Using the Swing Weight Matrix to Weight Multiple Objectives

Gregory S. Parnell, Ph.D.
Department of Systems Engineering
United States Military Academy
West Point, NY 10996
914-720-3989
gregory.parnell@usma.edu
and
Innovative Decisions, Inc
gparnell@innovativedecisions.com

Timothy E. Trainor, Ph.D.
Department of Systems Engineering
United States Military Academy
West Point, New York 10996
845-938-5534
timothy.trainor@usma.edu

Abstract. Multiobjective decision analysis is used for trade studies and the evaluation of alternative system and architecture designs. Attributes are identified to measure the achievement of each objective. Value (or utility) models are mathematical equations that assess the value (or utility) of a score on an attribute and relative weight of each attribute. One of the challenging concepts is that weights depend on both importance and variation of the range of the attribute. Many analysts, not familiar with the mathematical theory, assess weights using only importance. Several years ago, we developed the swing weight matrix to properly assess weights by explicitly defining importance and variation. A second motivation was to provide a tool for communication with stakeholders and decision makers. This paper presents the swing weight matrix theory, the approaches used to define importance and variation, and some illustrative applications. We conclude with the challenges, improvements, and benefits of the swing weight matrix.

Introduction

Complexity in System Design. Systems are designed to meet the future needs of stakeholders including owners, users, and consumers of products and services. Typically, as the complexity of the system (or system of systems or enterprise) increases, systems engineers must involve more stakeholders, define more system interfaces, consider more system constraints, and identify more requirements. Furthermore, since systems must be designed to consider future needs, the uncertainty of the future system environment and the potential risks of changing interfaces, new requirements, and system failures contribute to the increase in system design complexity.

Multiple, Conflicting Objectives. As a general rule, as the number and diversity of stakeholders increase, the number of objectives increases. As a result of the increased stakeholders and increased complexity, the number of conflicting objectives that systems engineers must identity and measure to assess the potential future performance increases.

Design Trade-off Studies and System Decisions. After identification of systems needs and quantification of system performance, one of the most important roles of systems engineers is to evaluate design trade-offs. As system complexity increases, it becomes more challenging to assess potential designs and perform trade studies that provide fact based information on multiple objectives to support system decision making.

Multiobjective Decision Analysis. Systems engineers use operations research methods to assess and improve the performance of potential system designs. Among the operations research techniques, multiobjective decision analysis is a technique that focuses directly on complex decisions, multiple objectives, and uncertainty (Keeney and Raiffa, 1976, Kirkwood, 1997). Since systems design involves complex alternatives, multiple objectives, and uncertainty, decision analysis is a commonly used technique for system decision making (Buede, 2000 and Parnell, Driscoll & Henderson, 2008).

Additive Value Model. Multiobjective decision analysis uses many mathematical equations to evaluate alternatives. While many value (or utility) models have been developed in the literature, the additive value model is the most commonly used model is multiobjective decision analysis (Kirkwood, 1997 and Parnell, 2007). The following equation is used to calculate each alternative's value:

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

where

$v(x)$ is the alternative's value

$i = 1$ to n is the number of the value measure (attribute)

x_i is the alternative's score on the i^{th} value 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} value measure

and $\sum_{i=1}^{n} w_i = 1$ (all weights sum to one)

The additive value model quantitatively assesses the trade-offs between objectives by evaluating the alternative's contribution to the value measures (a score converted to value by single-dimensional value functions[1]) and the relative importance of each value measure (weight). Each value function, $v_i(x_i)$, measures returns to scale on the range of the value measure and converts a score (x_i) to a value. Weights play a key role in the additive value model. The weights quantify the trade-offs between value measures that assess the achievement of objectives. The weights are normalized to sum to 1. Since our values do not depend on the alternative, the additive value model has no index for the alternatives and we use Equation 1 to evaluate every alternative.

[1] Utility functions measure returns to scale and risk preference (Kirkwood, 1997)

Paper Overview. While multiobjective decision analysis with the additive value model has been used over 40 years, one of the most challenging concepts to explain to students and professional engineers is that the weights depend on both importance and variation. Many individuals, not familiar with the mathematical theory, assess weights using only importance. Several years ago, we developed the swing weight matrix to properly assess swing weights. A second motivation was to provide a tool for communication with stakeholders and decision makers. This paper describes the theory, practice, challenges, and benefits of the swing weight matrix.

Swing Weights versus Importance Weights

This section provides a brief introduction to swing weights and describes some common techniques.

Importance Weights. Importance weights are assigned to measures independent of the variation of the measure range. The question asked is: how much do you prefer measure i to measure j? Unfortunately, this is an inadequately defined question and there is no mathematical definition of importance weights.

