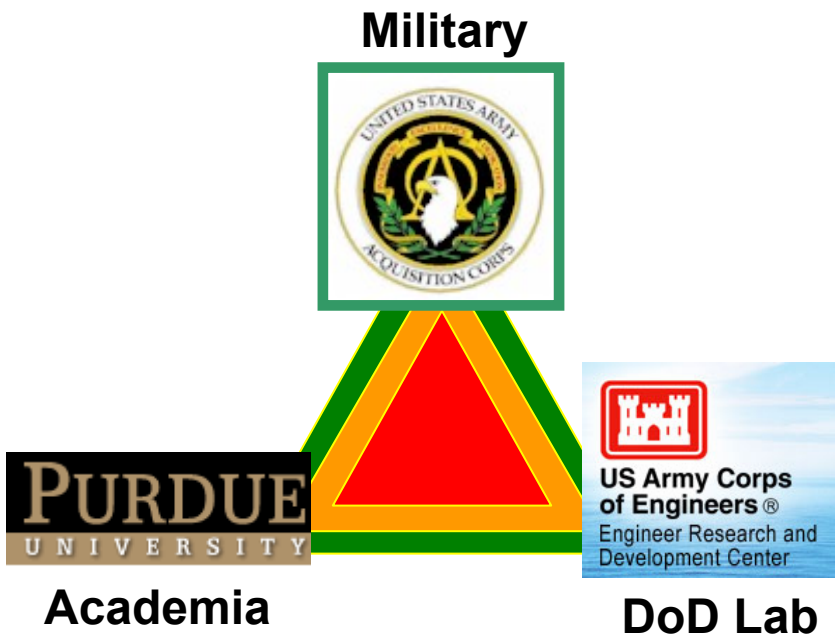
A System-of-Systems (SoS) Approach to Effective Organizational Decision-Making For Infrastructure Project Selection

Ph.D. Committee: Daniel DeLaurentis, Dulcy M. Abraham, Philip Dunston, Paul Mlakar



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Conceptual Modeling Workshop, UAH
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Agenda

- Background
- Conceptual Modeling Framework
- Research Methodology
  - Definition Phase
  - Abstraction Phase
    - Paper Model
  - Implementation Phase
    - Host Nation Agent-Based Model (ABM)
    - Optimization Model
- On-going Work

Humanitarian Assistance

"…the best way to prevent terrorists from gaining strategic footholds in developing nations is to improve peoples quality of life…(and) help a given country help itself…with a holistic approach…which takes into account the full spectrum of potential nation-building missions." Joint Task Force-Horn of Africa, *Army Times*, Jan. 29, 2007

"…Our foreign assistance must help people get results…In the final analysis, we must now use our foreign assistance to help prevent future Afghanistans – and to make America and the world safer."-- Secretary Rice, Jan. 19, 2006

Humanitarian Assistance

The Huntsville Times, Thursday, Oct 18 2007 pg A3

Revised naval strategy focuses on cooperation

Uses aid, training and other efforts to foster stability

By PAULINE JELINEK
The Associated Press

WASHINGTON – In the first major revision of U.S. naval strategy in two decades, maritime officials said Wednesday they plan to focus more on humanitarian missions and improving international cooperation as a way to prevent conflicts.

"We believe that preventing wars is as important as winning wars," said the new strategy announced by the Navy, Marine Corps and Coast Guard.

The strategy reflects a broader Defense Department effort to use aid, training and other cooperative efforts to encourage stability in fledgling democracies and create relationships around the globe that can be leveraged if a crisis does break out in a region.

"Although our forces can surge when necessary to respond to crises, trust and cooperation cannot be surged," says the 16-page document entitled "A Cooperative Strategy for 21st Century Seapower."

It also says forces will be concentrated "where tensions are high or where we wish to demonstrate to our friends and allies our commitment to security" – something the U.S. did earlier this year in sending an additional aircraft carrier to the Persian Gulf region as a show of force toward Iran.

"Credible combat power will be continuously posted in the Western Pacific and the Arabian Gulf/Indian Ocean to protect our vital interests, assure our friends ... and deter and dissuade potential adversaries," the strategy document said.

Result of two-year study

The strategy was unveiled before naval representatives of 100 countries who are attending an international symposium on the seas at the Naval War College in Rhode Island. It was described to them by Navy Adm. Gary Roughead, chief of naval operations; Gen. James T. Conway, commandant of the Marine Corps; and Adm. Thad W. Allen, commandant of the Coast Guard.

Roughead said the Navy completed a two-year study to create the new strategy.

"What came through was that our security and our prosperity is completely linked to the security and prosperity of other nations throughout the world," he said.

It represents the first time the Navy, the Marine Corps and the Coast Guard have collaborated on a single, common strategy for defending the U.S. homeland and protecting U.S. interests overseas.

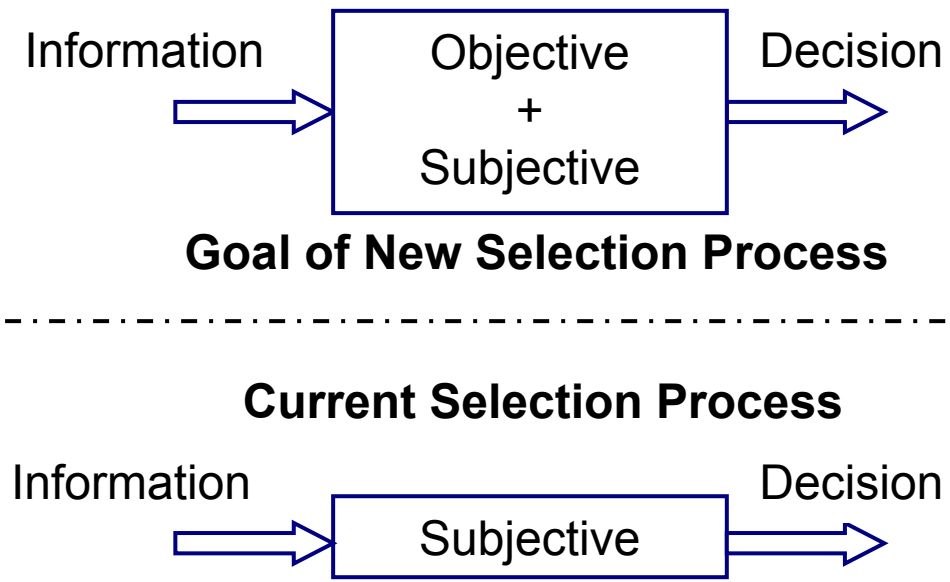
The Sept. 11 terror attacks demonstrated how the Navy's last major strategy, released publicly in 1986, had become irrelevant, Navy Cmdr. Bryan McGrath said. Drafted during the Cold War, the old plan focused on countering Soviet naval power across the globe.

Research Questions

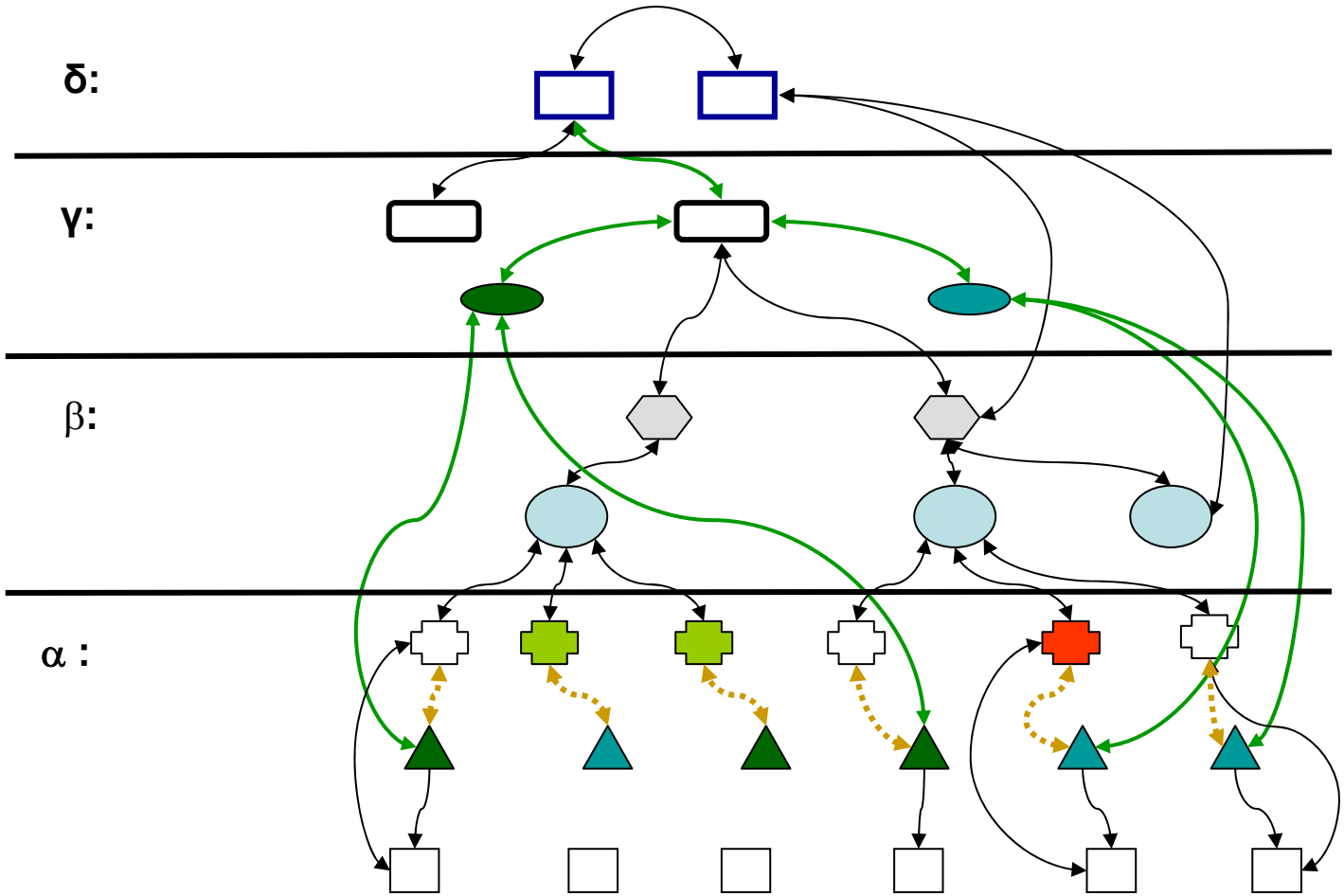
- In a resource constrained environment, how can the U.S. Department of Defense (DoD) make effective decisions on the type of humanitarian projects to fund outside the U.S.?
- What impact do the following have on robustly optimal organizational decision-making?
  - **(topology)** Organizational structure
  - **(relationships)** Agent relationship type (levels of competition and communication between the agents (groups within the organization))
  - **(infrastructure)** Infrastructure network status

DoD Civil Infrastructure Project Selection

Goal: Provide both objective and subjective information to the DoD decision-makers to use to make their decisions about civil infrastructure project selection



Notional Stakeholder Model



Simulation

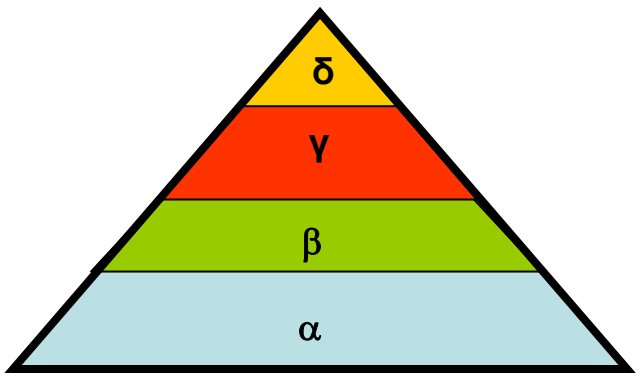
- Complexity frequently takes the form of *hierarchy*
- Source of new knowledge
  - System understood: Implications of the large number of variable involved (weather prediction)
  - Mechanisms governing behavior not well understood: Simplified models of key properties (market behavior)
- Man-made systems (like infrastructure networks and large organizations) are particularly suited for simulation via simplified models
  - Behavior of the system at each level depends only on a very approximate, simplified, and abstracted characterization of the system at the next level beneath it

