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Use of Decision Analysis in the Army Base Realignment and Closure (BRAC) 2005 Military Value Analysis

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In 2001, Congress enacted legislation that required a 2005 Base Realignment and Closure (BRAC) round to realign military units, remove excess facility capacity, and support defense transformation. The United States Army used multiple-objective decision analysis to determine the military value of installations and an installation portfolio model to develop the starting point to identify potential unit realignments and base closures, providing the basis for all recommendations. Ninety-five percent of the army's recommendations were accepted by the BRAC 2005 Commission. The army expects these recommendations to create recurring savings of $1.5 billion annually after completion of BRAC implementation. This paper offers four contributions to decision analysis literature: an instructive application of multiple-objective decision analysis methods to portfolio selection, a useful method for constructing scales for interdependent attributes, a new method for assessing weights that explicitly considers importance and variation (Swing Weight Matrix), and practical advice on how to use multiple-objective decision analysis methods in a complex and controversial political environment.

Key words: decision analysis; BRAC; army; military value; Swing Weight Matrix; portfolio analysis
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1. Introduction

> Recent world events have not altered the need to transform the military infrastructure to meet future needs. In fact, these recent events have exacerbated the need to rapidly accomplish transformation and reshaping... Excess infrastructure does exist and is available for reshaping or needs to be eliminated... Only a comprehensive Base Closure and Realignment (BRAC) analysis can determine the exact nature or location of potential excess. In preparing a list of realignment and closure recommendations in May 2005, the Department will conduct a thorough review of its existing infrastructure in accordance with the law and Department of Defense BRAC 2005 guiding procedures, ensuring that all military installations are treated equally and evaluated on their continuing military value to our nation.
>
> Secretary of Defense Donald Rumsfeld
> March 23, 2004

The U.S. Department of Defense (DoD) conducted the first four Base Realignment and Closure (BRAC) rounds in 1988, 1991, 1993, and 1995, which resulted in 97 major domestic base closures, 55 major realignments, and 235 minor installation closures or realignments. Even with the infrastructure reductions achieved in the four rounds, DoD determined that excess capacity still existed and requested authorization for another BRAC round. In 2001, the U.S. Congress enacted legislation that called for a 2005

BRAC to remove excess facility capacity and support DoD transformation. The DoD completed several BRAC studies and provided recommendations for realignments and closures. The President and Congress appointed the BRAC 2005 Commission to review all DoD candidate recommendations and provide its final recommendations. The commission's recommendations became law in November 2005.

This paper describes how we used decision analysis to support the U.S. Army's BRAC decision makers. We believe this paper offers four contributions to decision analysis literature:

- an instructive application of multiple-objective decision analysis methods to portfolio selection;
- a useful method for constructing scales for interdependent attributes (§6.4),
- a new method for assessing weights that explicitly considers importance and variation (Swing Weight Matrix, §6.5), and
- some practical advice on how to use multiple-objective decision analysis methods in a complex and controversial political environment.

Congress stipulated that an installation's military value must be the primary consideration for BRAC 2005 recommendations, and the army's BRAC Report (Department of Defense, DoD 2005) states that "military value was the primary consideration in making closure and realignment recommendations." The BRAC Commission evaluated each proposal by how well it supported military value as well as each service's force structure plan. Thus, the critical first step in the overall BRAC analysis was to determine each installation's military value.

The Army Basing Study Group was responsible for all army BRAC analysis and was led by Deputy Assistant Secretary of the Army for Infrastructure Analysis, Dr. Craig College. The group conducted research and interviewed senior army leaders to identify BRAC objectives, priorities, challenges, and opportunities, which supported military value and our decision analysis work; this paper discusses the army's analysis.

The army military value analysis considered the army's stationing principles set forth in its Stationing Strategy (Department of the Army 2003). Below is the Army Stationing Vision, stated in the strategy:

> A campaign quality Joint and Expeditionary Army positioned to provide relevant and ready combat power to Combatant Commanders from a portfolio of installations that projects power, trains, sustains and enhances the readiness and well-being of the Joint Team.

This strategy is important to an installation assessment for two reasons. First, selected attributes must support this strategy and the first four of the DoD BRAC selection criteria (DoD 2004):

1. The current and future mission capabilities and the impact on operational readiness of the Department of Defense's total force, including impact on joint warfighting, training, and readiness.
2. The availability and condition of land, facilities, and associated airspace (including training areas suitable for maneuver by ground, naval, or air forces throughout a diversity of climate and terrain areas and staging areas for the use of the armed forces in homeland defense missions) at both existing and potential receiving locations.
3. The ability to accommodate contingency, mobilization, and future requirements at both existing and potential receiving locations to support operations and training.
4. The cost of operations and the manpower implications.

Second, an installation's ability to support the Stationing Strategy should increase the installation's value. The Army Stationing Strategy assigns installations to categories using the installation's primary mission of currently assigned units. The installation categories formed the basis for the BRAC 1995 installation assessment (Department of the Army 2003). Unlike BRAC 1995, we removed the installation category constraint. This allowed us to consider the military value of an installation for any army mission and increased the solution space by allowing possible alternatives that moved missions between installation categories. Thus, our approach assessed the value of installations *independent* of their *current* installation category, which allowed us to treat all installations from the same perspective and investigate an installation's potential military value unconstrained by its current mission.

This paper describes the military value assessment including the military value installation and the military value portfolio models, which provided the starting point for the BRAC scenario and option development and informed the army BRAC Senior Review Group's decision makers. The Senior Review Group was cochaired by the vice chief of staff of the army and the undersecretary of the army. The Senior Review Group evaluated potential army recommendations, provided guidance to the Army Basing Study Group, and reviewed all analysis and recommendations. For a complete listing of the Senior Review Group members and The Army Basing Study Group's structure, see the DoD Report to the Base Realignment and Closure Commission, Volume III, §§3 and 4 (DoD 2005).

Section 2 provides a method overview. Section 3 describes the qualitative military value model. Section 4 describes the quantitative military value model. Section 5 contains the military value portfolio model formulation and results. Section 6 highlights some important lessons learned and summarizes the paper.

