

Structuring T&E for Validation of Complex Systems Capabilities and Exploration of Emergent Behaviors



Josh Tribble
MILITARY ANALYST
AVW TECHNOLOGIES

Phone: 757-348-4013 (Mobile)
E-mail: tribble@avwtech.com
860 Greenbrier Circle, Suite 305
Chesapeake, VA 23320
<http://www.avwtech.com>

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Agenda






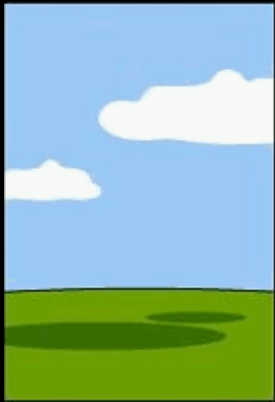


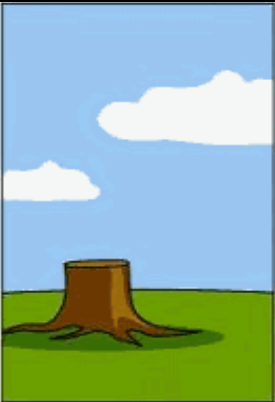

- SYSTEMS THEORY RELEVANT TO T&E
 - Complex Systems
 - Holism
 - Emergence

- STRUCTURING T&E FOR VALIDATION OF COMPLEX SYSTEMS
 - Complex System V&V
 - Complex System T&E
 - Considerations and Recommendations
 - Mission and Functional Analysis Based Test Planning
 - Risk Prioritized Integrated Testing across the Development Life-Cycle
 - Design of Experiments Based Test Planning and Analysis

- CONCLUSION

Systems Engineering

The way it really is?

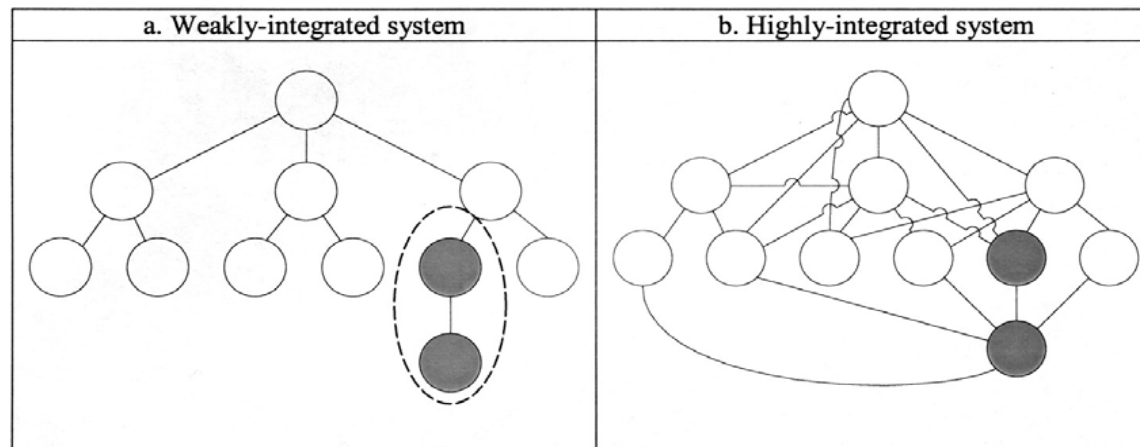
				
How the user described it	How the requirement was understood	How the contractor designed it	How the programmer wrote it	How the PM/sponsor described it
				
How the project was documented	What was actually installed	How the Government was billed	How the helpdesk supported it	What the user really needed

