- Adaptability
- Aggregation functions
- Alternative solutions
- Analysis of alternatives
- Architecture
- Attributes
- Attribute limit
- Attribute units
- Attribute weights
- Benefits
- Characteristics (required to satisfy performance standards)
- Changing operational environments
- Code fidelity
- Complexity
- Confidence analysis
- Constraints
- Constructed model

[102] Spero, E. Bloebaum, C., German, B., Pyster, A., Ross, A.M., "A Research Agenda for Tradespace Exploration and Analysis of Engineered Resilient Systems", Conference on Systems Engineering Research (CSER), March 2014

- Contexts
- Course of action
- Cost
- Cost model
- Cost v. capability analysis
- Decisions
- Design
- Design elements
- Design vector
- Design variables
- Enumeration (e.g., of design vector)
- Epoch
- Epoch variables
- Epoch-Era Analysis
- Era
- Evaluation
- Evidence
- Expense
- Exploration
- Feasible region
- Flexibility
- Generation
- High-level system design variables
- Ilities
- Infrastructure
- Key intermediate variables
- Lessons learned
- Lifecycle costs (based on stakeholder values)
- Lifecycle cost analysis
- Lifecycle data
- Lifecycle intelligence
- Lifecycle path analysis
- Lifecycle schedule analysis
- Mapping of stakeholder values to design variables
- Mental model
- Metrics (e.g., Filtered Outdegree, Pareto Trace, Normalized Pareto Trace, Fuzzy Normalized Pareto Trace)
- Mission context
- Mission data
- Mission scenario(s)
- MOP, MOE, and other performance attributes
- Multi-attribute utility
- Multi-concept tradespace
- Multi-dimensional data analysis
- Ontology
- Operational performance characteristics
- Options
- Optimization study
- Optimum feasible space
- Parameters
- Pareto frontier
- Performance model
- Perturbations
- Preferences

- Physics-based models
- Point-based design
- Post-analysis studies
- Predictable degradation
- Probabilistic risk assessment
- Qualitative/quantitative ranking of how alternatives meet measures
- Requirements generation
- Resilience
- Responses
- Robustness
- Sampling strategy
- Scenarios
- Selection (rules)
- Sensitivity plots
- Set-based design
- Single-attribute utility
- Stakeholder needs
- Stakeholder values (breakdown into roles, attributes, specific tasks)
- Surrogate models
- System lifecycle
- System parameters
- Swing weights
- Test for robustness
- Tradespace
- Tradespace analysis
- Tradespace database
- Tradespace information
- Tradespace metrics
- Tradespace plot
- Tradespace yield number
- Uncertainty analysis
- Utility-cost plot
- Utility curves
- Validation
- Value measures (for given mission scenarios and requirements)
- Value model
- Visualizations
- Weightings

The development of a lexicon for tradespace exploration by the tradespace exploration community is a desirable goal in the overall efforts to mature the practice. A recommended path of action is for the community to add to the preliminary list, define the terms in a general manner, and include specific uses and examples. Below is illustrative of what could result.

Term	**Definition**	***Example***
Attributes	stakeholder-defined criteria that reflect how well stakeholder-defined objectives are met for a system	*Maritime Security SoS Case:* • *Primary stakeholder identified the probabilities of detection/identification/interception as the main attributes that would generate value for the SoS.* • *A secondary stakeholder identified the probability of successful search and rescue as an additional attribute.*

PHASE 2 RESEARCH

In this phase of the research, TSE-related concepts were codified into key elements, processes, and descriptors in order to provide a framework for capturing knowledge generated during a TSE study, facilitating transfer to others, as well as enabling reuse and comparison within future studies. This phase was accomplished through coding TSE constructs, and testing this on a limited basis through an exploratory pilot case. Additionally, this phase investigated current the ERS architecture and artifacts in relation to knowledge capture and transfer of the identified core TSE constructs. Preliminary observations and next steps are provided for evolving the ERS TSE architecture toward achieving its vision as a key decision support capability for enabling resilient development processes and systems.

FRAMING TYPES OF KNOWLEDGE FOR CAPTURE

When considering the types of knowledge to be captured for TSE, it is important to identify the core constructs at the essence of a TSE study for decision support.

Figure 15 below illustrates the highest level abstraction for these core constructs.

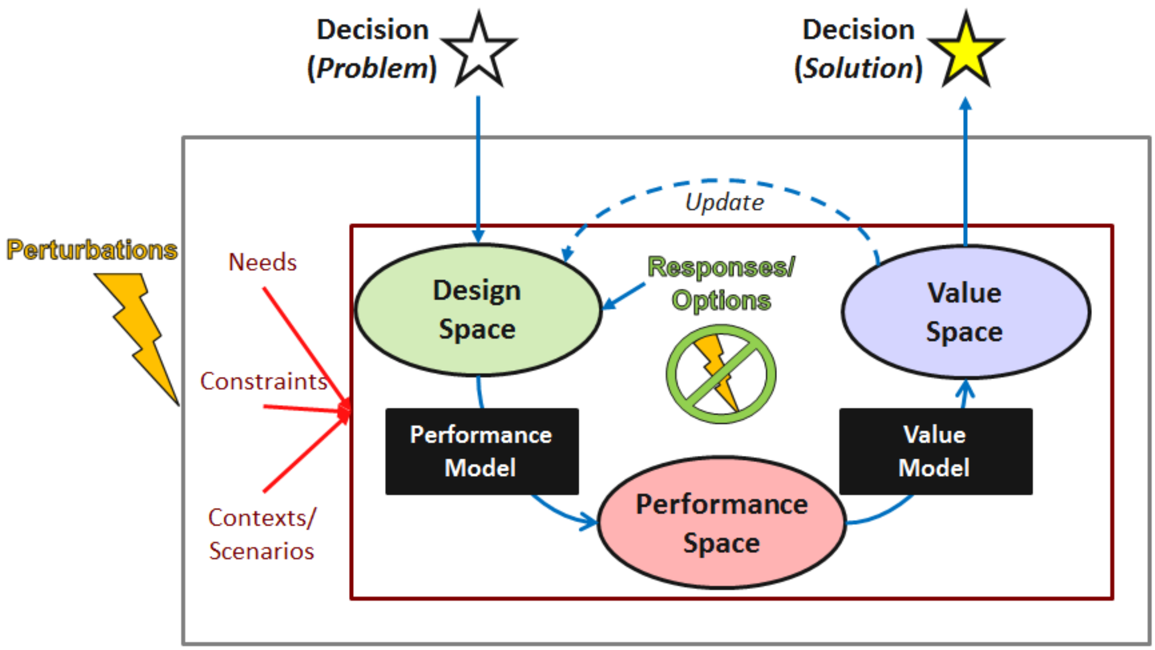

Figure 15 Key models and spaces in the "design loop" for decision support in TSE (based on Ricci et al 2014[103] and Ricci 2014[104])

