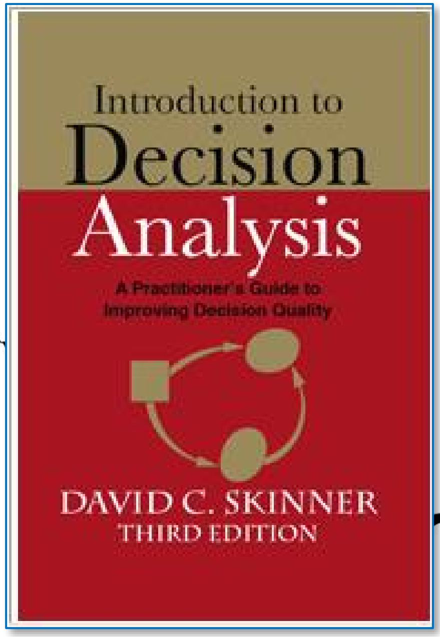
Multiple Objective Decision Analysis: Basics and the USAF 2025 Study

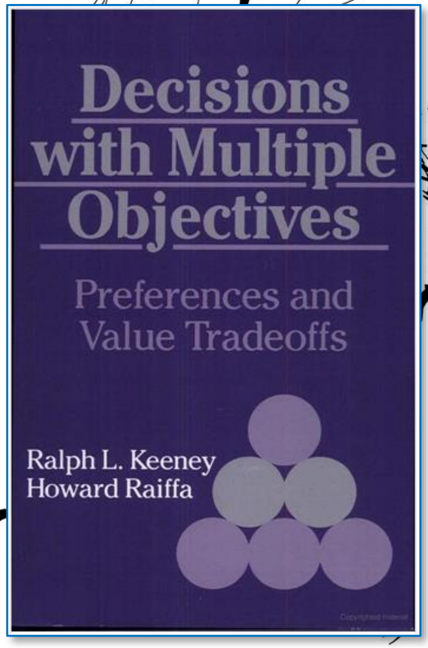
Bill Klimack, PhD PE CSEP CAP
DQ Manager
July 27, 2023

East Coast – West Coast DA

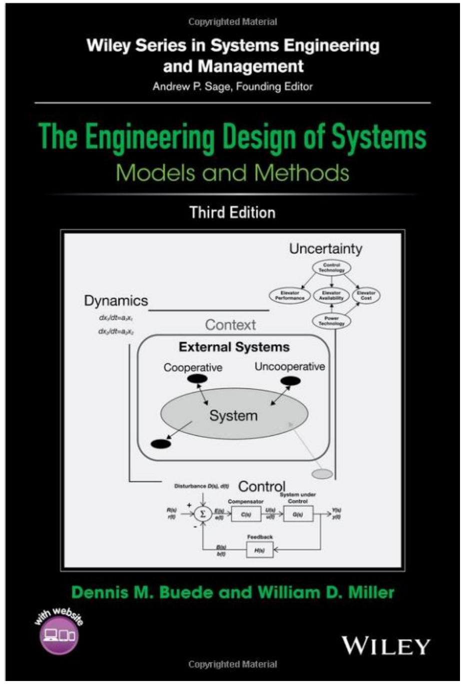
- Single Objective
- Private Sector Focus



- Multiple Objective
- Public Sector Focus



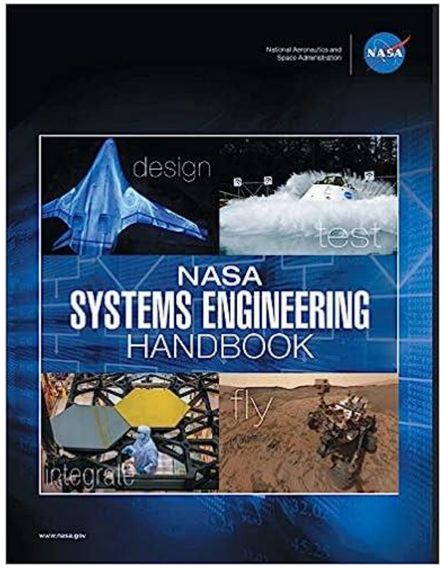
Multiple Objective Decision Analysis is a key component of systems engineering

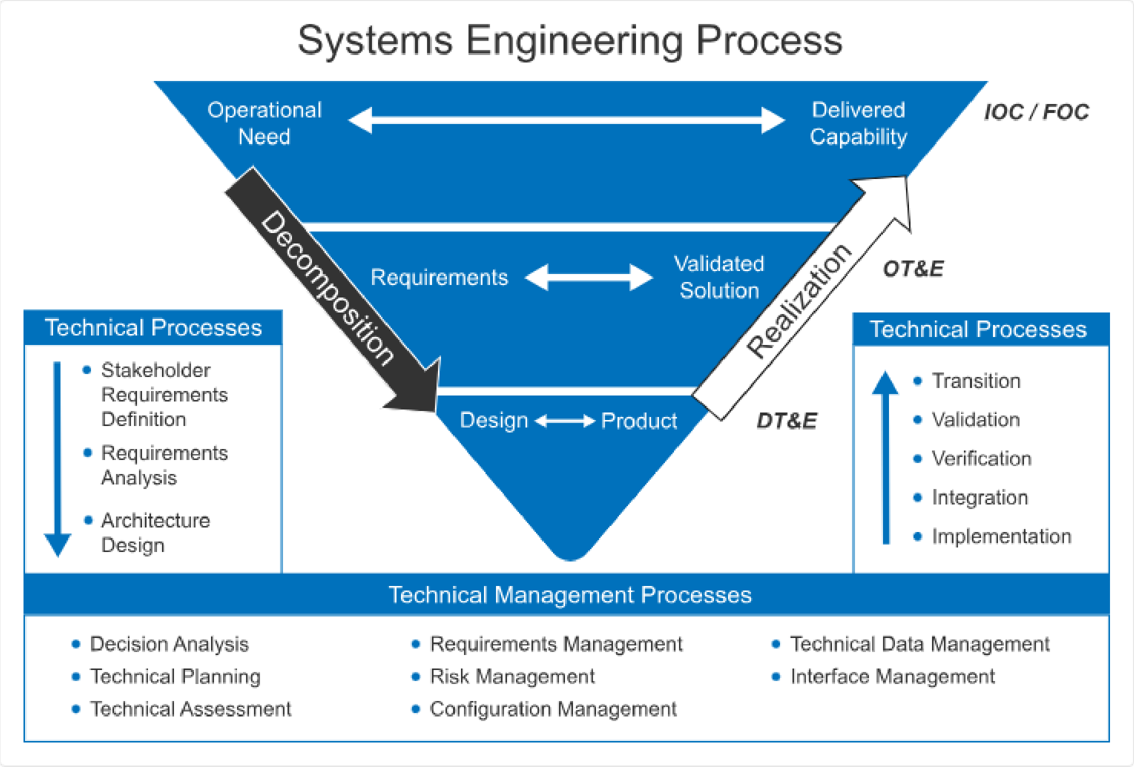


6.8 Decision Analysis

The purpose of this section is to provide an overview of the Decision Analysis Process, highlighting selected tools and methodologies. Decision Analysis is a framework within which analyses of diverse types are applied to the formulation and characterization of decision alternatives that best implement the decision-maker's priorities given the decision-maker's state of knowledge.

Source: nasa_systems_engineering_handbook_0.pdf, accessed 6/30/2023.

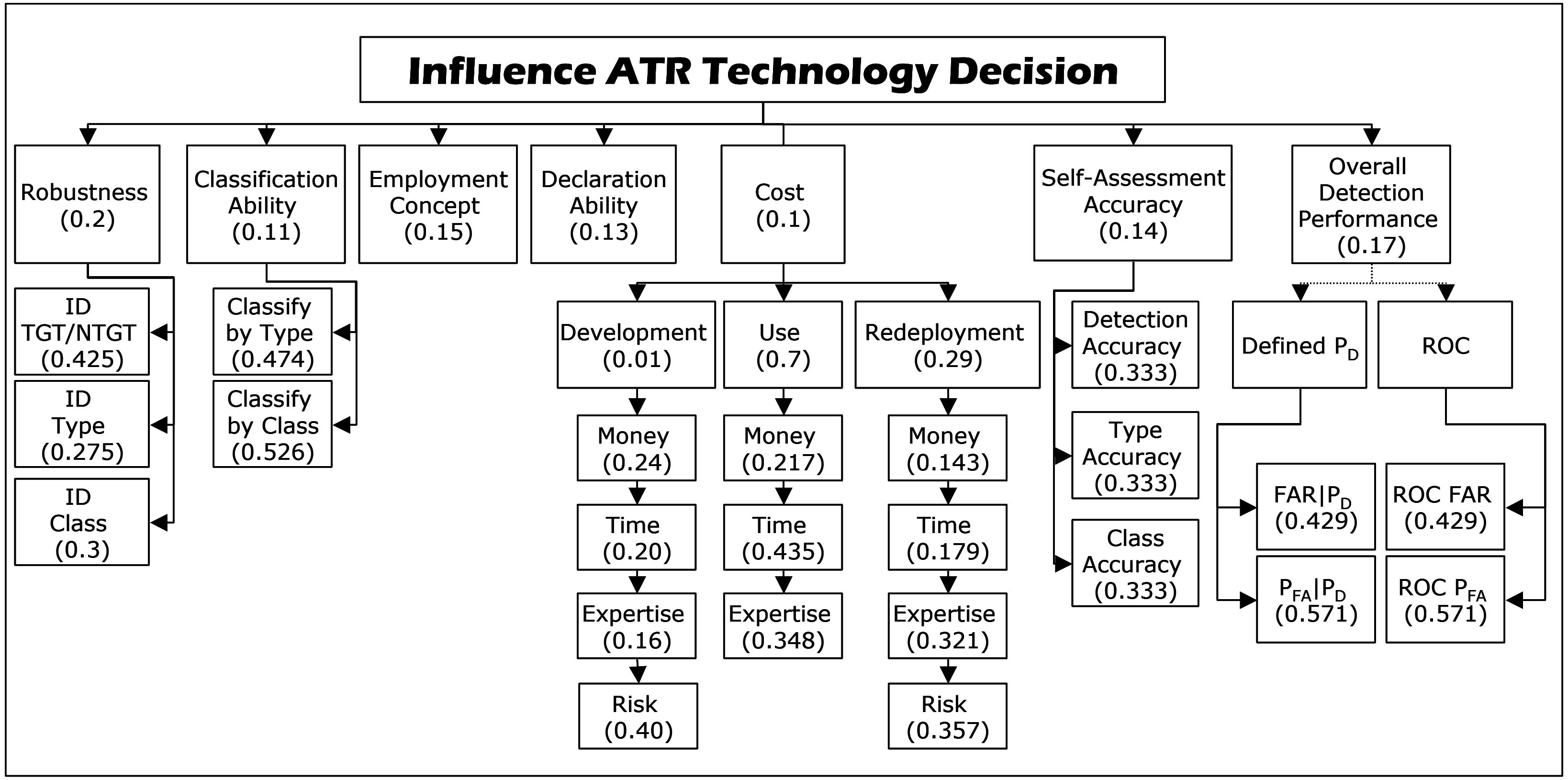


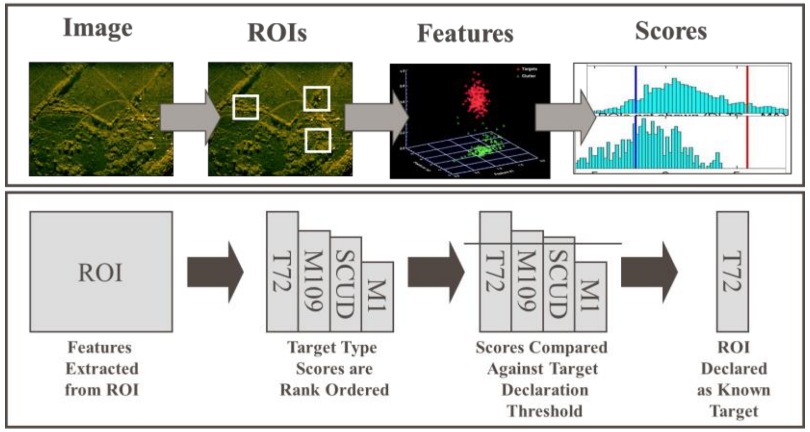


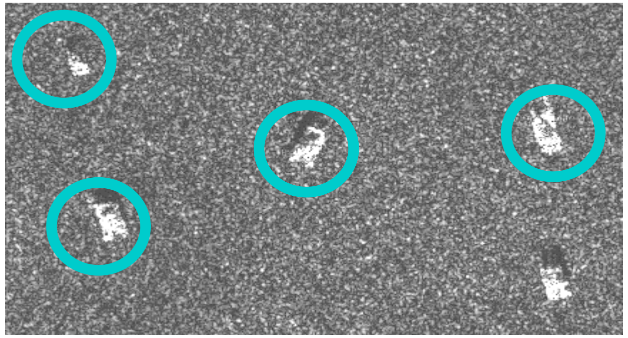
Source: SE Brainbook Home (dau.edu), accessed 6/30/2023.