2. Method

Multiple-objective decision analysis (Keeney and Raiffa 1976, Kirkwood 1997) has been applied to important military applications involving complex alternatives, conflicting objectives, and major uncertainties. Parnell (2006) compares 10 single-decision applications (similar to our installation model) and 14 portfolio decision value model (similar to our portfolio model) applications. Additional portfolio decision models include Golabi et al. (1981), Archer and Ghasemzadeh (1999), Kleinmuntz and Kleinmuntz (1999), and Stummer and Heidenberger (2003).

BRAC 1995 (Department of the Army 1995) and 2005 military value assessment used multiple-objective decision analysis, the most appropriate technique for defining value and analyzing alternatives involving multiple, conflicting objectives. The army's 2005 method involved several key steps:

Qualitative installation military value model. We developed a qualitative installation military value model based on document reviews and stakeholder analysis. The value model includes the first four BRAC criteria: We reviewed relevant legal, strategy, policy, and planning documents to define the military value of army installations. We interviewed senior army leadership to better understand the military value of installation characteristics.

Quantitative military value model. Using the qualitative model, we developed a quantitative model to determine the military value of an installation.

Portfolio military value model. We used the installation military value model and BRAC Capacity Analysis (DoD 2005) results to develop a portfolio model that would determine the minimum number of installations that met army capacity constraints.

Option analysis. Once we knew the preferred installations to keep, we developed and used decision analysis, cost analysis, and army stationing and portfolio optimization models to analyze the army's BRAC options. (This phase will be discussed in a subsequent paper.)

The military value analysis team consisted of decision analysts, operations research analysts, and army installation experts from the Army Basing Study office, the Center for Army Analysis, and the United States Military Academy. The authors played a major role in the modeling and analysis to support the Army BRAC effort. Colonel Tarantino served as the modeling team chief for the deputy assistant secretary and was responsible for developing the methods and implementing the entire analysis effort. Dr. Parnell led the stakeholder analysis and served as a subject matter expert on decision analysis. He developed and implemented the plan for interviewing the senior leaders of the army and conducted the majority of the interviews. Major Ewing developed and implemented the decision analysis and optimization models used to support military value analysis. The BRAC planning, analysis, and documentation was approximately 20 man-years over a five-year period, which does not include the time of subject matter experts or decision makers.

3. The Qualitative Installation Military Value Model

Before developing the BRAC 2005 installation military value model, we embarked on a research effort, including document reviews and interviews with senior leaders, to develop an understanding of historical BRAC issues, the changes since BRAC 1995, current defense objectives, and critical future uncertainties.

We reviewed army, DoD, and joint service military-related documents and published reviews (e.g., Government Accountability Office, RAND Corporation, etc.), focusing on defense transformation, stationing, and BRAC.[1] We developed document summaries outlining the transformational or institutional changes that would impact an installation's value and require changes from the 1995 BRAC installation analysis. Key concepts relating to the future of army stationing emerged; the team incorporated these concepts into the installation military value model.

To complement the document research, we conducted stakeholder interviews with senior army and DoD leaders to obtain their views on BRAC 2005 objectives, priorities, challenges, and transformational or cost-reduction opportunities. We interviewed 36 senior army leaders (general- or civilian-equivalent-level officers). We used an interview protocol as a guide for the one-hour interview. The results validated the document research, provided further insights that were not found in any reference, and helped refine the research findings. A summary of the interview effort and the complete listing of the interview statements and findings are included in a Center for Army Analysis report (Center for Army Analysis 2004). After completing senior leader interviews, we met with their organizations' experts to follow up on issues raised during the interviews and to develop value measures for the military value attributes.

Figure 1 illustrates the installation military value qualitative model, which we define as installation capabilities, as well as missions (subcapabilities). The first column of Figure 1 contains the six capabilities that support the overall objective of *Determine the Military Value of an Installation*. The second column shows the subcapabilities under one of the six capabilities.

Attributes are specified for each of the capabilities and subcapabilities and represent installation characteristics that differentiate installations, are measurable, and have certifiable data sources (BRAC legal requirement). The appendix provides further information on each of the six capabilities and a description of the attributes. For each attribute, value measures assess how an installation supports the attribute and a value function quantifies the value of returns to scale on each value measure.

[1] See DoD (2005) for a complete list of these documents.

4. The Quantitative Installation Military Value Model

The BRAC is an extremely complex and difficult problem. We needed a modeling process that was objective, traceable, and defendable, so we used an additive value model (Kirkwood 1997). We developed the qualitative value model, assessed single-dimensional and two-dimensional value functions to measure returns to scale, and assessed weights based on the relative importance and variation of each value measure using the Swing Weight Matrix. We ensured that we satisfied the required assumptions for an additive value model (Kirkwood 1997). The Senior Review Group approved the quantitative military value model. This section emphasizes the two most interesting technical issues: two-dimensional measures to avoid value dependence and the Swing Weight Matrix to improve weight development, assessment, and explanation.

4.1. Value Functions

This section describes the types of value functions we used and our assessment. We completed the value model assessment with subject matter experts (e.g., a training expert assisted with maneuver space, an engineer expert assisted with water evaluation) on the army staff. Keeney and Raiffa (1976) prove a value function $v(x_1, x_2, \ldots, x_n)$ is *additive* if the attributes $\{X_1, X_2, \ldots, X_n\}$ are mutually preferentially independent (for $n > 3$). They demonstrate that mutual preferential independence is a necessary condition for an additive value function of more than two dimensions. Mutual preferential independence implies that the overall value function can be separated into entities that represent different attributes. Furthermore, if the additive value function is difference consistent and X_1 is difference independent of the remaining attributes, then the military value for an installation, $v(x)$, can be written as an additive measurable value function (Dyer and Sarin 1979) with the form

$$v(x) = \sum_{i=1}^{40} w_i v_i(x_i), \quad \text{where } \sum_{i=1}^{40} w_i = 1. \qquad (1)$$

We paid careful attention to the decomposability property of the objective hierarchy during model design. After questioning the Army Basing Study installation experts, it was fairly straightforward to

