New Digital Engineering Enabled Systems and Mission Engineering Performance Measures

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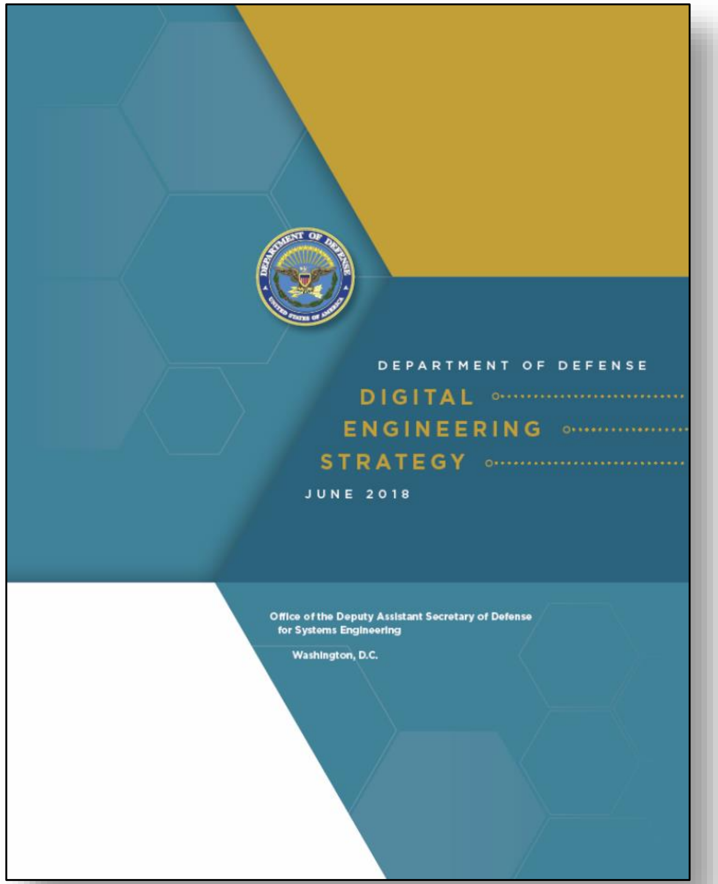
Introduction

- **Traditional Systems Engineering measures (TRL, IRL, SRL, MRL) are adequate for prescribing systems engineering stages, configuration management, and interface control documentation but do not provide esential knowledge to support quantified Risk Informed Decision Analytics (RIDA).**
- **Any technology or design feature introduced into a component, subsystem, system, or system of systems should have *measurable technical performance* which impacts the Value of the system.**
- **Digital Engineering enabled development, calibration, and use of model-based engineering and authoritative truth sources provides a formal, structured approach to quantifying and tracing maturation of technical performance measures (TPMs) and their impact on support to RIDA and Value creation.**

The Revolutionary Idea Separating the Future from the Past is the Collaborative use of Knowledge to Master Risk at the Speed of Need

DoD Digital Engineering Strategic Guidance (June 2018)

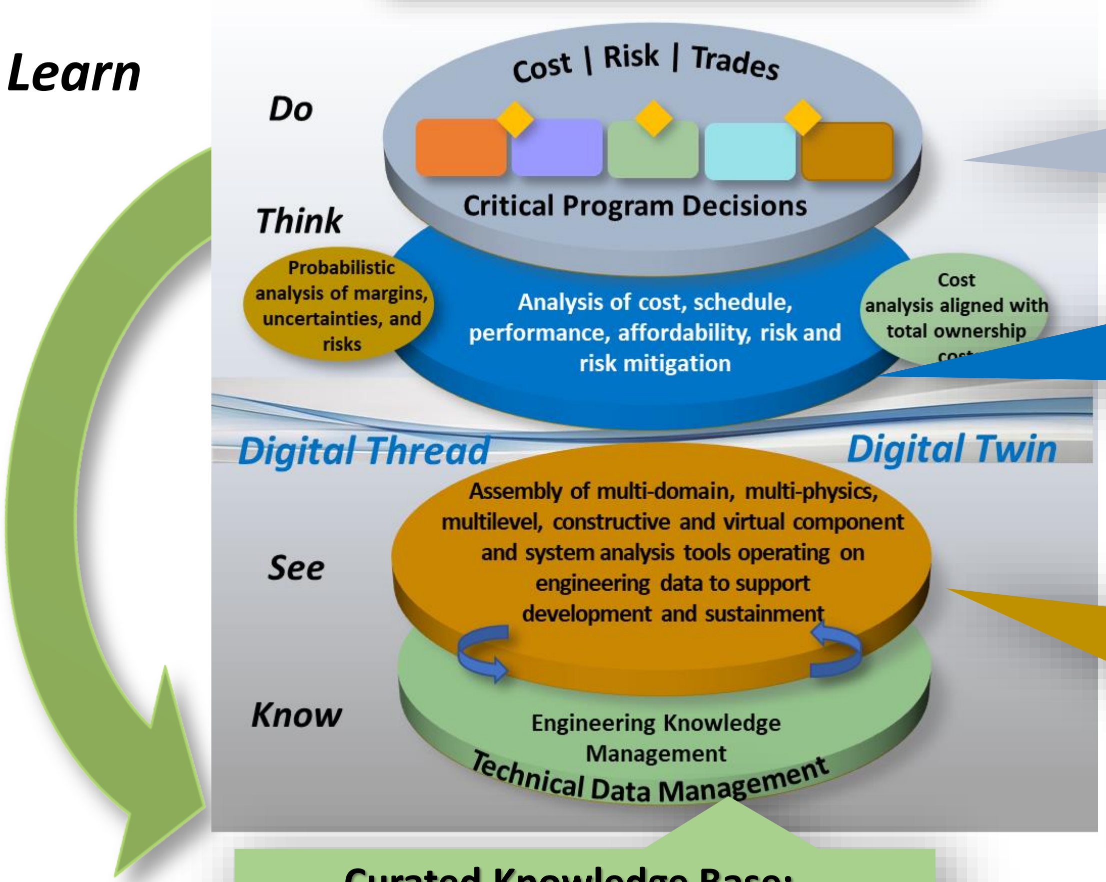
1. Formalize the development, integration, and *use of models to inform enterprise and program decision making*
2. Provide an *enduring, authoritative source of truth*
3. Incorporate technological innovation to *improve the engineering practice*
4. *Establish a supporting infrastructure* and environment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