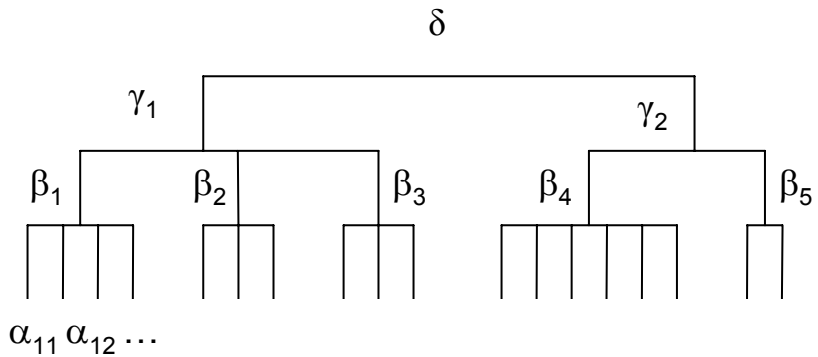
Emergent Behavior

- Not sure how to manage emergent behavior in a precise manner
- Simulation – can do many runs, explore possible trajectories and variations over time of the model
  - Identify when and what type emergent behavior can be expected when these changes are made to the SoS
  - Examine and explore a multitude of “what if” scenarios and examine the results for any persistent patterns that appear
- Identifying the underlying mechanisms causing the emergent behavior will help decision-makers manage it
- Save the U.S. money - fund fewer projects that do not meet the programs goals
- Provide more benefit to the local people in the Host Nations

Conceptual Model – SoS Framework

- Establishes common lexicon
- Decomposes the complex problem into categories and hierarchical levels
- Determines the critical components of the system



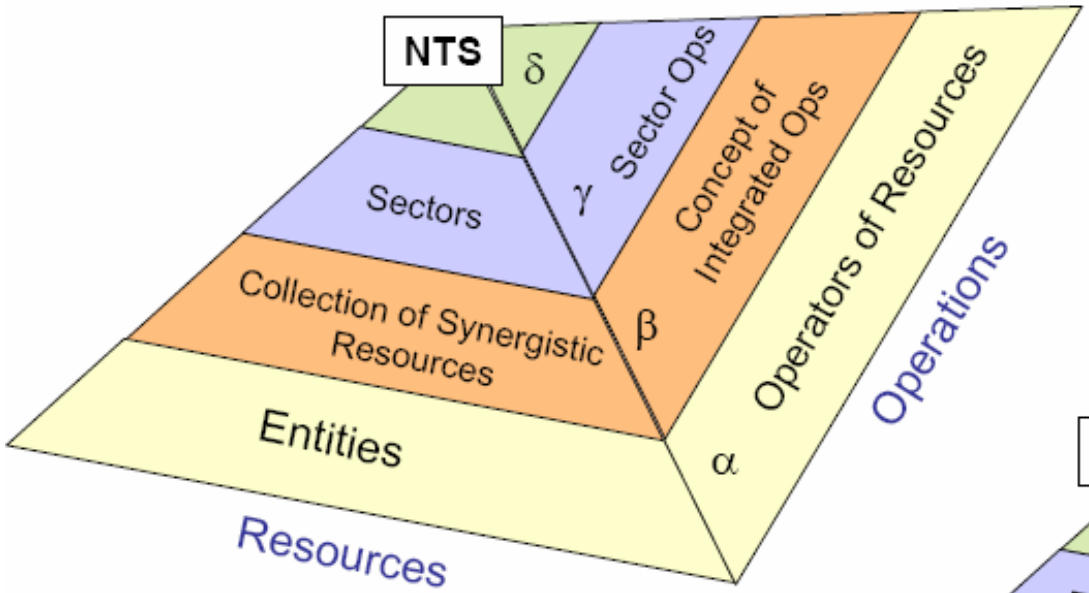


SoS Traits – Maier Criteria[1]

- **Operational Independence of the Elements –** The organizations/ entities involved must be able to usefully operate independently.
- **Managerial Independence of the Elements –** Component systems can and do operate separately.
- **Evolutionary Development -** The entities and stakeholders involved change over time, with functions and purposes added, removed, and modified with experience.
- **Emergent Behavior -** No one entity has all the capabilities and functions needed. Interactions between entities results in the principal functions and purposes of the SoS.
- **Geographic Distribution –** The geographic extent of the component systems is large. The primary exchange between the entities is information and not mass or energy.

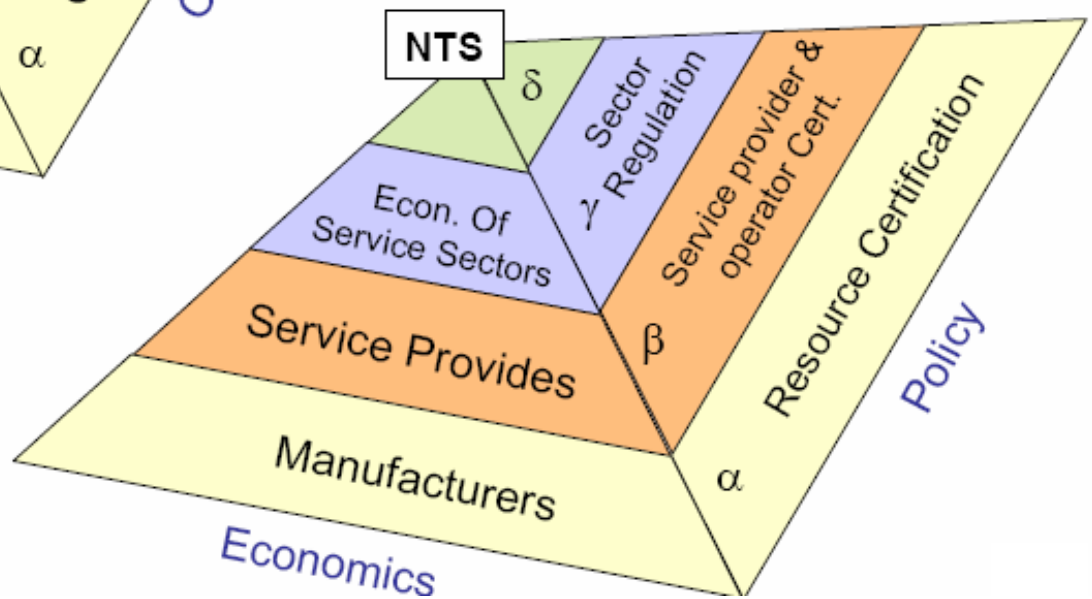
Example: National Transportation System (NTS)²

Categories and Levels— A Unifying Lexicon



Examples

- Aircraft : α-level resource
- Deregulation: γ-level policy

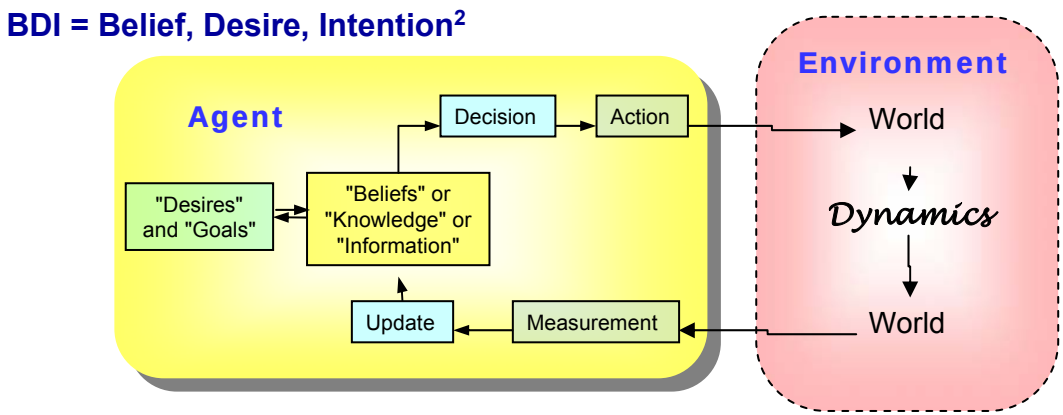


Lexicon Benefits

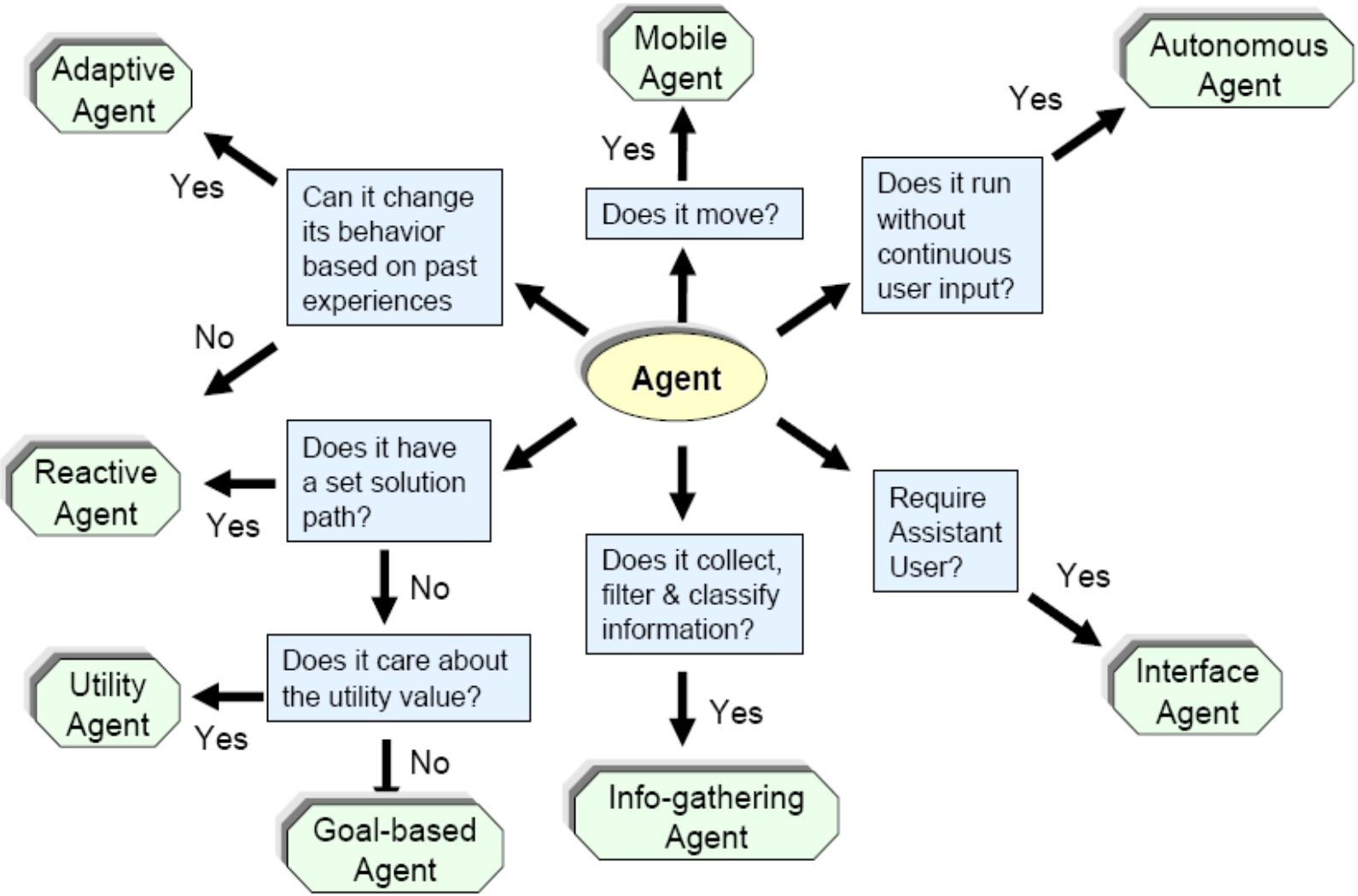
- ✓ Minimize confusion
- ✓ Foster trans-domain modeling
- ✓ Better informed decisions at upper levels

