Tutorial: Emerging Issues in Application of Model-Based Systems Engineering (MBSE)

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Abstract: This tutorial is concerned with emerging issues in applying Model-Based Systems Engineering (MBSE), in two categories, and is divided into two half-day sessions:

- **Part I (Morning):** Planning and Assessing Your Path to Value from MBSE--
  - In its earliest years, MBSE enthusiasm has been focused on technical model content and methodology, tools, languages, and standards. As MBSE reaches for mainstream use, larger groups of non-technical stakeholders are involved, and larger questions of strategy and paths forward for propagation appear. This tutorial session will address key developments emerging from efforts toward standardization and transformation, being pursued in two professional societies in particular (ASME and INCOSE). In Part I, attendees will learn how to apply the planning framework, and take a copy home to use. Attendees will also learn about introducing re-usable MBSE Patterns into work processes, and learn how to get started addressing model credibility issues.

- **Part II (Afternoon):** Applying MBSE Patterns for Increased Leverage: Examples from Smart Manufacturing and the Internet of Things (IoT)--
  - Models are interesting to construct, and modelers are enthusiastic to do so. However, the business case for originating a “clean sheet” model for each project grows weaker as systems become more complex, as more is at stake, and as the demands for model content and credibility grow. This tutorial session will address the use of MBSE Patterns—formal models that are configurable and re-usable for different projects—as pursued in recent years by the INCOSE MBSE Patterns Working Group. In Part II, attendees will learn about the Embedded Intelligence Pattern and the Smart Manufacturing Pattern. Attendees will also learn about the strategy of financial capitalization of MBSE Patterns.
Introduction of Tutorial Participants

Thanks to Harry Potter.

11th Annual INCOSE Great Lakes Regional Conference

SUPERIOR SYSTEM SOLUTIONS FOR TODAY’S COMPLEX ENVIRONMENTS

11 - 14 October 2017 Twin Cities, Minnesota
Part I (Morning):

- **Targeting Purpose**: Planning development, use, and life cycle of models based on a standard model planning framework, neutral as to modeling tools, languages, methods.
- **Institutionalizing Learning**: Practical steps to improve on organizational learning, using models as a focus of organizational learning and knowledge, based on model-based Learning Systems and Autonomous Systems.

Part II (Afternoon):

- **Representing Intelligence**: The Embedded Intelligence (EI) Pattern, for any embedding of intelligence, in the form of automation, human operators, or other systems of management, feedback, regulation.
- **Advancing Production**: The Smart Manufacturing Pattern, for the IoT Age, for any manufacturing process, and with varied forms of instrumentation and management.
- **Capitalizing IP** of MBSE Patterns as Financial Assets, to shift the burden of model cost to the time of model use and benefit.
Enthusiasm for Models

The INCOSE systems community has shown growing enthusiasm for “engineering with models” of all sorts:

- Historical tradition of math-physics engineering models
- A World in Motion: INCOSE Vision 2025
- Growth of the INCOSE IW MBSE Workshop
- Growth in systems engineers in modeling classes
- INCOSE Board of Directors’ objective to accelerate transformation of SE to a model-based discipline
- Joint INCOSE activities with NAFEMS

Potentially for any ISO 15288 processes:

- If there is a net benefit . . .
- Some more obvious than others.
- The INCOSE MB Transformation is using ISO 15288 framework as an aid to migration planning and assessment.
Many potential purposes for models
Model-based methods have multiple connections to ISO15288 system life cycle management practices:

- The INCOSE Model-Based Transformation project provides means for assessing and planning the migration of ISO15288 practices to model-based approaches.
- The INCOSE Agile SE Life Cycle Management Discovery Project provides inputs to a future version of ISO15288 including agile SE, and includes the model-based ASELCM Pattern and its representation of the roles of models in innovation.
- The INCOSE MBSE Patterns Working Group supports improving the leverage of model-based practices using formal S*Patterns, and is partnering with ASME toward standards for the verification and validation of computational models for ISO15288 purposes.
- This tutorial will summarize how these efforts are being fit together to provide usable practitioner value, and how to get involved.
• Maturity in MBSE is not only about our models, methods, and tools—although it includes them:
  • What will we use models for (intended purpose)? Who is “we”?
  • How do we go about trusting our model?
  • Is our learning effectively enhanced?
• State of art & practice in some of these areas still low:
  • So, expect significant continuing change.
  • Measuring against current base may not reflect “maturity”.
• There are overall requirements we can use to measure our MBSE maturity:
  • Based on, but enlarging, the interpretation of ISO 15288, existing maturity models, and computational models.
  • Providing a foundation for future maturity assessment, planning.
• The emerging foundation opens up thinking about scope of impacts, and therefore scope of maturity assessment.
One way to stay focused pragmatically is to be very clear about explicit purposes for models.

Because ISO 15288 offers a (relatively) well-known and accessible reference model for the life cycle management of systems, it provides a convenient “menu” listing of potential high level purposes of models in the life cycle of systems.

The INCOSE Model-Based Transformation team is using this as the basis of an MBSE migration and maturation planning and assessment instrument . . .
The INCOSE MBSE Transformation products are based on identification of --

Stakeholders in the MBSE Transformation:

1. Model Consumers (Model Users);
2. Model Creators (including Model Imrovers);
3. Complex Idea Communicators (Model "Distributors");
4. Model Infrastructure Providers, Including Tooling, Language and Other Standards, Methods;
5. INCOSE and other Engineering Professional Societies.

Notice that group (1) is by far the largest population of stakeholders, for future MBSE impact potential.
Further analysis of the Transformation Stakeholders
(also shows Energy Tech 2016 Conference ratings of needs, opportunities)

<table>
<thead>
<tr>
<th>Stakeholders in A Successful MBSE Transformation</th>
</tr>
</thead>
<tbody>
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<td>(showing their related roles and parent organizations)</td>
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### Model Consumers (Model Users):
- Non-technical stakeholders in various Systems of Interest, who acquire / make decisions about / make use of those systems, and are informed by models of them. This includes mass market consumers, policy makers, business and other leaders, investors, product users, voters in public or private elections or selection decisions, etc.

### Model Creators (including Model Improvers):
- Product visionaries, marketers, and other non-technical leaders of thought and organizations
- System technical specifiers, designers, testers, theoreticians, analysts, scientists
- Students (in school and otherwise) learning to describe and understand systems
- Educators, teaching the next generation how to create with models
- Researchers who advance the practice
- Those who translate information originated by others into models
- Those who manage the life cycle of models

### Complex Idea Communicators (Model "Distributors"):
- Marketing professionals
- Educators, especially in complex systems areas of engineering and science, public policy, other domains, and including curriculum developers as well as teachers
- Leaders of all kinds

### Model Infrastructure Providers, Including Tooling, Language and Other Standards, Methods:
- Suppliers of modeling tools and other information systems and technologies that house or make use of model-based information
- Methodologists, consultants, others who assist individuals and organizations in being more successful through model-based methods
- Standards bodies (including those who establish modeling standards as well as others who apply them within other standards)

### INCOSE and other Engineering Professional Societies
- As a deliverer of value to its membership
- As seen by other technical societies and by potential members
- As a great organization to be a part of
- As promoter of advance and practice of systems engineering and MBSE
Each 15288 process definition suggests potentially assessable model impacts

a) “Stakeholders of the system are identified.
b) Required characteristics and context of use of capabilities and concepts in the life cycle stages, including operational concepts, are defined.
c) Constraints on a system are identified.
d) Stakeholder needs are defined.
e) Stakeholder needs are prioritized and transformed into clearly defined stakeholder requirements.
f) Critical performance measures are defined.
g) Stakeholder agreement that their needs and expectations are reflected adequately in the requirements is achieved.
h) Any enabling systems or services needed for stakeholder needs and requirements are available.
i) Traceability of stakeholder requirements to stakeholders and their needs is established.”
System of Innovation (SOI) Pattern Logical Architecture
(Adapted from ISO/IEC 15288:2015)