SYSTEMS THEORY RELEVANT TO T&E

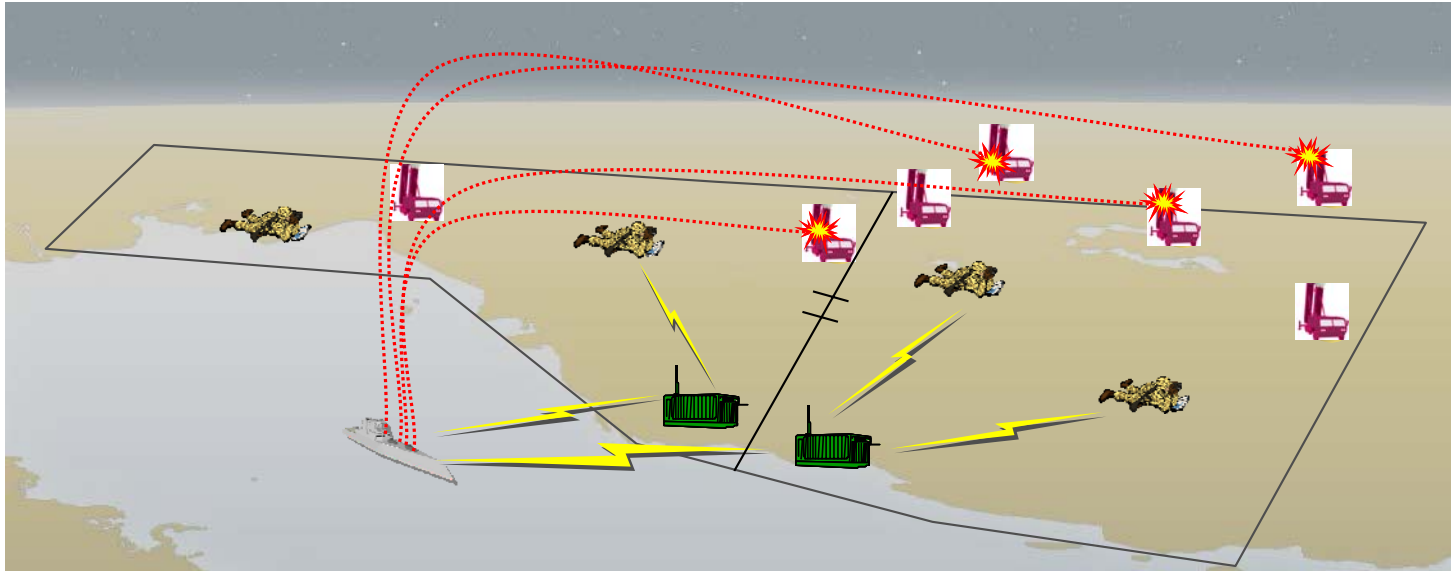
- Complex Systems
- Holism
- Emergence

Complex Systems

- **Holistic**, hierarchal, transient, **emergent**, non-deterministic, large number of elements and states, etc...
- **Detail complexity**—hierarchical relationships dominate; complex in size and scope but straight forward causal relationships; somewhat predictable; risks in contributing parts (Calvano & John, 2004)
- **Dynamic complexity**—lateral interfaces dominate; complex integration and behaviors; unpredictable; system risks dominate; causal relationships difficult if not impossible to determine (Calvano & John, 2004)



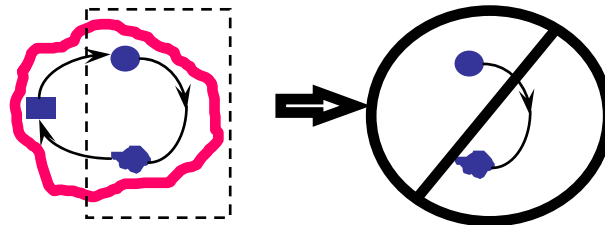
Complex Systems Example: Naval Surface Fire Support



- Very Complex System; also possibly a System of Systems
- Dynamic Complexity – many parts, high degree of coupling and interaction across a large number of complex interfaces; integration challenge!
- Diverse, separated, component systems; transient states & deterministic behavior
- Variability and unpredictability of human behaviors and interaction w/ system
- Emergent behaviors from coupling of sensors, weapons, & employment methods

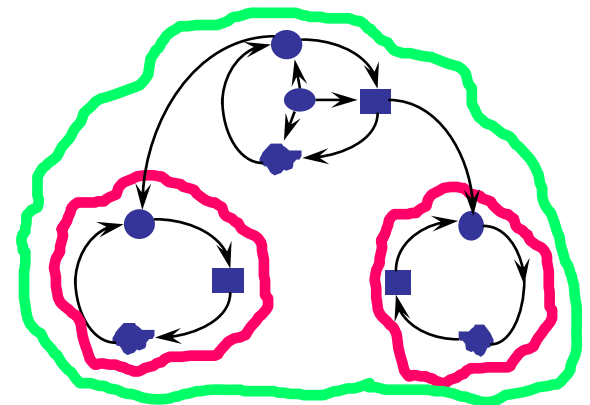
Holism

- “A system has holistic properties possessed by none of its parts. Each of the system parts has properties not possessed by the system as a whole.” Clemson (1984, p. 201)
- Holism emphasizes whole over parts; organizational level analysis ensuring elements function together to serve the purpose of the system. Jackson (2006, p. 650)
- Reductionism serves to help in building up a system design, but a holistic view is needed in order to evaluate complex systems.



Emergence

- A systems principle that whole entities exhibit properties that are meaningful only when attributed to the whole, not its parts – e.g. the pungent smell of ammonia, which comes from the properties of the molecule, not those of the constituent nitrogen and hydrogen atoms.
(Hitchens, 2003)
- Generally accepted aspects of emergence (see backup slides for references from literature):
 - Unpredictable / unexpected
 - Derives from integration, interfaces, and interaction of the systems' elements
 - Not present in the systems' elements nor can it be predicted by evaluating each of those – although can influence them



Emergence?



MISTAKES

IT COULD BE THAT THE PURPOSE OF YOUR LIFE IS
ONLY TO SERVE AS A WARNING TO OTHERS.

STRUCTURING T&E FOR VALIDATION OF COMPLEX SYSTEMS

- Complex System V&V
- Complex System T&E
- Considerations and Recommendations

Verification & Validation

- **Verification**: Confirmation by examination and provisions of objective evidence, that specified requirements have been fulfilled. (IEEE Std 1012, 1998, p.71)