Swing Weights. Swing weights are assigned to value measures based on importance and variation of the scales of the value measures. We assess swing weights by "swinging" the value measure from its worst to its best level. If we hold constant all other measure ranges and reduce the range of one of the measure scales, the measure's relative weight decreases, and the weight assigned to the others increases since the weights add to 1. Swing weights have a sound mathematical foundation derived directly from the additive value model equation (Kirkwood, 1997). The following quotes from the decision analysis literature emphasize the importance of using swing weights instead of importance weights**.**

- Observe that when you are asked to compare (two subsets of measures) T to S you are essentially asked this question: "Suppose the x profile were at the worst case … and that you had the option of improving some … from the worst to the best position. Would you rather improve the levels of the attributes in the subset T or Subset S?"… (Keeney and Raiffa, 1976)
- The correct concept of value weight is the swing weight, in which the decision-maker is explicitly comparing the swing in value (worst to best) of the attributes in question… (Watson and Buede, 1987)
- Within each objective category we asked Mr. Smith to allocate 100 points to represent the relative values of moving the attributes from their minimum acceptable levels to their maximum desirable levels… (Keeney, 1992)
- But the Simple Multiattribute Rating Technique)(SMART) ignores the fact that the range as well as importance must be reflected in any weight…Obviously the degree of importance of an attribute depends on its spread; that dependence was ignored in SMART weight elicitation. This error is the reason why SMART is not intellectually acceptable… (Edwards and Barron, 1994)
- (The analyst) must take into consideration the ranges of the attributes…Paying attention to the ranges in attributes in assigning weights is crucial…to often we are tempted to assign weights on the basis of vague claims that Attribute A (or its underlying objective) is worth three times as much as Attribute B… (Clemen,1996)
- Some experimentation with different ranges will quickly show that it is possible to change the rankings of the alternatives by changing the range that is used for each

evaluation measure. This does not seem reasonable. The solution is to ..(use swing weights)…(Kirkwood, 1997)

- It doesn't make sense to say that one objective is more important than another without considering the degree of variation among the consequences for the alternatives under consideration… (Hammond, Keeney and Raiffa, 1999)
- Weights depend on the importance and the range of the value measure scales. All other measure ranges being held constant, if we reduce the range of one of the measure scales, the relative weight of the measure is decreased and the weight assigned to the others increases… (Parnell, 2007)

Standard Swing Weight Methods. All of the authors listed above describe swing weight assessment techniques for individuals. Some common approaches include the value increment approach (Kirkwood, 1997), the balance beam method (Watson and Buede, 1987), and the Simple Multi-Attribute Rating Technique Exploiting Ranks (SMARTER) method (Edwards and Barron, 1994). Addition techniques can be found in decision analyst text books (e.g., Clemen, 1996). The value increment approach uses absolute pairwise judgments about value measures (e.g., the value increment of the best to worst outcome of measure 1 is 2.5 times the value increment of the best to worst outcome of measure 2) similar to the judgments used to develop value functions. The balance beam approach uses relative pairwise judgments about preferences between groups of value measures to develop swing weight inequalities and then uses limited value increment judgments to solve for a set of weights that satisfy the inequalities (Watson and Buede, 1987). The SMARTER method uses an ordinal ranking of value measures based on swings and then converts to cardinal normalized weights using the rank order centroid method (Edwards and Barron, 1994).

Most complex system design problems involve multiple stakeholders. Resource allocation is one common way to assess weights from a group of stakeholders. In this technique we use voting to obtain ordinal and then cardinal weights. After carefully explaining swing weighting, the procedure uses the following steps.

1. Vote. Have each individual spread 100 points over the value measures based on the measures' importance and range of variation in the measure scale.
2. Discuss significant differences. Have the "outliers" discuss their rationales.
3. Revote until the group agrees on the ordinal ranking of the value measures.
4. Vote again requiring each person's weights to follow the group's ordinal ranking of the value measures.
5. Average the weights (cardinal ranking of weights) and normalize so they sum to one.
6. Discuss significant differences. Have the "outliers" discuss their rationales.
7. Repeat steps 4-6 until the group agrees on the normalized cardinal weights.

If we can not resolve all disagreements about the weights, we record them. When we evaluate alternatives, we do a sensitivity analysis to determine if the disagreements are significant. Often, the preferred alternatives are not sensitive to the weight range of disagreement.

While the analyst can record comments as the weights are being assessed in individual or group swing weighting, none are these techniques explicitly capture the rationale for the weights assigned.

Why a New Swing Weight Method? Since several techniques exist, why do we need a new swing weight method? There are two reasons that motivated us to develop a new swing weight method. First, many analysts continue to use importance weights. In spite of very clear literature, practice does not always follow the literature. We have years of intuitive experience in thinking about importance. We have found that students say they understand swing weights and then return to intuitive importance weights when they assess the weights on measures that they think they understand. Second, none of the existing swing weight techniques (individual or group) explicitly document the rationale that was used to determine the weights. Large studies involve multiple stakeholders and many decision makers. Many times we need to justify for our weights to higher levels of management or senior review groups.

Swing Weight Matrix

This section describes the theory, mathematics, and history of the swing weight matrix.

Elements of the Swing Weight Matrix. The key concept of the swing weight matrix is to define what we mean in the decision context by the importance and range of variation for the value measures. The idea of the swing weight matrix is straightforward. A measure that is very important to the decision should be weighted higher than a measure that is less important. A measure that differentiates between alternatives, that is, a measure in which value measure ranges vary significantly, is weighted more than a measure that does not differentiate between alternatives. The first step is to create a matrix (Figure 1) in which the top defines the value measure importance and the left side represents the range of value measure variation. The levels of importance and variation should be thought of as constructed scales that have sufficient clarity to allow the stakeholders to uniquely place every value measure in one of the cells. A measure that is very important to the decision and has a large variation in its scale would go in the upper left of the matrix (cell labeled A).[2] A value measure that has low importance and has small variation in its scale goes in the lower right of the matrix (cell labeled E).