Multiple Objective Decision Analysis (MODA)

- MODA is useful when it is difficult to assess alternatives in terms of money.



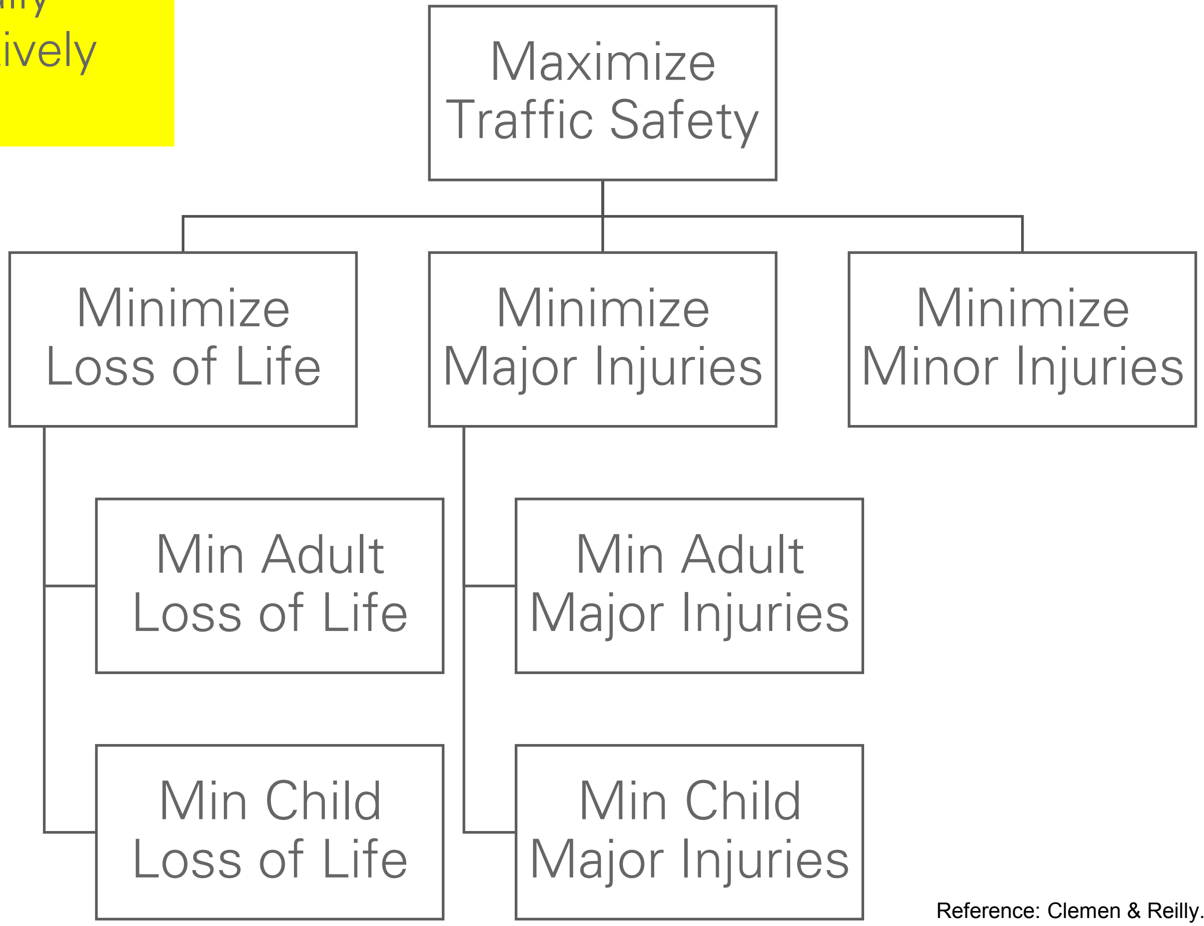




Bassham, C. Brian, William K. Klimack, and Kenneth W. Bauer, Jr., “ATR Evaluation Through the Synthesis of Multiple Performance Measures,” *Signal Processing , Sensor Fusion, and Target Recognition* XI, Ivan Kadar, editor, *Proceedings of SPIE* Vol 4729, pages 112 – 121 (2002).

Example Objectives Hierarchy

It should be mutually exclusive and collectively exhaustive.

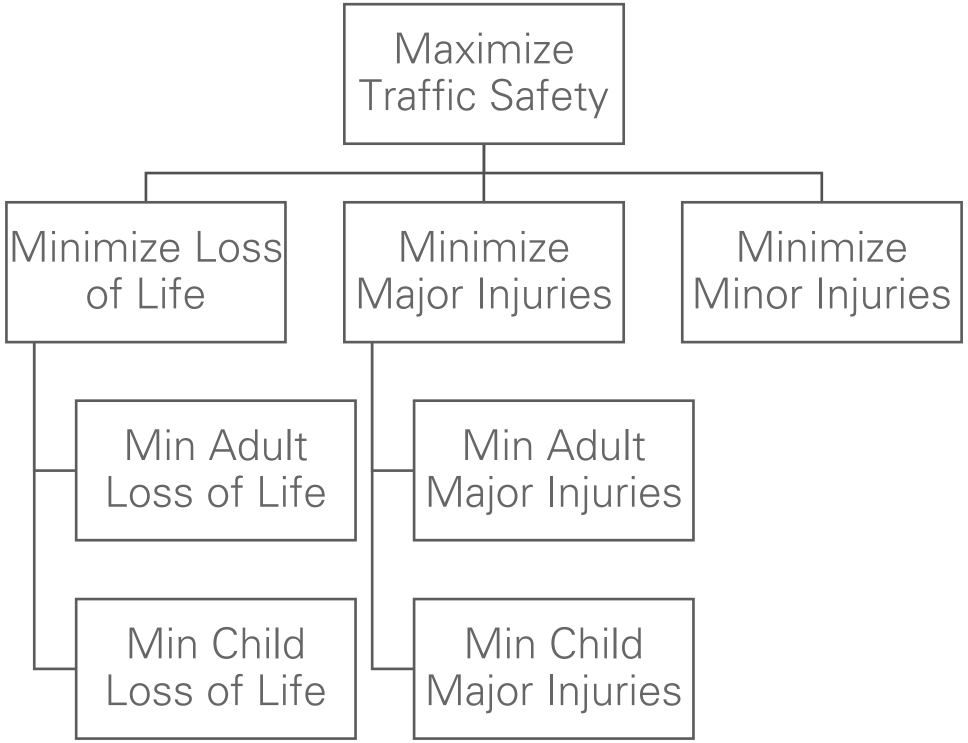


Reference: Clemen & Reilly.

Two objective structures are used in decision analysis.

Hierarchy of Fundamental Objectives

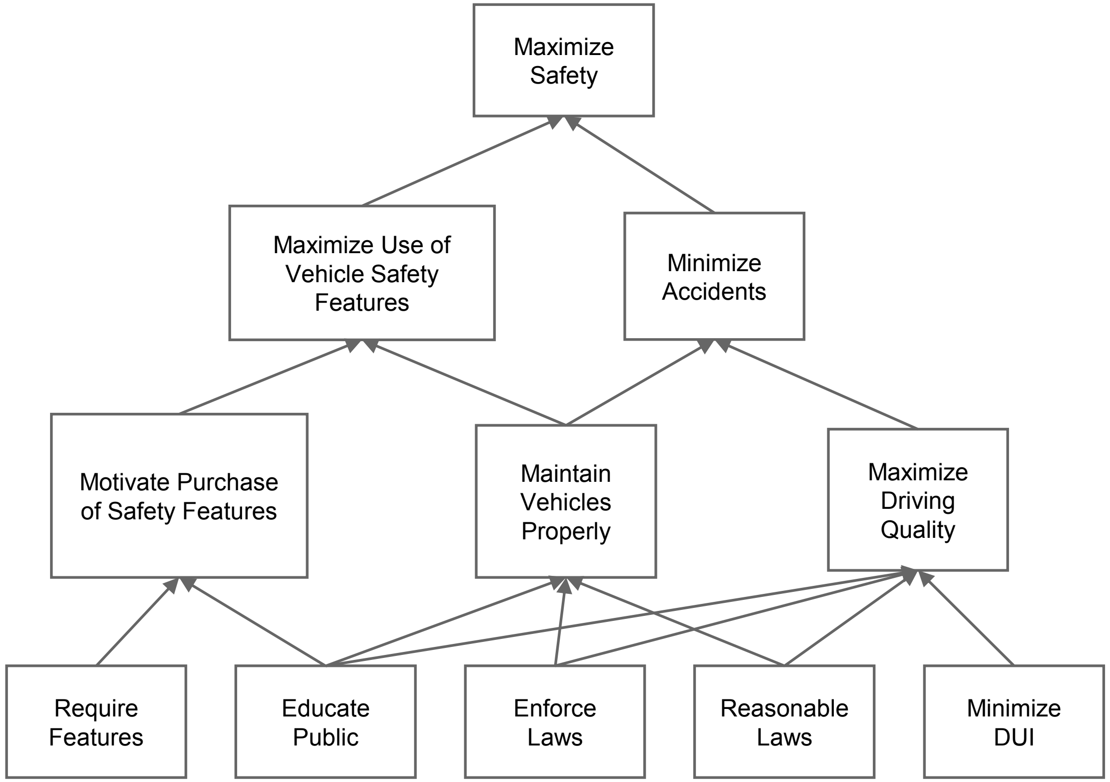
what you care about, what criteria to use



Reference: Clemen & Reilly.

Network of Means Objectives

suggests creative alternatives



After: Clemen & Reilly.

Step 1: Silent generation of ideas

What are the capabilities needed in a new “Marine One” Presidential helicopter?

Affinitization* to Identify
Values and Objectives

Source: Klimack et al, Soft Skills Workshop, 2014.

* Sometimes referred to as the KJ Method.

Step 2: Recording of ideas

Cards on the wall,
Mural canvas, etc.

