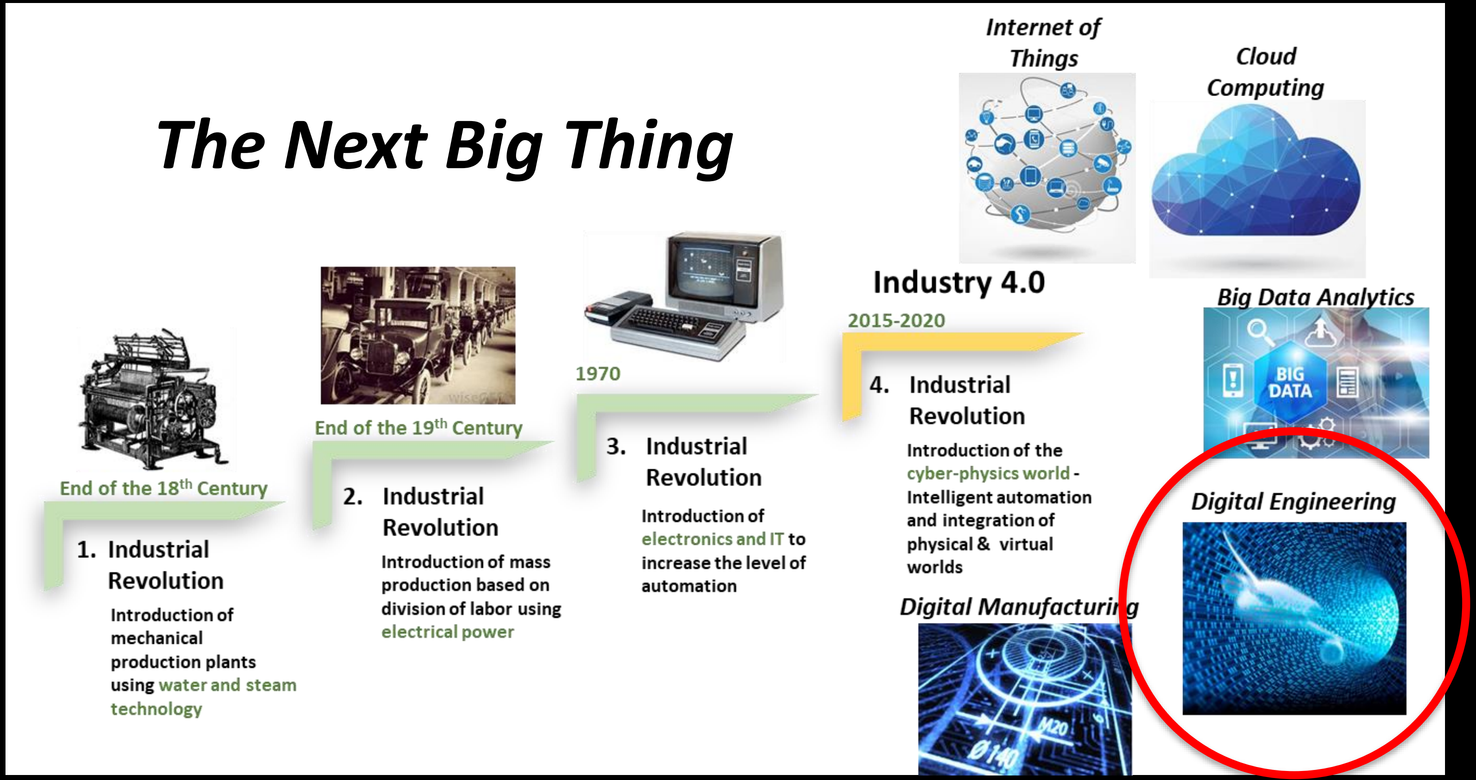
Transforming Systems Engineering to Take Advantage of the Digital Revolution



