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# Tradespace Exploration for the Engineering of Resilient Systems

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**Abstract**

Tradespace exploration supports the Systems Engineering Technical Management Process of Decision Analysis by identifying compromises, revealing opportunities, and communicating the impacts of decisions across a system's development lifecycle. Critical program decisions are made based on the outcomes of trades; trades being performed with multiple types and quantities of data coming out of tools and methods employing qualitative and quantitative analyses. Tradespace exploration for Engineered Resilient Systems (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. This study provides an ERS view of tradespace exploration, which reveals that having a valid set of attributes, and an understanding of how a cross-section of tools can satisfy them, is insufficient – what is needed is a deeper understanding of how these tools are used and, more importantly, how they can be used when performing tradespace exploration in support of the Decision Analysis Process. Gaining this understanding will enable users to better assess if they possess the appropriate tradespace exploration tools. A holistic view of 81 candidate tradespace exploration tools is provided. This study seeks to address a fundamental aspect of tradespace exploration by assembling a "best common practice" process for their requirements, identifying a set of attributes that defines an ideal tradespace exploration tool, and surveying existing tools that satisfy these attributes. In this way, a set of tools can be selected to enable the ERS tradespace vision on a particular project. A paradigm shift towards common tradespace methods, tools, cost models, and steps is emphasized.

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## 1. Background

As the Department of Defense (DoD) moves towards addressing geopolitical environments marked by rapidly changing threats, tactics, mission scenarios, technologies, and available funding, advanced methods, processes, and tools are needed to effectively engineer resilient system solutions. The resulting resilient systems must be adaptable to a wider range of mission contexts, across multiple alternative futures. To support resilient system design – and a correspondingly resilient design process – tradespace exploration (TSE) provides decision makers an understanding of capabilities, gaps, and potential compromises facilitating the achievement of system metric objectives. The decisions being made throughout a system's development lifecycle are continuously redefining its capabilities, performance, cost, manufacturability, delivery schedule, and sustainability. To be effective, decision makers must have deep knowledge of the component elements of a system, including how these elements interact internally to the system and externally with the operational environment. TSE provides decision makers an understanding of candidate system component choices and the implications on multiple missions across joint Warfighting environments[1].

Throughout a system's development lifecycle, and across its hierarchy, trades are being performed with multiple types and quantities of data coming out of varying levels of analysis fidelity. From a system's functional perspective, capabilities (e.g., lighter weight, higher performing) map to system measures of performance, which in turn map to measures of effectiveness, which ultimately affect operational figures of merit that determine how well a system, or a portfolio of systems, meets a required capability. Concurrently, there is a product hierarchy within which various technologies can be applied, from the component level, and up to subsystem, system, and finally a portfolio of heterogeneous systems working concurrently to fulfill a role. Additionally, there are process considerations such as industrial base, training, policy, and procedures, which are often omitted from the decision analysis process for various reasons. Although the decisions being made throughout these functional, product, and process perspectives differ, decision makers at the highest levels will execute based on the relationship between the benefit achieved by, and the lifecycle cost (LCC) associated with, a particular asset mix. Therefore, if the tradeoff between benefit and cost can be generated, explored, and then presented in the context of the holistic system, a more informed decision can be made across the system perspectives.

To aid the decision maker in performing effective TSE under these complex circumstances, the ERS effort involves providing the necessary engineering concepts, methods, processes, and tools[2]. The goals of ERS are to provide to engineering, warfighting, and acquisition decision makers the needed capability to manage TSE activities with full and consistent information throughout the life of the systems by[2]:

- Producing more complete and robust requirements pre-Milestone A
- Making the engineering design process much more efficient and effective
- Considering the manufacturability of a proposed design explicitly
- Establishing baseline resiliency of current capabilities

The TSE methods, processes, and tools should enable deeper consideration of system design alternatives while keeping the space as open as possible to address resiliency and robustness to changing conditions and constraints.

The tradespace frontier of Fig. 1[3] depicts that information coming out of knowledge databases must support decision making across the lifecycle by communicating to multiple perspectives and across the system hierarchy, while taking into account fiscal and environmental constraints. What this means is that TSE tools and processes are needed at different levels of the product hierarchy, commensurate with the decisions being made, the information available to make decisions, and the person or organization making decisions.