DoD defines Digital Engineering as an integrated digital approach that uses authoritative sources of system data and models as a continuum across disciplines to support lifecycle activities from concept through disposal

Risk Informed Decision Analytics in a Digital Engineering Ecosystem

Risk – Uncertainty with Consequences



Curated Knowledge Base:

- **Configuration Management**
- **Pedigree**
- **Provenance**

Prescriptive Analytics:
Use probabilistic inference to recommend the best course of action to *master risk and maximize Value*

Predictive Analytics:
Probabilistic analysis of system state, used to forecast what might happen or could be accomplished – rigorous approach to *credible* quantified margins and uncertainties (QMU)

Descriptive Analytics:
Rigorous, disciplined approach to the development, calibration, and application of authoritative digital surrogate models

UQ is the Connective Tissue Between Analysis and Decisions

Value Mapping in a Digital Engineering Environment
The Centerpiece of Lifecycle Decision Analytics

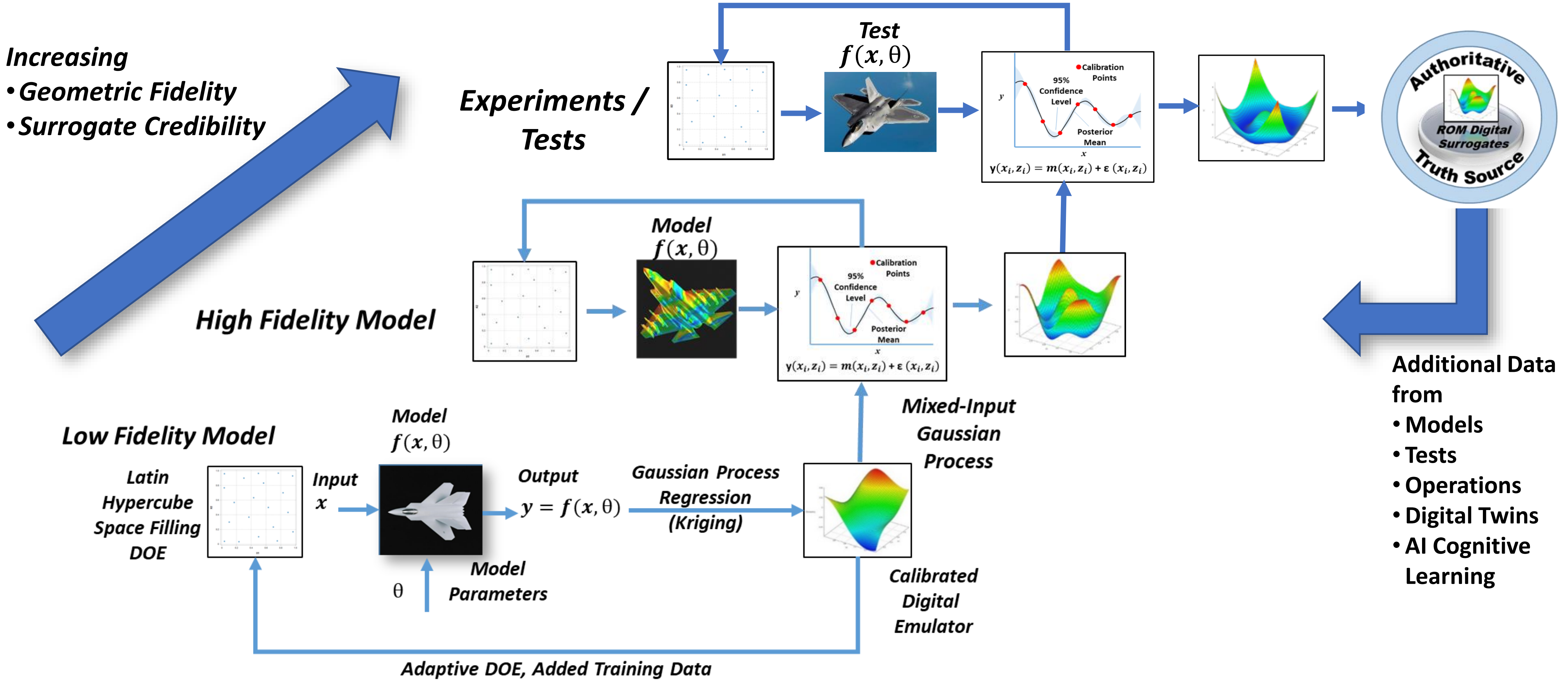
Value Objective = Mission Utility • Robustness / Total Ownership Cost