		Importance of the value measure to the decision		
		High	Medium	Low
Range of variation of the value measures	High	A	B2	C3
	Medium	B1	C2	D2
	Low	C1	D1	E

Figure 1. The elements of the swing weight matrix

Consistency Rules. Since many individuals may participate in the assessment of weights, it is important to insure consistency of the weights assigned. It is easy to understand that a very important measure with a high variation in its range (A) should be weighted more than a very

[2] Many people like to place very important, high variation in upper RH corner, or cell C3.

important measure with a medium variation in its range (B1). It is harder to trade off the weights between a very important measure with a low variation in its range (C1) and an important measure with a high variation in its range (B2). Weights should descend in magnitude as we move on the diagonal from the top left to the bottom right of the swing weight matrix. Multiple measures can be placed in the same cell with the same or different weights. If we let the letters represent the diagonals in the matrix A, B, C, D, and E; A is the highest weighted cell, B is the next highest weighted diagonal, then C, then D, and then E. For the swing weights in the cells in Figure 1 to be consistent, they need to meet the following relationships:

Any measure in cell A must be weighted greater than measures in all other cells.
Any measure in cell B1 must be weighted greater than measures in cells C1, C2, D1, D2, and E.
Any measure in cell B2 must be weighted greater than measures in cells C2, C3, D1, D2, and E.
Any measure in cell C1 must be weighted greater than measures in cells D1 and E.
Any measure in cell C2 must be weighted greater than measures in cells D1, D2, and E.
Any measure in cell C3 must be weighted greater than measures in cells D2 and E.
Any measure in cell D1 must be weighted greater than measures in cell E.
Any measure in cell D2 must be weighted greater than measures in cell E.
No other strict relationships hold.

If we denote i to be the label of the cell in the swing weight matrix and f_i to be the unnormalized swing weight of the value measures in each cell, then the following strict inequalities relationships of non-normalized swing weights must hold:

$f_A > f_i$ for all i in all other cells

$f_{B1} > f_{C1}, f_{C2}, f_{D1}, f_{D2}, f_E$

$f_{B2} > f_{C2}, f_{C3}, f_{D1}, f_{D2}, f_E$

$f_{C1} > f_{D1}, f_E$

$f_{C2} > f_{D1}, f_{D2}, f_E$

$f_{C3} > f_{D2}, f_E$

$f_{D1} > f_E$

$f_{D2} > f_E$

No other specific relationships hold.

Assessing Unnormalized Swing Weights. Once all the value measures are placed in the cells of the matrix, we can use any swing weight technique to obtain the unnormalized weights as long as we follow the consistency rules cited above. In assigning weights, the stakeholders need to assess their tradeoffs between level of importance and level of variation in measure scale. One approach would be to assign the measure in cell A (the upper left-hand corner cell) an arbitrary large unnormalized swing weight, for example, 100 ($f_A = 100$). Using the value increment approach (Kirkwood 1997), we could assess the weight of the lowest weighted measure in cell E (the lower right-hand corner) the appropriate swing weight, for example, 1. This means the swing weight of measure A is 100 times more than that of measure E. It is important to consider what the maximum in cell A should be. Common choices are 1000 and 100. Of course f_E can be other numbers besides 1. If we use 100 and 1, we have three orders of magnitude. If we use 1000 and 1 we have four orders of magnitude. Using a value increment approach, unnormalized swing weights can be assigned to all the other value measures relative to f_A by descending through the very important measures, then through the important measures, then through the less important measures.

Calculating Normalized Swing Weights. We can normalize the weights for the measures to sum to 1 using Equation 2.

$$w_i = \frac{f_i}{\sum_{i=1}^{n} f_i}, \qquad \text{Equation 2}$$

where f_i is the unnormalized swing weight assessed for the i^{th} value measure, i = 1 to n for the number of value measures, and w_i are the normalized swing weights from equation 1.

Again, it is important to note that any of the swing weight techniques in the literature (e.g. balance beam, SMARTER, etc.) could be used to assess the swing weights.

History of Early Swing Weight Matrix Uses. The swing weight matrix was initially used on three West Point research projects. The first project was a cadet capstone project lead by the second author. He asked the first author for ideas for swing weight approaches that could be used over a videoconference. The first author proposed using what we now call the swing weight matrix. The project group was able to successfully explain the matrix and obtain weights from stakeholders over a video conference. The second use was a major Army study to design a regional installation management agency (Trainor et al., 2007). The third project was the Army Base Realignment and Closure (BRAC) study (Ewing, Tarantino, and Parnell, 2006). In the BRAC work, we very clearly defined the levels of importance in terms of the decision process. After the success of the swing weight matrix in these applications, colleagues at Innovative Decisions Inc. and other organizations have used the swing weight matrix for trade studies and system decision making. Based on the continued success of the swing weight matrix, we included the swing weight matrix as our primary technique to assess swing weights in our chapter of the first draft of our book in Fall 2006 (subsequently this draft book became Parnell, Driscoll, and Henderson, 2008). A complete systems design example using the swing weight matrix is included in chapters 9-12 of the book. Also, in Fall 2006, we began teaching the swing weight matrix in our two introductory systems engineering courses at West Point that use the additive value model to evaluate and improve system designs. We now also teach weight sensitivity analysis using the swing weight matrix judgments.