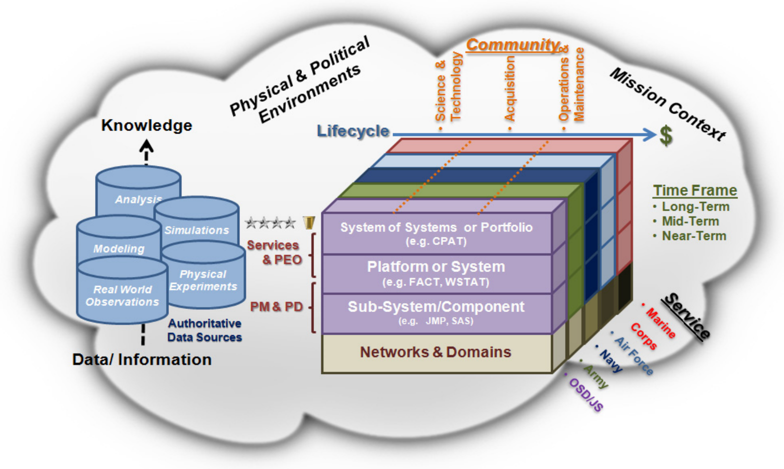


Fig. 1. ERS tradespace frontier

## 2. Assumptions

- TSE is performed throughout a system's lifecycle, in support of decision making, in a step-by-step process.
- There exist organization-specific best practice methods, processes, and tools for performing TSE.
- TSE is often performed to justify selection of a reduced set of options from a broader set of alternatives, rather than for understanding how compromises in system design can increase value delivered to stakeholders.
- TSE is largely performed ad hoc, and with the tools on-hand, without investigation into how other tools can be brought in to fill gaps in a TSE process.
- TSE is performed in order to "make better decisions", but without criteria for measuring the effectiveness, efficiency, correctness, or consistency of decisions across the lifecycle.

## 3. Approach

To reveal whether tradespace exploration best practices are on a trajectory to meet the needs of ERS, sources of TSE methods, processes, and tools were identified, common approaches in TSE were documented, a set of TSE tool "requirements" was developed, the most commonly used TSE tools, as well as other tools that could be implemented in a formal TSE process, were identified, and an evaluation was performed.

When making a decision, in this case regarding the tools to use in exploring a tradespace, a common approach is to start with alternatives and determine which alternative best meets the decision maker's intent. A preferred approach is one based on value-focused thinking, where value-producing objectives are developed, alternatives are identified, and decisions are made based on how much value the alternatives provide across the objectives[4]. Applied formally, a value-focused thinking approach involves interviews with decision makers to help translate the perceived increase in an evaluation metric into a value curve. In this study, a modified value-focused thinking approach was started; a recommendation will be made for expanding the current approach to include generating value curves and assigning swing weights to value measures for application to an additive value model.

To initiate a value-focused thinking approach, a fundamental objective was developed assuming that TSE is a process that uses tools to arrive at decisions: 'Use a tradespace tool, or set of tools, to make actionable decisions across the system hierarchy and throughout the system lifecycle.' In order to evaluate a tool's performance within a TSE process, several pieces of information were needed: TSE tools, TSE process steps, attributes that define TSE tools, and attributes that define what users are doing with their TSE tools.

## 4. Tradespace Analysis Tool Requirements Identification

An audit was performed to identify the existing TSE tools used by the ERS Demonstration Projects (DP)[1], as well as elsewhere in the Services and Industry, throughout a system's lifecycle. A set of attributes that define various TSE tools was developed, and the tools were mapped to the attributes to aid in identifying existing tools that are closely aligned with needed capabilities.

### *4.1. TSE Tools*

The sources shown in Table 1 were used to identify TSE tools. After completing the audit of tools, it was apparent that what most refer to as a decision analysis or data mining tool could be misconstrued as a satisfactory ERS TSE tool. To better understand how a decision analysis tool is viewed, a definition of Decision Analysis developed by Buede[5], and referred to in the 2010 Operations Research / Management Sciences (OR/MS) Today survey summary[6], is provided: "Decision analysis is the discipline of evaluating complex alternatives in the light of uncertainty, value preferences and risk preference." Although the process of Decision Analysis, as described in the Defense Acquisition University's (DAU) Defense Acquisition Guidebook (DAG)[12], is not TSE in and of itself, it is supported by TSE. In the case of data mining tools, the corresponding Survey[8] does not provide a formal definition, but similarities to TSE activities are apparent with terms such as regression, models, and data visualization.