- ***Mission (or Military) Utility*** **-** ***set*** **of required technical attributes of the system that provides a distinct advantage over competitors in the marketplace**

- ***Robustness*** **- normalized measures of how well the system performs over time (Reliability, Availability, Maintainability), in unanticipated circumstances, and in alternate uses (Resiliency)**

- ***Total Ownership Costs*** **- lifecycle cost of development, production, fielding, operations, sustainment, and demilitarization**

Strategy 1 – Use of Models to Support Decisions
Developing an Authoritative Digital Surrogate Reduced Order Model



Edward M. Kraft, “Development and Application of a Digital Thread / Digital Twin Aerodynamic Performance Authoritative Truth Source,” AIAA-2018-4003. Aviation Systems Conference, Atlanta, GA, June 25-29, 2018

Strategy 2 - The Essence of Digital Engineering
Enduring, Authoritative Truth Sources and Digital Surrogates

- Shifts primary means of communication from documents to digital models and data
- Provides the technical elements for creating, updating, retrieving, and integrating models and data
- Enables access, management, analysis, use, and distribution of information from a common set of models and data
- Provides authorized stakeholders current, authoritative, and consistent information for use over the lifecycle
- Essential for making decisions under risk across the lifecycle

Measures of the Maturity and *Credibility* of Authoritative Truth Sources Will Enable a More Knowledge-Based Informative Understanding of the Risks of Achieving the Value Objective

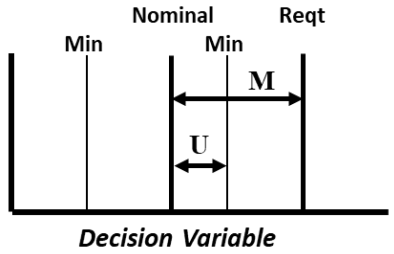
Quantified Margins and Uncertainty (QMU)
Key to Mastering Risks

QMU is a technical framework for producing, combining, and communicating information about performance margins of complex systems to support risk-informed decision making

QMU Requires:

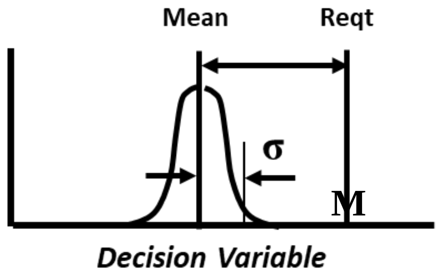
- **Performance Threshold –**a specification of a necessary performance achievement, typically in quantitative form.
- **Performance Margin -** difference between the required performance of a system and the demonstrated performance of a system
- **Uncertainty -** begins with the requirements that provide a foundation for the definition of performance thresholds, accumulates and transforms as the various science and engineering activities that lead from design to qualification to evaluation are executed.
- **Credibility** – ***requires a consistent, disciplined approach to the validation and calibration of models used to develop the probability and cumulative distribution functions***

Epistemic Uncertainty

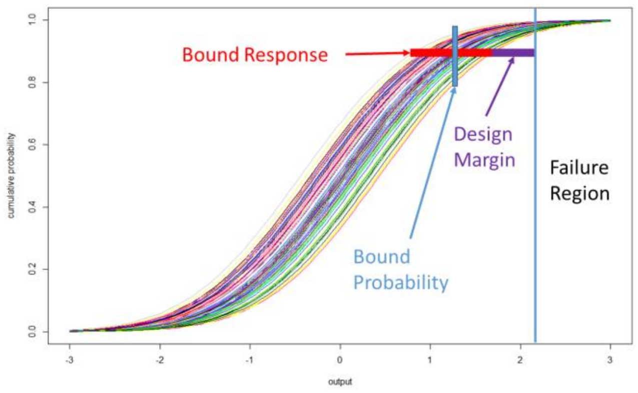


Confidence Factor $= \frac{M}{U}$

Aleatory Uncertainty



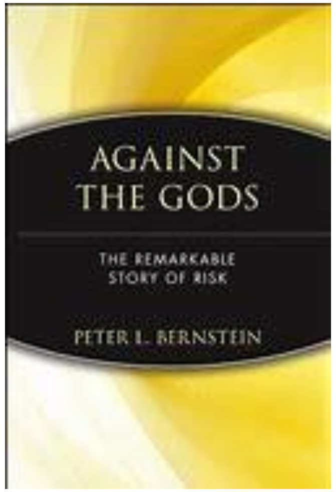
Reliability Factor $\beta = \frac{M}{\sigma}$



If M/U > 1 for all components, subsystems, and systems have high confidence system will be reliable

Mastering Risk

- Mastering risk using digital engineering principles may be the single most important aspect that separates the future of systems engineering from the past
- Using statistical methods to determine probabilities of the state of a system is a quantification of incomplete information or uncertainty at a time instant
- A current measure of uncertainty should not be conceived in terms of disorder, but rather as a measure of the probability distribution that characterizes the amount of missing information
- Employing authoritative digital surrogate models with uncertainty quantification methods can project the best means to obtain the missing information to achieve an acceptable level of uncertainty and maximize Value – the mastery of risk



