Broad Utility: Architecting Flexible and Robust Systems for a Complex Operational Environment

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Research Motivation & Scope

Research Motivation

The Operational Environment of today and tomorrow is increasingly complex—the interactions of systems and operators generate unpredictable outcomes—and the equipment Soldiers employ during the conduct of their assigned mission must remain effective, despite changing conditions.

Research Objective

Provide defense-oriented Systems Engineers and Architects with a useful approach for architecting technical systems, employed by U.S. Army Soldiers, that can appropriately respond to a dynamic, complex Operational Environment in order to achieve mission success.

Emerging Trends in the Operational Environment

- Economic Inequality
- Big Data
- Artificial Intelligence
- Climate Change
- Resource Competition
- Population Growth
- Urbanization
- Wide Range of Missions and Adversaries

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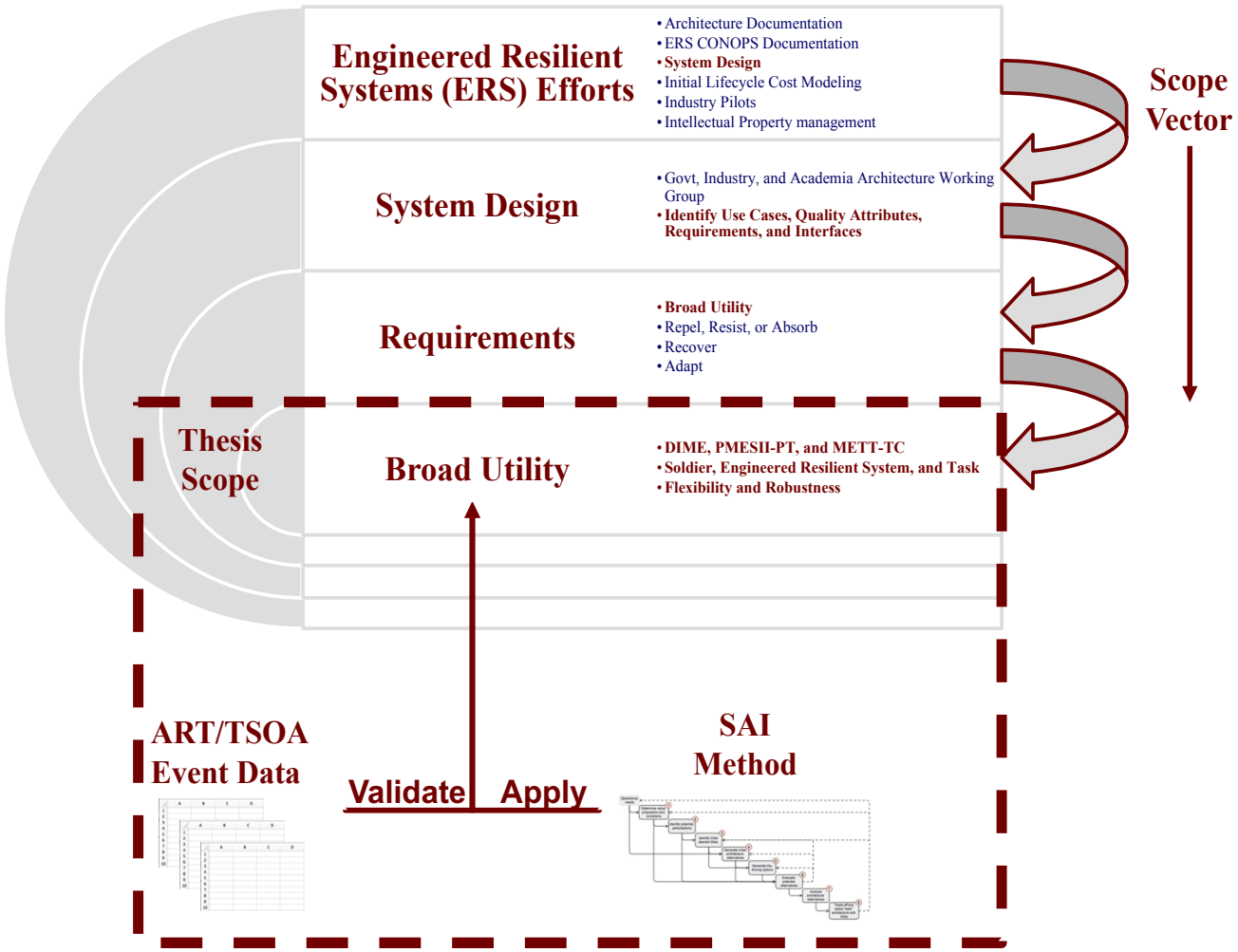
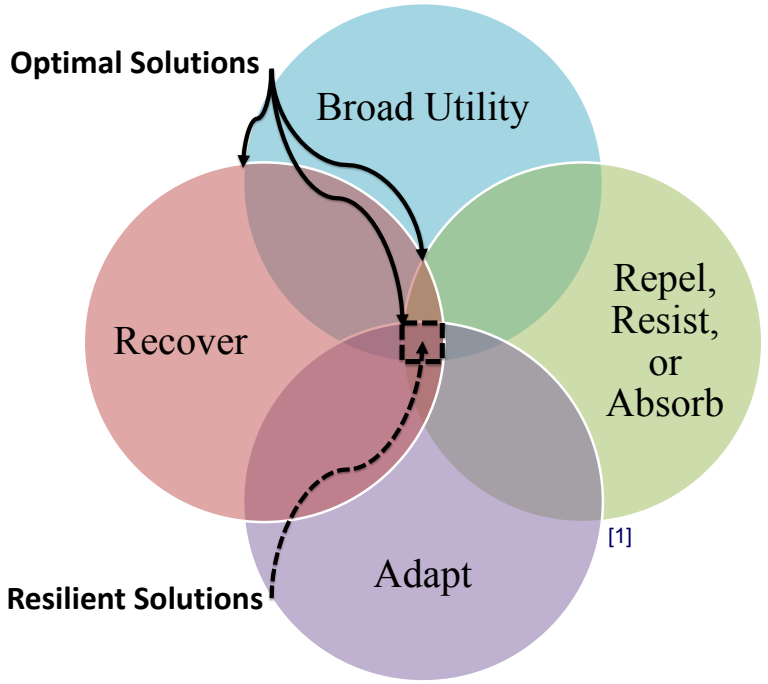


Executive Summary:
Broad Utility Architectural Decisions

Properties of Engineered Resilient Systems



[1]

Broad Utility: the ability of a system to "perform effectively in a wide range of operations across multiple futures ***despite experiencing disruptions***." [1]

Architectural Decisions: "the subset of design decisions that are most impactful" [2] and the source from which all future system requirements stem.

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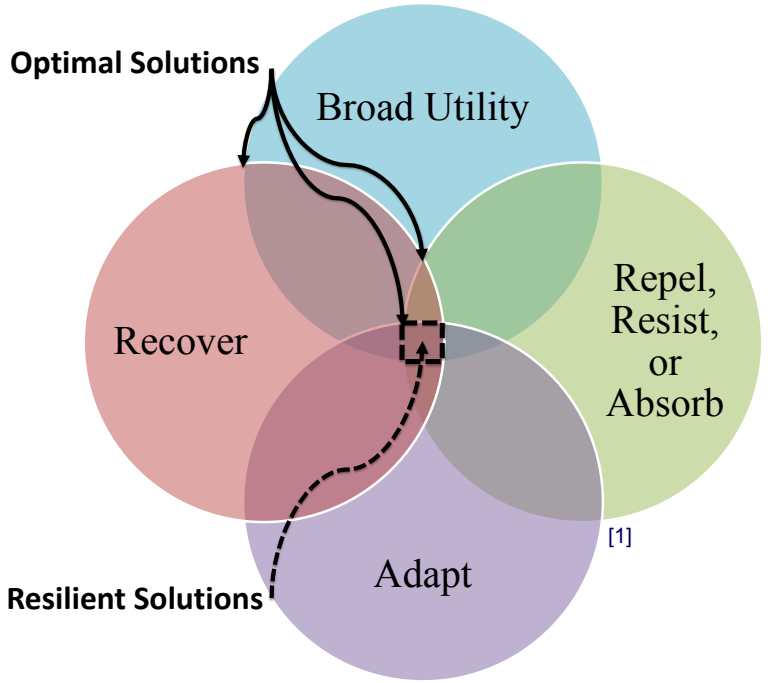

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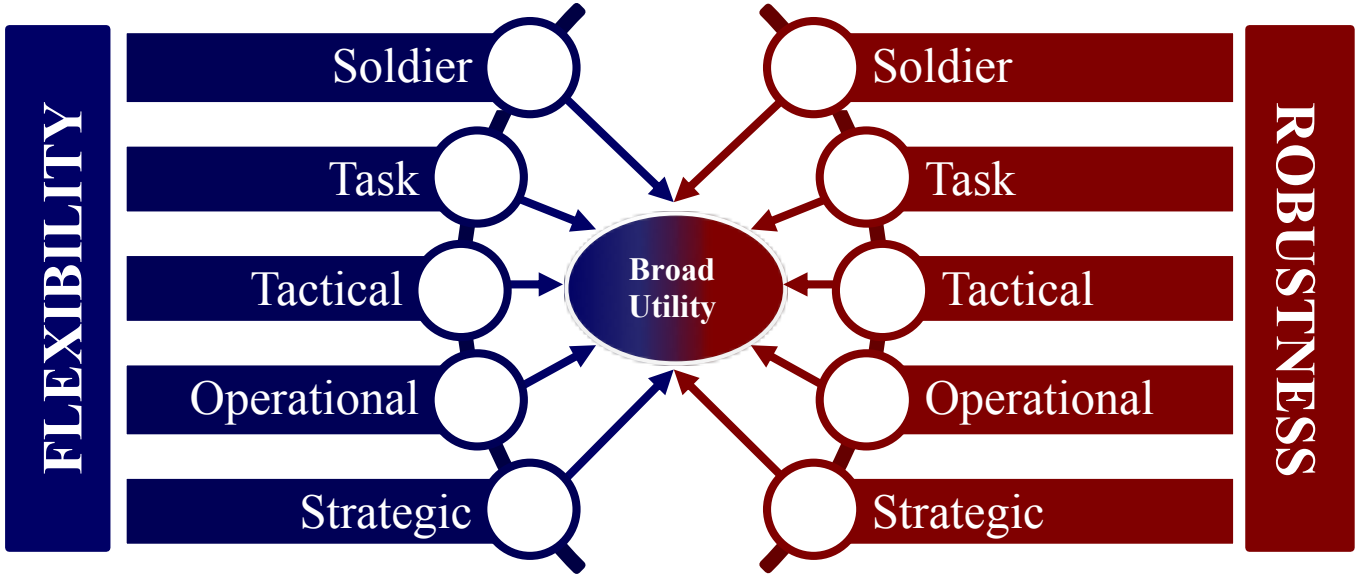
Research Contribution: In order to develop systems that exhibit Broad Utility, system designers should architect the system to be Flexible and Robust to the variables of the Operational Environment.

Broad Utility Architectural Decisions



Agenda

- Research Motivation and Scope
- **Operational Environment Exchange Network (OEEN):** Modeling a Complex Operational Environment
- **Flexibility and Robustness:** Critical Measures of Effectiveness in the Operational Environment
- **Broad Utility Architectural Decisions:** System Flexibility and Robustness in the Operational Environment
- Summary and Conclusions

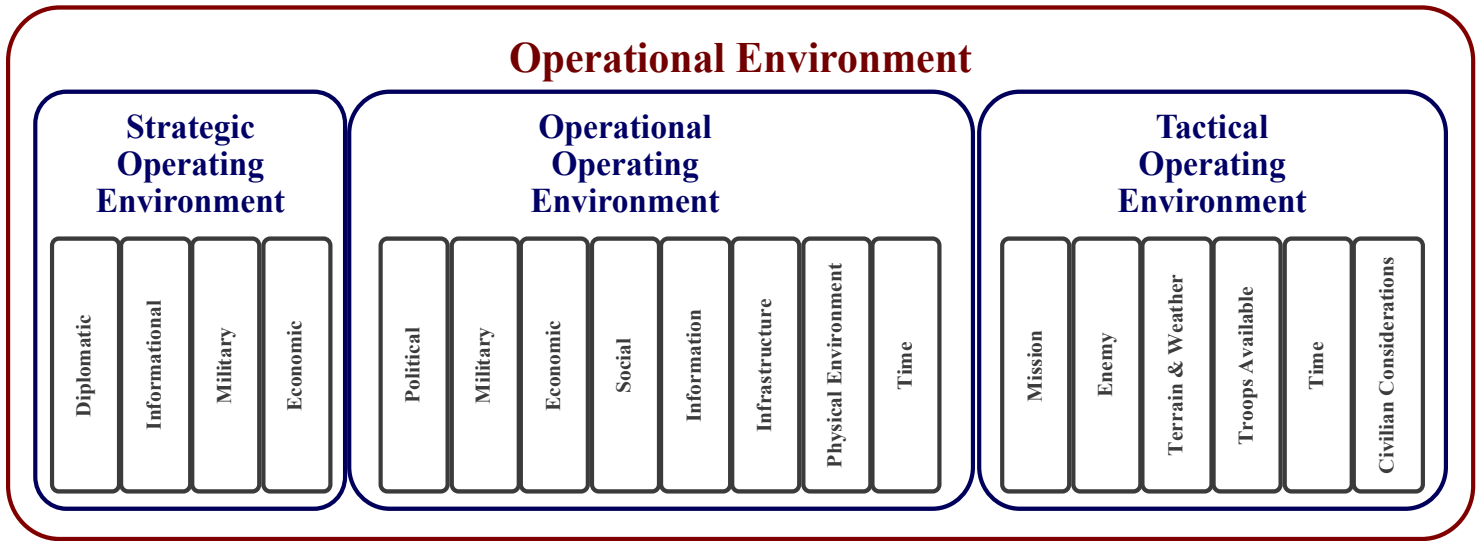
Understanding the Operational Environment

Doctrinal Gaps in Architecting for Broad Utility

1) Integrating the Strategic, Operational, and Tactical Environments

2) Including the Soldier, their Equipment, and their Task in the Operational Environment