The "design loop" depicted in the figure above essentially represents the key elements needed for tradespace exploration for decision support. The *design space* represents the space of

[103] Ricci, N., Schaffner, M., Ross, A.M., Rhodes, D.H., and Fitzgerald, M.E., "Exploring Stakeholder Value Models via Interactive Visualization," in Conference on Systems Engineering Research, Redondo Beach, CA, March 2014.

[104] Ricci, N., *Dynamic System Perspective on Design: Ility-Driving Elements as Responses to Uncertainty*, Dual Master of Science Thesis, Aeronautics and Astronautics and Technology and Policy Program, MIT, June 2014.

possible solutions; the *performance space* represents the design space evaluated in terms of performance criteria of interest; the *value space* represents the performance space valuated in terms of value metrics of interest. *Models*, both performance and value, are used for the transformations between the spaces as indicated. Models are essential tools in system design and are used by analysts and engineers throughout the design process. A key function of models is to generate data when empirical sources are not available; this data is then used by analysts and decision makers to discern among potential alternatives. Against the backdrop of spaces and models are supplied inputs including *needs* (e.g. mission objectives, requirements), *constraints* (e.g. workforce rules, regulations, inherited technology, etc.), and *contexts/scenarios* (e.g. operational environments, regulatory regimes, budgetary conditions, etc.). In addition to these factors, two additional ones must be considered, which relate fundamentally to the dynamic uncertainties faced by the system. *Perturbations* describe anticipated imposed changes on any of the inputs, models, or spaces. R*esponses/options* describe potential system design and/or operational choices that can be used to mitigate downside impact (i.e. risk) or take advantage of upside impact (i.e. opportunities) of the perturbations. The "design loop" is followed from problem formulation through the spaces and model transformations until sufficient evidence is generated as to justify a solution (or set of solutions). Updating the problem formulation, inputs, space definitions, and models can all occur during TSE activities.

Construct	Role
Decision (problem)	The particular top level formulation of what needs to be "solved" by a system development activity
Decision (solution)	The particular set of answers to the decision problem, possibly including one or more proposed system solutions with appropriate supporting evidence
(Perceived) Needs	The espoused objectives (typically mission-related), goals, criteria of desired capabilities; can vary across individuals/organizations/time; sometimes represented as requirements
Constraints	Imposed limitations on system design, operation, resources, etc.
Contexts/scenarios	The particular exogenous factors that affect perceived system success, including operating environment, regulatory regime, budgetary conditions, etc.
Design Space	The span of potential system designs from which specific alternatives will be evaluated
Performance Space	The span of performance evaluated system alternatives; the definition of this space is determined by which performance metrics are of interest, these can include "cost" as well as behavior
Value Space	The span of value provided by system alternatives via value model interpretation of the performance space; the span of this space illustrates what is "possible" in terms of benefits and costs and is subjectively
Performance model	A model used to predict the performance (e.g. behavior, cost) of a system; a formal representation of how design alternatives perform subject to contexts and constraints

Value model	A model used to predict the value (e.g. goodness) of a system; formal representation of how performance criteria relate to perceived value (i.e. benefit at cost), subject to perceived needs. Note: value-models attempt to codify perception and therefore can and will vary across individuals/organizations/time
Perturbations	Imposed changes to any of the inputs, models, or spaces (E.g. requirements change)
Responses/Options	The design and/or operational response of the system in order to mitigate the downside consequences of perturbation(s); this is what enables resilience in systems (i.e. robustness, versatility, adaptability/flexibility, survivability, etc.)

In addition to these tradespace elements, the information about the study itself, as well as the process followed, should be captured. The study description at a top level should include an overview, identification of key decision makers, the goals for the study (including description of "problem to be solved" and criteria for determining when a solution is in hand), approach for the study, findings of the study (e.g. the proposed solution), and outcome (i.e. impact/results of using/deploying the findings). The process description should be standardized, such as the generic tradespace exploration set of processes described earlier in this report under "Scope: Tradespace Exploration" and repeated here: generation, enumeration, sampling, evaluation, exploration, and selection. Use of a standard description facilitates knowledge capture and transfer across TSE studies.

EXPLORATION CASE STUDY

One of the tasks in this research project was to conduct an exploratory case study to identify tradespace exploration artifacts in practice and how they relate to knowledge goals within ERS. Unfortunately delays in data availability cut short the intended timeframe across which to perform this case study. What follows are some observations based on limited data availability to two Navy tradespace exploration activities conducted in concert with the ERS Program.

NAVY TSE STUDY 1: POINT VS. SET-BASED DESIGN

Overview: In this study, a team at Naval Surface Warfare Center-Carderock conducted a ship design study using an "ERS" approach. The vision included "solid 'framing assumptions' in pre-milestone A efforts" in order to manage the fact that "early decisions drive significant and expensive results." Specifically ERS would enable these improved decisions through "physics based data-driven trade space exploration," and "robust analysis of requirements, design concepts, CONOPs, mission effectiveness, technology, and cost".[105]

Key decision makers: Navy internal, ERS Program

[105] Mackenna, A., and Hough, J., "Engineered Resilient Systems (ERS) for Ship Design & Acquisition," Distro A briefing, May 21, 2014, slide 6.