Table 1. TSE tool sources

| TSE tool source |
|---|
| Operations Research / Management Sciences (OR/MS) Today Decision Analysis Software (DAS) Survey[6,7] |
| Rexer Analytics Data Miner Survey[8] |
| ERS DP[9,10,11] |
| ERS Priority Steering Council (PSC) Tools Assessment[13] |
| ARL internal organization research and experience |

The ERS PSC assessment[13] was filtered for tools in the "Data Driven Tradespace Exploration and Analysis" section. In addition to the source materials in Table 1, the ERS DP leads provided overview presentations and were informally interviewed via telephone. These sources all revealed that there are many tools in use across academia, government, and industry for performing TSE. In all, 81 tools were identified (the authors recognize that more tools exist than are captured here).

### *4.2. TSE Tool Reduction*

After identifying a large number of tools for initial consideration, the next step was to reduce the set to a manageable size, knowing that the subsequent tasks would involve identifying attributes and then mapping tools to those attributes in an attribute-by-tool sized matrix. A set of keep-or-reject criteria was developed. The first criterion was a gate: if the tool was in use by any of the ERS DP teams then it was kept for consideration in the present study, and if not then it entered into a set of filter criteria. The first filter criterion was whether the tool or developer was still available; in several cases an Internet search for the tool or developer returned limited results or no web page. The next filter criterion was whether the tool was included as part of a larger suite of tools; in several cases individual tools were rolled into a larger suite by the developer, in which case the suite was assessed for evaluation as opposed to the individual tool. The final filter criterion was if the tool was specific to a domain outside of system design and analysis (e.g., medical or service industry); tools with a niche function were omitted in order to focus on tools encompassing a broad TSE process. This initial filtering reduced the tool set by 38.

The remaining 43 tools were reassessed to determine if they should be evaluated in the current effort or deferred to a follow-on effort. The first filter criterion at this level was if the tool's development or use was supported by any known DoD TSE effort, or if it is receiving DoD funding for continued development and application; if so, then it was kept for current consideration. The next filter criterion was if the tool received high ranking and/or positive feedback from other tool surveys; several tools showed consistent or rising popularity, which the authors assessed as indicative of high user satisfaction. The final filter criterion was if the authors had any familiarity with the tool whatsoever; if none, then the tool was deferred for assessment since the only other information available was developer marketing and advertising literature, and the authors felt it inappropriate to rely on secondary knowledge to complete the initial assessment. Using these criteria, the subset of 43 tools was reduced to 13. Regardless of which tools were selected for immediate evaluation, the recommendation is for the 43 tools to be assessed against the forthcoming attributes, either by a user or the developer, because of the TSE capability they potentially bring through individual use or in concert with other tools.

### *4.3. TSE Tool Functionality*

After applying the filter criteria, the entire landscape of tools was revisited to see if each tool could be assigned a primary function. The purpose for doing this was twofold: determine how many decision analysis tools had been carried over for assessment, and address the observation that all of the tools appeared to be meeting a repetitive set of functions. The apparent functions are shown in Table 2, along with a brief description and the number of tools that have the function as their primary and secondary. As expected based on relying on the OR/MS DAS Tool surveys for tool input, Decision Analysis tools made up a large portion of the initial tool landscape for this assessment. It should be noted that although a Multi-Disciplinary Optimization (MDO) function is specified in Table 2, ERS is not focused on identifying an optimum system but rather on assessing resilience across multiple use cases.

Table 2. TSE tool functionality

| Function | Short description of function | Tools with primary | Tools with secondary |
|---|---|---|---|
| Capturing Value | Using weightings, value measures, surveys, or other techniques to capture user-perceived value | 3 | 9 |
| Multi-Disciplinary Optimization (MDO) | Linking multi-disciplinary models for the purpose of optimizing a constrained or unconstrained objective function | 12 | 5 |
| Statistical Data Analysis | Identifying trends or patterns in data, and developing models to help forecast outputs based on inputs | 25 | 15 |
| Visualization | Displaying information graphically with static or dynamic charts and tables | 4 | 19 |
| Decision Analysis | Evaluating sets of alternatives against preferences on outcomes | 25 | 17 |
| Project / Process Portfolio Management and Simulation | Assessing how much corporate value can be achieved from project portfolio combinations, resource allocation options, and scheduling | 12 | 2 |

While the tools conveniently fell under these five primary function categories, they should not be considered to perform only these functions. Tools can readily be differentiated from each other when considering lower-level functions such as process simulation, data mining, regression, decision trees, brainstorming, Monte Carlo simulation (MCS), sensitivity analysis, and requirements analysis. Not all tools were assessed to have a secondary function.

