

A Descriptive Guide to Conducting Trade Space Analysis



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A Descriptive Guide to Conducting Trade Space Analysis

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ABSTRACT

This is one of two products exploring trade space analysis. This guide provides a description of the components of trade space analysis. It is meant to be idea generating, not necessarily idea providing. The guide asserts there are three primary components that make up trade space analysis: physical characteristics, capability attributes, and applied utility (value or priority). Finding the balance between all three of these components is what drives decision outcomes. The purpose of trade space analysis is to understand the critical components, explore the relationships between them, and apply value to those relationships in a way that facilitate informed decision making. It also provides a description of several challenges associated with the conduct of trade space analysis and elements that must be contended with throughout the analysis. The guide offers a potential framework with which to build out a capabilities trade space analysis using the Quality Function Deployment model. Its structure facilitates communication, planning, and decision making at a variety of levels throughout the requirement or system development process. The second document is a technical report that outlines the assignment approach, TRAC case study, and recommendations for further exploration.

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LIST OF ACRONYMS AND ABBREVIATIONS

AoA	Analysis of Alternatives
BOD	Board of Directors
C-BA	Cost Benefit Analysis
CDD	Capabilities Development Document
CNA	Capability Needs Analysis
CPR	Capabilities Portfolio Review
DAU	Defense Acquisition University
DCO	Defense Connect Online
DoD	Department of Defense
DOTMLPF-P	Doctrine, Organization, Training, Material, Leadership and Education, Personnel, Facilities, and Policy
ECP	Engineering Change Proposal
FLIR	Forward-Looking Infrared Radar
FLVN	Fort Leavenworth
GCV	Ground Combat Vehicle
HD	Human Dimension
HSI	Human Systems Integration
ICD	Initial Capabilities Document
IED	Improvised Explosive Device
JCIDS	Joint Capabilities Integration and Development System
LRPF	Long Range Precision Fires
MMT	Methods, Models, and Tools
M&S	Models and Simulations

MS	Mile Stone
MOE	Measure of Effectiveness
MOP	Measure of Performance
MTRY	Monterey
NPS	Naval Postgraduate School
OR	Operations Research
OSD CAPE	Office of the Secretary of Defense Cost Assessment and Program Evaluation Office
PD	Professional Development
QFD	Quality Function Deployment
RSM	Response Surface Method
RSE	Response Surface Equation
SE	Systems Engineering
SME	Subject Matter Expert
TEDS	TRAC Employee Data System
TRAC	Training and Doctrine Command Analysis Center
TRADOC	Training and Doctrine Command
USAF	United States Air Force
V&V	Validation and Verification
WSMR	White Sands Missile Range

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GUIDE

1. INTRODUCTION

TRAC conducts trade space analyses as part of our analytical support to inform Army decision makers. Other industries might consider these ‘trades’ as design decisions or design tradeoffs (Decision Driven Solutions, 2008). Regardless of their title, the purpose is the same: facilitate decisions. The intent of this document is to provide an overview of trade space analysis; to include terminology, key principles, characteristics, and challenges. The objective is to keep these descriptions generalized to emphasize their application regardless of the analysis’ focus. This is a different approach.

This document is a *descriptive guide*¹. It is intended for those analysts conducting or supporting a trade space analysis or other trades-related study. This guide may provide some utility to those overseeing the execution of the study as a primer for trades analysis study updates or methodology reviews. This guide will not tell you *how* to do trade space analysis, but describe the various components of what is considered trade space analysis. The intent is, by describing these components and associated attributes, that it helps generate ideas, facilitate planning and methodology selection, etc. There are links to a number of resources throughout; these are provided to support the conduct of a thorough literature review and to reduce the time spent searching for potential references.

To formally introduce the topic, let’s use a familiar example of trade space analysis. Consider the elements of project planning depicted in Figure 1: Project Management Triangle. (aka the “Good, Fast, Cheap” model). This is a very simple example of trades but the same elements hold true for more complex examples.

Studies can be completed with a high level of quality, using extensively developed scenarios, high resolution modeling, detailed data sets, with multiple analysts’ expertise and methodologies applied. Studies can be completed quickly given the requisite resources (i.e. personnel, computational power, accessibility to data, etc). All of these descriptors of quality and timeliness are associated with a cost. Without fail, limitations to these financial or other finite resources force compromise. So, what gives? This shapes trade space.

Each of the relationships between the elements in the triangle can be described. Some relationships are concrete, more easily measurable while others are more ambiguous. Different priorities amongst the elements will affect the outcome. The purpose of trade space analysis is to identify the significance of those relationships and quantify them in a meaningful way.



Figure 1: Project Management Triangle

¹ This document is supplemented by the contents of the [Trade Space Community of Practice page](#). On the page: articles, briefs, links to TRAC products, and areas for analysts to collaborate on the topic and share their experience. This is intended to be a living document. Please feel free to reference any part of this guide as a discussion topic for recommendations for further revisions or topics to cover.

2. DEFINITION OF TRADE SPACE

In literature and TRAC work there are a number of instances where this term has different meanings.

Tradespace (synonymous with *trade space*, *Trade Space*, *trade-space*): a combination of the words “tradeoff” and “playspace”² (the mathematical optimal boundary, aka, Pareto Frontier).

- *Tradeoffs* (synonymous with *trades*, *trade-offs*, *trade offs*): (noun) alternative key objectives all of which cannot be attained together in a decision, design, or project and their associated benefits and opportunity costs. (Business Dictionary)
- *Tradeoff*: (verb) reducing or forgoing one or more desirable outcomes in exchange for increasing or obtaining other desirable outcomes in order to maximize the total return or effectiveness under given circumstances. (Business Dictionary)

Here are two separate academic articles’ definitions of the same term in a military context:

Trade space: “the set of program and system parameters, attributes, and characteristics required to satisfy performance standards” (Brantley, MAJ USA, McFadden LTC USA, & Davis LTC USA (Ret), Winter 2002).

Trade space: “is a wide spectrum of potential outcomes spanned over a set of operational and system parameters, attributes and characteristics to provide possible design options and satisfy operational expectations and system performance criteria.” (Hong, Wee, & Kiat).

Is it the “set” or is it the “potential outcomes of the set”? These definitions are specifically related to system design. As the example in the introduction suggests, there are other trades and spaces to consider. Since TRAC studies are not uniform, our definitions must be generalized enough to encompass the variation:

Trade: an attribute or characteristic [of a design, decision, etc.] with associated benefits and opportunity costs which may be exchanged in part or totality. Related term(s): *parameters*, *input variables*, *objectives*, *constraints*.