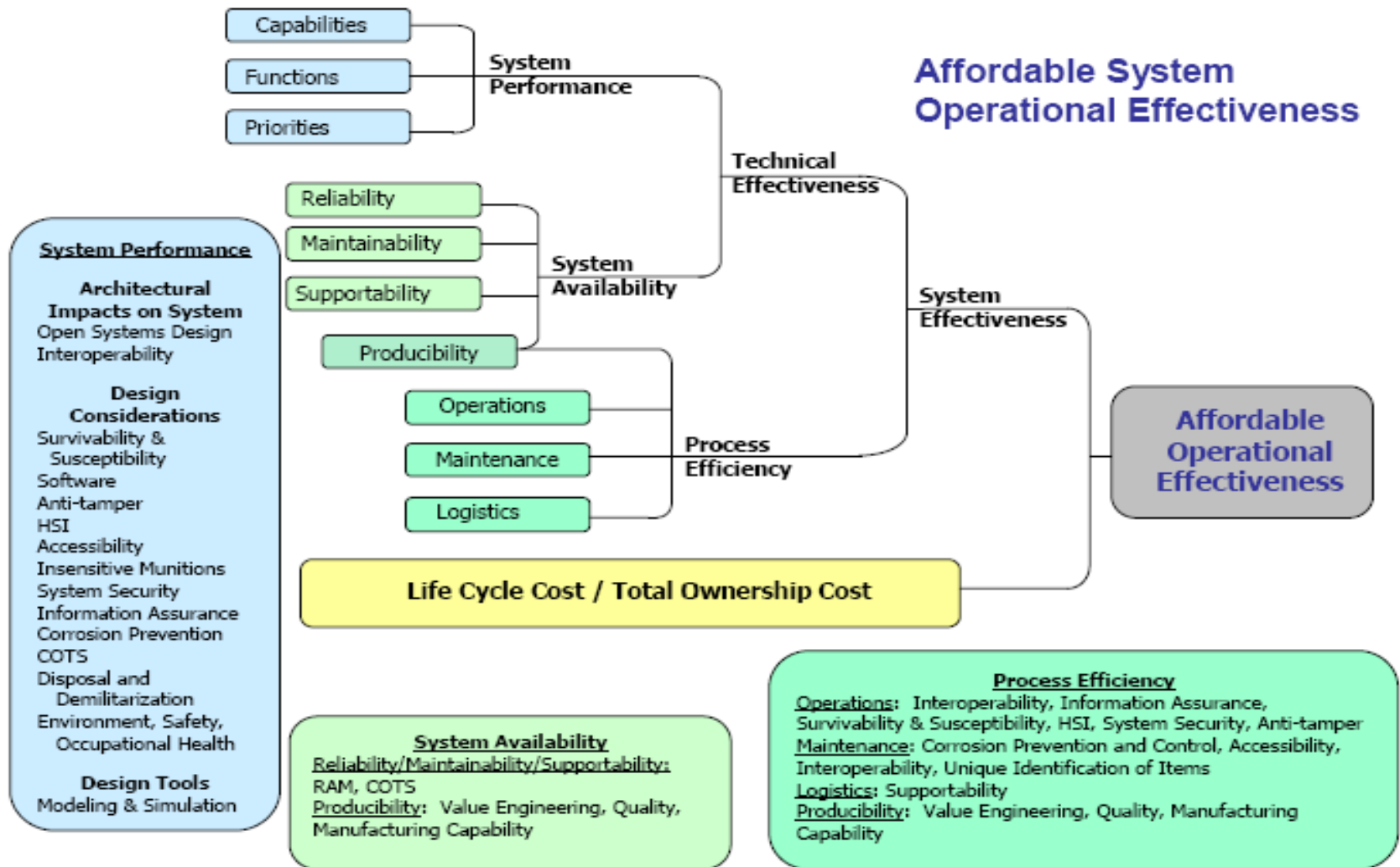
Did you build what you said you were going to build?

- **Validation**: Confirmation by examination and provisions of objective evidence that the particular requirements for a specific intended use are fulfilled. (IEEE Std 1012, 1998, p.71)

Did you build what the user needed?

- V&V is a broad set of activities for software or whole systems applied across the life-cycle, supporting a variety of activities from assessing technical alternatives in conceptual design to ensuring the as-built system meets its specifications and the user's need.

What encompasses a user's needs?



Test & Evaluation

- Test = procedure to measure performance under various conditions. (Parker, 1994)
- Testing = linchpin, intelligence/feedback loop for systems engineering. (Laskey, 1999, p. 6)
- T&E at its best = goal to provide necessary info to ensure quality.
At its worst = political game where programs fight for survival and money. (Laskey, 1999, p. 6)
- T&E ~ experiment & theory; predict outcome, validate points of doubt (Goode & Machol (1957, p. 509)
 - Unfortunately complex systems are often non-deterministic if not completely unpredictable

Focus of T&E

- “How well did the system actually perform, and did it accomplish its mission objective?” –
 - Mission accomplishment not just specs
 - System effectiveness + Support system capability (suitability)
- “Does the system meet all of the requirements as covered through the specified technical performance measures?”
 - Technical verification; developmental testing
- “Does the system meet all [user] requirements?”
 - Verification and validation?
 - Could a system meet the user’s requirements as stated and yet be not operationally effective/not suitable?



