Proceedings of the Annual General Donald R. Keith Memorial Conference
West Point, New York, USA
May 2, 2024
A Regional Conference of the Society for Industrial and Systems Engineering

Trading off cost, schedule, and performance – An analysis of TRAC's MCDM methodology

William Boehlke, Timothy Fowler, Braden Golinski, Carter Sample, Joshua Van Wert, and Matthew Dabkowski

Department of Systems Engineering,
United States Military Academy,
West Point, NY 10996

Corresponding author's Email: william.t.boehlke.mil@army.mil

Author Note: William Boehlke, Timothy Fowler, Braden Golinski, Carter Sample, and Joshua Van Wert are First Class (senior) Cadets at the United States Military Academy at West Point. COL Matthew Dabkowski serves as their advisor. In May 2024, these Cadets will commission into the United States Army as Second Lieutenants. They will serve in the Infantry, Quartermaster, and Field Artillery Branches. The authors would like to express their appreciation to Dr. Brian Wade for his support on this project, as well as the many leaders and experts at The Research and Analysis Center (TRAC) whose guidance and feedback provided many useful contributions. The views expressed herein are those of the authors and do not reflect the position of the United States Military Academy, the Department of the Army, or the Department of Defense.

Abstract: The Research and Analysis Center (TRAC), an organization under Army Futures Command, is committed to conducting relevant and credible research to improve military operations analysis. A central way TRAC accomplishes its mission is analysis of alternatives through multi-criteria decision making (MCDM) methods. TRAC leverages these tools to analyze alternatives' cost, schedule, and performance (CSP). The team focused on helping TRAC refine their MCDM process using the System Decision Process (SDP). The problem statement is: To examine TRAC's current MCDM approach, assess its performance, and if necessary, develop alternative MCDM frameworks, streamline data collection, and improve visualization to articulate the tradespace between CSP. The team has worked through the Problem Definition and Solution Design phases of the SDP and is working on the Decision Making phase. Ultimately, the team will recommend an alternative for how TRAC can communicate its CSP findings to decision makers.

Keywords: TRAC, Analysis of Alternatives, MCDM, Cost, Schedule, Performance, SDP

1. Background

The Research and Analysis Center's (TRAC's) mission is to "conduct relevant and credible applied research to improve military operations analysis" (Jablonski, 2023). TRAC was established in 1986 under the Training and Doctrine Command but recently began to operate under the Army Futures Command (Rodriguez, 2021). The organization is in four locations across the United States: Monterey, CA; White Sands Missile Range, NM; Fort Leavenworth, KS; and Fort Gregg-Adams, VA (Jablonski, 2023).

One of TRAC's primary missions is to conduct analyses of alternatives (AOAs). At its core an AOA is "a study that is used to assess alternatives that have the potential to address capability needs or requirements that are documented in a validated or approved capability requirements document" (USAF Office of Aerospace Studies [USAF OAS], 2016). It is a systematic process used to evaluate separate alternatives to fulfill a need or address a capability gap. An AOA develops cost, schedule, and performance (CSP) analysis for possible solutions to an operational capability gap and presents the analysis to a decision maker (DM) to inform and enable their decision (Schank, 2012). Furthermore, TRAC typically conducts multiple AOAs at the same time and assigns one study team to each AOA.

For the combination of CSP analysis, the study teams begin by collecting the stakeholders' and DMs' requirements (Schank, 2012). Then, the study teams gather data and conduct check-ins with their study advisory group to address questions and, if necessary, adjust their AOA's scope (USDAS, 2021). A key part of the AOA process is trade-off analysis. Trade-off analysis displays the various metrics of each alternative while comparing the alternatives to each other (Schank, 2012). Lastly, the study team documents their findings and briefs the DMs on their recommendations and conclusions (USDAS, 2021).

For the capstone project, the team used the Systems Decision Process (SDP) to evaluate and improve TRAC's current tradespace methodology. The SDP is a collaborative, iterative, and value-based decision process that can be applied in any stage of the system life cycle (Parnell et al., 2023). The SDP consists of four different phases: Problem Definition, Solution

Design, Decision Making, and Solution Implementation. At this point the group has completed steps inside of the Problem Definition, Solution Design, and Decision Making phases. At the end of the academic year, the team will brief TRAC's leadership on the proposed course of action, allowing TRAC to progress into the Solution Implementation phase. This paper captures the team's work to date and charts the path forward.