Trade space: the bounded area which considers the range of possible values (inherent or applied) for any number of attributes and characteristics, the relationships between them, and impacts on potential (design, decision, operational) outcomes.

*Trade space analysis*³: the search of the bounded space to highlight the relationships between trades, their values (inherent or applied), and outcome objectives to inform decision makers. Related terms(s): *multi-attribute*, *interdependent*, *decision makers*.

² (1) Pareto Frontier is referred to as “playspace” in several instances in the literature. (2) Interestingly, according to [Wikipedia](#), the term tradespace has application as an organizational process management term; a collection of processes spanning multiple organizations. Consider the use of this definition in the context of Force Design or other organizational analyses (i.e. identifying organizational efficiencies).

3. WHEN DOES TRAC CONDUCT TRADE SPACE ANALYSIS?

The DoD analytic communities recognize that there are challenges and shortcomings within DoD decision making processes (program overruns, delays, etc.). The basic source of these challenges is the stove piped nature of decision making processes. In the corporate world, all decisions at every level are aligned with a corporate strategy. Analytic approaches are usually finance-centric, marketing, or economics driven. Figure 2 shows that it is not necessarily that simple in the analytical environment in which we work.

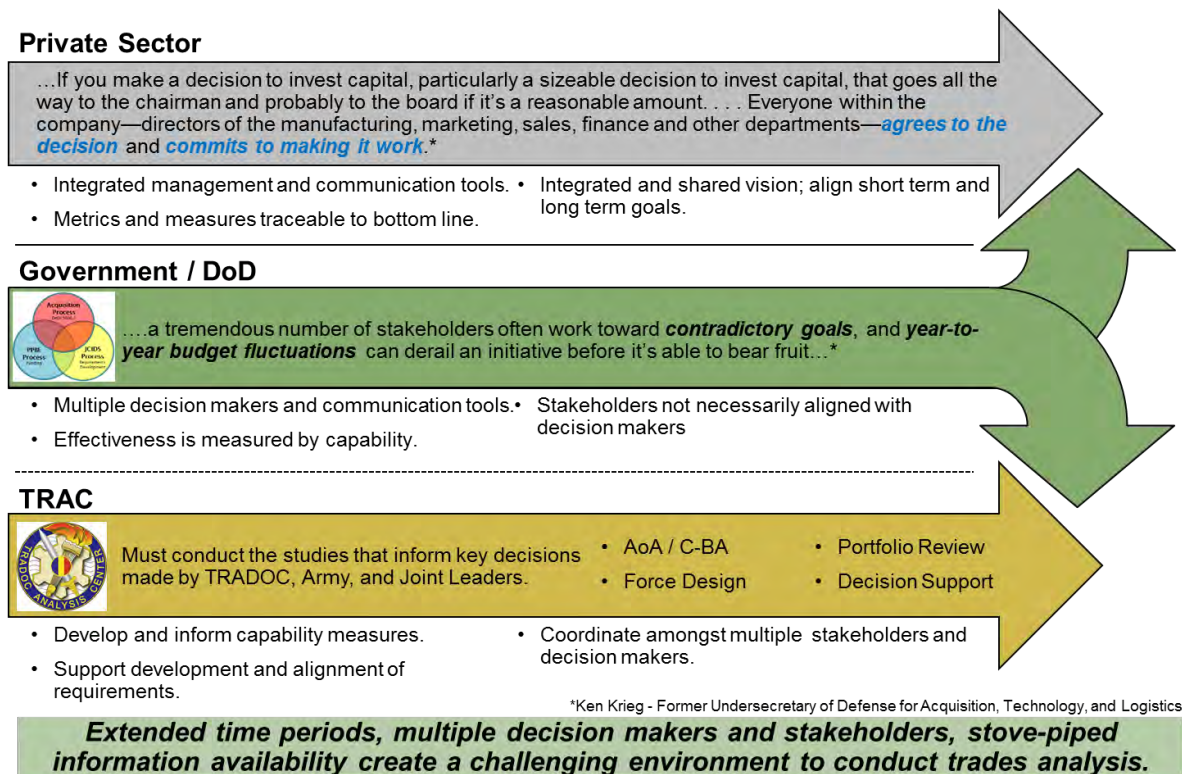


Figure 2: The challenge associated with trade space analysis

TRAC supports a number of different types of studies⁴. The introduction alluded to the fact there is really no limit to situations where trades occur. Trades are most commonly referred to in a capability based context, either supporting an analysis of alternatives (AoA) or the initial determination of capability requirements type studies. Each decision point within the JCIDs acquisition process presents an opportunity to conduct a trades-related assessment. However,

³ One observation from this research was that there is a slight, but relevant, difference between trade space analysis and tradeoff analysis. Trade space analysis is the umbrella term. However, based on the literature review, tradeoff analysis insinuates a certain level of “concrete-ness” of alternative definitions, attributes, capabilities, and desired outcomes.

⁴ The project report (TRAC-M-TR-15-028) associated with this guide contains a list of example TRAC studies along with descriptions of their trades analysis objectives, methodologies, and trades considered. The Trade Space Community site links to a majority of these project reports.

there are budget, planning and composition, and mix problems where any combination of capability, cost, and value attributes are traded.

4. ELEMENTS OF TRADE SPACE ANALYSIS

If you keep the elements of decision making⁵ in mind when you think about the trade space analysis process, there is nothing too special or complicated: define criteria, define alternatives, evaluate alternatives, and select/commit to a best-fit alternative for implementation. “The trade space exploration 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.” (Spero, Avera, Valdez, & Goerger, 2014). Figure 3, from the referenced article above shows the types of information that is required to support decision making across the lifecycle of a particular system. It takes into account the number of perspectives, environmental constraints, fiscal decision types, etc. that must be considered. This graphic emphasizes the complexity of data involved when conducting trades analyses.

