Systems Engineering Tradeoff Study Process Framework

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Abstract. Tradeoff studies are a critical tool to provide information to support decision making for discipline engineers, systems engineers, and program managers throughout the system life cycle. Unfortunately, the quality of trade studies is inconsistent between organizations and within organizations. This paper reports on part of an INCOSE effort to improve tradeoff studies and discusses a proposed INCOSE Decision Management Process aligned with ISO/IEC 15288. The proposed process discussed in this paper integrates decision analysis best practices with systems engineering activities to create a baseline from which future papers can explore possible innovations to further enhance tradeoff study quality. The process enables enterprises to develop an in-depth understanding of the complex relationship between requirements, the design choices made to address each requirement, and the system level consequences of the sum of design choices across the full set of performance requirements as well as other elements of stakeholder value to include cost and schedule. Through data visualization techniques, decision makers can quickly understand and crisply communicate a complex trade-space and converge on recommendations that are robust in the presence of uncertainty.

Introduction

Successful Systems Engineering requires good decision making. Many systems engineering decisions are difficult decisions in that they include multiple competing objectives, numerous stakeholders, substantial uncertainty, significant consequences, and high accountability. In these cases, good decision making requires a formal decision management process. The purpose of the decision management process, as defined by ISO/IEC 15288:2008, is "…to provide a structured, analytical framework for identifying, characterizing and evaluating a set of alternatives for a decision at any point in the life-cycle and select the most beneficial course of action." This paper aligns with the structure and principles of the Decision Management Process Section of the INCOSE Systems Engineering Handbook v4.0 DRAFT (INCOSE SE Handbook Working Group, 2014) and presents the decision management process steps as described therein (written permission from INCOSE Handbook Working Group pending). Building upon the foundation laid by the handbook, this paper adds a significant amount of text and introduces ten illustrations to provide richer discussion and finer clarity.

New product developments entail an array of interrelated decisions. Table 1 provides a partial list of decision situations (opportunities) that are commonly encountered throughout a system's lifecycle. Many of these decisions may benefit from the holistic perspective of the systems engineering discipline coupled with a decision model that aggregates and translates the data produced by engineering, performance, and cost models into terms meaningful to the various stakeholders, most importantly, the decision makers.

Table 1 - Partial List of Decision Situations (Opportunities) Throughout the Lifecycle

Life Cycle Stage	Decision Situation (Opportunity)
Exploratory Research	Assess Technology Opportunity / Initial Business Case • Of all the potential system concepts that could incorporate the emerging technology of interest, do any offer a potentially compelling and achievable market opportunity? • Of those that do, which should be pursued, when, and in what order?
Concept	Inform, Generate, and Refine a Capability Development Document • What requirements should be included? • What really needs to be accomplished and what is able to be traded away to achieve it within anticipated cost and schedule constraints? • How should requirements be expressed such that they are focused yet flexible? • How can the set of requirements be demonstrated to be sufficiently compelling while at the same time achievable within anticipated cost & schedule constraints?
	Create System Architecture Alternatives and Select Best • After considering the system level consequences of the sum of architecture design choices across the full set of stakeholder value (to include cost and schedule), which architecture alternative should be pursued?
Development	Select/Design Subsystems • After considering the system level consequences of the sum of subsystem design choices across the full set of stakeholder value (to include cost and schedule), which subsystem alternatives should be pursued?
	Select/Design Components / Parts • After considering the system level consequences of the sum of component design choices across the full set of stakeholder value (to include cost and schedule), which component alternatives should be pursued?
	Select/Design Test and Evaluation Methods • What is the prototyping plan? • What tests and evaluation should be performed? • What is the verification plan?
Production	Craft Production Plans • What is the target production rate? • To what extent will low rate initial production be utilized? • What is the ramp up plan? • What production process will be used? • Who will produce the system? • Where will the system be produced?
Operation, Support	Generate Maintenance Approach • What is the logistics concept? • What is the preventive maintenance plan? • What is the corrective maintenance plan? • What is the spare parts plan?

Decision Process Context

A formal decision management process is the transformation of a broadly stated decision situation into a recommended course of action and associated implementation plan. The process is executed by a resourced decision team that consists of a decision maker with full responsibility, authority, and accountability for the decision at hand, a decision analyst with a suite of reasoning tools, subject matter experts with performance models, and a representative set of end users and other stakeholders (Parnell G. S., Bresnick, Tani, & Johnson, 2013). The decision process is executed within the policy and guidelines established by the sponsoring agent. The formal decision management process realizes this transformation through a structured set of activities described in the balance of this paper. Note the process presented here does not replace the engineering models, performance models, operational models, cost models, and expert opinion prevalent in many enterprises but rather complements such tools by synthesizing their outputs in a way that helps decision makers thoroughly compare relative merits of each alternative in the presence of competing objectives and uncertainty. (Buede, 2009; Parnell, G. S., Driscoll, P. J., and Henderson D. L., 2011)

Inputs

Inputs to the decision management process are often little more than broad statements of the decision situation. As such, systems engineers should not expect to receive a well-structured problem statement as input to the decision management process. In addition, the inputs usually include models and simulations, test results, and operational data.

Outputs

The ultimate output of the decision management process should be a recommended course of action and associated implementation plan provided in the form of a high quality decision report. The decision report should communicate key findings through effective trade space visualizations underpinned by defendable rationale grounded in analysis results that are repeatable and traceable. As decision makers seek to understand root causes of top level observations and build their own understanding of the tradeoffs, the ability to rapidly drill down from top level trade-space visualizations into lower level analyses and data supporting the synthesized view is often beneficial.

Process Activities

The decision analysis process can be decomposed into ten process steps: (i) frame decision and tailor process, (ii) develop objectives and measures, (iii) generate creative alternatives, (iv) assess alternatives via deterministic analysis, (v) synthesize results, (vi) identify uncertainty and conduct probabilistic analysis,(vii) assess impact of uncertainty, (viii) improve alternatives, (ix) communicate tradeoffs, (x) present recommendation and implementation plan. The process used for each decision can be tailored to the decision situation.

Process Activities Elaboration

The decision analysis process is depicted in Figure 1 below. The decision management approach is based on several best practices:

A. Align the decision process with the systems engineering process.
B. Use sound mathematical technique of decision analysis for trade off studies. Parnell (2009) provided a list of decision analysis concepts and techniques.
C. Develop one master decision model and refine, update, and use it as required for tradeoff studies throughout the system development life cycle (Parnell et al, 2013).
D. Use Value-Focused Thinking (Keeney, 1992) to create better alternatives
E. Identify uncertainty and assess risks for each decision (Parnell et al., 2013).