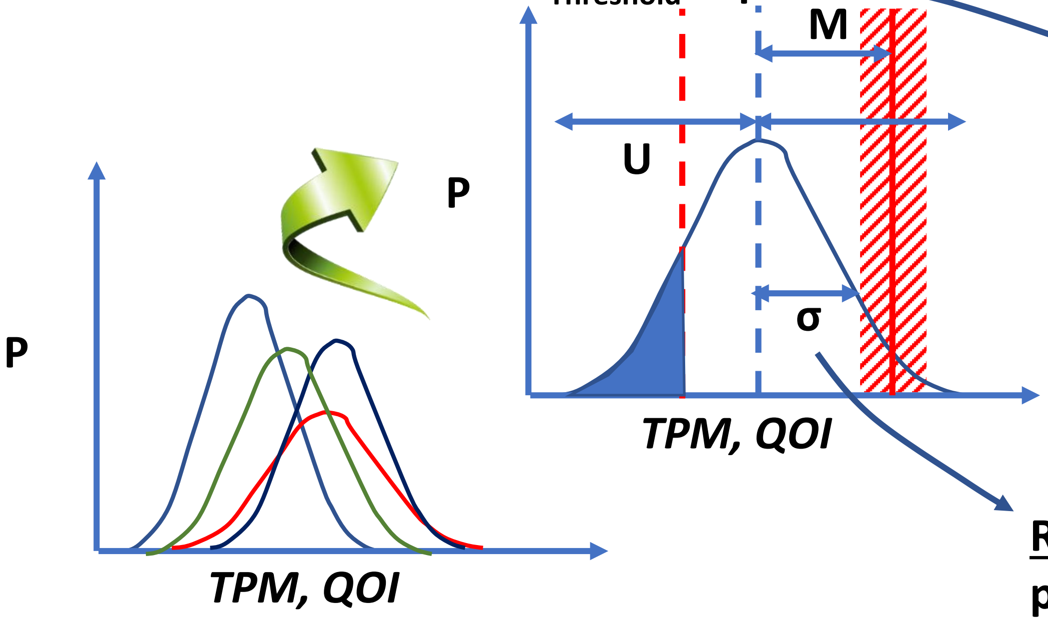
"The revolutionary idea that defines the boundary between modern times and the past is the mastery of risk: the notion that the future is more than a whim of the gods and that men and women are not passive before nature."

Peter Bernstein, "Against the Gods: The remarkable story of risk"

Discovery of defects or insufficient performance that negatively impact a program late in the lifecycle is not bad luck – it is a failure to properly quantify and master the risks associated with each decision along the way

QMU, System Robustness / Reliability, and Decision Analytics

Requirement → Mission Utility → Value Objective

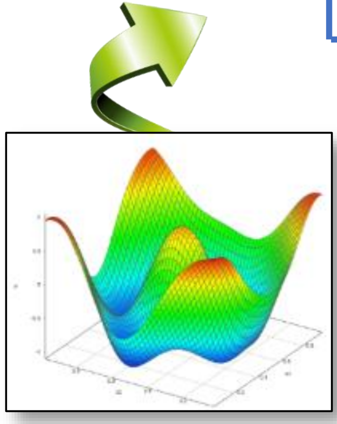


Reliability – probability of success in meeting a performance criterion

→ Shift the mean, μ, closer to the requirement typically by redesign

Robustness – property of a system that enables it to survive unusual circumstances

→ Reduce the variance, σ, by additional modeling and experimentation with a focus on reducing uncertainties, particularly epistemic uncertainties

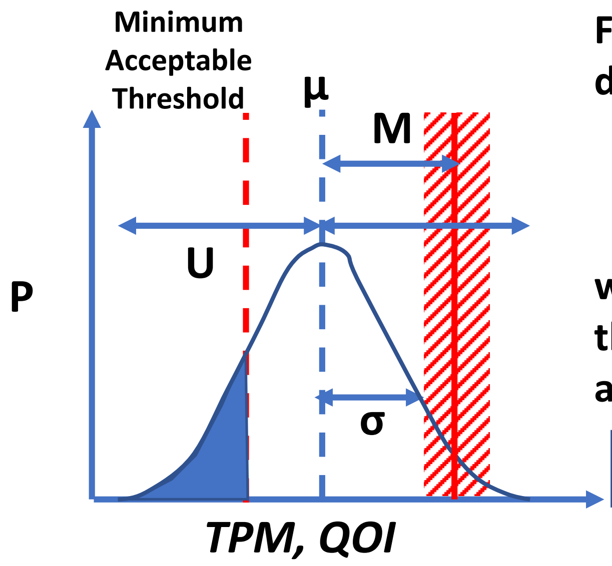


Calibrated Digital Surrogate

TPM – Technical Performance Measure
QOI – Quantity of Interest

See ***Think*** ***Do***

Prescriptive Analytics - Risk Informed Decision Analytics to Master Risk

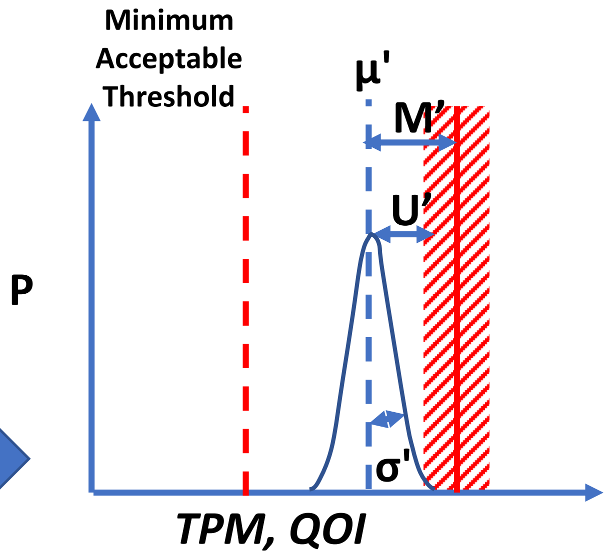


For a TPM/QOI related variable *Y* with a probability density function *p(y), Shannon's* information entropy is

$$H(Y) = -\sum_i p(y_i) \log p(y_i)$$

which is the average amount of information contained in the random variable Y, it is also the uncertainty removed after the actual outcome of Y is revealed