Figure 1 Installation Military Value Qualitative Model

Capabilities	Value measures
Support army and joint training transformation	
Maneuver space/air space	Airspace
Maneuver space	Heavy maneuver area
	Light maneuver area
Impact area and ranges	Direct-fire capability
	Indirect-fire capability
	Military operations on urban terrain capabilities
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 facility 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

assume that the difference-independence conditions are met for the attributes within each installation and the conditions for Equation (1) are met. We also needed to provide an overall value for a portfolio of installations. If y_i is the evaluation attribute for evaluation consideration i at the portfolio level, we would like to determine $y_i = (x_{i1}, x_{i2}, \ldots, x_{iN})$ for N installations. In §7 we assume that the necessary independence conditions are met for both attributes across installations (necessary for development of the portfolio) and within each installation. Unlike the application of Golabi et al. (1981), we are able to make simplifying assumptions for the assessment process by decomposing the set of attributes for a particular installation such that each expert only needs to assess the set of M attributes $(x_{1j}, x_{2j}, \ldots, x_{Mj})$ for a given base j. Because the conditions for the additive measurable value function held, we assessed the value function using the "value difference approach" outlined by Kirkwood (1997, pp. 243–244). The installation military value model used these steps:

Step 1. Determine the attributes that best measure the attainment of the model objectives.

Step 2. Confirm that the attributes obey mutually preferentially independence, are difference consistent, and test for difference independence.

Step 3. Assess the individual value functions for the 40 attributes using the value increment approach.

Step 4. Determine the weights using the Swing Weight Matrix Method.

Our attribute measures satisfy these requirements by combining the dependent attributes into multidimensional aggregated scales.

4.2. Attributes

We use two types of attributes. The first type of attribute contains a value measure that uses a single-dimension scale. The direct scale for the corresponding value function is either a *natural* scale, e.g., square feet or dollars, or a constructed scale, e.g., square feet quality, where quality represents the condition of a building. The model contains single-dimension attributes, which require that a scale be constructed, e.g., Research Development Test and Evaluation Mission Diversity. The second type of attribute combines multiple value measures, which we refer to as a multidimensional scale. For this type of attribute, we develop a constructed scale for an attribute that must capture the value dependence between several measures. The installation military value model uses 40 attributes; 26 of the attributes are the single-dimensional type, and 14 were the multidimensional type.

4.3. Single-Dimension Attribute Assessment

Keeney and Raiffa (1976) present two methods to assess value functions based on natural scales: the *Lock-Step Procedure* and the *Midvalue Splitting Technique*, with the latter being the most used in practice. The midvalue of a range is defined to be the level, x_i^m, such that the difference in value between the lowest score in the range and the midvalue is the same as the difference between the midvalue and the highest score in the range.

Kirkwood and Sarin (1980) extend the *Midvalue Splitting Technique* to include some useful analytic forms when the attributes meet specified conditions. We used an assessment approach based on this technique using the logical decisions (Smith 1999) function: *Midlevel Splitting Approach*. If constant trade-off attitude holds (Kirkwood 1997) then the following value function for monotonically increasing preferences of X_i is

$$v_i(x_i) = \begin{cases} \dfrac{1-\exp[-(x_i - x_i^L)/\rho_i]}{1-\exp[-(x_i^H - x_i^L)/\rho_i]}, & \rho_i \neq \infty \\[2ex] \dfrac{x_i - x_i^L}{x_i^H - x_i^L}, & \text{otherwise,} \end{cases} \tag{2}$$

where x_i^L (and x_i^H) are the lowest (and highest) level of interest of x_i, and ρ_i is the single-dimensional value function exponential constant. A similar form for preferences that are decreasing in x_i can be specified (Kirkwood 1997). The value function shown above is scaled so $v_i(x_i)$ varies between 0 and 1. Other scales are permissible, however, and leader preference persuaded us to scale the $v_i(x_i)$ for the value functions to vary between 0 and 10. The value of ρ_i defines the shape of the exponential curve. A closed-form solution for Equation (2) does not exist; however, we determine the value for ρ_i numerically.

For example, we used the Midlevel Splitting Approach to assess the attribute, *Interservice and Partnering with Industry*. Interservice workload includes work being performed in support of another service and work being performed for an Army Combatant Command, or both. Partnered workload is any work being performed in support of a commercial- or private-sector customer under one or more of the specific authorities. We use the proxy measure of direct labor hours to measure an installation's ability to perform interservice workload and partnered workload for maintenance and manufacturing operations (less munitions-related operations). The range of scores (in

Figure 2 **Interservice and Partnering with Industry Value Function Example**

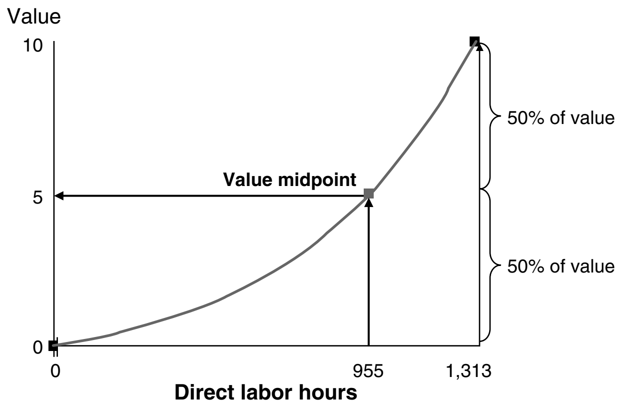


Figure 3 **Traditional Multidimensional Constructed Scale Example**

	Definition	Score
Label 1	Current capability allows for high capacity with green quality	10
Label 2	Current capability allows for high capacity with amber quality	8
Label 3	Current capability allows for med capacity with green quality	7
Label 4	Current capability allows for med capacity with amber quality	4
Label 5	Current capability allows for high capacity with conversion **OR** low capacity with green quality	3
Label 6	Current capability allows for med capacity with conversion **OR** low capacity with amber quality	2
Label 7	Current capability allows for low capacity with conversion	1
Label 8	No capacity or conversion available	0

thousands) varies from 0 to 1,313 direct labor hours and the resulting value function is shown in Figure 2.