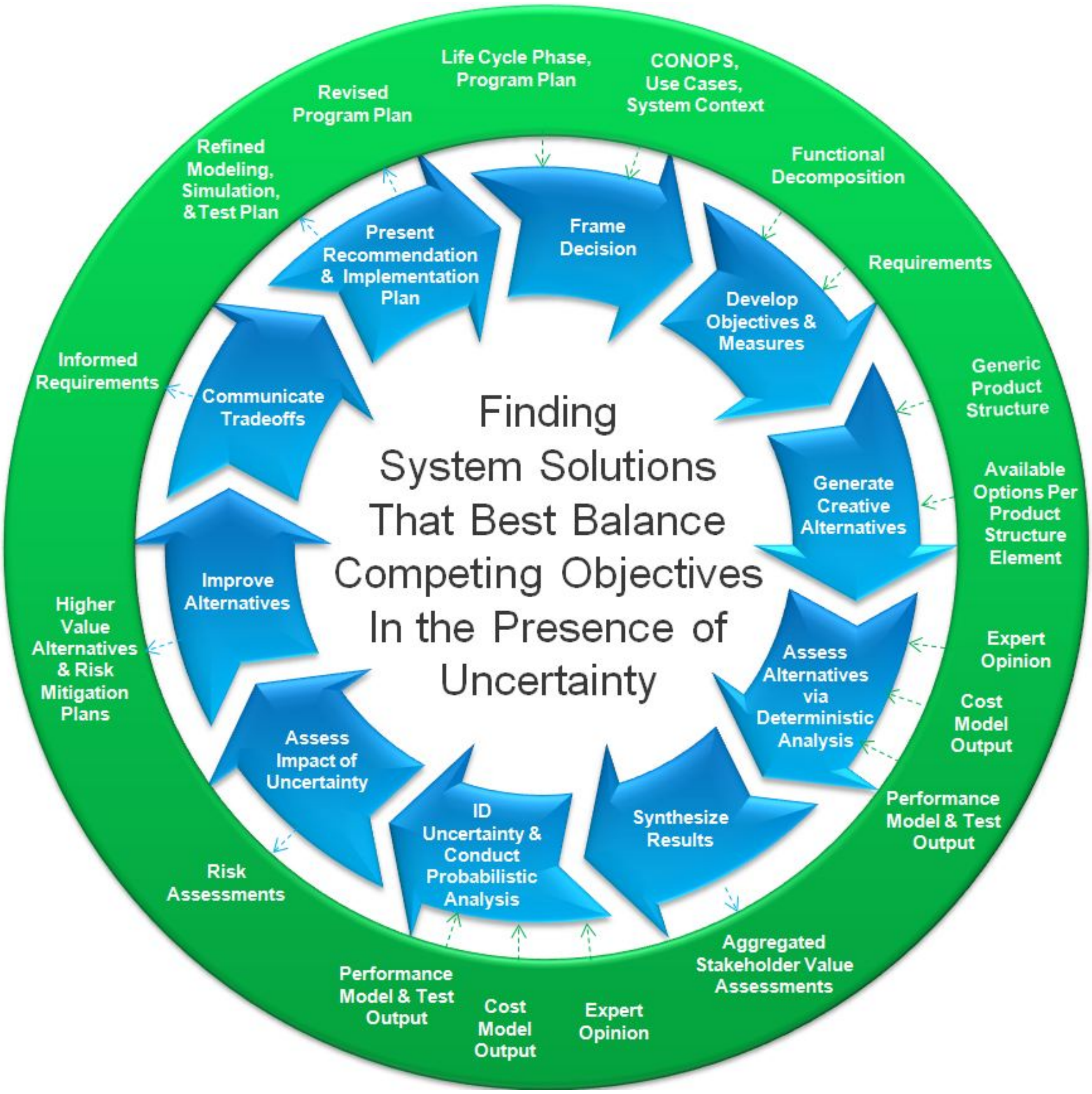

Figure 1: Decision Management Process Map

The white text within the outer green ring identifies elements of a systems engineering process while the ten blue arrows represent the ten steps of the Decision Management Process. Interaction between the systems engineering process and the Decision Management Process are represented by the small, dotted green or blue arrows. Note these interactions are not explicitly addressed here but are the subject of a future paper.

The focus of the process is to find system solutions that best balance competing objectives in the presence of uncertainty as shown in the center of the figure. This single focus is important as it can be argued that all systems engineering activities should be conducted within the context of supporting good decision making. If a systems engineering activity cannot point to at least one of the many decisions embedded in a systems lifecycle, one must wonder why the activity is being conducted at all. Positioning decision management as central to systems engineering activity will ensure the efforts are rightfully interpreted as relevant and meaningful and thus maximize the discipline’s value proposition to new product developers and their leadership.

The decision analysis process is an iterative process with an openness to change and adapts as understanding of the decision and the trade-space emerges with each activity. The circular shape of the process map is meant to convey the notion of an iterative process with significant interaction between the process steps. The feedback loops seek to capture new information regarding the decision task at any point in the decision process and make appropriate adjustments.

Framing Decision & Tailoring Process

The first step of the decision management process is to frame the decision and to tailor the decision process. To help ensure the decision makers and stakeholders fully understand the decision context and to enhance the overall traceability of the decision, the systems engineer should capture a description of the system baseline as well as a notion for how the envisioned system will be used along with system boundaries and anticipated interfaces. Decision context includes such details as the timeframe allotted for the decisions, an explicit list of decision makers and stakeholders, available resources, and expectations regarding the type of action to be taken as a result of the decision at hand as well as decisions anticipated in the future. (Edwards et al. 2007) The best practice is to identify a decision problem statement that defines the decision in terms of the system life cycle. Next, three categories of decisions should be listed: decisions that have been made, decisions to be made now, and subsequent decisions that can be made later in the life cycle. Effort is then focused on the decisions to be made now.

Once the decision at hand is sufficiently framed, systems engineers must select the analytical approach that best fits the frame and structure of the decision problem at hand. For deterministic problems, optimization models can explore the decision space. However, when there are “… clear, important, and discrete events that stand between the implementation of the alternatives and the eventual consequences…” (Edwards, Miles Jr., & Von Winterfeldt, 2007), a decision tree is a well suited analytical approach, especially when the decision structure has only a few decision nodes and chance nodes. As the number of decision nodes and chance nodes grow, the decision tree quickly becomes unwieldy and loses some of its communicative power. However, decision trees and many optimization models require consequences be expressed in terms of a single number. This is commonly accomplished for decision situations where the potential consequences of alternatives can be readily monetized and end state consequences can be expressed in dollars, euros, yen, etc. When the potential consequences of alternatives within a decision problem cannot be easily monetized, an objective function can often be formulated to synthesize an alternative’s response across multiple, often competing, objectives. A best practice for type of problem it the multiple objective decision analysis (MODA) approach.