Digital Surrogate Model Projection of QMU'



Sensitivity Analysis

MC or Sobol Methods to determine which input parameters influence the mean and variance the most

Entropy Based Inference

- Kullback-Lieber Divergence or relative entropy
- Bayesian Inference
- Maximum Entropy

Resource Allocation

- Budget / Schedule Constraints
- Stakeholder Preference
- Impact on Value Objective

Directly relates current measures of uncertainty to determining an activity that produces a new probable state that will move the system closer to meeting the Value Objective

Digital Thread – Connected Available Knowledge for Decisions

Digital Thread at Any Time Increment, t

$$D_t \in I_t \subseteq P_t \times T_t \times \mathcal{D}_t$$

Design information

- *Geometries, Materials, Design, Manufacturing, Testing and Operating Specifications; 3-D CAD, eBOM, Critical Drawings; Digital Surrogate Models*

Tools, methods, and processes

- *Information and protocols of methods, tools, processes, and algorithms*

Statistics of uncertain inputs

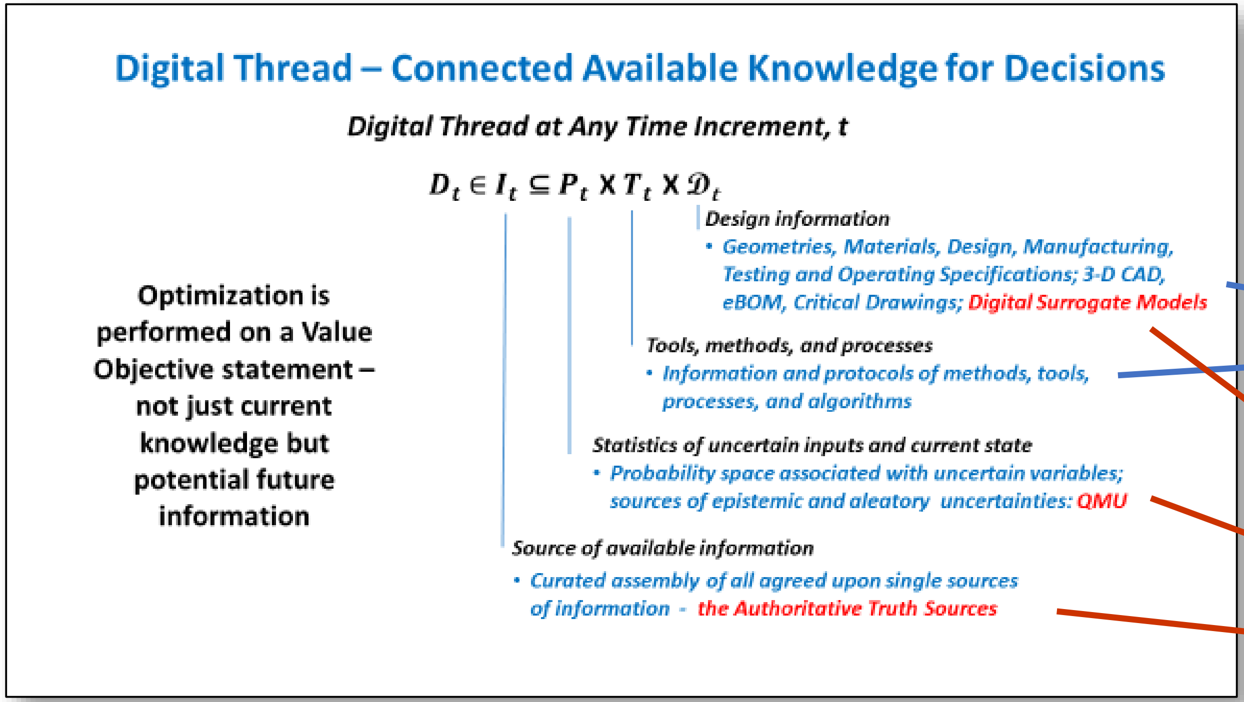
- *Probability space associated with uncertain variables; sources of epistemic and aleatory uncertainties: QMU*