Technical Processes

- Human Design Connection
- Stronger CONSOS
- Legacy Systems

Service Life: Top System
- Transition
- Operation
- Maintenance
- Disposal

Project Processes

- Realization Top System
  - Verification (by Test)
  - Solution Validation
  - Integration

- Design Subsystem 1
  - Requirements Validation
  - Verification (by Analysis & Simulation)
  - Integration

- Design Subsystem 2
  - Requirements Validation
  - Verification (by Analysis & Simulation)

- Design Top System
  - Requirements Validation

Process-Data Quality, Security, Concurrency

Explainable Learning

Domain Patterns, MBSE, Libraries

“Modeling Life”

Organizational Project-Enabling Processes

- Project Portfolio Management
- Infrastructure Management
- Human Resource Management
- Knowledge Management Process

Financial Management Processes

- Acquisition
- Supply

Each ISO15288 process offers higher level targeting, assessment (Example: Energy Tech 2016 Feedback on MBSE in ISO15288)

Innovative Model Logic

Analytics, Graph DBs, Model LC Management

Model Validation

MBSE Views 5 to Stakeholders, Styles, Perspectives

Metamodel Sufficiency
Systems of Modeling, practiced, must be sufficient for their intended purposes, and preferably minimal / not overly complex, proliferated:

- A lot of (continuing) effort by the modeling community being invested in sufficiency and also minimality.
- Understanding of what is needed improving, but lists of future capabilities are long.

- More is involved than modeling languages, tools, methods, alone; for example:
  - Fitness to non-technical users and uses
  - Strong enough conceptual foundation, based on STEM, not just information models.
  - Credibility of model content (trust in the model)

What is the Smallest Model of a System?

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Systems of Innovation II: The Emergence of Purpose

Volkan Demirel
ICT Systems Science
ademirel@ictt.com

Got Phenomena? Science-Based Disciplines for Emerging Systems Challenges

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ICT System Sciences
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Abstract

- Sufficiency for Purposes and Minimality: Systems of Modeling, practiced, must be sufficient for their intended purposes, and preferably minimal / not overly complex, proliferated:
- A lot of (continuing) effort by the modeling community being invested in sufficiency and also minimality.
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  - Credibility of model content (trust in the model)
Scientific heritage (~300 years)

• The eventual flowering of the physical sciences depended upon the emergence of strong enough underlying model constructs (of math, physics) to better represent Nature.

• Specifically, the System Phenomenon (Newton, Lagrange, Hamilton):

A traditional view of systems engineering

External "Actors"

Our view of systems engineering

Traditional Physical Phenomena

Emerging Engineering Disciplines

Traditional Engineering Disciplines

Systems Engineering Discipline

System

System Component
Sufficiency for Purposes; Minimality

• Example: Fitness of model to use
  • Includes fitness of model views to intended uses, users.

• See discussions by E. Tufte, N Levinson, concerning NASA shuttle model views

• Culture plays a key part in this.

• So, measuring maturity of MBSE will take us across more subjects than technical practitioners might expect.

• Modeling more than just the “engineered” System 1

• Intended model uses and users, along with culture, are “System 2” issues . . .
# Stakeholders for Models

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INCOSE MBSE Assessment and Planning Pattern: Model Stakeholder Features Overview

Legend:
- Model Representation
- Model Scope and Content
- Model Identity and Focus
- Model Utility
- Model Credibility
- Model Life Cycle Management

Model Identity and Focus

- Modeled System of Interest
- Modeled Environmental Domain

Model Scope and Content

- Modeled Stakeholder Features
- Modeled System External (Black Box) Behavior
- Explanatory Decomposition
- Failure Modes and Effects

Model Utility

- Model Intended Use
- Perceived Model Value and Use
- Third Party Acceptance
- Model Ease of Use