We assessed the single-dimensional constructed scales the same way as the natural measures. We assumed a linear scale unless the experts offered a compelling argument as to why the value function should be otherwise. As an illustration, we use the *General Instructional Facilities* attribute, which measures an installation's existing capability to support training with general-purpose facilities used for general instruction.

The attribute is multidimensional because we used interval data to develop a quantitative measure (square feet) as well as ordinal data to construct the qualitative measure (quality factors). The army quality standards are represented as green, amber, and red, which loosely corresponds to high, medium, and low quality. One approach to constructing a scale for this type of measure is to develop a scale definition and determine the subdivisions of the value measures corresponding to the labels, as illustrated in Figure 3. The drawbacks to this approach include the time and difficulty in properly structuring the scale and assessing the value with experts.

As an alternative, we used the weighted sum (by quality standard) of the square footage of general instructional facilities (GIF) on an installation to transform the two dimensions into a single-dimensional constructed scale through the following linear transformation:

$$\text{GIF Score} = G * (1.0) + A * (0.71) + R * (0.36),$$

where G, A, and R equal available square feet of green, amber, and red general instructional space, respectively.[2]

Analogous to the example shown in Figure 2, the GIF score (x-axis) is then converted to a *value* (y-axis), normalized on a value scale of 0 to 10 based on the curvature of the value function. The linear transformation uses the natural measure of square feet and a proxy for quality. In practice, we found it difficult to find an analogous mathematical transformation for some of our measures. This left us with measures that were not independent in terms of preference and therefore were inconsistent with the application of an additive value model. Our approach to transform these attributes and then use them in an additive value function is described in the next section.

4.4. Multiple-Dimension Attribute Assessment

Kirkwood (1997) describes several issues associated with using constructed scales and shows a small example with two constructed scales using a piecewise linear approach. We did not find mature literature on the development and assessment of multidimensional constructed scales. One related use of these scales for combining indices is described in Wenstop and Carlsen (1988). Our

[2] The coefficients are the cost factors that would bring amber- and red-quality facility space up to green-quality standards.

problem required constructed scales to account for the interactions between dependent measures and, in some cases, combined qualitative and quantitative measures using nominal and interval data. Because we found it difficult to develop simple equations, or for subject matter experts to assess traditional constructed scales (Figure 3), we developed a visual representation to assist within the multimeasure attribute development and assessment.

The constructed scales must pass the *clairvoyance test* (Kirkwood 1997). This test requires that scales be well defined and include all possible outcomes. For most of our multidimensional attributes, the definition of individual scales was straightforward because we use natural scales, e.g., square feet and/or acres. Only in the cases where we needed to use qualitative measures was the definition difficult.

To develop the constructed scale levels of the value measures, we considered the capability that the attribute measures. For example, Figure 4 shows the visual representation of the multidimensional constructed scale for the *Heavy Maneuver Area* attribute, which supports the *Maneuver Space* subcapability in the *Support Army and Joint Training Transformation* capability. This attribute determines an installation's capability to support training and maneuvering of heavy mechanized forces.

The *Heavy Maneuver Area* attribute has two value measures: total heavy maneuver area (quantity) and the largest contiguous area of an installation (a measure of heavy maneuver area quality). We chose the *bins* (constructed scale levels) based on the installation data and expert's determination of how much value the area represented in the bin would provide to a mechanized infantry brigade (this operational relationship for bin determination is similar to the process to determine break points in a piecewise linear single-dimension value function). For example, if an installation contains more than 100,000 acres, but only has 40,000 acres of contiguous maneuver area, then the installation would receive a value associated with Label 7. By representing the attribute visually, we are able to discuss with the subject matter expert how the attribute should be assessed. Once we establish the bins for the multidimensional constructed scales, we used the following steps:

Figure 4 Multidimensional Constructed Scale for Heavy Maneuver Area

Largest contiguous area (1,000s acres)	Total heavy maneuver area (1,000s acres)			
	≤10	>10 and ≤50	>50 and ≤100	>100
≤10	Label 1	Label 2	Label 3	Label 4
>10 and ≤50		Label 5	Label 6	Label 7
>50 and ≤100			Label 8	Label 9
>100				Label 10

Step 1. Label the cells in order from left to right and top to bottom. Place the lowest label number in the top left-hand cell of the matrix and the highest label number in the bottom right-hand cell of the matrix. The reference zero value, i.e., "Label 0," is not shown in the matrix of Figure 4. Much like the process used to assess piecewise linear "single"-dimensional value functions, we assess the relative value increments to be specified between each of the possible evaluation measure scores (associated with each dimension of the multidimensional scale, i.e., bin range).

Step 2. The value assessment for the multidimensional scales is a two-pass process. In the first pass, we make a holistic assessment based on value increments for each cell. For example, we begin by fixing the amount of total heavy maneuver area between 10,000 and 50,000 acres (Label 2 and Label 5). We then determine the value increment moving from less than or equal to 10,000 acres of contiguous area to greater than 10,000 and less than or equal to 50,000 acres of contiguous area (Label 2 to Label 5). Progressing in this manner we are able to obtain initial value increments of adjacent bins. To adjust for possible inconsistencies in the value increments for bins that are not adjacent, we use a second pass as described in the next and final step.

Step 3. The second pass of the multidimensional constructed scale assessment process uses pairwise comparisons to *refine* the value increments obtained by the holistic assessment described previously. The subject matter expert answers a series of questions designed to assess relative pairwise value increments. We use a pairwise preference scale to assess the bins, e.g., where a 1 indicates no change between the value increments of the two bins being assessed, and a 2 would indicate the value increment of one bin is twice as great as the other. For example, we would ask the subject matter experts by how much (if any) the value increments differ from Label 5 (corresponding to total heavy maneuver area between 10,000 and 50,000 acres and largest continuous area between 10,000 and 50,000 acres), and Label 8 (corresponding to total heavy maneuver area between 50,000 and 100,000 acres and largest contiguous area between 50,000 and 100,000 acres). A subject matter expert may answer with "2.5 times." Once the assessment was complete, we calculated a consistency ratio to ensure the pairwise comparisons were consistent. Figure 5 shows the final values for the example multidimensional scale.