3) Specifying the Operational Environment Variable Exchanges



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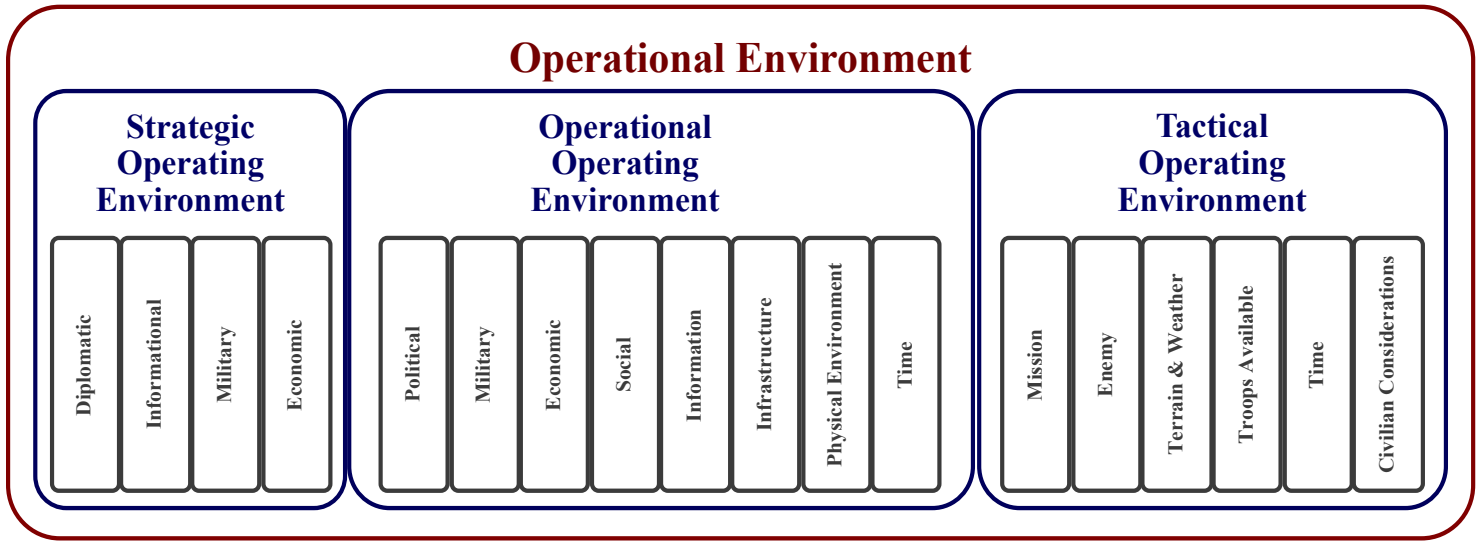
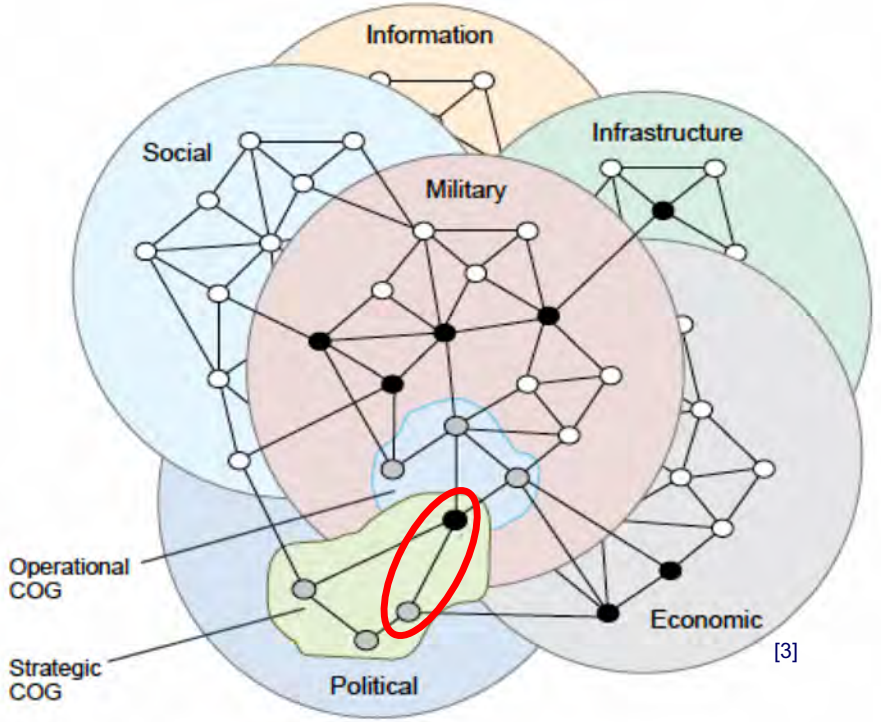
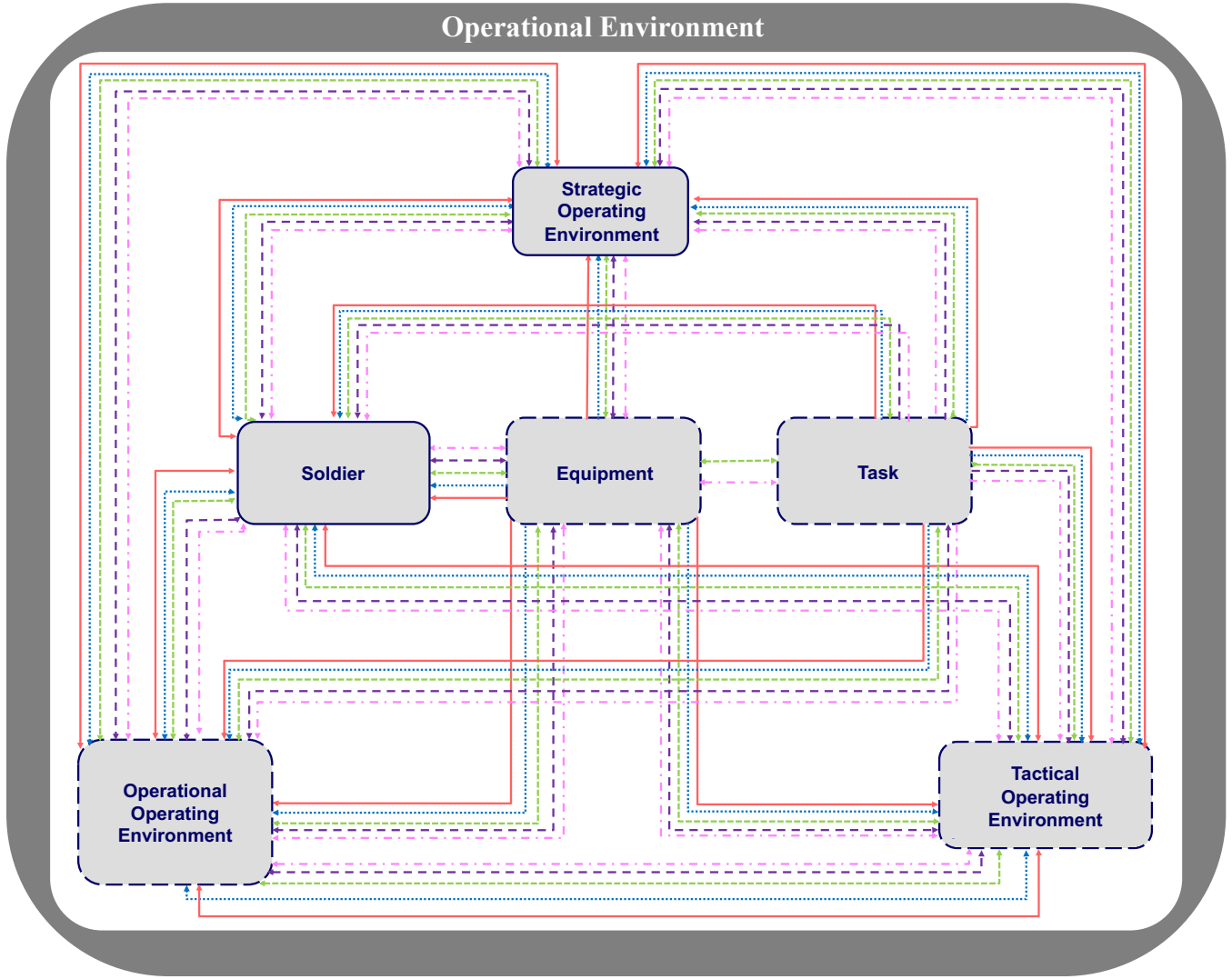




By resolving gaps in current DoD doctrine, Systems Engineers and Architects can better understand how the variables of the Operational Environment impact a system's Broad Utility.

Operational Environment Exchange Network:
Modeling the Operational Environment



OE Variable Exchanges

- Social
- Cultural
- Physical
- Informational
- Psychological

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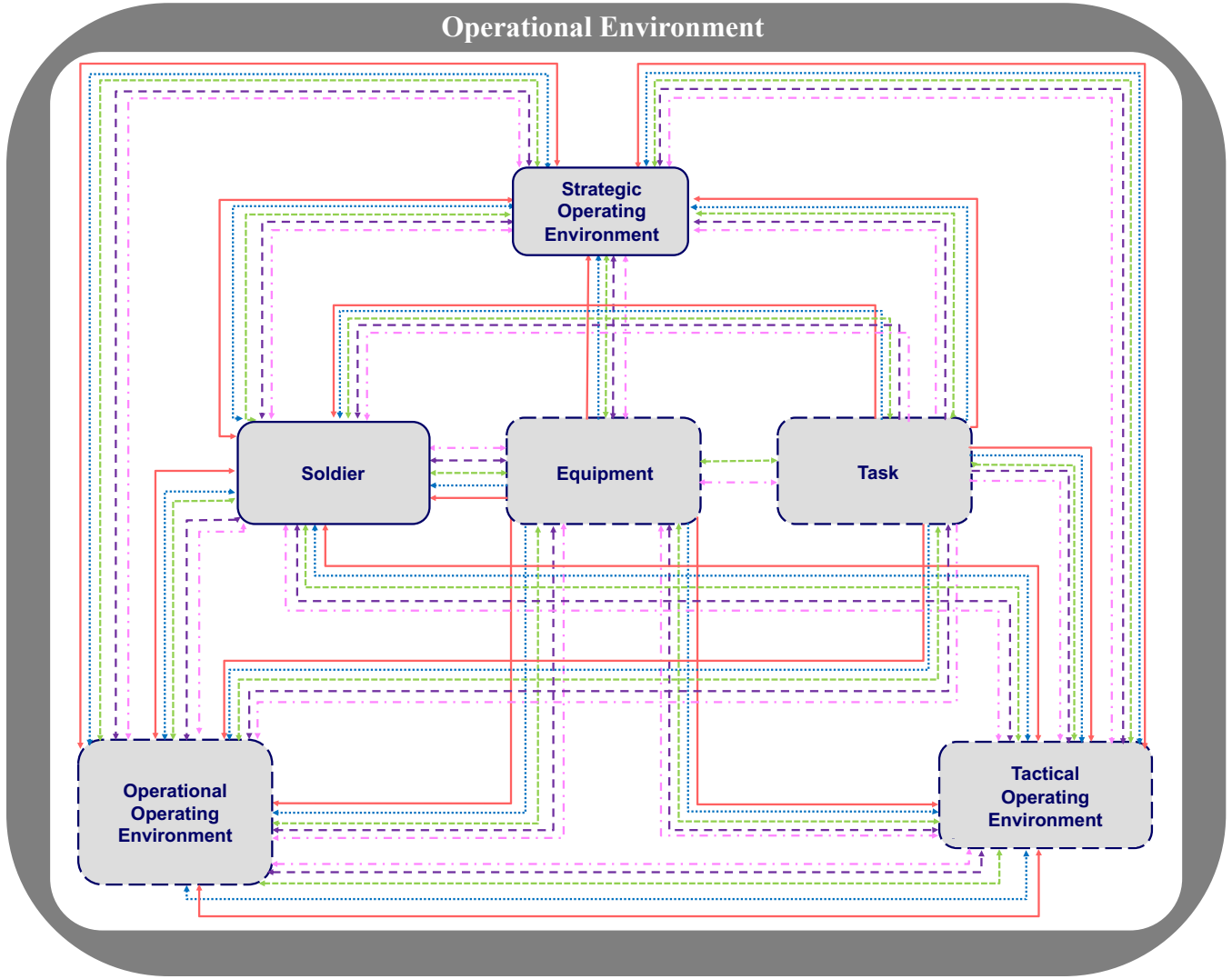

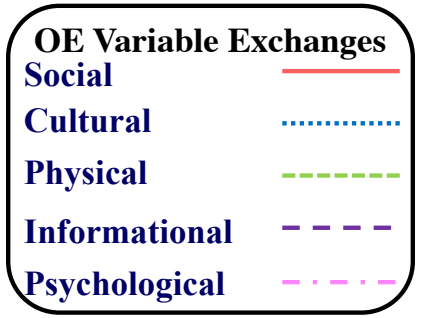

"Today, there is an increasing realization that much of the value that Engineering Systems generate depends on the degree to which they possess certain lifecycle properties, a.k.a. 'ilities'." [4, p. 3]

Flexibility and Robustness: Measures of Effectiveness in the Operational Environment

Ilities (System Lifecycle Properties): system properties that "often manifest and determine value after a system is put into initial use. Rather than being primary functional requirements, these properties concern wider impacts with respect to context, time, and stakeholders. [5]

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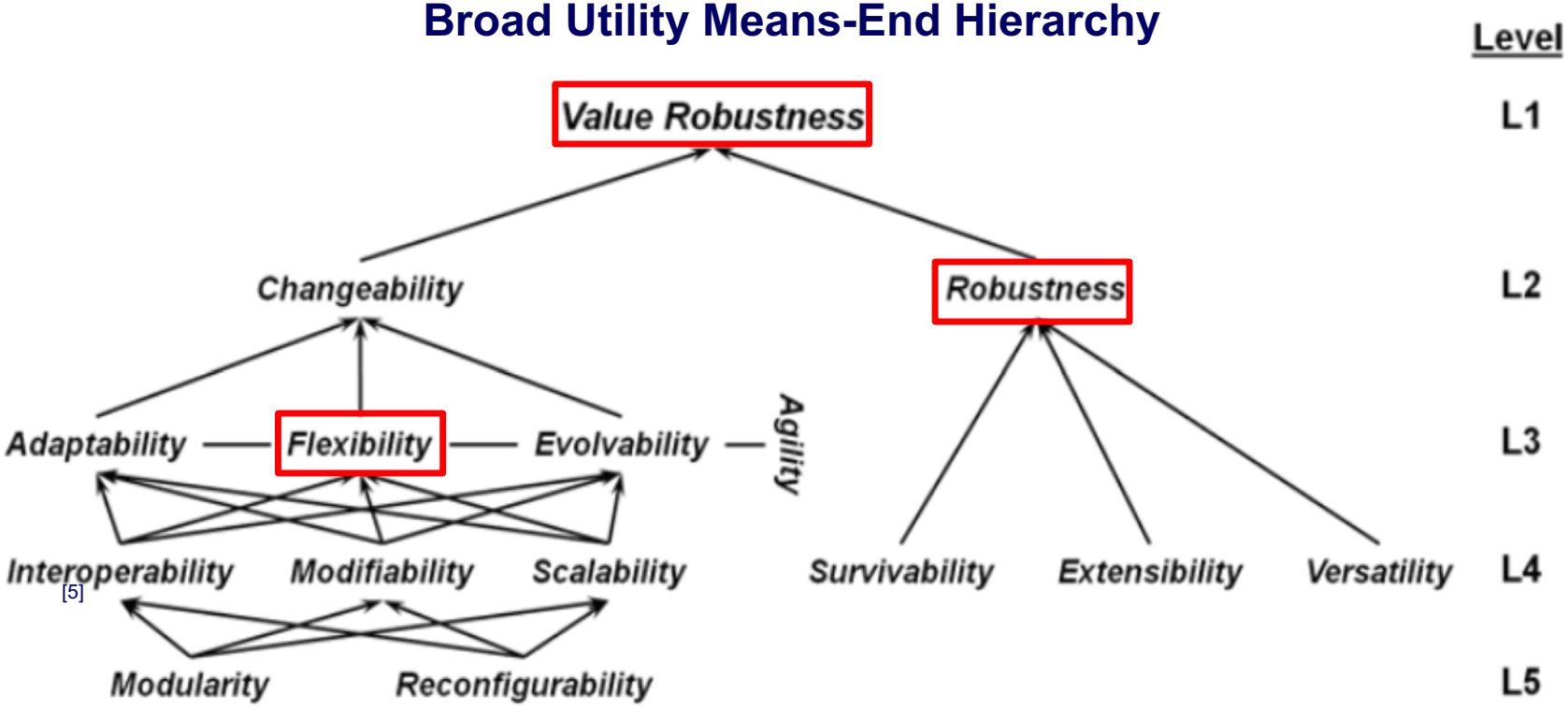
Broad Utility Means-End Hierarchy



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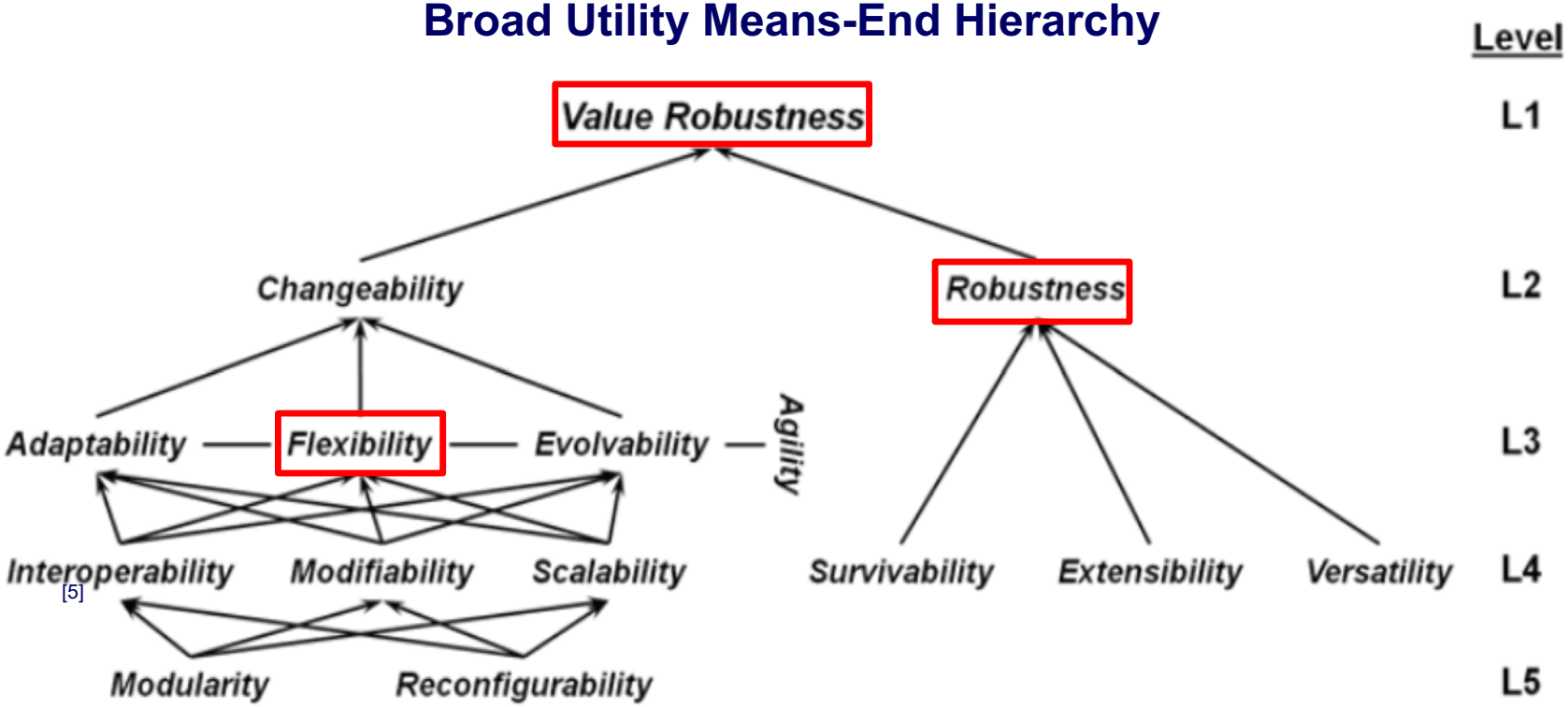