### *4.4. TSE Tool Attributes*

Continuing with the reduced set of tools, the next task was to identify attributes that constitute a TSE tool, and that define the functionality desired in such a tool. Referring back to the sources in Table 1, an initial set of 25 attributes was developed.

Other sources were then reviewed in the areas of visualization, optimization, and value[15,16,17,18,19,20], and the industry surveys[6,7,8] were more thoroughly reviewed given their popularity and the quality in their results based on the assumed standardization of their questions and corresponding attributes.

An interesting discovery was made when attempting to validate the assumed standardization. The OR/MS Today DAS Surveys are set up as online questionnaires. A hyperlink is provided for tool vendors and developers to describe their software by entering in yes ("y"), no ("n"), or a limited textual description. The 2010 Survey[6] did not provide rationale or descriptions of the survey questions. There was also no indication of the provenance of the questions, other than a short statement about the industries from which new questions were pulled: "For this year's [2010] survey…questions based on the input of decision analysis practitioners from government, airline, oil and gas and pharmaceutical sectors were added." In the 2012 Survey[7], the same questions were provided to the vendors who had responded in previous years, as well as to vendors familiar to the survey moderator – not unlike what was done in this assessment when filtering for tools to include for immediate evaluation. An electronic mail inquiry sent to the 2010 and 2012 Survey moderators revealed that the origin of the Survey questions most likely traces back to a single individual, and there is no recorded pedigree on the questions or attributes, nor are formal, objective, unambiguous definitions available. Further, each moderator responsible with delivering the survey in a given year is permitted to update attributes as they see necessary (e.g., when technology advances result in a question or attribute being no longer applicable). Lastly, the tool vendors are permitted to "self-assess" their product's capability against the attributes, meaning the attributes are open to interpretation by those completing the Survey.

Based on the above description of the DAS Surveys, the authors of this paper have recommended to the Institute for Operations Research and the Management Sciences (INFORMS) that the 2014 OR/MS Today DAS Survey moderator consider standardizing the questions and attributes by developing unambiguous definitions, possibly using the work performed here as a starting point.

After revisiting the initial TSE tool attributes, the set increased to 91, practically eliminating the ability to perform a value focused thinking approach at this stage. The attributes were then grouped into common, higher level affinity categories, which are shown in Table 3 with a short description and the number of attributes per category. It should be noted that these categories are a mix of quantitative and qualitative, including binary (e.g., y or n), enumerated (e.g., small, medium, large), textual, currency, and integer.

Table 3. Top-level TSE tool attribute categories

| Category | Short description of category | Number of attributes |
|---|---|---|
| Class | Is the product better classified as a tool, or a process | 2 |
| Usage | Industries, market segments, or applications the is tool used in | 3 |
| Operating Systems | On which operating systems can the product operate | 6 |
| Pricing | What is the price, or pricing structure, of the product | 4 |
| Training Classes Offered | What training options available for the product | 4 |
| Training/Experience Needed | Knowledge level of subject matter to effectively use the product | 3 |
| Software Attributes | Limitations, expandability, and help options | 8 |
| Applications | Decision making, preference, risk, and uncertainty capabilities | 8 |
| Software Features | Meaningful functions and user experience | 34 |
| Decision Algorithms Implemented | How does the product rank order alternatives | 3 |
| Availability of Graphical Elicitation Techniques | How does the product capture values and preferences | 9 |
| Types of Output Display | How does the product present results for manipulation | 7 |

A key capability worth noting is the expansion of a tool's functionality through custom coding/programming/scripting, or integrating code developed by others. The significance of this capability can readily be appreciated when understanding that a tool which supports customization through programming can be modified to include any conceivable function, if the user has the time and knowledge to perform the programming. A familiar example is the ubiquitous Microsoft® Excel® spreadsheet software. The built-in functionality of this tool is primarily for tabulation and charting of data, statistical analysis, and numerical solving. However, if familiar with the Visual Basic for Applications (VBA) language, the user can expand and customize Excel® to perform any of the primary and lower-level functions described above.