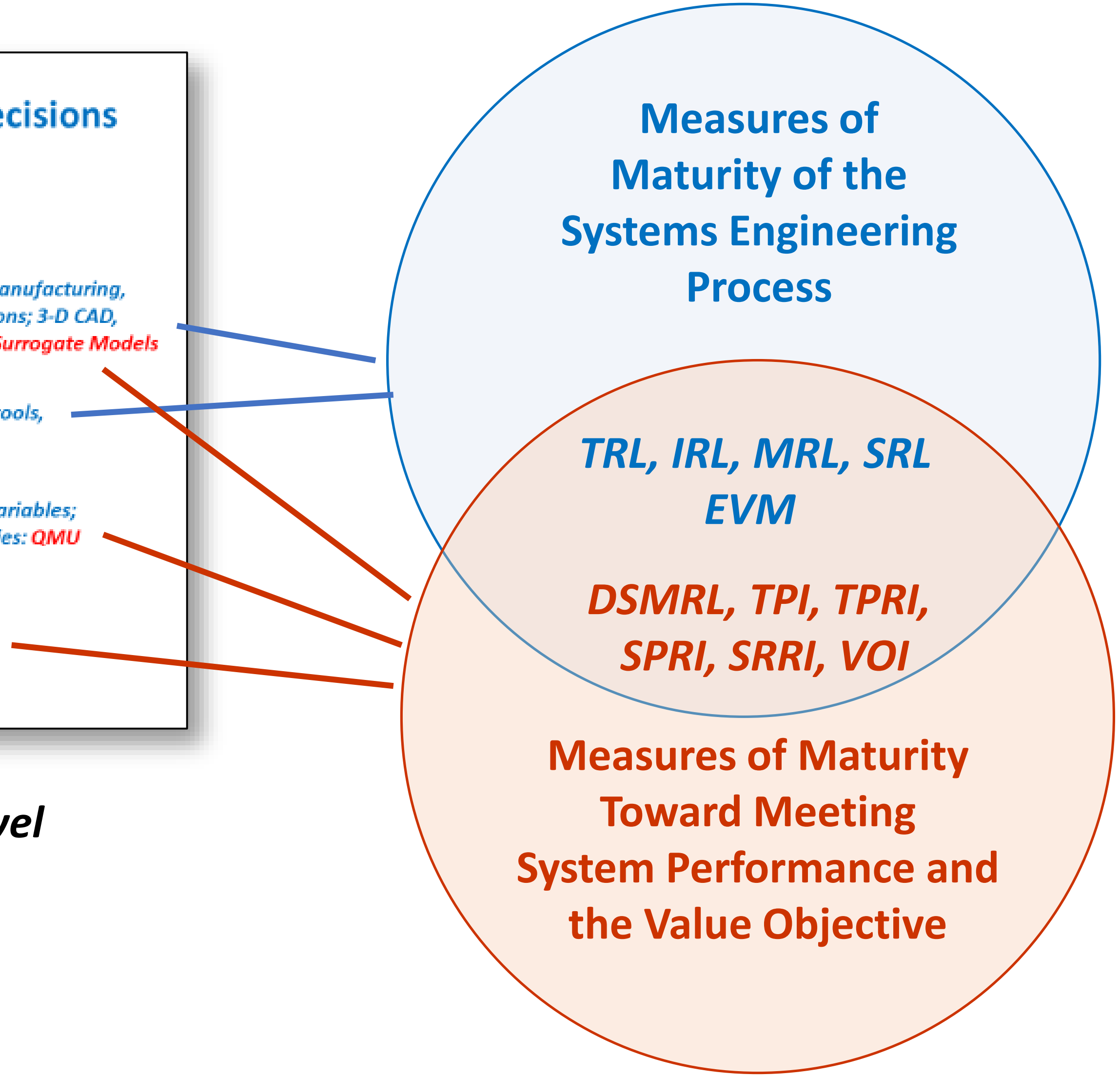
Source of available information

- *Curated assembly of all agreed upon single sources of information - the Authoritative Truth Sources*

Optimization is performed on a Value Objective statement – not just current knowledge but potential future information

Strategy 3 - Rethinking Systems Engineering Maturity/Readiness Levels





A New Set of Measures

DSMRL – Digital Surrogate Model Readiness Level
TPI – Technology Performance Index
TPRI - Technology Performance Risk Index
SPRI – System Performance Risk Index
SRRI - System Readiness Risk Index
VOI – Value Objective Impact

Digital Surrogate Model Readiness Level (DSMRL) for Performance Models

- Introduce a readiness level associated with the very essence of Digital Engineering – the Authoritative Truth Source
- A Digital Surrogate Model Truth Source enables Quantification of Margins and Uncertainties (QMU) of performance at the component, assembly, subsystem, system, and mission level
- Applications of calibrated Digital Surrogate Performance Models will enable a quantification of performance levels and provide knowledge for decision analytics to determine the best course of action to meet Stakeholder expectations

DSMRL Provides a Consistent, Disciplined Approach to Assuring the Credibility of Surrogate Models Used for QMU Analyses

DSMRL	Maturity of MBE Derived Digital Surrogate Performance Models
1	Un-validated, deterministic models of basic physical principles, no geometry details
2	Validated models using generic legacy data for class of problems, notional geometries; material / component level reduced order models (RSM)
3	Low-fidelity, model-generated, calibrated RSM digital surrogates using set-based inputs, parametric sensitivity studies, design for variations; initial UQ sensitivity analysis; initial program model-based performance truth source curation
4	Recalibrated RSM using high-fidelity models and/or laboratory data for system of interest parameters; closer to final component, subsystem geometry; identification of epistemic- (EU) and aleatory- (AU) uncertainties
5	Recalibrated RSM using empirical data generated from component / breadboard tests in a relevant environment; EU/AU uncertainties propagated
6	Recalibrated RSM using developmental test data from system/subsystem prototype or in a relevant environment; as-prototyped geometry; EU/AU accounted for
7	Recalibrated RSM using data from operational testing; as-built, as-flown geometry; comprehensive set of managed RSM models from material/component to system
8	Recalibrated RSM using data from operations; as-built, as-operated geometry; lifecycle curation of comprehensive digital surrogates in a PLM system
9	Recalibrated RSM using data from a digital twin and artificial intelligence gathered from an as-built, as-operated, as-optimized system