Fuel Economy

Reliable

Dependable

Speed

People

Defense Systems

Range

Cargo

All Wx

Reliability

Living Space

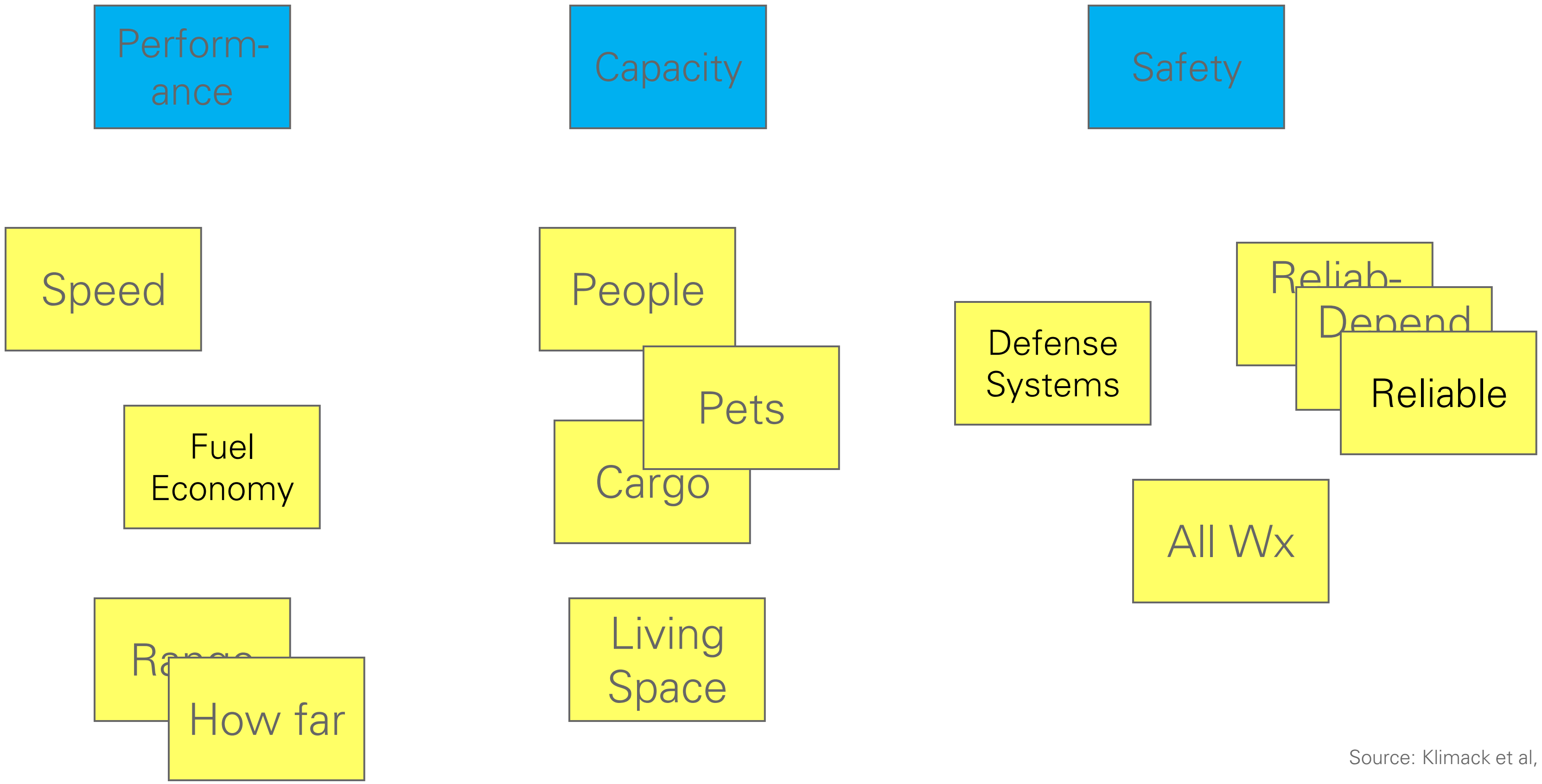
How far

Pets

Source: Klimack et al, Soft Skills Workshop, 2014.

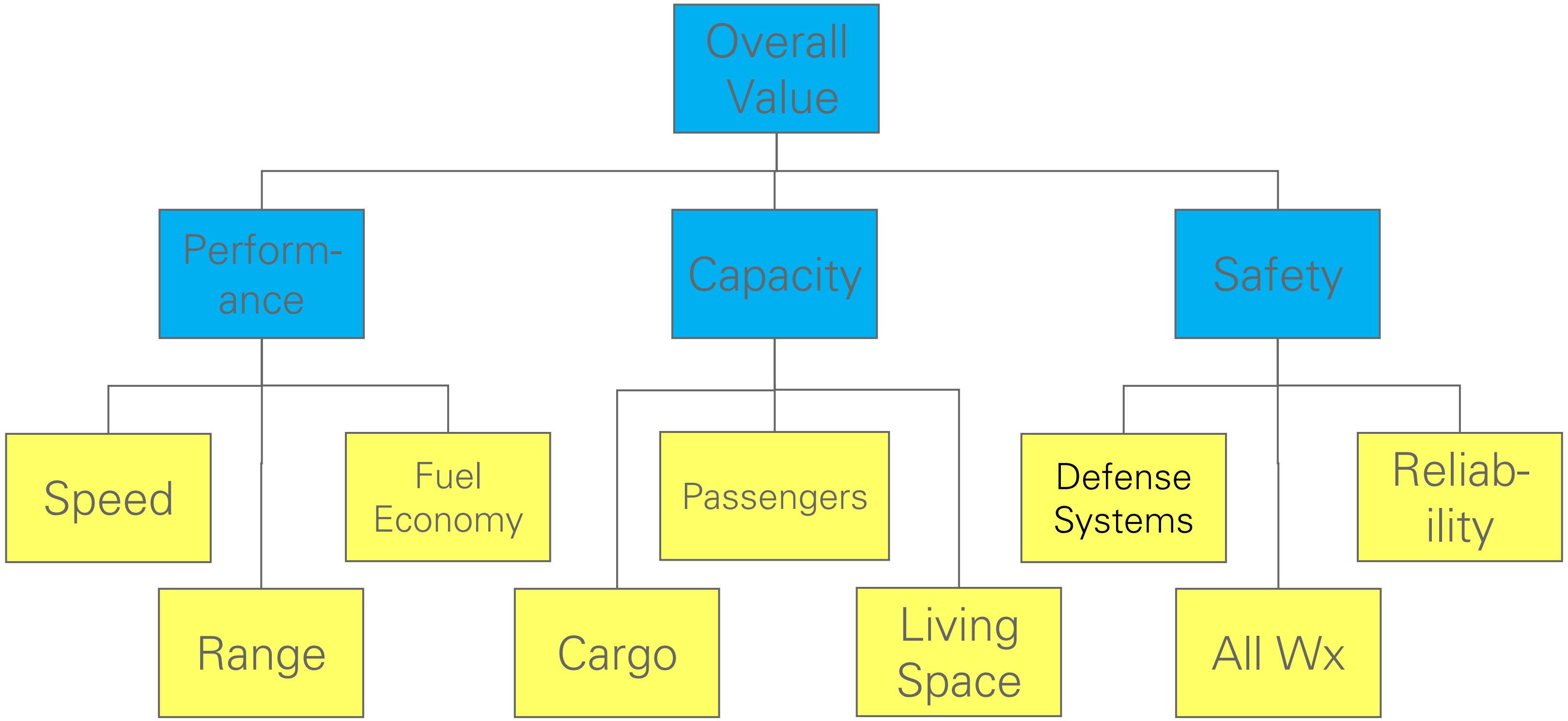
Step 3: Affinitize and categorize

Category Headers



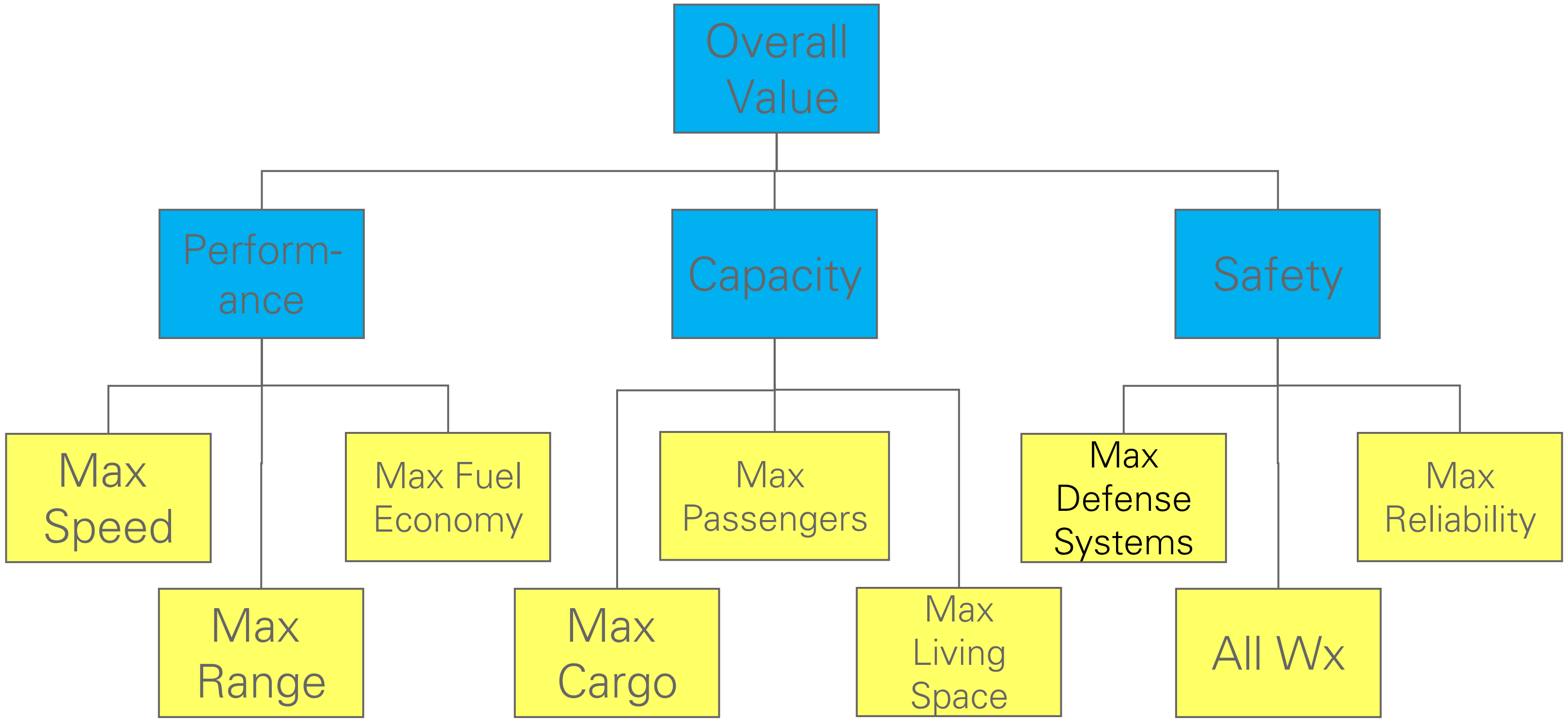
Source: Klimack et al, Soft Skills Workshop, 2014.

Step 4: Value Hierarchy – simplified



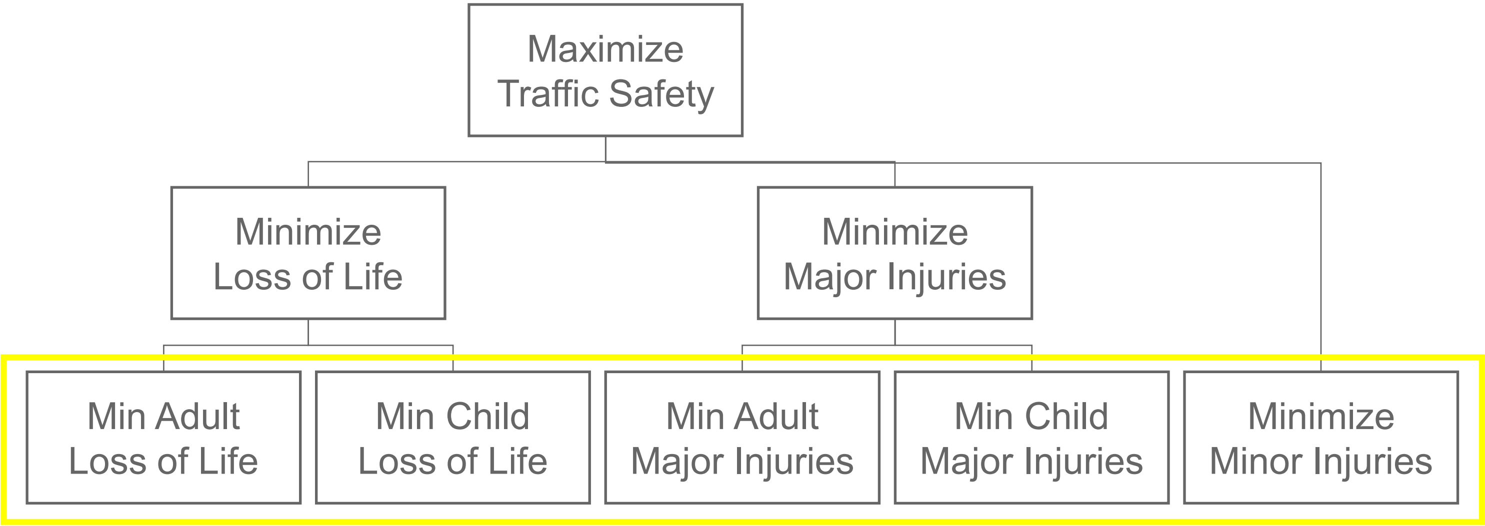
Source: Klimack et al, Soft Skills Workshop, 2014.

Step 4: Value Hierarchy – clarified



Source: Klimack et al, Soft Skills Workshop, 2014.