Goal(s) for the study: "Demonstrate ability to design a resilient ship, with a resilient process, through application of physics based modeling & trade space informed set-based design"

Approach: start with baseline design; two independent teams to develop final ship design; perturbations introduced during design and after initial "final design" (e.g. midlife upgrade scenario) to test resiliency of design process and of final design

Tradespace elements description:

Type	Element	Description
Inputs	Needs	unknown
	Constraints	unknown
	Contexts/Scenarios	early stage design phase, service life phase
Spaces	Design Space	inherited baseline design; set-based team used Rapid Ship Design Environment (RSDE) to expand space
	Performance Space	unknown
	Value Space	measure of effectiveness, cost, and risk
Models	Performance Model	ASSET-LEAPS (includes semi-empirical and physics-based analysis tools and performance-based cost model)
	Value Model	MS-Excel spreadsheets for MOE and risk assessment
Changes	Perturbations	requirements shift during design phase and service phase
	Responses/Options	to requirement shift in design phase: point-based had to redesign, while set-based just picked different design; to requirement shift during service phase: unknown

Tradespace processes description:

Process	Description
Generation	begin with baseline design
Enumeration	point-based team: propose few variants off of evolved baseline; set-based team: use RSDE leveraging multi-discipline optimization to propose alternatives
Sampling	point-based team likely uses full enumerated (small) set as sample; set-based team appears to have leveraged RSDE's optimization capabilities to derive samples from full potential enumeration
Evaluation	Both teams used ASSET-LEAPS to evaluate performance and cost of sampled design points, with value evaluated through a MS-Excel spreadsheet model; surrogate modeling is available through RSDE as well (including Kriging, among others)
Exploration	unknown for point-based team; set-based team uses RSDE GUI to generate visualizations of design space for exploration
Selection	each team proposed a "final design" at the end of each phase to be judged by highest MOE and lowest cost (and risk)

Infrastructure used: ASSET-LEAPS and RSDE tools

Key findings: When faced with design phase requirements change, point-based design team had to conduct rework, while set-based design team did not; when trying to meet cost goals, point-based team had to “guess on way to achieve cost goal based on experience of team members,” whereas set-based team “gained knowledge of design & cost drivers” and therefore “had knowledge on how to meet cost goal” without having to guess or rely upon team experience; point-based team tended to pick higher risk designs than set-based team as requirements changed

Outcome: Pilot study validated ERS hypothesis through results of point vs set-based design processes in response to requirements change perturbation (i.e. tradespace “facilitates rigorous requirements analysis” allowing “deliberate cost vs. capability decisions at earliest stages of design acquisition (pre-milestone A).” Additionally, it was found that using physics based analysis tools enabled early identification of unobtainable or unaffordable requirements (i.e. the infeasible regions of the evaluated tradespace). It also became apparent that the knowledge embedded in the structure of the tradespace mimicked that of experienced members and could be used to educate inexperienced ship designers, potentially serving as a knowledge transfer mechanism when the experienced team members are unavailable. The vision for ERS Ship Design includes expanded sets of physics-based modeling, and more formal representations for decision support (i.e. showing requirements tradeoffs, MOE, cost versus requirements, risk, etc.)

NAVY TSE STUDY 2: AOA EXTENSION

Overview: In this study, a formal AoA (~9 mos level of effort) was conducted, resulting in approximately 5 point designs. The results of the study were not conclusive, with ships deemed to be too expensive and not capable enough. In order to demonstrate the potential benefit of moving beyond a traditional AoA and into a cost versus capability analysis (i.e. a TSE study), the ERS program extended the study by 3 months (~6-8 person months of additional effort), from 1 Oct 2013 to 15 Jan 2014. Insights gained in the tradespace activity resulted in Navy directing next effort to conduct cost versus capability analysis rather than a formal AoA.

Key decision makers: Navy-internal (unknown)

Goal(s) for the study: Unknown

Approach: Generate additional design alternatives from the baseline designs and evaluate them using models in support of a cost versus capability analysis

Tradespace elements description:

Type	Element	Description
Inputs	Needs	unknown
	Constraints	unknown, but included upfront cost limit
	Contexts/Scenarios	unknown
Spaces	Design Space	TBD
	Performance Space	TBD
	Value Space	TBD
Models	Performance Model	TBD
	Value Model	TBD
Changes	Perturbations	TBD
	Responses/Options	TBD

Tradespace processes description:

Process	Description
Generation	unknown
Enumeration	traditional AoA results in ~5 designs; unknown how larger set is enumerated in cost v. capability analysis extension
Sampling	unknown (full?)
Evaluation	unknown
Exploration	unknown
Selection	unknown

Infrastructure used: unknown

Key findings: initial AoA resulted in 5 point designs with insufficient capability and high cost; the Cost v. Capability TSE extension resulted in capability versus cost correlation insights (i.e. design drivers)

Outcome: Navy liked the approach enough to direct the next effort (1 Apr 2014 to 15 Aug 2014) to conduct a Cost v. Capability analysis rather than a formal AoA

Reflection on Exploration Cases

Emergent in the application of the TSE descriptors to the exploration case was the realization that the data needed should be readily available to the team, but difficult to capture by an outsider. This may be obvious after the fact, but it means that any proposed framework should be readily available to the TSE team prior to and during a study, both to assist with study conduct and to help with knowledge capture. Not obvious in the exploratory case is the fact that in spite of the multitude of "unknown" responses, each item is directly relevant to any TSE study and should be readily answerable by the TSE team. Additionally, the item "infrastructure used" was not originally proposed as an item, but emerged as a useful item for capturing aspects like "tools used" or other supplied items that are potentially useful beyond this particular study. Once broad knowledge capture is underway using the ERS architecture, such information could become very valuable in tracking "popular" tools and computing capabilities, as well as to provide some insight into future infrastructure planning (e.g. unused policy documents or oversubscribed HPC clusters, etc.)

FRAMEWORK FOR A LARGER-SCALE CASE STUDY

Based on a synthesis of the literature, interviews, and the exploratory case, the following is a preliminary template for a description of an ERS-relevant tradespace study.

