Theory, Best Practices, and An Illustrative Example

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Useful Quotes

- .." when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind …" Lord Kelvin

- "If you can not measure it, you can not improve it." Lord Kelvin

- "Money is the measure of all things" Unknown

Agenda

- Definitions
- Terms
- Disciplines
  - Policy Analysis
  - Systems Analysis
  - Decision Analysis
  - Organizational strategy
  - System Engineering
  - System Thinking
  - Capability Based Planning
- Mathematics
- Illustrative Example
- Principles

Some Basic Definitions

- Metric: a standard of measurement
- Measure: a standard of comparison
- Measurement: an act or process of measuring

Source: http://www.merriam-webster.com/

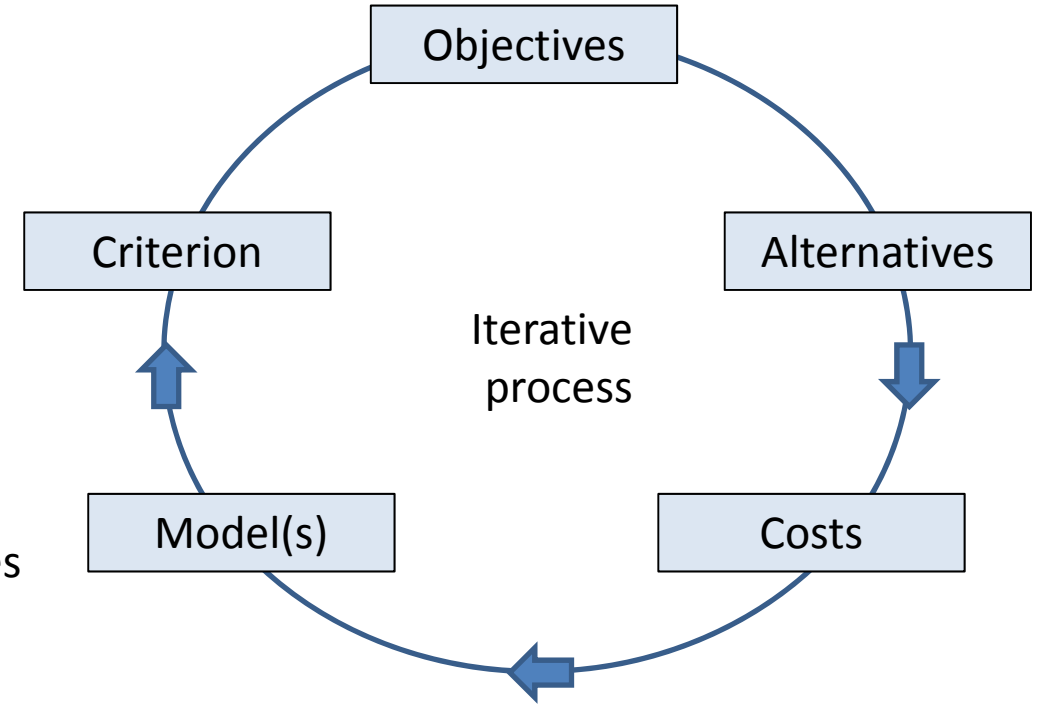
There are lots of terms for metrics.

- Value Measure
- Measure of Effectiveness
- Measure of Merit
- Measure of Outcome
- Measures of Performance
- Output measure
- Efficiency Measure
- Process measure
- Input measure
- Resource measure
- Leading indicators
- Lagging indicators
- Environmental measures
- Adversary measures
- Criteria
- Attribute
- Metric

Systems Analysis

Quade E. S. & Boucher, W. I., Systems Analysis and Policy Planning: Applications in Defense, R-439-PR, Rand, June 1968

"The first and most important task is to define the objectives of the decision makers"



Standard for ranking alternatives

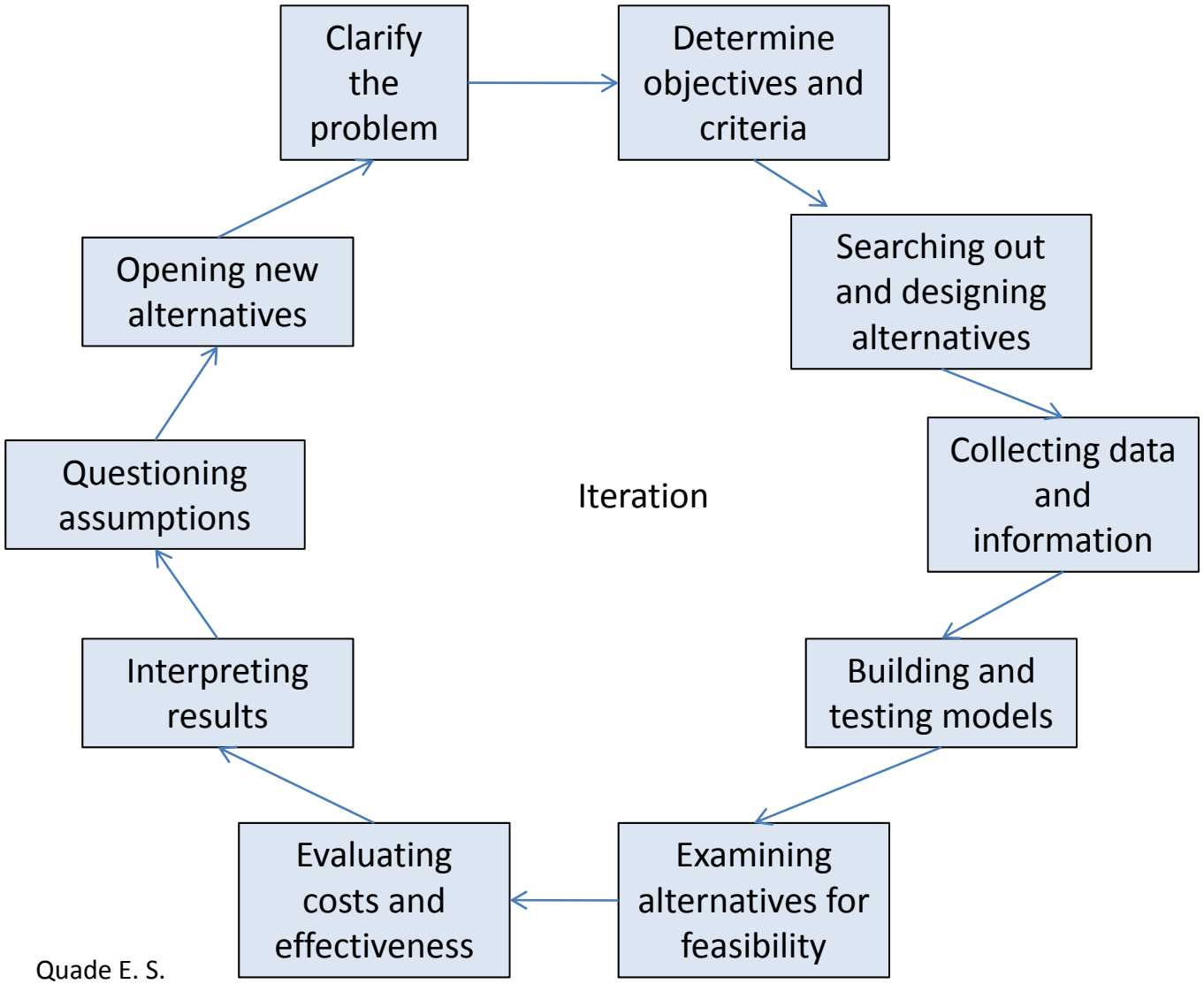
Means to obtain objectives

Means to estimate consequence of choices

Resources to obtain objectives

1. Objectives play a fundamental role
2. Principal criterion was cost-effectiveness
3. Attempted to use one measure of effectiveness
4. Models used to calculate effectiveness and costs
5. Critical assumption was that all relevant factors could be included in effectiveness or cost.