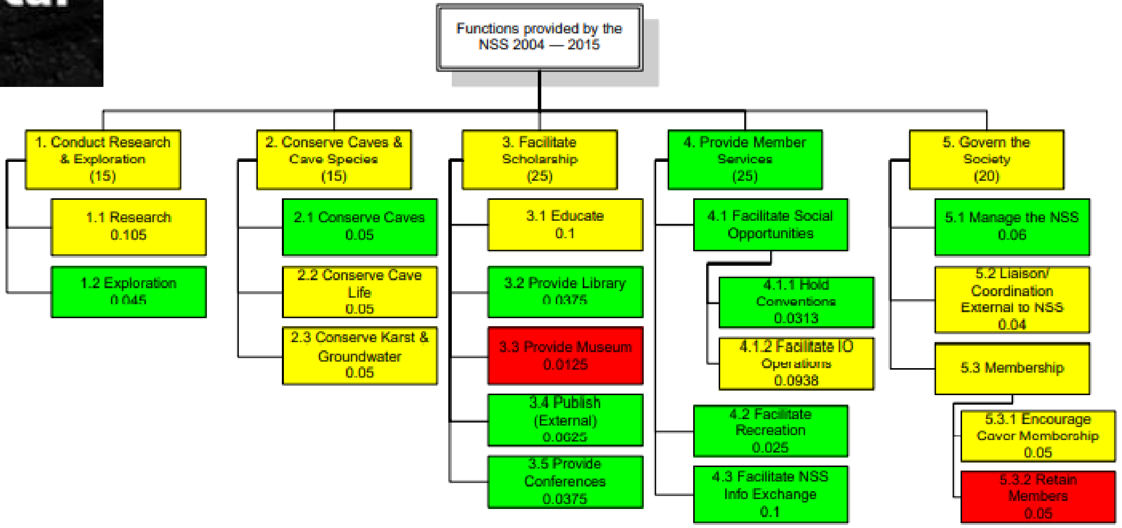
Decision criteria on the fundamental objectives hierarchy.

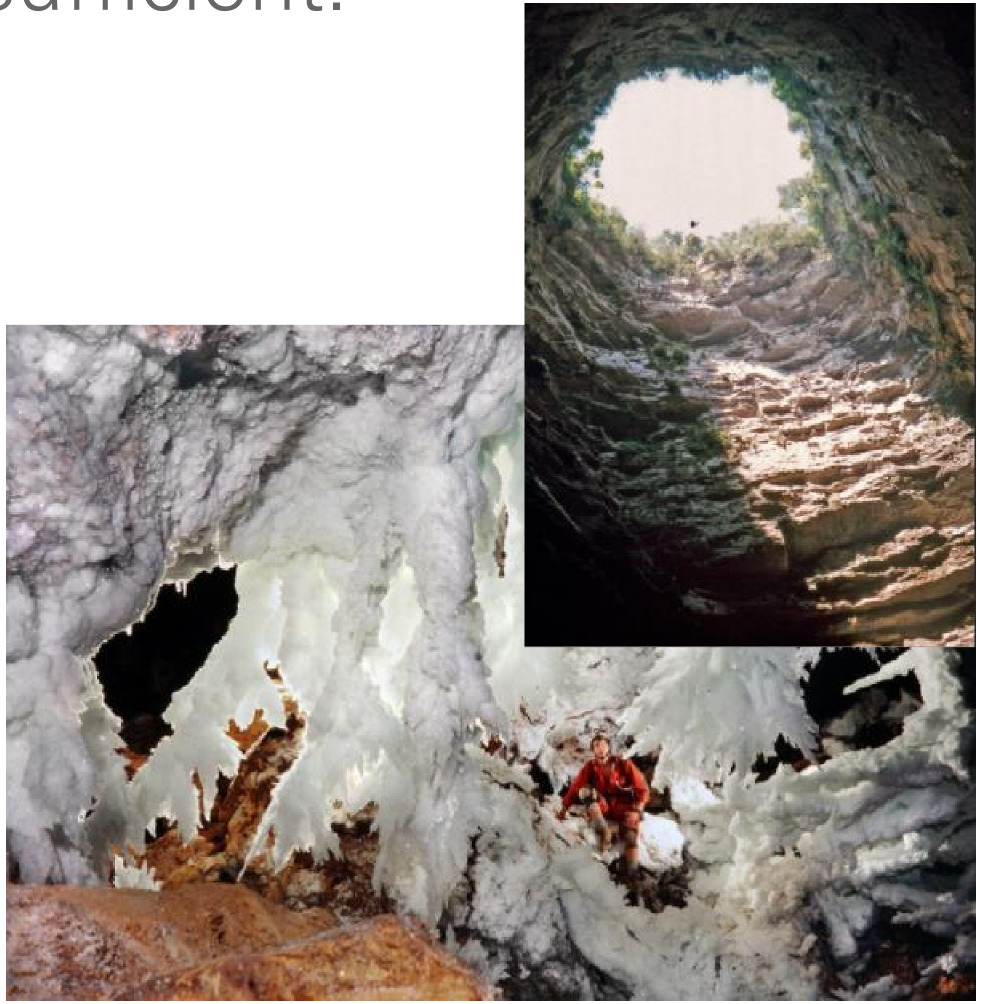


After Clemen & Reilly, Figure 3.1

- The lowest-level fundamental objectives form the evaluation measures.
- The full set or sometimes a subset of these will be the decision criteria.
- Decompose the values/objectives until they are clearly measurable to provide clarity.

National Speleological Strategic Planning is an example where a qualitative assessment was sufficient.

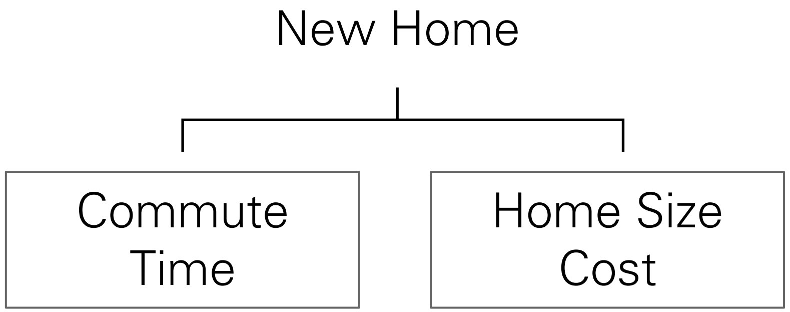




[Lechuguilla cave: Jewel of the Underground (geologyin.com)]
[Sotano de las Golondrinas - Cave of the Swallows | Wondermondo]

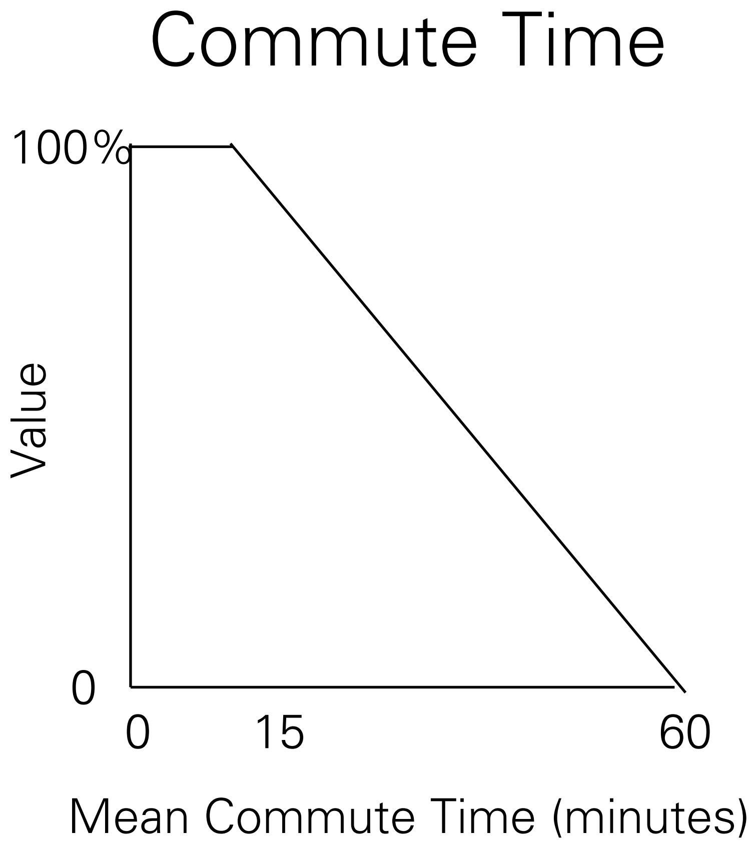
A Quantitative Model: Selecting a Home

- Suppose you have moved to a new large city and I'm helping you select where to choose a home.
- For this discussion we will focus on commute time and home size and ignore other objectives.
- You will have to commute to the office downtown.
- The further away you live, your money buys more home (we're assuming you are purchasing).
  - Measured in dollars/square foot.
- The closer you live, the shorter commute time you have.
  - Measured in minutes of commute time.



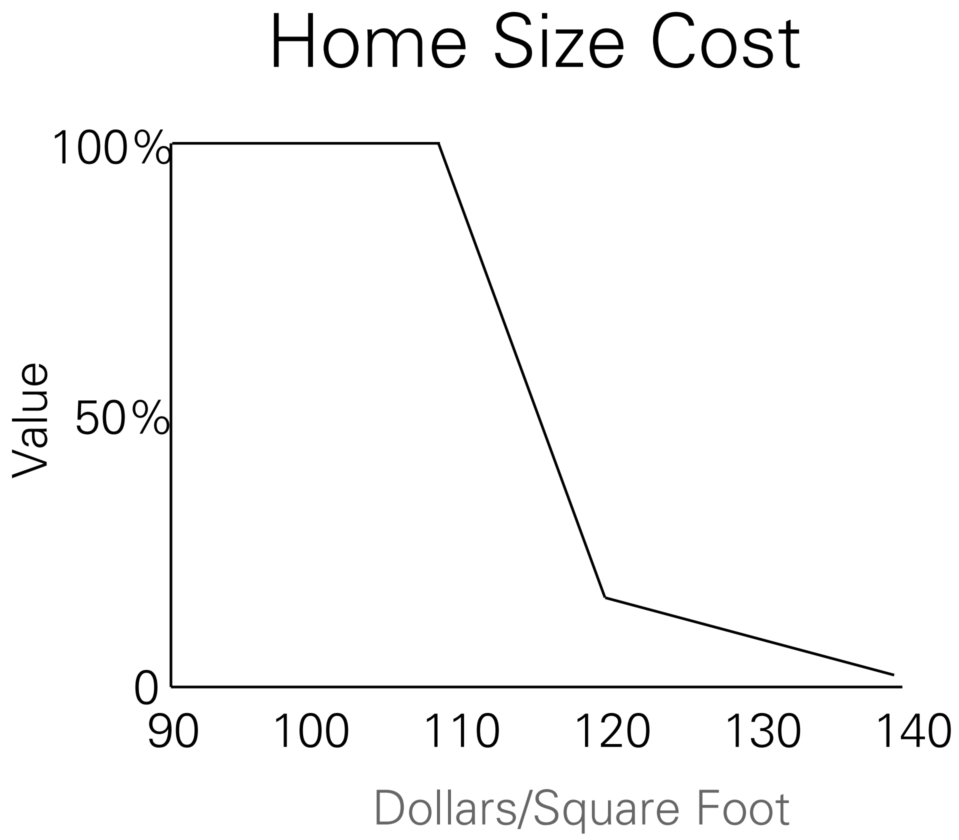
Selecting a Home: Commute Time

- In discussion, you say (in different words):
- The commute value is linear – each minute increment longer decreases the value equally.
- But anything at 15 minutes or below is all equal at full value.
- And anything 60 minutes and above is of zero value.
- But above 60 minutes is acceptable but of no value.
  - There is likely some screening criterion but that could be discussed.
- The plot shows the single dimensional value function.