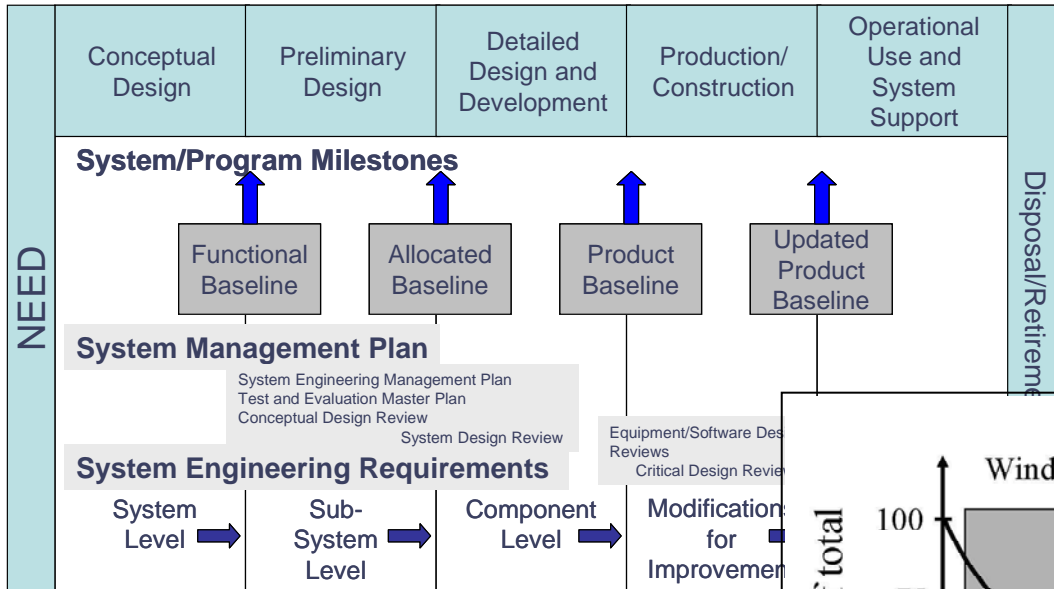
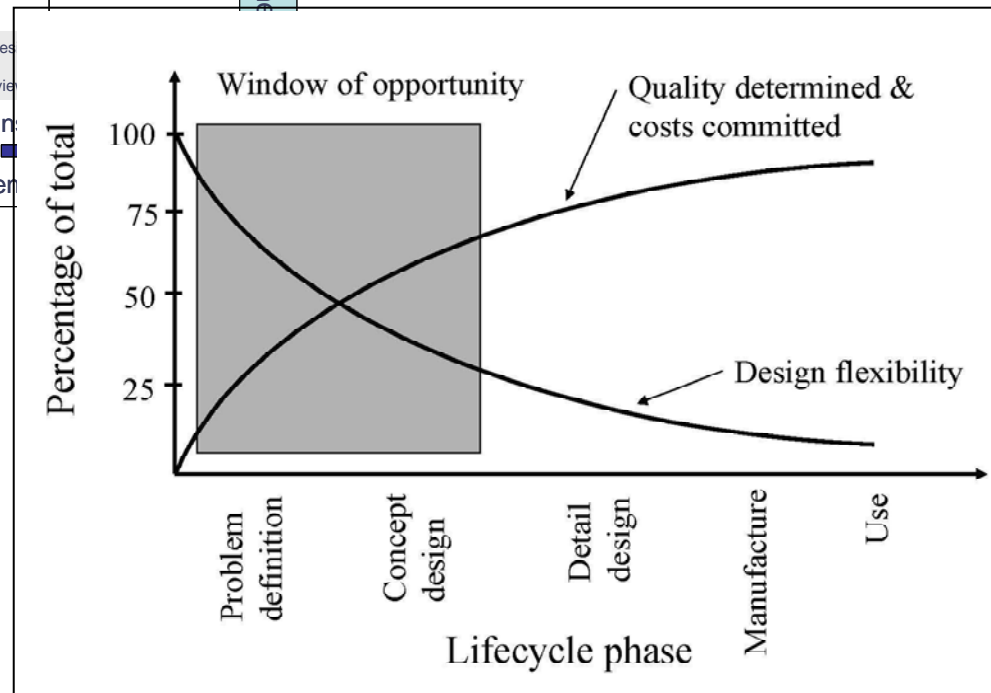


Figure adapted from Blanchard, S. & Fabrycky, W. J. (2006). *Systems Engineering and Analysis*. (4th ed.) Upper Saddle River, NJ: Prentice-Hall.

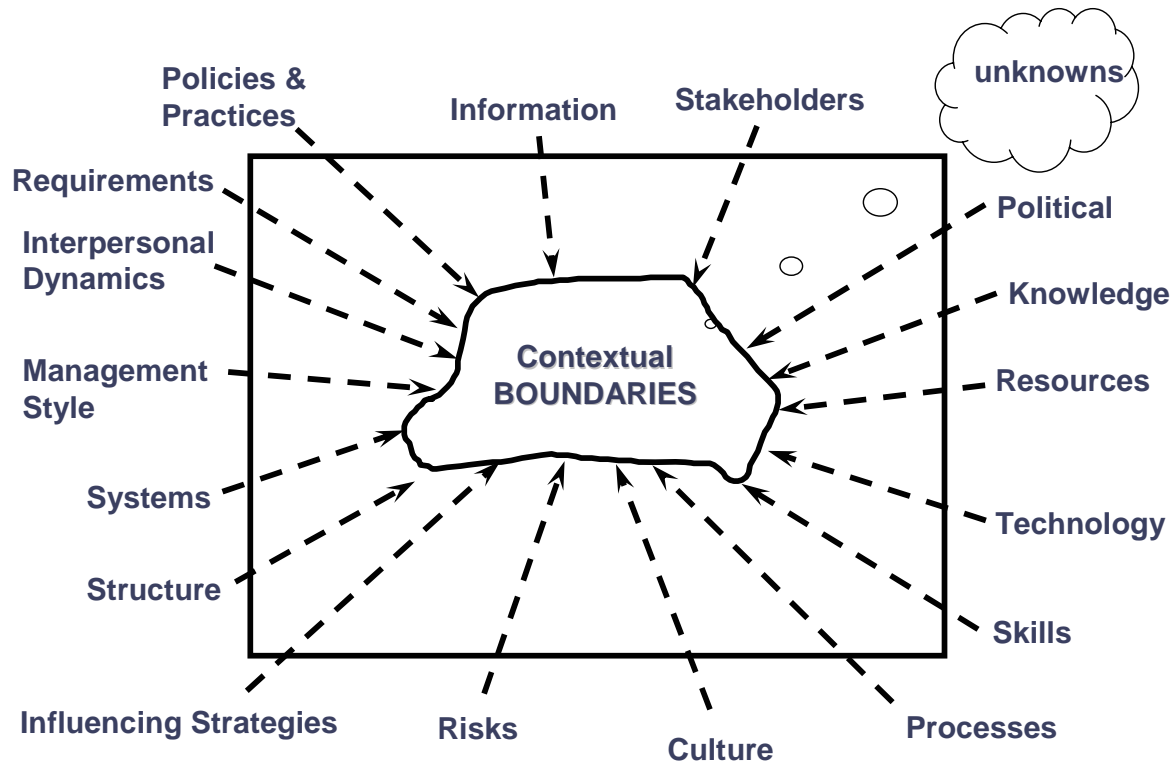
Get it right early!