Policy Analysis

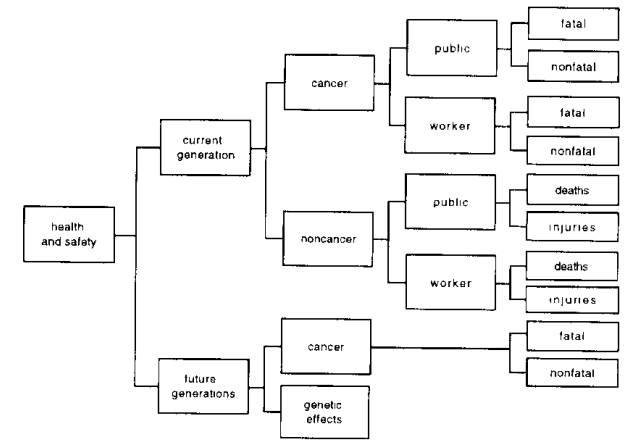


1. Clarifying the problem plays important role
2. Again, objectives are linked to criteria
3. Principal criterion was cost-effectiveness
4. Models used to calculate effectiveness and costs
5. Critical assumption was that all relevant factors could be included in effectiveness or cost.

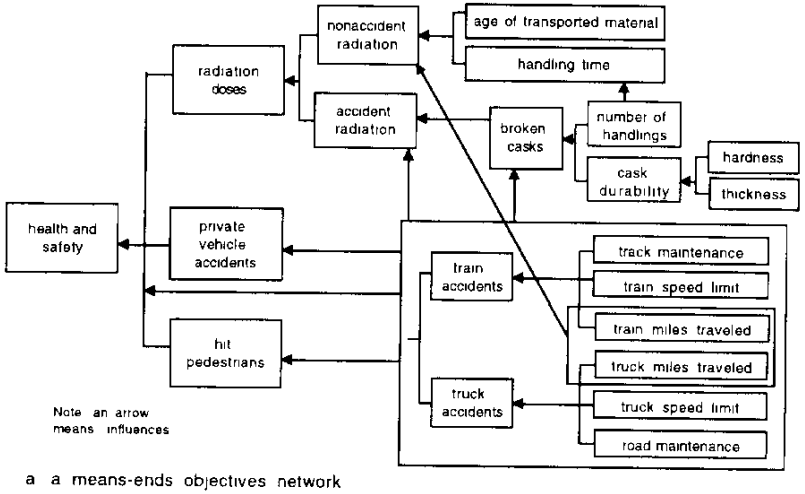
Quade E. S. Analysis for Public Decisions, Elsevier, 1975

Multiple Objective Decision Analysis

- Qualitative
  - Defining our values and objectives helps identify measures
  - Objectives
    - Fundamental objectives – what we care about (who, why, what, when, and where)
    - Means objectives – how we attain the fundamental objectives (how)
- Quantitative
  - Provided mathematics for evaluating the attainment of objectives using measures, value/utility functions, and weights.



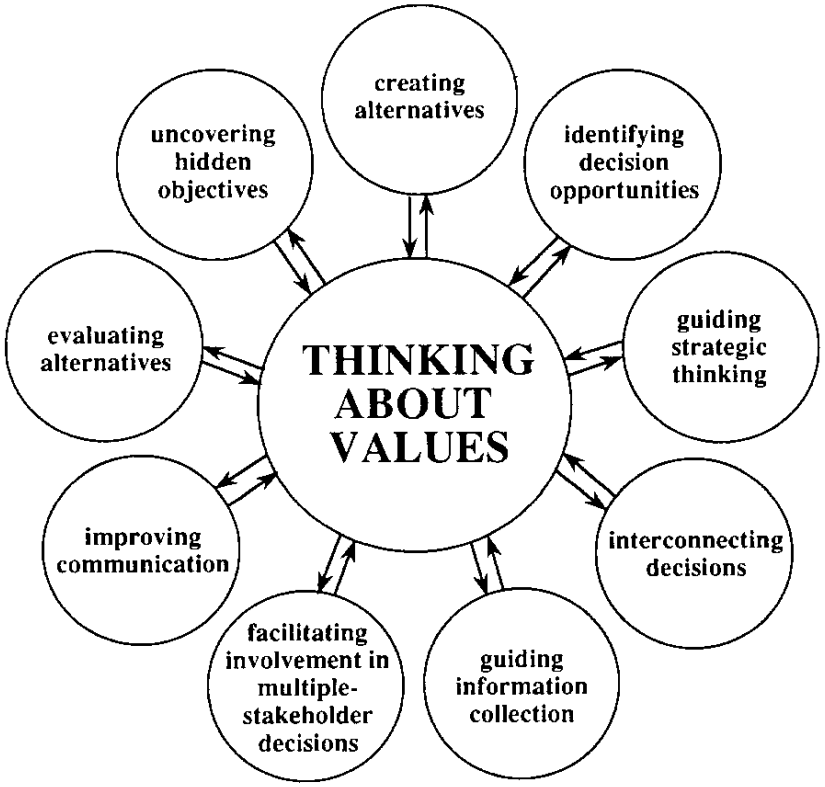
b a fundamental objectives hierarchy



a a means-ends objectives network

Keeney, R.L. and Raiffa H. *Decision Making with Multiple Objectives Preferences and Value Tradeoffs*. New York: Wiley, 1976.

Value-Focused Thinking



- Thinking about our values has many benefits
- Value-focused thinking is a philosophy
  - Create decision opportunities
  - Start first with your values
  - Use you values to identify better alternatives
  - Use your values to evaluate alternatives
- Values to objectives to measures

Keeney, R.L. **Value-Focused Thinking: A Path to Creative Decision making**. Cambridge, Massachusetts: Harvard University Press, 1992.

Objective identification is difficult.

- "In three empirical studies, participants consistently omitted nearly half of the objectives that they later identified as personally important.
- More surprisingly, omitted objectives were as important as the objectives generated by the participates on their own.
- These empirical results were replicated in real-world case study of decision making at a high-tech firm.
- Decision makers are considerably deficient in utilizing personal knowledge and values to form objectives for the decisions they face."