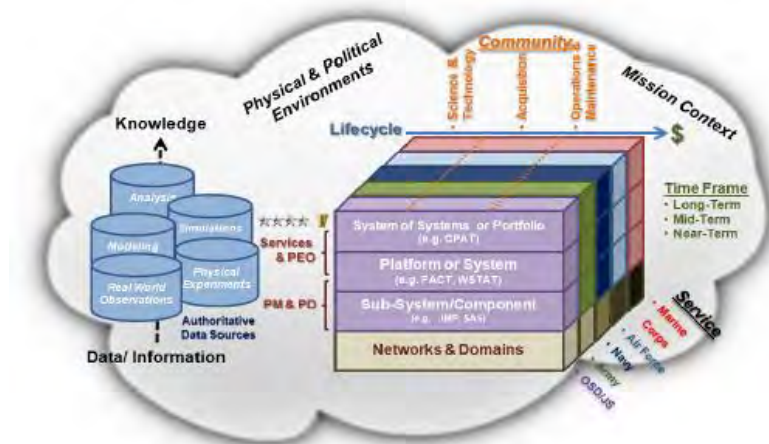


Figure 3: Tradespace Frontier

Not all of TRAC trades analyses focus on system design. However, in the past, a greater proportion of them do. The article “Tradespace Exploration for the Engineering of Resilient Systems”⁶ succinctly presents 12 best common steps of conducting trade space exploration. Even though the list was written specifically about the conduct of trades analysis at the engineering design level, the same practices apply:

Table 1: Best Common Practice Steps

1. Determine mission scenario(s) and their requirements, and keep them open as long as possible.

⁵ Even decisions have ‘ility’ attributes (e.g.) flexibility, adaptability, responsiveness. These are not commonly assessed / considered as part of TRAC trade space analysis.

⁶ The [article](#) is on the community page.

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.

The following sub-sections are broken out into more general steps of conducting a study in order to highlight attributes common to any type of problem. The related steps from Table 1 will be in the brackets at the beginning of each section.

4.1 Define the problem.

(1) Any analysis effort starts with problem definition. The output from the initial problem decomposition or “Front End Analysis” and development of [measurement space](#) should provide the majority of starting conditions and requirements for any trade space analysis.

4.2 Define (identify) trades.

(2) Through the systematic decomposition of the problem, the attributes and characteristics become clear. There are a number of activities that provide that clarity: workshops (e.g. Measurement Space Drill or other workshops), stakeholder analysis, M&S, and document reviews. Depending on the problem type, there will be requirements documents (e.g. ICD or CDD) that will help define attributes and characteristics. It “is important to qualitatively and, if possible, quantitatively describe the interactions between the trade space entities. These interactions highlight stakeholders that are impacted by decisions for each of the trade space entities and identify the critical interactions that will require data collection, modeling, or simulation to understand the relationship. This process can also reduce the problem complexity using known relationships constraints and thresholds.” (Brantley, MAJ USA, McFadden LTC USA, & Davis LTC USA (Ret), Winter 2002). There are a number of descriptors that are related, but may not affect the outcome.

Note: Trades may originate from any domain within the DOTMLPF-P spectrum. Each domain is considered a separate bin of different kinds of products and services necessary to conduct business. A gap or capability requirement might have alternative solutions which originate from specific or across bins. It is usually assumed that trades assessments are confined within the DOTMLPF-P domains and not necessarily between domains.⁷

4.3 Describe trades.

Recall from the trade space definitions that attributes may have *inherent* and / or *applied* values.

(3) *Inherent Value*. These describe the attributes directly. Each of these descriptors has their own unit of measure. Regardless of the type of value or the problem scope, some attributes already have threshold or objective levels defined. These values can be ridged objectives and constraints that must be accounted for, while others are more flexible or elastic. Based on all of the descriptors, these attributes become the parameters or input variables, objectives, and constraints, areas for sensitivity analysis. Values should articulate provided benefit (e.g. performance effectiveness or efficiency) and operational costs (e.g. price tag, risk, etc.) associated with the element. From the project management example; time can be measured in any increment or as man hours. Whereas, cost can also be measured in terms of man hours or dollars, or other resource costs, like computational power units (e.g. number of machines).

(4/5) *Applied Value*. These include stakeholder and decision maker priorities and / or the attributes and characteristics they might value over others. Again, from our example, let's say that decision makers are more concerned with maintaining quality, within a restricted time frame than cost. The question becomes, how much more?

TRAC has several guides to elicitation that may help: [SME Elicitation Community Page](#), Survey Code of Practice, SME Elicitation Technical Report I and II. Related topics are: Stakeholder analysis, value focused thinking, decision analysis methods such as qualitative value modeling, multi-attribute decision making techniques. TRAC has a [Multi-Attribute Decision Making Code of Best Practice](#)⁸ that provides an overview of methodologies and considerations.

4.4 Assess trades.

At this point, we articulate relationships between trades. The curves in the graphic below describe the relationships between the attributes in the project management triangle.

⁷ All of DOTMLPF-P domains are tied to Doctrine. Any change in the other domains will ultimately have an effect on Doctrine and vice versa. (Alfred, 2007) The common currency across domains is usually dollars; however, there are certain domains where comparable benefit / opportunity cost related measures are difficult to articulate.

⁸ The TRAC SharePoint main page has a link to all [Codes of Best Practices](#).

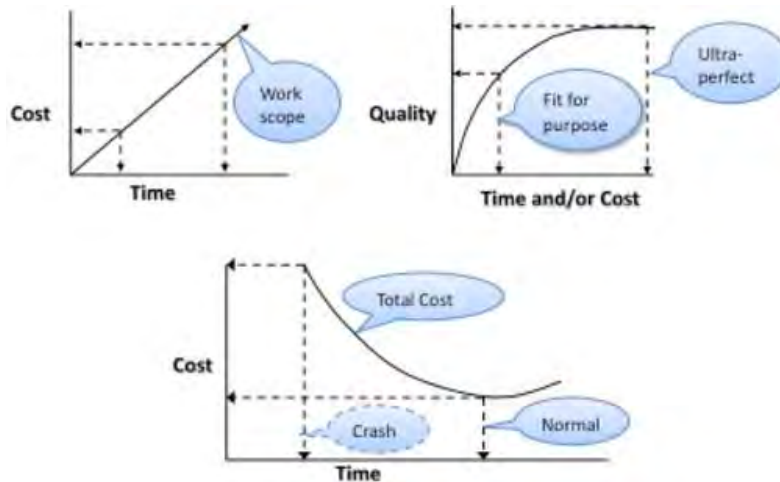


Figure 4: Relationships between Project Management Trades

- Scope (upper left): given enough resources you can achieve almost anything.
- Quality (upper right): there is a certain level of quality that will be sufficient. However, there is a certain point where it doesn't matter how much more time or money you throw at it, it may not get any better.
- Cost (bottom)⁹: If it needs to be done faster, it will be more expensive. However, there is a threshold where it will compromise the integrity of the project if you spend less than x time.