Value Robustness: the ability of a system to maintain value delivery in spite of *changes in needs or context*. [6]

Robustness: the ability of a system to *maintain its level and/or set of specified parameters* in the context of change system external and internal factors.[6]

Flexibility: the ability of a system to be *changed by a system-external change agent* with intent[6]

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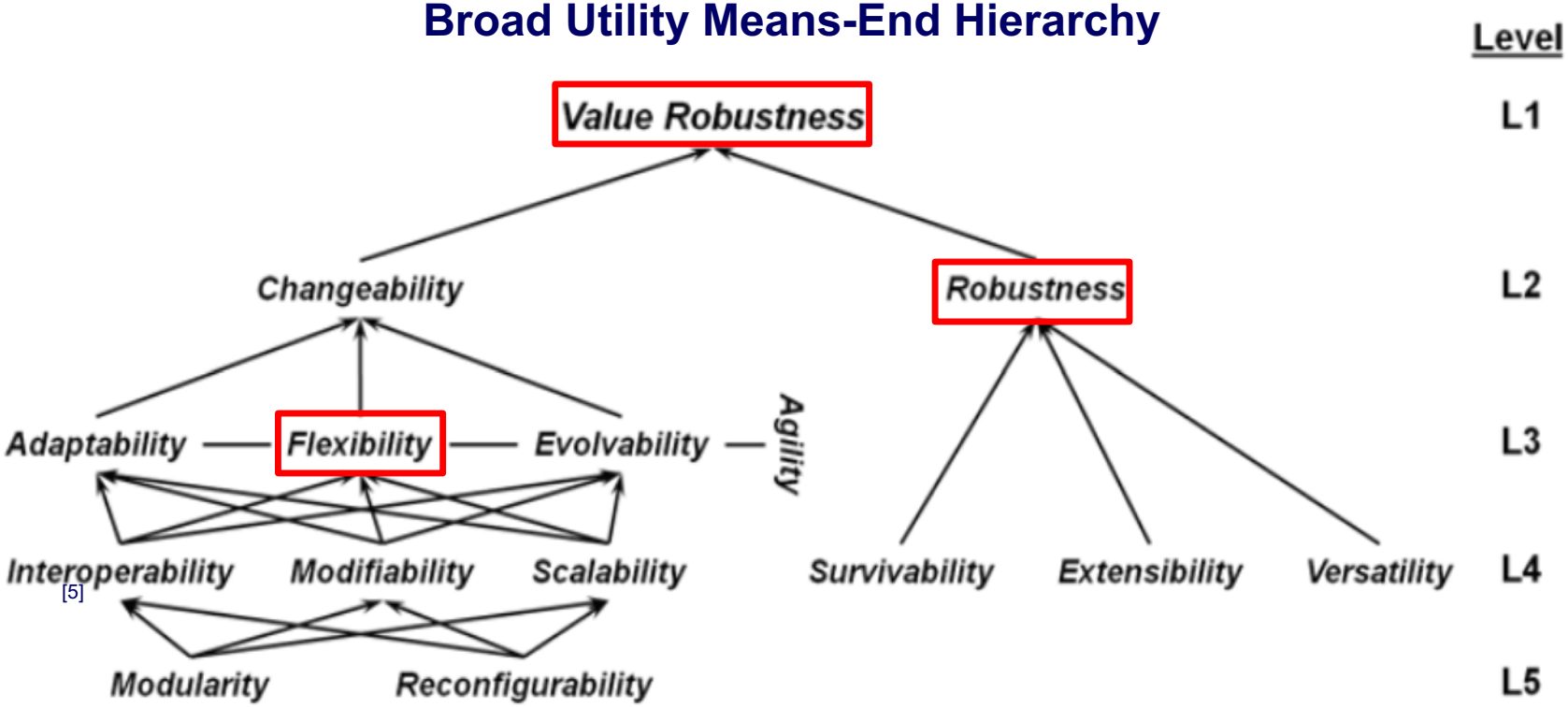

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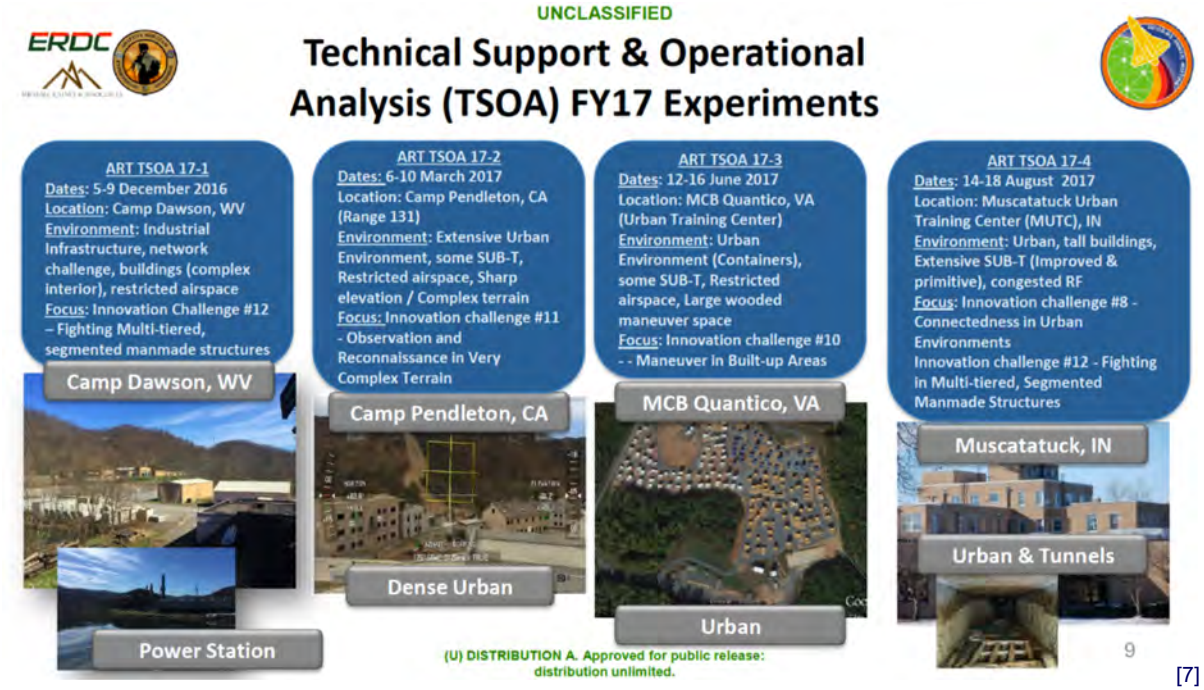
Conclusions

- Ilities are related, but not conclusively; however, Changeability (Flexibility) and Robustness are critical.
- **Hierarchies represent subjective assessments—is there empirical evidence to support these claims?**

Validating Flexibility and Robustness: ART/TSOA Program



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The **Technical Support and Operational Analysis (TSOA)** system evaluation program, "is the centerpiece of the Adaptive Red Team (ART). TSOA consists of ***live field experiments*** that integrate developers and warfighters ***in complex environments*** to stress systems through mission scenarios…***with teams invested in creating solutions for the warfighter.***" [7]

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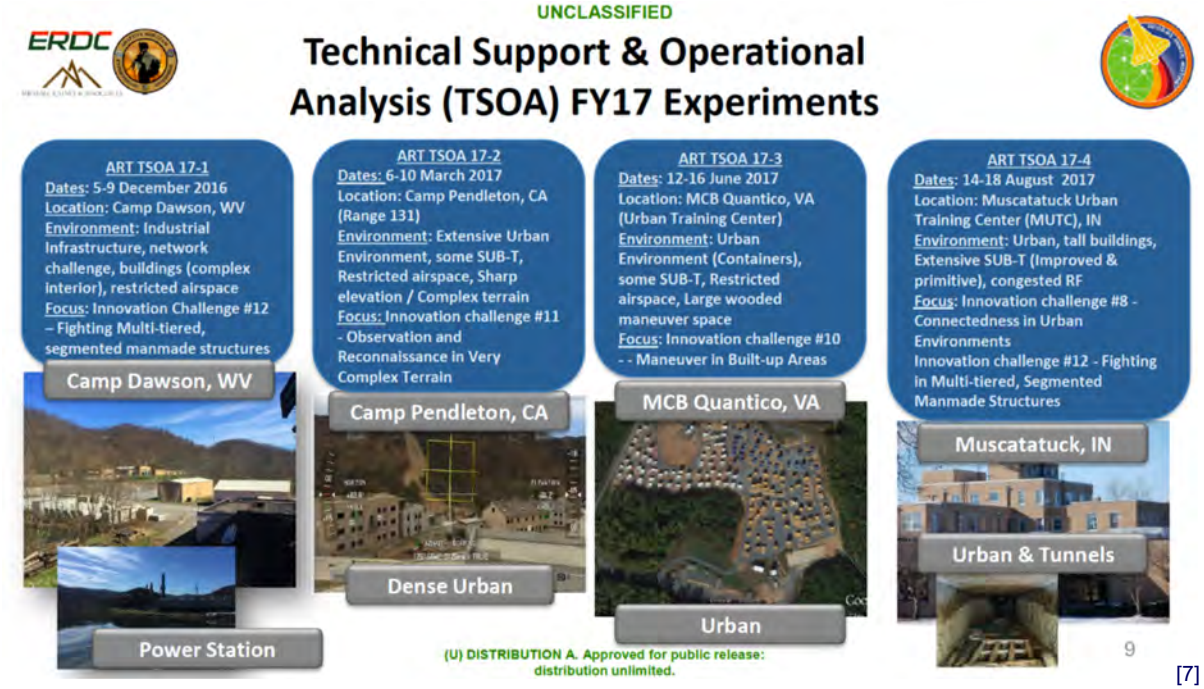
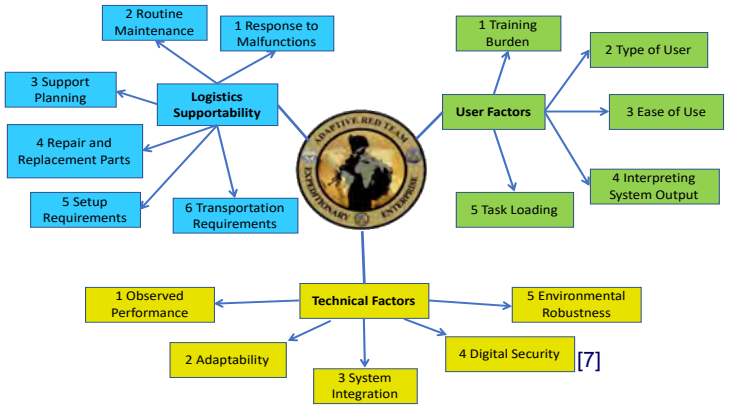


[7]

TSOA System Evaluation Criteria



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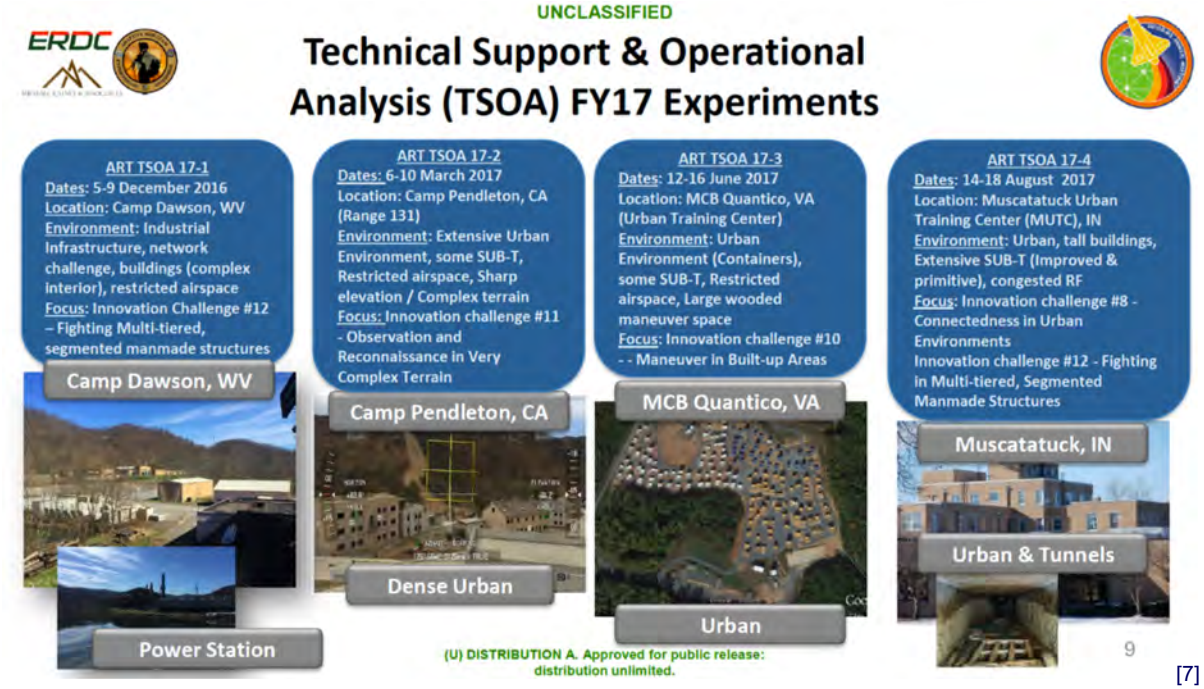

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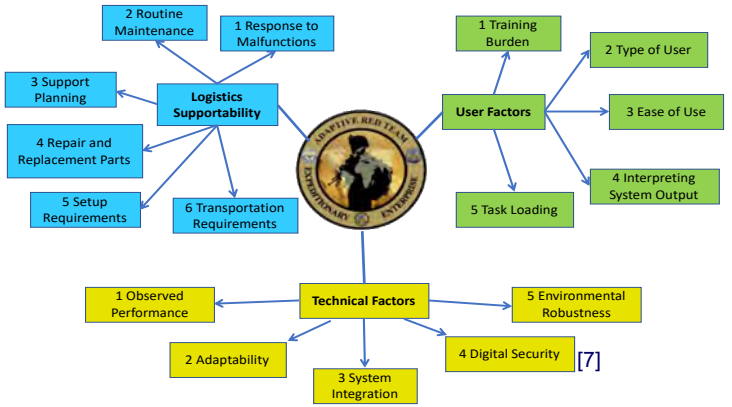