Overview: TBD

Key decision makers: TBD

Goal(s) for the study: TBD

Approach: TBD

Tradespace elements description:

Type	Element	Description
Inputs	Needs	TBD
	Constraints	TBD
	Contexts/Scenarios	TBD
Spaces	Design Space	TBD
	Performance Space	TBD
	Value Space	TBD
Models	Performance Model	TBD
	Value Model	TBD
Changes	Perturbations	TBD
	Responses/Options	TBD

Tradespace processes description:

Process	Description
Generation	TBD
Enumeration	TBD
Sampling	TBD
Evaluation	TBD
Exploration	TBD
Selection	TBD

Infrastructure used: TBD

<u>Key findings</u>: TBD

<u>Outcome</u>: TBD

A larger scale study would aim to populate this template to the next level of detail, and should also be applied across additional cases. Most importantly, a catalogue of responses to each of these descriptors can be used to inform the ERS architecture and knowledge repositories to facilitate future ERS TSE studies and tools. Additionally, further enhancement of the descriptor set can be used to guide practitioners to explicitly consider essential elements necessary to determine resilience of their systems within their studies.

PRELIMINARY PRESCRIPTION TO THE ERS PROGRAM ON TSE

In spite of the limited availability of data for the exploratory case study in this research, enough insights were gained to support preliminary prescription for ERS going forward. These are described in the following sections.

ASSESSMENT OF "TODAY"

The journey of the ERS program in meeting its ambitious goals is not a short one and requires many milestone accomplishments along the way. For example see
Figure 16 below for the architecture roadmap. The roadmap illustrates the rollout of key components of the ERS infrastructure for supporting TSE.

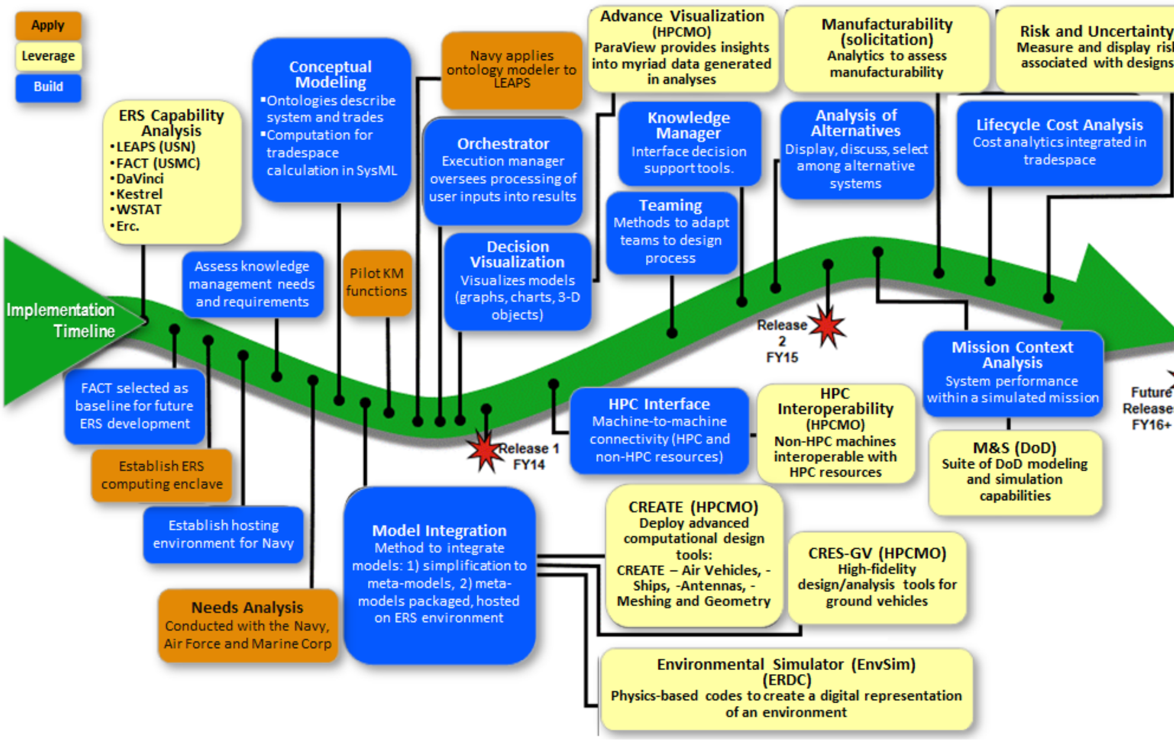

Figure 16 ERS architecture roadmap (from Holland, May 2014)

The ERS program has made excellent progress in both developing an infrastructure vision with capabilities, and conducting pilot studies to validate the intended benefit of using an ERS perspective. The ERS contributions are based partly on employing the following:

- HPC and physics-based models to provide broad and deep data evidence
- Surrogate modeling techniques to enable broader design space exploration
- Multi-discipline optimization for enumeration and sampling of design space
- Improved visualizations of cost versus capability and other metrics for supporting decision making
- An initial investigation of perturbation-response on system design process as well as system design
- Plan to provide infrastructure to the community, including standardized tools, databases, and processes

Based on the knowledge capture template in the previous section, moving forward ERS should make explicit effort to also incorporate the following:

- Coupling of scenarios/context evaluation with the tradespace exploration activities
- Explicit "value model" use/leverage
- Explicit consideration of a range of perturbations, representing dynamic uncertainties (risks and opportunities) to both development processes and systems under consideration in a TSE
- Explicit consideration of a variety of responses/options of both development processes and systems to the perturbations in order to evaluate their resilience
- Explicit consideration of operations trades in addition to physical system trades

IMPORTANT AUGMENTATIONS TO TRADITIONAL TRADESPACE ANALYSIS

Since the purported goal of tradespace exploration is to support decisions (at least as represented in the ERS Program overview and within this document), the framing of each TSE study should be positioned to most easily assist in that capacity. This means the input factors should be "decision variables" (i.e. factors within the control and/or influence of the decision maker), and the output factors should be the key decision criteria to be used by the decision maker. In its most general guise, this is similar to an applied decision analysis exercise, with the added complexity that the study can generate additional alternatives (i.e. an open-ended set for evaluation). A "value-driven" perspective has been adopted since it most directly reflects this decision-oriented perspective. Values are simply the top level benefit and cost perceptions of a given decision maker, including possible selection rules (i.e. I care about the performance of my system in terms of spatial resolution, tracking latency, and reliability, as well as O&M costs and political palatability in terms of manufacturing and sustainment). By focusing on values (i.e. the decision criteria), this opens up the design space to include vastly different alternatives and therefore increases the likelihood of finding a feasible, or possibly better, solution. The value-driven perspective is in contrast to the alternatives-focused thinking, which starts with a solution[106]. The value-driven perspective also frees up engineers to focus on engineering and decision makers to focus on making decisions, rather than the other way around.