2. Problem Definition

The first phase of the SDP is Problem Definition. The project group started this phase with the initial problem statement: "To examine TRAC's current multi-criteria decision making (MCDM) approach, assess its performance, develop alternative MCDM frameworks, streamline data collection and analysis procedures, and/or design intuitive visualization charts or dashboards." As the SDP is an iterative process, the team returned to the Problem Definition phase as needed to refine the problem statement and properly scope the project. Within Problem Definition, there are three steps: research and stakeholder analysis, functional and requirements analysis, and value modeling. To conduct research and stakeholder analysis, the team completed individual literature reviews on topics critical to TRAC's mission and met with two members of TRAC to get a better understanding of what they expected from the team. In functional and requirements analysis, the team took the insights gleaned from TRAC and developed a functional hierarchy containing functions, subfunctions, and objectives that build towards the fundamental objective. In the value modeling step, the team created quantitative value measures for the objectives that would be used in the Decision Making phase to assess alternatives. Problem Definition was the most time-consuming phase for the team, as it was critical to fully define the problem before designing solutions.

Through topic specific literature reviews, the team gained a deeper understanding of the topics specific to TRAC and broadly across other federal and private entities. From the AOA literature review, the team found that AOA is a systematic process that TRAC leverages to provide DMs with trades between CSP. In the MCDM literature review, the team learned that for TRAC, MCDM is an invaluable tool when the method used is tailored to the unique needs of a problem. In general, TRAC utilizes a modified Multi-Attribute Value Analysis (MAVA) technique (Anderson & Johnson, 2013) and the Analytic Hierarchy Process (AHP) (Saaty, 1987). From the CSP literature reviews, the team learned that cost analysis is not only received from the Office of the Deputy Assistant Secretary of the Army for Cost and Economics (DASA-CE) but also executed internally within the cost department of TRAC. Schedule analysis is performed entirely externally by the Army Combat Capabilities Development Command Analysis Center (DAC). Performance analysis is TRAC's specialty and is completely internal. Upon gaining a deeper understanding of these topics of interest, the team scheduled initial client meetings with TRAC-Monterey's principal analyst Dr. Brian Wade and data analyst Major Sean Eskew. The team grouped the findings from the meetings into general conclusions and recommendations on scoping the project. The most significant of these recommendations was to focus the problem statement on the articulation of the CSP tradespace and its uncertainty to DMs.

The next step was functional and requirements analysis. This step entails identifying system functions and creating a functional hierarchy. The first step of this was to create a fundamental objective based on the problem statement that fully encompasses the project's scope. This fundamental objective – "To assess and, if necessary, redesign TRAC's methodology to articulate cost, schedule, and performance analysis in the AOA process" – is the highest echelon of the hierarchy. To accomplish the fundamental objective, the team identified three top-level functions, namely: *1.0 Prepare Components of the Tradespace*, *2.0 Build Tradespace*, and *3.0 Communicate Results*. These functions were further expanded into the eight subfunctions seen in Figure 1. For example, to successfully *2.0 Build the Tradespace*, TRAC needs to 2*.1 Analyze Alternatives Across Multiple Components of the Tradespace* and *2.2 Compare and Contrast Efficient (i.e., Pareto optimal) Alternatives*.

Once the functional hierarchy was approved, the team added objectives to the subfunctions and value measures to the objectives. When the objectives and value measure are added to the functional hierarchy in Figure 1, they form a value hierarchy that allows us to model how well an alternative meets TRAC's fundamental objective. Each value measure was quantitatively assessed using a value function. Since none of the objectives had naturally quantifiable scales, the team constructed proxy Likert-type scales (e.g., scores from 1 to 5, where 5 is best) for each value measure. Examples of these Likert-type scales for objectives *3.1.2 Maximize Detail Provided by Cost Analysis Method* and *3.4.1 Optimize Visualization of Tradespace* are shown in Figure 2.

To finish the value modeling and complete the Problem Definition phase, the team needed to assign weights to each value measure based on the value measure's importance to the DM. To acquire these weights, the team sent a survey to Dr. Wade and three other TRAC analysts and asked them to evaluate each value measure's importance using a scale of 0 to 100. One respondent at a time, the team summed the swing weights for all the value measures and divided each value measure's swing weight by the sum to get a global weight for each value measure.