Dr. Ed Kraft

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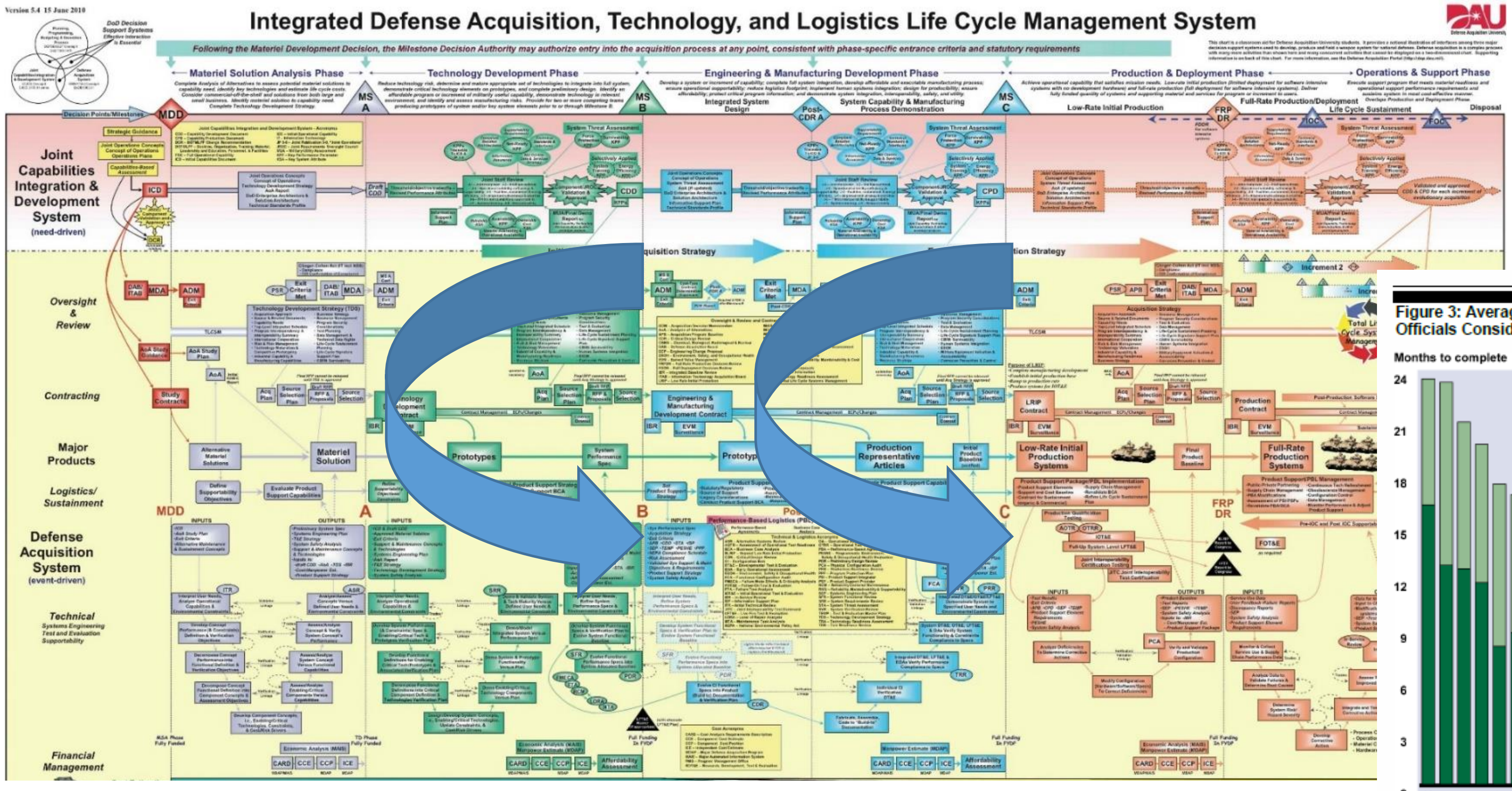
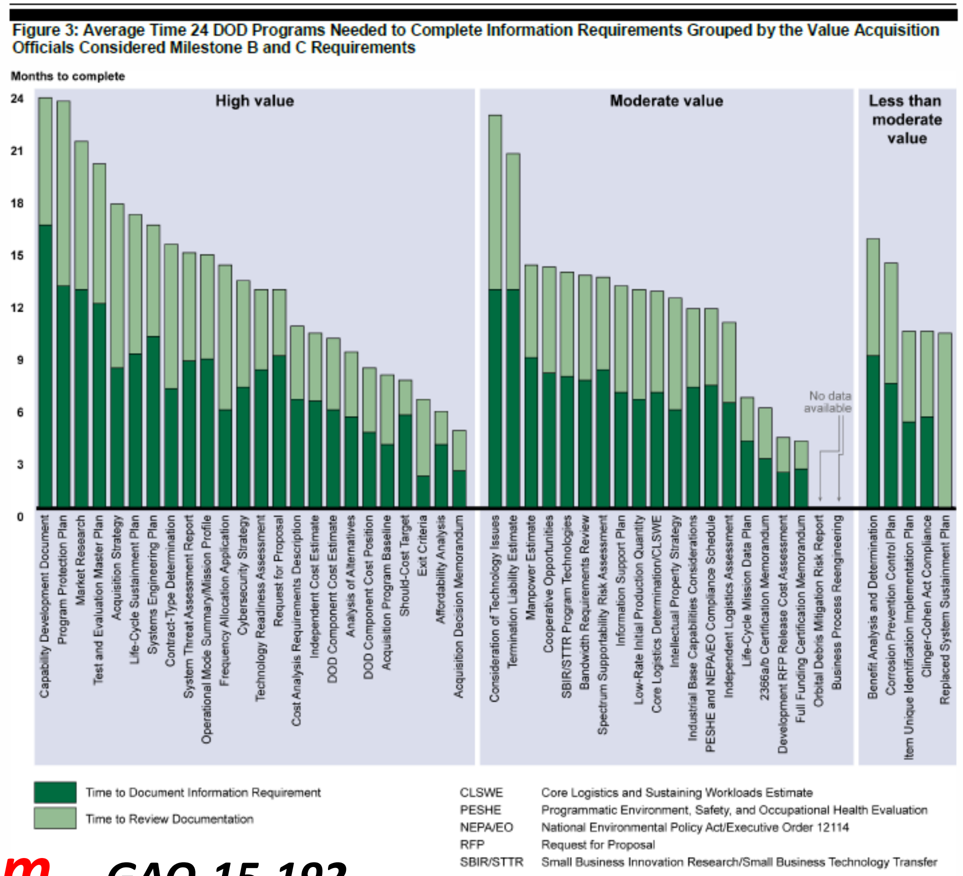
University of Tennessee Space Institute

October 25, 2018

Current DoD Systems Engineering – Linear, Document Centric, Positional Process





GAO-15-192

Two key findings from GAO reports (06-66, 06-391, 06-110) :

- **Contractors not held accountable for achieving desired outcomes, including cost goals, schedule goals, and desired capabilities.**
- **Programs do not capture, early on, requisite knowledge needed to effectively manage program risks**

Not incompetence or malfeasance but a systemic problem

DoD Digital Engineering Strategic Guidance (June 2018)

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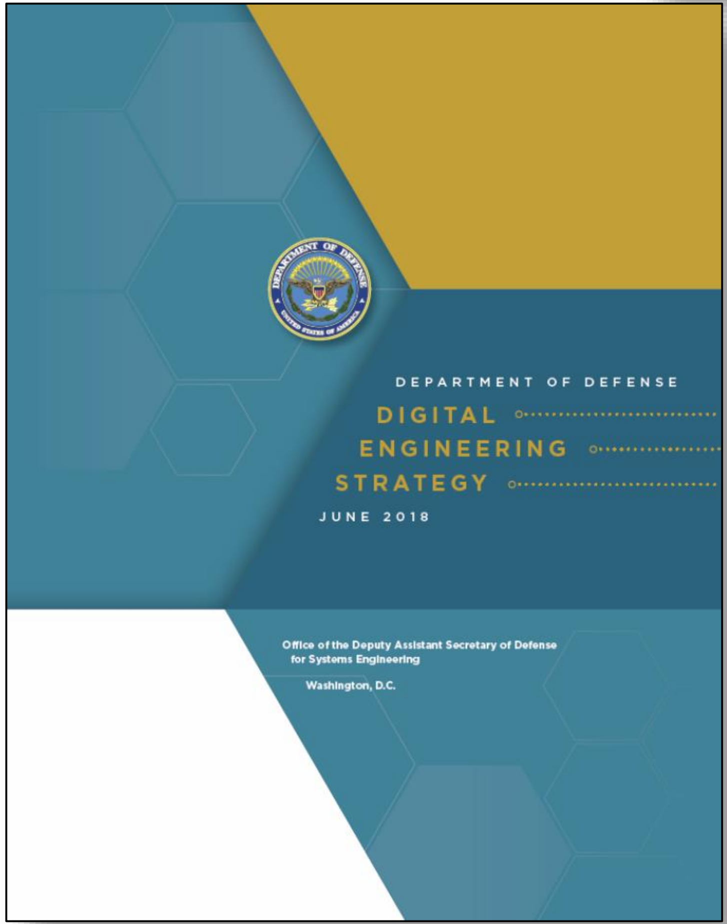
- Formalize the development, integration, and *use of models to inform enterprise and program decision making*
- Provide an *enduring, authoritative source of truth*
- Incorporate technological innovation to *improve the engineering practice*
- *Establish a supporting infrastructure* and environment to perform activities, collaborate and communicate across stakeholders
- *Transform the culture and work*