4.5. Weights

To properly assess weights, we must account for the decision makers' preferences (relative importance of the attribute) and for the variation or range of installation data within the attribute measure. The weight process is subjective by nature; decision makers, stakeholders, and subject matter experts involved in the process provide their preferences. Reaching consensus on the weight assessment with a group of decision makers is sometimes difficult. We considered several common weight-assessment approaches: direct assessment, Simple Multiattribute Rating Technique (SMART), Simple Multiattribute Rating Technique using Swings (SMARTS), AHP, and SMARTER.

We initially selected the SMARTS method because it is a global assessment method based on measurable value theory, but due to the large number of attributes, we determined that the SMARTS method would be too difficult to implement and defend within the BRAC environment of stakeholder scrutiny. Therefore, we helped to develop and then extended the technique introduced by Trainor et al. (2004), the Swing Weight Matrix Method, which explicitly defines the two major weighting factors:

Figure 5 Assessed Multidimensional Constructed Scale

Largest contiguous area (1,000s acres)	Total heavy maneuver area (1,000s acres)			
	≤10	>10 and ≤50	>50 and ≤100	>100
≤10	0.1	0.2	1.4	2.0
>10 and ≤50		3.2	4.3	5.2
>50 and ≤100			6.1	7.6
>100				10.0

importance and variation prior to the weighting assessment. This method is applied in four steps:

Step 1. *Define the importance and variance dimensions*. For military value, the relative importance of an attribute depends on the army's *ability to change* an installation's attribute level. For example, an installation cannot simply expand its acreage, but it could expand administrative space by building additional facilities. The ability to change is represented in the columns, and the second criterion, the variability of range of the attribute, is in the rows. Figure 6 shows the matrix with increasing ability to change from right to left 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. As an example, the heavy maneuver area attribute is 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, while others have extensive areas for heavy maneuver training. The shading represents the level of importance corresponding to an attribute and is used to facilitate the discussion and gain concurrence on the attribute weights. Determining the relative variance of each measure requires some discussion for different types of measures. Once presented to the decision makers, the discussion first focuses on what importance level and variation the attribute is assigned.

Step 3. *Assess the swing weights*. After the leadership approves 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 swing weights from 0 to 100. We place the highest swing weight, $f_1 = 100$, in the upper left corner of the matrix. 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, $f_{3,6} = 1$, is in the lower right corner of the matrix. The remaining matrix swing weights are placed in the matrix according to the importance level and variation.

Figure 6 Swing Weight Matrix

← 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)	
Heavy mnvr area **Direct fire** **Brigade capacity** **100**	**Light mnvr area** **Indirect fire** **90**	**Int./partnering** **Area cost factor** **75**	*Housing avail.* *Crime index* *Maint./manuf.* *50*	*RDTE diversity* *20*	Supply & storage Ops/admin Ammo storage 10
Force deploy **Materiel deploy** **Airspace** **90**	**Critical infrastr.** **Proximity** **Test ranges** **Mob. history** **75**	*Munitions prod.* *Accessibility* *Urban sprawl* *50*	*Connectivity* *Work force* *Availability* *20*	MOUT 10	Applied instructional General instructional 5
Buildable acres **75**	*Soil resiliency* *Joint facilities* *50*	*Employment op.* *Water quantity* *Inst unit cost* *ENV. elasticity* *20*	Medical avail. Noise contours Air quality In-state tuition 10	C2 TGT facility 5	1

Level of importance		
HIGH	*MEDIUM*	LOW

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

$$w_i = \frac{f_i}{\sum_{w_i}^{40} f_i}, \quad \text{where } f_i = \text{matrix swing weight, corresponding to attribute } i. \qquad (3)$$

The Swing Weight Matrix Method provided an efficient and effective means to discuss, assess, brief, and explain the attribute weights. We believe this method has four advantages over traditional weighting methods. First, it develops an explicit definition of importance. Second, it forces explicit consideration of the variation of measures. Third, it provides a framework for consistent swing weight assessments. Fourth, it provides a simple yet effective framework to present and justify the weighting decisions.

In BRAC 2005, we used the matrix to assess weights with the army subject matter experts and key stakeholders. In addition, we used the matrix to explain our weighting process to auditors and senior decision makers. As an example, during the military value briefing to the Senior Review Group, a key stakeholder questioned the weight assignment to Military Operations in Urban Terrain Facilities. His logic was that these facilities were critical to provide training for current army operations. After we explained the Swing Weight Matrix, he agreed with the original weight assessment. The authors have successfully used the Swing Weight Matrix Method in several additional applications. We have found it a very effective and efficient method in each of these applications.

Once we obtained the certified data for each installation, the installation military value model provided a "1 to n" list of army installations. A complete discussion of installation results is in the Military Value Assessment Results document (DoD 2005); the technical discussion of the installation model is contained in Annex 4 of the Military Value Supporting Document (DoD 2005). As the primary BRAC 2005 consideration, the installation's military value was used in all subsequent analyses.

5. Military Value Portfolio Analyses

In a perfect world, we would have used an optimization model to determine the highest military value for a given budget. Unfortunately, the army does not have a model that would assess the feasibility and cost of moving units from one installation to all other possible installations. In addition, the development of transformational alternatives required the intervention of subject matter experts to develop creative alternatives. Instead, we developed the military value portfolio model to determine a portfolio of installations that maximized the total military value subject to army capacity requirements. If the army does not need an installation, then closing the installation and using the associated savings for other projects may be the best outcome. The portfolio model helped the army determine the minimum-sized portfolio that meets army requirements. The model did not *close* or *realign* installations. The model provided a portfolio of installations that the Senior Review Group used as the basis for its analysis for BRAC options. Using the results of the portfolio model, subject matter experts developed unit realignment and base closure options.