- Importance of Conceptual Design
- Get testers involved (OT/DT/LFT)
- Understand mission environment
- Understand what constitutes operational effectiveness & suitability; what user really needs!
- Test early & often w/ honest assessment of risk to sustained mission capability



Source: Ford, R. B. & Barkan, P. (1995) "Beyond Parameter Design --A Methodology Addressing Product Robustness at the Concept Formation Stage", *Design for Manufacturability, 1995 Concurrent Engineering and Design Manufacturing Integration*, ASME DE-Vol. 81, J.R. Behun (Ed.), National Design Engineering Conference, Chicago, IL, March 13-16.

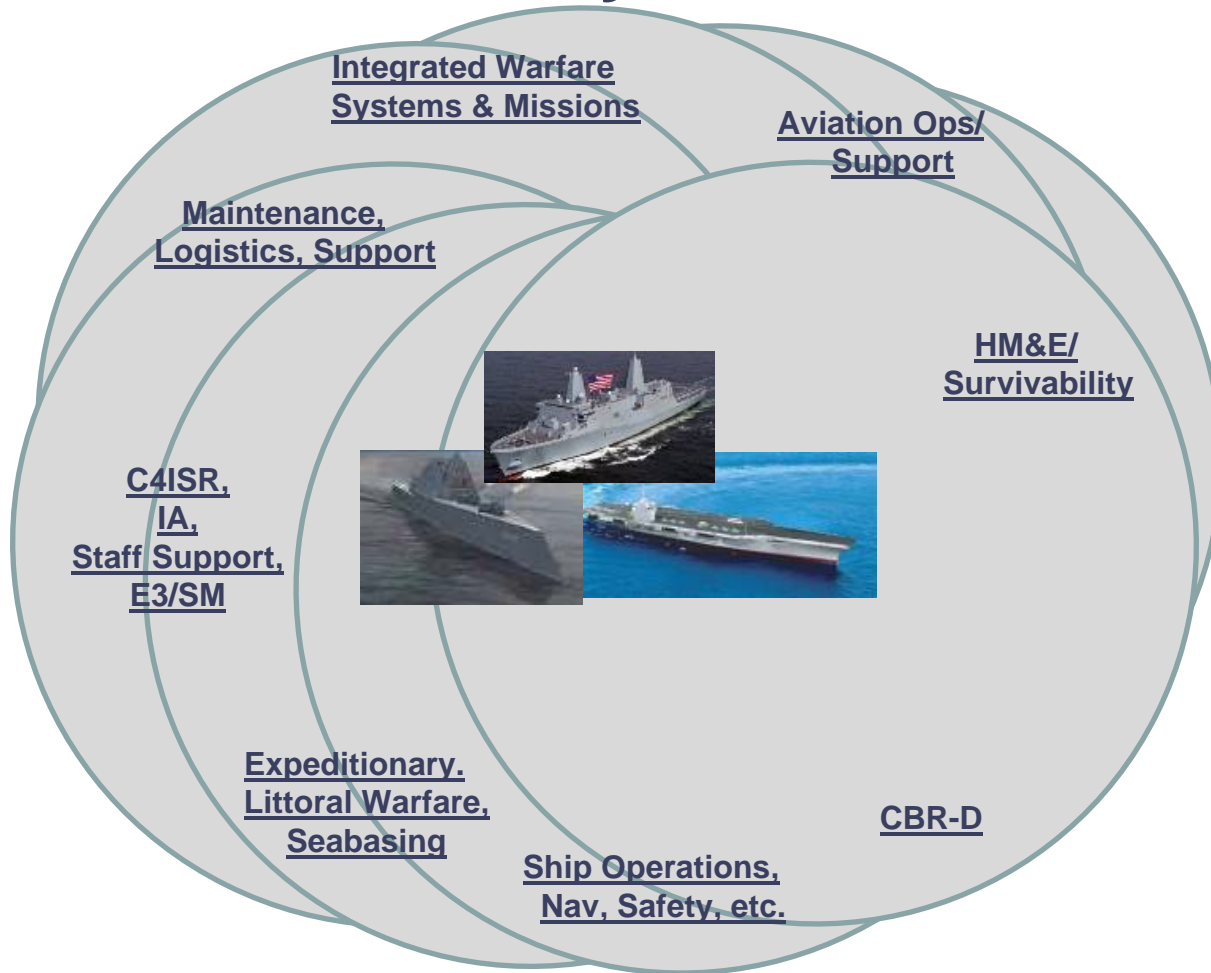
Program Context and Systems Evaluation



Implications for complex system T&E

- Understand mission environment and ensure testing explores those boundaries
- Evaluation of system/program performed in context of the program & many external and internal influences and drivers
- These also affect capabilities and limitations of T&E itself