These can be generated through heuristics; however, there are a number of MMT that apply to this problem. Much of the literature has extensive detail about the input and outputs associated with trades analysis and little detail about the actual methodologies applied to exercise the data. The associated M&S effort (i.e. venues, methodologies, tools, etc.) is unique to each set of parameters being assessed. TRAC has an [OR Guide](#) that provides a good overview of a number of methods for grouping and comparing multivariate data output from the M&S.

4.1.1 System Attributes and Capability Requirements Trades

(6, 7, 8, 9, 12) Across literature these system related trade space analysis focus on performance, capability, *and* utility values. These are most commonly characterized by cost, risk, performance, and schedule trades in TRAC work.

To facilitate this portion of the discussion, consider using the structure of the Quality Function Deployment (QFD) model as a framework for building out a trades assessment. It is part of the Six Sigma "Define Phase." QFD is "a structured method in which customer requirements are translated into appropriate technical requirements for each stage of product development and production". The primary components are: defined capability (*what*) requirements (e.g. effectiveness against target type x (lethality), mission duration and capacity for follow-on tasks

⁹ As an example of an advanced method for conducting trades analysis, there is a paper related to applying a genetic algorithm to a time-cost trade off resource planning problem located on the Community Site.

(efficiency), protection against IEDs (mobility), etc.), prioritized rating of those capabilities, performance characteristics that enable capabilities (*how*), the codified interrelationships between the capabilities and performance characteristics along with the tradeoffs between performance characteristics, target values (i.e. performance (e.g. speed, probabilities of kill, capacity), risk, cost, etc), and comparative areas for why the requirement exists. Figure 4 maps the essence of the best common steps to components of the model. See APPENDIX C. Q for a notional example using LRPF-like attributes.

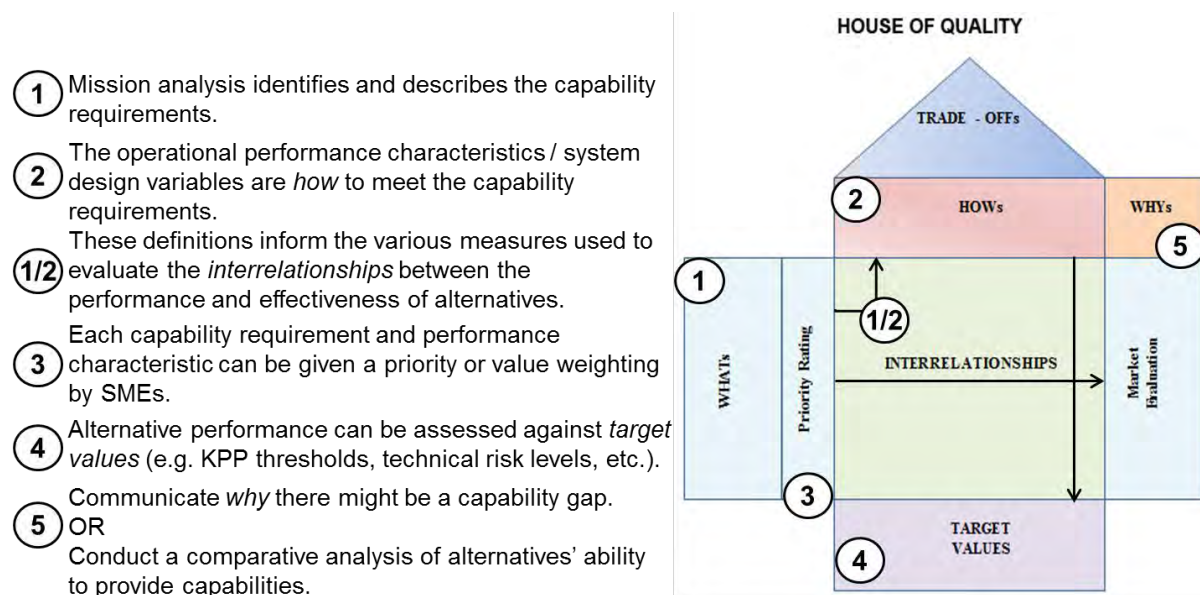


Figure 5: Quality Function Deployment

The house of quality identifies two types of relationships to describe through analysis. These are the relationships between capability and performance *inherent* values, as stated above, as well as the *tradeoffs* between performance attributes. They may be explored qualitatively; however, quantitative analysis is usually preferred. Step seven in the “Best Common Practice Steps” articulates the creation of “**reduced-order surrogate models**”¹⁰ to show iterative ability of adjusting scenarios and requirements to physical feasibility”. These are referred to as response surface models or meta-models. They mimic the behavior of the simulation as closely as possible but focus primarily on the input-output relationship to be able to handle more exploration with less computational resources required in more high fidelity modeling. These are most commonly employed in engineering design; however, there is application in a number of areas where simulation/experimentation is expensive. If only one design variable is involved, the process is called curve-fitting.

¹⁰ One example is the Relational Oriented Systems Analysis Engineering Technology Tradeoff Assessment ([ROSETTA](#)) Initiative by the Aerospace Systems Design Laboratory. This methodology uses qualitative SME data built as a QFD model with model and simulation data captured using response surface method (RSM) / response surface equations (RSEs) as surrogate models. It uses the RSEs with Monte Carlo simulation to quantitatively explore changes across the surfaces to develop greater understanding of the relationships represented in the QFD. (ROSETTA, 2015)

As a side note, Multi-objective decision analysis techniques can be very effective for understanding the relationships at the attribute level between what is desired and what is affordable. Recently, the Brownout Rotorcraft Enhancement Sensor (BORES) AoA team used a related approach. The AoA supports the establishment of a baseline degraded visual environment capability and inform a MSA DAB (TEDS). The Air Force has actually developed a MODA guide to facilitate their capability cost analysis¹¹.