The decision management method most commonly employed by systems engineers is the trade study, and more often than not employ some form of MODA approach. The aim is to define, measure, and assess shareholder and stakeholder value and then synthesize this information to facilitate the decision maker’s search for an alternative that represents the optimally balanced response to often competing objectives. Major system projects often generate large amounts of data from many separate analyses performed at the system, subsystem, component, or technology level by different organizations. Each analysis, however, only delivers one dimension of the decision at hand, one piece of the puzzle that the decision makers are trying to assemble. These analyses may have varying assumptions, and may be reported as standalone documents, from which decision makers must somehow aggregate system level data for all alternatives across all dimensions of the trade space in his or her head. This would prove to be an ill-fated task as all decision makers and stakeholders have cognitive limits that preclude them from successfully processing this amount of information in their short term memory (Miller 1956). When faced with a deluge of information that exceeds human cognitive limits, decision makers may be tempted to oversimplify the trade space by drastically truncating objectives and/or reducing the set of alternatives under consideration but such oversimplification runs a high risk of generating decisions that lead to poor outcomes.

By providing techniques to decompose a trade decision into logical segments and then synthesize the parts into a coherent whole, a formal decision management process offers an approach that allows the decision makers to work within human cognitive limits without oversimplifying the problem. In addition, by decomposing the overall decision problem into smaller elements, experts can provide assessments of alternatives as they perform within the objective associated with their area of expertise. Buede and Choisser put it this way,

> *These component parts can be subdivided as finely as needed so that the total expertise of the system design team can be focused, in turn, on specific, well-defined issues. The analyses on the component parts can then be combined appropriately to achieve overall results that the decision makers can use confidently. The benefits to the decision maker of using this approach include increased objectivity, less risk of overlooking significant factors and, perhaps most importantly, the ability to reconstruct the selection process in explaining the system recommendation to others. Intuition is not easily reproducible. (Buede & Choisser 1992)*

MODA approaches generally differ in the techniques used to elicit values from stakeholders, the use of screening techniques, the degree to which an alternative's response to objectives (and sub-objectives) are aggregated, the mathematics used to aggregate such responses, the treatment of uncertainty, the robustness of sensitivity analyses, the search for improved alternatives, and the versatility and quality of trade space visualization outputs. If time and funding allow, systems engineers may want to conduct tradeoff studies using several techniques, compare and contrast results, and reconcile any differences to ensure findings are robust. Although there are many possible ways to specifically implement MODA, the discussion contained in the balance of this paper represents a short summary of best practices. An anticipated future paper will apply various MODA approaches to a detailed case study in order to illustrate strengths, weaknesses, and limitations of each approach as well as to identify potential synergies across approaches.

Developing Objectives & Measures

Defining how a decision will be made may seem straightforward, but often becomes an arduous task of seeking clarity amidst a large number of ambiguous stakeholder need statements. The first step is to use the information obtained from the Stakeholder Requirements Definition Process, Requirements Analysis Process, and Requirements Management Processes to develop objectives and measures. If these processes have not been started, then stakeholder analysis is required. Often this begins with reading documentation on the decision topic followed by a visit to as many decision makers and stakeholders as reasonable and facilitating discussion about the decision problem. This is best done with interviews and focus groups with subject matter experts and stakeholders.

For systems engineering trade-off analyses, top-level stakeholder value often includes competing objectives of performance, development schedule, development cost, unit cost, support costs, and long term viability. For corporate decisions, shareholder value would be added to this list. With the top level objectives set, lower levels of objective hierarchy should be discovered. For performance related objectives, it is often helpful to work through a functional decomposition (usually done as part of the requirements and architectural design processes) of the system of interest to generate a thorough set of potential objectives. Start by identifying inputs and outputs of the system of interest and craft a succinct top level functional statement about what the system of interest does, identifying the action performed by the system of interest to transform the inputs into outputs. Test this initial list of fundamental objectives for key properties by checking that each fundamental objective is essential and controllable and that the set of fundamental objectives is complete, non-redundant, concise, specific, and understandable. (Edwards et al. 2007) Beyond these best practices, the creation of fundamental objectives is as much an art as it is a science. This part of the decision analysis process clearly involves subjectivity. It is important to note however, that a subjective process is not synonymous with an arbitrary or capricious process. As Keeney points out,

> *Subjective aspects are a critical part of decisions. Defining what the decision is and coming up with a list of objectives, based on one's values, and a set of alternatives are by nature subjective processes. You cannot think about a decision, let alone analyze one, without addressing these elements. Hence, one cannot even think about a decision without incorporating subjective aspects (Keeney 2004)*

The output of this process step takes on the form of a fundamental objectives hierarchy as illustrated in Figure 2.

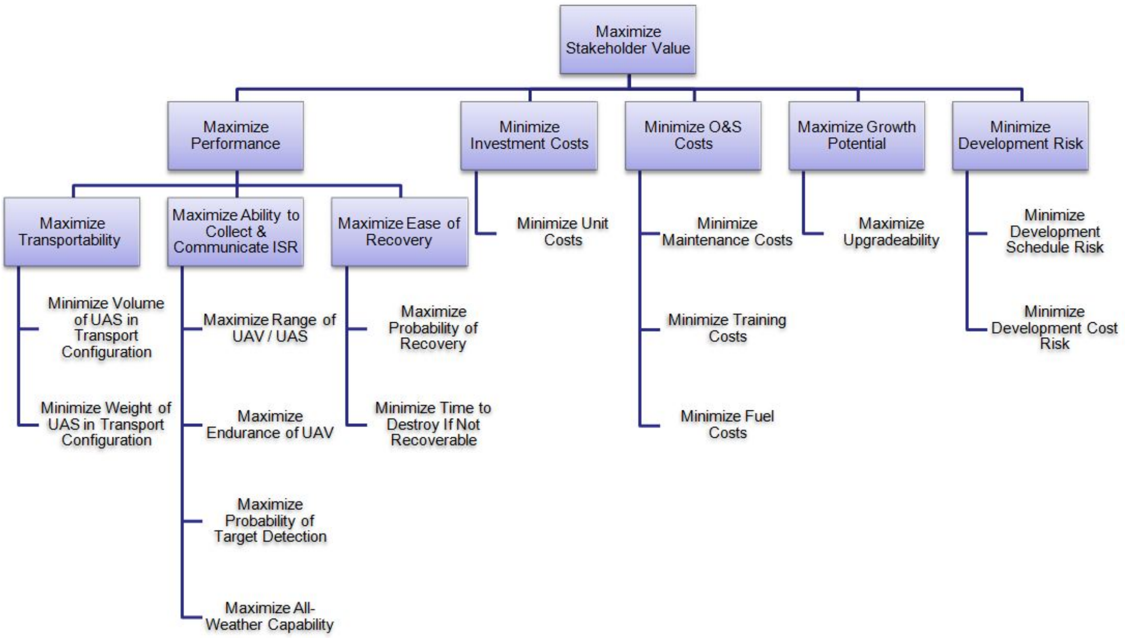

Figure 2: Example of a Fundamental Objectives Hierarchy for a Hypothetical UAV Decision