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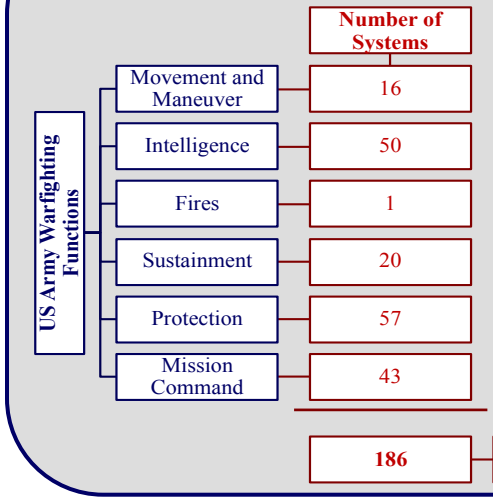
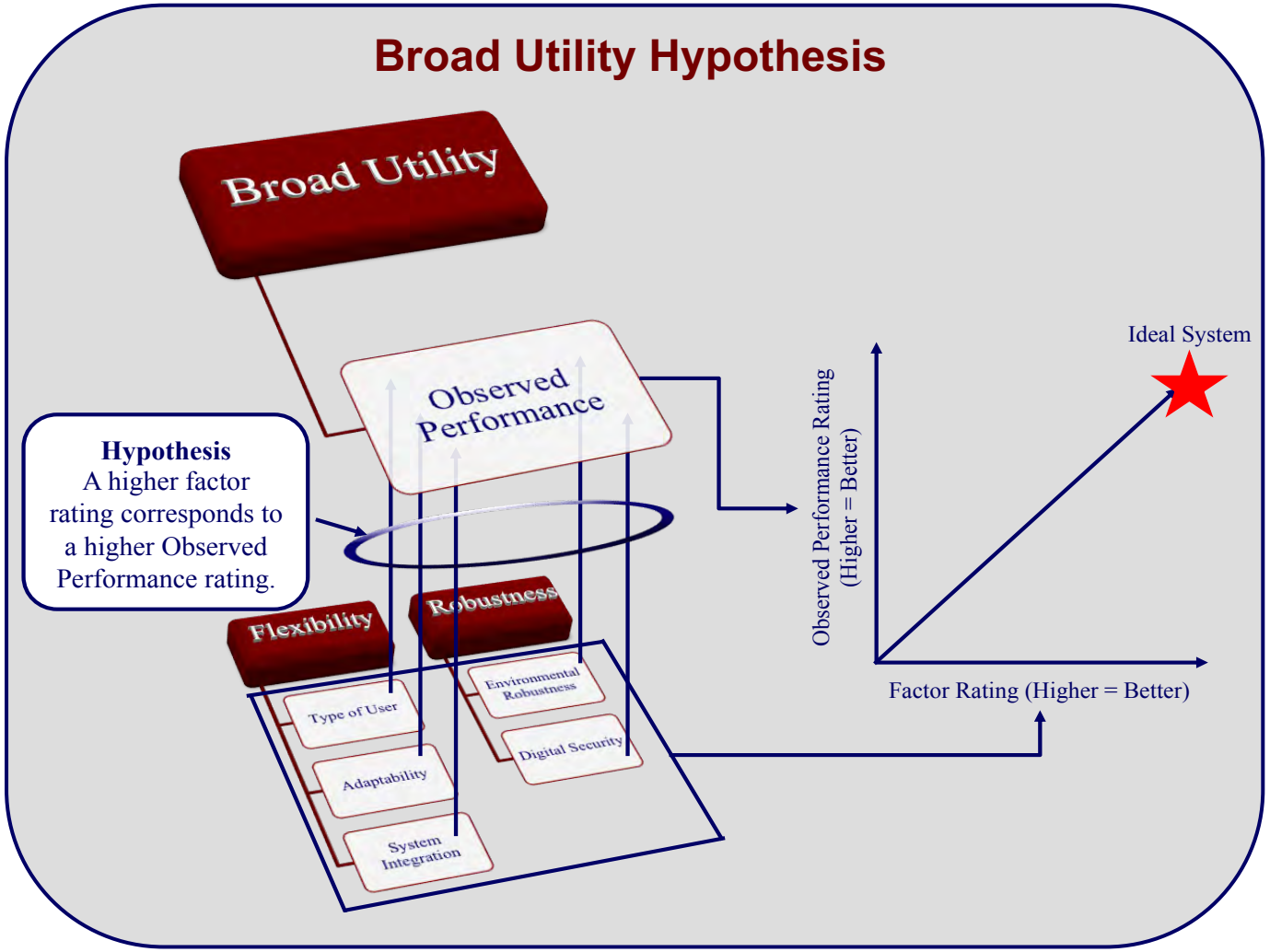
TSOA Dataset Summary



Total System Observations: 533

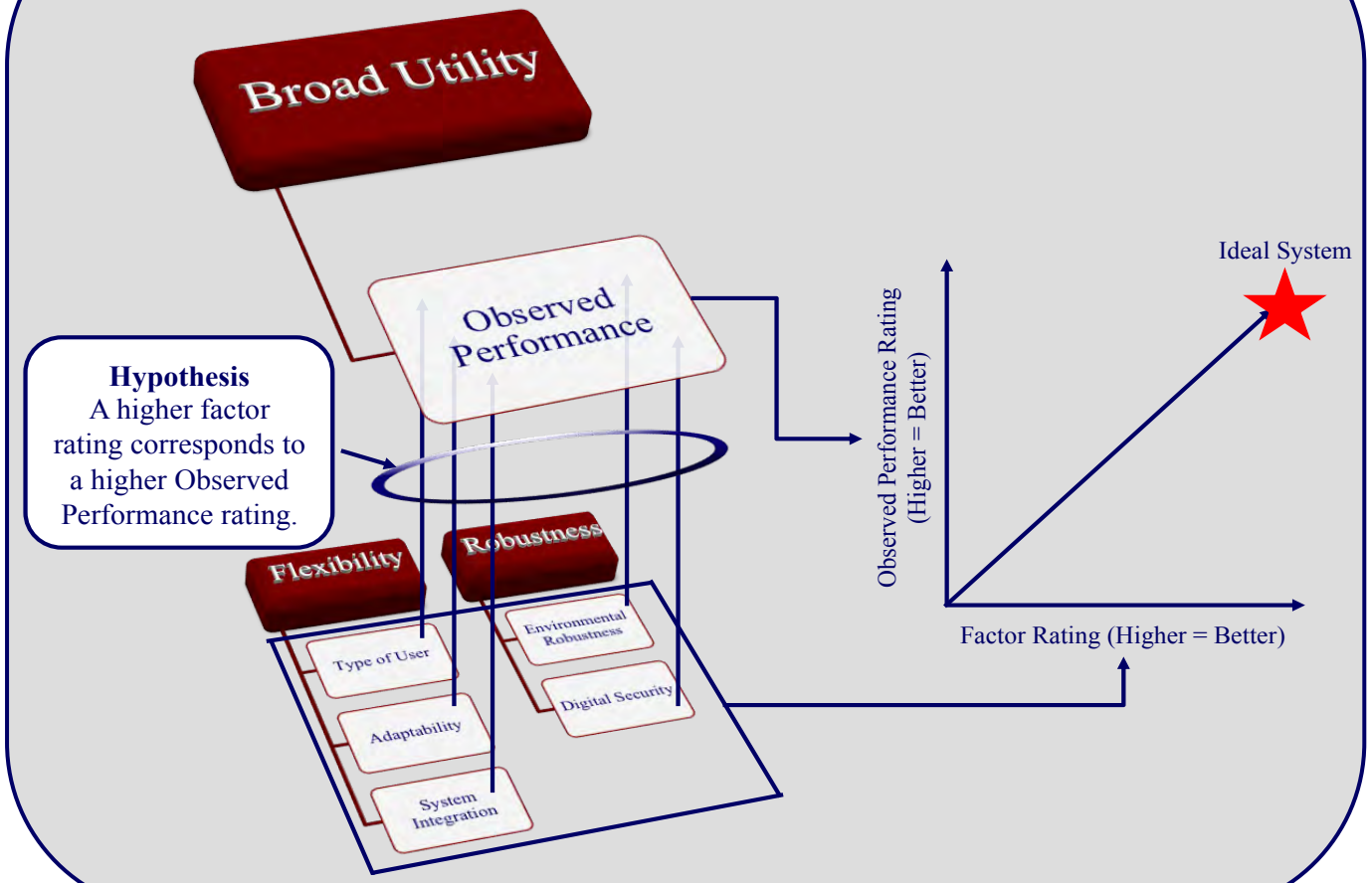
Number of System Assessors: 157

Validating Flexibility and Robustness: Hypothesis and Factor Selection



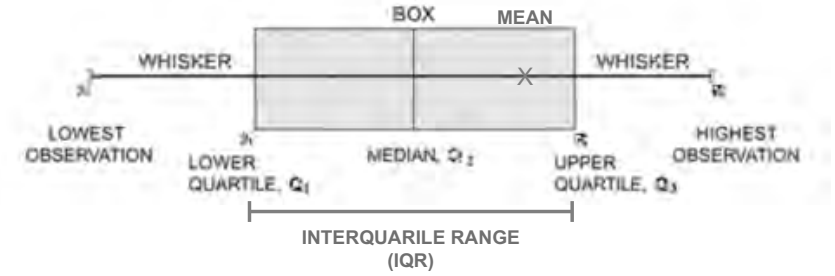
Validating Flexibility and Robustness:
Hypothesis and Factor Selection

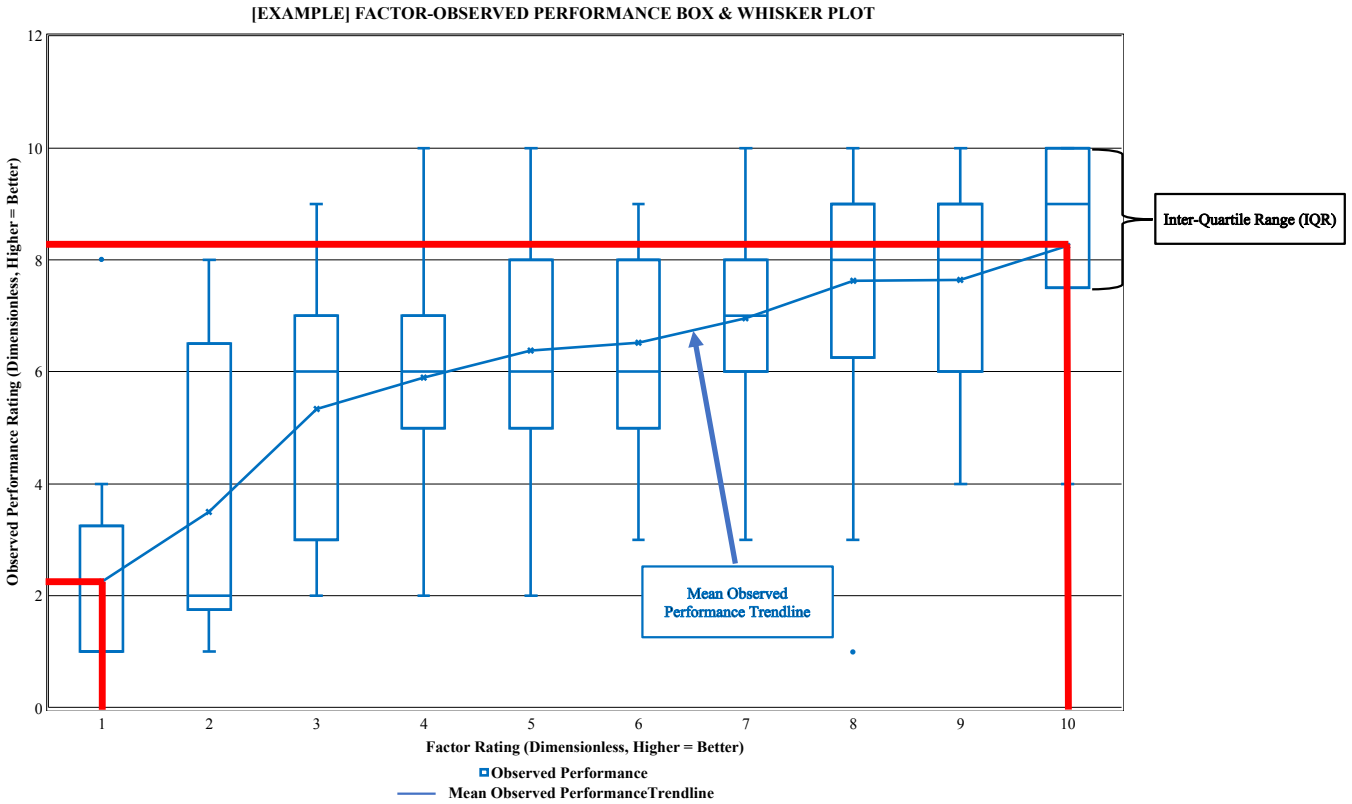
Broad Utility Hypothesis



Observed Performance	The ability of a system to execute its intended Warfighting Function (WFF), despite experiencing external disruptions within a specified Tactical Operating Environment (TOE).
Type of User	The ability of a system to be utilized by the greatest number of personnel, regardless of training or mission experience.
Adaptability	The ability of a system to be reconfigured by the user without subject matter expert assistance.
System Integration	The ability of a system to operate effectively with one or more external mechanical or electromechanical systems.
Environmental Robustness	The ability of a system to withstand external environmental elements.
Digital Security	The ability of a system to safely and securely receive, store, and transfer data.

Validating Flexibility and Robustness:
Data Analysis Method





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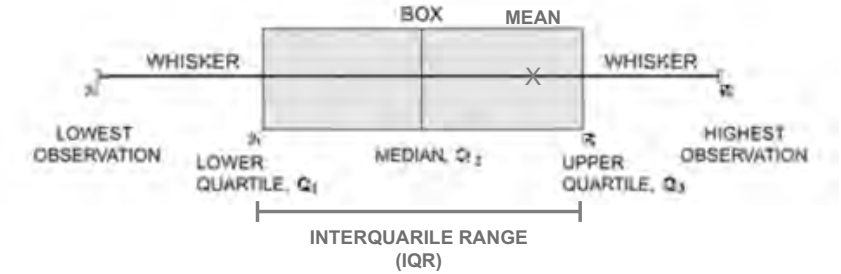
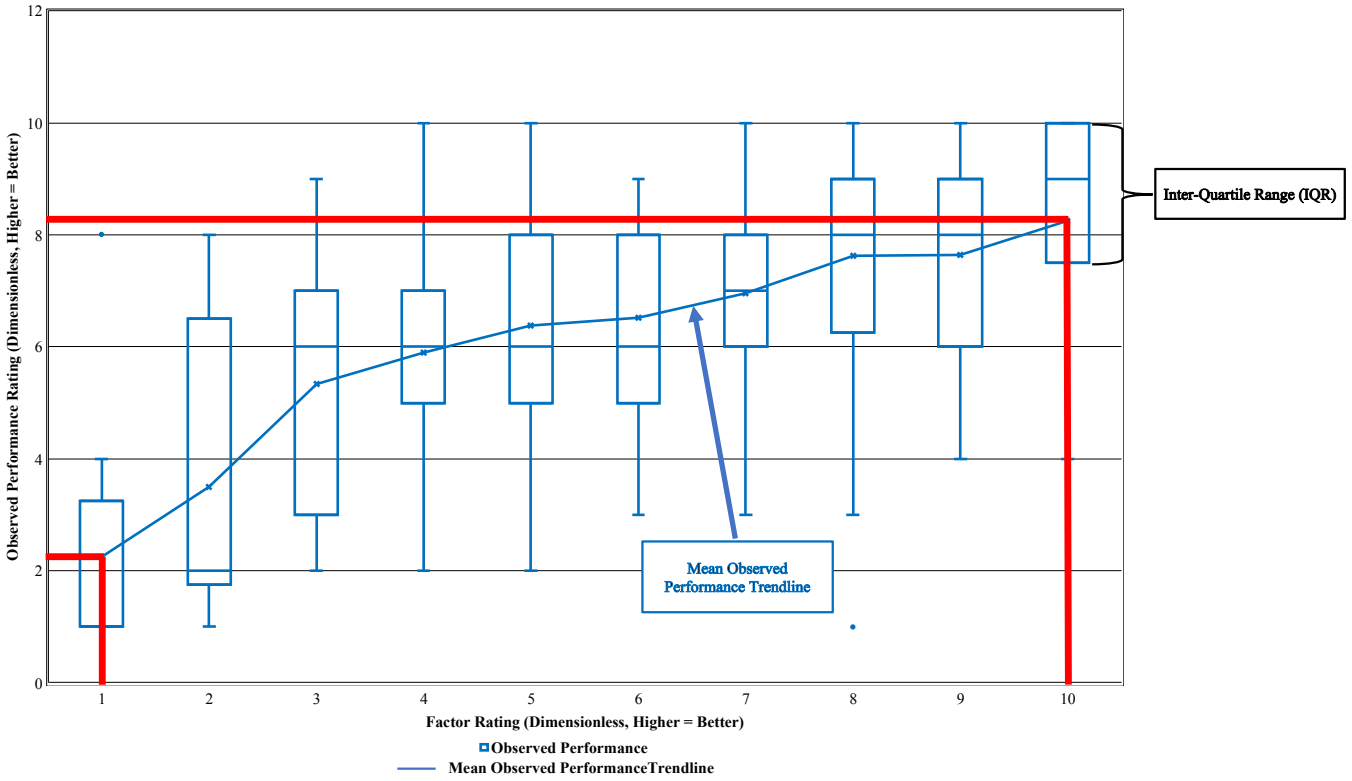