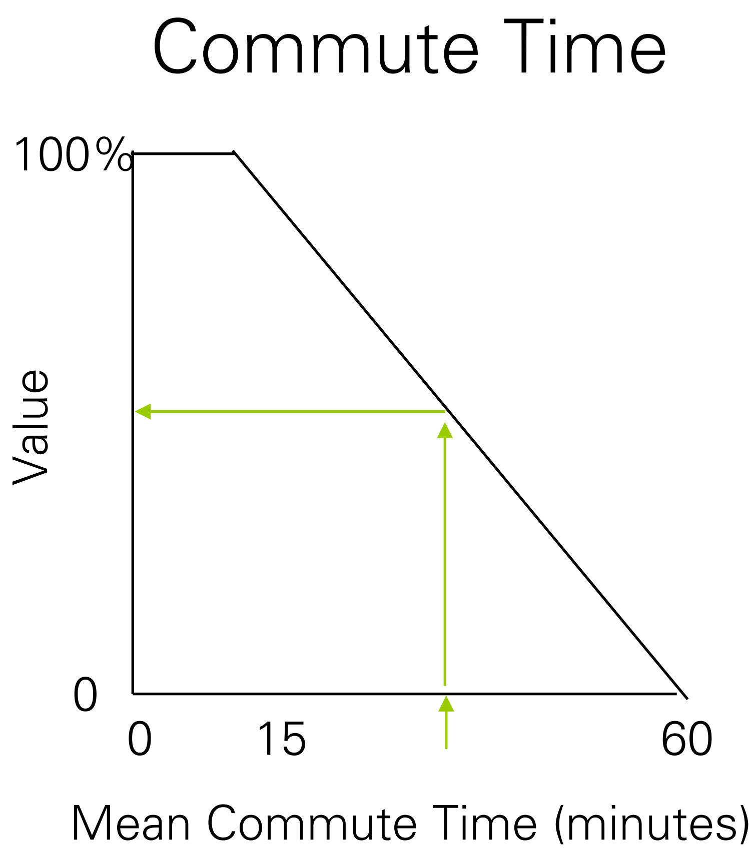


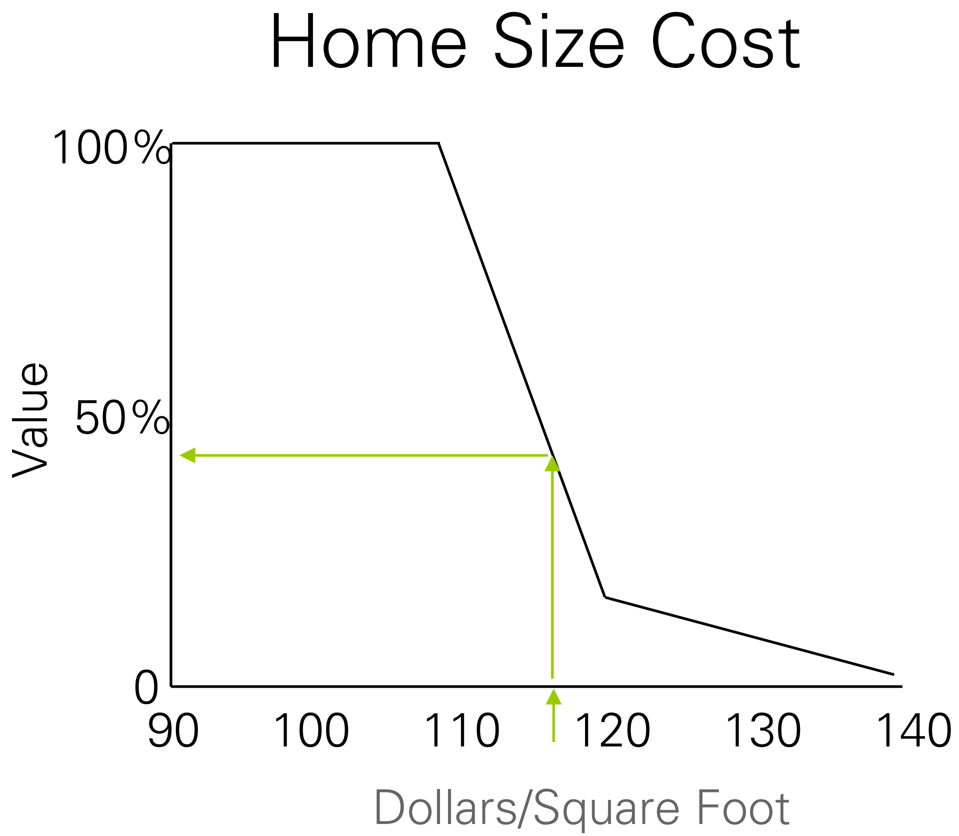
Selecting a Home: Home Size Cost

- A discussion similarly provides a single dimensional value function for Home Size Cost.



We can now see the value of a property for each of our two objectives.





But we need to be able to compare between these objectives.

- How important is commute time compared to home size cost?
- Often people use a Weight and Rate approach.
  - Is this valid?
- Let’s consider a different example.

Suppose I'm buying a new vehicle and you are helping me.

- New personal vehicle criteria:
  - Sticker price
  - Operating cost
  - Cargo capacity
- Asking importance, you might get:
  - $w_{sp} = 0.8$
  - $w_{oc} = 0.15$
  - $w_{cc} = 0.05$

- Applying screening criteria:
  - Only three models are alternatives
  - They differ only by $100
- Considering variability of alternatives:
  - $w_{sp} = 0.01$
  - $w_{oc} = 0.90$
  - $w_{cc} = 0.09$

Variability of alternatives must be considered for the weighting.

Why we don't weight and rate

Determining the Weights

- There are several approaches.
- One approach is to ask your subject to order the objectives from least to greatest importance.
  - Do this by asking if all objectives are at the least preferred level, which objective would they "swing" from least to most preferred?
  - That is the most important.
  - Remove it from the list and continue the process.
- Then assign a weight to the least important.
- Ask for weights for the other objectives in terms of the least important.
- Normalize the weights to sum to 100%.

Determining the Weights

- For:
  - Sticker price
  - Operating cost
  - Cargo capacity
- Priority order:
  - w_{oc}: Most important
  - w_{cc}
  - w_{sp}: Least important

- Assigning swing weights:
  - $w_{sp} = 1$
  - $w_{cc} = 9 * w_{sp} = 9$
  - $w_{oc} = 90 * w_{sp} = 90$
- Normalizing:
  - $w_{sp} = 0.01$
  - $w_{oc} = 0.90$
  - $w_{cc} = 0.09$

The Swing Weight Matrix

		Importance of the Value Measures		
		High	Medium	Low
Range of Variation Of Value Measures.	High	A	B2	C3
	Medium	B1	C2	D2
	Low	C1	D1	E

Reference: Parnell and Trainor, "Using the Swing Weight Matrix to Weight Multiple Objectives," 2009.

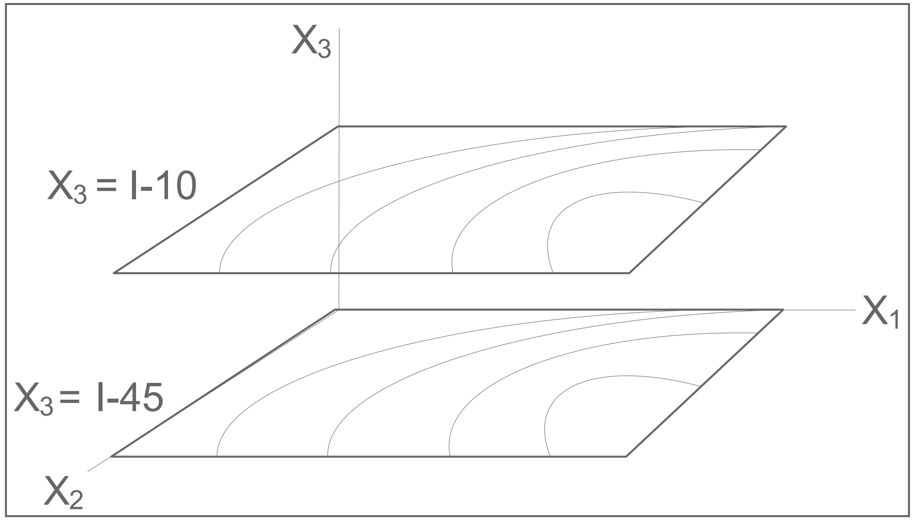
Swing Weight Matrix Rules

- 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

		Importance of the Value Measures		
		High	Medium	Low
Range of variation of value measures.	High	A	B2	C3
	Medium	B1	C2	D2
	Low	C1	D1	E

Technical requirements for the additive value model. This is key to what makes MODA "good science."

- A set of attributes is **preferentially independent** if the rank ordering of alternatives does not depend on common attribute levels not in the set.
- A set of attributes are **mutually preferential independent** if all partitions are preferentially independent.
- If any one attribute is pair-wise preferentially independent of the other *n* -1 attributes, the *n* attributes have mutual preference independence.

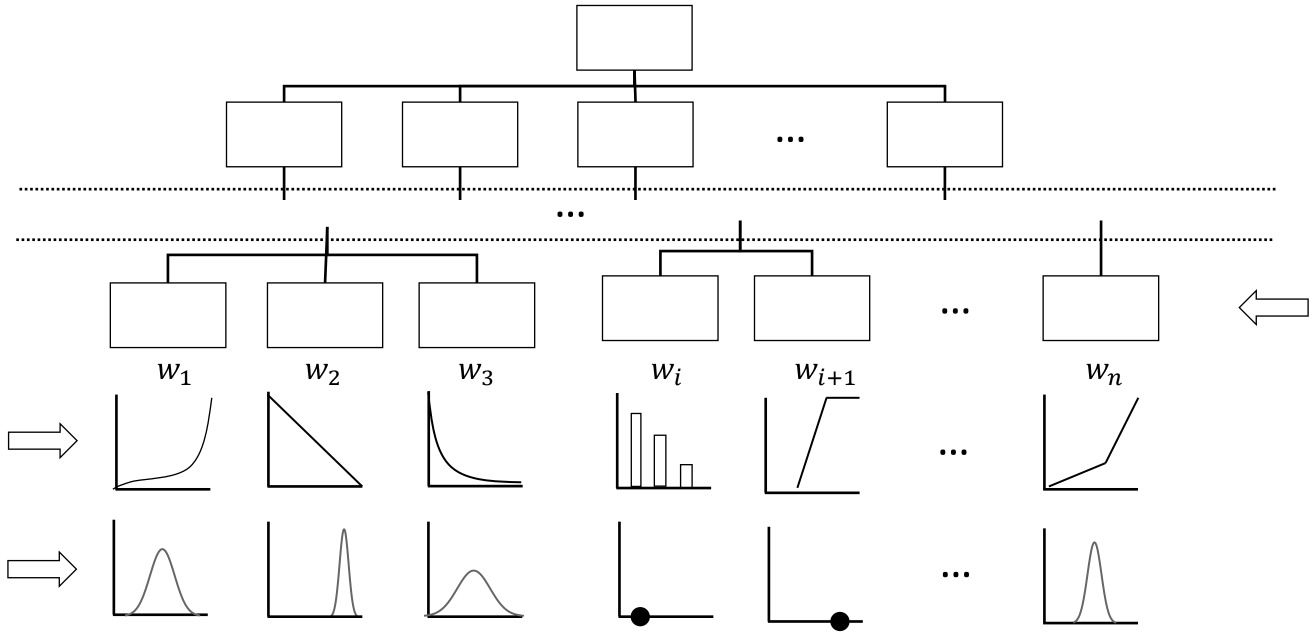


After Kirkwood, *Making Strategic Decisions*, 1997.

MODA Structure

Qualitative Value Model

Value Hierarchy



Evaluation Measures

Quantitative Value Model

Preference Functions

Alternative Scores

Value or Utility Functions

Multiple Objective Value Function

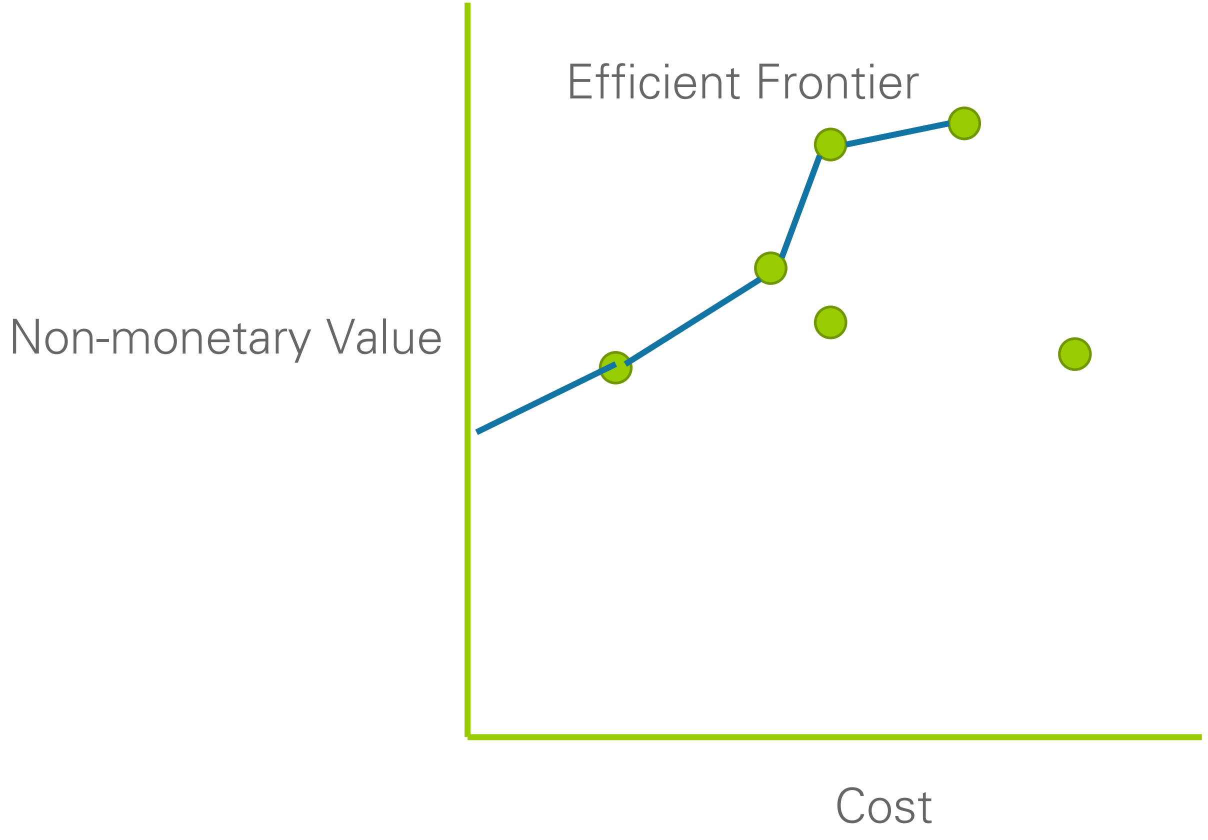
$$V = \sum_{i=1}^{I} w_i v_i(x_i)$$

or

Multiple Objective Utility Function

$$U = \sum_{i=1}^{I} w_i u_i(x_i)$$

Often, we plot non-monetary value of alternatives as a function of monetary cost.