Agent-Based Modeling

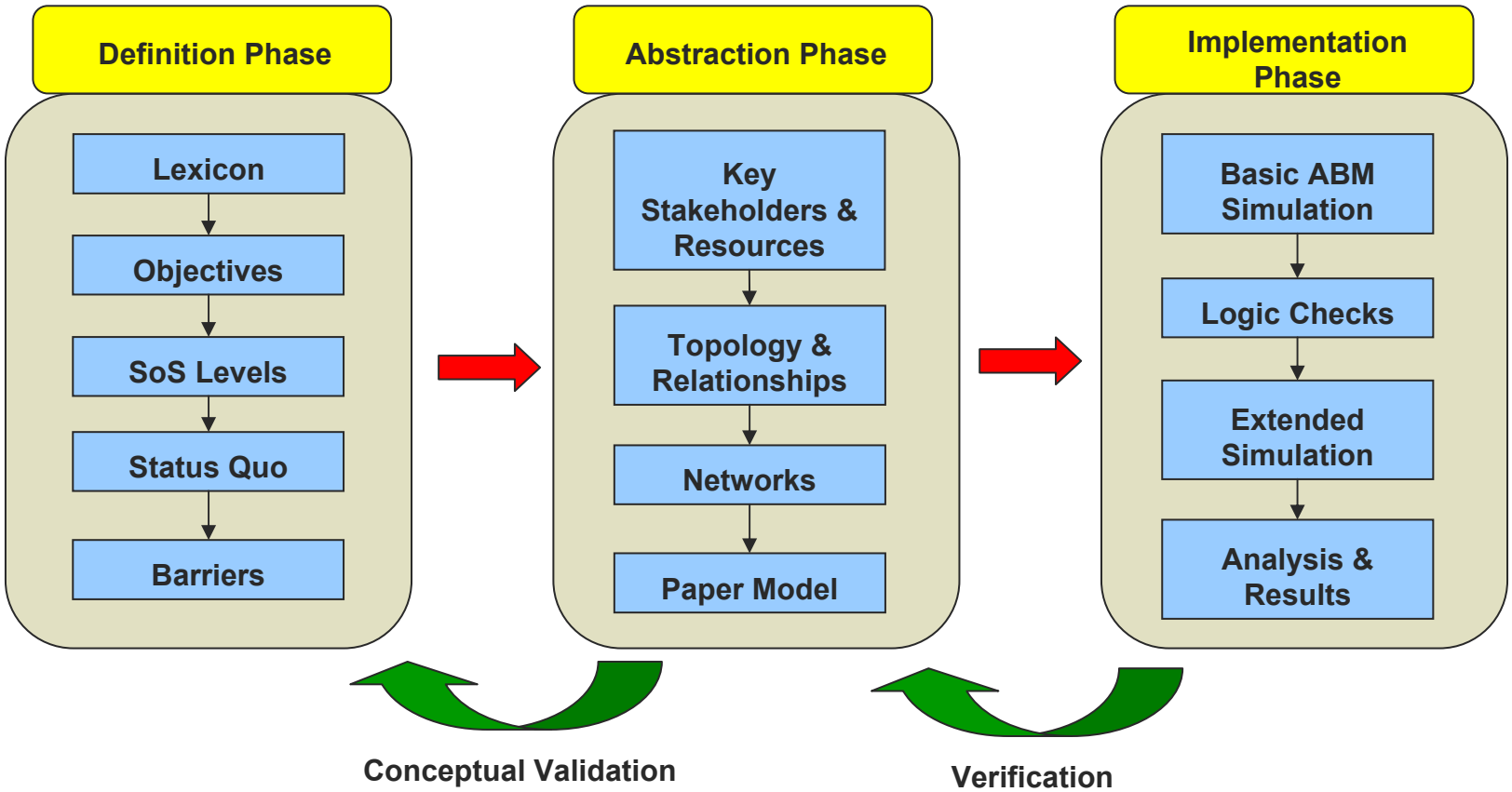
- Goal - provide support for decision-makers
- Advantages - modularity, robustness, maintainability, and extendibility
- Unique research area - investigating emergent phenomena



Agent Classification[2]



Research Methodology



Lexicon (1 of 2)

General System-of-System (SoS) Framework[2]

Categories	***Descriptions***
Resources	The physical entities that give physical manifestation to the system-of-systems
Operations	The application of policies/procedures to direct the activity of physical entities
Economics	The non-physical, sentient systems that give a "living system" character to the operation of the physical entities in a market economy
Policies	The external forcing functions that impact the physical & non-physical entities
Levels	***Descriptions***
Alpha (α)	The base level of entities, for which further decomposition will not take place. Alpha level components can be thought of as building blocks.
Beta (β)	Collections of α-level systems, organized in a network.
Gamma (γ)	Collections of β-level systems organized in a network.
Delta (δ)	Collections of γ-level systems organized in a network.

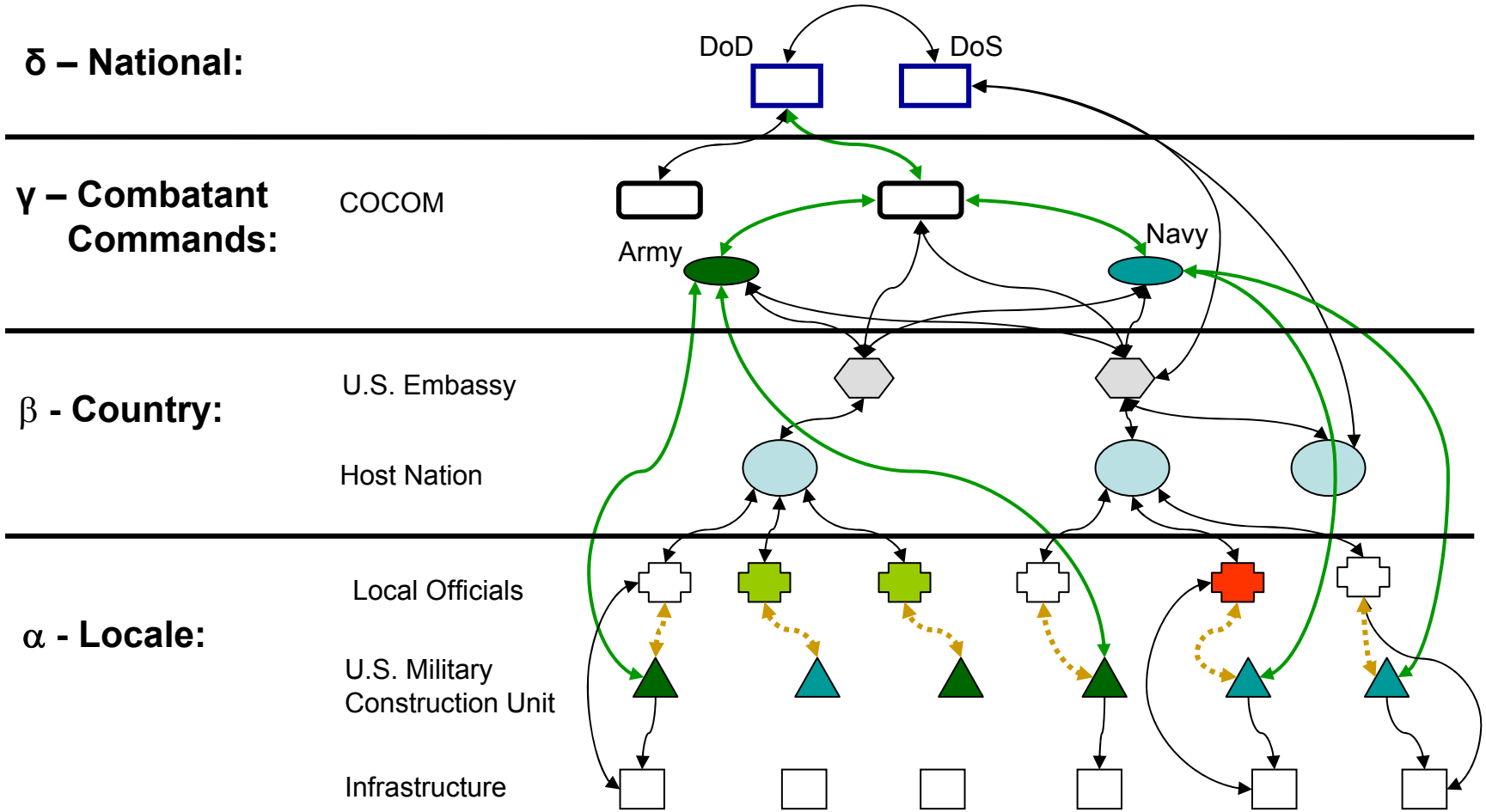
Lexicon (2 of 2)

Adapt	The same as optimize but can also change the rules that constrain decision making process (*intelligent behavior*)
Complex system/ organization	A system (organization) composed of a large number of parts (entities) that have many interactions
Effective	Producing the intended result
Humanitarian construction	Construction projects committed to improving the lives of the people living in the local community
Local community	A group of people who live in the same area as the construction project. People in the village/ town serviced by the construction project
Long-term	Greater than 10-years
Maintainable	Ability of the local community to ensure that the constructed facility continues to work effectively using local tools and practices
Optimize	Develop efficient methods to accomplish a certain goal within a given set of rules
Sustainable	Ability of the local community to maintain the facility in working order over the life of the project

Organizational Research Summary

Research Team	Application & Tools Used	Features
Cannon and Cole (2006)	Application: Organizational design to meet desired outcomes Tool: Experts and workforce surveys	• Changing demands on Army acquisition caused by the War on Terrorism require changes to the strategies of acquiring new products, which require organizational design and structure changes. • Key desired outcomes were an organization that was able to get products to the Soldier faster, system availability and readiness improved, the separation between procurement and sustainment communities eliminated, and life-cycle costs minimized. • Congruence of organizational elements and changing the culture of the existing workforce were critical challenges.
North (2001)	Application: Social and Organizational modeling for utility markets Tool: ABM	• Complex Adaptive Systems (CAS) are used to investigate large-scale socio-cognitive-technical systems. • Social and organizational models used for policy analysis of integrated natural gas and electric power markets, focusing on organizational interdependencies between these markets. • Emergent behavior of the SMART II+ model indicates that there is radically increasing interdependence between these two markets.
Lawless (2003)	Application: Investigate social interactions between individuals and between organizations Tool: ABM	• Uses an agent-based social quantum model (SQM) to better understand social interactions, concluding that social debated between 'champions' with orthogonal positions results in superior decisions. • Finds that during times of economic stability there is an increase in organizational competition and that instability results in mergers.
Chaturvedi et al. (2004)	Application: Model integration Tool: ABM	• *Measured Response* bio-terrorist ABM developed at Purdue University uses three underlying models: epidemiological, traffic/transportation, and crowd physiology. • Simulates the consequences of a bio-terrorist attack in fictitious mid-sized cities. Models human behavior, emotions, mobility, epidemiology, and well-being (financial and physical security).

SoS Modeling Framework

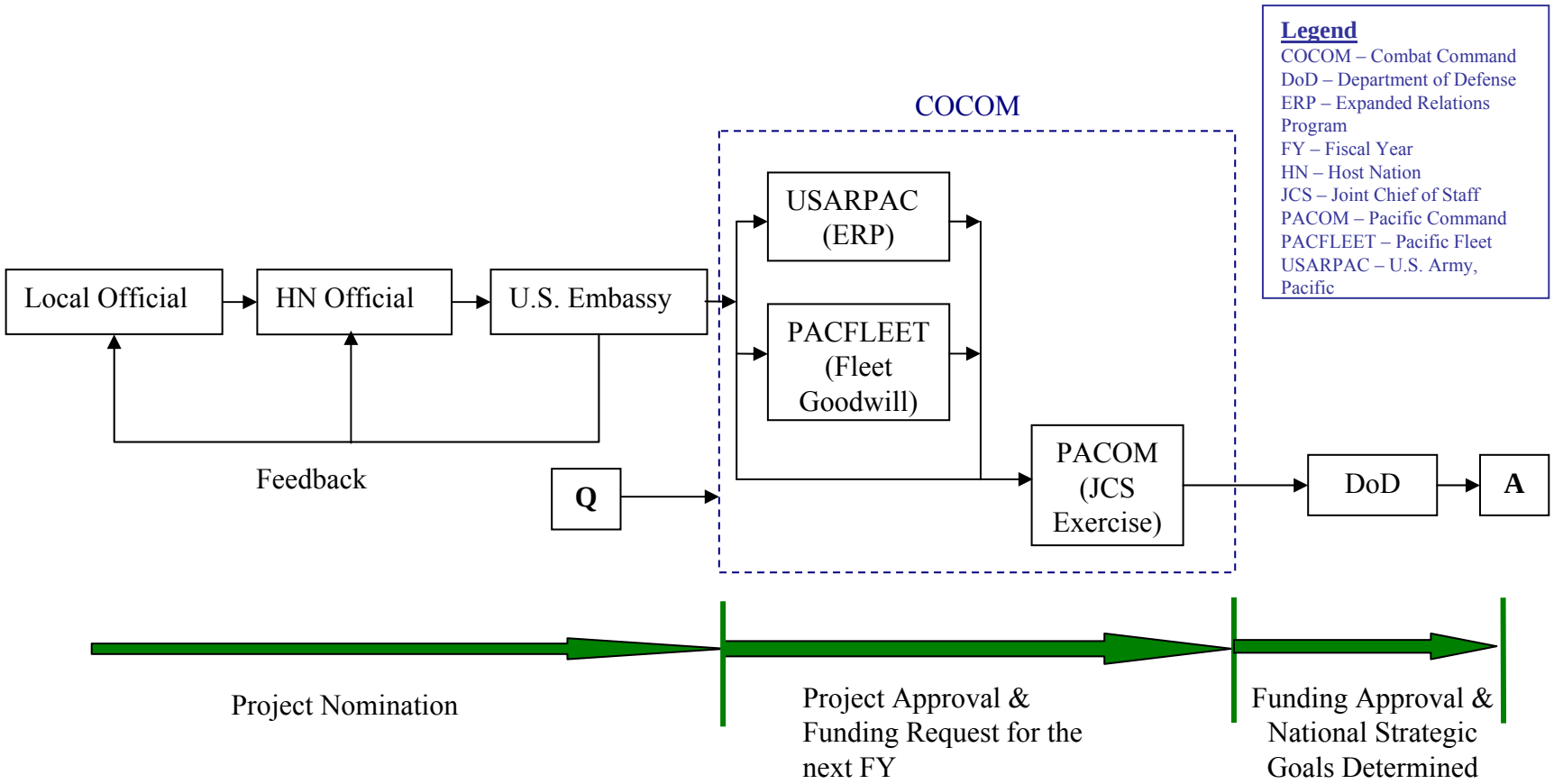


Legend:

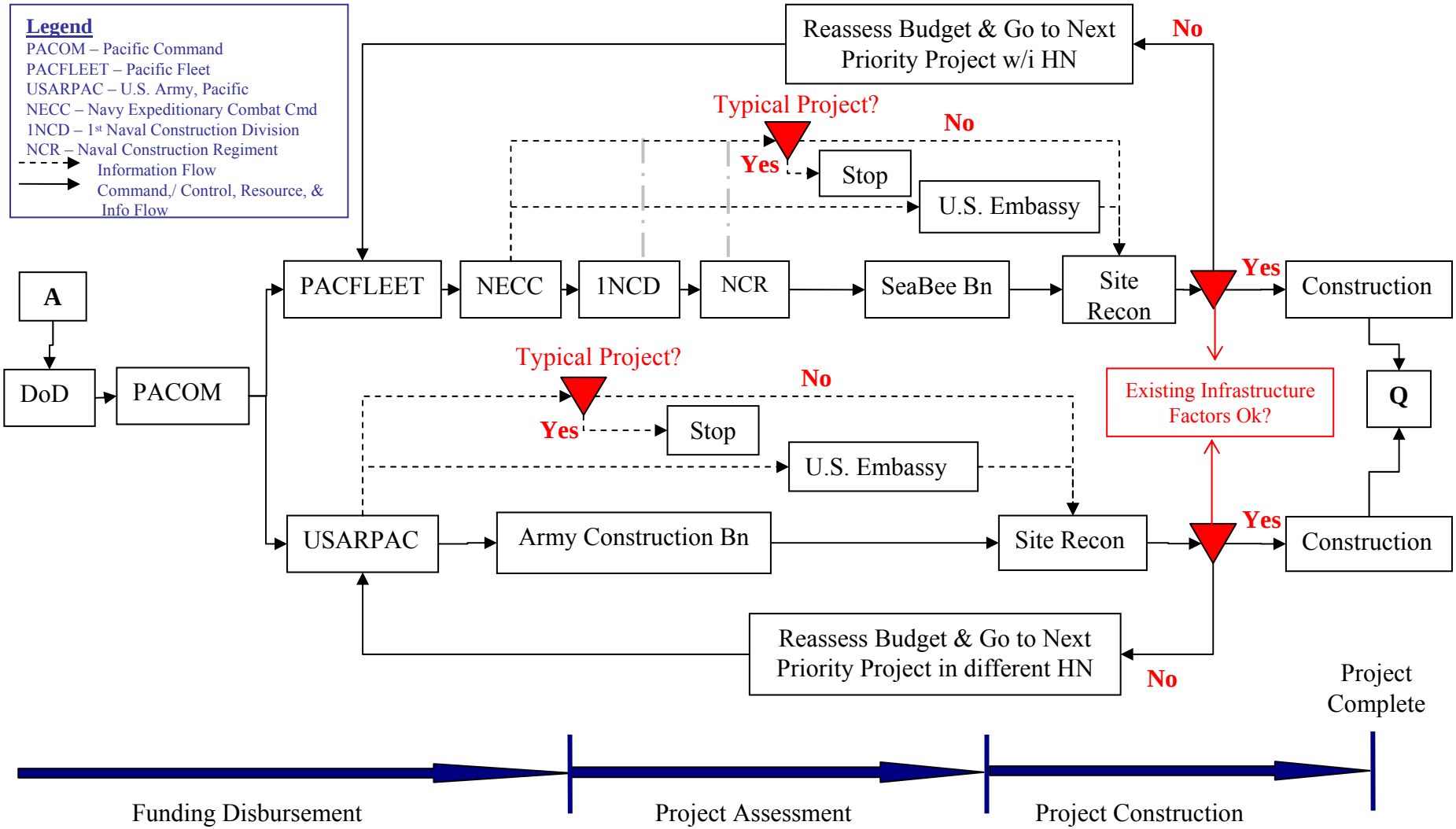
- Information only
- Information & Funding/ Resource Flow
- Informal Coordination

DoD – Department of Defense
DoS – Department of State
COCOM – Combatant Command

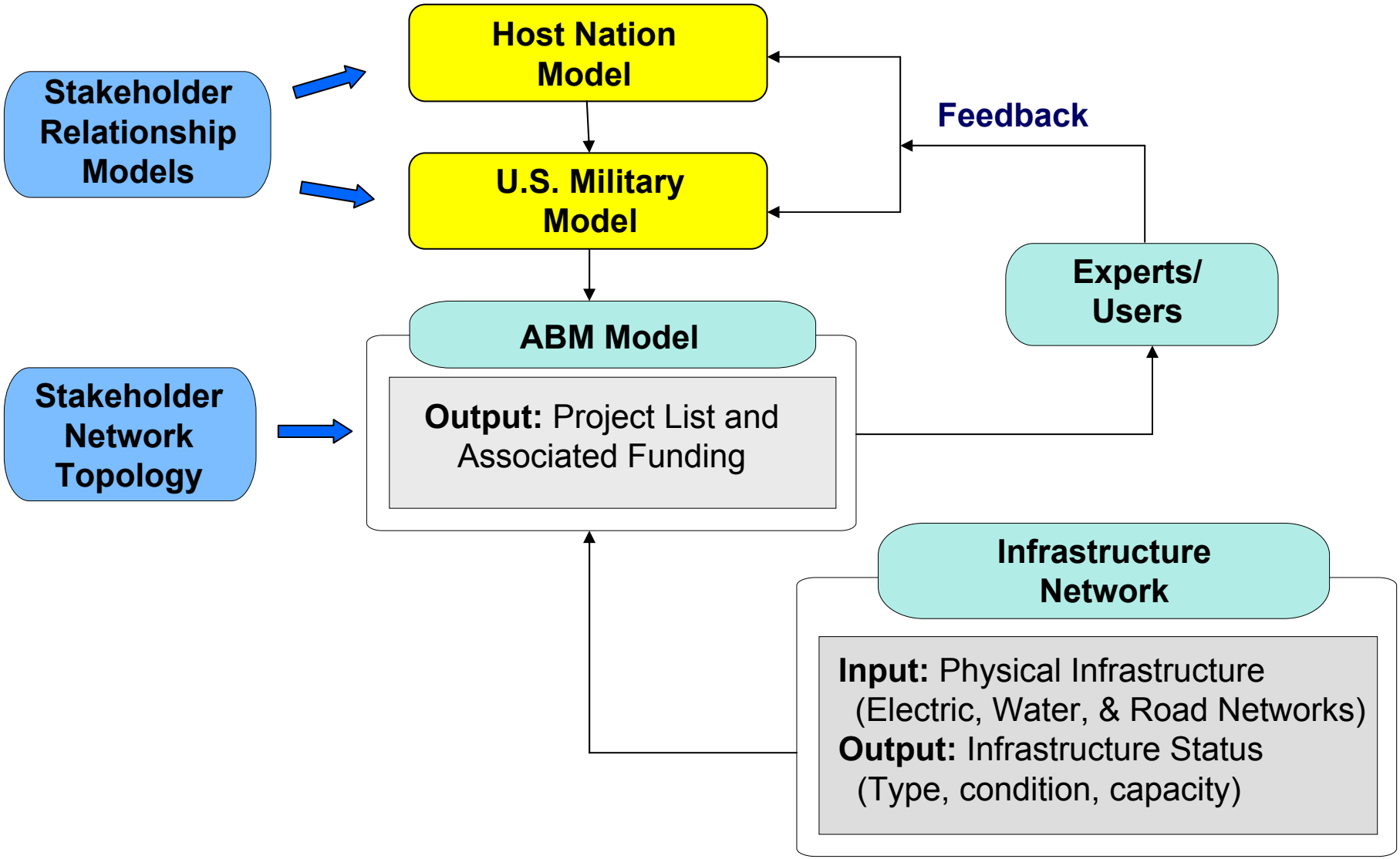
Actual Humanitarian Project Selection (1 of 2)



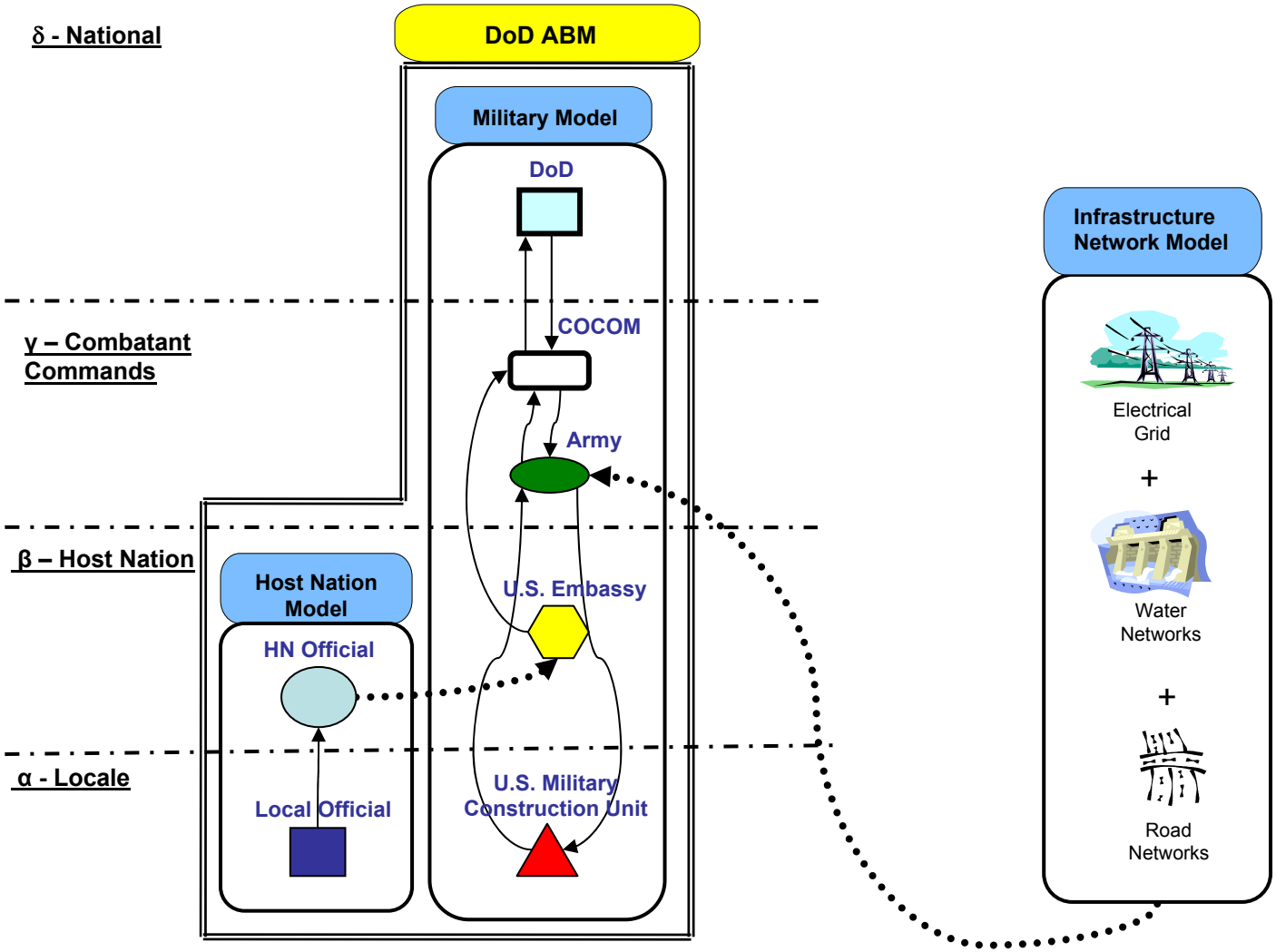
Actual Humanitarian Project Selection (2 of 2)