Alternatives focused thinking:

- May result in only small number of (possibly inappropriate, or subpar) solutions considered
- More quickly reduces ambiguity in the problem by quickly getting to the concrete evaluation and specification part of design
- May result in using scarce resources developing solutions that need to be justified (e.g., "sold" through altering expectations)

Value focused thinking:

- Allows for "re-casting" of a "problem" into an "opportunity"
- Increases likelihood of solution performing well in value
- Aligns scarce resources on the proper questions
- Allows for consideration of new solutions (helps to break anchoring)

Some engineers do not like the use of "subjective" factors for evaluating their designs. The fact of the matter is that good decision makers use all necessary and relevant information for making their decisions. Sometimes these factors are non-technical, including issues of economic and social equity or even political. Good tradespace exploration supports these decisions in a layered fashion by addressing the technical factors and leaving room for decision makers to incorporate addition information, as needed. It is important to also note that subjectivity enters into decision making even on technical factors. This subjectivity comes about as people interpret risk and uncertainty, which is inherent in any estimated performance or cost figures in system studies. By

[106] Keeney, R.L., "Value-Focused Thinking: A Path to Creative Decisionmaking," Harvard University Press, Cambridge, MA, 1992.

layering in the "subjectivity" through tradable value models, the tradespace analyst of the future will be able to identify not only the impact of varying "subjective" preferences on what makes a "good" solution, but also be able to identify potential solutions that are insensitive to changes in those preferences.

An additional challenge for future tradespace exploration and analysis is the explicit consideration of the impact of time and context on the tradespace results. What may appear to be a good solution today may change in the future under difference circumstances. While sensitivity analysis and some scenario planning does occur today, it is done insufficiently to identify truly resilient system solutions. Sensitivity analysis across changing contexts over time should be built explicitly into the ERS program architecture and associated MPTs to ensure that the analysis is done, rather than relegated to the end and likely to be omitted when projects run into time constraints.

Additionally, tradespace exploration studies must explicitly consider the impact of perturbations on the needs (e.g. requirements change), constraints (e.g. budget shift), contexts (e.g. new mission environment), design space (e.g. new concepts), performance space (e.g. new performance metric), value space (e.g. new benefit metric), performance model (e.g. new physics based model or cost model), or value model (e.g. new utility function). Resilience is achieved by the design process and the system design itself through their responses to these perturbations. Thus it is essential that ERS TSE considers both perturbations and responses as necessary components of any study. Otherwise, resilience considerations likely will be ad hoc and less likely to be present by intent.

DEVELOPING FURTHER ENABLERS

The research investigation has emphasized the need for enablers for ERS tradespace exploration. Infrastructure in support of computation, data storage, visualization, and other enablers are necessary to achieving the ERS TSE vision. A preliminary lexicon, included in this report, needs to be further developed. Having a common set of terms will support the maturation of TSE processes and enable better communication across the TSE research and practitioner community. There are many contributors to, and beneficiaries of, ERS TSE. Further development of a "map" of the activities and involved organizations will enable continued growth of a community of research and practice.

USE OF TRADESPACE EXPLORATION FOR KNOWLEDGE CAPTURE

As mentioned earlier, TSE has shown promise for codifying expert knowledge into a concise format that is accessible to novices and other experts alike[107,108]. The following sections revisit

[107] Wolf, D., An Assessment of Novice and Expert Users' Decision-Making Strategies during Visual Trade Space Exploration, MS Thesis, Mechanical Engineering, Penn State University, May 2009.

[108] Even the recent ERS-supported Navy Ship Design project found this to be the case when the set-based design team could leverage knowledge in the tradespace revealing cost drivers, whereas the point-based design team had to rely on expert knowledge to guess at how to reduce cost, resulting in the project suggesting that TSE would be

the concepts uncovered in this research and their applicability for capturing and transferring knowledge.

Revisiting the types of knowledge for capture

When proposing knowledge capture in TSE activities, each of the elements in Figure 17 represents a body of knowledge both for the specific study at hand and the domain (or decision process more generally).