We made the following key linear programming assumptions:

(1) *The portfolio military value is the sum of installation military values*. The army portfolio value is the sum of the measurable installation values. Preference theory, on which multiple-objective decision analysis models are based, usually provides ordinal values, i.e., they only rank preferences. We systematically assessed the attributes and swing weights to ensure measurable value functions. To use the additive value model in Equation (1), all installations must be treated equally in the assessment process. This was reasonable in the BRAC application, because the within-installation value function and weight assigned was the same for every installation. Therefore, values for different installations can be added to obtain a portfolio value. In addition, for Equation (1) to hold at the portfolio level, it is necessary for pairwise preferential independence (or difference independence) to hold for evaluation attributes across installations, not just for attributes within each installation. Because constraints are imposed so that the minimum army BRAC requirements are guaranteed to be met by any portfolio, these independence conditions were reasonable approximations, both within and across installations. In addition to the independence conditions, the formulation in Equation (4) also assumes that installations not in the portfolio have values of zero, i.e., an installation not in the portfolio has a value equal to a (hypothetical) installation in the portfolio that has the worst possible level of each evaluation attribute.[3]

(2) *The alternatives could be separated*. We assume for the installation military value model that installations do not interact or provide synergies that affect military value.

(3) *The input data were deterministic*. All data used for the installation military value were provided through an auditable source and certified as correct by the responsible army agency.

Military value does not consider the army units that currently occupy an installation; instead, it considers an installation's potential capability and flexibility to support different unit types. The portfolio model does not have the ability to station units; it only evaluates potential stationing. Because units are not moved, stationing action costs are not captured. For example, the model does not account for new or upgraded military construction required because of unit moves. Stationing costs are captured in other BRAC 2005 analyses by a separate costing model as required by the BRAC legislation.

The portfolio model had two types of inputs—the objective function and the constraints. The sole input for the objective function was provided by the installations' military values. However, there were 14 capacity constraints, critical infrastructure and geographical coverage constraints, and Research Development Test and Evaluation (RDT&E) process constraints.

The 14 capacity constraints were used to ensure that army requirements would be satisfied by the installations' assets within the chosen portfolio. Using the capacity constraints, the model ensures that the sum of all assets across army installations represented within the constraints is contained within the portfolio. The critical infrastructure and geographical coverage constraints ensure that sufficient coverage exists for the installations contained within the feasible portfolio.

[3] This discussion follows Kirkwood (1997), Golabi et al. (1981), and the referee's suggestions.

Table 1 **Current Army RDT&E Capability**

RDT&E cover constraints	Number of processes
Weapons (munitions and armaments and direct energy)	13
Ground vehicles (land combat)	8
Information systems technology (C4ISR)	7
Air platforms (air combat)	7
Sensors, electronics, and electronic warfare	6
Chemical and biological defense	3
Human systems	3
Space platforms (space combat and ballistic missiles)	2
Battlespace environments	2
Materiel and processes	1
Sea vehicles (sea combat)	1

Table 1, Column 2, shows the total number of processes available in the current army inventory corresponding to the RDT&E capability in Column 1. The feasible portfolio must satisfy the army's RDT&E requirement by including at least one installation for each of the processes shown in Table 1. Of course, an installation could have more that one of the processes.

The portfolio model is formulated as a 0-1 integer program (Nemhauser and Wolsey 1988).

Indices

$j =$ installation

$c =$ army requirement

Parameters

$v_j =$ MV for installation j [MV units]

$g_{jc} =$ installation's j capacity for army requirement c [square feet, acres-days]

$K_c =$ army capability for requirement c [square feet, acres-days]

$N_{\min} =$ the minimum number of installations that satisfy army capacity requirement c

Decision variable

$$x_j = \begin{cases} 1, & \text{if installation } j \text{ is contained in the portfolio} \\ 0, & \text{otherwise.} \end{cases}$$

Objective function

$$\max \sum_j v_j x_j \tag{4}$$

$$\text{s.t.} \sum_j g_{jc} x_j \geq K_c \tag{5}$$

$$\sum_j x_j \leq N_{\min} \tag{6}$$

$$x_j \in \{0, 1\} \quad \forall j.$$

The objective function, Equation (4), maximizes the military value of the installations in a given portfolio. Beginning at 1, we incremented $N_{\min}$, Equation (6), until the first feasible portfolio was obtained (satisfies all constraints), and continued until the last iterated portfolio included all army installations. Each model solution after the constraints were satisfied includes additional excess capacity but also includes additional value.

We conducted three forms of sensitivity analysis. First, we examined how installations moved in and out of the solution as the model determined different size portfolios. There existed possibilities of installations being "in" a solution, but they were later excluded as the number of installations in the portfolio increased. This phenomenon is due to the different installation capacities and how adding installations changes the total army capacity.

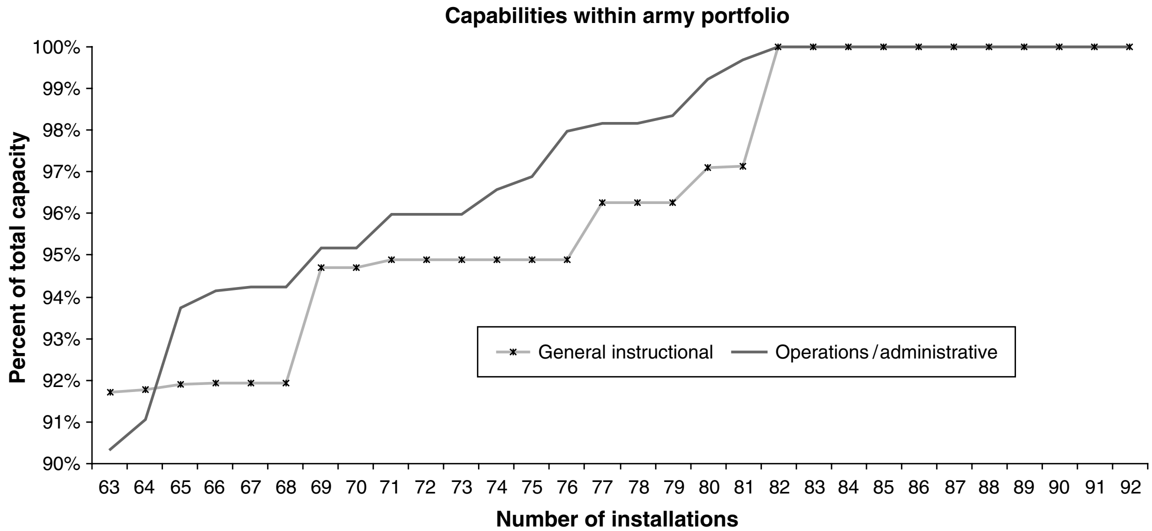
To conduct this sensitivity analysis, we incremented $N_{\min}$ and iterated the model up to the maximum-sized portfolio, and then considered the result. Table 2 provides an example showing a subset of five installations in the first four feasible portfolios. The second row shows the number of installations contained in the solution and the third row is the resulting military value. For example, Column P1 contains the first feasible portfolio, with 63 installations and a total military value of about 207.