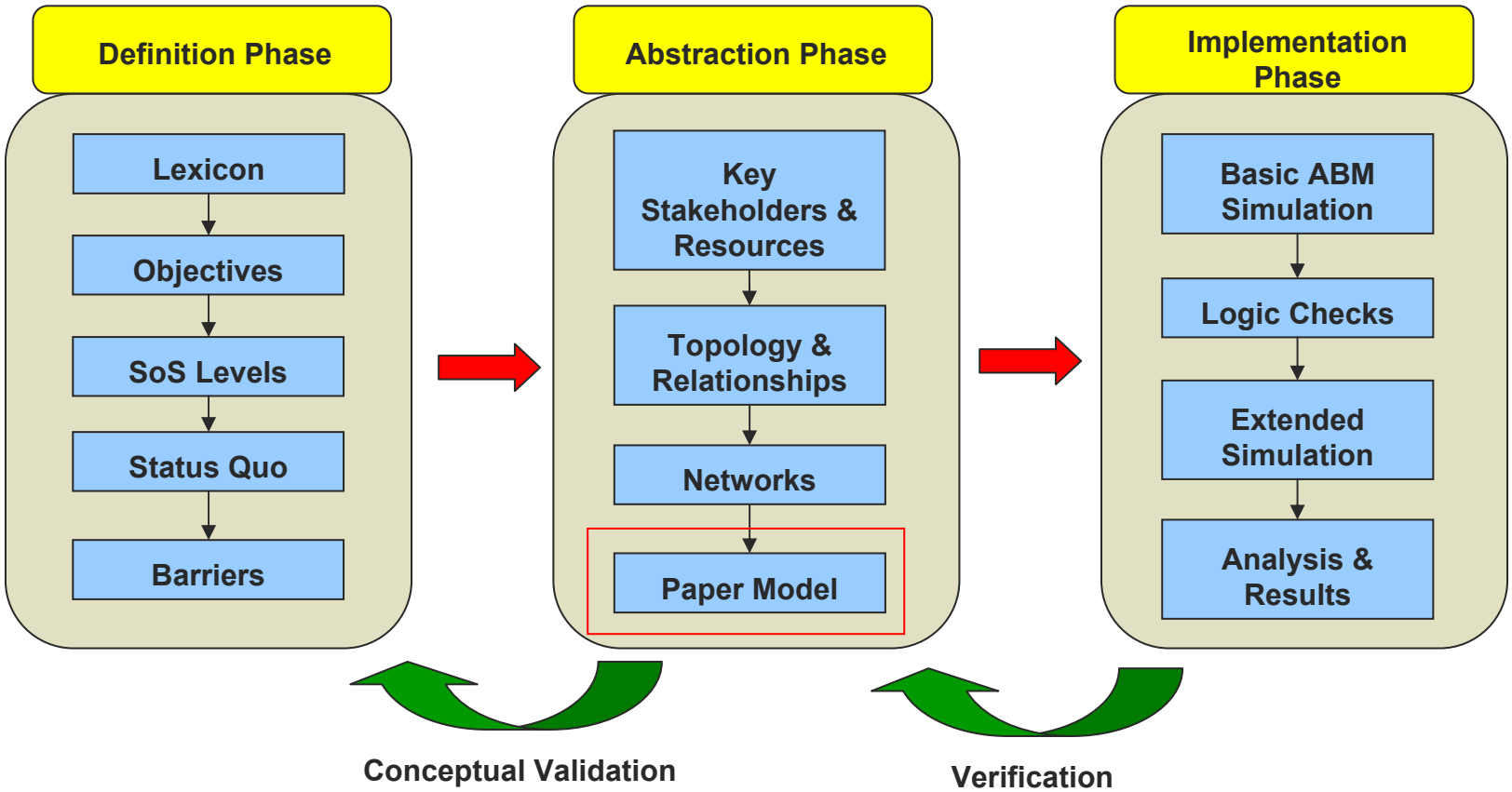
Analysis Framework



Paper Model

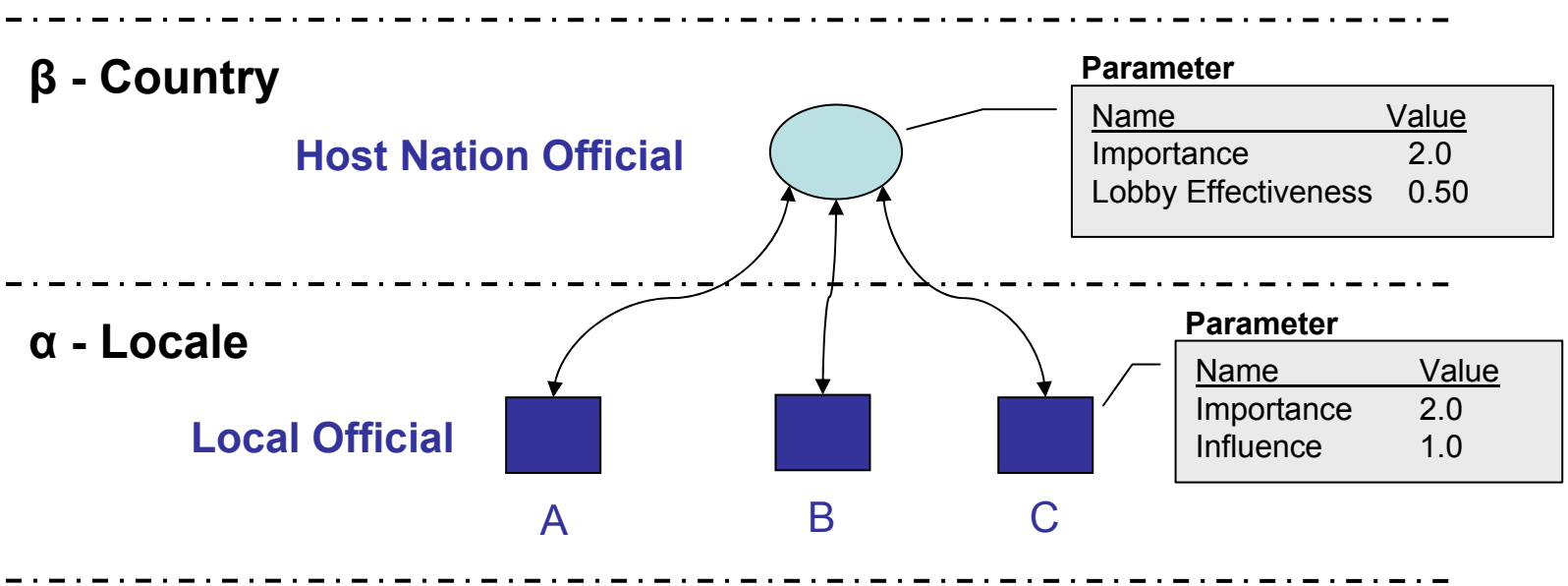

δ - National
DoD ABM
Military Model
DoD
COCOM
γ – Combatant Commands
Army
β – Host Nation
Host Nation Model
U.S. Embassy
HN Official
α - Locale
Local Official
U.S. Military Construction Unit
Infrastructure Network Model
Electrical Grid
+
Water Networks
+
Road Networks

Research Methodology



Host Nation (HN) ABM

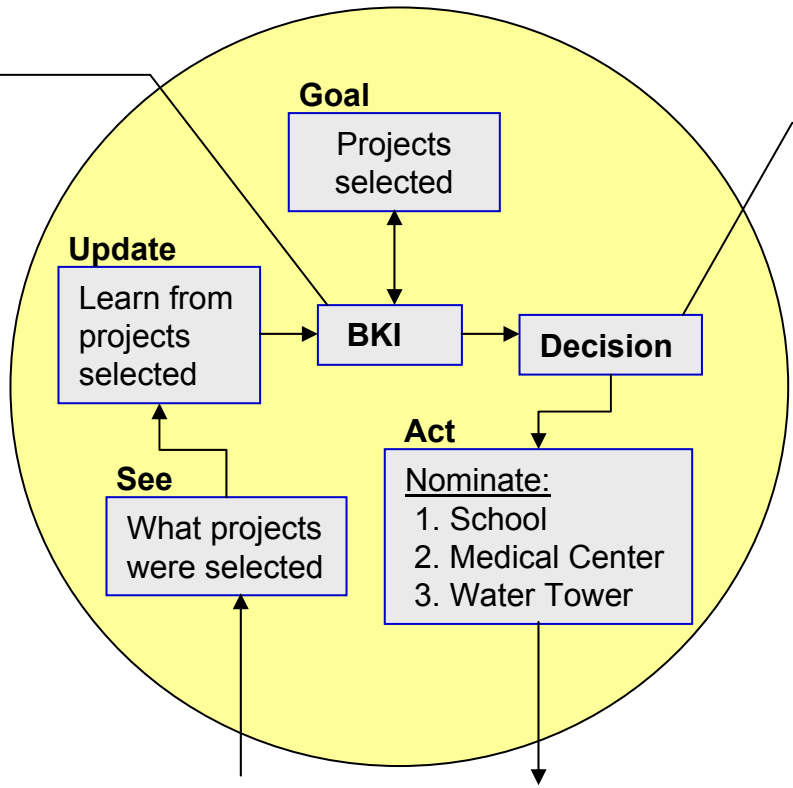
- HN model with five regions
- Five possible project types: School, Medical Clinic, Water Distribution, Community Center, & Road Improvement



Local Official Agent

- One *Local Official* per region of *Host Nation*
- Responsible for deciding which if any projects to nominate

1. Must nominate projects to be selected
2. Projects with direct benefits to local population more likely to be selected
3. Influence with Host Nation Official increase chance of being selected
4. Increasing Region's importance increases chance of being selected
5. Nominating less than 3 projects decreases chance of being selected



1. Nominate at least 3 projects that directly benefit local population
2. Attempt to influence Host Nation Official
3. Attempt to increase importance of region

Local Project List

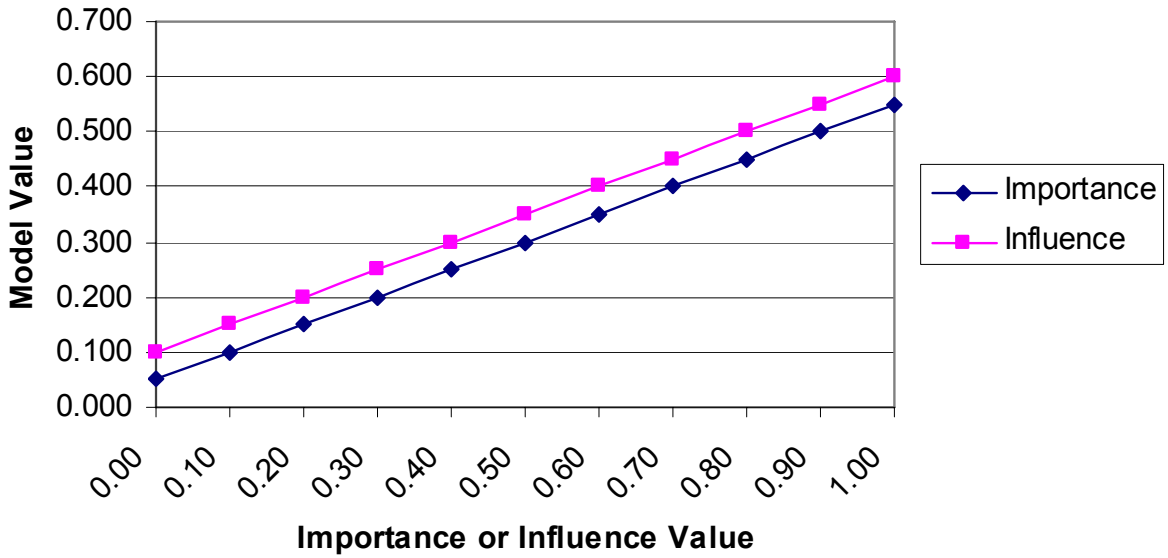
- Sent from Local Official to National Official
- Five parameters
  1. Priority – Local Official project priority
  2. Project Type – one of the 5 possible types
  3. Location – region of the country
  4. Project Cost
     - Building Materials
     - Transportation
  5. Distance from Base Camp (km)