Model Credibility

- Model Envelope
- Validated Conceptual Model Credibility
- Verified Executable Model Credibility

Model Life Cycle Management

- Model Versioning and Configuration Management
- Model Maintainability
- Model Deployability
- Model Cost

Model Representation

- Conceptual Model Representation
- Executable Model Representation

Legend:

- Stakeholder Feature
  - Feature PK
  - Attribute
  - Other Feature PK
  - Other Attribute

Stakeholder Feature Model for Computational Models

Version: 1.5.4  Date: 31 Aug 2017  Drawn By: B Schindel
The ISO 15288 Processes provide the Model Stakeholder Feature Set for Planning & Assessment

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(Other Features on previous slide)
Vision for a Practical Aid to Model Community

• In establishing model credibility, a computational model is verified and validated (VV), including quantification of related uncertainties (UQ):
  • With respect to not just the system it represents, but also the Model Requirements, specifying the intended use(s), user(s), and characteristics of that model.

• This vision is to make the generation of those Model Requirements easier, more complete, and more successful than would otherwise be the case—using the Model VVUQ Pattern.
Vision for a Practical Aid to Model Community

- Vision of a guideline that includes a practical pattern for the efficient and effective planning and generation of computational models that have a higher likelihood of VVUQ and successful service.
- The smallest set of ideas necessary to achieve that goal.
- Makes use of ideas used in Pattern-Based Systems Engineering, a form of MBSE, for configurable models:
Vision for a Practical Aid to Model Community

• The foundation of this capability are the computational model’s Stakeholder Features and the computational model’s Requirements . . .
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<tr>
<td>IT Environment Maintainer</td>
<td>A person or organization that maintains the IT environment utilized by a computational model.</td>
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### Computational Model Feature Groups: Configurable for Specific Models

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<th>Feature Group</th>
<th>Description</th>
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<tr>
<td>Model Identity and Focus</td>
<td>Identifies the main subject or focus of the model.</td>
</tr>
<tr>
<td>Model Scope and Content</td>
<td>Describes the scope of content of the model.</td>
</tr>
<tr>
<td>Model Life Cycle Management</td>
<td>Describes the related model life cycle management capabilities.</td>
</tr>
<tr>
<td>Model Credibility</td>
<td>Describes the credibility of the model.</td>
</tr>
<tr>
<td>Model Utility</td>
<td>Describes the intended use, user, utility, and value of the model.</td>
</tr>
<tr>
<td>Model Representation</td>
<td>Describes the representation used by the model.</td>
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Computational Model Feature Groups: 27 Features, in 6 Feature Groups, Configurable for Specific Models

Model Identity and Focus
- Model Scope of Interest
- Model Environment Domain

Model Utility
- Model Intended Use
- Perceived Model Value and Use
- Third Party Acceptance
- Model Ease of Use

Model Scope and Content
- Model Stakeholder Value
- Model System External (Black Box) Behavior
- Explanatory Decomposition
- Failure Modes and Effects

Model Credibility
- Model Envelope
- Validated Conceptual Model Credibility
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Model Life Cycle Management
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Model Representation
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Legend:
- Stakeholder Feature Model for Computational Models
- Version: 1.5.4
- Date: 31 Aug 2017
- Drawn By: B Schindel
The Stakeholder Features are configurable Stakeholder expectations, intentions, and valued aspects for a computational model:

- These can be “configured” like Lego® blocks, as a form of checklist to rapidly create the stakeholder-level expectations for a computational model.
- And from them, the more technical Requirements for the model follow.
Generation of Model Stakeholder Features

• The Model Stakeholder Feature Pattern is configured for a specific project by populating or depopulating the pattern’s generic Features, and setting the values of its Feature Attributes:
System Reference Boundaries: Computational Modeling Domain

Overall Model System
- Computational Modeling System
  - IT Hardware
  - Model Authoring Software
  - Model Execution Software
  - Model CM & Distribution Software
  - Automated Implementation of Model
  - Model Datasets (Inputs, Outputs, Configurations)