4.1.2 Budget / Planning / Composition Mix Trades

(10, 11) These assessments can be described as a subset of the “Best Common Practice Steps”. These are characterized by any number of attributes (cost, performance measures) usually associated with *applied* values. These analyses can be heavily influenced or driven by priorities, scheduling constraints, and numerous combinatorial considerations. TRAC studies successfully employ math programming methods to such problems. Military application of optimization methods to acquisition planning, BRAC closures, quantity mixes is well documented¹². The following example¹³ describes a simple knapsack problem considering all the elements we have been discussing. It includes characteristic “levers” enabling exploration of the trade space:

The Squad: Foundation of the Decision Force (SFDF) Model that supported a study of the same name. It was a fairly simple knap sack problem, fueled by SME established utility values for capabilities, cost, gap priorities, and a number of “levers” on key attributes to run the model. It could be run in two forms: (1) with an upper and lower limit budget and a defined increment and (2) with a fixed budget. Its output was either the top capability package for each budget amount or the x number of top mixes at a fixed budget.

4.5 Communicate trades.

(8) The basic element relevant to trades analysis is how to display multivariate data. Seeing and understanding the interaction between driving factors or the elements more highly valued is essential. These parameters become the axis or levers that displays should revolve around. Presenting multiple dimensions of data in a single display is an art. Basic principles are: the use of color, shape, and size. There are a number of chart types that are not readily available in Excel, but available as online chart templates or as R packages¹⁴. Textbooks on Multivariate

¹¹ This information was shared via an email dated 20 April 15 from Matthew Boetig. The [guide](#) is in DRAFT form and available to review on the Community Page.

¹² See the article on [Optimizing Military Capital Planning](#) for an overview of a number of related problem types and insights on formulation development.

¹³ The TRAC Math Programming Community page has a number of [examples](#).

¹⁴ TRAC’s R user community is growing. As an example, the TRADOC Accessions OPT study team at TRAC-FLVN is using GoogleVis to display some of their data. They are using it as an exploratory tool, but it has benefit as a communication tool as well. [GoogleVis](#) is an R package that provides an interface between R and google charts API. It allows users to use charts like: Motion Charts, Annotated Time Lines, Maps, Geo Maps, Geo Charts, Intensity Maps, Tables, Gauges, Tree Maps, further Line, Bar, Bubble, Column, Area, Stepped Area, Combo, Scatter, Candlestick, Pie, Sankey, Annotation, Histogram, Timeline, Calendar and Org Charts.

Analysis are obviously a good resource for ideas. Section 3.4 in Rencher & Christensen's Text: [Methods of Multivariate Analysis](#) outlines several methods for plotting three or more variables in a two dimensional space. Additionally, data presentation texts like those by Edward Tufte describe techniques to try. One technique he recommends is to use small multiples¹⁵ to display effects of changing variables.

The world of “what if” dictates even more finesse. The use of decision support tools such as “dashboards” have become common practice.¹⁶ Graphs show the relationships between effectiveness measures, physical performance measures, and cost and constraints. ‘Levers’ are on critical attributes. These facilitate the visualization of multiple relationships simultaneously; highlighting interactions in a meaningful way; identifying data gaps and outliers and correlations dynamically based on decision maker driven areas of interest. Imagine supplementing briefing results using something like this. These are built using surrogated meta-models, like those mentioned in the previous section.

5. CHALLENGES

Each of the following sub-sections relates to potential challenges related to the process of conducting trade space analysis. The majority of these were collected through discussions with analysts who had participated in some of the trades work reviewed for this study. The intent of this section is to describe the nature of the challenge or present an alternative approach to meeting the implied challenge.

5.1 Identifying Trades.

Alternative focused thinking vs. value focused thinking. A major advantage of alternative-focused thinking is that the analysis focuses directly on the alternatives of interest to those who put forth the set of alternatives; however, this assumes that the overall intent can be met with these alternatives. Value-focused thinking presents an approach to expand the scope of potential alternatives. It starts with values, uses values to generate alternatives, and then uses values to evaluate those alternatives (usually through a multiple objective decision analysis technique)(Loerch & Rainey, 2007). A value-focused thinking approach may help identify additional areas for trades.

5.2 Constructing the Trade Space.

Trade space links requirement and capability attributes. TRAC analysis supports requirements determination during Pre-MSA work through the entire life cycle of a program. For example, The Task Force 120 GCV analysis work focused on determining the initial requirements for the

¹⁵ Small multiples show the same combination of variables, indexed by changes in another variable. “...showing shifts in the relationship between variables as the index variable changes (in turn revealing interaction or multiplicative effects).” (Tufte, 2001)

¹⁶ There are a number of examples of trade space analysis and related decision support tools that have been designed across the DoD. These examples span a number of decision types, maturity of system development, etc. See APPENDIX A. DoD EXEMPLARS for a brief description of a few of them.

GCV program using a number of qualitative value modeling approaches, followed by MSA and MSB work that leveraged more and more quantitative M&S work; the advantage being the pedigree of linkage back to initial requirements. Not all studies are so lucky. For example, the Bradley ECP C-BA had to link each technology they assessed as potential upgrade back to a requirement to begin their analysis.

5.3 Defining input variables.

Tight study schedules and the murkiness of early project phases, present a challenge to not only identifying trades areas, but identifying data elements that will be available to inform analysis. LRPF trades team mentioned that their planning was scoped by the tools that were identified as data sources to collect data to inform metrics / measures instead of the other way around.

5.4 Assess trades.

The art and science of trade space identifies, qualifies, and quantifies the relationships between factors, levels, inputs, outcomes, etc. There is usually a necessity to use numerous, and potentially, stove-piped tools. This presents a challenge in identifying and communicating relationships between findings from various tools.

5.5 Communicating the results.

Data Visualization is a trendy topic and there are a number of associated challenges. For example, our graphics should highlight which factors contribute to the overall value / effectiveness (attributing cause and effect), but be able to identify artificial relationships as well. These might be the result of “modelisms” or applied assumptions. Another challenge is just the sheer number of attributes our analysis usually needs to articulate simultaneously. The disparate nature of these attributes makes it difficult to visualize all at once. There are a number of academic articles that use utility curves and plots as a general practice for displaying alternatives with all of their associated disparate attributes.

6. CONTENTIOUS ELEMENTS OF TRADE SPACE ANALYSIS

Each of the following sub-sections describe an element associated with conducting analysis – not necessarily limited to trade space analysis – that seemed to be related to or a source of challenge for either the conduct or communication of analysis. The intent of this section is to help analysts consider these during methodology development or in the documentation of CLA.¹⁷

6.1 Ambiguity.

There are a number of sources for ambiguity. Some of these are related to performance values while others focus on measuring benefit (aka utility values).