Baseline Host Nation Model

	LocaleA	LocaleB	LocaleC	LocaleD	LocaleE
Initial # Schools	4	1	0	1	1
Initial # Medical Clinics	3	0	0	1	0
Initial # Water Towers	2	2	1	0	0
Initial # Community Centers	1	1	3	1	1
Initial # Road/Culverts	0	1	6	0	0
Total =	**10**	**5**	**10**	**3**	**2**

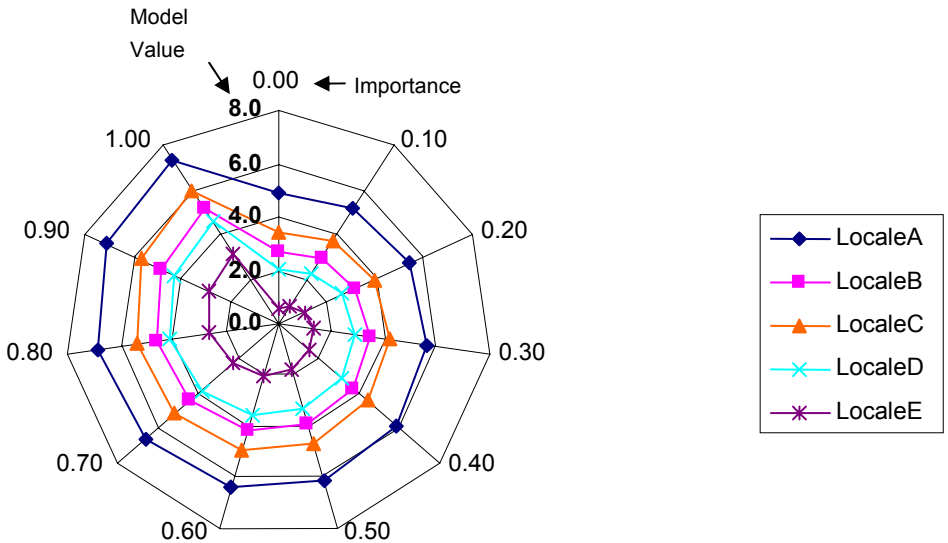
- Model 1: 0.5*importance + 0.5*influence
- Model 2: 0.25*importance + 0.25*influence + 0.25*number of projects + 0.25*type of projects
  - Z: # of projects nominated factor
    - < 3 z = 0
    - = 3 z = 4
    - = 4 z = 5
    - = 5 z = 7
    - > 5 z = 10

Model 1 Results: Importance + Influence



- Importance or influence – either can dominate this model's results
- Bribe/ corruption - could control the projects nominated from a Host Nation, despite low regional importance

Model 2 Results

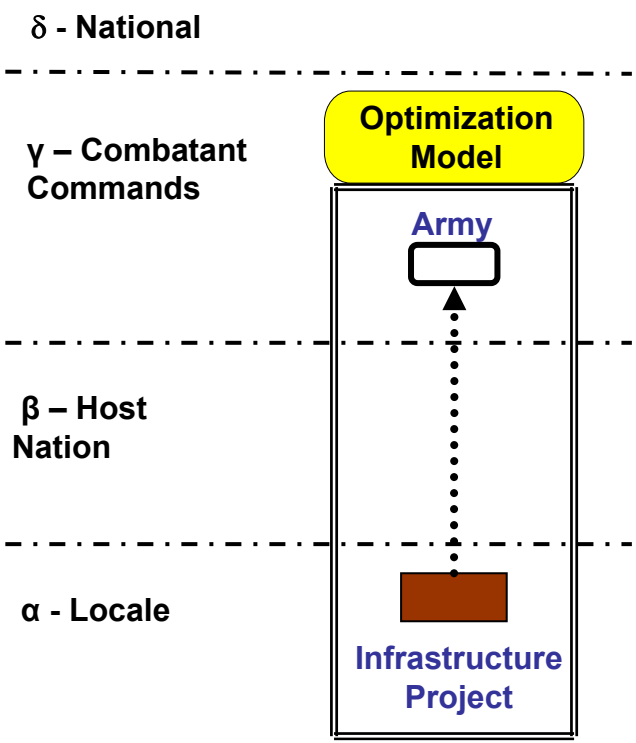


- Nominating more projects usually results in that Locale being selected
- If less than three projects are nominated, there is low chance (approximately 3%) that the locale will be selected if there are other locales that have submitted at least five projects
- Maximum influence score - Locale approximately 50% more likely to be nominated by the Host Nation (contrast with Model 1)

Host Nation ABM Lessons Learned

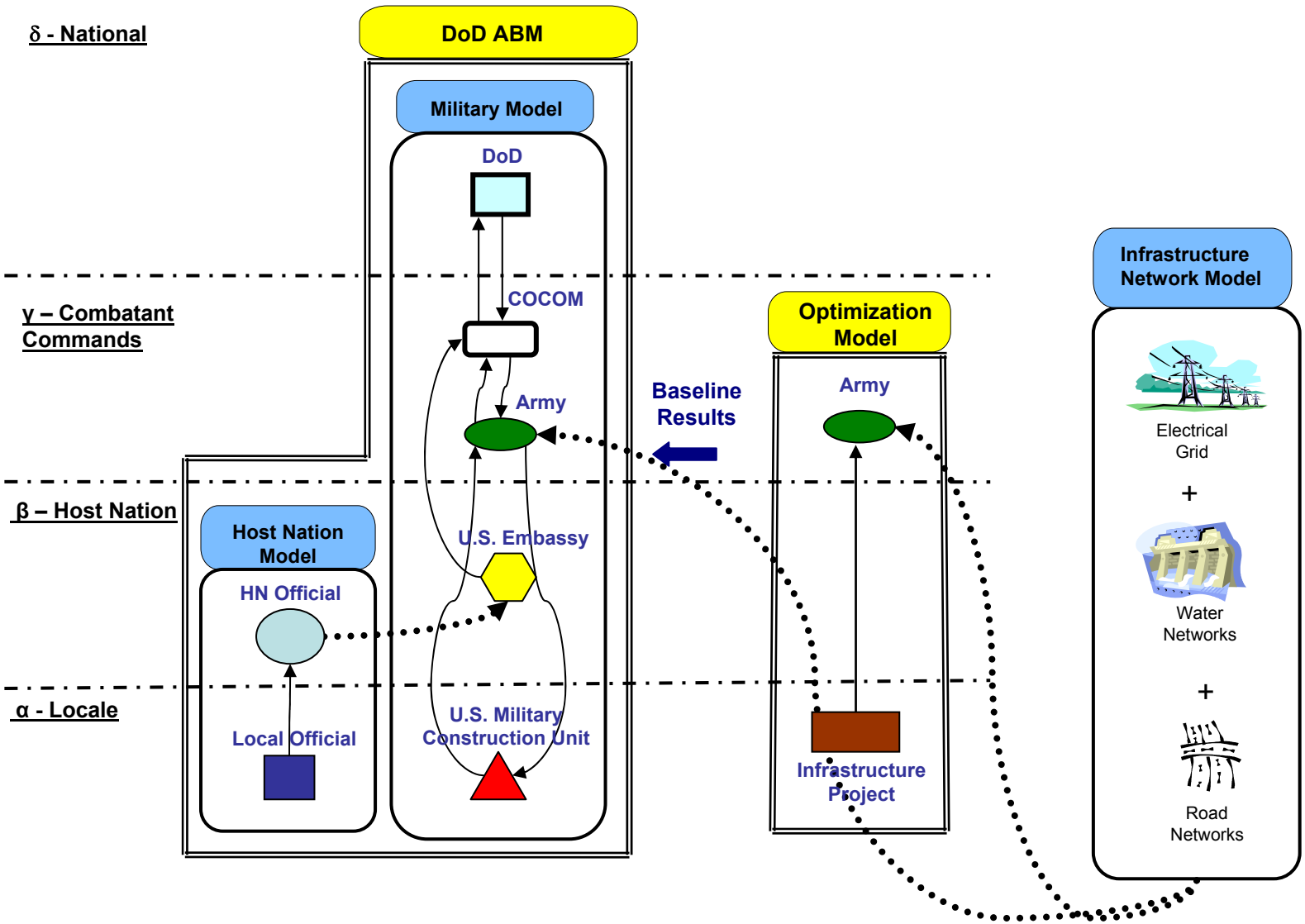
- Coding/ programming takes a lot longer than planned
- Using a commercial software program for the GUI interface and writing custom application code is probably more trouble than it is worth
- ABM simulation great for “what if” scenarios
- It is worth the time up front to create models that are easily extendable

Optimization Model



- "Greedy" model – selections based solely on Army objectives
- Baseline - Compare with results of the ABM of the DoD Humanitarian project selection to determine the effects topology, communication, and relationships have on project selection

DoD Humanitarian Project Selection Models



Min-Max Multi-Objective Optimization

- Min-Max method is solved by minimizing β subject to the additional constraints:

  $a_l [(f_l(\mathbf{x}) - f_l^{min})/ f_l^{min}] - \beta \leq 0, l = 1 \text{ to } p,$

  where p = # objective functions

- Advantages[3]:
  - Provides a clear interpretation of minimizing the largest difference between $f_l(\mathbf{x})$ and f_l^{min}
  - Provides all the Pareto optimal points
  - always provides (at least) a weakly Pareto optimal solution
  - Generates the complete Pareto optimal set (with variation in the weights)

Optimization Model for USARPAC

- 23 historical Host Nations with infrastructure factors
- 7 project types
- 161 decision variables
- 4 Objective functions
- 328 constraints, not including non-zero and integer constraints
- Approximately 100 model runs conducted to verify model results
- Over 400 model runs for data

Project Selection Factors

Projects	Project Value to U.S.	Cost ($k)	Training Value	Project Infrastructure Dependence:		
				Water	Power	Trans
School	7	50	7	4	4	4
Medical Clinic	7	50	8	3	2	3
Water Distribution	5	30	3	6	6	7
Community Center	4	65	7	6	8	6
Road Improvement	5	50	7	7	9	2
CAT	10	100	10	10	10	10
Joint Exercise	9	100	9	10	10	10

Countries	Trans. Cost ($k)	Locale Support	Hazards	HN Import to U.S.	Cost Scale Factor	Infrastructure Network Condition:		
						Water	Power	Trans
Kosrae	70	9	9	10	1	7	8	9
Kwajalein	60	10	10	10	1	10	9	10
Thailand	80	9	8	9	1	7	7	8
Philippines	95	9	6	9	1	7	7	8
Cambodia	120	6	4	7	2	6	6	7
Laos	150	4	4	10	1.8	5	3	3
…	…	…	…	…	…	…	…	…

Multi-Objective Optimization

Project Decision Variable: x_{ij} (integer number of projects, 161 total)