[EXAMPLE] FACTOR-OBSERVED PERFORMANCE BOX & WHISKER PLOT



Hypothesis Evaluation Criteria

- Linear Relationship between Flexibility/Robustness and Observed Performance (Pearson's Correlation Coefficient, *Rp)*
- Monotonic Relationship between Flexibility/Robustness and Observed Performance (Spearman's Rank-Order Correlation Coefficient, *Rs)*

Size of Correlation	Interpretation
.90 to 1.00 (−.90 to −1.00)	Very high positive (negative) correlation
.70 to .90 (−.70 to −.90)	High positive (negative) correlation
.50 to .70 (−.50 to −.70)	Moderate positive (negative) correlation
.30 to .50 (−.30 to −.50)	Low positive (negative) correlation
.00 to .30 (.00 to −.30)	negligible correlation

Validating Flexibility and Robustness: Data Analysis Results

Flexibility and Robustness Factor to Observed Performance Summary, Overall

Ility	Factor	Data Analysis Evaluation Criteria							
		All System Observations (w/ Assessor Variability)		Mean Trendline (Averaging Out Assessor Variability)				Inter-Quartile Range (IQR)	
		Rp Value	Linear Relationship	*Rp* Value	Linear Relationship	*Rs* Value	Monotonic Relationship	Minimum (Rating(s))	Maximum (Rating(s))
Flexibility	Type of User	0.46	Low Positive	0.94	Very High Positive	1.00	Very High Positive	2.00 (4)	4.75 (2)
	Adaptability	0.63	Moderate Positive	0.99	Very High Positive	0.98	Very High Positive	1.00 (4,9)	4.50 (1)
	System Integration	0.48	Low Positive	0.96	Very High Positive	0.95	Very High Positive	2.00 (4,8,9)	4.75 (3)
Robustness	Environmental Robustness	0.56	Moderate Positive	0.98	Very High Positive	0.99	Very High Positive	1.50 (10)	5.00 (1)
	Digital Security	0.52	Moderate Positive	0.95	Very High Positive	0.96	Very High Positive	1.00 (4)	4.50 (3)

Findings

- For all 533 observations, regardless of system function, Flexibility and Robustness displayed a positive linear and monotonic relationship to Observed Performance (Broad Utility).
- **Flexible and/or Robust systems are more likely to exhibit Broad Utility.**

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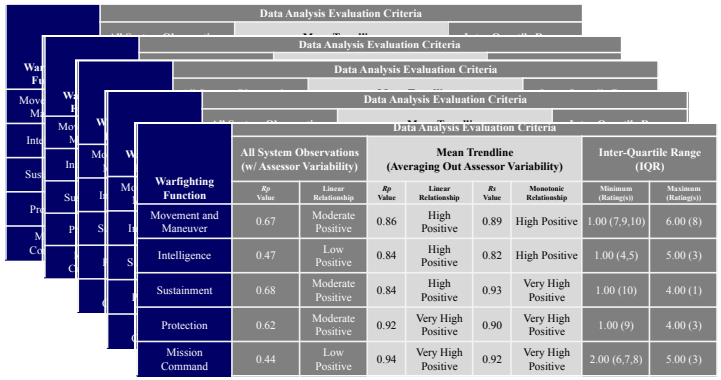
Additional Analysis

- Applied identical analysis method to each Warfighting Function group
- Movement and Maneuver Systems: Type of User and Digital Security
- Intelligence Systems: Adaptability and Digital Security
- Sustainment Systems: Adaptability and Digital Security
- Protection Systems: Adaptability and Digital Security
- Mission Command Systems: Adaptability and Environmental Robustness



Broad Utility Architectural Decisions

Recall:

- ✓ Holistically modeled the Operational Environment, including the Strategic, Operational, and Tactical levels, as well as the Soldier, their Equipment, and their assigned Task
- ✓ Validated Flexibility and Robustness as key Ilities for achieving Broad Utility

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Flexibility	Robustness
Soldier Flexibility: the ability of the system to be *physically, informationally, or psychologically* changed by the *Soldier* variable.	**Soldier Robustness:** the ability of the system to maintain its level and/or set of specified parameters despite *physical, informational, and/or psychological* changes in the *Soldier* variable.
Task Flexibility: the ability of the system to be *physically and/or psychologically* changed by the *task* variable.	**Task Robustness:** the ability of the system to maintain its level and/or set of specified parameters despite *physical and/or psychological* changes in the *Task* variable.
Tactical Flexibility: the ability of the system to be *physically, informationally, or psychologically* changed by the *mission, enemy, terrain, troops available, time, and/or civilian considerations* variable(s) in the *Tactical Operating Environment*.	**Tactical Robustness:** the ability of the system to maintain its level and/or set of specified parameters despite *physical, informational, and/or psychological* changes in the *mission, enemy, terrain, troops available, time, and/or civilian considerations* variable(s) in the *Tactical Operating Environment*.
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Strategic Flexibility: the ability of the system to be *physically, informationally, or psychologically* changed by the *diplomatic, information, military, and/or economic* variable(s) in the *Strategic Operating Environment*.	**Strategic Robustness:** the ability of the system to maintain its level and/or set of specified parameters despite *physical, informational, and/or psychological* changes in the *diplomatic, information, military, and/or economic* variable(s) in the *Strategic Operating Environment*.

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Broad Utility Architectural Decisions: An approach for increasing the likelihood that the system will appropriately respond to the system-external variables of the Operational Environment.

Benefits:

- Doctrinally-grounded
- Qualitatively and quantitively validated
- System-agnostic Foundational Requirements

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Applying Broad Utility Architectural Decisions to System Design

Position, Navigation, and Timing System:

- Fundamental Objective: Enable Soldiers to navigate the battlefield in GPS-enabled and denied environments.
- Future OE: Dense Urban Terrain
- System Function: Maximize Position Accuracy
- Use Broad Utility Architectural Decisions to mitigate adverse effects.

Applying Broad Utility Architectural Decisions to System Design

Position, Navigation, and Timing System:

- Fundamental Objective: Enable Soldiers to navigate the battlefield in GPS-enabled and denied environments.
- Future OE: Dense Urban Terrain
- System Function: Maximize Position Accuracy
- Use Broad Utility Architectural Decisions to mitigate adverse effects.

1 **Perturbation & System Objective:** Source of Uncertainty Impacting System Objective

Urbanization → Maximizing Position Accuracy

Applying Broad Utility Architectural Decisions to System Design

Position, Navigation, and Timing System:

- Fundamental Objective: Enable Soldiers to navigate the battlefield in GPS-enabled and denied environments.
- Future OE: Dense Urban Terrain
- System Function: Maximize Position Accuracy
- Use Broad Utility Architectural Decisions to mitigate adverse effects.

1 **Perturbation & System Objective:** Source of Uncertainty Impacting System Objective

Urbanization → Maximizing Position Accuracy

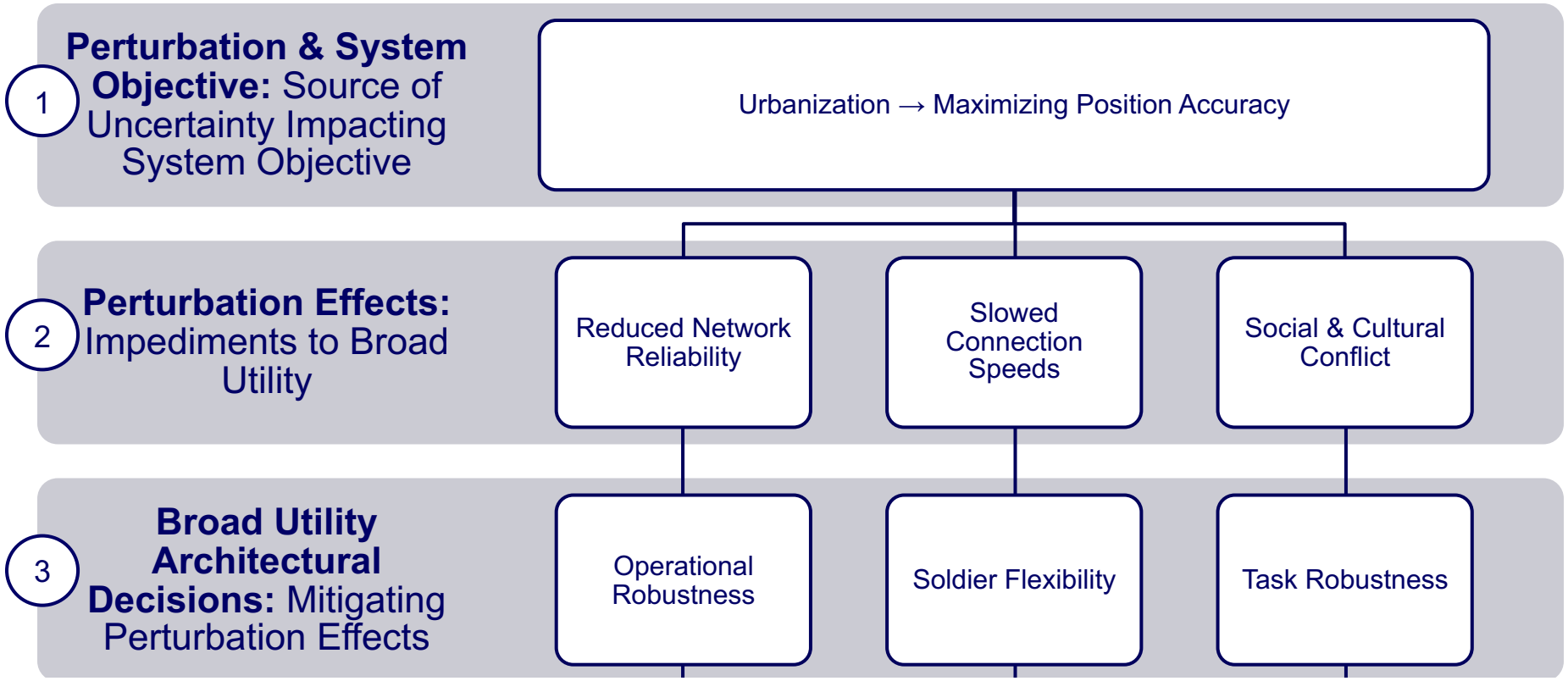
2 **Perturbation Effects:** Impediments to Broad Utility

- Reduced Network Reliability
- Slowed Connection Speeds
- Social & Cultural Conflict

Applying Broad Utility Architectural Decisions to System Design

Position, Navigation, and Timing System:

- Fundamental Objective: Enable Soldiers to navigate the battlefield in GPS-enabled and denied environments.
- Future OE: Dense Urban Terrain
- System Function: Maximize Position Accuracy
- Use Broad Utility Architectural Decisions to mitigate adverse effects.



Applying Broad Utility Architectural Decisions to System Design

Position, Navigation, and Timing System:

- Fundamental Objective: Enable Soldiers to navigate the battlefield in GPS-enabled and denied environments.
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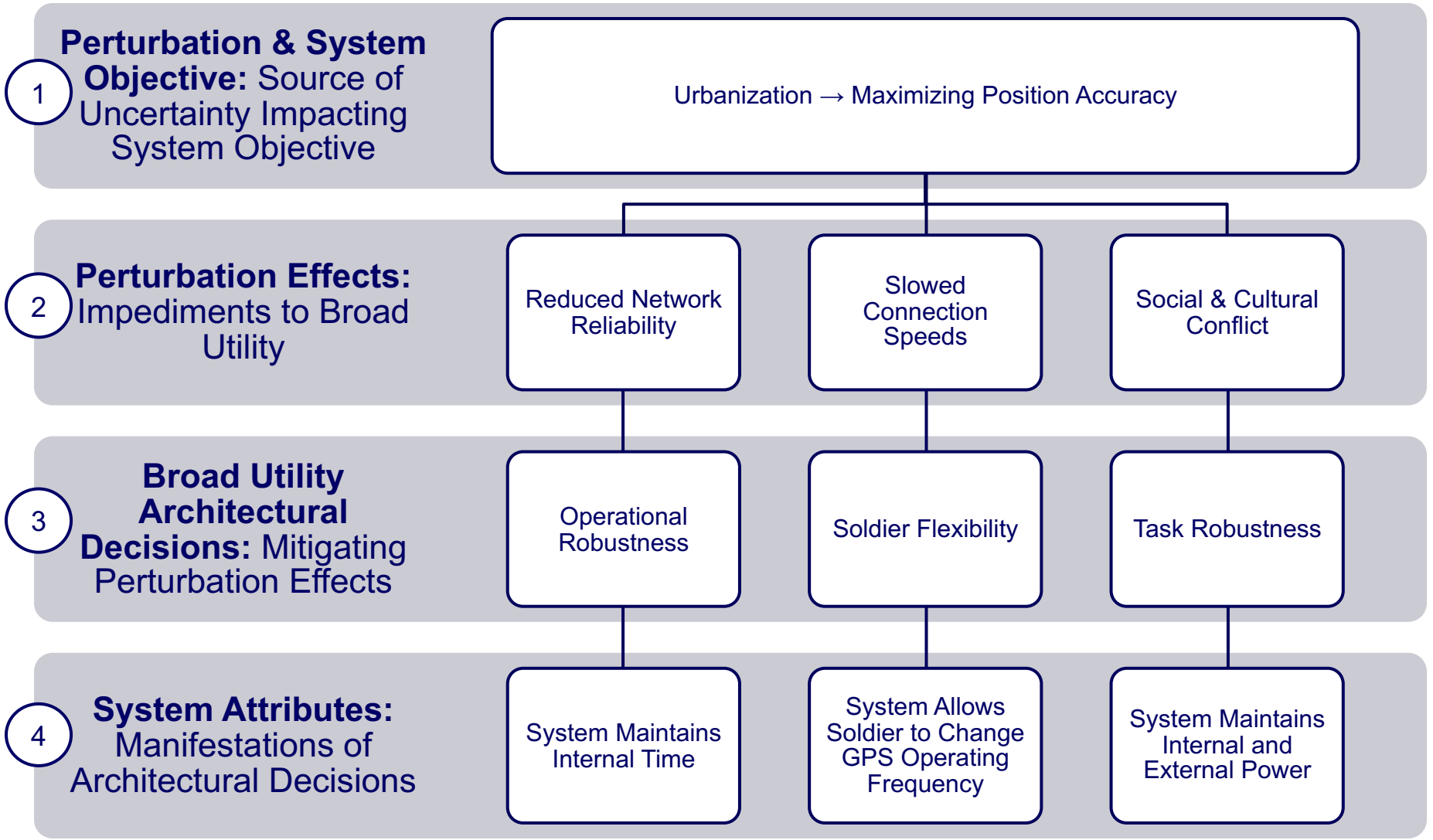
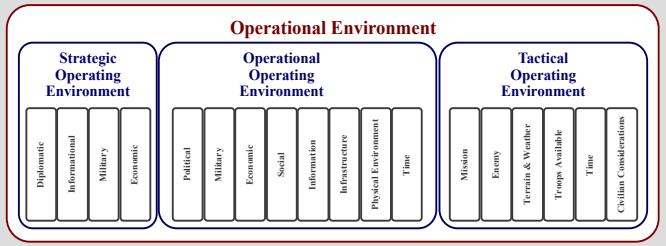
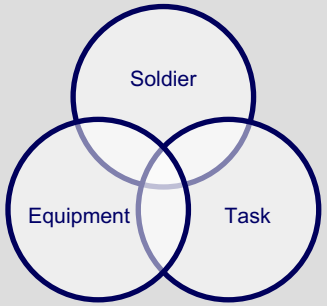


Research Summary and Conclusions

1

OE Variables Disrupt System Broad Utility
Socially, Culturally, Physically, Informationally, and Psychologically