TPM, a Technology Performance Index (TPI), and a Technology Performance Risk Index (TPRI)

- **At each stage in the technology maturation process should be able to provide a quantified assessment of the impact of a technology on specific TPM measures, the uncertainty in the technology performance, and the related influence on System and Mission performance – will the technology provide the required impact on Mission Utility?**

- **A Technology Performance Index (TPI) for each Technology is the measure of the achieved performance of a Technology or design feature at time *i* as the percentage of the threshold TPM for component *j* relative to its measured performance, m_{ij}, or**

$$TPI_{ij} = \min \left\{ \frac{m_{ij}}{TPM\ threshold}, 1 \right\}$$

- **A Technology Performance Risk Index (TPRI) * to link technical performance risk measures to the readiness of a technology to be transitioned into a system can be defined as**

$$TPRI = 1 - \frac{TPI}{1 + (1 - TPI) * DD}$$

and *DD* is the Degree of Difficulty

*Sherica S. Holloman, Steven M. Stuban, and Jason Dever "Validating the Use of Performance Risk Indices for System-Level Risk and Maturity Assessment" *Engineering Management Journal* , Vol 28, No. 2, 2016.

Degree of Difficulty – an Additional Risk Assessment

- **Enables an assessment of the challenges to maturing a technology to desirable levels at pending critical decision points**
- **The challenges include technical and non-technical factors that at a minimum could impact the cost and schedule of the program to achieve the required technology maturity or even include the possibility the technology required for full system implementation cannot be achieved**
- **Some non-technology factors could included changing budgets, non-availability of material or critical development facilities, skill capacity, and the difficulty in obtaining appropriate certifications**