BRAC 2005 – An Illustrative Swing Weight Matrix Example

As an illustrative example of the swing weight matrix, we use the Army Base Realignment and Closure (BRAC) study (Ewing, Tarantino, and Parnell, 2006).

Background. In 2001, Congress enacted legislation that required a 2005 Base Realignment and Closure (BRAC) study to realign military units, remove excess facility capacity, and close installations to support defense transformation. The United States Army used multiobjective decision analysis with an additive value model to determine the military value of its installations. By law, each of the approximately 100 Army installations had to be evaluated with the same model.

Developing the BRAC 2005 Value Model. Based on extensive stakeholder analysis, we developed the value hierarchy in Figure 2. The overall objective (not shown in the figure) was to maximize the military value of an installation. The military value of an installation depended on its capabilities and missions (sub-capabilities). The first column of Figure 2 contains the six capabilities which support the overall objective. The second column shows the sub-capabilities under one of the six capabilities. Of the fifteen sub-capabilities, three have two value measures; the remaining sub-capabilities have three or more value measures. Value measures represent installation attributes that differentiate installations, are measurable, and have certifiable data sources (BRAC legal requirement). For each value measure, a value function quantified the value of returns to scale on each value measure. The DoD BRAC report (2005) describes the complete value model and the analysis.

Capabilities			Value Measures
Support Army and Joint Training Transformation	*Maneuver Space / Air Space*		Airspace
		Manuever Space	Heavy Maneuver Area
			Light Maneuver Area
	Impact Area and Ranges		Direct Fire Capability
			Indirect Fire Capability
			Military Operations on Urban Terrain Capabilites
	Environmental Impact on Training		Soil Resiliency
			Noise Contours
			Air Quality
	Institutional Training		Applied Instructional Facilities
			General Instructional Facilities
Maintain Future Joint Stationing Options	*Mission Expansion*		Brigade Capacity
			Buildable Acres
	Mission Expansion Factors		Critical facilitiy proximity
			Urban Sprawl
			Environmental Elasticity
			Water Quantity
Power Projection for Joint Operations	*Power Projection*		Force Deployment
			Materiel Deployment
			Mobilization
	C2/Admin		Accessibility
			Connectivity
			Operations / Administrative Facilities
Support Army Materiel and Joint Logistics	*Support Joint Logistics*		Supply and Storage Capacity
		Maintenance Production	InterService/Partnering Workload Flexibility
			Maintenance / Manufacturing Capability
		Munitions	Munitions Production Capability
			Ammunition Storage Capacity
	RDT&E		Test Range Capability
			Research, Develop, Test, and Evaluation Mission Diversity
Achieve Cost Efficient Installations			Workforce Availability
	Installation / Facilities		Area Cost Factor
			Joint Facilities Cost Sharing
			Installation Unit Cost Factor
			C2 Target Focus Facilities
Enhance Soldier and Family Well-Being			In-State College Tuition Policies
	Local Community		Crime Index
			Housing Availability
			Employment Opportunity
			Medical Care Availability

Figure 2. Installation Military Value Qualitative Model

The swing weight matrix was developed in four steps:

Step 1. *Define the importance and variance dimensions*. It is worthwhile to note that is took three experienced Ph.D. analysts (Ewing, Tarantino and myself) several hours to develop the swing weight matrix. We thought hard about what determined the value of an Army installation. Finally, we realized that the future value of an installation was primarily a result of the inherent attributes of an installation and not the particular set of missions, facilities, and people that were currently on the installation. Next, we asked the following question: what was the most valuable attribute of an installation? The answer was that the Army's critical mission requirement was the ability to maneuver large Army units for training. We called this an immutable attribute of the installation since the Army would have a very difficult time procuring large parcels of land today to use for maneuver areas. Also, only a few of the large installations had the contiguous land to maneuver large Army units.

Therefore, for installation military value, we concluded that the relative importance of an attribute depends on the Army's ability to change an installation's attribute level. For example, an installation cannot easily increase its acreage, but it can increase administrative space by building additional facilities. The ability to change is represented in the columns while the variability of range of the attribute is in the rows. The variance depended on the range of the value measure scores over the 100 installations. Figure 3 shows the matrix with increasing ability to change from left to right and decreasing variation in range from top to bottom.

Step 2. *Place the value measures in the matrix*. Once the matrix is defined, the attributes are added to the matrix in Figure 3. As an example, the heavy maneuver area attribute was placed in the upper left corner of the matrix. Heavy maneuver (e.g., heavier armored vehicles) area is usually impossible to obtain and some installations (e.g., in urban areas) have no heavy maneuver area at all, while others have extensive areas for heavy maneuver training. Determining the relative variance of each measure required some discussion for different types of measures.