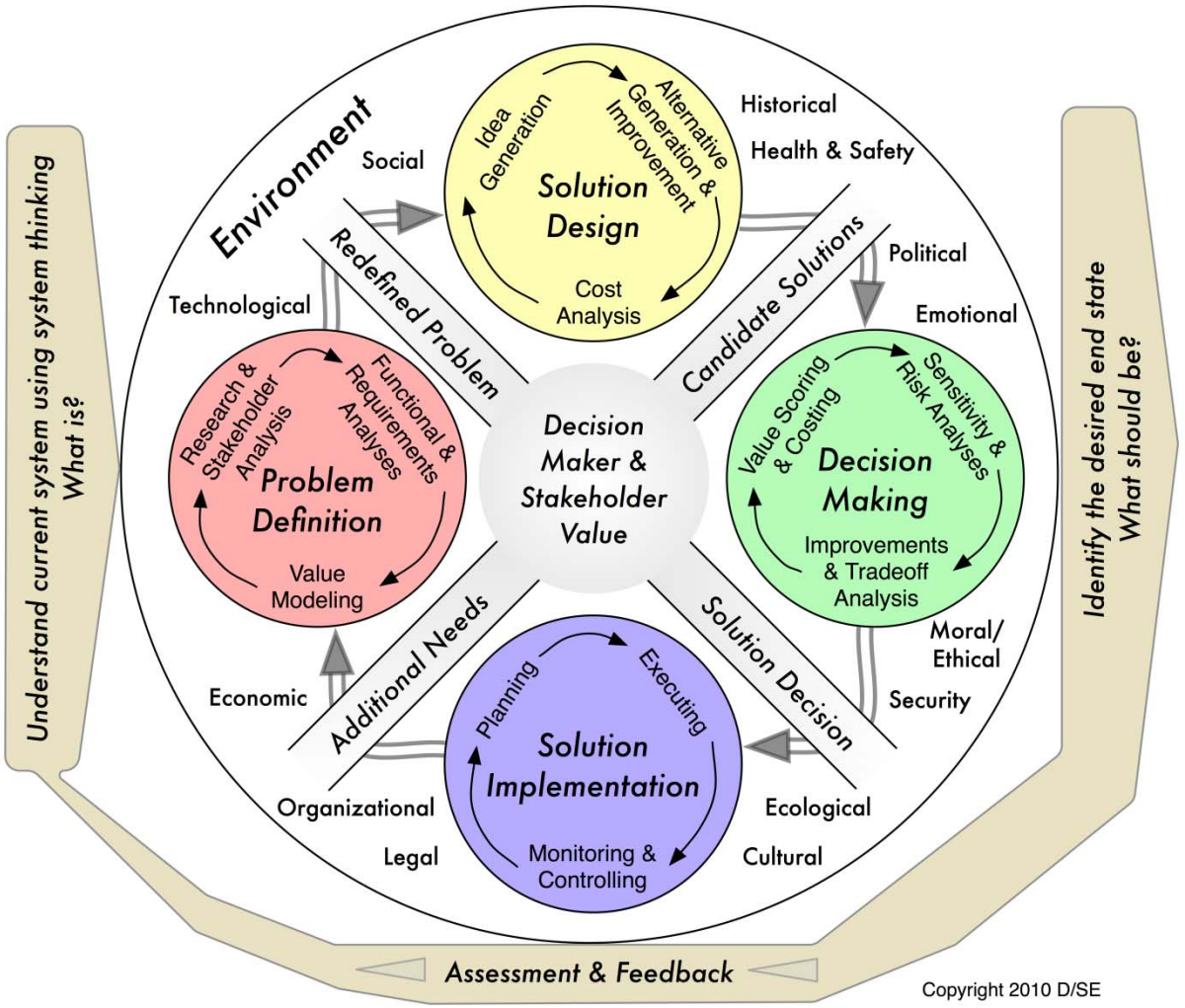
Bond. S., Carlson, D., & Keeney, R., "Generating Objectives: Can Decision Makers Articulate What They Want?" Management Science, Vol. 54, No. 1, January 2008, pp. 56-70

Metrics play a key role in the development and implementation of organizational strategy.

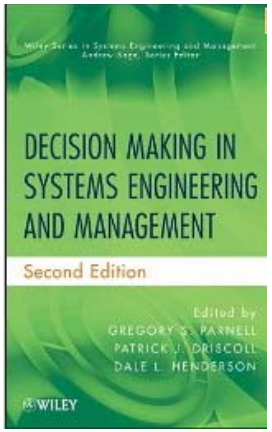
- Metrics play a critical role identifying performance targets and aligning business processes.
- Requires hard thinking about organizational strategy and measurement

http://www.senalosa.com/services/consulting

Using of metrics in Systems Engineering

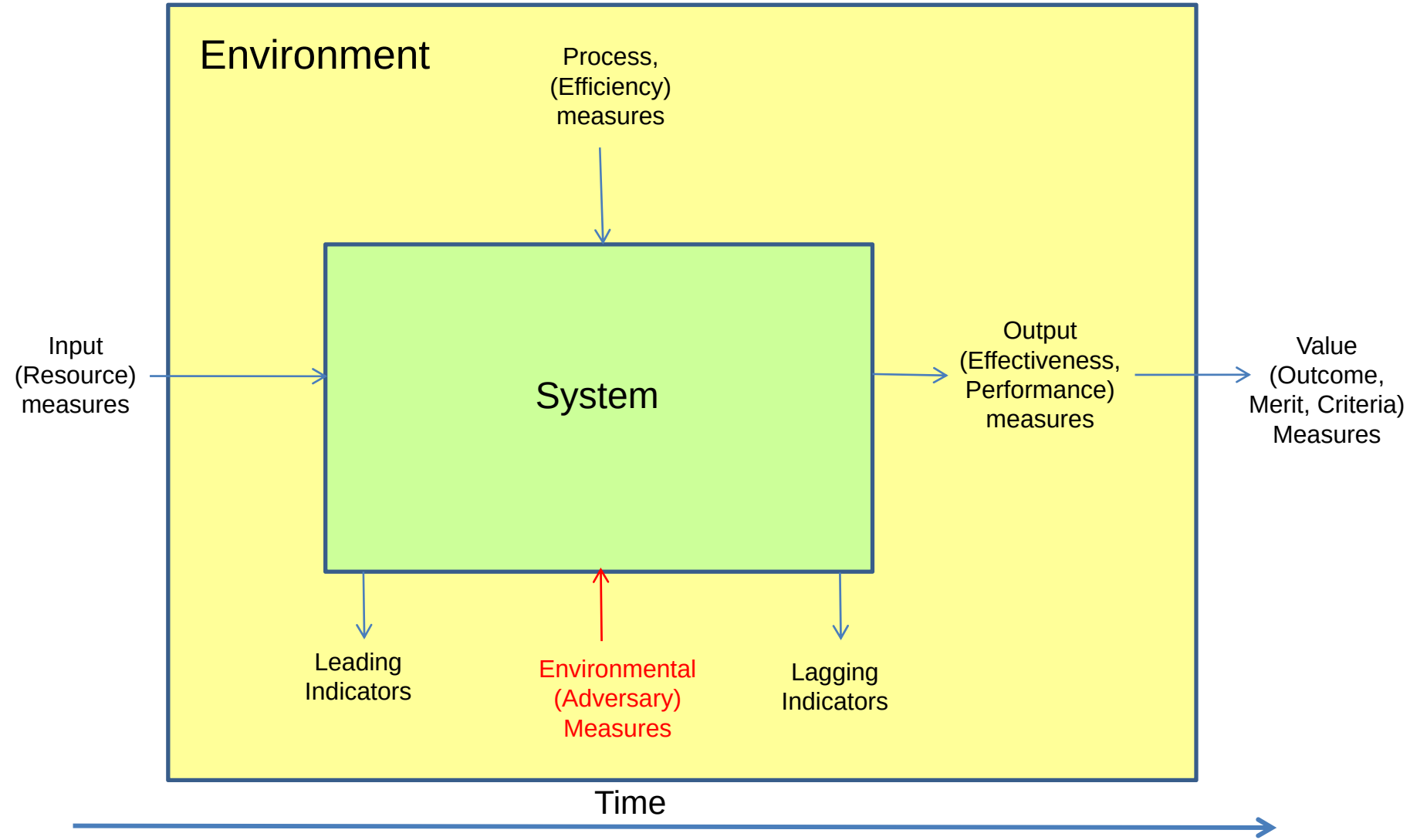


- Use functional hierarchies to identify the functions that have to be performed by a system
- Use value hierarchies to identify the value measures