For each fundamental objective, a measure must be established so that alternatives that more fully satisfy the objective receive a better score on the measure than those alternatives that satisfy the objective to a lesser degree. A measure (also known as attribute, criterion, and metric) must be unambiguous, comprehensive, direct, operational, and understandable. (Keeney & Gregory 2005)

A defining feature of Multiobjective Decision Analysis (also called multiattribute value theory) is the transformation from measure space to value space that enables mathematical representation of a composite value score across multiple measures. This transformation is performed through the use of a value function. Value functions describe returns to scale on the measure. When creating a value function, one must ascertain the walk-away point on the objective measure scale (x-axis) and map it to 0 value on the value scale (y-axis). A walk-away point is defined as the measure score where regardless of how well an alternative performs in other measures; the decision maker will walk away from the alternative. Working with the user, find the measure score beyond which an alternative provides no additional value, label it "stretch goal" (also called ideal) and map it to 100 (1 and 10 are also common scales) on the value scale (y-axis). If the returns to scale are linear, connect the walk-away value point to the stretch goal value point with a straight line. If there is reason to believe stakeholder value behaves with non-linear returns to scale, pick appropriate inflection points and draw the curve. The rationale for the shape of the value functions should be documented for traceability and defensibility (Parnell et al, 2011). Figure 3 provides examples of some common value function shapes.

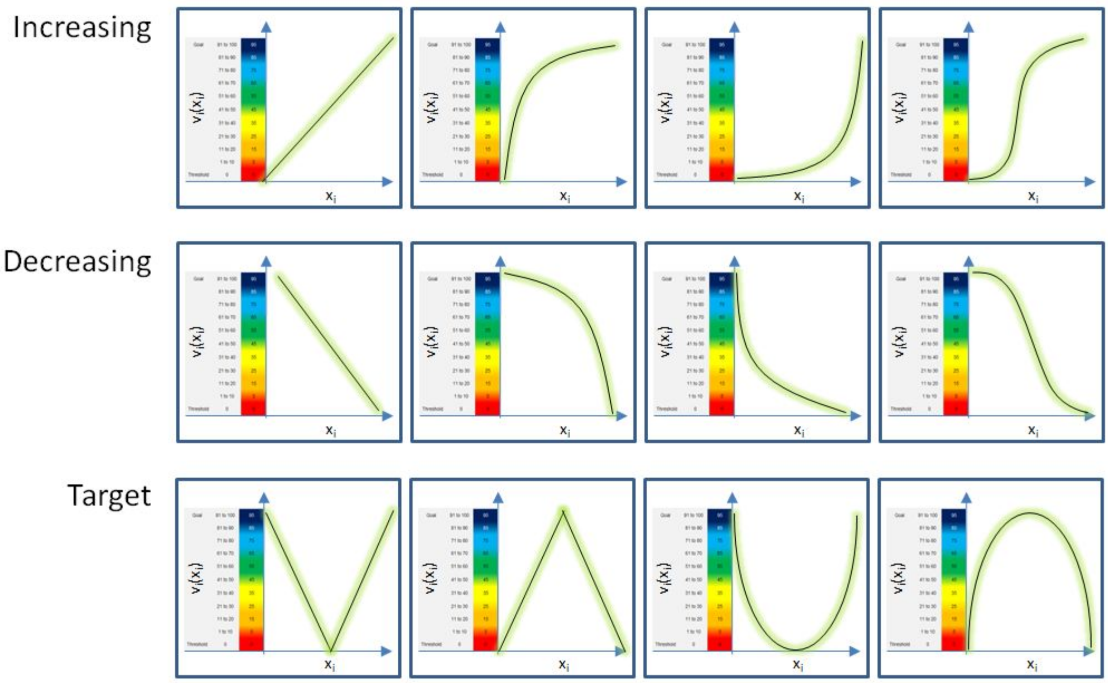

Figure 3: Value Function Examples

In an effort to capture the voice of the customer, system engineers will often ask a stakeholder focus group to prioritize their requirements. As Keeney puts it,

> *Most important decisions involve multiple objectives, and usually with multiple-objective decisions, you can't have it all. You will have to accept less achievement in terms of some objectives in order to achieve more on other objectives. But how much less would you accept to achieve how much more? (Keeney 2002)*

The mathematics of Multiobjective Decision Analysis (MODA) requires that the weights depend on importance of the preferentially independent measure and the range of the measure (walk away to stretch goal or ideal). A useful tool for determining weightings is the swing weight matrix. For each measure, consider its importance by determining if the measure corresponds to a defining capability, a critical capability, or an enabling capability and also consider the variation measure range by considering the gap between the current capability and the desired capability and put the name of the measure in the appropriate cell of the matrix. Swing weights are then assigned to each measure according to the required relationship rules described in Figure 4. Swing weights are then converted to measure weights by normalizing such that the set sums to one. (Parnell et al, 2011) For the purposes of swing weight matrix use, consider a defining capability to be one that directly traces to a verb/noun pair identified in the top level (level 0) functional definition of the system of interest – the reason the system exists. Consider enabling capabilities to trace to functions that are clearly not the reason the system exists but somehow allow the core functions to be executed more fully. Let critical capabilities be those that are more than enabling but not quite defining.