Ability to change

Variation of scale	Mission immutable (Very difficult to change)		Mission support (Difficult to change without external support)		Mission enablers (Change with Army dollars)	
Large	Hvy maneuver area Direct fire Brigade capacity 100	Light maneuver area Indirect fire 90	Inter-service partnering Area cost factor 75	Housing avail. Crime index Maintenance / manuf. 50	RDTE diversity 20	Supply & storage Operation/administrative Ammo storage 10
Moderate	Force deploy Materiel deploy Airspace 90	Critical infrastructure Test ranges Mobilization history 75	Munitions production Urban sprawl Accessibility 50	Work force availability 20	Military Operations Urban Terrain 10	Applied instruction General instruction 5
Small	Buildable acres 75	Soil resiliency Joint facilities 50	Employment opportunity Water quantity Installation unit cost Environmental elasticity Connectivity 20	Medical availability Noise contours Air quality In-state tuition 10	C2 target facilities 5	1

Level of importance		
High	Medium	Low

Figure 3. BRAC 2005 Swing Weight Matrix

It is interesting to note that we developed the swing weight matrix *before* we obtained the scores of the 100 installations on each of the 40 attributes. After reviewing the scores, we did not change any of the column placements but we did change some of the row placements. For example, if there was more variation in the scores than we anticipated, we moved the attribute up one row and, if less variation than anticipated, we moved it down one row. Of course, when the range of the attribute changed we also had to also revise the value functions.

Step 3. Assess the unnormalized swing weights. The shading in Figure 3 represents the level of importance corresponding to an attribute and is used to facilitate the discussion with stakeholders and gain concurrence on the attribute weights. After the leadership approved the placement of the attributes in the matrix, we assign the matrix swing weight, f_i to all of the cells of the matrix. As in all weighting methods, it is important to ensure the proper range of weights between the highest and lowest weighted attribute. For our application, we used unnormalized swing weights from 1 to 100. We assigned the highest swing weights, $f_1 = f_2 = f_3 = 100$, in the upper left corner of the matrix[3]. Because of the large number of attributes in the model, we ensured at least two orders of magnitude between the highest and lowest matrix weight. The lowest matrix swing weight, $f_{41} = 1$, was assigned to the lower right corner of the matrix with no measures. The remaining matrix swing weights are placed in the matrix according to the importance level and variation. We used the value increment approach to assessing weights but any swing weighting technique can be used.

Two additional features of our weighting approach are useful to note. First, weight assessments are inherently subjective and we wanted to avoid a sense of false precision. Therefore, we assessed the weights to the nearest increment of 5. We used 75 instead of 74. Second, any attribute proposed by a stakeholder that fell in the lower RH corner of the matrix would have a very small normalized weight. Since every attribute required certified scores from all 100 installations, scoring a very low weight attribute would not impact the installation value and would be a waste of effort and, therefore, we did not include the attribute in our analysis. As noted in our benefits section, this approach was the key to keeping the size of the value model reasonable.

Step 4. *Calculate the normalized swing weights.* The normalized global weights, w_i, used in the additive value function in equation 1, are found with the following equation:

$$w_i = \frac{f_i}{\sum_{i=1}^{40} f_i}, \text{ where } f_i = \text{matrix swing weight, corresponding to value measure } i. \quad \text{Equation 3}$$

Step 5. *Explaining the normalized swing weights.* In the BRAC study, we used the matrix to assess weights with the Army subject matter experts and key stakeholders. We also used the matrix to explain our weighting process to Army auditors, Army senior decision makers, the Government Accountability Office, and the BRAC Commission. Although we originally used the 3 columns, after assessing the 40 weights, we found it easier to display the matrix using the 6 columns with each cell having measures with the same swing weight. The swing weight matrix proved to be effective for both purposes. As an example, during one military value briefing to the Senior Review Group, a key decision maker questioned the weight assignment to Military Operations in Urban Terrain (MOUT) facilities. His logic was that MOUT facilities were critical to provide training for the Global War on Terrorism. After we explained the swing weight matrix, he agreed with the original weight assessment since a MOUT facility was not an immutable attribute of the installation but could be purchased with dollars at a new installation.

---

[3] The unnormalized swing weights in any cell do not have to be the same.

Additional Examples of the Swing Weight Matrix

In this section, we describe three additional uses of the swing weight matrix for systems decisions.

Family of Individual Optics (FOIO) Business Case Analysis. The Family of Individual Optics (FOIO) Business Case Analysis (BCA) (Booz Allen Hamilton, 2008) identified capability gaps and technology shortcomings of current and near-term U.S. Marine Corps optics systems, and provided recommendations for a system of systems to resolve those gaps including vulnerability to adversary capability. This study provided the Program Manager with recommendations to enhance the ability of warfighters to perform their mission while reducing the burden placed upon the dismounted Marine. The study had several objectives including to: develop a systems/capability matrix and perform capability set analysis to define solutions that fulfill capability gaps, assess materiel solutions associated with the capability sets, provide an analytical basis for selecting the best alternative(s), analyze courses of action based upon risk-derived investment strategies, and provide cost data for budget preparation.