Parnell, G. S., Driscoll, P. J., and Henderson D. L., Editors, 2nd Edition, **Decision Making for Systems Engineering and Management**, Wiley Series in Systems Engineering, Wiley & Sons Inc., 2011

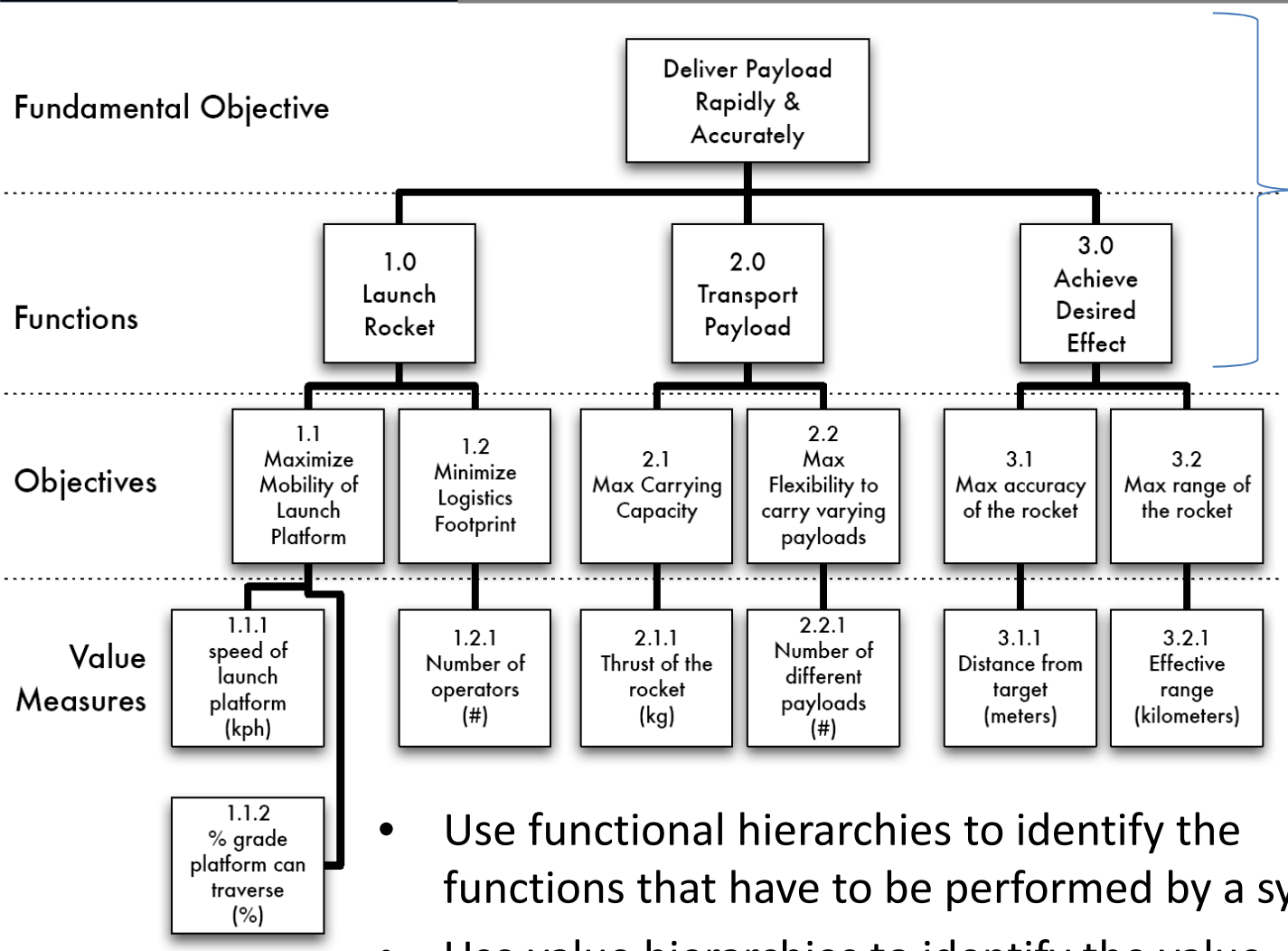
A System Thinking View of Metrics



All measures are dynamic and assessed over time.

Environmental (Adversary) measures are sometimes not considered.

Functional hierarchies can help identify measures.



Functional Hierarchy

Value Hierarchy

- Use functional hierarchies to identify the functions that have to be performed by a system
- Use value hierarchies to identify the value measures

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Capability Based Planning with Value-Focused Thinking

Develop Fundamental Objective

Provide a *lethal, mobile, protected vehicle for an infantry squad* capable of conducting the full range of military operations in a joint environment, *with future growth capability.*

Develop System Functions (Capabilities)

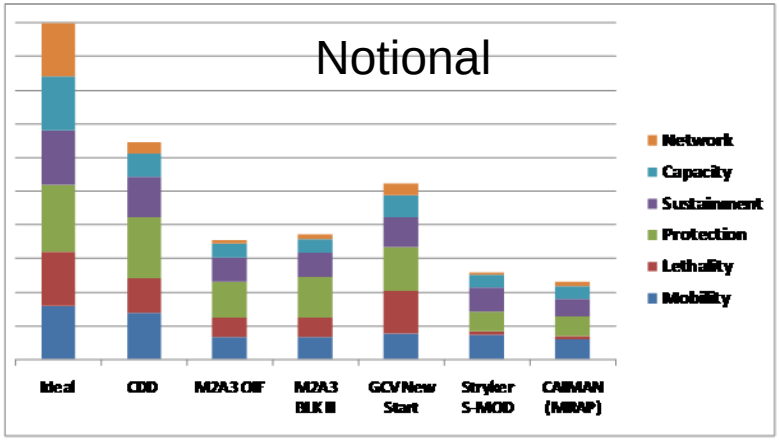
- Provide Force Protection / Vehicle Survivability
- Provide Mobility
- Provide Lethality
- . . .

Develop Objectives

- Maximize Force Protection
- Maximize Vehicle Survivability
- Maximize Acceleration
- . . .

Identify Value Measures (Attributes)

- Frontal Threat (1-5 Scale)
- Underbelly Threat (1-5 Scale)
- Overhead Threat (1-5 Scale)
- Side Threat (1-5 Scale)
- Rear Threat (1-5 Scale)



Army's Ground Combat Vehicle Analysis of Alternatives

Measures are characterized by alignment with objective and the type of scale.