¹⁷This is a good opportunity for TRAC analysts to share their experience about when and where assumptions must be included to address areas where NOT accepting them would invalidate analysis as a whole.

Performance value. There are only so many computational resources available. “Boundaries of the input parameters and value spacing [had to be] carefully thought through...excessive inputs create so vast a solution space that it might be difficult or impossible to make analytical insights” (Hong, Wee, & Kiat). To counter this, one suggestion is to set a minimum and maximum value for the variable and then a “most likely value”. As a friendly reminder, it is important that there is an associated study assumption that addresses the selected set of parameter values.

Design of Experiment¹⁸ is strongly recommended to minimize, while justifying, the number of runs required. The GCV MSB AoA Phase 1 conducted a parametric analysis of the vehicle attributes using a fractional factorial DoE to combat time and resource constraints. They looked at four vehicle factors (gun, hit avoidance, sensors, and vehicle) at two levels (base and improved).

Another note on performance values: depending on the maturity or nature of the attributes being assessed, rough order magnitude estimations are required. One example provided from the CPR work was cost: “trying to get cost figures for solutions that were / are nothing more than initiatives with no real definitions, or cost figures for solutions that are not materiel - like costing for training a BCT's worth of Ranger school graduates”¹⁹.

Utility value²⁰. It is a “dimensionless parameter that reflects the ‘perceived value under uncertainty’ of an attribute. A utility function is typically yields a value from least desirable, 0, to most desirable, 1. There are a number of benefits and drawbacks to applying Utility Theory. However, utility values enable the application of a unit-less measure to a number of disparate factors that is representative of benefit. This reduces the number of dimensions required to communicate the specific performance of a set of disparate parameters.

6.2 Uncertainty vs. Risk.

Uncertainty is a related term to ambiguity. “Oftentimes the uncertainty inherent in system development is treated synonymously with risk and as such carries negative connotations. (Hastings and McManus, 2003) describes a more generalized framework for thinking about uncertainty, highlighting the fact that there is both upside as well as downside risk associated with uncertainty...” (Ross & Hastings, *The Trade Space Exploration Paradigm*, 2005). In terms of trade space representations there are a number of approaches for including such uncertainty. The article points to another reference (Walton, Myles. *Managing Uncertainty in Space Systems Conceptual Design Using Portfolio Theory*. PhD, Massachusetts Institute of Technology, 2002) which explores using: error ellipses, best-worst case lines, and color-coding to represent tradespace uncertainties, as well as an uncertainty-value plot. Consider the levels of risk

¹⁸ You can find an [Overview of DoE](#) on the TRAC SharePoint COBP.

¹⁹ Mr. Larimer, Principle Analyst 13Mar15 Email.

²⁰ “The Tradespace Exploration Paradigm” article by A. Ross and D. Hastings from MIT, articulates a process of value-focused, broad trade space exploration that provides some valuable insights into communicating and quantifying the impact of changing requirements, and uncertainty, along with other system properties. This, along with several related articles are available on the Trade Space Community Page.

adversity a decision maker may want to explore in terms of cost, schedule, and or technology risk.

6.3 Sphere of Influence.

Regardless of the topic, there is only so much that is in our sphere of influence.

Example related to the data used to run analysis: The utility values used to run the IBCT / ABCT / SBCT CPR optimization model were collected using the CNA SME elicitation methodology. TRAC did not create those values, nor were they 100% privy to the details of execution of the elicitation.

Example related to the analysis: The Abrams ECPII C-BA assessed the benefits of a set of technologies to the Abrams platform, established if the technologies could be implemented as an ECP, and developed COA to cost-effectively modernize the tank. The analysis evaluated nine technologies, some of which were not necessarily under program control (e.g FLIR).

6.4 Noise.

Depending on the type of trades being assessed, there is a certain amount of “noise” that must be accounted for. Noise factors can be inflicted by the operational environment, such as enemy behavior or weather conditions. Others are directly related to the physical components of the system, such as failure rates, especially at early stages of concept development. Some of these considerations are accounted for in our modeling, others are not.

7. SUMMARY

On a conceptual level, a successful approach to trades analysis must include (1) an approach that provides transparency of assumptions and constraints, (2) a method to simultaneously evaluate the costs and benefit of decision not often measured in dollars, and (3) the means to examine broader sets of alternatives over multiple scenarios and to allow decision makers to visualize and interest with the data that supports their decisions (Kane, MAJ GEN USAF & Bartolomei, PhD LT COL USAF, March-April 2013).

With regard to the execution of trade space analysis, it spans three dimensions: physical performance, operational capability, and value or utility. These have unique measures, but should use the same input variables. Trade space analysis concepts pertain to any combination of dimensions. This guide focused describing elements of trade space analysis as it relates to TRAC work. It does not prescribe methods, but hopefully provides enough detail to generate ideas. It links to numerous resources (some TRAC had already created on method descriptions); codes of practice, texts, and articles related to specific tools and techniques, etc.

This document is supplemented by the contents of the Trade Space Community of Practice page²¹: articles, briefs, links to TRAC products, and areas for analysts to collaborate on the topic

²¹ APPENDIX B. COMMUNITY OUTLINE is an overview of the Community Site contents.

and share their experience. This is intended to be a living document. Reference any part of this guide as a discussion topic for recommendations for further revisions or topics to cover.

Additionally, given the short suspense of this project and the large scope of the topic, a number of the topics discussed herein are missing a visual example (e.g. chart types, multiple dimensional plots, etc.) It would be valuable if others can submit examples for the guide to reference. It would also be valuable if each of the articles on the community site had an abstract summarizing the article and identifying its relevance to the TRAC trades community.

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APPENDIX A. DOD EXEMPLARS²²

Each of these tools combines capability, performance, and value measures into the tool structure.

[FACT \(Framework Assessing Cost Technology\) Model](#)

Summary of the FACT Overview Brief. This is a model built for the Marine Corps System Command in cooperation with Georgia Tech Research Institute. The model's foundation is Systems of Systems Engineering concepts. It leverages SysML software and accepted systems engineering standards to incorporate design parameter trades including performance, reliability, and cost of a system design. Its purpose is to understand interactions and identify implications; addressing elements like cost, reliability, maintainability, and availability. It is advertised as a decision support tool to manage decision consequences and conduct risk management. Numerous performance models are accessed using metadata and cost is integrated using a trusted O&S cost model. Confidence analysis is also included. Subject matter expert distributions can be applied to variables of interest; there are probability and cumulative distribution functions that quantify uncertainty of reaching thresholds and objectives. It is a browser based tool that enables analysis as a web-service for system design from the component level to a composite design. There is ongoing work to integrate [a second research effort](#) being led by ARL to develop an interface between FACT and the Executable Architecture Systems Engineering (EASE) model that links system concepts to combat simulation. (Gaughan & Metevier, 2014) Input would be system designs from FACT. EASE model output would go back to FACT as measures of effectiveness.