Finally, after multiple iterations of the Problem Definition phase, the team refined the problem statement, which TRAC subsequently approved. It is: "To examine TRAC's current MCDM approach, assess its performance, and if necessary, develop alternative MCDM frameworks, streamline data collection, and improve visualization to articulate the tradespace between CSP." With this refined problem statement, the team moved into the next phase of the SDP: Solution Design.

Function	Sub-Function	Objective
1.0 Prepare Components of Tradespace	1.1 Synthesize Cost Analysis	1.1.1 Max Synthesis and Simplicity
	1.2 Execute Performance Analysis	1.2.1 Max Process Effectiveness and Efficiency
		1.2.2 Max Incorportation of Uncertainty
2.0 Build Tradespace	2.1 Analyze Alternatvies Across Multiple Components of Tradespace	2.1.1 Max Ease of Use of MCDM Method
		2.1.2 Min Potential Alternatives
	2.2 Compare and Contrast Efficienct Alternatives	2.2.1 Max Quality of Report
		2.2.2 Max Ability to Differentiate Alternatives
3.4 Communicate Tradespace	3.1 Communicate Cost Analysis	3.1.1 Max Simplicity of Cost Analysis Method
		3.1.2 Max Detail Provided by Cost Analysis
	3.2 Communicate Performance Analysis	3.2.1 Max Simplicity of Performance Analysis Method
		3.2.2 Max Detail Provided by Performance Analysis
	3.3 Communicate Schedule Analysis	3.3.1 Max Simplicity of Schedule Analysis Method
		3.3.2 Max Detail Provided by Schedule Anaylsis
	3.4 Communicate Tradespace	3.4.1 Optimize Visualization of Tradespace
		3.4.2 Max Simplicity of Tradespace Method
		3.4.3 Max Quality of Documentation
		3.4.4 Max Communication of Uncertainty

Figure 1. Value Hierarchy

3.1.2 Maximize Detail Provided by Cost Analysis		3.4.1 Optimize Visualization of Tradespace
3.1.2.1 Detail Provided		3.4.1.1 Visual Appeal
There is no detail provided in the report, either because there is too much information to clearly understand, or the information is too broad to glean any relevant findings.	1	The visualization is overbearing and prevents the audience from understanding the relevant information.
As good as the previous level, but either filters out a marginal amount of irrelevant information (resulting in extraneous information) or over-filters information (resulting in a significant amount of critical information getting excluded).	2	The visualization is better than the previous level but worse than the level below.
As good as the previous level, but either filters out a moderate amount of irrelevant information (resulting in less extraneous information) or over-filters information (resulting in a moderate amount of critical information getting excluded).	3	The visualization distracts the audience from identifying key information, and some graphics detract from presentation comprehension.
As good as the previous level, but either filters out a significant amount of irrelevant information (greatly reducing extraneous information) or over-filters information (resulting in a marginal amount of critical information getting excluded).	4	The visualization is better than the previous level but worse than the level below.
Ideal amount of detail; there is a balance of useful information provided to the audience with no important information spared.	5	The visualization is precise and concise. It conveys all relevant information with clean and simple graphics.

Figure 2. Likert-Type Scales for Objectives 3.1.2 and 3.4.1

3. Solution Design

The second phase of the SDP process is Solution Design, which includes idea generation, alternative generation, and cost analysis. The primary methodology for conducting idea generation was utilizing Zwicky's Morphological Box, which includes a color-coded depiction of the options the team chose for each alternative. As seen in Figure 3, the team developed design parameters that fit TRAC's objectives and the system's functions. The team's design parameters can be separated into two broader concepts: how TRAC creates the tradespace and how the overall tradespace is communicated to DMs. Since the scope of the project is focused on the presentation of results, the design parameters that focus on the presentation of the overall tradespace attempted to provide TRAC with a few objects that would allow TRAC to best convey their results in a presentation.