- Types of measures
  - Natural: in general use and common interpretation by all (profit)
  - Constructed: developed for a particular objective (level of security classification)
  - Direct: focuses on the attainment of the objective (profit)
  - Proxy: focuses on the attainment of an associated objective (GNP for economic well being, # of tanks killed for success in battle)
- Preference lessons learned

Alignment with objective

Type of Scale	Direct	Proxy
Natural	1	3
Constructed	2	4

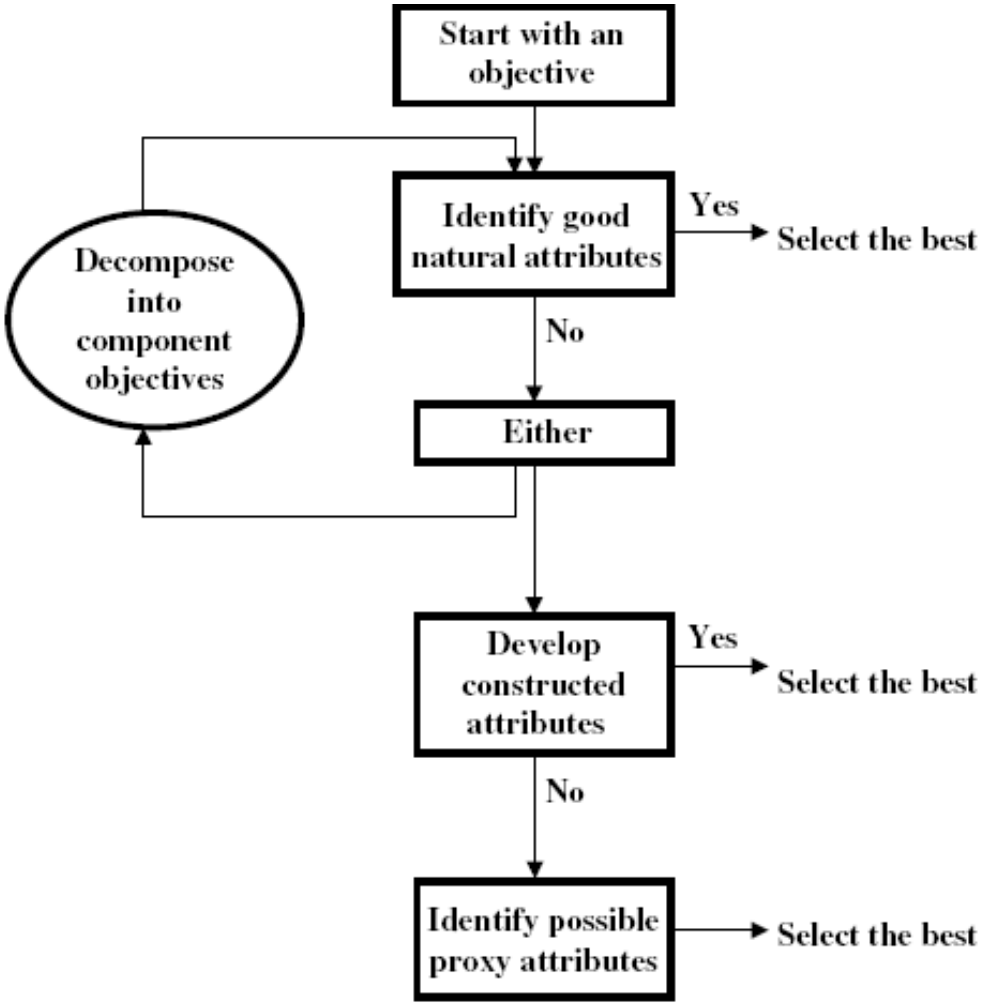
Kirkwood, C. W., *Strategic Decision Making: Multiobjective Decision Analysis with Spreadsheets*, Belmont, California: Duxbury Press, 1997.

Examples of measure categories.

Type of Scale	Alignment with objective: Direct	Alignment with objective: Proxy
Natural	1	3
Constructed	2	4

Objective	Measure(s)	Category
Maximize fuel efficiency	Miles per gallon	1
Maximize safety in crash	National Highway Traffic Safety Administration (NHTSA) 5 star crash test rating	2
Minimize impact on environment	Miles per gallon	3
Maximize vehicle safety	Number of seatbelts Vehicle stopping distance Depth of tire tread remaining Number of airbags	3
Maximize automobile safety	National Highway Traffic Safety Administration (NHTSA) 5 star crash test rating	4

Process for developing measures.



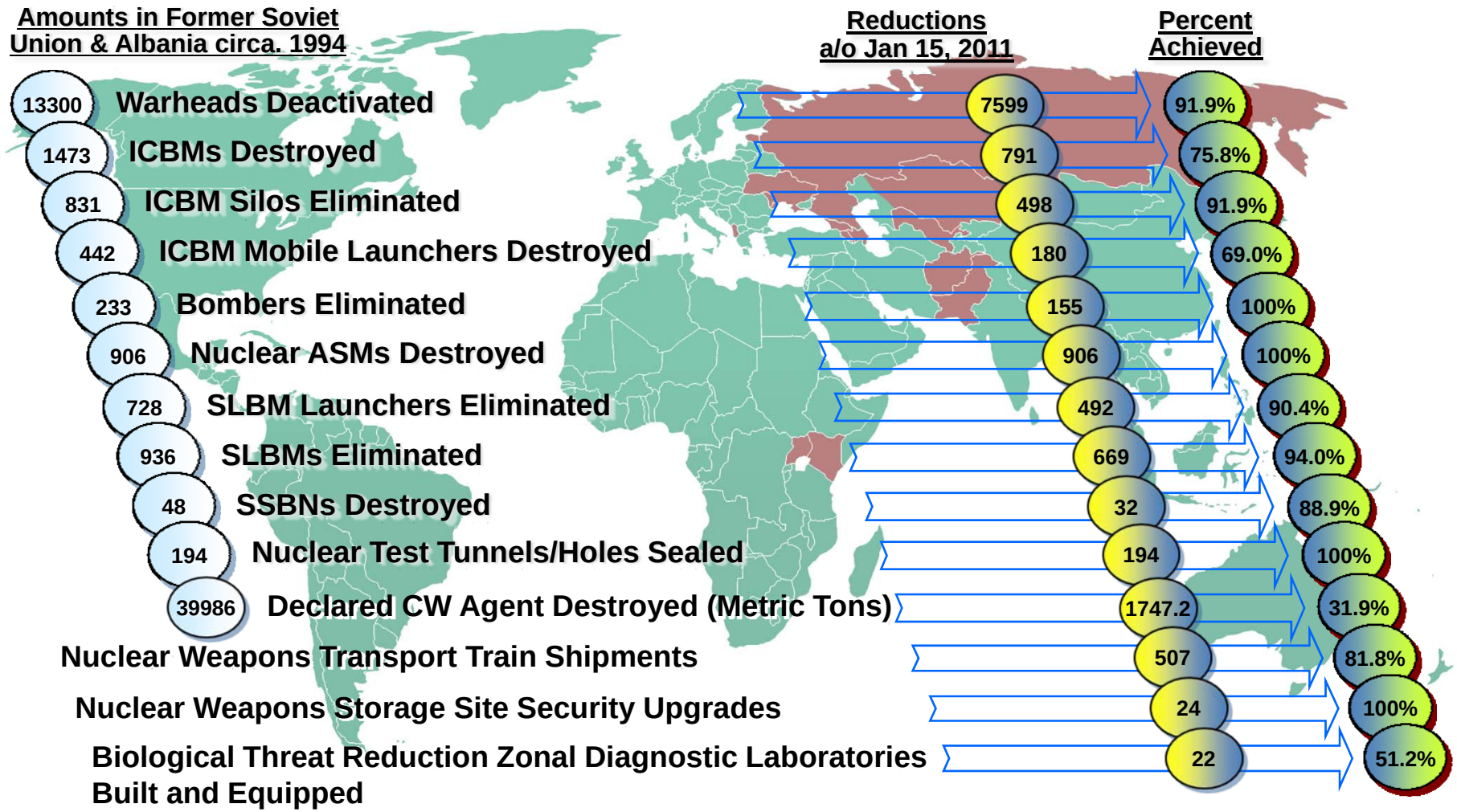
Shows measure preferences and the key role of decomposition.