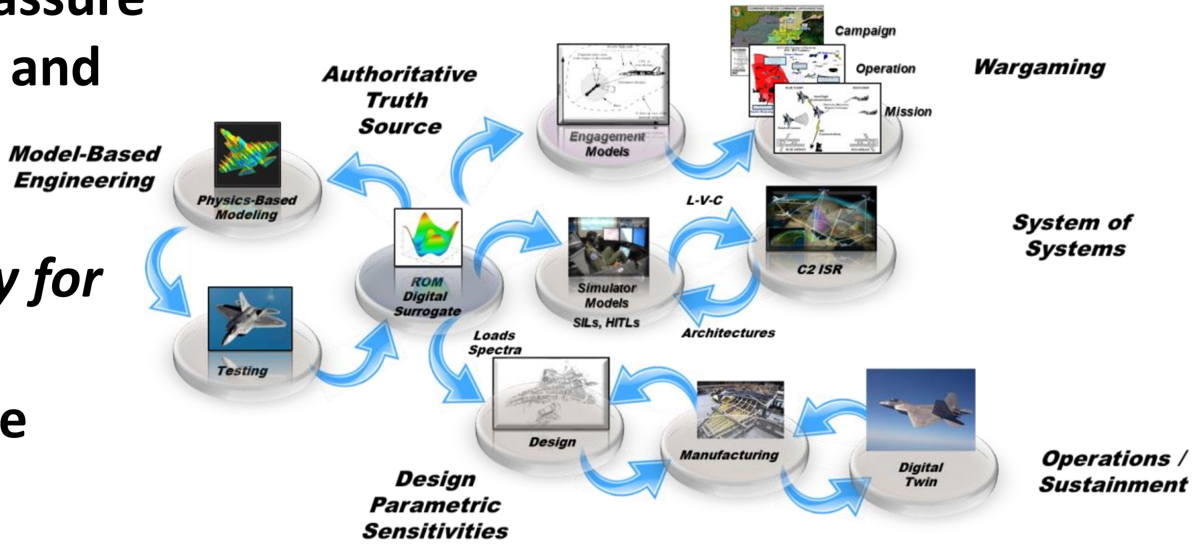
Authoritative Truth Sources –
the Key to Shifting from a Design-Build-Test-Fix Paradigm to an Integrate-Analyze-Design-Build-Test-Operate-Learn Systems Engineering Paradigm

Authoritative Truth Sources

Develop, integrate, and curate models to digitally represent the system of interest over its lifecycle

- **<u>Authoritative</u> connotes a governance process to assure the pedigree and provenance of the truth source and related models and data over the lifecycle**
- **<u>Truth</u> connotes a validated, verified source with quantified margins and uncertainties, *particularly for epistemic uncertainties***
- **<u>Digital</u> connotes a calibrated emulator that can be used across all engineering functional domains**

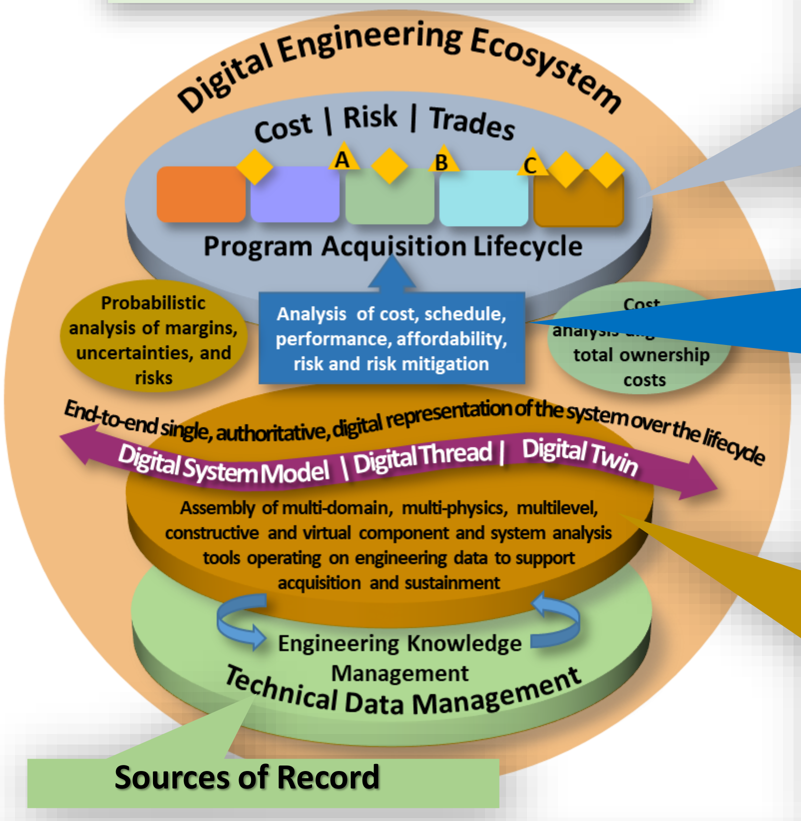
Digital Surrogate Modeling Commons



Requires a Structured, Disciplined Integration of Model-Based Engineering, Testing, and Uncertainty Quantification

Using Truth Models to Support Engineering Activities and Decision Making Across the Lifecycle