While the actual performance analysis is done by TRAC and is outside the scope of the project, the team's contribution to the creation of the tradespace was assisting TRAC in the communication of these components. The creation of the tradespace's design parameters focused on the depth in which the components of CSP analysis are reflected into the tradespace. A brief description of each design parameter used is shown in Figure 3. Of note, there are several asterisks in Figure 4 for the MAVA method. The single asterisk indicates the usage of a single attribute analysis with some sensitivity analysis, and the double asterisk is a far more in-depth pairing of MAVA with advanced ranking methods that consider uncertainty to a higher degree. Throughout the presentation of the tradespace, the team also included an outsource option that would allow TRAC to hire external contractors and experts to help develop these components and make recommendations to TRAC.

Cost Analysis	The collection of cost analysis, either from DASA-CE or through TRAC internal analysis.
MCDM Method Used	Refers to the MCDM method selected for the project. Options include single and multiple weighting versions of MAVA (Multi-Attribute Value Analysis) and AHP (Analytic Hierarchy Process). MAVA, which is based on utility theory, focuses on value measures and can be adapted to incorporate uncertainty with certain ranking methods. AHP is a classic, more simplistic methodology that does account for uncertainty without significant modification.
Presentation of Differences	Refers to the method in which differences between alternatives are presented. Options include narrative, numerical metrics, or visual supplements.
Communicate CSP Analysis	Refers to the level of analysis and the amount of information TRAC presents for CSP.
Dynamism	Step 1 of communicating the tradespace. Refers to the style of presentation and its adaptability. A dynamic presentation presents a decision maker with an interactive presentation to see changes in real time. A static presentation is a direct reflection of the work presented to the decision maker in an immutable format.
Perspective on Alternatives	Step 2 of communicating the tradespace. The perspective on alternatives sets the attributes within an alternative as fixed or flexible. A fixed perspective locks in an alternative "as is" and allows for a direct comparison between alternatives, while a flexible perspective gives a study team room to change alternatives and capitalize on trades.
Focus of the Trades	Step 3 of communicating the tradespace. Refers to the tradeoffs by highlighting differences between or within objects. Between objects captures how an alternative performs on CSP compared to the other alternatives. Within objects captures how an alternative's CSP relate to each other. A hybrid option is also considered that allows for a focused balance between alternatives and attributes, which would work in conjunction with a more dynamic style presentation.
Presentation of Uncertainty	Includes options from basic expected value to full probabilistic analyses in the presentation of alternatives.
Documentation of Tradespace Analysis	Refers to the product TRAC releases to the DM. An annotated presentation provides the decision maker with the presentation to include notes for clarity and explanation. A video allows for a more narrative approach to presenting a product. A technical report provides a writeup of the methods, processes, and findings of the analysis.

Figure 3. Design Parameters Explanation

The alternatives the team generated for this phase cover feasible and realistic options that TRAC has at its disposal. These alternatives are denoted by color-coded squares that appear on the options of the design parameters. The alternatives cover a range of themes from minimizing time to maximizing total effort, allowing TRAC to appropriately explore its options. As seen in Figure 4, the alternatives were named *Bare Bones*, *Do-It-Yourself* (*DIY*), *Goldilocks*, *Fat Calf*, and *External*. Bare Bones focuses on minimizing the time required to produce an analysis. DIY focuses on handling all design parameters internally to promote analyst understanding when presenting results. Fat Calf focuses on maximizing effort to include all findings and results in a way that withholds no information. Goldilocks tries to find a medium between Bare Bones and Fat Calf by relying on hybrid methods or allowing users to prioritize what they value in a presentation while providing a DM with the most flexible options to evaluate alternatives. Finally, External allows TRAC to conduct its own analysis but leverages the expertise of an outside organization to assist in the creation of desired products.