Alignment with objective

Type of Scale	Direct	Proxy
Natural	1	3
Constructed	2	4

Keeney, R, & Gregory, R. "Selecting attributes to measure the achievement of objectives," Operations Research, Vol 55, No 1. 2005, pp1-11

Example – Nunn–Lugar CTR Scorecard
Ukraine, Kazakhstan, & Belarus are Nuclear Weapons Free
Albania is Chemical Weapons Free (20 year program)



Challenge: How can DTRA develop metrics for biological threats?

Program is currently teaming with Armenia, Azerbaijan, Kazakhstan, Ukraine, Georgia, Uzbekistan, and the Russian Federation to achieve six objectives.

Objectives
1. Secure and consolidate collections of especially dangerous pathogens (EDP) and their associated research at a minimum number of secure facilities
2. Enhance partner country/region's capability to prevent the sale, theft, diversion, or accidental release of biological weapons (BW)-related materials, technology, and expertise by improving biological safety and security (BS&S) standards
3. Enhance partner country/region's capability to detect, diagnose, and report endemic and epidemic, man-made or natural EDPs, bio-terror attacks, and potential pandemics
4. Ensure the developed capabilities are designed to be sustainable
5. Facilitate engagement of partner country's/regional scientific and technical personnel in research areas of interest to both the partner country/region and the U.S
6. Eliminate any BW-related infrastructure and technologies encountered

Measures of Effectiveness

- Define end-state goals, derived from Office of Secretary of Defense guidance
- Focuses on objective data as indicators of success
- Use internationally recognized regulations, standards, and best practices
- Use passive means of data collection wherever possible

Georgia, Armenia, Azerbaijan, Kazakhstan, Uzbekistan, Ukraine, and the Russian Federation

Objective	MOE	GG	AM	AJ	KZ	UZ	UA	RF
1 Consolidate & Secure	1-Consolidate	G	I	Y	R	G	Y	I
Max 10 pts possible	2- Secure	Y	R	Y	R	G	Y	R
2 Enhance ability/prevent theft	1- Consolidate	G	I	Y	Y	G	Y	I
	2- Secure	Y	R	Y	R	G	Y	I
	2-3-1 - Legal Framework	Y	R	G	R	Y	Y	Y
	2-3-2 Regulation	Y	R	G	R	I	I	G
	2-4-1 BioSafety Guidlines	R	R	Y	R	R	I	G
Max 55 pts possible	2-4-2 Facility Plans	R	I	G	G	R	Y	G
	2-5-1 Biosecurity Standrds	I	I	Y	R	Y	Y	
	2-5-2 Biosecurity Plan	R	I	G	R	R	Y	
	2-6-1 BS&SStandards Available	I	I	Y	R	Y	Y	G
	2-6-2 Biosecurity event notification	R	I	G	Y	I	Y	G
	2-6-3 Biosafety event notification	R	I	G	Y	I	Y	G

Examples of MOE Data Gathering Report

Percentage Complete	Obj 1	Obj 2	Obj 3	Obj 4	Obj 5	Overall percent complet
GE	80%	25%	35%	15%	60%	43%
AM	0%	0%	5%	0%	33%	8%
AJ	60%	82%	60%	60%	87%	70%
KZ	0%	25%	46%	15%	37%	25%
UZ	100%	35%	42%	45%	37%	52%
UA	60%	49%	22%	45%	50%	45%
RF	0%	60%	61%	50%	67%	47%

West Point
The United States Military Academy

Georgia overall percent complete not accepted by committee or DTRA.

Objective	MOE	GG	AM	AJ	KZ	UZ	UA	RF
1 Consolidate & Secure	1-Consolidate	G	I	Y	R	G	Y	I
Max 10 pts possible	2- Secure	Y	R	Y	R	G	Y	R
2 Enhance ability/prevent theft	1- Consolidate	G	I	Y	Y	G	Y	I
	2- Secure	Y	R	Y	R	G	Y	I
	2-3-1- Legal Framework	Y	R	G	R	Y	Y	Y
	2-3-2 Regulation	Y	R	G	R	I	I	G
	2-4-1 BioSafety Guidlines	R	R	Y	R	R	I	G
Max 55 pts possible	2-4-2 Facility Plans	R	I	G	G	R	Y	G
	2-5-1 Biosecurity Standrds	I	I	Y	R	Y	Y	
	2-5-2 Biosecurity Plan	R	I	G	R	R	Y	
	2-6-1 BS&SStandards Available	I	I	Y	R	Y	Y	G
	2-6-2 Biosecurity event notification	R	I	G	Y	I	Y	G
	2-6-3 Biosafety event notification	R	I	G	Y	I	Y	G
3 Enhance ability to detect	3-1 Biosafety guidlines	Y	I	G	I	Y	Y	I
	3-2 Biosecurity standards	R	I	Y	I	R	Y	I
	3-3-1 Natl Pandemic plan	G	Y	G	I	G	R	I
	3-3-2 Bioterorism plan	Y	R	Y	I	I	I	I
	3-3-3 Natl. Multi-hazard resp plan	R	R	G	I	Y	I	I
	3-3-4 Natl resp plan for animal diseas	R	R	R	I	I	I	I
	3-4-1 Natl. Disease Surv plan	R	Y	G	I	Y	Y	Y
	3-5-1 System to detect EDP cases	Y	I	Y	I	I	Y	Y
	3-5-2 EDP data shared	R	I	Y	Y	I	I	G
	3-5-3 Lab results to proper officials	R	I	Y	Y	I	I	G
Max 125 pts possible	3-5-4 Human reports to WHO	Y	I	G	G	G	I	G
	3-5-5 Animal reports to OIE	Y	I	R	G	G	I	G
	3-5-6 Case data shared properly	R	I	R	G	I	Y	G
	3-6-1 Epi data properly reported	G	I	R	I	I	G	G
	3-6-2 Lab results properly reported	Y	I	R	I	I	I	G
	3-6-3 PHEIC reported to WHO	Y	I	G	I	G	I	G
	3-6-4 Animal diseases reported to OI	Y	I	R	I	G	I	G
	3-7-1 EDP Investigations	G	I	R	G	I	Y	G
	3-7-2 Proper sample collection	I	I	G	Y	G	I	G
	3-7-3 ability to diagnose EDP	I	I	G	Y	G	I	G
	3-7-4 Utilize Intl Ref Labs	I	I	G	G	R	I	I
	3-8-1 Cases promptly reported	G	I	R	G	Y	G	G
	3-8-2 Proper sample transportation	I	I	G	G	Y	I	G
	3-8-3 Prompt diagnosis of Endemic	I	I	G	G	Y	I	I
	3-8-4 Use Intl labs when needed	I	I	G	G	R	I	I
4 Sustainability	1 Plan to maintain collection	R	I	Y	R	Y	Y	G
	2 Sustainment costs/ BS&S	R	I	Y	R	Y	Y	I
Max 20 pts possible	3 Sustainment costs	R	I	Y	R	Y	Y	I
	4 Trainee test results	Y	I	Y	Y	Y	Y	G
Supplemental Objective 5	1 Credible research results	R	G	G	G	R	G	G
	2-1 US access to datza	G	G	G	I	Y	I	I
	2-2 Copies of EDP to US	G	I	G	Y	R	I	G
Max 30 pts possible	2-3 Contribution to Intl Scientific community	G	I	G	Y	G	G	G
	3 Biosafety guidelines	Y	I	Y	I	Y	Y	G
	4 Biosecurity Standards	R	I	Y	I	I	G	I

G = 5 Points // Completed
Y = 3 Points // In process
R = 0 Points // Not started or just starting
I = No information available

Point totals	Obj 1	Obj 2	Obj 3	Obj 4	Obj 5
GE	8	14	44	3	18
AM	0	0	6	0	10
AJ	6	45	75	12	26
KZ	0	14	57	3	11
UZ	10	19	53	9	11
UA	6	27	28	9	15
RF	0	33	76	10	20

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RF	0%	60%	61%	50%	67%	47%

West Point
The United States Military Academy

Cooperative Biological Engagement Program metrics assessment.