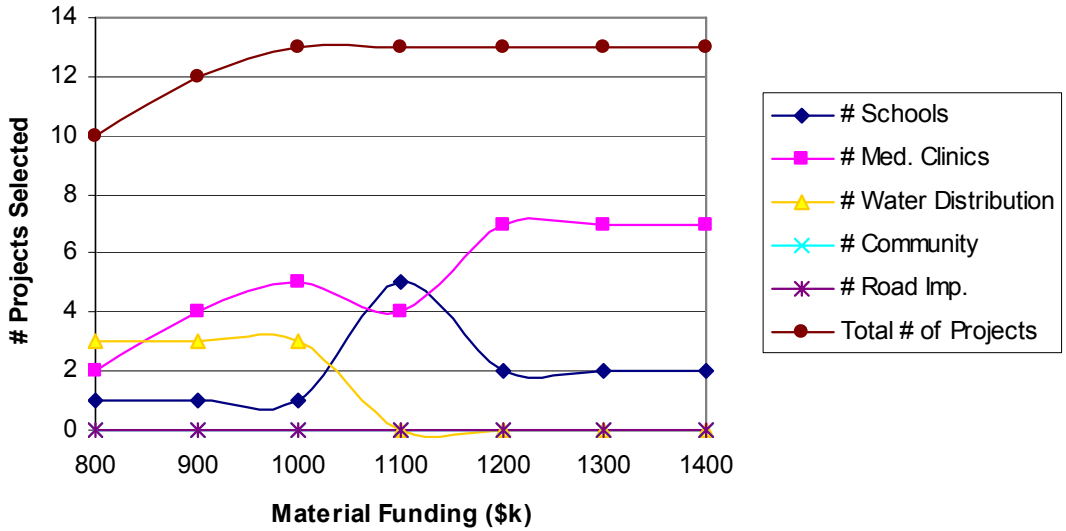
i = project location (1=Kosrae, 2=Kwajalein, 3=Thailand,…, 23=Palau)

j = project type index (1=School, 2=Medical Clinic, 3=Water Distribution, 4=Community Center, 5=Road Improvement, 6=Civic Action Team (CAT), 7=Joint Exercise)

Objective Functions:

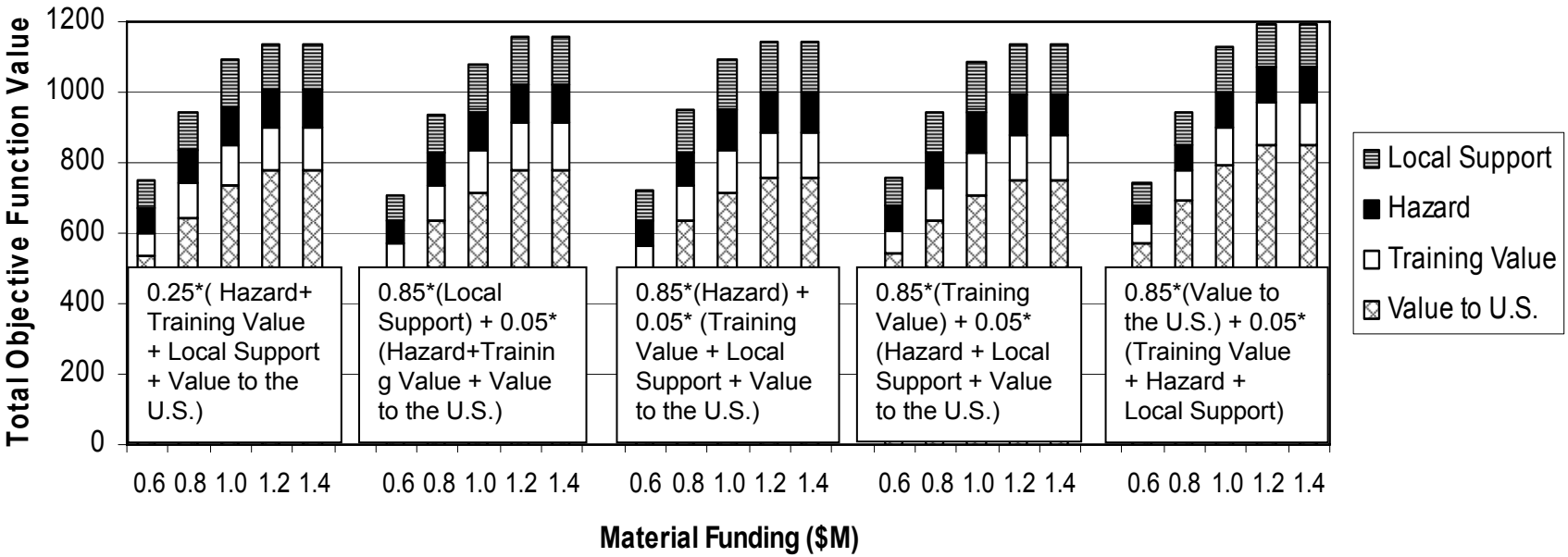
- max $f_1(\mathbf{x})$ = Value to U.S. (country importance * project value)
  $= \Sigma_i \Sigma_j a_i * b_j * x_{ij}$, where a_i = country importance factor, b_j = project value factor
- max $f_2(\mathbf{x})$ = Training value to U.S. construction unit soldiers
  $= \Sigma_i \Sigma_j c_j * x_{ij}$, where c_j = training value for each project type
- max $f_3(\mathbf{x})$ = Local Support
  $= \Sigma_i \Sigma_j d_j * x_{ij}$, where d_j = local support for the project
- min $f_4(\mathbf{x})$ = Hazard to soldiers
  $= \Sigma_i \Sigma_j e_j * x_{ij}$, where e_j = hazards to U.S. soldiers in a country

Optimization Results



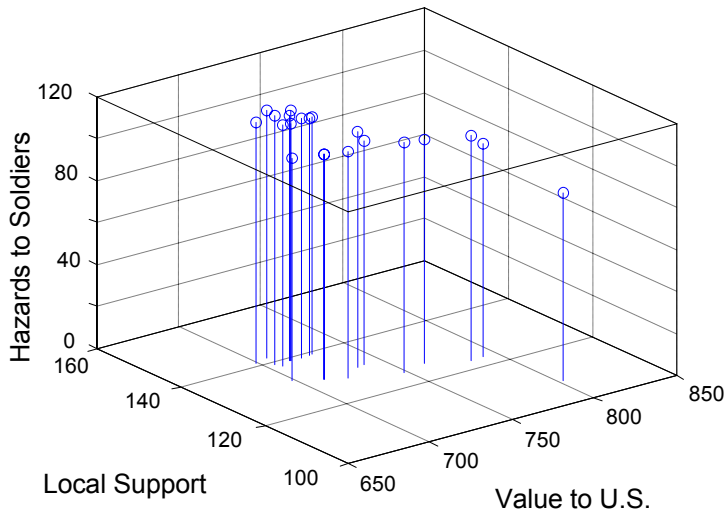
- Funding above $1.2M does not change the projects selected - transportation funding becomes the critical limiting constraint
- When the transportation funding > material funding by $500k, an additional project is selected by shifting funding to water towers since they require the lowest material cost

Objective Function Values at Various Weights for different Material Funding Amounts



- The 0.7 or 0.85*(Value to the U.S.) models most closely matched the actual projects selected
- The # projects selected:
  - Minimum of 10 at $800k of material funding available
  - 13 when material funding is $1M or greater

Example 3-D plot of USARPAC optimization model objective functions

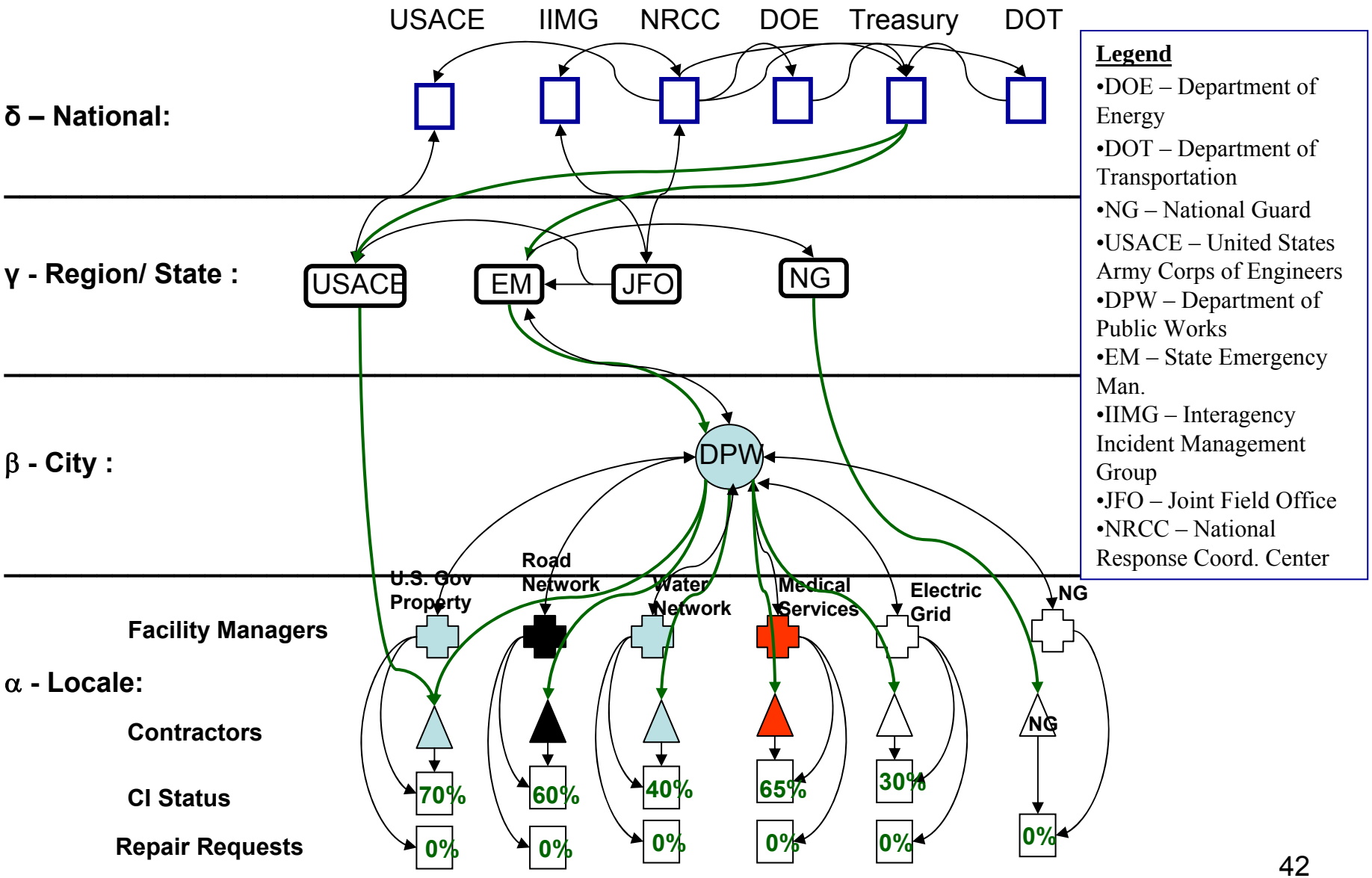


- Transportation funding = $1.5M, Material funding = $1.0M
- Weighted value for each objective function varies between 0 and 1
- Outliers occur when less that all four objective functions are used
- Values obtained using Min-Max are quite tightly clumped, indicating that the Min-Max method performed well in minimizing the largest difference between $f_i(\mathbf{x})$ and $f_I^{\min}$
- This narrows down the various project combinations into a smaller set of better choices from which the decision-maker can select
- While a global optimal solution is hard to identify, results within the range of the clumped region are likely ‘good’ solutions

On-going Work

1. Model Extension
   - Creation of the Military ABM
   - Modeling of the impact of the physical infrastructure status on decision-making
2. Model exploration:
   - Effect of changing organizational topology on decision-making
   - Impact of competition between entities within the organizational framework
   - The role of agent learning and communication
   - Assessment of corruption and type of government on decision-making

U.S. Emergency Management Organization



Legend

- •DOE – Department of Energy
- •DOT – Department of Transportation
- •NG – National Guard
- •USACE – United States Army Corps of Engineers
- •DPW – Department of Public Works
- •EM – State Emergency Man.
- •IIMG – Interagency Incident Management Group
- •JFO – Joint Field Office
- •NRCC – National Response Coord. Center

Integrated Air Defense Example

Proceedings & Presentations

Conference Papers

- "A System-of-Systems (SoS) Approach to Effective Organizational Decision-Making for Civil Infrastructure Project Selection", *Proceedings of the 2007 ASCE Construction Research Congress*, Grand Bahamas, May 6-8, 2007.
- "Effective Decision-Making for DoD Humanitarian Infrastructure Projects using Agent-based Modeling", *Proceedings of the 2007 IEEE International Conference on System of Systems Engineering (SoSE)*, April 16-18, 2007.
- "Framework for Research into Disaster Response for Critical Infrastructure Reconstruction", *Proceeding of the 2006 Canadian Society of Civil Engineering (CSCE), 1st Specialty Conference on Disaster Mitigation*, Calgary, Canada, May 23-26, 2006 (electronic proceedings).

Other Presentations

- "Organizational Decision-making For Civil Infrastructure Project Selection," *ASCE Construction Research Council Ph.D. Scholar's Workshop*, Chicago, Illinois, October 21, 2006.