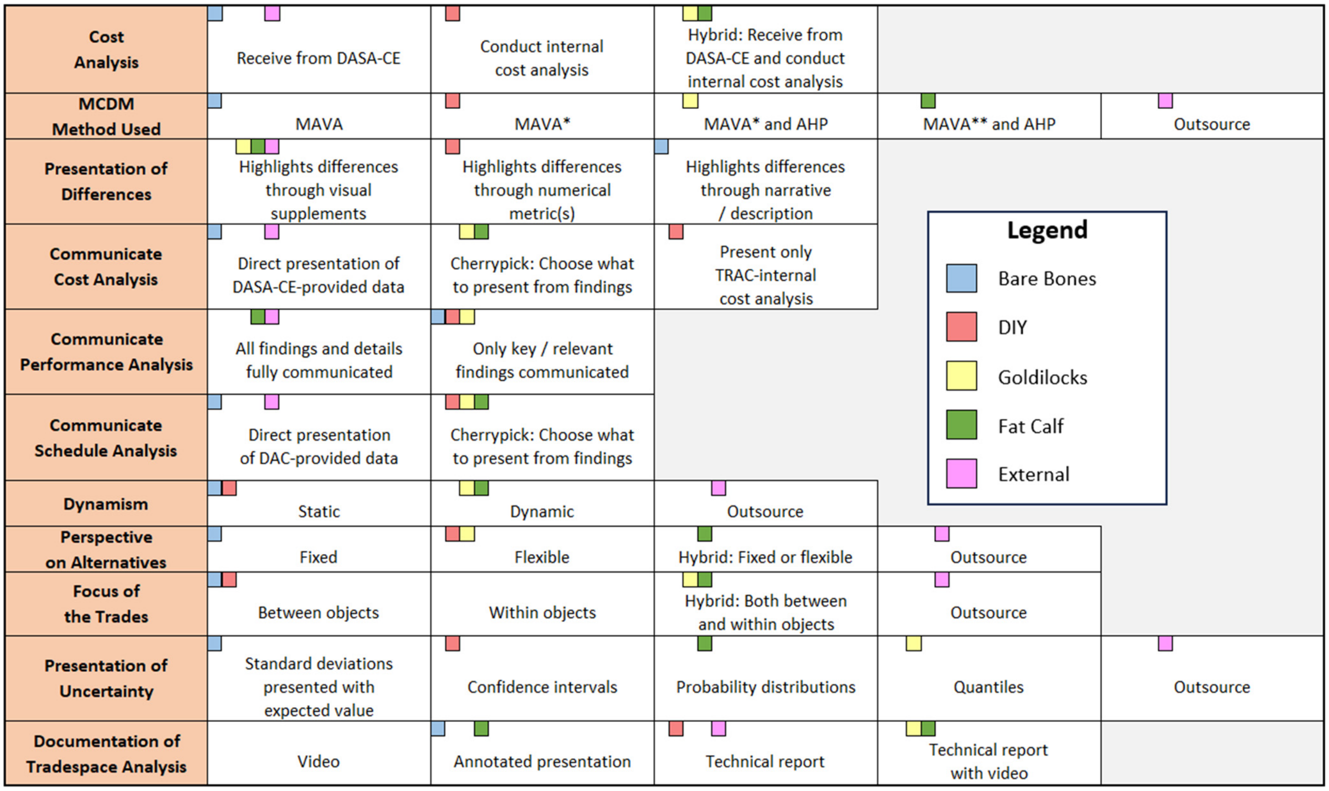

Figure 4. Zwicky's Morphological Box

4. Decision Making

Continuing in the SDP, the Decision Making phase centers around the fundamental objective and recommending an alternative that best accomplishes it. The first step was to design a survey to collect TRAC's scores for the alternatives developed in Solution Design. The team separated the value measures into individual tables, seen in Figure 2. Beside each table, the team designed an input matrix for TRAC analysts to score each alternative on the value measure, seen in the right panel of Figure 5. The team asked TRAC analysts for a minimum, maximum, and most likely score for each alternative on each value measure. To mathematically aggregate the data from TRAC, the team used the additive value model $V(x) = \sum_{i=1}^{n} w_i v_i(x_{ij})$, where w_i is TRAC's global weight for value measure i, x_{ij} is the survey score for alternative j on value measure i, and $v_i(\cdot)$ is the value function for value measure i. On the latter, the team applied linear value functions (i.e., $v_i(x_{ij}) = (100 - x_{ij})/4$) to each of the 14 value measures, which transformed the 1 to 5 survey scores onto 0 to 100 value scales. In the end, TRAC provided four sets of swing weights and four sets of survey responses. A representative excerpt from a TRAC analyst can be seen in Figure 5.

To fully leverage the data TRAC provided, the team modeled the survey scores of respondents as random variables (X_{ij}) from triangular distribution functions using @Risk's RiskTriang function and created a Monte Carlo simulation model in Excel. Specifically, on each iteration of the simulation, the model randomly selected a set of global weights and a set of survey responses. These inputs were used as w_i and X_{ij}, respectively, and the model generated realizations of X_{ij} (i.e., x_{ij}) for every alternative on each value measure. These inputs were subsequently combined using the function $V(x)$, and the total value scores for the alternatives were saved. Ultimately, 1,000 iterations were conducted, and each alternative's total value scores were plotted as histograms and analyzed. The results of the team's value modeling will be presented to TRAC in a final decision brief and technical report.