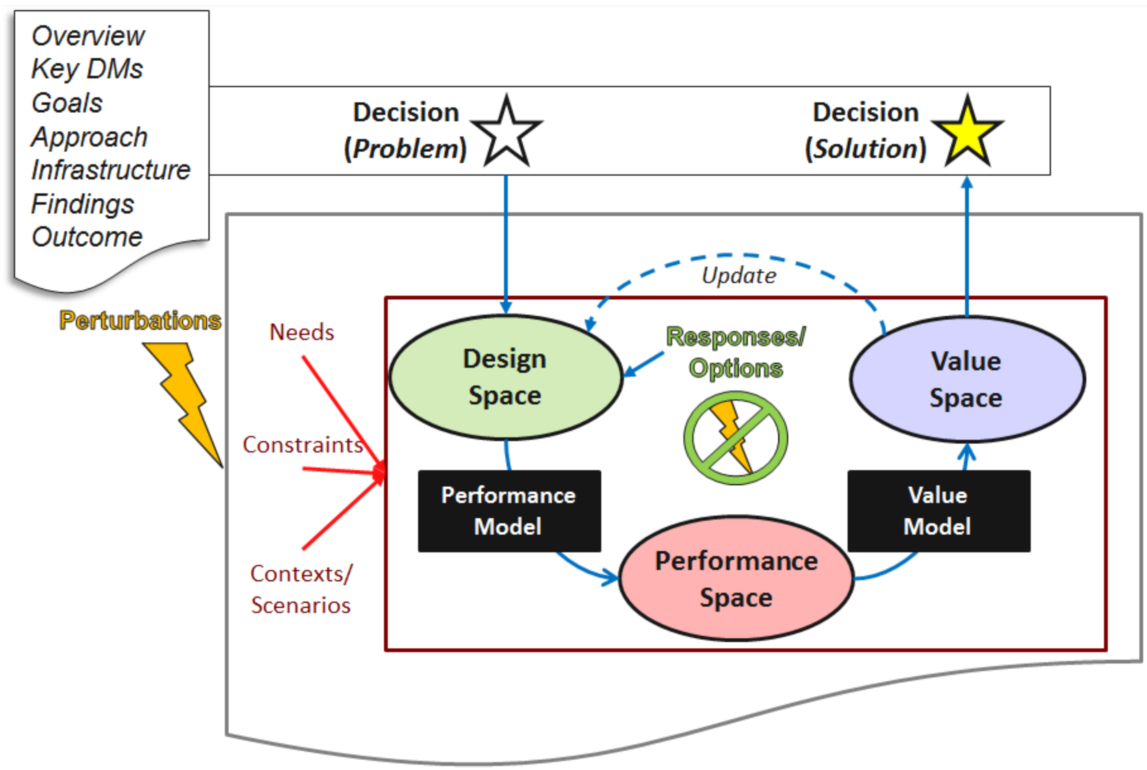

Figure 17 Review of the key study data, inputs, models, and spaces for decision support in TSE

For example, for a given project (as described by the ERS ontology, capturing system type, domain, etc.), historical data on similar projects should be accessible as desired in order to report their relevant inputs (e.g. needs, contexts, constraints), as well as previously defined design, performance, and value spaces and associated models.

In the space domain, ISR systems tend to have similar top level KPPs, which should be readily accessible in future ISR TSE studies. Associated data with these decision criteria should be captured and reportable (e.g. desired spatial resolution, revisit time, latency, etc.) In current practice (typically document or process-driven, rather than data-driven), this type of data may

useful for training novices (see Mackenna, A., and Hough, J., "Engineered Resilient Systems (ERS) for Ship Design & Acquisition," Distro A briefing, May 21, 2014) not be readily accessible. Concerns relative to data sensitivity must be taken into account, but can be handled with the appropriate data partitioning and security policies.

Understanding how effort impacts confidence in knowledge

In practice, not every study has the same amount of resources available (including personnel, expertise, computation, etc.), and not every study requires the same level of effort for the decision problems posed. This leads naturally to an effort versus confidence (in knowledge gained) tradeoff in terms of how to conduct the TSE study. In the recent past, some work was done applying the same TSE process at varying levels of effort in order to begin to understand the inherent tradeoffs between spending more time on a particular activity (at the risk of not completing later activities) or less time on a particular activity in order to complete more activities (at the risk of not going "deep enough" in the generation of the results). In order to address this challenge, the research team developed a TSE method whose inherent structure led to incremental knowledge generation (i.e. as one progresses from earlier to later activities, insights build upon prior ones so that the analyst does not have to wait until the end to get insights). This incremental TSE method is called the Responsive Systems Comparison Method (RSC) and has seven processes, each building upon the prior (see Figure 18 figure below)[109,110,111]. For the effort versus confidence study, RSC was applied to several different case studies with imposed time constraints to force effort tradeoffs. These studies are more illustrative than conclusive, as more data would need to be generated for statistically valid prescription (

Figure 19). However, these studies are suggestive that it would be valuable to conduct broader investigations into this very practical issue of how to allocate project resources when conducting a TSE study within ERS.

[109] Ross, A.M., McManus, H.L., Long, A., Richards, M.G., Rhodes, D.H., and Hastings, D.E., "Responsive Systems Comparison Method: Case Study in Assessing Future Designs in the Presence of Change," AIAA Space 2008, San Diego, CA, September 2008.
[110] Ross, A.M., McManus, H.L., Rhodes, D.H., Hastings, D.E., and Long, A.M., "Responsive Systems Comparison Method: Dynamic Insights into Designing a Satellite Radar System," AIAA Space 2009, Pasadena, CA, September 2009.
[111] Schaffner, M.A., *Designing Systems for Many Possible Futures: The RSC-based Method for Affordable Concept Selection (RMACS), with Multi-Era Analysis*, Master of Science Thesis, Aeronautics and Astronautics, MIT, June 2014

Responsive System Comparison method fidelity options and knowledge generated

The following are example options for particular activities within RSC Processes.

The options are listed from lowest to highest fidelity (and required effort)

Study Name: ________________ Respondant: ________________

Start time: _______ Goal end process: _______ Goal effort expended: _______ (person-hrs)

End time: _______ Actual end process: _______ Actual effort expended: _______ (person-hrs)

RSC Process

P1 Value-Driving Context Definition	P2 Value-Driven Design Formulation	P3 Epoch Characterization	P4 Design Tradespace Evaluation	P5 Multi-Epoch Analysis	P6 Era Construction	P7 Lifecycle Path Analysis
Defining value network	**Selecting DM(s)**	**Uncertainty categories**	**System Model types**	**Select epochs for analysis**	**Era samplig**	
list of stakeholders	Use past examples/data	Technology	Look-up table (opinion)	Set "choices"	Set "choices"	
stakeholders grouped by interest	Use proxy (team role-playing)	Policy	Look-up table (data-based)	Random sampling	Random sampling	
stakeholders with value flows	Use proxy (external rep.)	Budget	Parametric model(s)	Partial factorial (DOE-based)	Partial factorial (DOE-based)	
	Use real DM	Infrastructure	Simulation(s)	Full factorial	Full factorial	
	Attribute elicitation	End uses	**Design space sampling**	**Pareto tracing**		
	Attributes w/ranges only	**Epoch space enumeration**	Set "choices"	Qualitatively inspect Pareto Set movement in TS across epochs		
	... plus informal "weights"	Set "choices"	DV-driven point sampling(s)	Calculate Pareto Trace		
	.... plus formal "weights"	EV-driven point enumeration(s)	Extreme sampling	Calculate Fuzzy Pareto Traces		
	Utility elicitation	Extreme enumeration	Random sampling			
	None, assume linear	Partial factorial (DOE-based)	Partial factorial (DOE-based)			
	Qualitative "shape" w/key values	Full factorial	Full factorial			
	Formal utility interview		**Cross-epoch evaluations**	**Changeability analysis**		
	Generate concepts		inspect baseline epoch, indicate sensitivity (plus,minus w/ intensity)	Use max(OD) assessment using transition rules (filter=L,M,H)		
	Use past concept(s)		run "models" for each epoch	Calculate FOD using matrices		
	Use opinion-driven concepts					
	Use DVM to drive concepts					