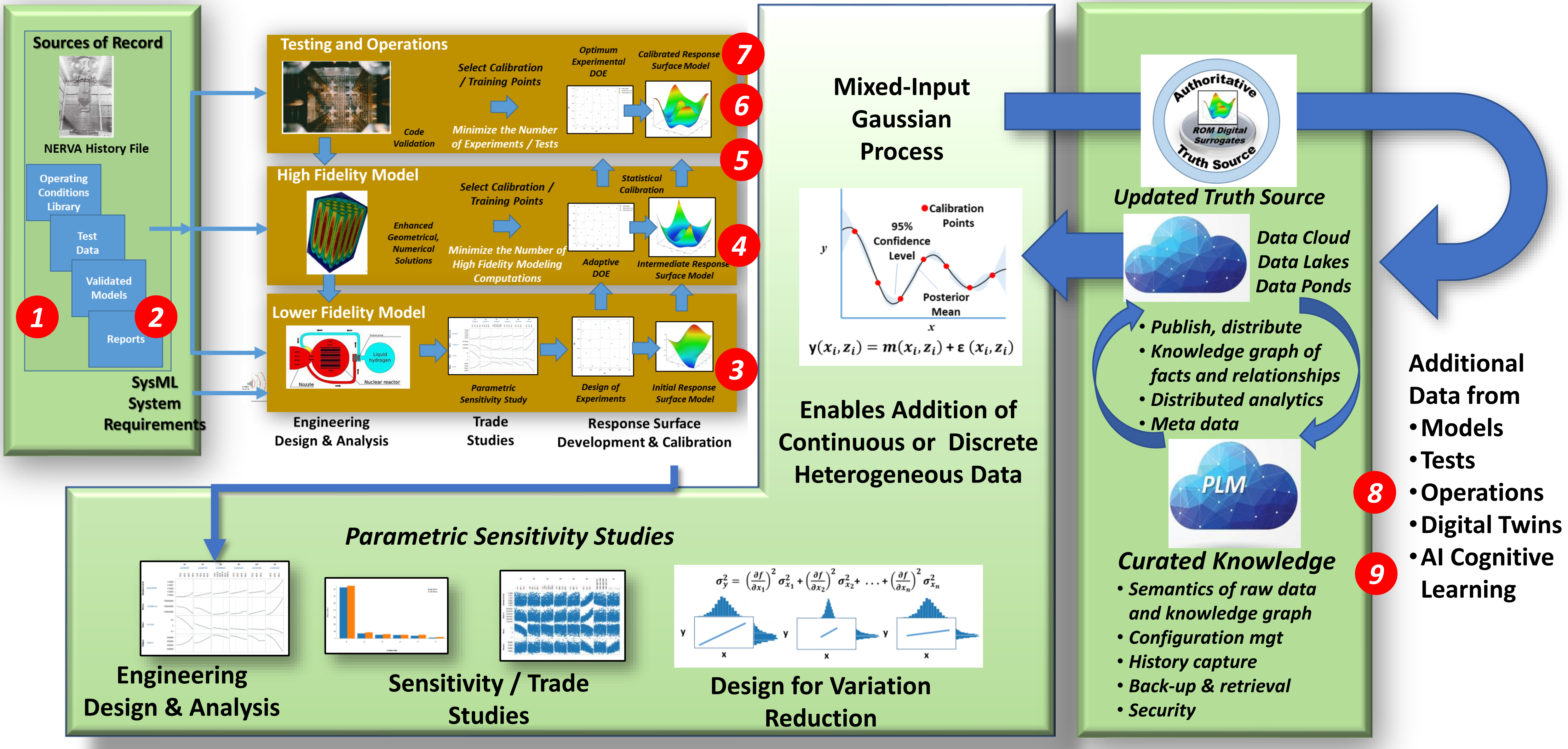
Degree of Difficulty*

0	No Risk
0.1	Very Low Risk
0.3	Moderate
0.5	High
0.7	Very High
0.9	Extremely High Risk
1.0	Guaranteed Failure

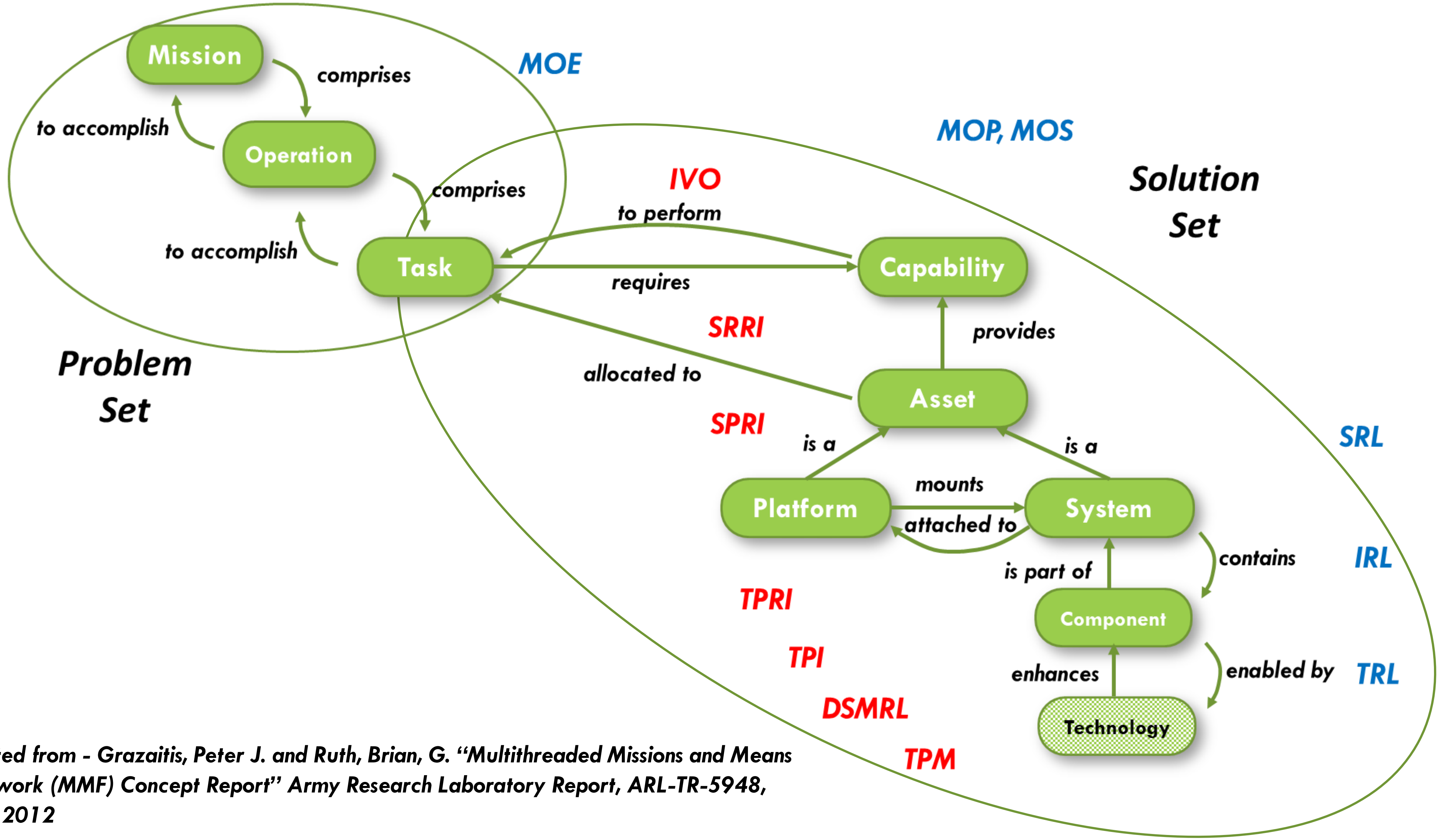
*Sherica S. Holloman, Steven M. Stuban, and Jason Dever "Validating the Use of Performance Risk Indices for System-Level Risk and Maturity Assessment" *Engineering Management Journal* , Vol 28, No. 2, 2016.

Development and Lifecycle Management of Digital Surrogate Models

 # Digital Surrogate Model Readiness Level (DSMRL)



Connecting Digital Engineering to Mission Engineering
Enhanced Mission Means Framework (MMF) Metrics



Adapted from - Grazaitis, Peter J. and Ruth, Brian, G. "Multithreaded Missions and Means Framework (MMF) Concept Report" Army Research Laboratory Report, ARL-TR-5948, March 2012

Summary

- A systematic translation of the DoD Digital Engineering Strategy into value added processes is outlined requiring
  - Well defined Value Objective to frame decision analytics
  - Early and persistent integrated analyses of a system using calibrated authoritative digital surrogates
  - Implementation of new performance-based measures enables processes for mastering risks
  - Optimizing SE processes and T&E campaigns to identify and mitigate uncertainty in Technical Performance Measures and Quantities of Interest
- Comprehensive Uncertainty Quantification is essential to the paradigm shift

SE, MBE and T&E with UQ Provides Value through Digital Engineering by Providing Knowledge for Risk Management and Better Decision Making

Questions?

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