Multiobjective decision analysis with an additive value model was used to assess the value of the over 30 optics systems for the Marine warfighter and identify the capability gaps. The swing weight matrix (Figure 4) with balance beam was used to assess the weights. A quote from the report illustrates how the lead analyst explained the swing weight matrix to the Marine stakeholders. "The axes serve as the overall importance of the measure and the variation within that measure. [as] a simple example, the price of a car might be very important when deciding to buy a car, but if the variation (difference in the car prices) was only $100, one would place less weight on price during the decision process. The swing weight matrix evaluates both of those factors and ensures that the variation is explicitly stated."[4]

	Importance of the value measure to the decision			
	Nice to Have	Low	Moderate	High
Large Variation	Operates in Nuclear Chemical Biological Environments		Field of View Range-Finding	Day/Night Capability Weight Night Range to Detect
Moderate			Battery-Life	Night Range to Identify
Little Variation	Battery-Type	Recovery	Detect Obscured Targets	

Figure 4. Family of Individual Optics (FOIO) swing weight matrix

DoD System Engineering Study[5]. Multiobjective decision analysis with an additive value model

[4] From Russell Mossier of IDI.

[5] This study was performed by Don Bucksaw and David Caswell. David programmed the automated swing weight matrix tool. The analysis team continues to improve the features of the tool.

was used to help decision makers select the best location for a growing mission with unique training requirements at remote locations. Figure 5 shows the swing weight matrix that was used in this study. This study incorporated three swing weight matrix innovations to improve the analyst interaction with stakeholders and decision makers. First, the “not relevant row” was added to the matrix. This row was added to help stakeholders understand that value measures in all importance levels may have very small or no variation and, therefore, not be relevant to the decision. In this study, the analysts were only allowed limited time with the senior stakeholders and decision makers for the weight assessments. In these sessions, they needed to be able to rapidly adjust the weights based on real-time guidance. As a result, the second innovation was the development of an automated swing weight matrix tool in Excel that used macros to automate weighting functions including the placement of the value measures in the cells and the calculation of the normalized swing weights based on the placement and the unnormalized swing weights. In a stakeholder or decision maker session, the analyst could move a value measure to another cell with the mouse automatically updating and the swing weights and all of the decision analysis results. The third innovation was preassigning the unnormalized swing weights to the cells of the matrix *before* the value measures were placed in the cell. The tool also allowed the analyst to display or hide the unnormalized swing weights as needed. In this study, stakeholders preferred preassigned weights to a more detailed and time-consuming weights assessment process. However, stakeholders were allowed to adjust the original analyst cell weight assignments.