### *4.5. TSE Tool Survey*

With the tools and attributes identified, the next task was to essentially self-take the survey for the 13 tools. Even with detailed knowledge and experience on a majority of these tools, gaps still existed in the assessment related to pricing as well as some of the attributes pulled in from the DAS Surveys. The latter is driven by attribute ambiguity and subjectivity as explained earlier. It is envisioned that the TSE Tool Survey will be fully populated by calling upon experienced users, and possibly developers, of the identified tools. To do this, the tool attributes query should be formatted as a questionnaire. The questions should follow survey best practices, being as specific and concise as possible to remove ambiguity and bias.

An important conclusion from this survey can be drawn based on the holistic view of TSE as described thus far: having a valid set of attributes, and an understanding of how a cross-section of tools can satisfy them, is insufficient – what is now needed is a deeper understanding of how these tools are used and, more importantly, how they can be used when performing TSE in support of the Decision Analysis Process. Gaining this understanding will enable users to better assess if they possess the appropriate tools for the TSE steps that they need to perform, as well as which TSE steps are capable of being performed given the tools in the user's possession.

## 5. Tradespace Analysis Decision Classification

This portion of the effort involved looking across several prominent TSE research activities to determine if there exists a common, best practice process for performing TSE. From these efforts, a consolidated process was outlined and steps compared across the ERS DPs and two other activities of interest to determine whether these efforts were consistently performing a TSE process and, if not, which steps were being omitted. A recommendation is offered for mapping TSE tools to attributes and to process steps.

### *5.1.1. TSE Process Audit*

Thus far, tools were identified that may be useful in performing TSE, their main functions documented, and their defining attributes collected. However, these tools are intended for use across the system development lifecycle, in the context of a process for performing TSE and making decisions (Fig. 1). Therefore, it is important to understand how these tools can be intentionally used to support a consistent TSE process.

TSE research activities across government and academia[21,22,23,24,25,26,27] were investigated to look for commonality in process execution. Additionally, TSE projects[9,10,11,28,29,30,31,32] under study within the government were investigated to better understand what steps were being executed across the full TSE activity.

### *5.1.2. TSE Process Steps and Coverage*

From the research activities and pilot projects, a set of 12 common steps emerged, as shown in Table 4. It is assumed that these steps can be considered "TSE best common practice", although this assumption is not tested here. The steps are not presented in flowchart format to stress that a formal TSE process is not being proposed but rather existing processes consolidated. The consolidation and subsequent comparison to select projects revealed that: 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).

Table 4. TSE best common practice steps

| 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 |

### *5.1.3. TSE Steps, Tools, and Functions*

Consider that each of the 81 identified tools, defined by a subset of the 91 identified attributes, gives the user an ability to perform many of the 12 identified TSE best practice steps. The fully populated TSE Tool Survey will provide a link between TSE best practice steps, tools, and functions, allowing a user to balance their TSE needs with their organizational capabilities and constraints. The survey will serve as a database that can be used in different ways: a user can decide which tools they should invest in by selecting the TSE steps that they desire to perform; or a user can identify which TSE steps can be performed with the tools currently available within their organization. Knowledge level, budget, and training can serve as filters in the user's decision process. A recommendation for future research is to develop a decision analysis style user interface for aiding the user in downselecting the most appropriate tools based on their TSE needs and goals.

## 6. Conclusions and Recommendations

This effort used attributes of tradespace exploration tools and the steps in a notional tradespace exploration process to illuminate relationships between tool capabilities and process steps in order to help existing ERS TSE efforts understand if they are sufficiently and consistently performing what is considered to be necessary TSE for ERS. Although a specified, or default standard, formal TSE process is not in use for DoD programs, this effort has provided insight into a possible standard TSE process for ERS programs. The notional process requires further investigation to determine if it makes an improvement over current TSE processes. Multiple tradespace efforts in government and industry were reviewed for TSE tools, TSE tool attributes, and TSE process steps. A holistic view of 81 candidate tradespace exploration tools is provided. Tools were grouped into common primary functions. Ninety one tool attributes were identified. A survey template was created based on an existing decision analysis tool survey, and the survey was populated for several tools.

Recommendations for future work include:

- Conduct a more formal value focused thinking approach, developing value measures for attributes and functions;
- Refine the list of attributes and tools identified in this effort;

- Complete the mapping of tools to attributes through a survey of experienced users and developers. Request rationale to support the survey entry. Possibly request an ordinal ranking of how well each tool meets each attribute for subjective inputs to mimic the surveys referenced within this paper;
- Validation of the TSE steps identified in this effort;
- Adoption by INFORMS of the attribute definitions developed here for their next OR/MS Today DAS survey; and
- Development of a decision analysis style user interface to make the database interactive for the user.


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