Principle Knowledge Generated

P1	P2	P3	P4	P5	P6	P7
Problem definition	Value proposition(s)	Key exogenous factors	Design-value tradeoffs	Time-based context effects	Possible long run scenarios	System evolution strategies
			Multi-DM tradeoffs	Value robust designs		

On a scale from 1-5, please assess your comfort with the knowledge generated by each process, given the scope of your study

1 Not at all	2 A little	3 Somewhat	4 Fairly	5 Very
no results or arbitrary placeholder results (should redo activity)	results likely to change (if redo activity)	results possibly might change (if redo activity)	results unlikely to change, but may grow (if redo activity)	results stable and mostly complete (no need to redo activity)

(Please enter '0' if process was not performed)

Figure 18 Example method scalability options with associate knowledge

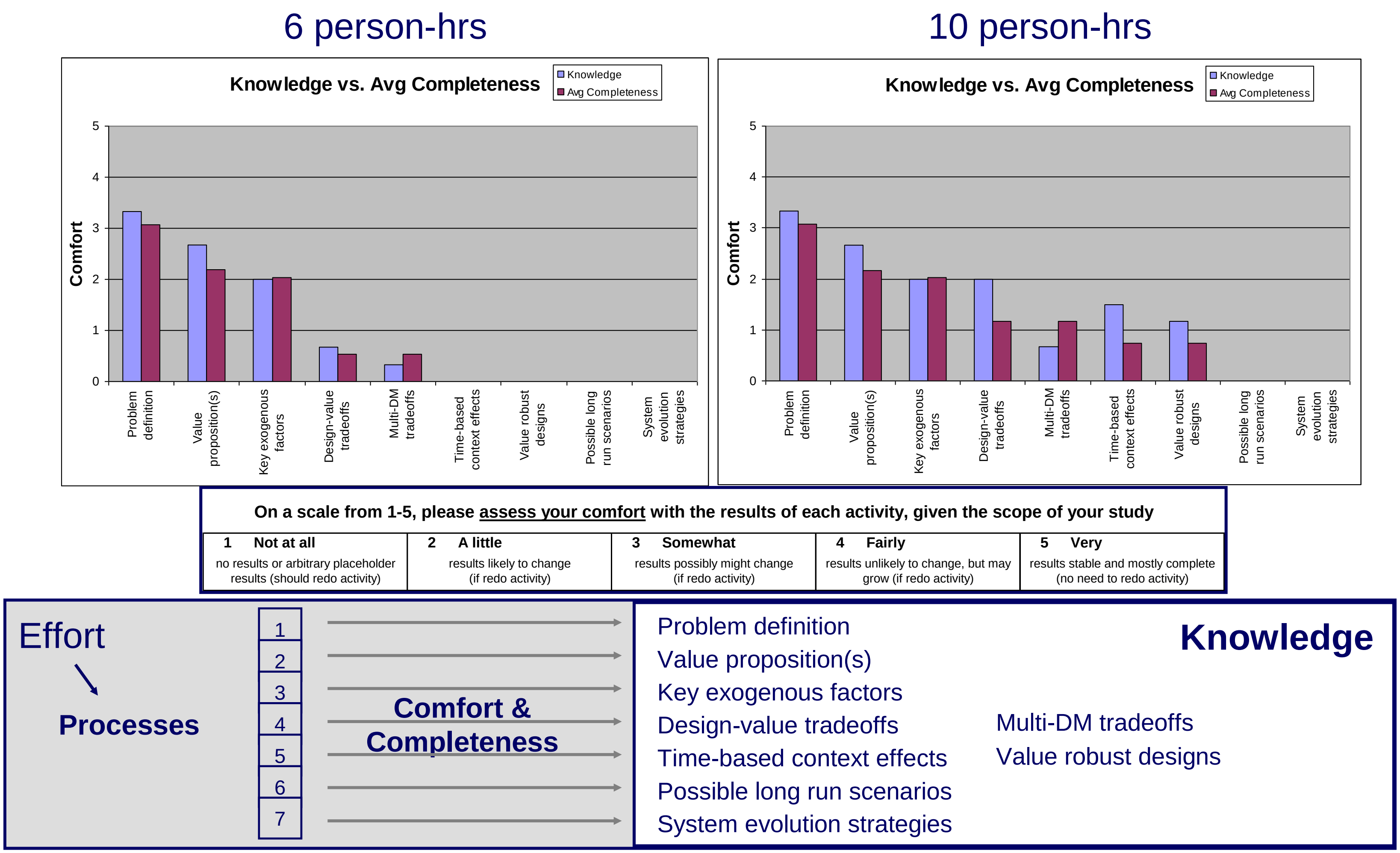

Figure 19 Example effort (completeness) vs. knowledge tradeoffs in a TSE study using RSC

Products similar to Figure 18 would be very useful to practitioners as well as for further refinement of the ERS architecture, toolset, and databases

Set of example cases available

In order to remove the “barrier” to entry and application of tradespace approaches, it is important to have example cases available to the community. This provides not only concrete representations of potential outputs, as well as intermediate artifacts, from a tradespace exploration activity, but also helps to ground abstract processes that can be found described in many policy and research documents. Additionally, eventually a “template” approach can be used to save time for future applications, providing for a standardized representation for a TSE study, as well as its interpretation. The example cases should include not only end-to-end TSE studies, but also partial TSE studies to demonstrate what could be accomplished with limited time and resources for such a study. It is essential, however, to also show application to different scales of system so as to appreciate the relationship of level of detail to scale of system and decision. This implies that having cases categorized by ACAT level, service, domain (e.g., land, sea, air, space), and so forth, would help build a body of knowledge and promote coherence in study representations and outputs. The ERS architecture plays an essential role in supporting the development of such example cases and knowledge codification for sharing. In the near term, pilot studies could be used to populate early examples of partial studies.