Risk – Uncertainty with Consequences

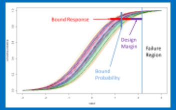


Prescriptive Analytics:
Used to understand what should be done or to recommend the best course of action for any pre-specified outcome

Risk = {Scenario, Probability, Consequence}

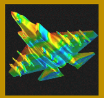
Do

Predictive Analytics:
Probabilistic analysis of system state, used to forecast what might happen or could be accomplished
– quantified margins and uncertainties



Think

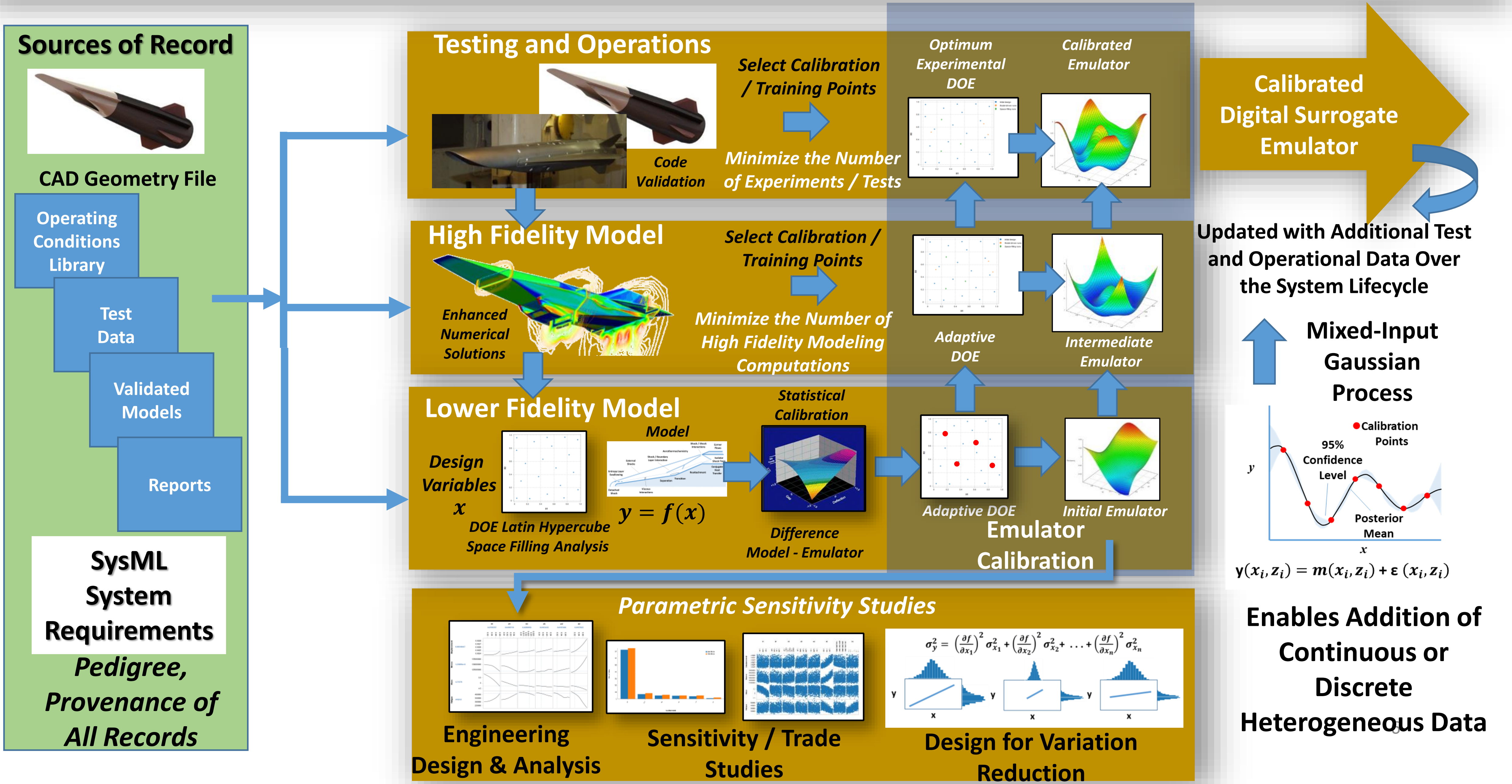
Descriptive Analytics:
Application of Model Based Engineering analysis tools to transform technical data into system state technical information – the authoritative digital surrogate "truth source".



See

UQ – The Connective Tissue Between Analysis and Decisions - The Disruptive Transformation

Develop, Integrate, and Calibrate an *Enduring* Digital Surrogate Truth Source



Paradigm Shift in the Role of T&E in Model Validation and Integration Into the Authoritative Truth Source Emulator

Rethinking Model Validation and Data Uncertainty

- Comparisons with experimental data is insufficient to determine the validity of a model
- Both the model and the experiment contain epistemic and aleatory uncertainties
- Model still in its original format which is not conducive to statistical analysis for decision analytics
- A model can never be completely validated, it can only be invalidated by contrary experimental evidence – to determine if it is invalid <u>for a particular application</u> requires the modeler to quantify margins and uncertainties compared to quantities of interest
- An iterative Bayesian approach to assimilation of the experimental data with model data to form an authoritative digital surrogate is required

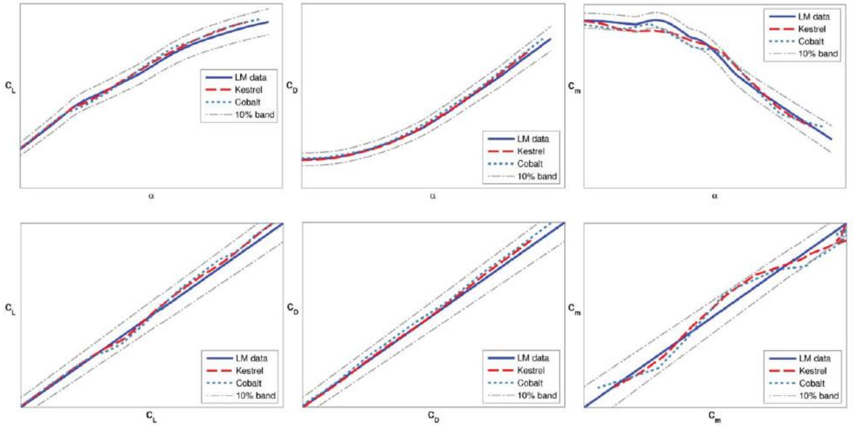
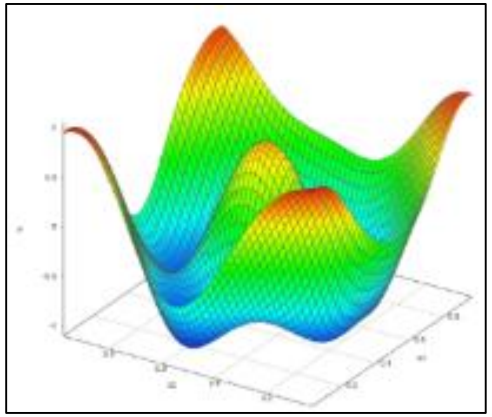