References

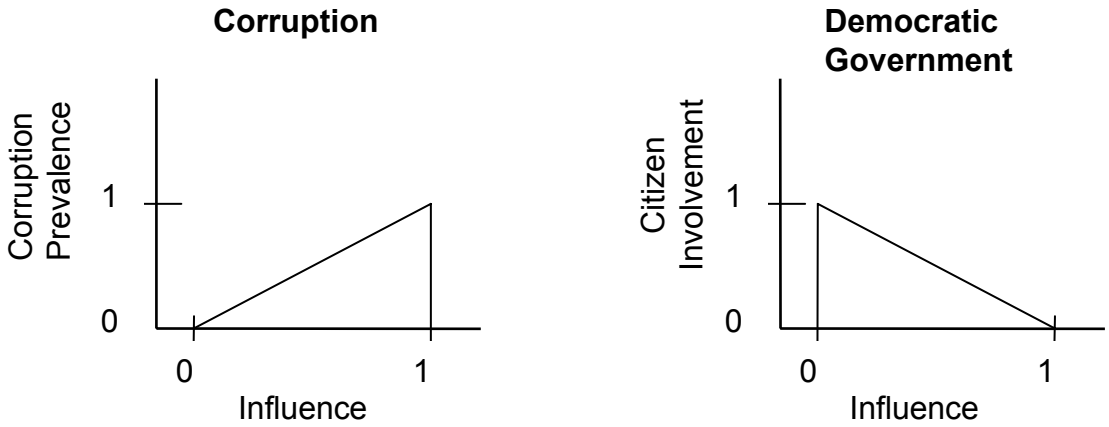
[1] Maier, M. (2004). "Architecting Principles for Systems-of-Systems." <http://www.infoed.com/Open/PAPERS/systems.htm> (May 24, 2004).

[2] Adapted from AAE 590K (Spring 2006) – Dr. D. DeLaurentis

[3] Arora, J.S. (2004). Introduction to Optimum Design, 2nd Ed. Elsevier, New York, New York.

Questions?

Model Exploration



Corruption and Government Type

- Hypothesis: Level of corruption & type of government are correlated to influence and importance values
- Incorporate mechanisms to use distributions for parameters

Verification & Validation

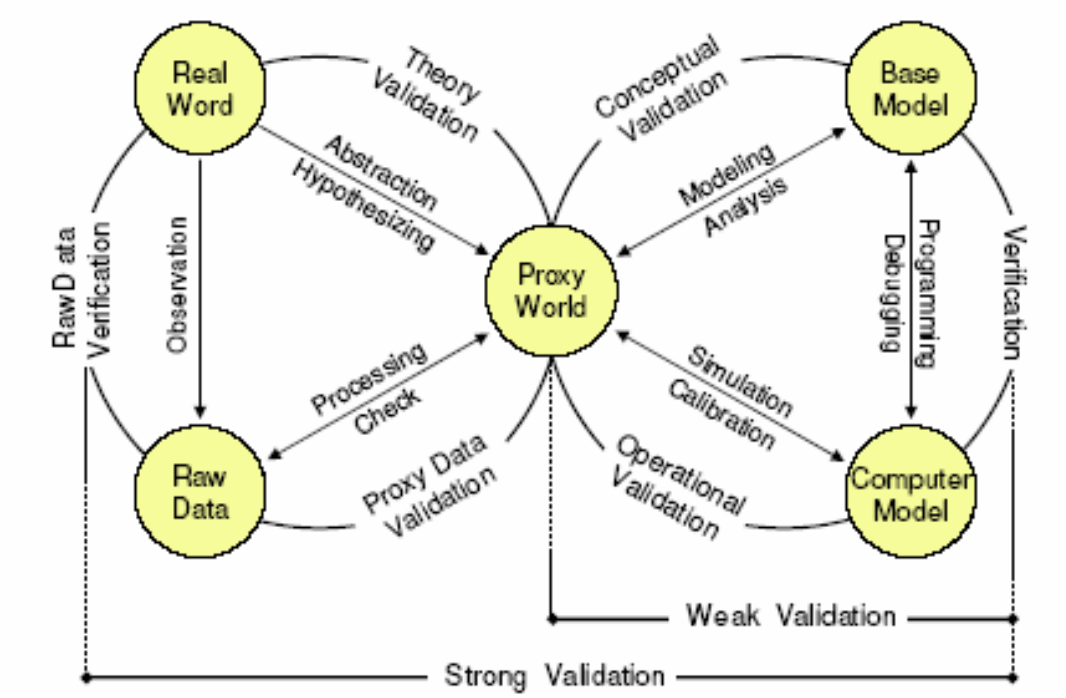
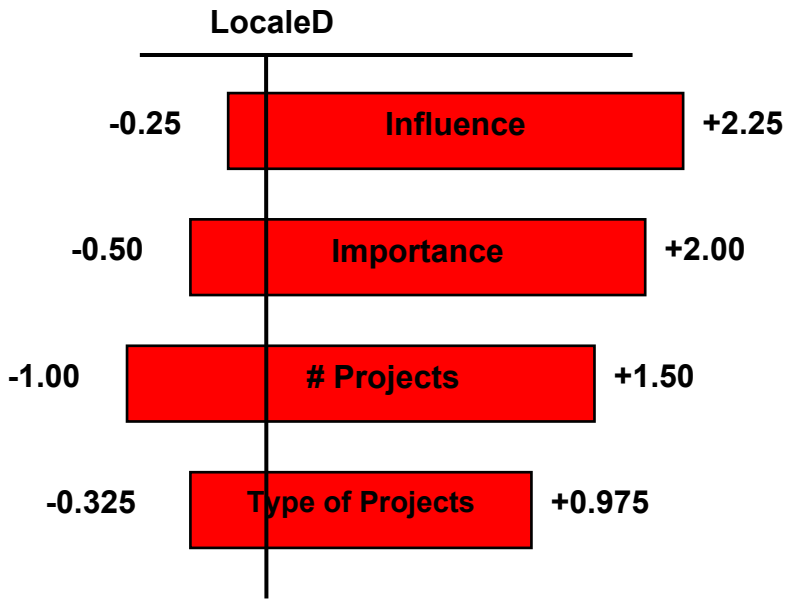


Figure from AAE590K course notes Spring 2006, Dr. D. DeLaurentis

- Verification
- “Weak” Validation
- Use expert and stakeholder feedback

Model 2: Sensitivity Analysis

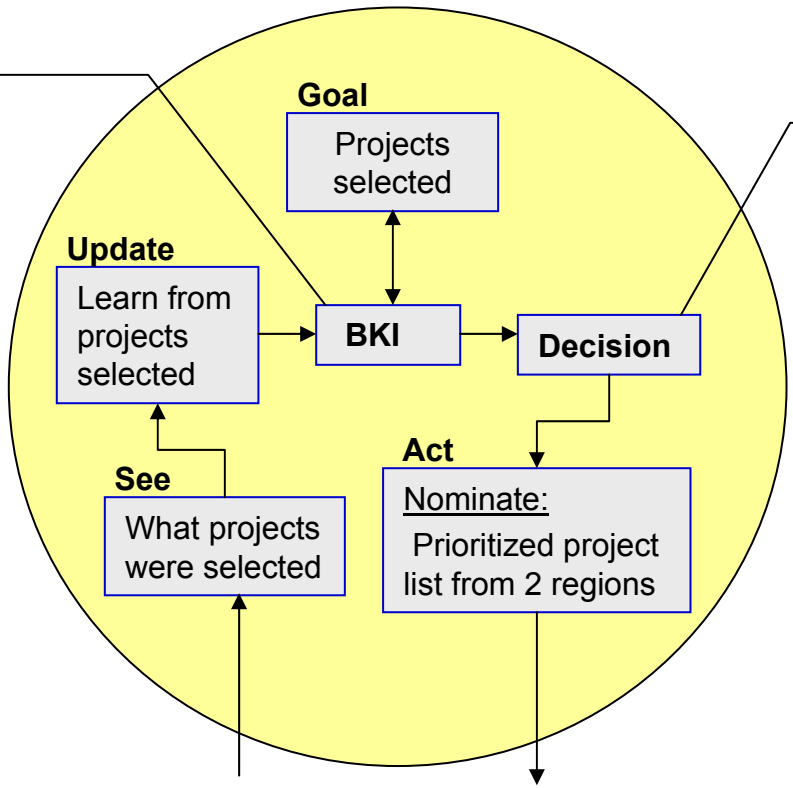


- LocaleD baseline model values used
- Least sensitive to Type of Project
- Equally sensitive to Importance, Influence, and # of Projects

Host Nation Official Agent

- One Host Nation Official per Country (Host Nation)
- Responsible for deciding which if any projects to nominate to the U.S. Embassy

1. Must nominate projects to be selected
2. Projects with direct benefits to local population more likely to be selected
3. Good relations with U.S. Embassy increase chance of being selected
4. Increasing Country's importance increases chance of being selected
5. Nominating less than 2 regions with at least 3 projects each decreases chance of being selected



1. Nominate 2 regions with at least 3 projects each that directly benefit local population
2. Lobby U.S. Embassy
3. Attempt to increase importance of Country

SoS Traits (Expanded)

- **Operational and Managerial Independence of Elements:** The organizations involved in the project selection both operate separately and are managed independently. For example, local officials will select and advocate project that are good for their locale, and will not be influenced by the types of project selected by other officials.
- **Evolutionary Development:** The entities (agents - organizations) involved in the selection of the DoD Humanitarian projects change over time with the restructuring of the U.S. military and the U.S. government, policy and national strategy changes, host country policy changes, and infrastructure status changes.
- **Emergent Behavior:** The input of all the stakeholders influences the decisions made and the infrastructure types selected.
- **Geographic Distribution:** The components are physically distributed, some in the U.S. and others in the host countries. Information is the only thing exchanged as part of the decision-making process. There is physical interaction and exchange when the U.S.

Case Study - Background

- **Foreign assistance** elevated to the third pillar of U.S. **national security**, along with defense and diplomacy (2002 National Security Strategy)
- "Foreign assistance is an essential component of our transformational diplomacy…Our foreign assistance must help people get results…In the final analysis, we must now use our foreign assistance to help prevent future Afghanistans – and to make America and the world safer." -- Secretary Rice on 19 Jan 06

Nearly $23 billion in all: U.S. government international assistance

TABLE 2

Total U.S. government international assistance by agency, classification, and selected programs, 2000

Official development assistance—$9.9 billion	Other government assistance—$12.7 billion
USAID	
Operations	Israel
Development assistance	Newly independent states
Child survival, humanitarian	Eastern Europe and Baltic States
Disaster relief, food aid	
State Department	
Refugees, narcotics	Operations
Asia Foundation	Broadcasting (Voice of America, Radio Marti)
International organizations	Peacekeeping
	Educational and cultural exchanges
	International organizations
	National Endowment for Democracy
Department of Defense	
Humanitarian	Military education and training
Peacekeeping development	Foreign military loans
	Antiterrorism, nonproliferation
Other agencies	
Peace Corps	Export-Import Bank
U.S. Trade and Development Agency	Overseas Private Investment Corporation
Multilateral institutions	Inter-American Foundation
Security assistance (Egypt and others)	

Source: U.S. Office of Management and Budget 2002.

(from USAID Doc PD-ABW-901 2002)

Constraints

1. $g_k(\mathbf{x}) = \Sigma_j x_{kj} \leq 1$, k = 1,…,23 (max of 1 projects in any one HN, except Cambodia & Laos w/ 2 projects allowed)

2. $g_{24}(\mathbf{x}) = \Sigma_i\Sigma_j$ (material cost) $x_{ij} \leq 1000$ ($k)

3. $g_{25}(\mathbf{x}) = \Sigma_i\Sigma_j$ (transportation cost) $x_{ij} \leq 1{,}500$ ($k)

4. $g_{26}(\mathbf{x}) = \Sigma_i x_{i3} \leq 3$ (sum of water distribution projects)

5. $g_{27}(\mathbf{x}) = \Sigma_i x_{i5} \leq 3$ (sum of road improvement projects)

6. $g_{28\text{-}327}(\mathbf{x}) = \Sigma_i\Sigma_j (f_i^* n_j^* x_{ij}) \leq 6$ where f_i = project dependence value

7. $g_{328\text{-}488}(\mathbf{x}) = 0 \leq x_{ij}$ (161 decision variables = 161 constraints)