[WSTAT \(Whole systems Trades Analysis Tool\)](#)

PEO GCS worked with Sandia National Labs for the tool's development along with ARDEC and Booz Allen. The tool has two purposes: "model the relationship between design decisions and stakeholder value in order to inform and potentially influence requirements documents" and "associated specifications and conduct cost informed trades analysis based on holistic design choices, while understanding the opportunity cost of each choice." The model integrates separate system models into a single view. It identifies five elements of Stakeholder value: performance, acquisition cost (unit cost), time to complete (schedule risk), O&S cost, Spiral upgrades (growth potential or long term viability). The whole system trade analysis process starts with understanding requirements and functional objectives, mapping requirements to those functional objectives, then identify and map to a product structure, then the technology options and metrics for evaluating those technology options can be integrated. The application of value functions and priority weightings provides the last amount of context for the graphical output of the model. The model uses a genetic algorithm evaluating generated alternatives. (Edwards (PEO GCS), Lawton (Sandia Nat'l Labs), Cilli (ARDEC), & Peterson (BA))

[CPAT \(Capability Portfolio Analysis Tool\)](#)

²² Each title is a link.

Summary of sections 1.2 and 1.3 of the CPAT V&V Report: CPAT is an acquisition tool designed to identify the optimum courses of action (cost, schedule and performance) for portfolio investment. Again, PEO GCS worked with Sandia National Labs for the tool's development. The tool was designed to complement the formal AoA process and support the transformation and modernization of the combat vehicle fleet. The performance model determines a *value* for 47 vehicles across 20 roles using 49 attributes. However, not all vehicles are considered for all roles. The performance attributes were selected using requirements documents, SME panel, and input from AMSAA. The results of the performance evaluation are combined with the cost analysis and schedule analysis as an optimization model within CPAT. It is designed to provide the ability to understand the trade space between cost, schedule, and performance to assist in planning for the overall Combat Vehicle portfolio and fleet modernization. CPAT's intended use: to identify COA for the PEO GCS portfolio investment, provide analytical underpinnings that support an achievable and affordability Combat Vehicle Modernization Strategy, act as a decision-making tool to provide rapid value assessment for alternative related questions (support the user community in requirements development for CBA-type analysis). Long term objectives: annual updates, support future investment decisions, what-if scenarios, integrate updated data to support PM's technology trade assessments. (Dell, Ewing, MacCalman, & Whitney, 2013) The V&V report provides insight into the mechanics of the tool along with some limitations and recommendations for improvement.

APPENDIX B. COMMUNITY OUTLINE

Status – 50% Complete. Site has been established. Needs: content to be organized, public notification that the site is available for use, guide products uploaded, permissions set to TRAC ALL to be able to contribute, add, delete, etc.

Mission/Purpose of the Trade Space Community:

The page is an open forum for anyone to contribute resources, post questions, post answers/responses, revise/refine content, collaborate on any topic related to TRAC trades studies or Trade Space Methodologies in general. The objective is to continue to expand TRAC state of the art in conducting trades analysis, provide a forum to leverage the collective experience of TRAC analysts.

Member List: Self nominated. In the spirit of knowledge sharing, if you put your name on the list, please make a commitment to visit it at a regular interval with a goal to contribute a discussion topic/question, comment, link, article, etc. during each visit. *There is a link to instructions on how to set up an alert on the page.*

Identified Users (those who might benefit / participate in the community and why)

Analyst – PD, literature search, find others to collaborate

Study Lead – Identify potential SME and resources, methodologies, etc.

Discussion Threads: These are enduring threads and should group the majority of discussion topics. However, please feel free to add others.

- Definitions
- Methodologies
- Trades and DOTMLPF-P
- Challenges
- Lessons Learned
- Analyst Guide

Resources – Desired end state: include a link to the document, and a brief abstract for each. Prefer minimal uploads.

- Study Links (TRAC)
- Article Links (Academic, DoD)
- Website Links
 - o Innovation / Things to try (Data Visualization, QFD model, etc.)
 - o Other online communities (milSuite?)

Note: there is no activated calendar associated with this community. Potential uses, if the group decides, would be: anyone may schedule events for the group (Focused PD topics, brainstorming sessions, collaborative meetings) or advertise when study trade workshops are being held, etc.

APPENDIX C. QFD

The following is a NOTIONAL example of the application of QFD. Figure 6: Notional QFD model 1 – Capabilities and Performance Attributes maps the relationship between the desired capability requirements of a long range precision munition and the performance characteristics that enable them. The matrix provides the ability to visually map characteristics of capability needs to performance requirements. The right side of the table below shows exemplar operational capabilities of a long range precision munition. The elements at the top of the table describe the requisite performance characteristics to enable the desired capabilities. The definitions help identify appropriate measures (MOE and MOP). The body of the table identifies the relationships between performance characteristics the capabilities. The triangular section at the top identifies any interaction between performance parameters. In QDF, these areas are codified to articulate the extent of the relationships. In the example below Upper case X's identify the most significant contributors to the capabilities and the + / - in the top section articulates the nature of the interrelationship of two attributes. Consider the desired capability of being able to service targets from a standoff position; the principle performance characteristic is an extended range munition. The framework provides the ability to map that directly to a threshold level of 400km. The upper portion of the map suggests there is a negative relationship between being able to provide an extended range and remain IM compliant. Additionally, it shows that there is a positive relationship between an extended range and having a responsive system.