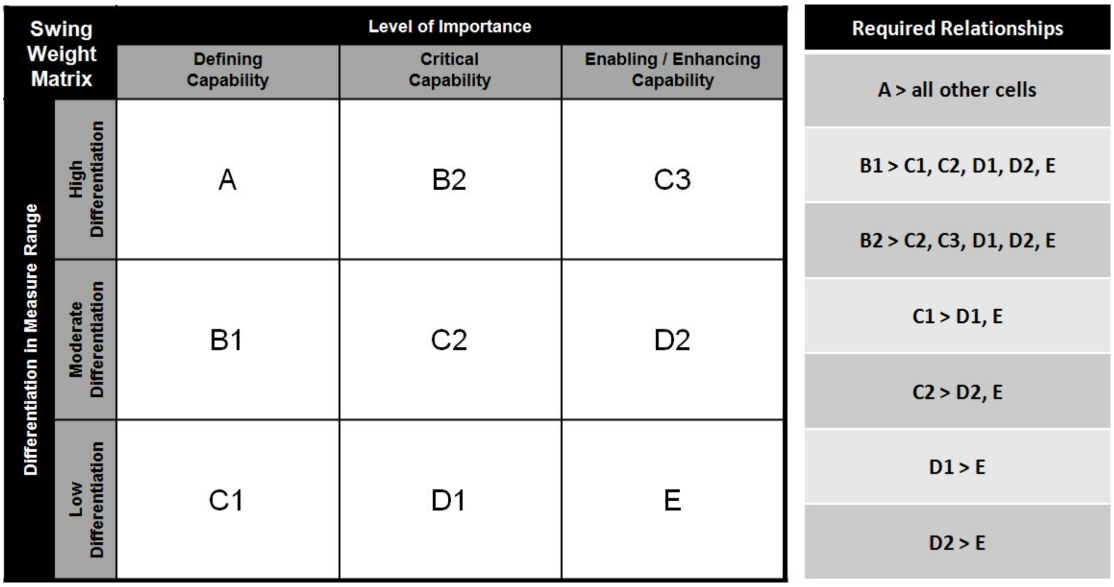

Figure 4: Swing Weight Matrix

Generating Creative Alternatives

For many trade studies, the alternatives will be systems composed of many interrelated subsystems. It is important to establish a meaningful product structure for the system of interest and to apply this product structure consistently throughout the decision analysis effort in order to aid effectiveness and efficiency of communications about alternatives. The product structure should be a useful decomposition of the physical elements of the system of interest.

Each alternative is composed of specific design choices for each product structure element. The ability to quickly communicate the differentiating design features of given alternatives is a core element of the decision making exercise. Figure 5 provides descriptions of fictitious small UAV alternatives as an example of efficient communication of differentiating design features. These subsystem design choices have system level consequences across the objectives hierarchy. Every subsystem design choice will impact system level cost, system level development schedule, and system level performance. It may be useful to think of design choices as the levers used by the system architect to steer the system design toward a solution that best satisfies the elements of shareholder and stakeholder value - the fundamental objectives hierarchy. These levers are very important and care should be given in this step of the process to clearly and completely identify specific design choices for each product structure element for every alternative being considered. Incomplete or ambiguous alternative descriptions can lead to incorrect or inconsistent alternative assessments in the process described in the next section. The ability to quickly and accurately communicate the differentiating design features of given alternatives is critical.

Subsystem	Cardinal	Buzzard	Crow	Pigeon	Robin	Dove
						
	Design Choice	Design Choice	Design Choice	Design Choice	Design Choice	Design Choice
Propulsion System	Electric 300W & Li P	Electric 300W w/ Li Ion	Electric 600W w/ Solar	Elect 600W w Fuel Cell	Piston Engine 2.5 HP	Piston Engine 4.0 HP
Fuel	NA	NA	NA	NA	JP-8	JP-8
Fuel Tank Capacity	NA	NA	NA	NA	5 liter	7 liter
Propeller	18" Rear	20" rear	22" rear	24" Front	26" Front	28" Front
Wing Configuration	5 ft, Conventional	6 ft, Canard	6 ft, Tandem Wing	7 ft, Three Surface	8 ft., Conventional	9 ft., Conventional
Fin Configuration	Twin Boom Conv.	Inverted V	V Tail	Conventional	H Tail	Cruciform
Actuators	Electromagnetic	Hydraulic	MEMS	Hydraulic	Hydraulic	Hydraulic
Fuselage X Section	12" Diameter	14" Diameter	16" Diameter	18" Diameter	20" Diameter	22" Diameter
Airframe Material	Graphite Epoxy	Graphite Epoxy	Aramid-epoxy	Boron-epoxy	Fiberglass-epoxy	Fiberglass-epoxy
Avionics Arch.	Simplex	Simplex	Triplex	Triplex	Triplex	Triplex
Navigation Sensor	MEMS GPS / INS	MEMS GPS / INS	MEMS GPS / INS	MEMS GPS / INS	MEMS GPS / INS	MEMS GPS / INS
External Comms	LOS COMM Link	LOS COMM Link	LOS + SATCOM Link	LOS + SATCOM Link	LOS + SATCOM Link	LOS + SATCOM Link
Internal Comms	MIL-STD-1553B	MIL-STD-1553B	MIL-STD-1553B	MIL-STD-1553B	MIL-STD-1553B	MIL-STD-1553B
Autopilot	Pre-Programmed, Auto	Semi-Autonomous	Remotely Piloted	Pre-Programmed, Auto	Pre-Programmed, Auto	Pre-Programmed, Auto
Launch / Recovery	Hand / Belly	Hand / Belly	Hand / Belly	Hand / Belly	Hand / Belly	Hand / Belly
Acquisition Sensor	Un-cooled IR	Day Video	Day Video, Cooled IR	Day Video, Cooled IR	Day Video	SAR, Acoustic, Day, IR
Sensor Actuation	Pan-tilt	Pan-tilt-roll	Roll-tilt	Pan-tilt	Pan tilt	Pan tilt
Characteristics	Measurement	Measurement	Measurement	Measurement	Measurement	Measurement
Weight	5 lbs	10 lbs	10 lbs	15 lbs	30 lbs	40 lbs
Max Airspeed	60 kph	50 kph	80 kph	70 kph	60 kph	80 kph
Climb Rate	200 m / minute	150 m / minute	250 m / minute	200 m / minute	200 m / minute	250 m / minute

Figure 5: Description of Alternatives Example

Assessing Alternatives via Deterministic Analysis

With objectives and measures established and alternatives identified and defined, the decision team should engage subject matter experts, ideally equipped with operational data, test data, models, simulation and expert knowledge. The decision team can best prepare for subject matter expert engagement by creating structured scoring sheets. Assessments of each concept against each criterion are best captured on separate structured scoring sheets for each alternative/measure combination. Each score sheet contains a summary description of the alternative under examination and a summary of the scoring criteria to which it is being measured. The structured scoring sheet should contain ample room for the evaluator to document the assessed score for the particular concept against the measure followed by clear discussion providing the rationale for the score, noting how design features of the concept under evaluation led to the score as described in the rating criteria. Whenever possible, references to operational data, test data, calculations, models, simulations, analogies, or experience that led to a particular score should be documented.