	Partner Domestic Stability (Environment)	Partner Capability			Partner Outcome	Total
		Input	Process (Existence)	Output (Conditional)*		
1. Secure & Consolidate			1		1^ (Consolidate EDP)	2
2. Improve bio security & safety standards			10	2	1^ (Consolidate EDP)	13
3. Detect, diagnose, & report			8	17		25
4. Sustain Capabilities		2 (Budget)	1	1		4
5. Engage scientific & technical people			2	3	1 (Copies of EDP stains sent to US)	6
6. Eliminate BW technologies					1 (Eliminate BW)	1
Total	0	2	22	23	4	51

EDP = Especially Dangerous Pathogens
* Output is conditional on the event occurring.
^ Same measure.

- 3 strong direct measures (outcomes) (1 duplicate).
- No attempt to present cost-effectiveness.
- No measures for domestic stability.
- Large number of process proxy measures.
- Large # of conditional outcome measures which are difficult to assess a priori.

Illustrative Use mathematics of Multiple Objective Decision Analysis – 1 of 4

Use the Swing Weight Matrix to prioritize measures.

		Importance of the measure		
		Direct reduction in biological threat	Demonstrated use of biosafety and biosecurity procedures	Develop biosafety and biosecurity plans , procedures, and programs
Range in the amount of effort to complete	Large	Consolidate EDP - 100 Secure EDP - 100	Copies of EDP strains sent to US - 50	Major biosafety and biosecurity plans - 10
	Medium	Budget sustainment resources - 50	Demonstrate EDP detection and timely reporting - 25	Other important detailed plans - 5
	Small	Research programs aligned with national & international EDP priorities - 10	Other detection and timely reporting - 5	All other plans - 1
	None	Eliminate known BW weapons (Assume none in 6 partner countries)		

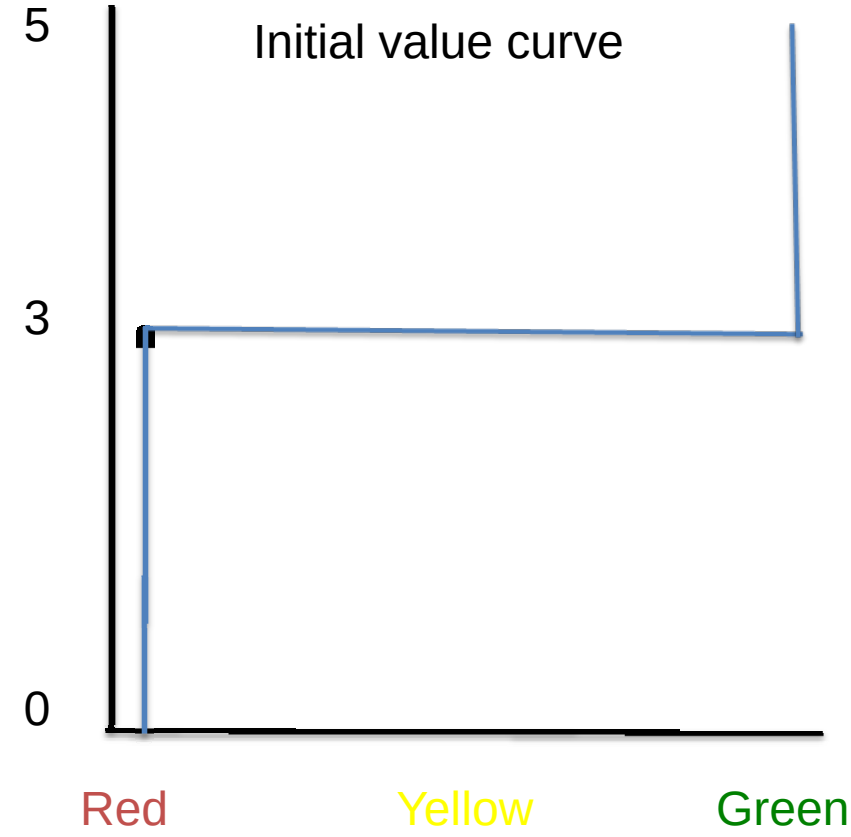
Measure name – non normalized swing weight, f_i for measure i

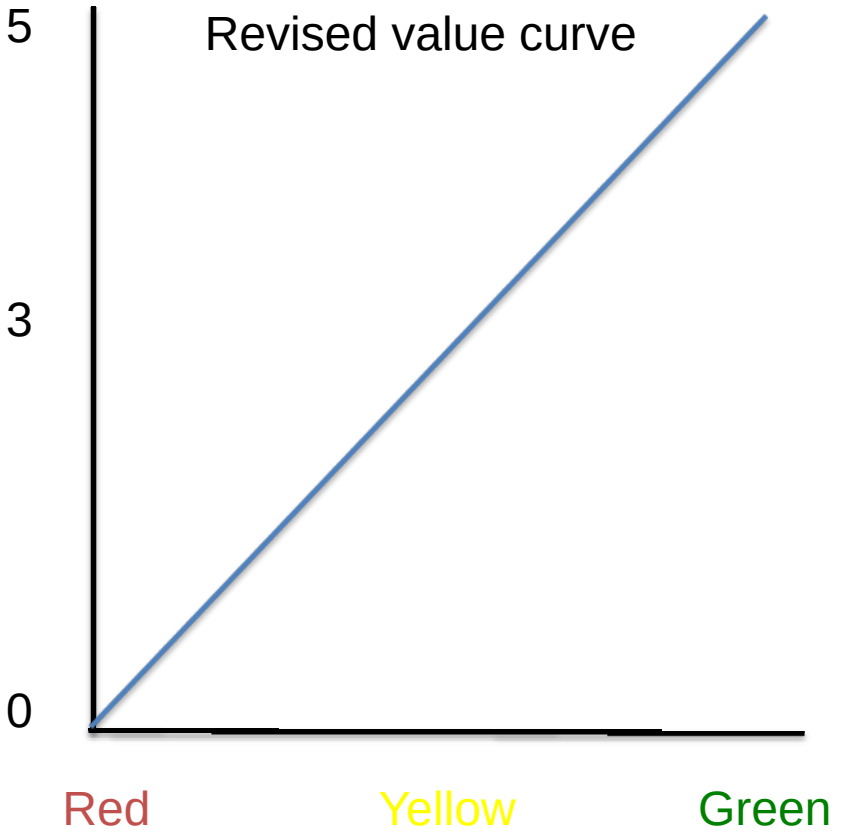
$$w_i = \frac{f_i}{\sum_{i=1}^{n} f_i} =$$

normalized swing weight corresponding to value measure *i*.

Parnell, G. S., Driscoll, P. J., and Henderson D. L., Editors, 2nd Edition, **Decision Making for Systems Engineering and Management**, Wiley Series in Systems Engineering, Wiley & Sons Inc., 2011

Illustrative Use mathematics of Multiple Objective Decision Analysis – 2 of 4





The value curves for each measure normalizes the percent completion to a scale of 0 to 5. It may simpler to just use 0 to 100%.