Research Summary and Conclusions

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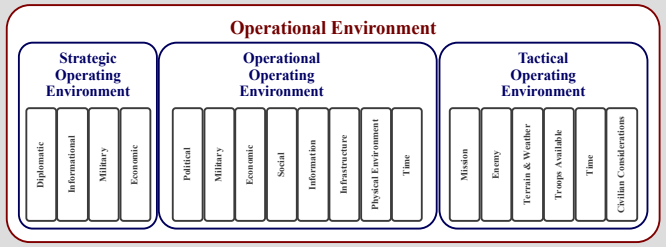
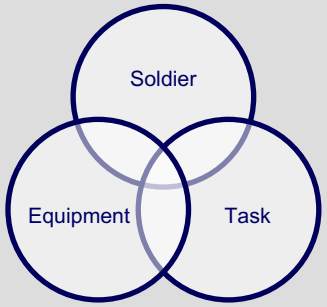
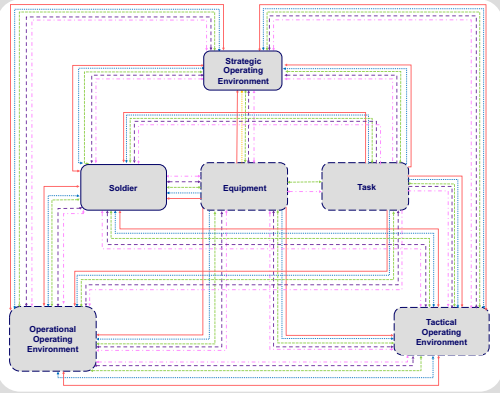




2

Variable Interactions Generate Complexity



Research Summary and Conclusions

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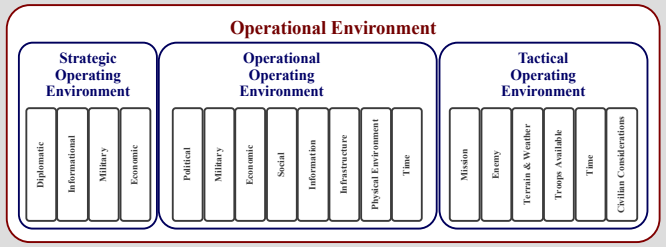

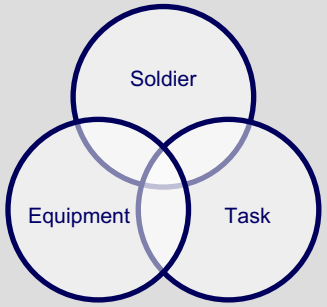

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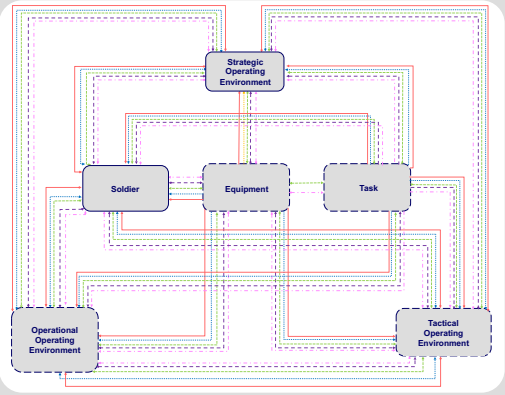
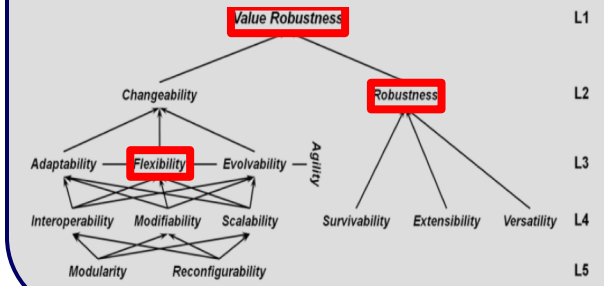


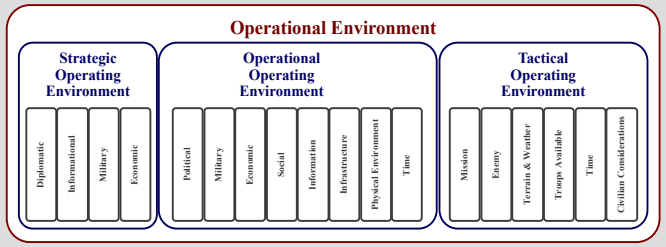
3

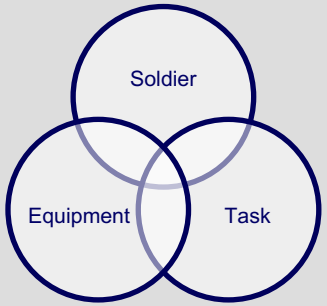
Ilities Manage OE Complexity



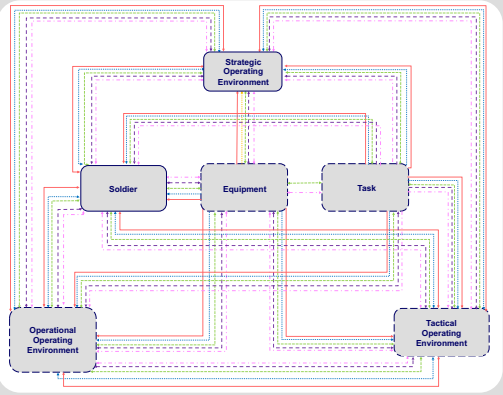
Research Summary and Conclusions

1 OE Variables Disrupt System Broad Utility Socially, Culturally, Physically, Informationally, and Psychologically

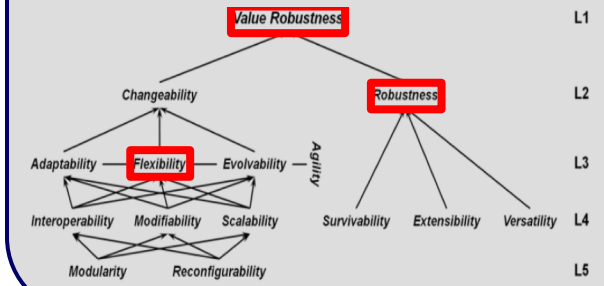




2 Variable Interactions Generate Complexity



3 Ilities Manage OE Complexity



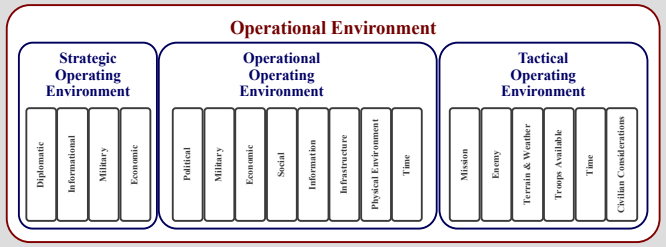
4 Flexibility and Robustness Increase Broad Utility

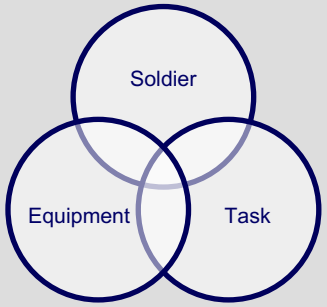
Flexibility and Robustness Factor to Observed Performance Summary, Overall

Ility	Factor	Data Analysis Evaluation Criteria							
		All System Observations (w/ Assessor Variability)		Mean Trendline (Averaging Out Assessor Variability)				Inter-Quartile Range (IQR)	
		R_P Value	Linear Relationship	R_P Value	Linear Relationship	R_S Value	Monotonic Relationship	Minimum (Rating(s))	Maximum (Rating(s))
Flexibility	Type of User	0.46	Low Positive	0.94	Very High Positive	1.00	Very High Positive	2.00 (4)	4.75 (2)
	Adaptability	0.63	Moderate Positive	0.99	Very High Positive	0.98	Very High Positive	1.00 (4,9)	4.50 (1)
	System Integration	0.48	Low Positive	0.96	Very High Positive	0.95	Very High Positive	2.00 (4,8,9)	4.75 (3)
Robustness	Environmental Robustness	0.56	Moderate Positive	0.98	Very High Positive	0.99	Very High Positive	1.50 (10)	5.00 (1)
	Digital Security	0.52	Moderate Positive	0.95	Very High Positive	0.96	Very High Positive	1.00 (4)	4.50 (3)

Research Summary and Conclusions

1 OE Variables Disrupt System Broad Utility Socially, Culturally, Physically, Informationally, and Psychologically





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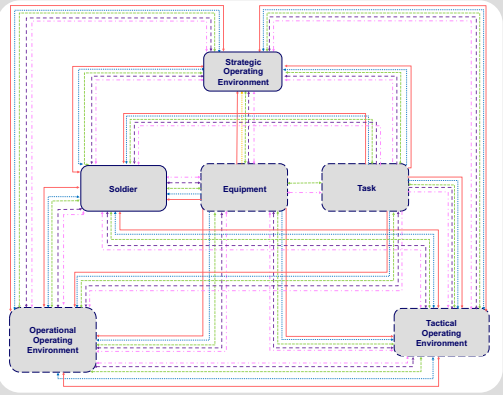

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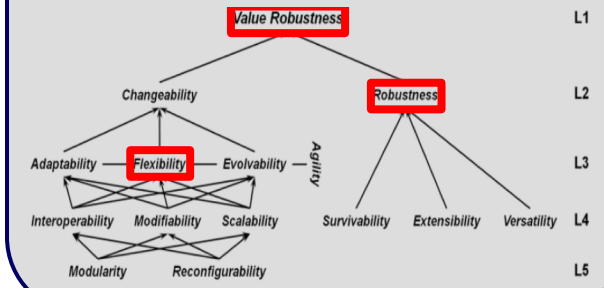

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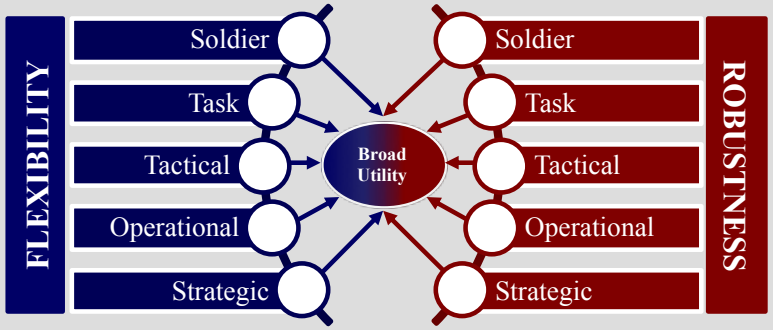
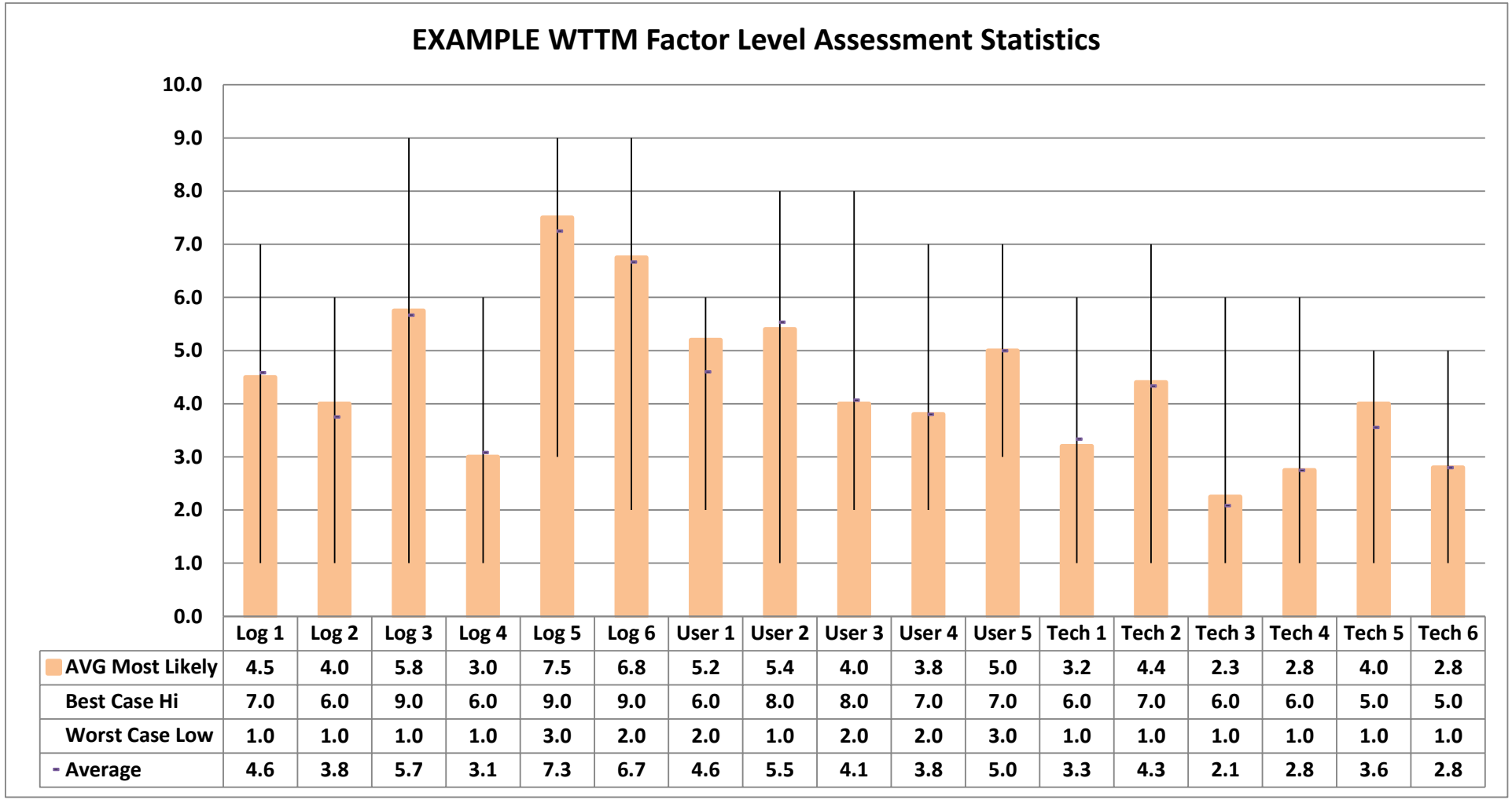
5 Broad Utility Architectural Decisions Enable Resilient System Design



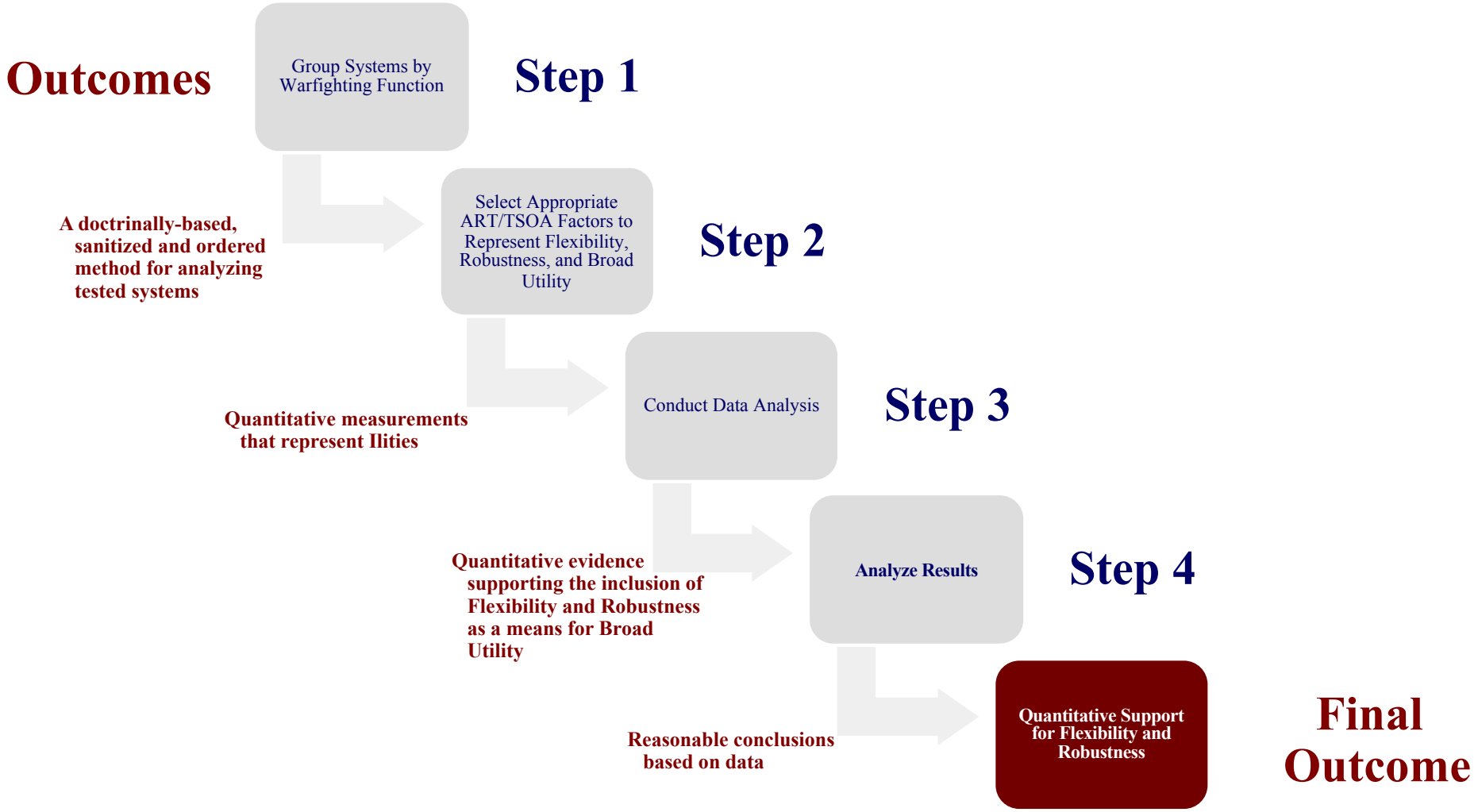
DETAILED DATA ANALYSIS METHOD AND RESULTS