After all the structured scoring sheets have been completed for each alternative/measure combination, it is useful to summarize all the data in tabular form. Each column in such a table would represent a measure and each row would represent a particular alternative. Figure 6 provides a sample structure of such a table, identified here as a consequences scorecard. Note the table itself includes notional results for the fictitious small UAV alternatives introduced in the previous section.

Raw Scorecard (expected pefromance values)			RELOCATE UAV		EMPLOY UAV				RECOVER UAV		GROWTH POT.	UNIT COST	DEVELOPMENT RISK		OPERATION & SUPPORT COST		
			Minimize UAV weight	Minimize UAV volume	Maximize all weather capability	Maximize UAV range	Maximize UAV probability of detection	Maximize UAV endurance	Maximize probability of recovery	Minimize time to destroy if not recoverable	Maximize upgradability	Minimize unit cost	Minimize development schedule risk	Minimize development cost risk	Minimize training cost	Minimize maintenance cost	Minimize fuel cost
ID	Name	Image	(lbs)	ft3	index	km	P[D]	hours	P[R]	sec	index	FY13$K	index	index	FY13$	FY13$	FY13$
1	Cardinal		5	12	3	10	0.92	0.5	0.6	1	0.3	250	0.9	0.9	300	300	0
2	Buzzard		10	15	1	10	0.9	1	0.7	2	0.6	300	0.8	0.8	300	300	0
3	Crow		10	20	3	70	0.92	1	0.8	2	0.6	350	0.7	0.7	300	300	0
4	Pigeon		15	30	3	80	0.92	1.5	0.9	2	0.6	400	0.6	0.6	300	300	0
5	Robin		30	40	1	90	0.9	2	0.9	2	0.6	500	0.5	0.5	500	500	300
6	Dove		40	50	5	100	0.94	2	0.9	3	0.9	700	0.4	0.4	500	500	500
7	Ideal		5	10	5	100	1	2	0.9	1	1	200	1	1	250	0	0

Figure 6: Example of Consequences Scorecard

Note that in addition to identified alternatives, the consequences scorecard includes a row for the ideal whose performance measure scores are those that meet the stretch goal for each objective. The ideal helps us to understand if we need to add new alternatives or new technologies to existing alternatives to get closer to the ideal and is an element of value-focused thinking covered later in this section.

Synthesizing Results

At this point in the process the decision team has generated a large amount of data as summarized in the consequences scorecard. Now it is time to explore the data and display results in a way that facilitates understanding. Transforming the data in the consequences scorecard into a value scorecard is accomplished through the use of the value functions developed in the decision analysis process step described above. In an effort to enhance speed and depth of comprehension of the value scorecard, consider associating increments on the value scale with a color according to heat map conventions as shown in Figure 7.

Heat-indexed Value Scorecard			RELOCATE UAV		EMPLOY UAV				RECOVER UAV		GROWTH POT.	UNIT COST	DEVELOPMENT RISK		OPERATION & SUPPORT COST		
			Minimize UAV weight	Minimize UAV volume	Maximize all weather capability	Maximize UAV range	Maximize UAV probability of detection	Maximize UAV endurance	Maximize probability of recovery	Minimize time to destroy if not recoverable	Maximize upgradability	Minimize unit cost	Minimize development schedule risk	Minimize development cost risk	Minimize training cost	Minimize maintenance cost	Minimize fuel cost
ID	Name	Image	0.06	0.11	0.14	0.28	0.14	0.23	0.03	0.01	1	1	0.5	0.5	0.33	0.33	0.33
1	Cardinal		100	97	90	13	59	1	47	100	31	94	83	83	83	85	100
2	Buzzard		86	92	1	13	42	60	77	90	61	88	67	67	83	85	100
3	Crow		86	85	90	83	59	60	90	75	61	82	50	50	83	85	100
4	Pigeon		72	57	90	90	59	80	100	75	61	76	34	34	83	85	100
5	Robin		29	29	1	95	42	100	100	60	61	56	18	18	17	67	51
6	Dove		1	1	100	100	75	100	100	1	91	1	1	1	17	67	18
7	Ideal		100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Figure 7: Example of a Value Scorecard with Heat Map

This view can be useful when trying to determine which objectives are causing a particular alternative trouble. In addition, one can use this view to quickly see if there are objectives for which no alternative scores well. From this view, the systems engineer can also see if there is at least one alternative that scores above the walk-away point for all objectives. If not, the solution set is empty and the decision team needs to generate additional alternatives or adjust objective measures.

Beyond the consequence scores for each alternative on each measure, all that was needed to construct the visualizations covered in Figure 7 were the value functions associated with each objective. Introducing the weighting scheme, the systems engineer can create aggregated value visualizations. The first step in assessing an alternative's aggregated value is a prescreen for alternatives that fail to meet a walk-away point for any objective measure and set that alternative's aggregated value to zero regardless of how it performance on other objective measures. For those alternatives that pass the walk-away prescreen, the additive value model[1] uses the following equation to calculate each alternative's aggregated value:

$$v(x) = \sum_{i=1}^{n} w_i v_i(x_i)$$

where
$v(x)$ is the alternative's value,
$i = 1$ to n is the number of the measure,
x_i is the alternative's score on the i^{th} measure,
$v_i(x_i)$ = is the single dimensional value of a score of x_i,
w_i is the weight of the i^{th} measure,

$$\sum_{i=1}^{n} w_i = 1$$

and (all weights sum to one).

One such aggregated visualization is the value component graph as shown in Figure 8. In a value component graph, each alternative's total value is represented by the total length of a segmented bar. Each bar segment represents the contribution of the value earned by the alternative of interest within a given measure by the weighted value (Parnell et al. 2011).

[1] The additive model assumes preferential independence. See Keeney & Raiffa, 1976, and Kirkwood, 1997 for additional models.