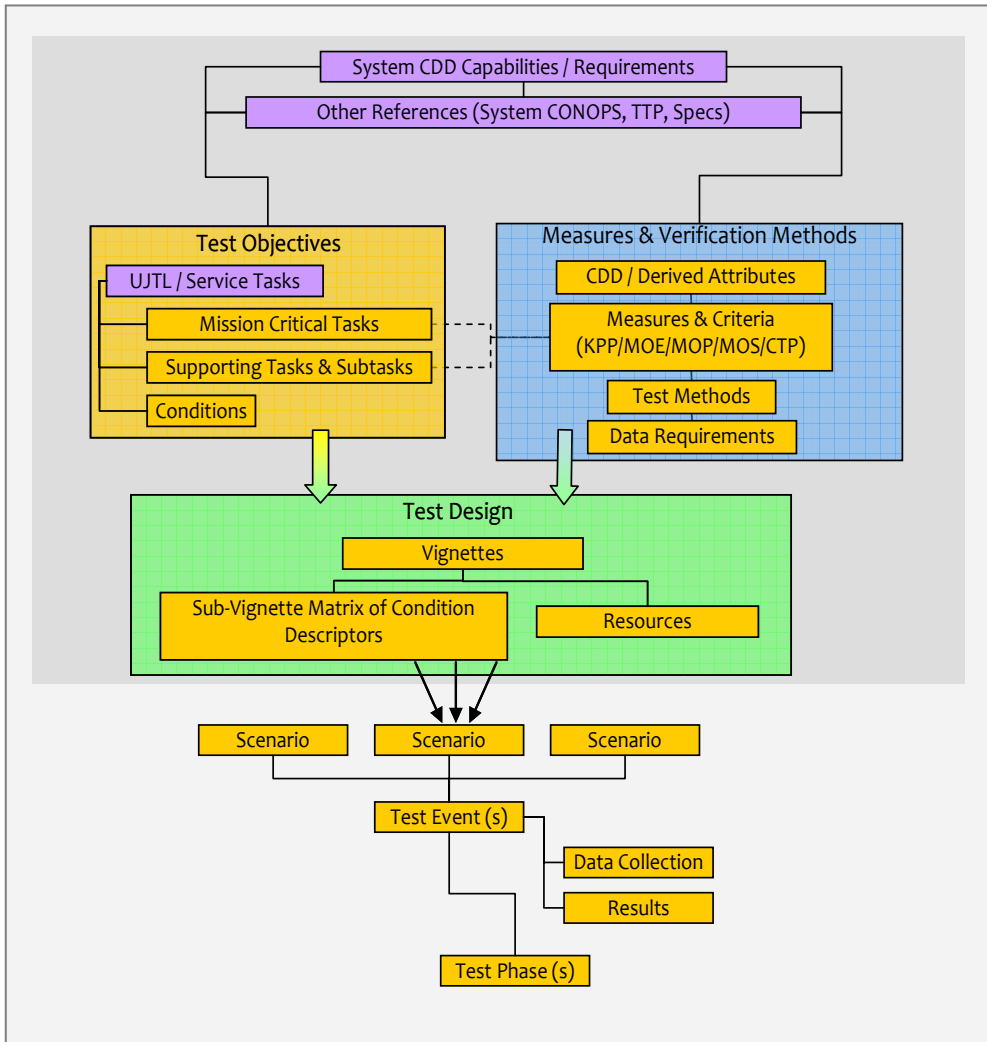
Total Platform/System Mission Context



Implications for complex system T&E

- Multiple, concurrent missions evaluated in complex scenarios

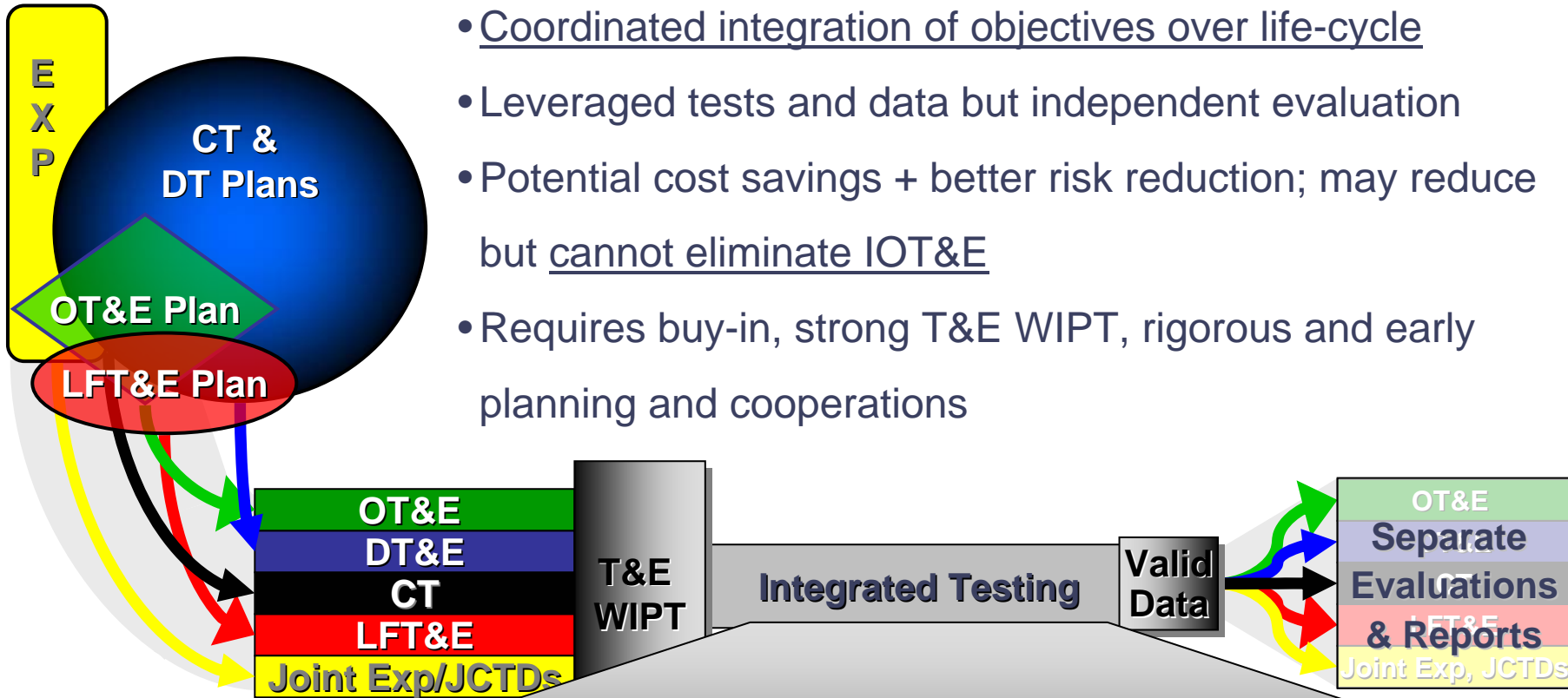
Mission Based Testing T&E Framework Toolset Architecture