In Table 2, a "1" (bold) signifies that the corresponding installation was contained in the portfolio, whereas a "0" signifies exclusion. For example, I1 is contained within all portfolios. I2 does not enter a portfolio until I5 exits and another installation (not

Table 2 **Selection of the First Five Feasible Portfolios**

Portfolio	P1	P2	P3	P4
# of installations in portfolio	63	64	65	66
Total military value	207.05	209.25	211.39	213.35
Installation name				
I1	**1**	**1**	**1**	**1**
I2	0	0	**1**	**1**
I3	**1**	**1**	**1**	**1**
I4	**1**	**1**	**1**	**1**
I5	0	**1**	0	**1**

Figure 7 **Example Capabilities Across Portfolios**



shown) enters P3. I5 reenters the solution in portfolio P4. In all cases, an installation enters the solution as the model increases the size of the portfolio. Installations that remain in the solution at all times are considered more essential to meet army requirements than installations that move in and out of the solution.

Our second sensitivity analysis examined the robustness of the capability constraints. For example, Figure 7 provides the amount of general instructional space and operational plus administrative space within portfolios with different numbers of installations (63 to 82).

The portfolio with 63 installations has ~90% of the army's total operations/administrative space and ~91% of the general instructional space. With 82 installations, percentages of these capabilities increase until all installations are in the portfolio with 100% of both capabilities.

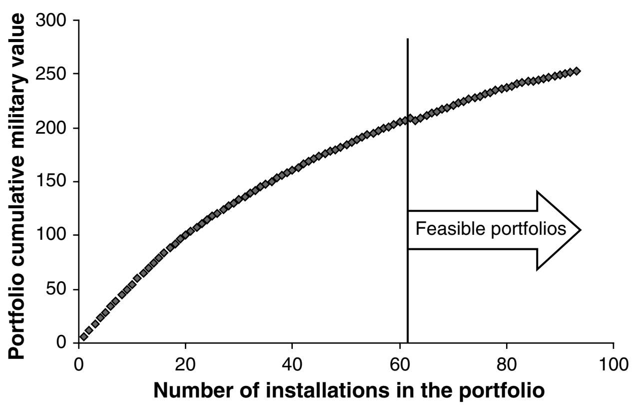
We identified the constraints that were the most binding. Binding refers to those constraints that force the model to add the last installation into the first feasible portfolio. As these binding constraints are relaxed, fewer installations are required to satisfy the capability, and thus, fewer installations are in the portfolio.

For example, if we require 88% of the administrative capability instead of 90%, then we would expect an installation to fall out of the portfolio unless another constraint was binding and forced installations to remain. We examined each of these constraints and determined the installations that would leave the portfolio if the constraints were relaxed (or enter if they were increased). This type of sensitivity analysis allowed us to answer questions from the Senior Review Group about the impact of changes to constraints on the baseline army portfolio.

For the last sensitivity analysis, we investigated the impact of varying the number of installations in the final portfolio. As previously discussed, at least one of the army BRAC constraints is not satisfied for $N_{\min} < 63$. For $n < 63$, MVP was determined by summing the MV of the n top-ranked installations. This is illustrated in Figure 8. Our procedure produces a nonmonotonic curve, because when $N_{\min} = 63$, a combination other than the 63 top-ranked installations satisfies the constraints. The slightly diminishing returns shape of the curve means that the installations the army has recommended for closure have military value but are not required to meet the capacity assumptions. Because the army has already had four BRAC rounds that closed numerous other installations, the curve may not be as pronounced as some might expect.

The installation military value and portfolio models identified the minimum number of installations in the army portfolio, which provided the basis for scenario

Figure 8 **Maximum Military Value Curve for a Portfolio of Installation**



analysis and all recommendations. Before we ran the portfolio model, the Senior Review Group determined that nine army installations provided unique capabilities that the army should retain. We fixed these installations into the portfolio solution and ran the initial baseline. This army portfolio contained 63 installations, which were subsequently approved as the army baseline.

On May 13, 2005, the final army portfolio that was sent forward to the DoD for inclusion in the consolidated BRAC recommendations to the commission contained 71 installations and 2 leases. Five of the installations contained in the initial baseline army portfolio were removed and not included in the final portfolio, whereas 13 other installations were added to the final army portfolio. These changes were made by the Senior Review Group based on recommendations from the Joint Cross Service Groups and the other criteria considerations (Criteria 5–8: cost and savings, economic impact, local area infrastructure, and environmental analysis). For BRAC 2005, there were seven Joint Cross Service Groups divided among different functional areas with the mandate to look across all of the service's business processes. The army's military value model did not include all of the factors that led to the Joint Cross Service Groups' decisions. Nor did the military value model consider the one-time implementation cost for stationing actions, as stated earlier; BRAC cost analysis was separate from military analysis as a fifth criterion and was considered in other modeling efforts and later in the military value assessment process.

A complete discussion of the military value portfolio model is in the Military Value Assessment Results document (DoD 2005).

6. Summary

The following are our most important lessons learned.

Be prepared. The army analysis team had significant experience in the problem domain (army stationing and BRAC) and extensive experience performing operations research and decision analysis for senior leaders.