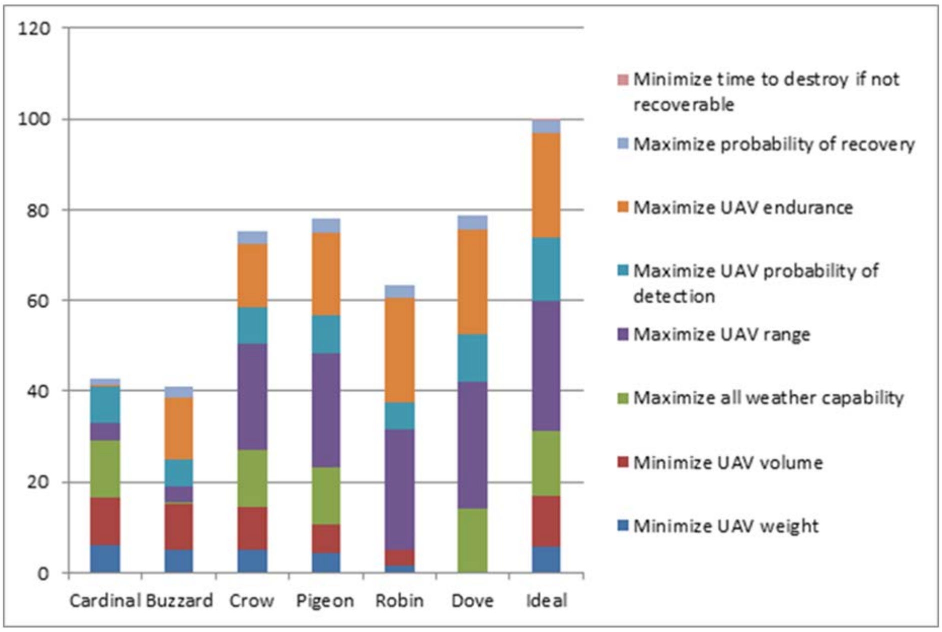

Figure 8: Value Component Graph

The heart of a decision support process for systems engineering trade analysis is the ability to integrate otherwise separate analyses into a coherent, system level view that traces consequences of design decisions across all dimensions of stakeholder value. The stakeholder value scatterplot shows in one chart how all system level alternatives respond in multiple dimensions of stakeholder value.

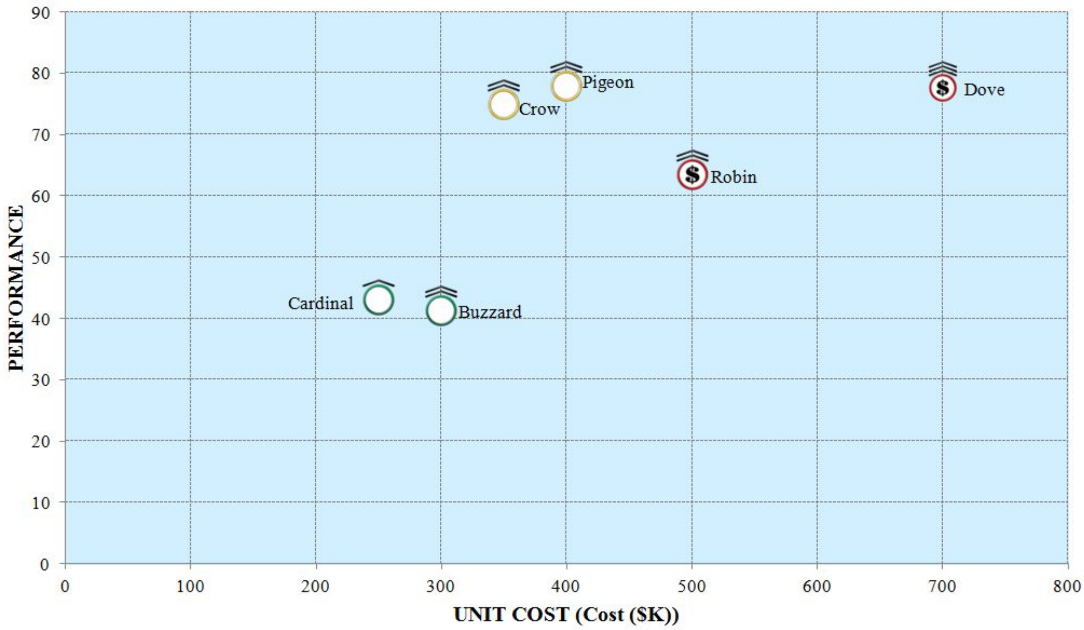

Figure 9: Example of a Stakeholder Value Scatterplot

Figure 9 is an example of a stakeholder value scatterplot, showing how the six hypothetical UAV alternatives respond to five dimensions of stakeholder value - unit cost, performance, development schedule, growth potential, and operation and support costs. Each system alternative is represented by a scatterplot marker. An alternative's unit cost and performance value are indicated by a marker's x and y position respectively. An alternative's development risk is indicated by the color of the circle (green-low, yellow-medium, red-high) while the degree of growth potential for a particular alternative is shown as the number of hats above the circular marker (1 hat – low growth, 2 hats – moderate growth, 3 hats – high growth). Figure 9 depicts an alternative with high operating and support (O&S) costs with a red dollar sign appearing inside the marker. An alternative with moderate or low O&S costs would appear with a black dollar sign or no dollar sign respectively.

Identifying Uncertainty & Conducting Probabilistic Analysis

As part of the assessment, it is important for the subject matter expert to explicitly discuss potential uncertainty surrounding the assessed score and variables that could impact one or more scores. One source of uncertainty that is common within system engineering trade off analyses that explore various system architectures is technology immaturity. System design concepts are generally described as a collection of subsystem design choices but if some of the design choices include technologies that are immature, there may be lack of detail associated with component level design decisions that will eventually be made downstream during detailed design. Many times the subject matter expert can assess an upper, nominal, and lower bound measure response by making three separate assessments 1) assuming a low performance, 2) assuming moderate performance, and 3) assuming high performance. Once the uncertainties have been assessed, Monte Carlo Simulations can be executed to identify the uncertainties that impact the decision findings and of the uncertainties that are inconsequential to decision findings.

Accessing Impact of Uncertainty - Analyzing Risk and Sensitivity

Decision analysis uses many forms of sensitivity analysis including line diagrams, tornado diagrams, waterfall diagrams and several uncertainty analyses including Monte Carlo Simulation, decision trees, and influence diagrams (Parnell et al., 2013). Due to space limits, only line diagrams of sensitivity to weighting will be discussed in this paper. Anticipated future papers will discuss potential innovations in the area of sensitivity analysis using Monte Carlo simulations.

Many decision makers will want to understand how sensitive a particular recommendation is to weightings and will ask questions regarding the degree to which a particular weighting would need to be changed in order to change in recommended alternative. A common approach to visualizing the impact of measure weighting on overall value is by sweeping each measure's weighting from absolute minimum to absolute maximum while holding the relative relationship between the other measure weightings constant and noting changes to overall score. The output of this type of sensitivity analysis is in the form of a line graph (Parnell et al. 2011). An example of such a graph for the hypothetical UAV example for the UAV Range measure is provided in Figure 10 below. Note this particular example shows how sweeping the weight associated with the UAV Range impacts performance value. The yellow vertical line in Figure 10 indicates the weight of the UAV Range as determined in earlier steps in the process. In this case, the best alternative sensitive to the weight assessed for UAV range. The graph in this example shows the alternatives with the highest performance value were Dove and Pigeon and as the weight of the UAV Range is increased, Dove emerges as the high performer and as UAV Range measure range is decreased, Pigeon is shown to be the alternative with the highest performance value. From this graph, a decision maker can see the differentiation in Pigeon's and Dove's performance value is not large, regardless of UAV range weight.