Figure 2. F-16C CFD (*Kestrel* and *Cobalt*, full-scale) with LEF = 0 degrees vs. LM Performance Data with LEF = 0 degrees for C_L, C_D and C_m, Mach 0.9.

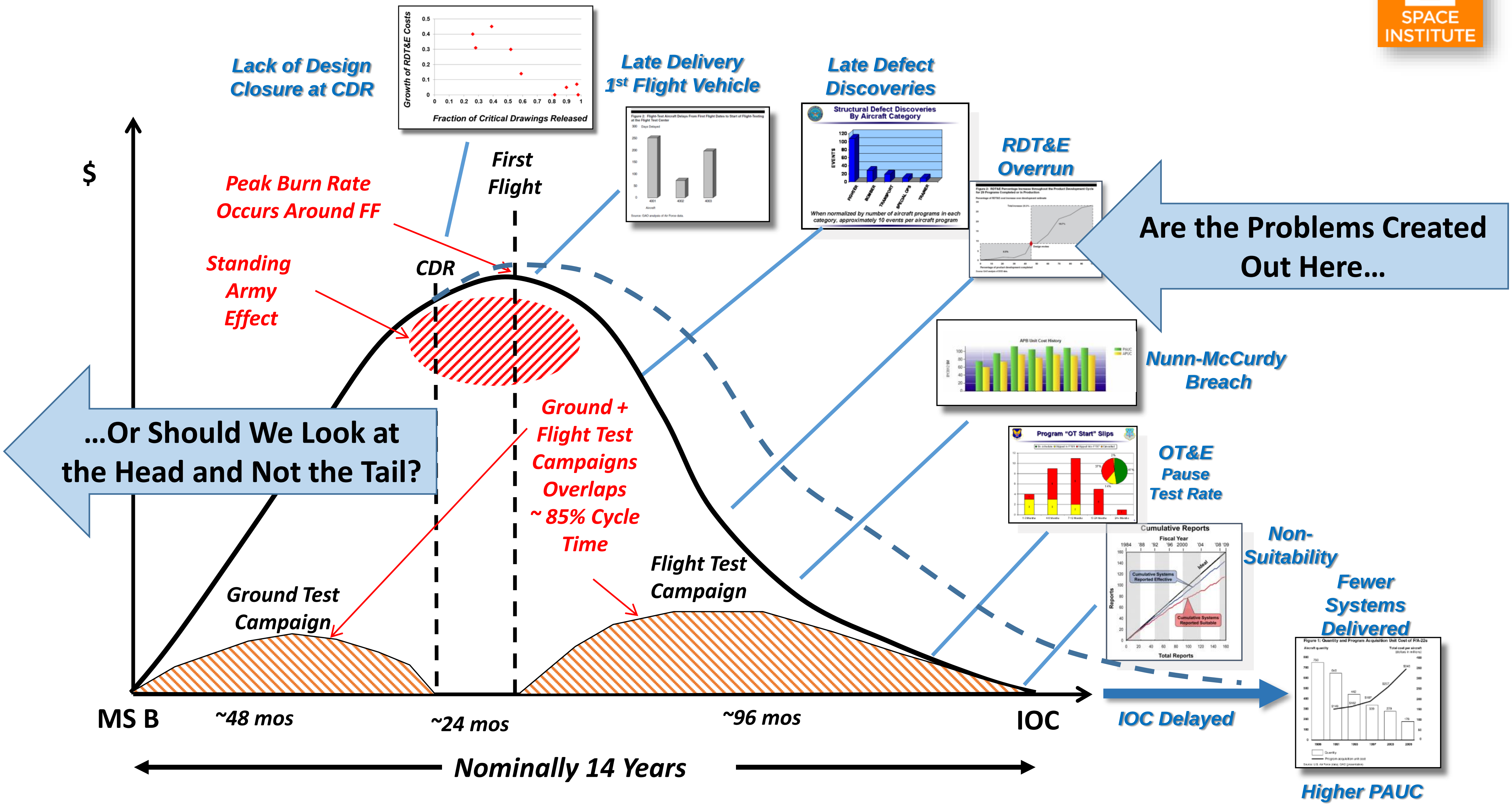
Dean, John P. et al "High Resolution CFD Simulations of Maneuvering Aircraft Using the CREATE-AV/Kestrel Solver" AIAA Paper 2011-1109, 49th Aerospace Sciences Meeting, 4-7 January 2011, Orlando, Florida



Truth Source
A single source of fully merged model and empirical data sets with quantified margins and uncertainties available to all stakeholders

Shifts the value of T&E to the production of knowledge required to provide the validated authoritative truth source to manage uncertainty