Underlying Model (Automation Independent)
- Physics-Based Model
- Data Driven Model

Real Target System to be Modeled
- Residual Stress for Milling Process

Observation System
- Instrumentation System
- Data Collection System
- Data Analysis System

Model User Interface

Model Life Cycle Configuration & Deployment Manager

Computational Model Developer (Model Tooling SME)

Conceptual Modeler

Residual Stress for Milling Process: An analytical model of residual stress for flank milling of Ti-6Al-4V, 15th CIRP Conference on Modelling of Machining Operations (Hybrid Models combine both the above)
Requirements for Models

• Requirements for a specific computational model are the basis of subsequent validation and verification of the model.

• The Requirements for a computational model are implied by the Stakeholder Features (see above), but with more details configured into them.

• Approximately 75 configurable general Requirements for Models have been identified and traced to the Stakeholder Features, in the current draft of the Model VVUQ Pattern.

• After these have been further vetted and polished in this project, they provide a rapid start way to generate a high quality set of Model Requirements in a production project.
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<td>Modeled System of Interest</td>
<td>Identifies the type of system this model describes.</td>
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<td>Data Driven</td>
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<td>Modeled Environmental Domain</td>
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<td>Identifies the type of external environmental domain(s) that this model includes.</td>
<td>Domain Type(s)</td>
<td>Name(s) of modeled domains (manufacturing, distribution, use, etc.)</td>
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**Model Type**

- **Feature Stakeholder**
  - Model User
  - Model Developer
  - Model Maintainer
  - Model Deployer-Distributor
  - Model Use Supporter
  - Regulatory Authority
  - Model Investor-Owner
- **Model Type**
  - Physics Based
  - Data Driven
The capability of the model to describe fitness or value of the System of Interest, by identifying its stakeholders and modeling the related Stakeholder Features.

The capability of the model to represent the objective external ("black box") technical behavior of the system, through significant interactions with its environment, based on modeled input-output exchanges through external interfaces, quantified by technical performance measures, and varying behavioral modes.

The capability of the model to represent the decomposition of its external technical behavior, as explanatory internal ("white box") internal interactions of decomposed roles, further quantified by internal technical performance measures, and varying internal behavioral modes.

The capability of the model to represent the physical architecture of the system of interest. This includes identification of its major physical components and their architectural relationships.
### Model Scope and Content

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<td>represent quantitative (parametric) couplings between stakeholder-valued measures of</td>
<td>X</td>
<td></td>
</tr>
<tr>
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<td>external black box behavior</td>
<td>effectiveness and objective external black box behavior measures.</td>
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<td>Parametric Couplings--</td>
<td>The capability of the model to</td>
<td>represent quantitative (parametric) couplings between objective behavior variables</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Characterization</td>
<td>and physical identity</td>
<td>(material of construction, part or model number).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Managed Model Datasets</td>
<td>The capability of the model to</td>
<td>include managed datasets for use as inputs, parametric characterizations, or outputs</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Managed Model Datasets</td>
<td>Dataset Type</td>
<td>The type(s) of data sets (may be multiple).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trusted Configurable Pattern</td>
<td>The capability of the model to</td>
<td>serve as a configurable pattern, representing different modeled system configurations</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>across a common domain, spreading</td>
<td>across a common domain, spreading the cost of establishing trusted model frameworks</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>the cost of establishing trusted</td>
<td>across a community of applications and configurations.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Feature Stakeholder

<table>
<thead>
<tr>
<th>Model User</th>
<th>Model Developer</th>
<th>Model Maintainer</th>
<th>Model Deployer</th>
<th>Distributor</th>
<th>Model Use</th>
<th>Siteiner</th>
<th>Regulatory Authority</th>
<th>Mdl Investor-Owner</th>
<th>Physics</th>
<th>Data Driven</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Pattern Type