	Weight Type	Value Measures		
		1.1.1.1	2.1.1.1	2.1.2.1
Respondent 1	Swing	75	75	25
	Global	0.0962	0.0962	0.0321
Respondent 2	Swing	70	80	40
	Global	0.0749	0.0856	0.0428

	Minimum	Maximum	Mode
Bare Bones	1	4	2
DIY	2	5	3
Goldilocks	3	5	4
Fat Calf	3	5	4
External	1	4	3

Figure 5. Representative Excerpt of Swing Weights for 2 of 4 Respondents on 3 of 14 Value Measures (Left Panel) and Alternative Survey Scores for 1 of 4 Respondents on 1 Value Measure (Right Panel)

5. Conclusion

Overall, the team leveraged the SDP to design and execute a project to provide meaningful data and analysis to TRAC about their MCDM process. The team gathered necessary background information through individual literature reviews focusing on the key facets of TRAC's process and their MCDM methods. The findings of the literature reviews and stakeholder analysis helped the team build the functional hierarchy and start to analyze the initial problem statement. The team distilled the problem statement into a fundamental objective; this, in turn, informed the functions, subfunctions, and value measures. Next, the team engaged TRAC to weigh the importance of each value measure. Following problem definition, the team conducted solution design to create possibilities and courses of action for TRAC. From the possibilities, the team built five alternatives for TRAC to score. The team used the scores from TRAC to build a Monte Carlo simulation model to compute the total value scores over 1,000 iterations for each alternative. The results of this analysis will be presented to TRAC in a final presentation and technical report. Throughout the project, the team made assumptions, mainly in reference to TRAC's internal systems and processes, to continue in the SDP and properly scope the problem. If one of the team's assumptions was incorrect, it would be a significant limitation of the project. Future work could go further into the details of TRAC's presentation to decision makers, specifically to incorporate uncertainty through an interactive dashboard or other dynamic visual aid.

6. References

Anderson, M. R., & Johnson, E. E. (2013). *Multi-Attribute Decision Making (MADM) and Associated Assessment Techniques in Support of Army Studies and Analyses Code of Best Practices (COBP)* (TRAC-F-TR-14-003). TRADOC Analysis Center.

Jablonski, J. (2023). *The Research and Analysis Center – Monterey*. Naval Postgraduate School. https://nps.edu/web/trac-monterey/home

Office of the Under Secretary of Defense, Acquisition and Sustainment. (2021). Assessment of analysis of alternatives studies in the Department of Defense as compared to best practices. https://www.acq.osd.mil/asda/ae/ada/docs/Assessment of Analysis of Alternative Studies in the Department of Defense as Compared to Best.pdf.

Parnell, G. S., Driscoll, P. J., & Henderson, D. L. (2023). *Decision Making in Systems Engineering and Management* (3rd ed.). Hoboken, NJ: Wiley.

Rodriguez, M. (2021). *The Research and Analysis Center Celebrates 35th Anniversary*. U.S. Army. https://home.army.mil/wsmr/index.php/about/news-home1/research-and-analysis-center-celebrates-35th-anniversary

Saaty, T. L. (1977). A Scaling Method for Priorities in Hierarchical Structures. *Journal of Mathematical Psychology*, *15*(3), pp. 234-281.

Schank, J. F. (2012). Analysis of alternatives: keys to success. *Ninth Annual Acquisition Research Symposium Wednesday Sessions, Volume I*, pp. 333-342. https://apps.dtic.mil/sti/pdfs/ADA563514.pdf

TRAC. (2023). US Army Futures Command The Research and Analysis Center (TRAC) Overview [PowerPoint Slides]. SharePoint.

USAF Office of Aerospace Studies. (2016). Analysis of alternatives (AoA) handbook: A practical guide to analysis of alternatives. https://www.acqnotes.com/wp-content/uploads/2014/09/Analysis-of-Alternative-AoA-Handbook-July-2016.pdf

Wade, B. (2023, December 5). IPR Client Meeting with TRAC [Personal Communication].