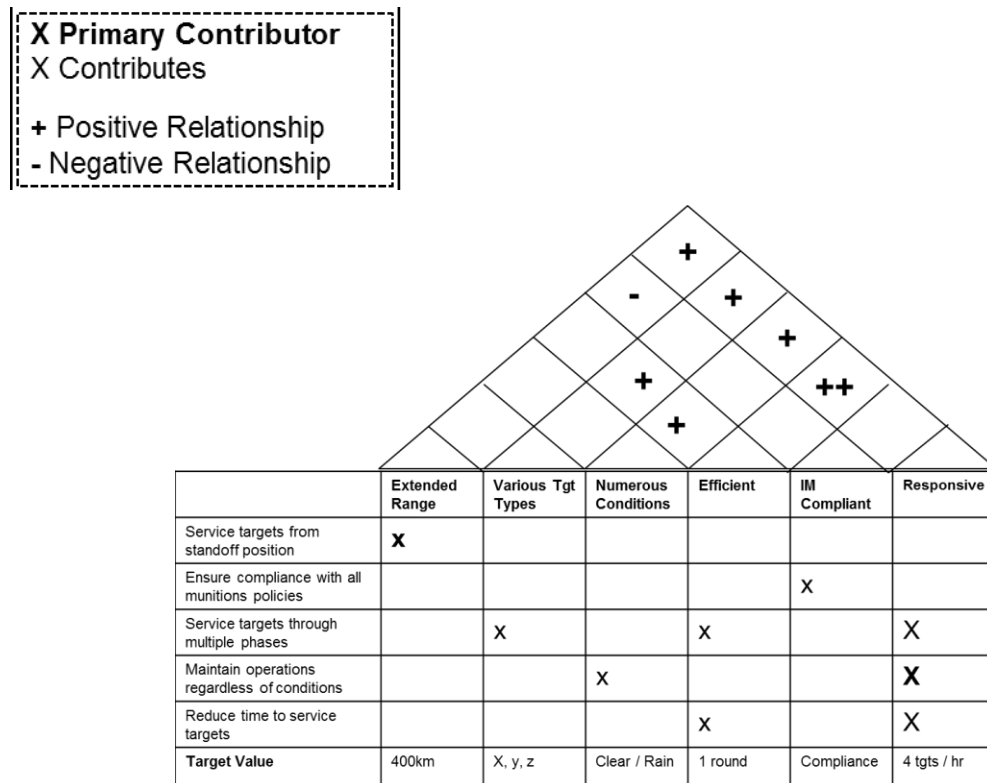


Figure 6: Notional QFD model 1 – Capabilities and Performance Attributes

Depending on the scope of the analysis, the same framework can map performance requirements to specific enabling technologies. Figure 7: Notional QFD model 2 – Performance Attributes and Enabling Technologies addresses another set of relationships, directly mapping back to the original capability requirements. The same simple codification is used to describe the relationships between each of the characteristics and the interactions between technologies. Now consider the performance attribute of extended range; it is enabled by having a low warhead weight. Having a low warhead weight might have a significantly positive relationship with being able to house more than one munition per pod. Having a low warhead weight might have a significantly positive relationship with being able to house more than one munition per pod.

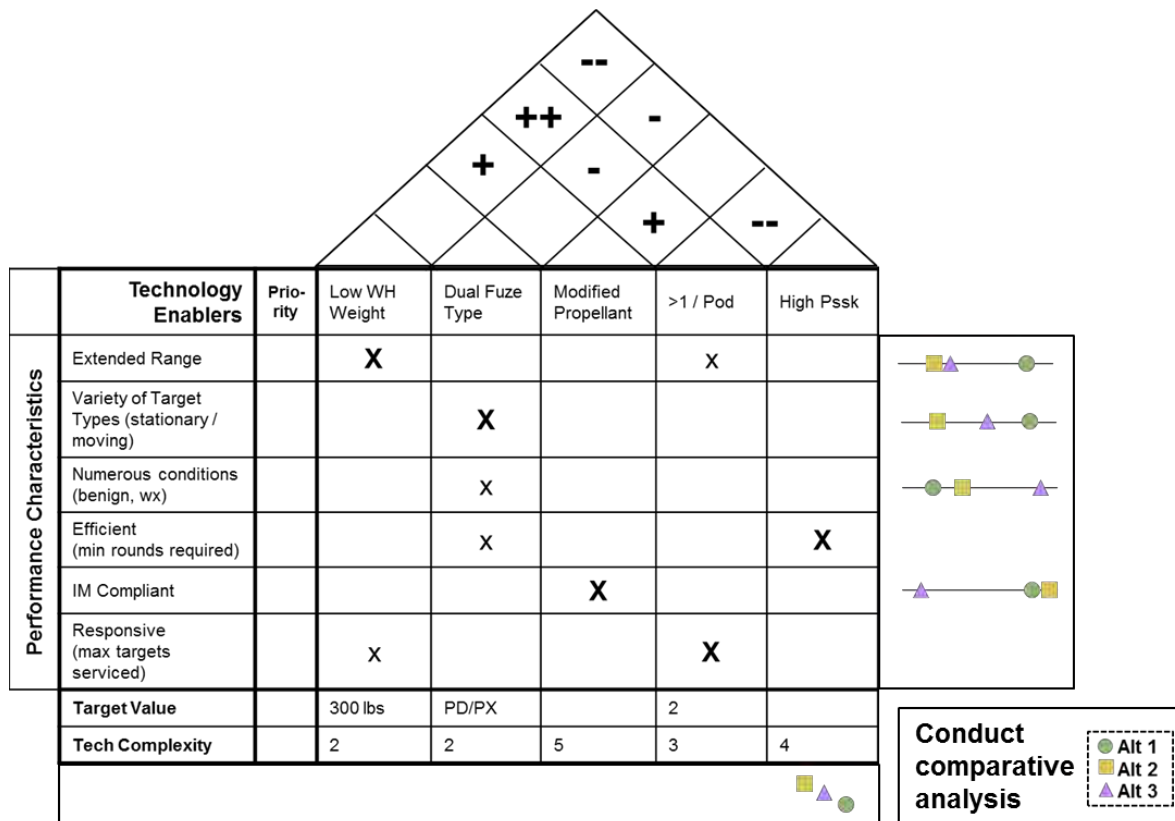


Figure 7: Notional QFD model 2 – Performance Attributes and Enabling Technologies

The areas at the bottom and to the right of the table provide the ability to communicate a number of other relationships. The area to the right of the chart could be used to conduct a comparative analysis of other technologies or options to achieve the desired capabilities. The area at the bottom could be used to identify target values, articulate which attributes contribute the highest cost, are technologically difficult to achieve, pose the greatest risk, or to conduct comparative analysis of a number of alternatives' performance. Additionally, priorities and importance weights can be included for both performance characteristics and capability attributes which may help illuminate the more "critical" elements / decisions.

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