<table>
<thead>
<tr>
<th>Feature Stakeholder</th>
<th>Model Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model User</td>
<td>Model</td>
</tr>
<tr>
<td>Model Developer</td>
<td>Model</td>
</tr>
<tr>
<td>Model Maintainer</td>
<td>Model</td>
</tr>
<tr>
<td>Model Deployer</td>
<td>Model</td>
</tr>
<tr>
<td>Distributor</td>
<td>Siteiner</td>
</tr>
<tr>
<td>Model Use</td>
<td>Regulatory Authority</td>
</tr>
<tr>
<td>Siteiner</td>
<td>Mdl Investor-Owner</td>
</tr>
<tr>
<td>Regulatory Authority</td>
<td>Physics</td>
</tr>
<tr>
<td>Mdl Investor-Owner</td>
<td>Data Driven</td>
</tr>
</tbody>
</table>
# Model Scope and Content

<table>
<thead>
<tr>
<th>Feature Group</th>
<th>Feature Name</th>
<th>Feature Definition</th>
<th>Feature Attribute</th>
<th>Attribute Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model Scope of Content</td>
<td>Failure Modes and Effects</td>
<td>The capability of the model to include identification and analysis of system failure modes, their impact effects, causes, and likelihoods of occurrence.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Feature Stakeholder</th>
<th>Model Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model User</td>
<td>Model Deployer</td>
</tr>
<tr>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
• A System is a set of interacting components:
  – By “interact”, we mean exchanging energy, forces, mass flows, or information, resulting in changes of state:

  ![Diagram of System Components](image)

  – So, a (Manufacturing or other) Process is a type of System (but not all Systems are such Processes):

  ![Diagram of Manufacturing Processes](image)

• The “Black Box” view of a system sees only its external behavior
• The “White Box” view of a system sees its internal interactions
**Physics-Based Model**

- Predicts the external behavior of the System of Interest, visible externally to the external actors with which it interacts.
- Models internal physical interactions of the System of Interest, and how they combine to cause/explain externally visible behavior.
- Model has both external predictive value and phenomena-based internal-to-external explanatory value.
- Overall model may have high dimensionality.

**Data Driven Model**

- Predicts the external behavior of the System of Interest, visible to the external actors with which it interacts.
- Model intermediate quantities may not correspond to internal or external physical parameters, but combine to adequately predict external behavior, fitting it to compressed relationships.
- Model has external predictive value, but not internal explanatory value.
- Overall model may have reduced dimensionality.

---

Data scientists and their math/IT tools can apply here (data mining, pattern extraction, cognitive AI tooling).

Tools and methods for discovery / extraction of recurring patterns of external behavior.
Hybrid Model: Both Data Driven and Physics-Based

- Predicts the external behavior of the System of Interest, visible externally to the external actors with which it interacts.
- Models (some aspects of) internal physical interactions of the System of Interest, and how they combine to cause/explain (some aspects of) externally visible behavior.
- Model has both external predictive value and (some) phenomena-based internal-to-external explanatory value.
- (Some) model intermediate quantities may not correspond to internal or external physical parameters, but combine to adequately predict external behavior, fitting it to compressed relationships.
- Model has external predictive value, but (for some aspects) not internal explanatory value.

Physical scientists and phenomena models from their disciplines can apply here.
- The hard sciences physical laws, and how they can be used to explain the externally visible behavior of the system of interest.
- Data scientists and their math/IT tools can apply here (data mining, pattern extraction, cognitive AI tooling).
- Tools and methods for discovery / extraction of recurring patterns of external behavior.

• Predicts the external behavior of the System of Interest, visible externally to the external actors with which it interacts.

References:
Samples from a simple illustrative example

- Product: Oil Filter
- Manufacturing System: Oil Filter Mfg System
Physical Architecture Models describes the physical portion of the technology, to which Functional Roles will later be allocated and optimized ...