Current ERS architecture in support of knowledge capture

As proposed by the ERS architecture, shown in
Figure 20, a number of knowledge artifacts are currently proposed. These include lessons (learned) within a knowledge repository, project (case examples) within a project database, language (ontology) within a document database, models (performance) within a model data store, and analysis tools (within a “Decision Analyzer” toolset). Each of these represent concepts identified above as important pieces to facilitate rapid studies (to meet the ERS goals of faster consideration of more alternatives), as well as to increase the likelihood of reducing wasted effort “reinventing the wheel”. The proposed artifacts also will serve to build an able-to-be-queried knowledge infrastructure that should enable expert knowledge to be accessible to less experienced users.

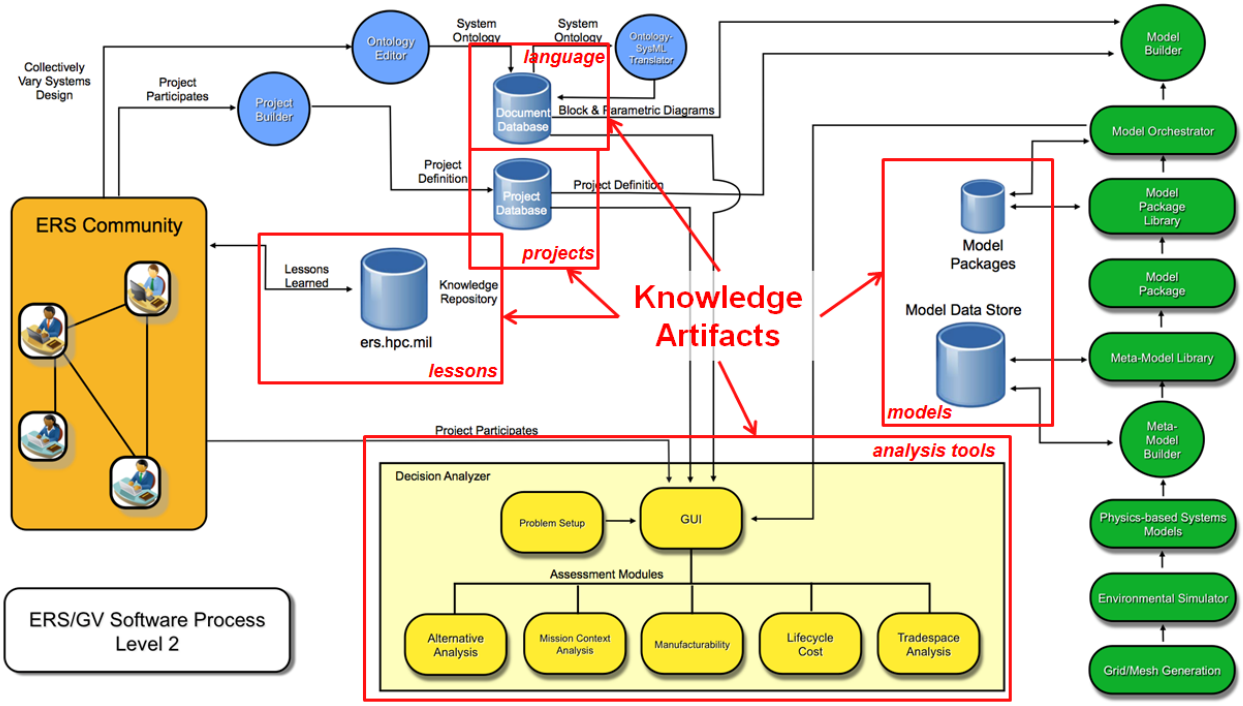

Figure 20 Annotated ERS Architecture Overview (from Holland 2014)

MOVING FORWARD

A number of next steps were identified over the course of this research which would enhance and enable the ERS vision, specifically as related to tradespace exploration activities.

These include:

- Efforts to begin compiling appropriate knowledge relative to the core constructs identified above including past needs, contexts, constraints, design space, performance space, value space, performance model, value model, lessons learned, language, case examples, and tools.
- Research into effort vs. confidence tradeoffs so that projects can scale effort on various activities within the TSE process to match their needs subject to available resources
- Development of fidelity tradeoff guidance and associated tools so that studies can scale TSE implementation appropriately
- Explicit incorporation of resilience-related ilities evaluation into the ERS architecture, including model libraries and decision analyzer toolset
- Inclusion of value models along with performance models in the model data store
- Continued piloting of parts of the ERS associated TSE processes, as well as full end-to-end studies
- Continued community building by the ERS program, including offices such as the various A9 (e.g. AF/A9, OAS, AFSPC/A9, etc.) and other entities with responsibilities overlapping with proposed ERS vision and capabilities

- Further research into supporting enabling methods, processes, and tools that can facilitate TSE knowledge capture and reuse, as well as resource-effective studies that can quantify and identify resilient, high value system solutions in diverse applications

CONCLUSIONS

This research is a first attempt at gathering expert knowledge and synthesizing emerging ERS-related research, toward a goal enabling novices to have expert-like decision capability through encoded knowledge and data-driven tradespace analysis framework and integrated tool suite. The resulting knowledge and information gained in this study contributes to various ongoing efforts across the systems community. The results will be used to directly inform work on two SERC research projects: RT-122, Interactive Model Centric Systems Engineering (IMCSE) and RT-113 Ilities Tradespace and Affordability (ITAP). Results will be shared with the SERC community and may possibly contribute to other relevant SERC projects. The research team will use the results of this investigation in its continuing work in tradespace exploration research. The results will be used toward the development of a publishable paper to transfer findings to the broader systems community. Specific findings will be shared with the ERS sponsor and its technical team and partners in appropriate discussions, workshops and research exchanges to potentially influence and extend the ongoing initiatives in support of the ERS vision. While this research investigation has focused on tradespace exploration, the approach taken in this research project can be applied to other areas within the ERS program.

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