Typical DoD RDT&E Profile for an Air Vehicle

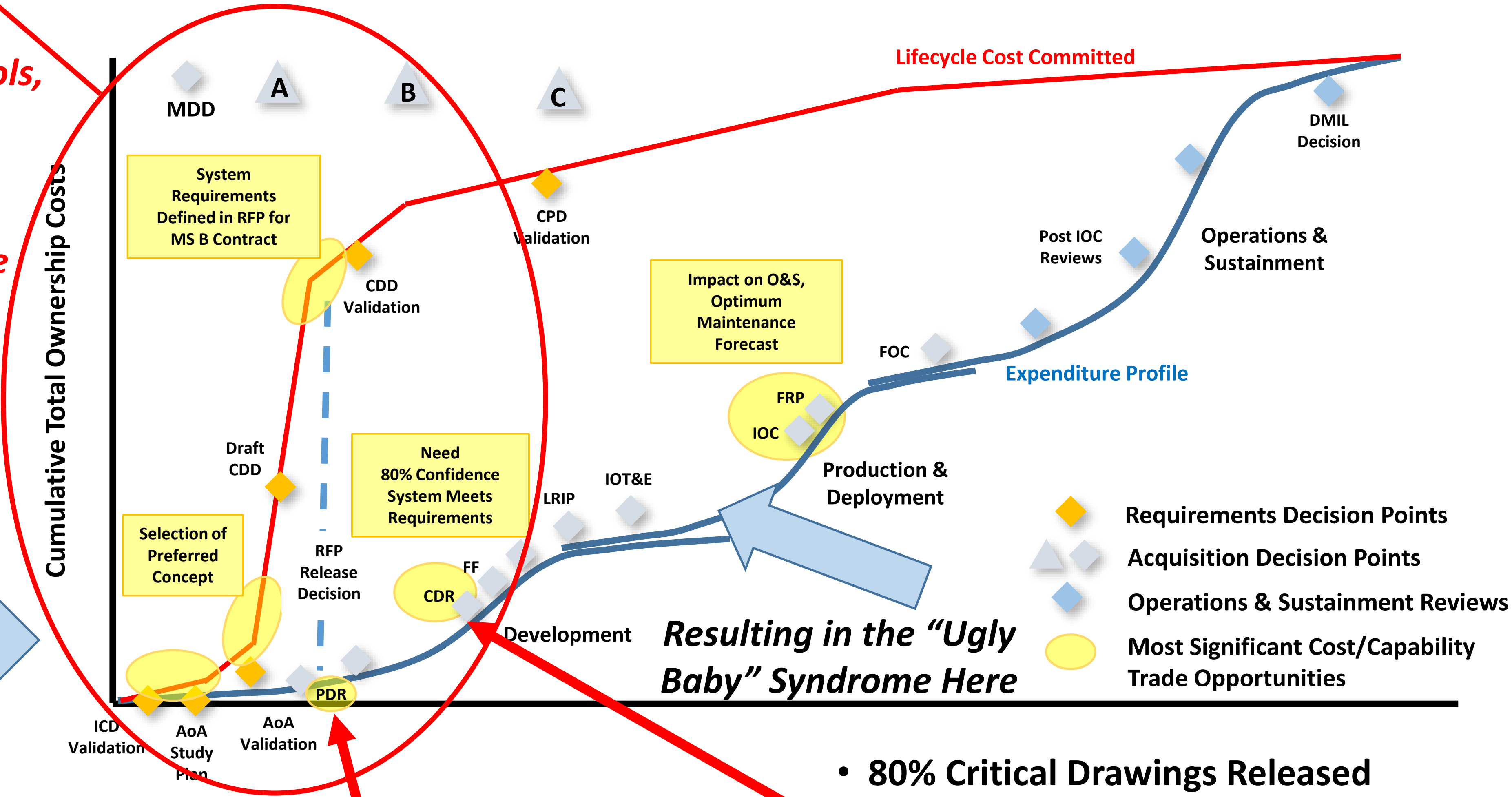


Decision Framework for Defense Systems

Systemic Problem

Organization, tools, processes, and resourcing not conducive to creating requisite knowledge

Critical Factors Impacting Acquisition Occur Back Here



Resulting in the "Ugly Baby" Syndrome Here

- 80% Critical Drawings Released
- TRL ≥ 6 for key technologies
- MRL≥ 6 new mfg technologies
- IRL ≥ 7 to assure system integrability
- *SRL at 80% or better*

Requisite Knowledge

Can We Deploy Digital Engineering Practices to Quantify Better Decisions Earlier?

- 15% Critical Drawings released
- TRL ≥ 4 for key technologies
- MRL≥ 4 new mfg technologies
- IRL ≥ 4 to assure system integrability
- *SRL at 40% or better*

Definitions of Readiness Levels*

- **Technology Readiness Level (TRL)**
  maturity of a particular technology – cannot be higher than the TRL level for the least mature component
- **Manufacturing Readiness Level (MRL)**
  current level of manufacturing maturity, identifies maturity shortfalls and associated risks
- **Integration Readiness Level (IRL)**
  integration readiness of any two TRL-assessed technologies
- **System Readiness Level (SRL)**
  normalized matrix of pair-wise comparisons of TRLs and IRLs of a system

$$[SRL]_{nx1} = [IRL]_{nxn}\ x\ [TRL]_{nx1}$$

LEVEL	TRL Definition	MRL Definition	IRL Definition	SRL Definition	SRL Value
1	Basic principles observed and reported.	Basic manufacturing implications identified.	An interface between technologies has been identified with sufficient detail to allow characterization of the relationship.	Concept Refinement	0.10 to 0.39
2	Technology concept and/or application formulated.	Manufacturing concepts identified.	There is some level of specificity to characterize the interaction between technologies through their interface.		
3	Analytical and experimental critical function and/or characteristic proof of concept.	Manufacturing proof-of-concept developed.	There is compatibility between technologies to orderly and efficiently integrate and interact.		
4	Component and/or breadboard validation in laboratory environment.	Capability to produce the technology in a laboratory environment.	There is sufficient detail in the quality and assurance of the integration between technologies.		
5	Component and/or breadboard validation in relevant environment.	Capability to produce prototype components in a production relevant environment.	There is sufficient control between technologies necessary to establish, manage, and terminate the integration.	Technology Development	0.40 to 0.59
6	System/subsystem model demonstration in relevant environment.	Capability to produce a prototype system or subsystem in a production relevant environment.	The integrating technologies can accept, translate, and structure information for its intended application.		
7	System prototype demonstration in relevant environment.	Capability to produce systems, subsystems, or components in a production representative environment (MRL 7).	The integration of technologies has been verified and validated with sufficient detail to be actionable.	System Development and Demonstration	0.60 to 0.79
		Pilot line capability demonstrated; ready to begin low-rate, initial production (MRL 8).			
8	Actual system completed and qualified through test and demonstration.	Low-rate production demonstrated; capability in place to begin full-rate production (MRL 9).	Actual integration completed and mission qualified through test and demonstration in the system environment.		
9	Actual system proven through successful mission operations.	Full-rate production demonstrated and lean production practices in place (MRL 10).	Integration is mission proven through successful mission operations.	Production	0.80 to 0.89
				Operations and Support	0.90 to 1.00