Perform senior leader stakeholder analysis. The army senior leader interviews provided important perspectives, helped identify transformation opportunities, and enabled later access to key subject matter experts to help develop models.

Eliminate unnecessary constraints. Unlike BRAC 1995, we removed the installation category constraint. This allowed us to consider the military value of an installation for any army mission. This increased the solution space by allowing possible alternatives that moved missions between installation categories.

Use good decision analysis practice. We used the appropriate techniques for this problem: multiple-objective decision analysis to provide a 1-to-n ranking of installations evaluated against conflicting objectives and a portfolio model to help determine the highest-value installations for the army installation portfolio. Three other practice issues were important. First, we minimized the number of attributes, which meant we could obtain high-quality data for fewer high-quality measures. Second, the two-dimensional measures addressed the value dependence problem and helped gain senior leader support. Last, the Swing Weight Matrix was very useful to assess, explain, and defend weights.

Ignore bad advice. We received three recommendations that we did not follow. First, during our initial assessment, some individuals who had worked on BRAC 1995 warned us not to change the successful BRAC 1995 process. We viewed BRAC 2005 as fundamentally different due to the emphasis on transformation and joint warfighting. Second, some thought it was a bad idea to interview senior leaders. This was easy advice to ignore because we knew the senior leaders interview would (1) provide substantive insights that we could not find in the literature,

(2) increase final result credibility, (3) confirm research assumptions, and (4) keep them involved in the analysis. Finally, some of our friends warned us not to "waste our time working on a process that was political." We viewed the opportunity to help the army transform and save resources in a time of war as well worth the professional and personal risk.

We developed the multiple-objective decision analysis approach to ensure the army had a technically sound, repeatable, and auditable method to determine military value, which by law was the basis for all BRAC recommendations. In addition, we combined our installation military value model with an portfolio optimization model to develop the baseline of 63 installations that formed the basis for the development of the army's base realignment and closure candidate recommendations. Senior army decision makers used this analysis to determine the military value of installations as a starting point for their installation portfolio and to provide the basis for all army scenario development and BRAC recommendations.

The army recommendations create a 20-year gross savings of $20.4 billion for a one-time cost of $12.8 billion and generate 20-year net savings of $7.6 billion, which are 1.2 times the net army savings of the first four BRAC rounds combined (DoD 2005). The BRAC Commission approved 95% of army and 86% of all service and Joint Cross Service Group recommendations. The BRAC recommendations became law on November 9, 2005; the army is implementing their program.

Disclaimer

The views expressed in this paper are those of the authors and do not reflect the official policy or position of the United States Military Academy, the Naval Postgraduate School, the Department of Defense, or the United States government.

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Appendix. Army BRAC 2005 Installation Value Model

This appendix lists the military value model's attributes by name, brief purpose, and the type of scale. In the table below, we denote direct (DIR) measures as those where an existing natural proxy scale is developed based on interval data. When only nominal or ordinal data was used for a measure, we constructed an appropriate scale (denoted below as CON). All Multidimensional Constructed (MDC) scales required the development of *bins*, and are therefore considered constructed, regardless of the underlying data type.

Attribute name	Attribute description	Measure
Airspace	Joint airspace's (controlled by the installation) ability to support training	MDC
Heavy maneuver area	Ability to support training and maneuver of mechanized forces	MDC
Light maneuver area	Ability to support training of light forces	DIR
Direct-fire capability	Range's and impact area's ability to support direct-fire weapons training	MDC
Indirect-fire capability	Ranges and impact area's ability to support indirect-fire weapons training	MDC
Military operations in urban terrain	Ability to support military operations in urban terrain training	MDC
Soil resiliency	Resiliency of training land using highly erodible land classification	CON
Noise contours	Degree of external encroachment as result of extension of noise contours off-installation	MDC

continued

Attribute name	Attribute description	Measure
Air quality	Degree of air quality status of air above an installation	CON
Applied instructional facilities	Capability to conduct applied instruction using existing or convertible facilities	CON
General instructional facilities	Capability to conduct general instruction using existing general-purpose facilities	CON
Brigade capacity	Current and future ability to support army maneuver brigades	DIR
Buildable acres	Capability if internal expansion on an installation	DIR
Critical facility proximity	Capability to support consequence management and homeland defense missions	DIR
Urban sprawl	Future expectations of encroachment around the installation	DIR
Environmental elasticity	Ability to absorb additional personnel given environmental constraints	MDC
Force deployment	Capability to support unit of action deployments	DIR
Materiel deployment	Capability to support materiel deployment	DIR
Mobilization	Potential future contribution to reserve component mobilization and deployment capability	DIR
Accessibility	Accessibility to joint and homeland command and control missions	MDC
Connectivity	Capability to provide the installation's tenants a robust communications network	CON
Operations and administrative facilities	Capability to accomplish operations and administrative missions using existing or convertible facilities	CON
Supply and storage capacity	Current total storage capacity (less ammunition and wet tank storage)	DIR
Interservice and partnering with industry flexibility	Ability of the depots and arsenals to support the operational readiness of other services	CON
Maintenance and manufacturing production capacity	Capacity to support additional maintenance and manufacturing workload	CON
Munitions production capability	Current capability to produce munitions	CON
Ammunition storage capacity	Capability to store ammunition	CON
Test range capability	Ranges' and impact area's capability to support test and evaluation	MDC
RDTE mission diversity	Ability to support research, development, test, and evaluation missions	CON
Workforce availability	Available workforce near the installation	CON
Area cost factor	Cost of construction or modernization	DIR
Joint facilities cost sharing	Level of joint activity on the installation	MDC
Installation cost factor	Relative unit cost of operating an installation	DIR
Target for focus facilities	Cost to bring Installations of special interest (Focus Facilities) to a specified quality level	MDC
In-state tuition policy	Education affordability for soldiers and families	MDC
Water quantity	Availability of water resources within the geographic region of the installation	CON
Crime index	Level of crime near the installation	DIR
Housing	Current availability of affordable housing near the installation	MDC
Employment opportunity	Current family employment opportunity near the installation	MDC
Medical care availability	Availability of medical care on and around the installation	CON

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