- Describe discrete tasks to perform system missions in user's language
- Define conditions affecting task outcome
- Extract attributes & measures from requirements & other references; correlate to tasks
- Assign test methods & data requirements to measures
- Group tasks w/ conditions & measures into testable/meaningful vignettes
- Repeat vignettes to account for variability due to conditions and settings
- Test vignettes grouped into scenarios run during test events

Integrated Testing

- Planning and development of individual test objectives;
- Coordinated integration of objectives over life-cycle
- Leveraged tests and data but independent evaluation
- Potential cost savings + better risk reduction; may reduce but cannot eliminate IOT&E
- Requires buy-in, strong T&E WIPT, rigorous and early planning and cooperations



$$T\&E_{\text{integrated}} \int_{\text{Program Conception}}^{\text{System Disposal}} = f(\text{CT, DT, OT, LFT\&E, Joint Exp, M\&S, Analysis, etc.}) dt$$

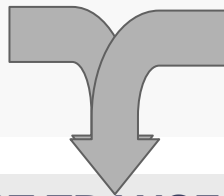
Integrated Testing

DT

- Test to specifications
- Limited test environment
- Focused on a specific set of criteria.
- Test threshold values not capability
- Critical technical parameters
- Integration testing designed around min performance criteria and interface specs.
- May not address all threats or missions.
- CT adds contractual issues

OT

- Operational environment & threat with end users & support
- End-to-end mission perf. & support
- Production representative; system/family of systems
- Test overall capability of an item to meet user's mission needs and value added for mission accomplishment.
- Test the limitations and capabilities of an item so that:
- Employ and assess doctrine/TTP
- Independent IOT&E & LFT&E mandates (Title X)

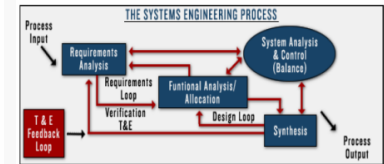
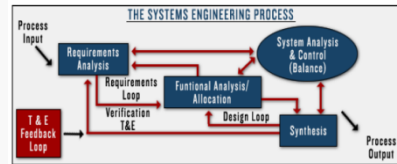
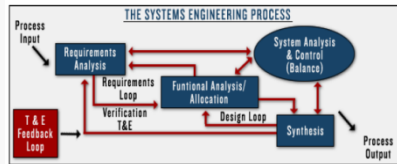
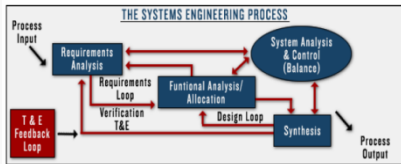


THIS MUST TRANSFORM INTO A CONTINUUM OF TESTING

- Increasing fidelity of technical and operational assessments
- Cooperating organizations
- Reduced budget and timeline ?
- Team/IPT structure not competitive



Systems Engineering + T&E within the Acquisition Cycle



Concept V&V
Prototype Testing/Exp/Analysis

Component Testing
Functional Arch V&V

Subsystem Testing
Physical Arch V&V

System DT & OT
Config Audits

Follow on OT
Upgrade/Re-arch V&V

MORE THAN TESTING ... CONTINUOUS EVALUATION

RISK MANAGEMENT...

MISSION CAPABILITY DELIVERY...

INTEGRATED T&E & SYSTEMS ENGINEERING

Ability to influence system design

System maturity & design/ upgrade cost

Design of Experiments Process Overview

Project description and process decomposition

- Problem statement and objective of experiment (test)
- Response variables, and potential causal variables – Ishikawa fish bone.



Plan test matrix

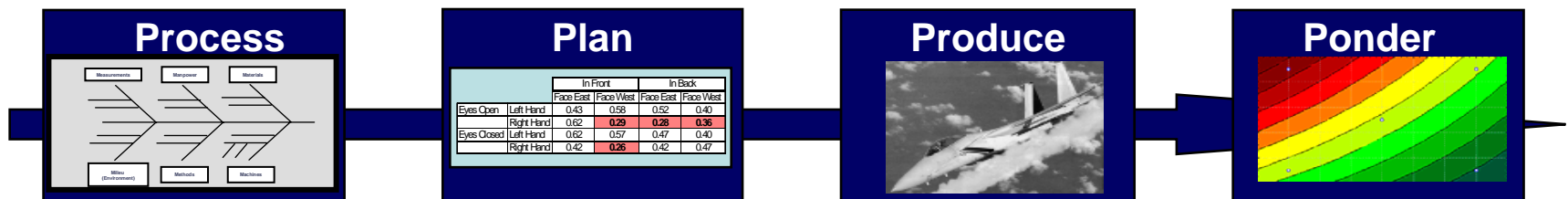
- Determine constraints, prioritize factors, and select statistical design (2^K vs. 3^K vs. mixed, Taguchi vs. classical arrays, full vs. fractional, non-linear effects?, replications?, blocking?)
- Write the test plan with sample matrices, profiles, and sample output; run sample analysis.