Example ART/TSOA Factor Scoring

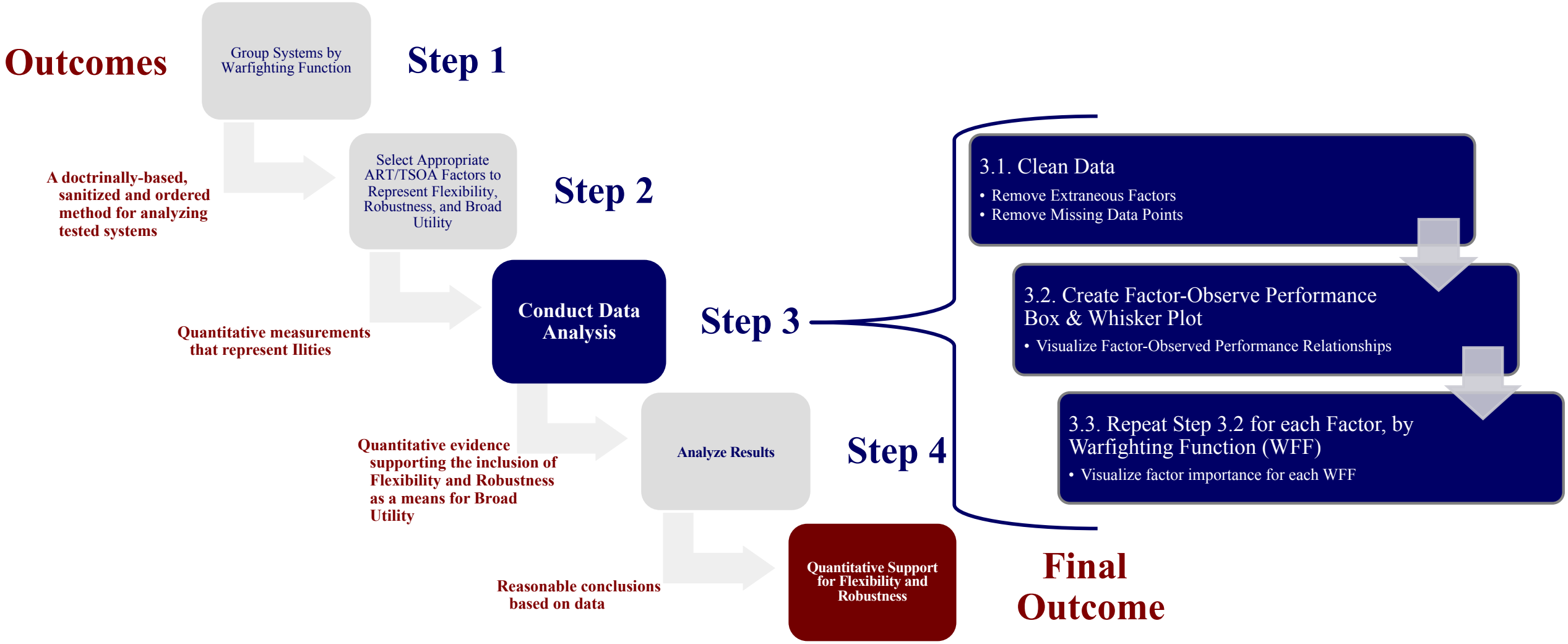


	Log 1	Log 2	Log 3	Log 4	Log 5	Log 6	User 1	User 2	User 3	User 4	User 5	Tech 1	Tech 2	Tech 3	Tech 4	Tech 5	Tech 6
AVG Most Likely	4.5	4.0	5.8	3.0	7.5	6.8	5.2	5.4	4.0	3.8	5.0	3.2	4.4	2.3	2.8	4.0	2.8
Best Case Hi	7.0	6.0	9.0	6.0	9.0	9.0	6.0	8.0	8.0	7.0	7.0	6.0	7.0	6.0	6.0	5.0	5.0
Worst Case Low	1.0	1.0	1.0	1.0	3.0	2.0	2.0	1.0	2.0	2.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0
Average	4.6	3.8	5.7	3.1	7.3	6.7	4.6	5.5	4.1	3.8	5.0	3.3	4.3	2.1	2.8	3.6	2.8

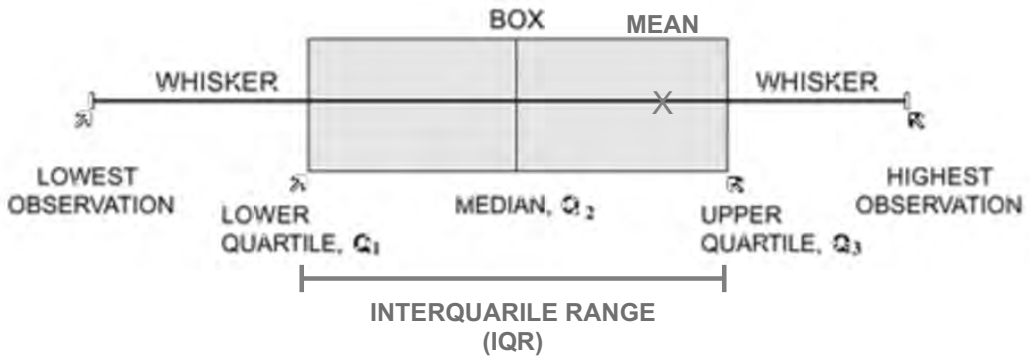
Data Analysis Method



Detailed Data Analysis

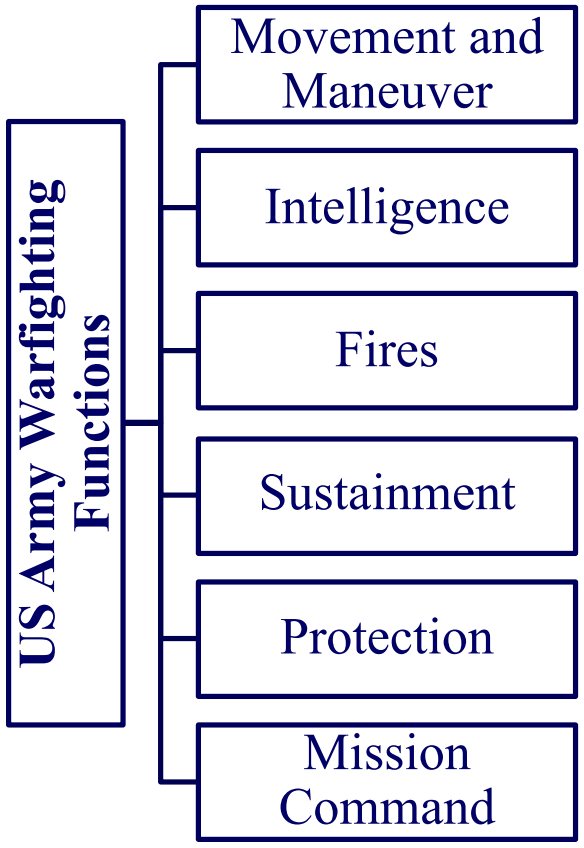


Box and Whisker Plots



Term	Definition	Thesis Application
Lowest Observation	"The least value, excluding outliers." [49]	At a given factor score, the ***lowest*** Observed Performance rating of all sampled system observations.
Lower Quartile (Q_1)	25th Percentile; "25% of the data is less than this value"; 75% of the data is greater than this value. [49]	At a given factor rating, the Observed Performance rating ***below which 25%*** of the systems scored.
Median (Q_2)	50th Percentile; "50% of the data is less than this value"; 50% of the data is greater than this value "middle of dataset." [49]	At a given factor rating, the Observed Performance rating ***below which 50%*** of the systems scored.
Mean (X)	"The sum of all values for the variable divided by the count of how many values the variable has.' [47, p. 45]	At a given factor rating, the average Observed Performance rating for all sampled system observations.
Upper Quartile (Q_3)	75th Percentile; 75% of the data is less than this value; "25% of the data is greater than this value." [49]	At a given factor rating, the Observed Performance rating ***below which 75%*** of the systems scored.
Highest Observation	"The greatest value, excluding outliers." [49]	At a given factor score, the ***highest*** Observed Performance rating of all sampled system observations.
Interquartile Range (IQR)	A measure of variability in the data; "the difference between the first and third quartiles." [50]	At a given factor rating, the ***area in which 50% of the Observed Performance ratings occurred*** for all sampled system observations.

US Army Warfighting Function Definitions



Movement and Maneuver: "the related tasks and systems that move and employ forces to achieve a position of relative advantage over the enemy and other threats." [10]

Intelligence: "the related tasks and system that facilitate understanding the enemy, terrain, weather, civil considerations, and other significant aspects of the operational environment." [10]

Fires: "the related tasks and systems that provide collective and coordinated use of Army indirect fires, air and missile defense, and joint fires through the targeting process." [10]

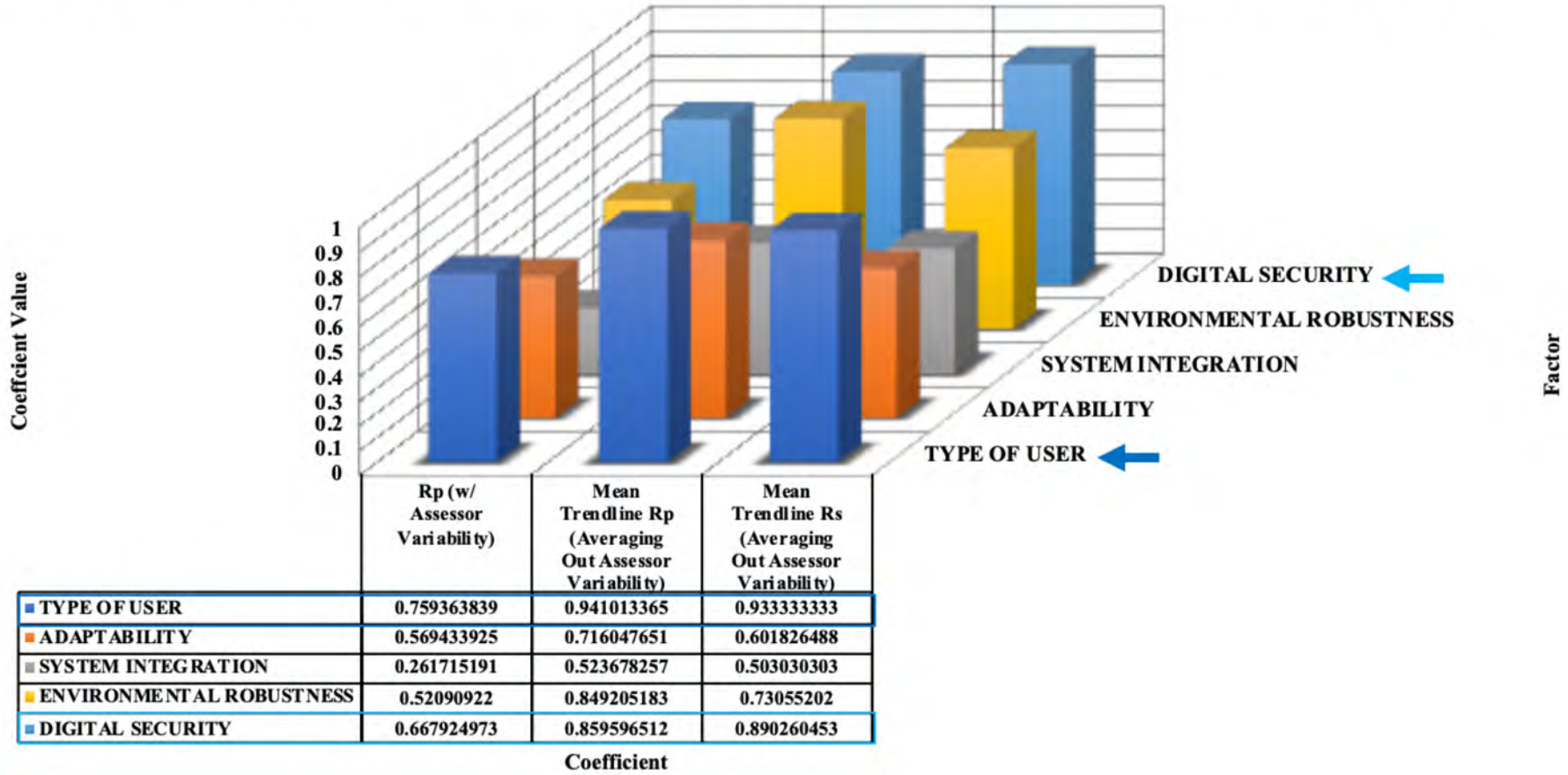
Sustainment: "the related tasks and systems that provide support and services to ensure freedom of action, operational reach, and prolong endurance." [10]

Protection: "the related tasks and systems that preserve the force so the commander can apply maximum combat power to accomplish the mission." [10]

Mission Command: "the related tasks and systems that develop and integrate those activities enabling the commander to balance the art of command and the science of control in order to integrate the other warfighting functions." [10]