Joseph A. Fernandez "Contextual Role of TRLs and MRLs in Technology Management" SANDIA REPORT SAND2010-7595, November 2010

Systems Engineering Paradigm Shift

NASA Systems Engineering Process

	Phase	Purpose	Typical Outcomes
Pre-Formulation	**Pre-Phase A** Concept Studies	To produce a broad spectrum of ideas and alternatives for missions from which new programs/projects can be selected. Determine feasibility of desired system, develop mission concepts, draft system-level requirements, assess performance, cost, and schedule feasibility; identify potential technology needs, and scope.	Feasible system concepts in the form of simulations, analysis, study reports, models, and mock-ups
Formulation	**Phase A** Concept and Technology Development	To determine the feasibility and desirability of a suggested new system and establish an initial baseline compatibility with NASA's strategic plans. Develop final mission concept, system-level requirements, needed system technology developments, and program/project technical management plans.	System concept definition in the form of simulations, analysis, engineering models and mock-ups, and trade study definition
	Phase B Preliminary Design and Technology Completion	To define the project in enough detail to establish an initial baseline capable of meeting mission needs. Develop system structure end product (and enabling product) requirements and generate a preliminary design for each system structure end product.	End products in the form of mock-ups, trade study results, specification and interface documents, and prototypes
Implementation	**Phase C** Final Design and Fabrication	To complete the detailed design of the system (and its associated subsystems, including its operations systems), fabricate hardware, and code software. Generate final designs for each system structure end product.	End product detailed designs, end product component fabrication, and software development
	Phase D System Assembly, Integration and Test, Launch	To assemble and integrate the system (hardware, software, and humans), meanwhile developing confidence that it is able to meet the system requirements. Launch and prepare for operations. Perform system end product implementation, assembly, integration and test, and transition to use.	Operations-ready system end product with supporting related enabling products
	Phase E Operations and Sustainment	To conduct the mission and meet the initially identified need and maintain support for that need. Implement the mission operations plan.	Desired system
	Phase F Closeout	To implement the systems decommissioning/disposal plan developed in Phase E and perform analyses of the returned data and any returned samples.	Product closeout

Design

Build

Test

Fix

First time "Integrate" appears in purpose

Digital Engineering Paradigm

Integrate **– develop and apply digital surrogate truth source models at the component, subsystem, system level; validate surrogate models with higher fidelity models and empirical data; deploy subsystem surrogate models in an MDO analysis; perform trade and cost studies at the integrated system level**

Analyze **– define subsystem and system level sensitivity to design variables; address uncertainty propagation across subsystems and impact on total system performance and costs; perform a probabilistic analysis to quantify margins and uncertainties on system meeting performance reqts.**

Design **– deploy design for variance reduction strategy for most sensitive design variables using updated digital surrogates; use mfg and sustainment digital surrogate models to design for manufacturing and sustainment**

Build **– use surrogate truth source models to account for variations in mfg and assembly tolerances, precursor to the development of a digital twin.**

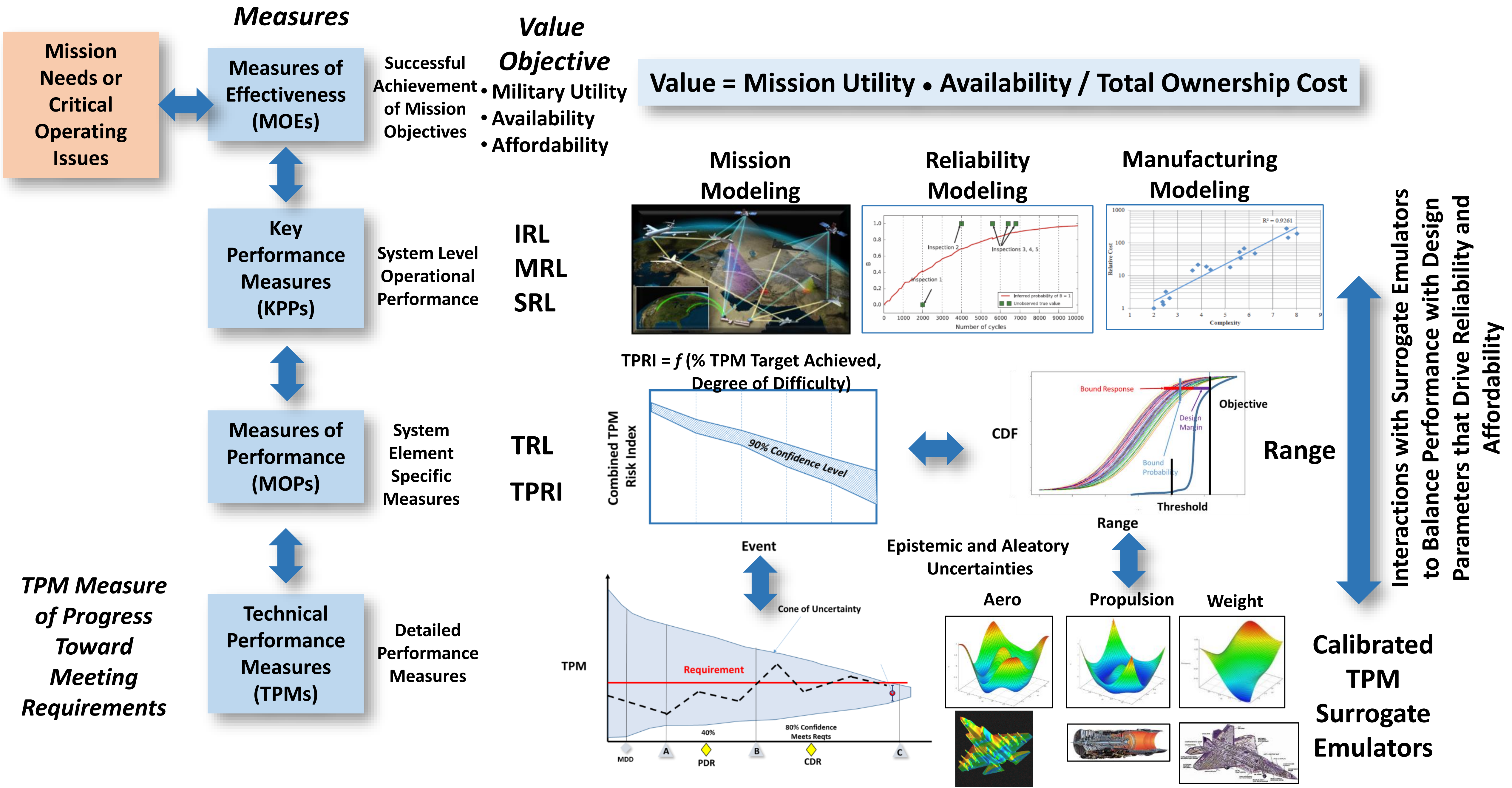
Test **–optimize tests to provide required knowledge to validate digital surrogate truth sources; use test to monitor and mitigate uncertainties in key technical performance parameters as a measure of progress toward requirements**