Produce observations

- Random run order & blocked against unknown effects
- Block runs to guard against uncontrollable unknown effects as needed.

Ponder the results

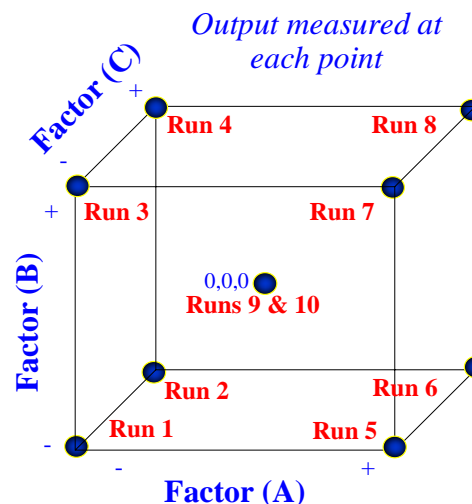
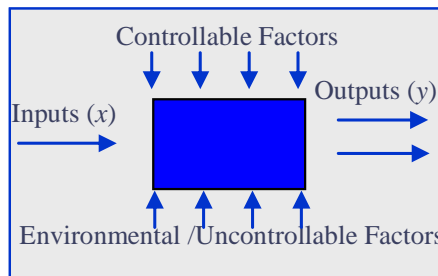
- Analyze and project data; draw conclusions, redesign test as necessary and assess results.
- Perform “salvo testing” (test-analyze-test); screen large # of factors then model



Design of Experiments Test Matrix Development

- Partial or full matrix of varying settings for the factors (usually 2 or sometimes 3 level)
- Perform larger matrices in increments, eliminating factors that are shown to be non-factors through analysis
- Goal is to determine cause of variability in output based on input factors

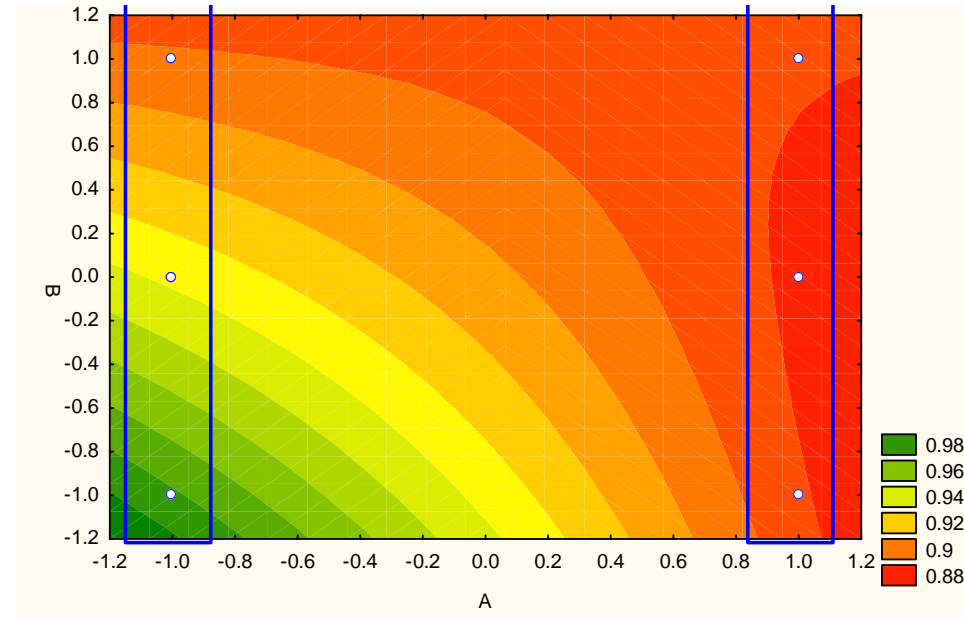
Run	Setting	A	B	C
1	Factorial point	-1	-1	-1
2	Factorial point	-1	-1	+1
3	Factorial point	-1	+1	-1
4	Factorial point	-1	+1	+1
5	Factorial point	+1	-1	-1
6	Factorial point	+1	-1	+1
7	Factorial point	+1	+1	-1
8	Factorial point	+1	+1	+1
9	Center point 1	0	0	0
10	Center point 2	0	0	0



Design of Experiments

Data Analysis

- Sample data analysis: produces regression model, predictions, response surface/curves as shown.
- Statistical analysis of the MOEs
- Exploration of mission performance variability across driving conditions



Design of Experiments Benefits

- Better way to design and test complex systems
- Systematically explores system performance, effectiveness, and suitability – breadth and depth of testing across the performance envelope
- Challenge assumptions and demonstrate real performance across the expected environment
- Better justification for sample sizes; potentially significant reduction from case or one factor at a time testing
- Better linkage between M&S and live test
- DOE works well in Mission Based Testing/Integrated Testing and relies on proper task derivation and attributes and conditions selection
- DOE can improve testing across all programs – it is simply smarter testing!



Conclusion

- Complex Systems
 - Complex Systems– detail vs. dynamic complexity
 - Holism
 - Emergence
- Structuring T&E to Validate Complex Systems
 - Understand program context and system mission context
 - Test early, test often...
 - Mission Based Test Design
 - Integrated Testing
 - CT + DT + OT + LFT + ...
 - Integrated testing and data collection
 - But...Independent evaluation
 - T&E as part of SE life-cycle
 - Design of Experiments
- Questions