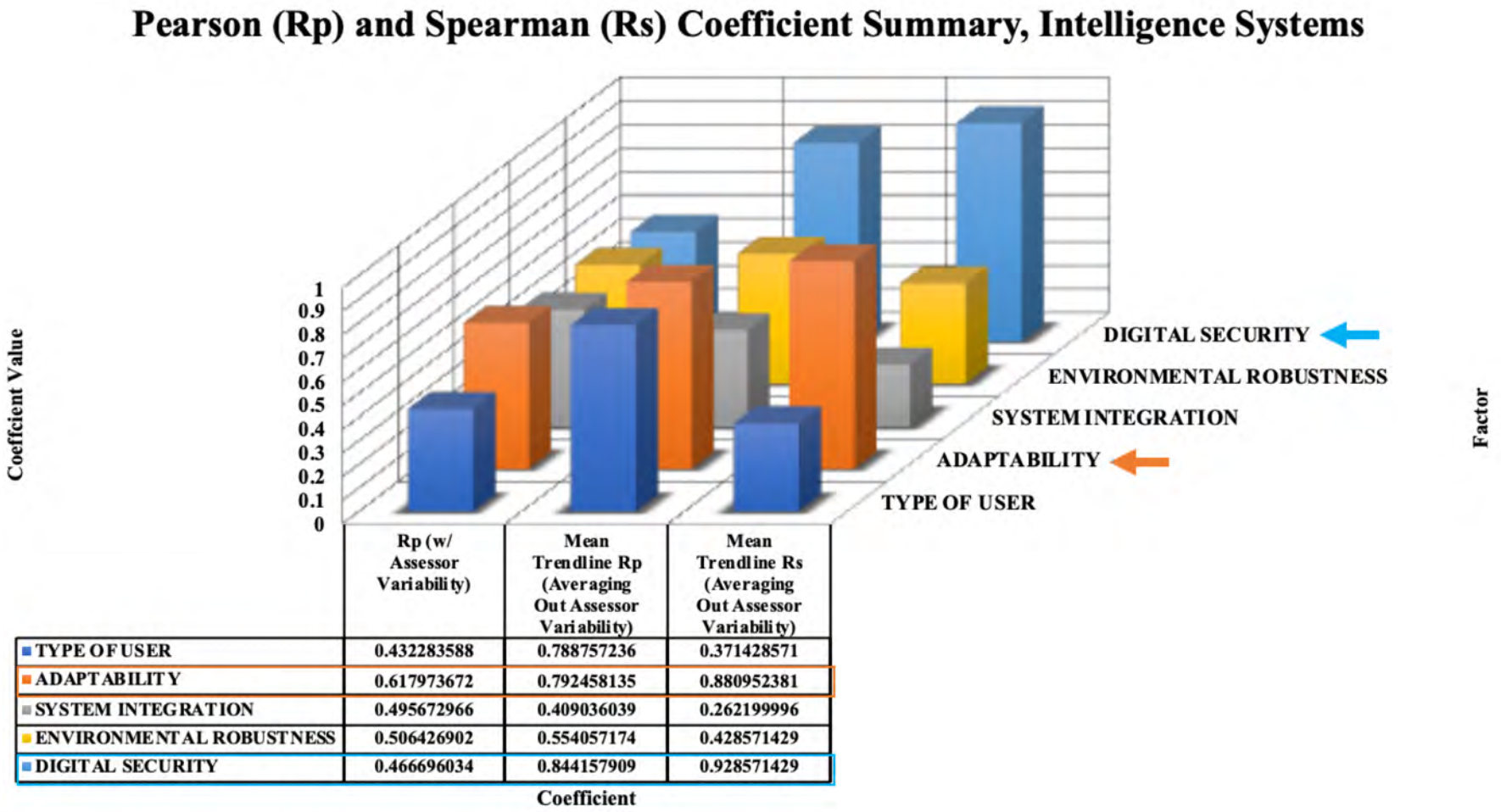
Movement and Maneuver Systems Analysis

Pearson (Rp) and Spearman (Rs) Coefficient Summary, Movement and Maneuver Systems



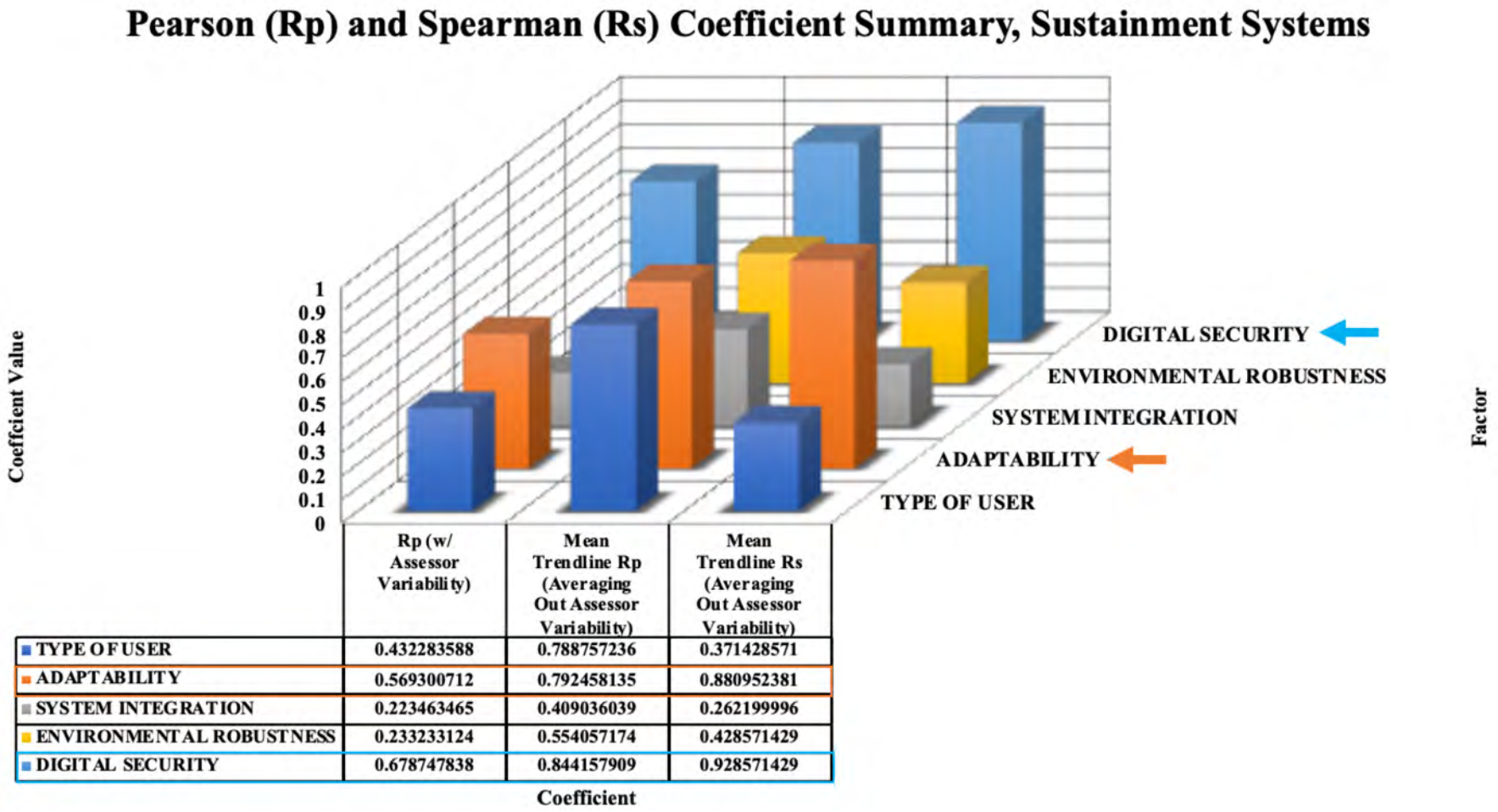
	Rp (w/ Assessor Variability)	Mean Trendline Rp (Averaging Out Assessor Variability)	Mean Trendline Rs (Averaging Out Assessor Variability)
TYPE OF USER	0.759363839	0.941013365	0.933333333
ADAPTABILITY	0.569433925	0.716047651	0.601826488
SYSTEM INTEGRATION	0.261715191	0.523678257	0.503030303
ENVIRONMENTAL ROBUSTNESS	0.52090922	0.849205183	0.73055202
DIGITAL SECURITY	0.667924973	0.859596512	0.890260453

Intelligence Systems Analysis



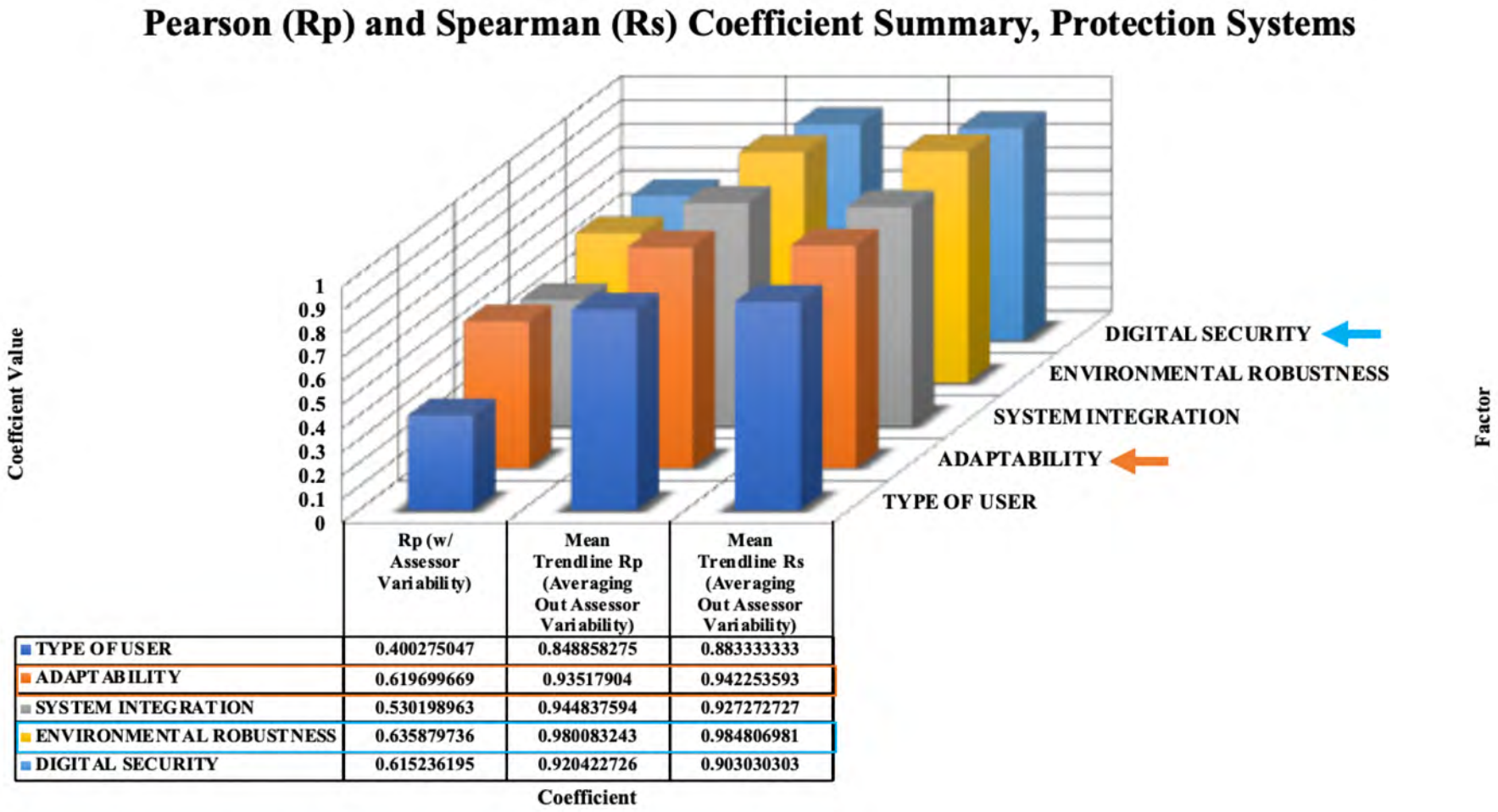
	Rp (w/ Assessor Variability)	Mean Trendline Rp (Averaging Out Assessor Variability)	Mean Trendline Rs (Averaging Out Assessor Variability)
TYPE OF USER	0.432283588	0.788757236	0.371428571
ADAPTABILITY	0.617973672	0.792458135	0.880952381
SYSTEM INTEGRATION	0.495672966	0.409036039	0.262199996
ENVIRONMENTAL ROBUSTNESS	0.506426902	0.554057174	0.428571429
DIGITAL SECURITY	0.466696034	0.844157909	0.928571429

Sustainment Systems Analysis



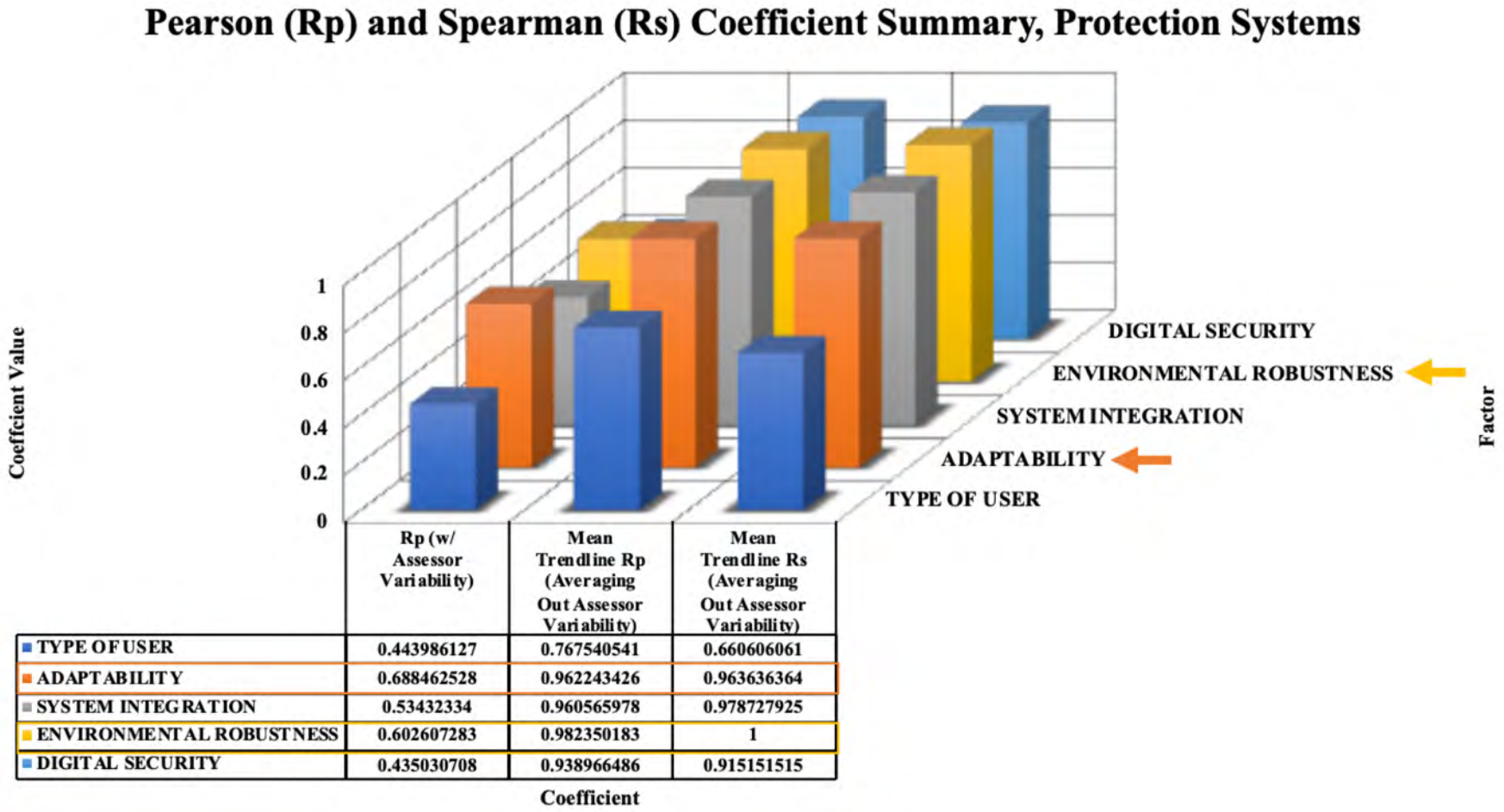
	Rp (w/ Assessor Variability)	Mean Trendline Rp (Averaging Out Assessor Variability)	Mean Trendline Rs (Averaging Out Assessor Variability)
TYPE OF USER	0.432283588	0.788757236	0.371428571
ADAPTABILITY	0.569300712	0.792458135	0.880952381
SYSTEM INTEGRATION	0.223463465	0.409036039	0.262199996
ENVIRONMENTAL ROBUSTNESS	0.233233124	0.554057174	0.428571429
DIGITAL SECURITY	0.678747838	0.844157909	0.928571429

Protection Systems Analysis



	Rp (w/ Assessor Variability)	Mean Trendline Rp (Averaging Out Assessor Variability)	Mean Trendline Rs (Averaging Out Assessor Variability)
TYPE OF USER	0.400275047	0.848858275	0.883333333
ADAPTABILITY	0.619699669	0.93517904	0.942253593
SYSTEM INTEGRATION	0.530198963	0.944837594	0.927272727
ENVIRONMENTAL ROBUSTNESS	0.635879736	0.980083243	0.984806981
DIGITAL SECURITY	0.615236195	0.920422726	0.903030303

Mission Command Systems Analysis



	Rp (w/ Assessor Variability)	Mean Trendline Rp (Averaging Out Assessor Variability)	Mean Trendline Rs (Averaging Out Assessor Variability)
TYPE OF USER	0.443986127	0.767540541	0.660606061
ADAPTABILITY	0.688462528	0.962243426	0.963636364
SYSTEM INTEGRATION	0.53432334	0.960565978	0.978727925
ENVIRONMENTAL ROBUSTNESS	0.602607283	0.982350183	1
DIGITAL SECURITY	0.435030708	0.938966486	0.915151515