Keeney, R.L. and Raiffa H. **Decision Making with Multiple Objective Preferences and Value Tradeoffs**. New York: Wiley, 1976.

Illustrative Use mathematics of Multiple Objective Decision Analysis – 3 of 4

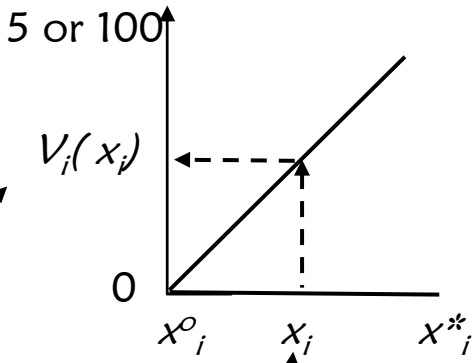
Total Value (% Complete)

Normalized swing weights for each value measure *i* assess importance and impact of range variation

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

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

Normalized swing weights sum to 1



Value function for each measure *i*: assess returns-to-scale and provide a 'common currency' across all measures

Score on value measure i

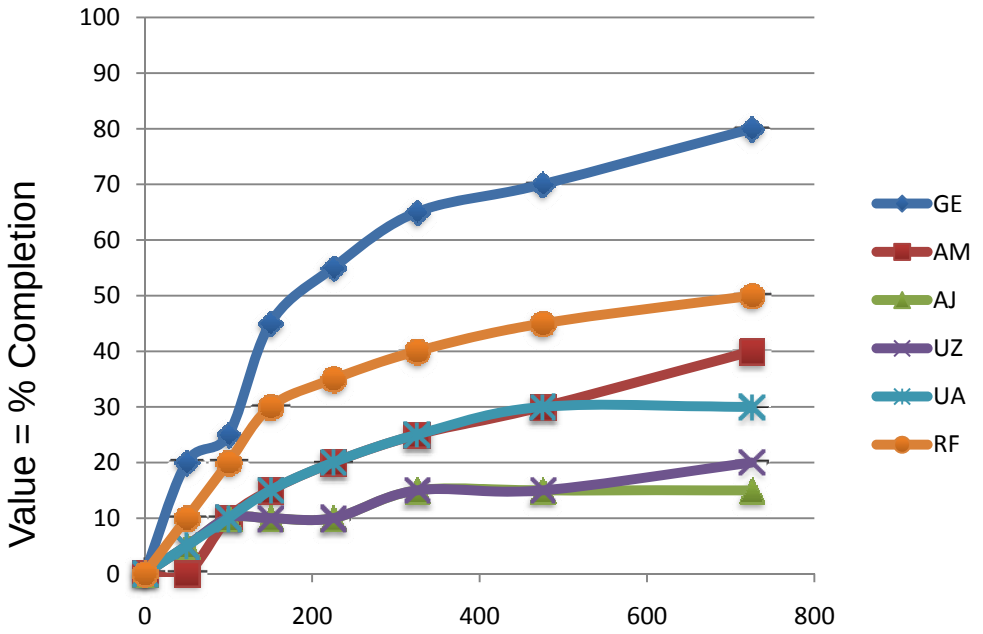
Screening criteria

The mathematics of multiple objective decision analysis are used to calculate the value (% completion).

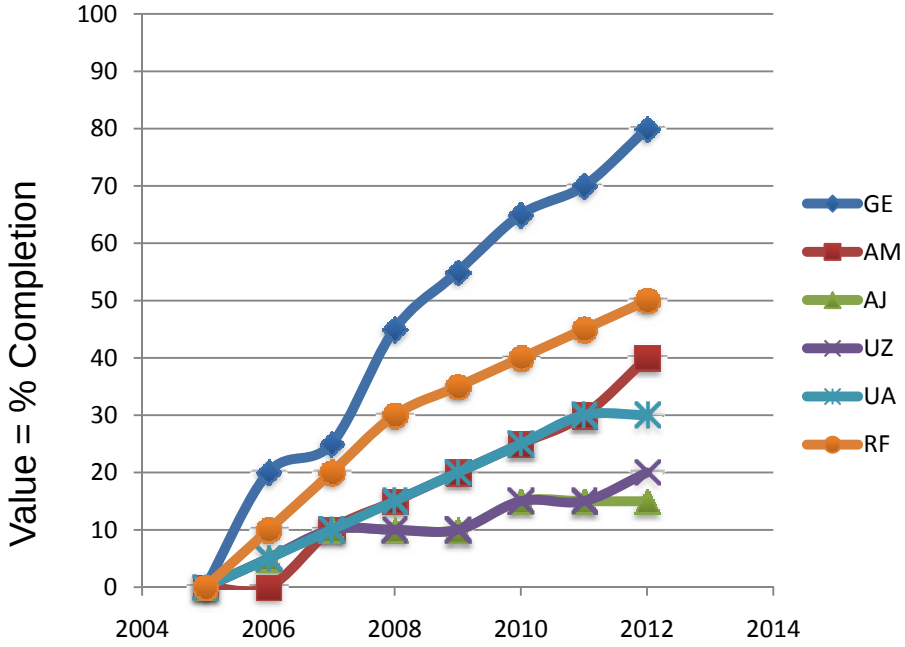
Keeney, R.L. and Raiffa H. **Decision Making with Multiple Objectives Preferences and Value Tradeoffs**. New York: Wiley, 1976.

Illustrative Use mathematics of Multiple Objective Decision Analysis – 4 of 4

Notional Data for Illustrative Purposes Only



Cumulative $ in CBEP budget (budget increasing)



Fiscal Year

The two plots show the cost-effectiveness of the CBEP program by amount of budget and over time. While illustrative, they show the growing budget, the progress over time and the allocation of the funds to the most cooperative partner countries.

Parnell, G. S., Driscoll, P. J., and Henderson D. L., Editors, 2nd Edition, **Decision Making for Systems Engineering and Management**, Wiley Series in Systems Engineering, Wiley & Sons Inc., 2011

Assessment Summary

- Credible measures can be used to support decision making
  - Program measures should include aggregated and simplified project metrics
- Good measures are difficult to identify and define
  - Measures should be aligned with organization strategy and strategic objectives
  - We should measure what is important, not only what we can easily measure
  - Direct measures (align with objectives) are much more useful (and more efficient) than proxy measures
  - Systems thinking can be an important framework for categorizing measures and looking for gaps
  - Fewer good measures are better than lots of proxy measures
- Multiple objective decision analysis is a sound mathematical technique to evaluate the progress on measures.
  - Only as good as the qualitative framework
  - Use of swing weights and value functions are essential
- Cost-effectiveness should be a key part of program evaluation.

Summary of Measurement Principles

- Credible measures can be used to support decision making
- Good measures are difficult to identify and define
  - Measures should be aligned with organization strategy and strategic objectives
  - We should measure what is important, not only what we can easily measure
  - It always helps to identify objectives and then to identify measures
  - It is useful to distinguish between fundamental and means objectives
  - Objectives decomposition is a useful tool to identify measures
  - In many complex problems, it is very useful to identify capabilities (functions), then objectives, and then measures
  - Direct measures (align with objectives) are much more useful (and more efficient) than proxy measures
  - Systems thinking can be an important framework for categorizing measures and looking for gaps
- Multiple objective decision analysis is a sound mathematical technique to evaluate the progress on measures.
  - Only as good as the qualitative framework
  - Use of swing weights and value functions are essential
- Cost-effectiveness should be a key part of program evaluation.