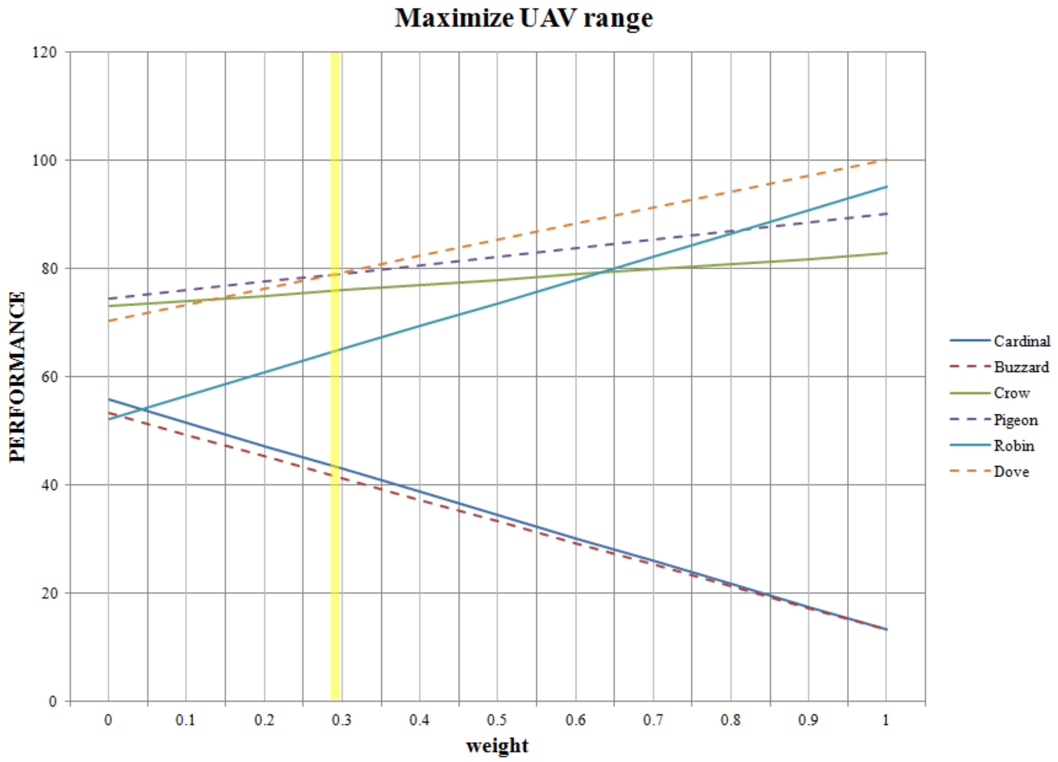

Figure 10: Weight Sweep Line Graph for Hypothetical UAV Example

Improving Alternatives

One could be tempted to end the decision analysis here, highlight the alternative that has the highest total value and claim success. Such a premature ending however, would not be considered best practice. Mining the data generated for the first set of alternatives will likely reveal opportunities to modify some subsystem design choices to claim untapped value and reduce risk. Recall the cyclic decision analysis process map and the implied feedback. Taking advantage of this feedback loop and using initial findings to generate new and creative alternatives starts the process of transforming the decision process from "Alternative-Focused Thinking" to "Value-Focused Thinking" (Keeney 1992). To complete the transformation from alternative-focused thinking to value-focused thinking, consider taking additional steps to spark focused creativity to overcome anchoring biases. As Keeney warns,

> *Once a few alternatives are stated, they serve to anchor thinking about others. Assumptions implicit in the identified alternatives are accepted, and the generation of new alternatives, if it occurs at all, tends to be limited to a tweaking of the alternatives already identified. Truly creative or different alternatives remain hidden in another part of the mind, unreachable by mere tweaking. Deep and persistent thought is required to jar them into consciousness. (Keeney 1993)*

To help generate a creative and comprehensive set of alternatives, consider conducting an alternative generation table (also called a morphological box) (Buede, 2009; Parnell et al. 2011) analysis to generate new alternatives.

Communicating Tradeoffs

This is the point in the process where the decision team identifies key observations regarding what stakeholders seem to want and what they must be willing to give up in order achieve it. It is here where the decision team can highlight the design decisions that most influence shareholder and stakeholder value and which are inconsequential. In addition, the important uncertainties and risks should also be identified. Observations regarding combination effects of various design decisions are also important products of this process step. Competing objectives that are driving the trade should be explicitly highlighted as well.

Presenting Recommendations & Implementing Action Plan

It is often helpful to describe the recommendation in the form of clearly worded, actionable task list to increase the likelihood of the decision analysis leading to some form of action, thus delivering some tangible value to the sponsor. Reports are important for historical traceability and future decisions. Take the time and effort to create a comprehensive, high quality report detailing study findings and supporting rationale. Consider static paper reports augmented with dynamic hyper-linked e-reports.

Conclusions

The process discussed in this paper integrates decision analysis best practices with systems engineering activities to create a baseline from which future papers can explore possible innovations to further enhance tradeoff study quality. The process enables enterprises to develop an in-depth understanding of the complex relationship between requirements, the design choices made to address each requirement, and the system level consequences of the sum of design choices across the full set of performance requirements as well as other elements of stakeholder value to include cost and schedule. Through data visualization techniques, decision makers can quickly understand and crisply communicate a complex trade-space and converge on recommendations that are robust in the presence of uncertainty.

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Biography

Matthew Cilli is a Systems Engineering Ph. D candidate at Stevens Institute of Technology in Hoboken, NJ and leads an analytics group at the U.S. Army's Armament Research Development and Engineering Center (ARDEC) in Picatinny, NJ. Mr. Cilli graduated from Villanova University, Villanova, Pennsylvania with a Bachelor of Electrical Engineering and a Minor in Mathematics in May 1989. He is also a graduate of the Polytechnic University, Brooklyn, NY with a Master of Science - Electrical Engineering received in January 1992 and in May 1998 graduated from the University of Pennsylvania, Wharton Business School, Philadelphia, PA with a Masters of Technology Management.

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