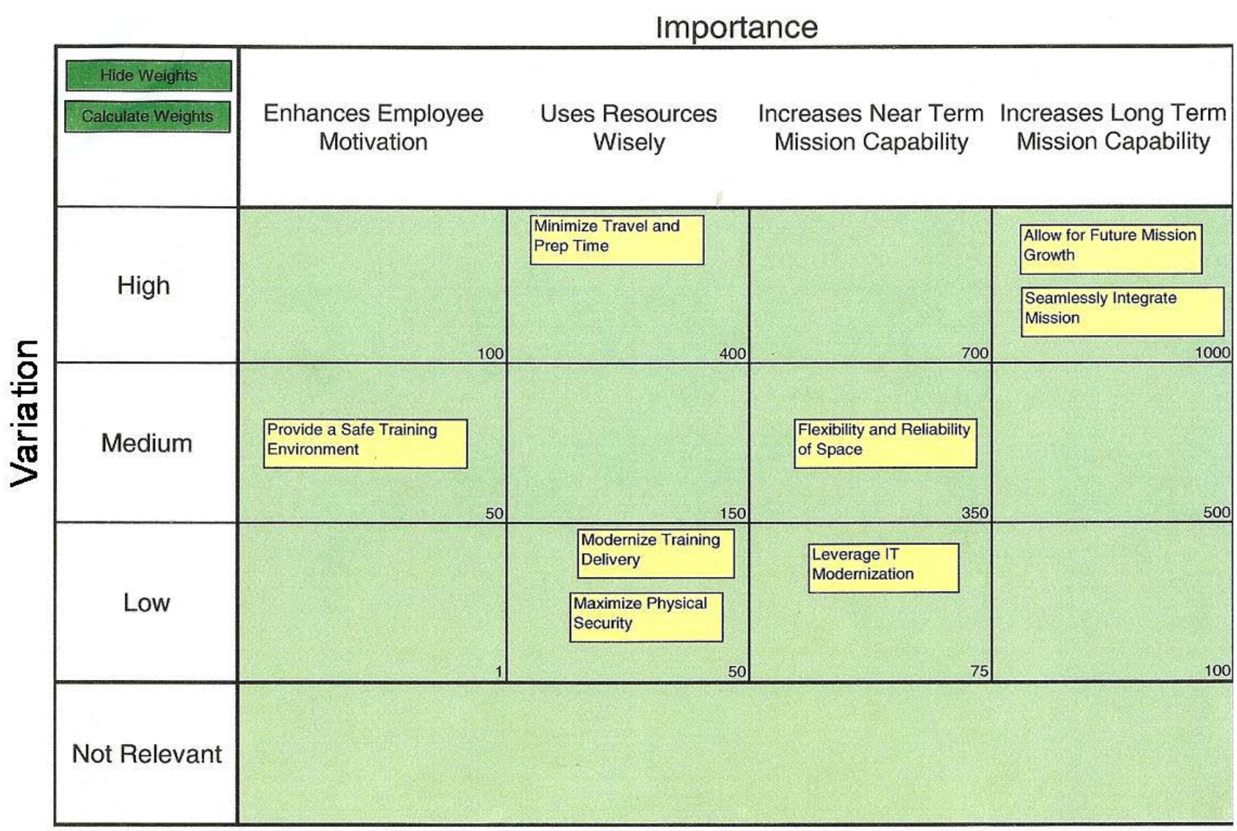

Figure 5. DoD System Engineering Study for a Site Location

Systems Engineering Gap Analysis[6]. The current DoD capability development process requires the identification of capability gaps as one of the first steps. Figure 6 shows the swing weight matrix that was used in an intelligence gap analysis. The abbreviation INT refers to the various intelligence collection capabilities, e.g., human intelligence, photographic intelligence, signals intelligence, etc. As with all of the studies using the swing weight matrix, it took the analyst team considerable thought to develop the most appropriate constructed scales for the importance and variation dimensions. They decided that the most relevant factor for importance would be the number of INTs that could provide the capability. For the most important capability gaps, only one INT could provide the capability to meet the intelligence need. If there are multiple sources possible, the capability gap is less important for this organization since other organizations can provide the capability. The second level of importance would be to provide confirmation for another INT since redundancy provides additional confidence in intelligence assessments. The least important would be when multiple sources exist. For variation, they decided that the target's ability to evade collection was the best distinction. Therefore, the swing weight matrix assigned the highest weight to a gap that only one INT would be likely to be successful and threat evasion capability was increasing compared to the current collection capability. An additional interesting swing weight matrix innovation was the use of continuous curves instead of discrete cells.

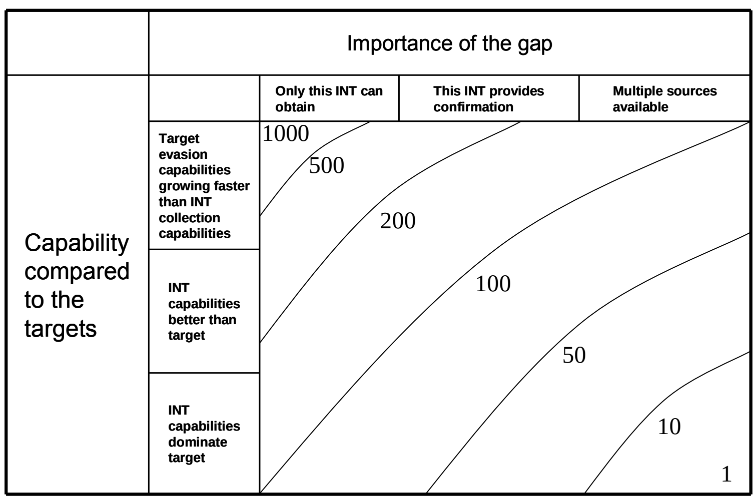

Figure 6. System Engineering Intelligence Gap Analysis Study

Swing Weight Matrix Implementation

Challenges. The major swing weight matrix challenges are the development of constructed scales that define importance of the value measure and the range of variation in the value measure scales. Three quotes from colleagues illustrate the challenges:

- "A very hard step, and very important one, is to choose the right words for the importance row. This gets to the heart of the problem. A lot of time needs to be spent

[6] The first author supported IDI colleagues Dennis Buede, Dan Maxwell, Jake Ulvila, Bob Liebe, and Don Bucksaw on this study.

here."

- "Also important is trying to define variation in a way that makes sense to the decision maker. This is non-trivial task!"
- "People don't understand variation. You explain it, they seem to get it, and they forget."

Improvements. Several ideas are being used to make the swing weight matrix more effective and the weights assessment more efficient.

- Some analysts have found that variation is easier to discuss with stakeholders as the "impact of the value measure on the decision.[7]"
- Many analysts have found that decision makers expect to see the highest weights in the upper right hand corner.
- Use of Excel tools that allow users to drag and drop value measures into cells (which can be tailored) in order to speed the process.
- Some analysts have found that filling in the matrix with notional numbers is a good way to speed up the process of weights assessment.
- The use of the "not relevant row" to account for stakeholder measures that will have no effect on the decision since their range of variation is very small.

New Swing Weight Matrix Template. Sometimes it is useful to begin a weighting session with a template that helps stakeholders understand weighting. Figure 7 is the template we now use. In the first session, we emphasize the following. Weights depend on the importance of the value measure to the decision makers and stakeholders and the range of the value measure. Importance is an intuitive judgment and variation is a factual assessment. The definition of importance and variation is different in each application and usually requires hard thinking. High, medium and low are placeholders for the two constructed scales appropriate for the decision. Defining variation is difficult because we routinely make intuitive judgments about importance without the impact of the actual variation for the decision under consideration. Variation may be easier to discuss as the impact of the value measure on the decision and will depend on the actual range of the value measure scale.