Operate **– deploy a digital twin to monitor health, gain more knowledge about system performance, project optimum sustainment, and/or provide a reference model for adaptive control**

Learn ***– Accumulate knowledge and implement into digital surrogate models to improve the next system's performance***

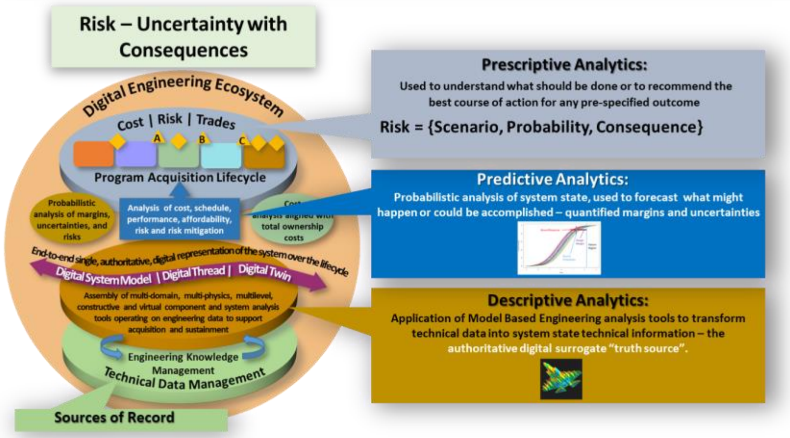
Not in lieu of current SE processes but as an enhancement

Quantifying and Managing Key Measures at Critical Decision Points



Decision Analytics – Moving to Digital Critical Decision Points

All Stakeholders have a continuous digital view of progress toward meeting requirements, potential impacts on the program; *can iterate emulator sensitivities to assess "what if" for different outcomes*



Near real-time discovery of notable states or state changes allowing program actions before a staged critical decision event can take place.

Do

- Quantify risks in achieving Mission Objectives
- Apply Bayesian Belief Network to evaluate potential scenarios to quantify probabilities of outcome and consequences
- Identify the Best Value option

Courses of Action

COA	Scenario	Performance Risk	LCC Cost Risk	Schedule Risk	Δ Military Utility	Value
#1	A					
#2	B					
#3 ✓	C					
#4	D					

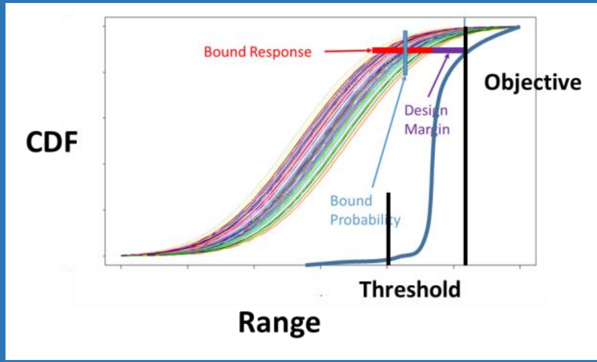
$$Value = \frac{Utility \times Availability}{Total\ Ownership\ Cost}$$

Risk Mgt

- Acceptance
- Avoidance
- Mitigation
- Transfer

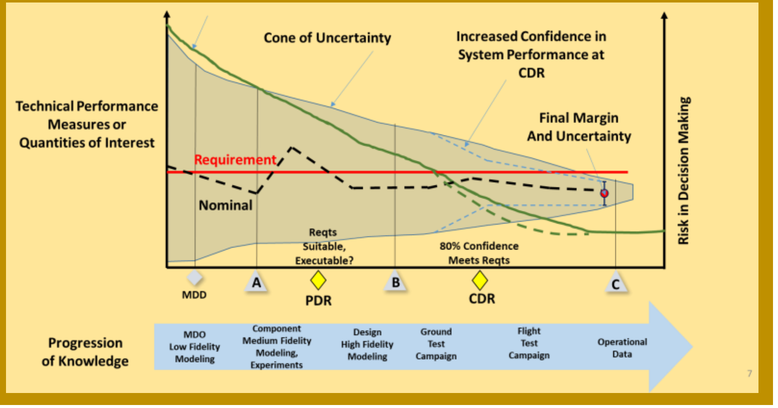
Think

- Perform a probabilistic analysis to quantify margins and uncertainties for vital performance measures
- Assess the impact of margins and uncertainties on achieving military utility and affordability



See

- Assess the state of the system comparing calibrated Truth Source Models with required TPMs /QOIs
- Quantify TRL, MRL, IRL, SRL
- Optimize next steps to reduce uncertainties through additional modeling, testing, or identify necessity to redesign



Summary

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The Digital Engineering strategy will enable a significant paradigm shift in Systems Engineering and T&E toward

- **Early integrated analysis of a system using authoritative digital surrogates – better knowledge earlier**
- **Methodology for designing / executing tests to develop, calibrate, and curate the authoritative truth source emulators**
- **Adopting uncertainty quantification and risk mitigation for key Technical Performance Measures as the value proposition for T&E**
- **Enabling better informed Digital Critical Decisions by quantifying system performance, risk, and analyzing best courses of action**

SE, MBE and T&E with UQ Provides Value to Digital Engineering as a Source of Knowledge for Risk Identification and Management