USAF 2025

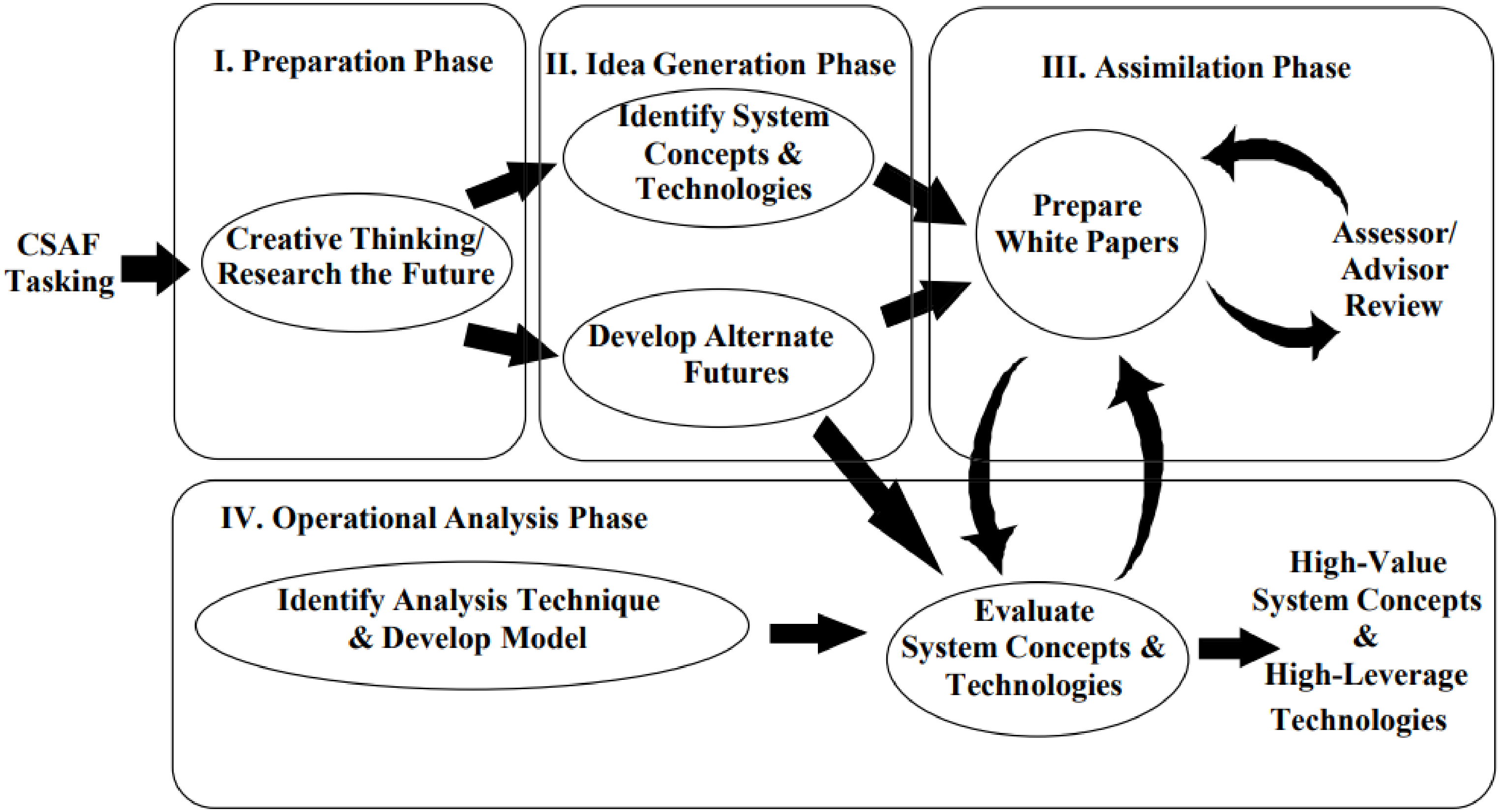
Peering thirty years into the future, the Air Force sees the need for stealthy air bases, high-powered lasers on trans-atmospheric craft, tiny "attack microbots," solar-powered weapons, and the biggest, fastest, most powerful information systems possible.

Source: Tirpak, *Air Force Magazine*, December 1996.

- 1995: The Air Force chief of staff tasked Air University to conduct a year-long study, **Air Force 2025**, to:
  - Generate ideas and concepts for the capabilities the United States will require to possess the dominant air and space forces in the future.
  - Detail new or high-leverage concepts for employing air and space power.
  - Detail the technologies required to enable the capabilities envisioned.
- An operational analysis was conducted to identify high-value system concepts and their enabling technologies **in a way that was objective, traceable, and robust**.
- This analysis determined which of the Air Force 2025 system concepts showed the greatest potential for enhancing future air and space capabilities and which of their embedded technologies have the highest leverage in making the high-value system concepts a reality.

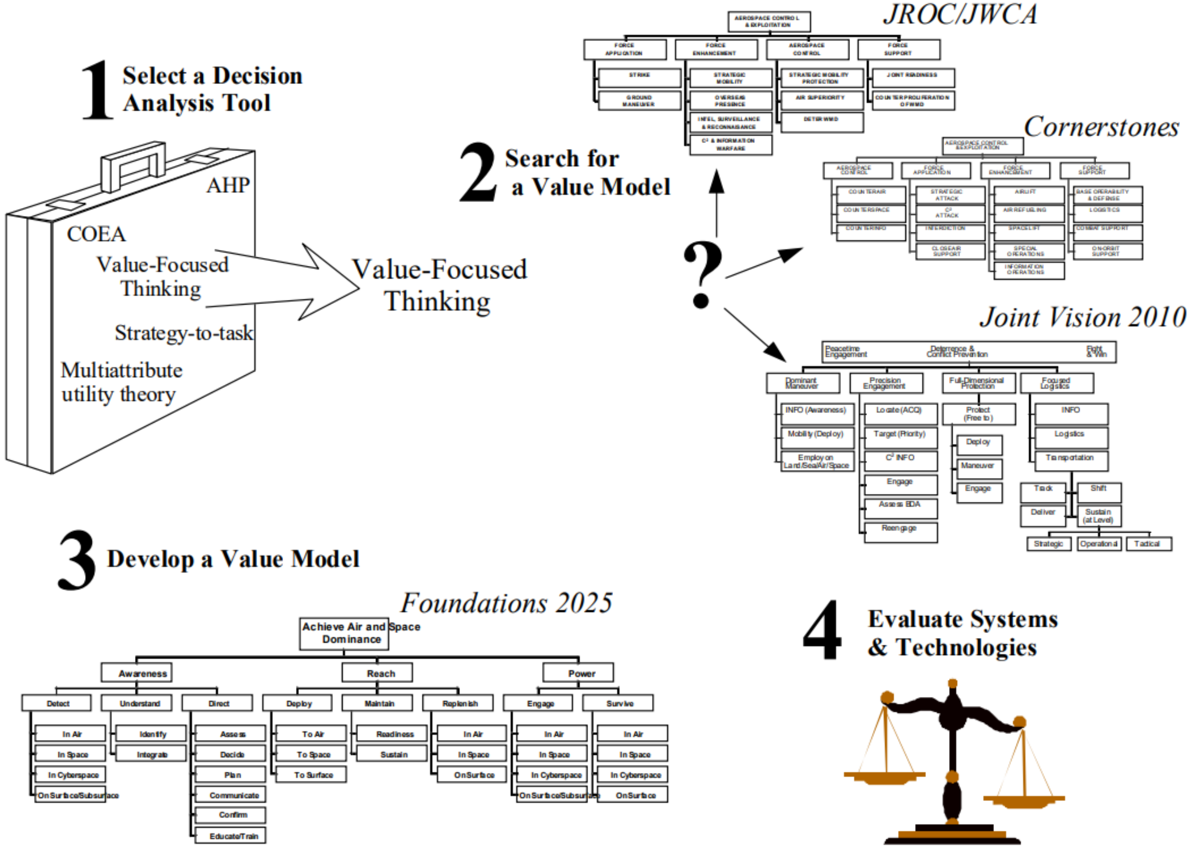
Reference: Jackson, et al. "An Operational Analysis for Air Force 2025," May 1996.

Air Force 2025 Study Process



Reference: Figure 1-1. Operational Analysis for Air Force 2025.

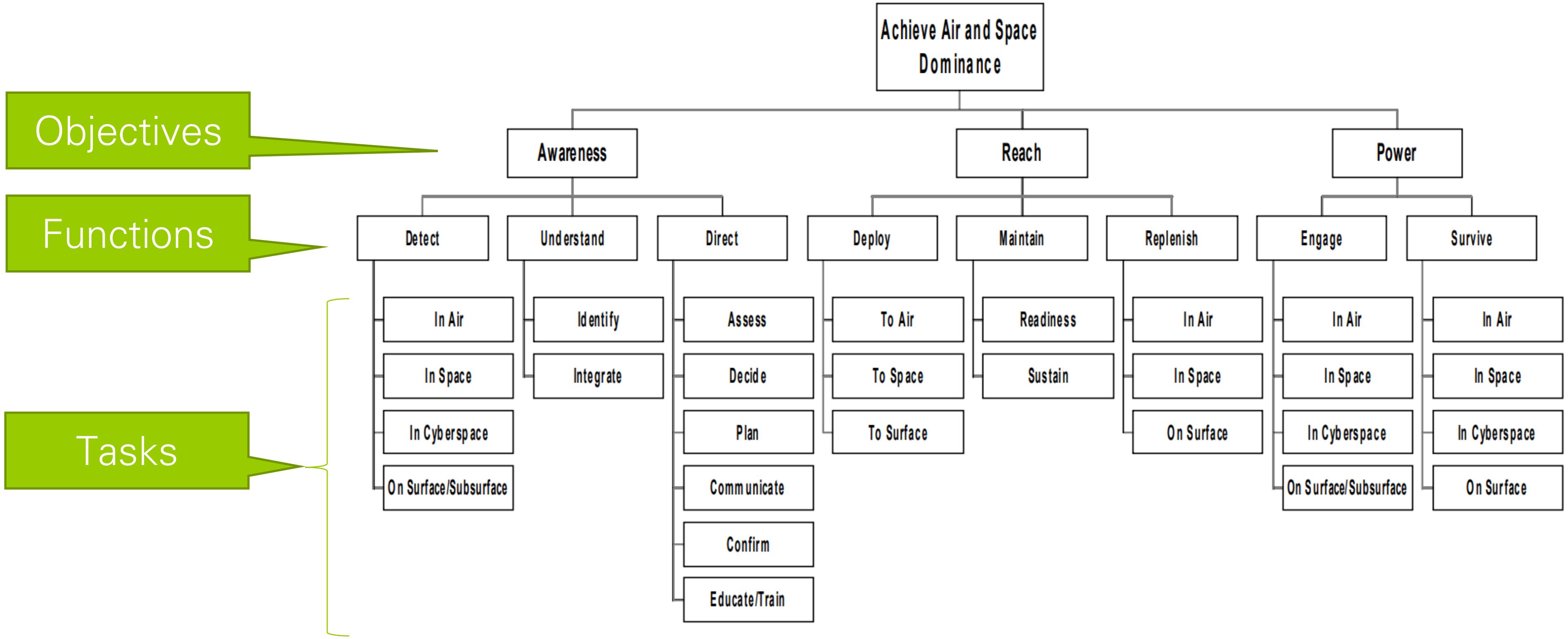
Operational Analysis Process



Reference: Figure 1-1. Operational Analysis for Air Force 2025.