---

[7] West Point colleagues Rob Dees and Matt Dabkowski have both advocated this approach.

		Importance of the value measure to the decision makers and stakeholders (intuitive)		
		Low	Medium	High
Impact of the value measure on the decision (factual)	High			
	Medium			
	Low			
	Not relevant			

Figure 7. Swing Weight Matrix Template

Summary

Benefits of the Swing Weight Matrix. The swing weight matrix can provide an efficient and effective means to understand, assess, present, and explain value measure weights used in a multiobjective decision analysis. This method has four advantages over traditional weighting methods. First, it develops an explicit definition of importance and insures consideration of the range of variation. Second, it provides a framework for consistent swing weight assessments. Third, it provides a simple yet effective framework to present and justify the weighting decisions. Fourth, it helps minimize the number of measures by showing stakeholders that some measures (even though they are important to them) will not be relevant to the decision. Fifth, the technique works well when the analysts have limited time to interact with stakeholder and decision makers to assess weights.

Conclusion. Assessing the weights with multiple, conflicting objectives is an important challenge in system engineering and decision analysis. The swing weight matrix can help stakeholders understand what is important and properly assess weights. As with any operations research technique, domain knowledge, communications skills, and the art of modeling is critical to successful design and implementation.

References

Booz Allen Hamilton. 2008. Family of Individual Optics (FOIO) Business Case Analysis (BCA)

Buede, D.M. 2000.The engineering design of systems: Methods and models. New York: Wiley.

Clemen, R. 1996. Making Hard Decisions, 2nd Edition, Duxbury Press.

Dillon-Merrill, R. L. Parnell, G. S. Buckshaw, D. L., Hensley, W. R., Jr. Caswell, D. J. 2008. Avoiding common pitfalls in decision support frameworks for Department of Defense analyses, Military Operations Research, 13 (2): 19-31.

Department of Defense. 2005. Report to the Defense Base Closure and Realignment Commission. Vol III. Department of the Army Analysis and Recommendations BRAC.

Edwards W. and F. H. Barron 1994. “SMARTS and SMARTER: Improved simple methods for multiattribute utility measurement”. Organizational Behavior and Human Decision Processes 60: 306-325

Ewing, P. and W. Tarantino G. Parnell 2006. Use of decision analysis in the Army Base

Realignment and Closure (BRAC) 2005 military value analysis, *Decision Analysis*. 3 (1): 33-49.
Hammond, J. S. and R. L. Keeney H. Raiffa. 1999. Smart Choices : A Practical Guide to Making Better Decisions, Harvard Business School Press.
Keeney, R.L. and Raiffa H. 1976. Decision Making with Multiple Objectives Preferences and Value Tradeoffs. New York: Wiley.
——— 1992. Value-Focused Thinking: A Path to Creative Decisionmaking. Cambridge, Massachusetts: Harvard University Press.
Kirkwood, C. W. 1997. Strategic Decision Making: Multiobjective Decision Analysis with Spreadsheets. Belmont, California: Duxbury Press.
Parnell, G. S. 2007. Chapter 19, Value-focused thinking, Methods for Conducting Military Operational Analysis, 619-656. eds A. Loerch and L. Rainey, Washington, DC: Military Operations Research Society.
———. Driscoll, P. J. and Henderson D. L. eds 2008. Decision Making for Systems Engineering and Management, Wiley Series in Systems Engineering, ed A. Sage, Wiley & Sons Inc.
Pöyhönen M. and R. P. Hämäläinen. 2001, On the convergence of multiattribute weighting methods, *European Journal of Operational Research.*129 (3):569-585.
Trainor, T. and G. Parnell, G. B. Kwinn, J. Brence, Tollefson, E., P. Downes 2007. The US Army uses decision analysis in designing its installation regions. *Interfaces.* 37 (3): 253-264.
Van Winterfeldt, D. and W. Edwards 1986. Decision Analysis and Behavioral Research, New York: Cambridge University Press.
Watson, S. R. and Buede, D. M. 1987. Decision Synthesis: The Principles and Practice of Decision Analysis, Cambridge: Cambridge University Press.

BIOGRAPHY

Dr. Gregory S. Parnell is Professor of Systems Engineering at United States Military Academy at West Point and teaches decision and risk analysis, systems engineering, and operations research. His research focuses on decision analysis, risk analysis, resource allocation and systems engineering for defense, intelligence, homeland security, and environmental applications. He co-edited Decision Making for Systems Engineering and Management, Wiley Series in Systems Engineering, Wiley & Sons Inc., 2008, and has published over 100 papers and book chapters. He is a senior principal with Innovative Decisions Inc., a decision and risk analysis firm. Dr. Parnell received his Ph.D. from Stanford University.

Colonel Timothy E. Trainor, Ph.D., is the Professor and Head of the Department of Systems Engineering at the United States Military Academy at West Point. He teaches courses in engineering economics, production operations management and systems engineering. His current research work is in the areas of organizational management and decision and risk analysis for the Army and Department of Defense. He holds an MBA from the Fuqua School of Business at Duke University, and a Ph.D. from North Carolina State University.