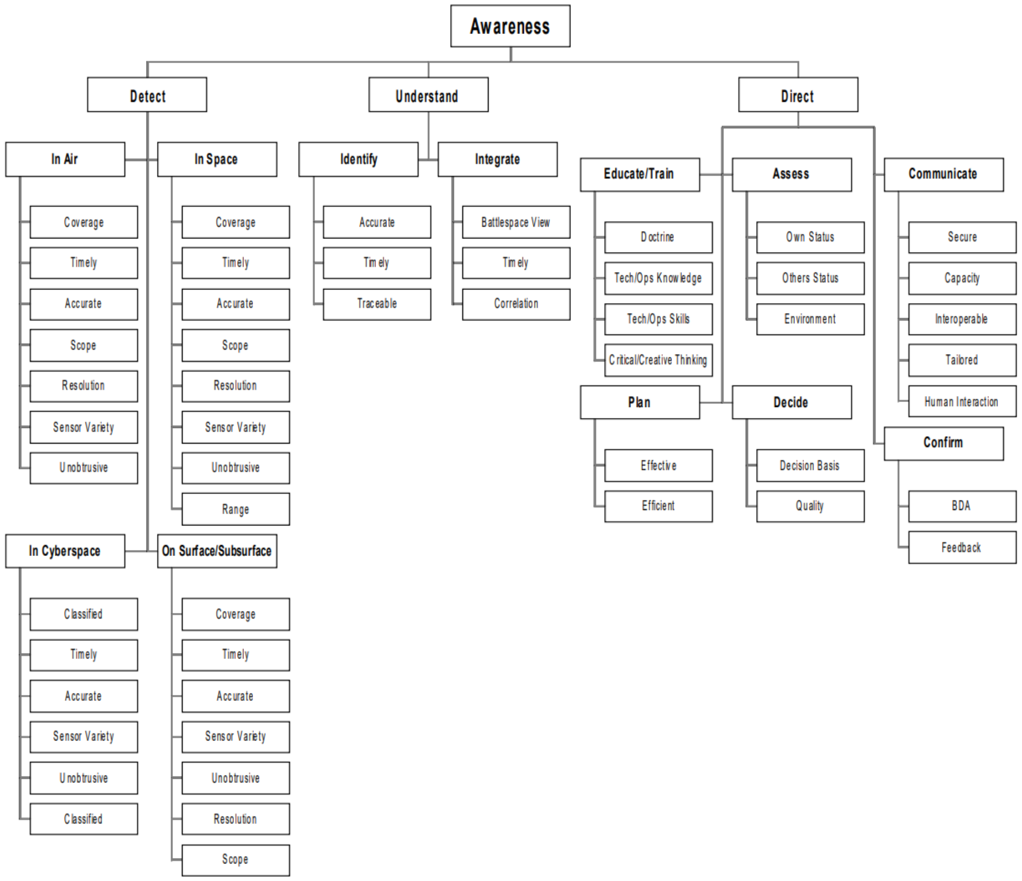
Reference: Figure 2-1. Operational Analysis for Air Force 2025..

Foundations 2025 Value Model: Top Level



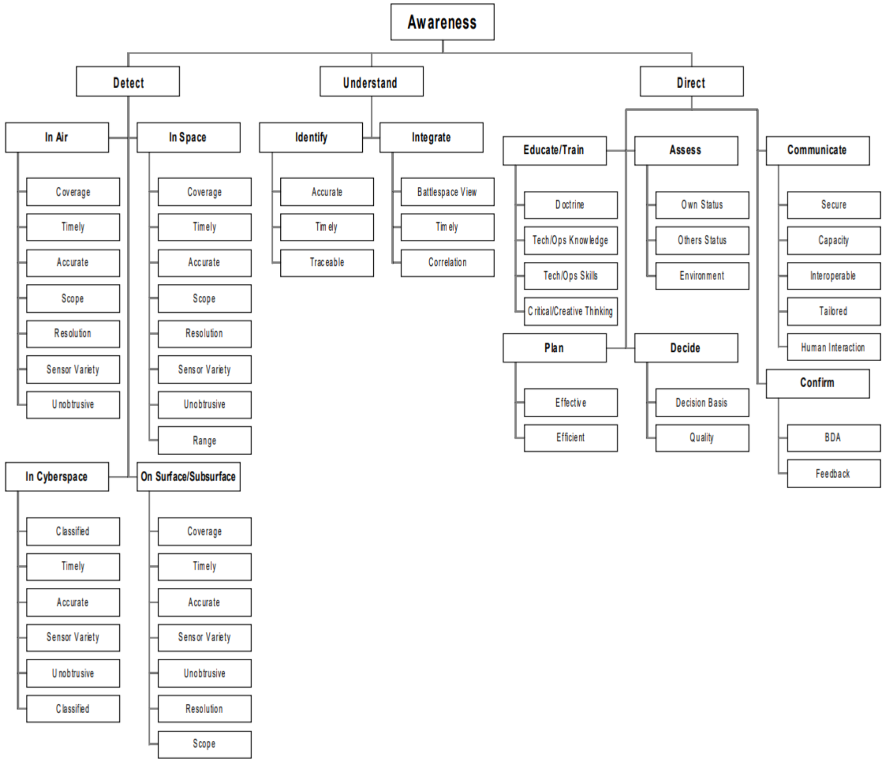
Reference: Figure 2-13. Operational Analysis for Air Force 2025.

Foundations 2025 Value Model: Awareness

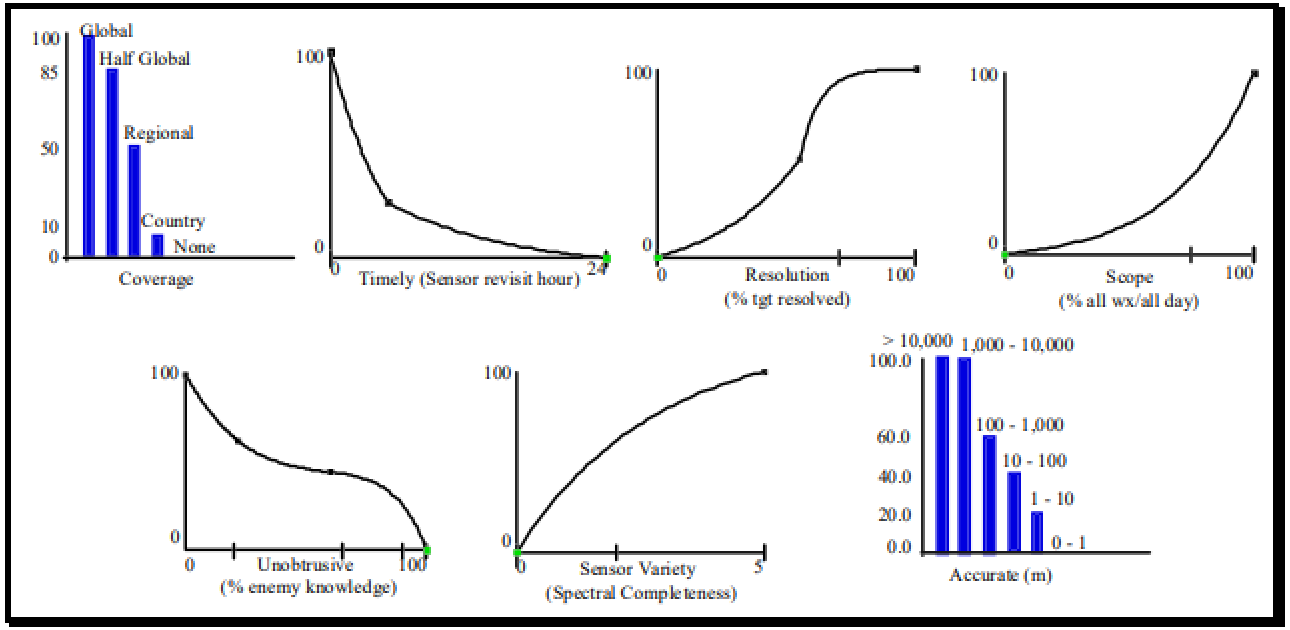


Reference: Figure 2-14. Operational Analysis for Air Force 2025.

Foundations 2025 Value Model: Top Level

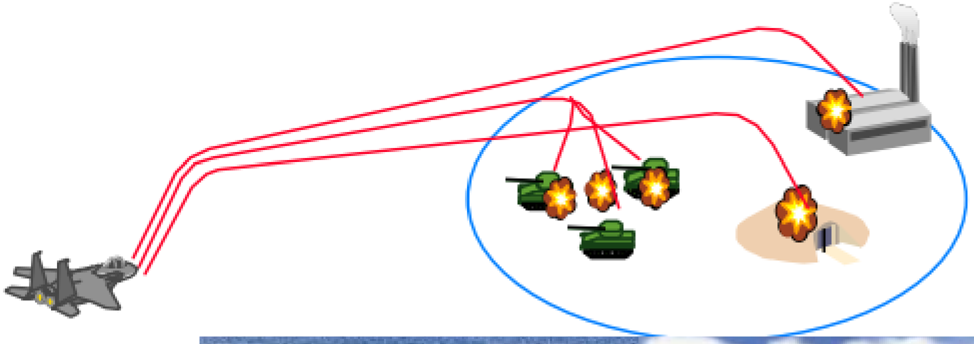


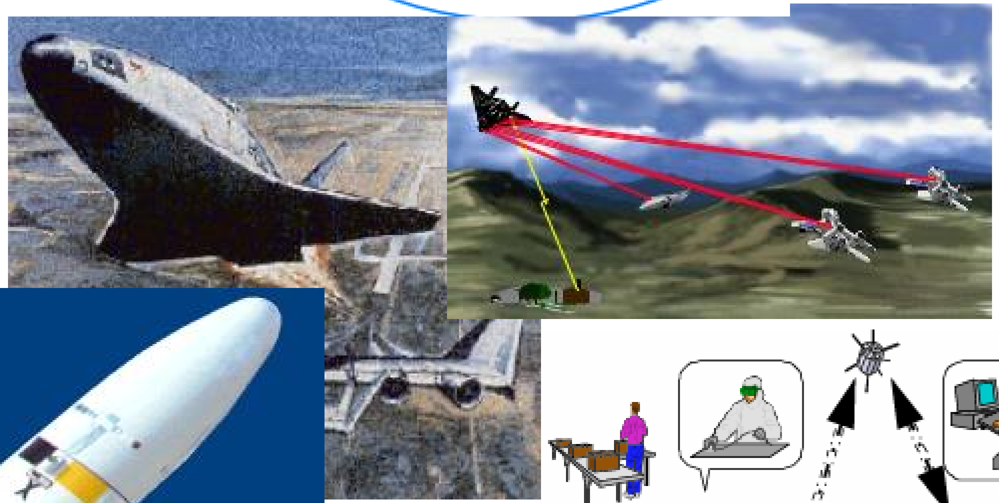
Reference: Figure 2-14. Operational Analysis for Air Force 2025.

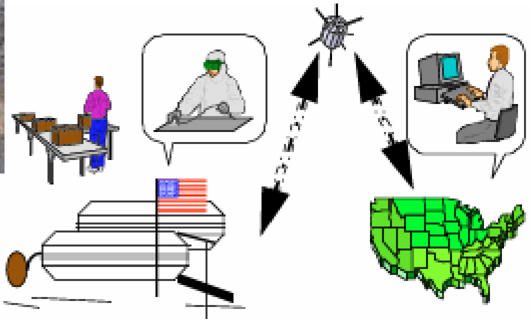


Reference: Figure A-5. Operational Analysis for Air Force 2025.

43 hypothetical systems were conjectured.







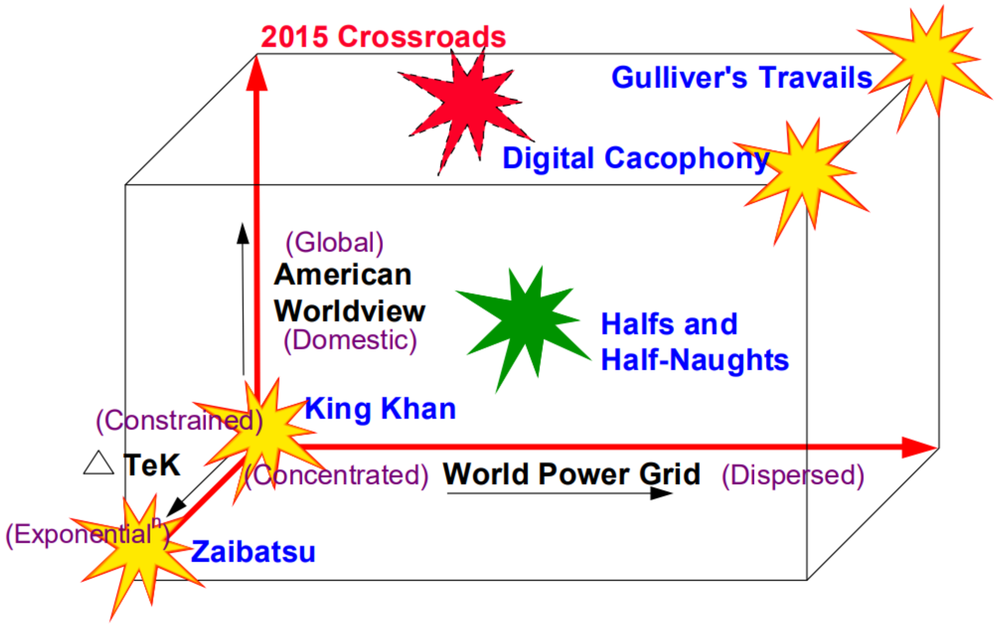
Reference: Appendix B. Operational Analysis for Air Force 2025.

Identified Systems

1. 0	Vehicles - Air Only (Piloted)
	1.1 Hypersonic Attack Aircraft
	1.2 Fotofighter
	1.3 Container Aircraft
	1.4 Lighter-than-Air Airlifter
	1.5 Supersonic Airlifter
	1.6 Stealth Airlifter
	1.7 Global Transport Aircraft
2.0	Vehicles - Air Only (Uninhabited)
	2.1 Strike UAV
	2.2 Reconnaissance UAV
	2.3 Uninhabited Combat Air Vehicle
	2.4 Precision Delivery System
	2.5 UAV Mothership
	2.6 Exfiltration Rocket
3.0	Vehicles - Space Only
	3.1 Orbital Maneuvering Vehicle
	3.2 Orbital Combat Vehicle
	3.3 Satellite Bodyguards
4.0	Vehicles - Air and Space
	4.1 Piloted SSTO Transatmospheric Vehicle
	4.2 Uninhabited Air-Launched Transatmospheric Vehicle
5.0	Weapons - Air and Ground-Based
	5.1 Adjustable Yield Munition
	5.2 Advanced Air-to-Air Missile
	5.3 Airborne High-Power Microwave Weapon
	5.4 Standoff Hypersonic Missile
	5.5 Attack Microbots
	5.6 Airborne Holographic Projector
	5.7 Hybrid High-Energy Laser System
6.0	Weapons - Space-Based
	6.1 Global Area Strike System
	6.2 Space-Based Kinetic Energy Weapon
	6.3 Space-Based High-Power Microwave Weapon
	6.4 Space-Based High-Energy Laser
	6.5 Solar-Powered High-Energy Laser System
	6.6 Solar Energy Optical Weapon
	6.7 Asteroid Mitigation System
7.0	Information Systems - Individual
	7.1 Spoken Language Translator
	7.2 Personal Digital Assistant
	7.3 Virtual Interaction Center
8.0	Information Systems - Global
	8.1 Global Information Management System
	8.2 Global Surveillance, Reconnaissance, and Targeting System
	8.3 Sensor Microbots
	8.4 Multiband Laser Sensor System
	8.5 Asteroid Detection System
9.0	Miscellaneous Systems
	9.1 Mobile Asset Repair Station
	9.2 Weather Analysis and Modification System
	9.3 Sanctuary Base

Reference: Table 1. Operational Analysis for Air Force 2025.

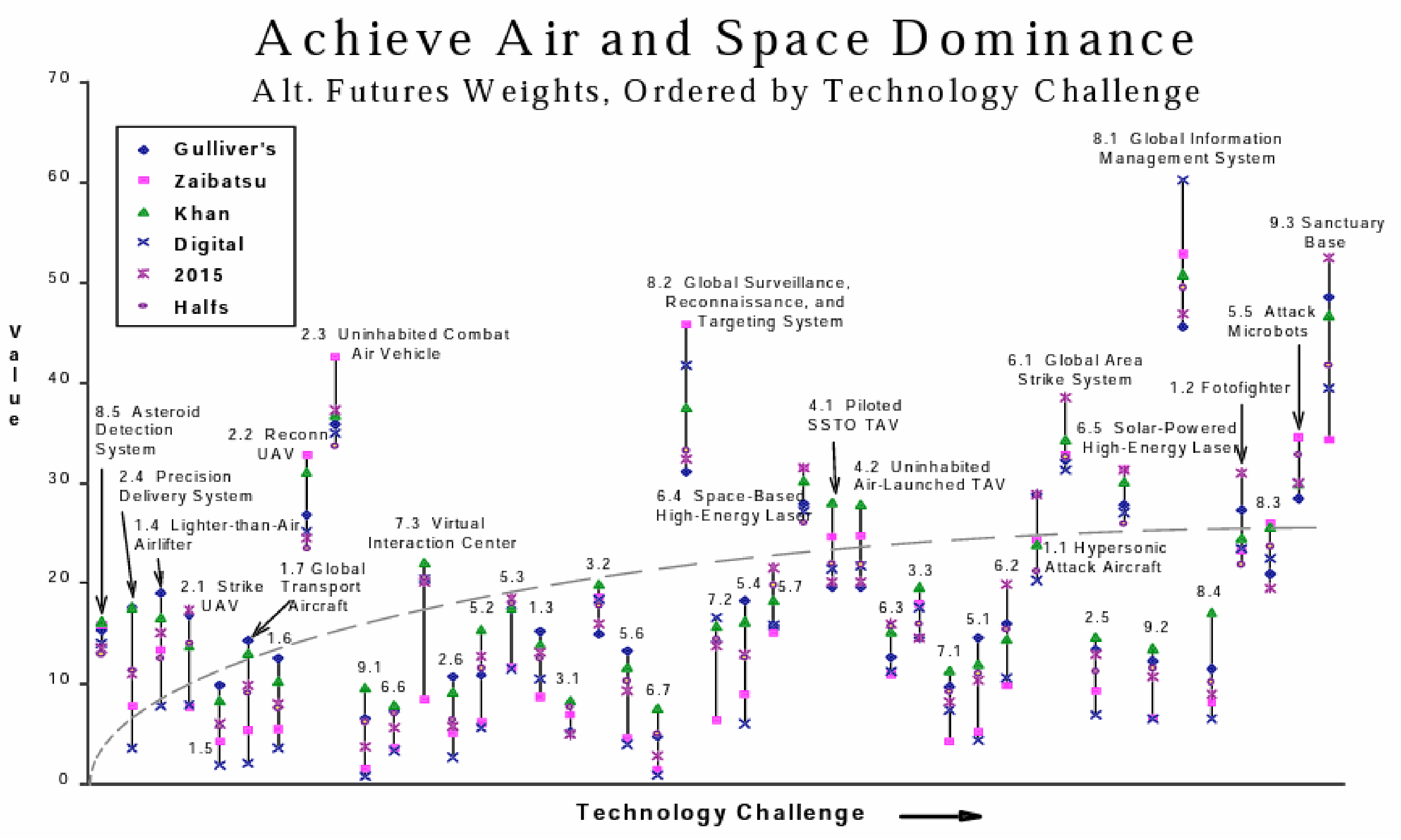
Alternate Futures Planning Space



Reference: Figure 2-18. Operational Analysis for Air Force 2025.

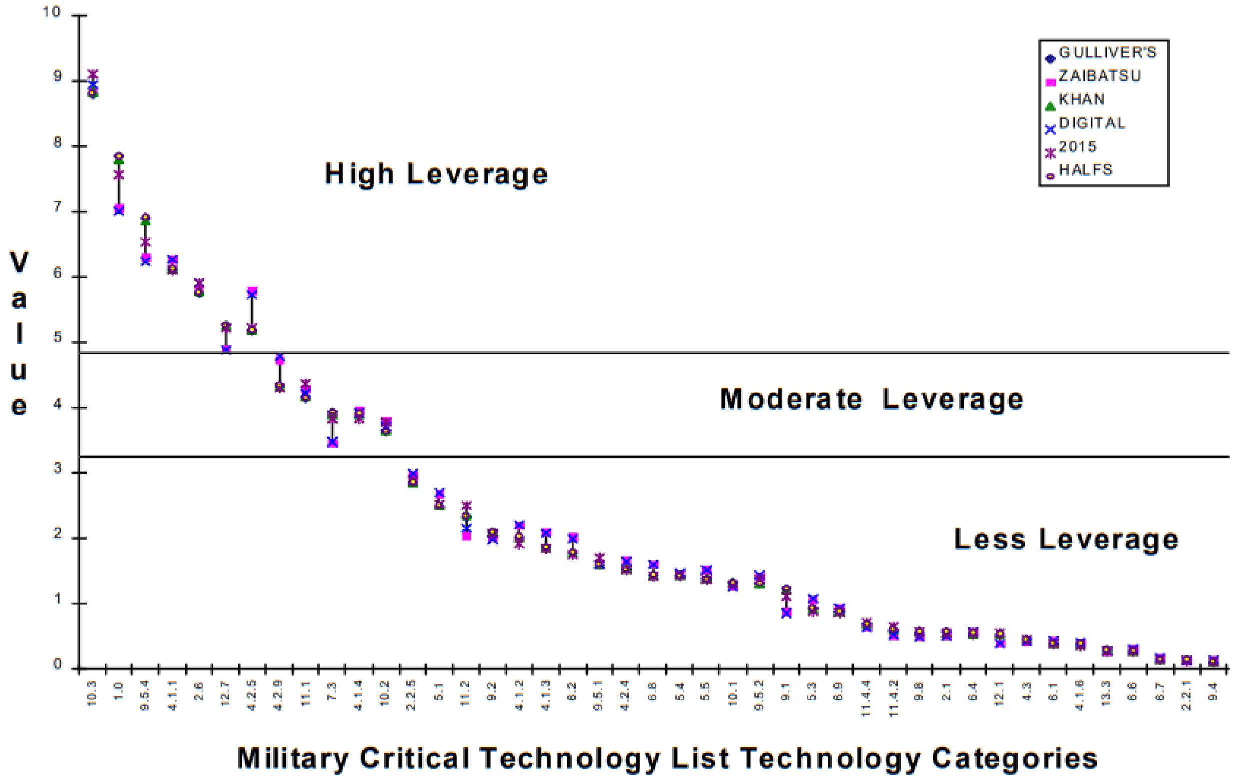
- World Power Grid describes the distribution and control of power throughout the world.
- ΔTeK is the differential in the growth rate of scientific knowledge and technical applications.
- American Worldview is the US willingness and capability to interact

System value as a function of technology challenge.



Reference: Figure 3-3. Operational Analysis for Air Force 2025.

Technology Rankings



Reference: Figure 3-10. Operational Analysis for Air Force 2025.

Results

System Concepts

The five highest value system concepts were:

- Global information management system
- Sanctuary base
- Global surveillance, reconnaissance, and targeting system
- Global area strike system
- Uninhabited combat air vehicle

Enabling Technologies

Six high leverage technologies support a large number of high-value system concepts:

- Data fusion
- Power systems
- Micromechanical devices
- Advanced materials
- High energy propellants
- High performance computing

References

1. Jackson, et al. "An Operational Analysis for Air Force 2025: An Application of Value-Focused Thinking to Future Air and Space Capabilities," Air Command and Staff College, 1996.
2. Tirpak, John A. "Air Force 2025," *AIR FORCE* Magazine, December 1996.
3. Ralph L. Keeney, *Value-Focused Thinking: A Path to Creative Decisionmaking* (Cambridge, Mass.: Harvard University Press, 1992).
4. Craig Kirkwood, *Making Strategic Decisions*, 1997.
5. Clemen and Reilly, *Making Hard Decisions with DecisionTools*, 3rd ed., 2014.
6. Klimack, et al, "Soft Skills Workshop: Real World Skills for Decision Analysis and OR/MS Professionals," 2014.


FRAMING
ALTERNATIVES
INFORMATION
TRADEOFFS
REASONING
COMMITMENT
DECISION QUALITY