Product Physical Architecture

**Architecture 1: Laminated and Accordion Pleated Filtration Media, Flow Orthogonal to Plane of Media, Additive Impregnated**

**Architecture 2: Wound Filtration Fiber, Flow Orthogonal to Plane of Windings, Additive Impregnated**
Domain Models directly help by discovering and capturing all the external systems physically interacting with the Subject System—these are the source of all Functional Requirements.
Stakeholder Feature Models address a key SE challenge by making explicit the ultimate stakeholder outcomes against which all decisions, trade-offs, optimizations, and outcomes will be scored and selected. This covers all Stakeholders, not just Customers (e.g., Shareholders, Community, etc.).

**Product Stakeholder Features, Feature Attributes**

<table>
<thead>
<tr>
<th>Feature Name</th>
<th>Config Rule Ref for Population</th>
<th>Feature Definition</th>
<th>Feature Attribute PK</th>
<th>Attribute Definition</th>
<th>Attribute Units</th>
<th>Attribute Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Lubricant Filtration Feature</td>
<td>Mandatory</td>
<td>The feature of maintaining a lubricating fluid at a required level of cleanliness while it is in service in a specified application, including the removal of contaminants associated with the application.</td>
<td>Service Application</td>
<td>The type of lubricated system application supported by a lubricant filtration system. More than one type may be instantiated for a single product configuration.</td>
<td>NA</td>
<td>Consumer Automotive, Commercial Automotive, Fixed Based Engine System, Harsh Environment, High Thermal Environment, Cold Environment</td>
</tr>
<tr>
<td>Engine Lubricant Filtration Feature</td>
<td>Mandatory</td>
<td>Lubricant Type</td>
<td></td>
<td></td>
<td>NA</td>
<td>0</td>
</tr>
<tr>
<td>Engine Lubricant Filtration Feature</td>
<td>Mandatory</td>
<td>Lubricant Flow Rate</td>
<td></td>
<td></td>
<td>NA</td>
<td>High, Medium, Low</td>
</tr>
<tr>
<td>Engine Lubricant Filtration Feature</td>
<td>Mandatory</td>
<td>Lubricant Pressure Range</td>
<td></td>
<td></td>
<td>NA</td>
<td>High, Medium, Low</td>
</tr>
<tr>
<td>Engine Lubricant Filtration Feature</td>
<td>Mandatory</td>
<td>Filter Efficiency Class</td>
<td></td>
<td></td>
<td>NA</td>
<td>0</td>
</tr>
<tr>
<td>Mechanical Compatibility Feature</td>
<td>Mandatory</td>
<td>The feature of being compatible in form factor and mechanical interface with the system in which the system will be installed.</td>
<td>Mechanical Interface Type</td>
<td>The mechanical form of an interface.</td>
<td>NA</td>
<td>0</td>
</tr>
<tr>
<td>Mechanical Compatibility Feature</td>
<td>Mandatory</td>
<td></td>
<td></td>
<td></td>
<td>NA</td>
<td>0</td>
</tr>
<tr>
<td>Cost of Operation Feature</td>
<td>Mandatory</td>
<td>The feature of supporting cost-effective lubrication of an application, by minimizing the cost of lubrication consumables per operating hour.</td>
<td>Lubricant Life</td>
<td>The amount of time, in operating hours, that a lubricant is intended to operate, meeting requirements within the specified environment, before it is replaced.</td>
<td>NA</td>
<td>Standard, Long Life</td>
</tr>
</tbody>
</table>
Features are collections of Functional Interactions (behaviors) having value to Stakeholders; their Attributes quantify that value impact. Features are in language of Stakeholders.

**Product Stakeholder Features, Feature Attributes**

Alternate designs, different configurations, and technology generations are all ultimately “Scored” in lower-dimension trade-off space defined by the Stakeholder Feature Attributes.

*For example:* Every FMEA (Failure Mode Effects Analysis) failure impact can be expressed in terms of Feature Attributes.
Functional Interaction Models a key SE challenge by discovering and describing all external interactions of a Subject System. This leads to all functional requirements and thereafter all other requirements, in the Detail Requirements Model.

Product Functional Interactions, Roles

<table>
<thead>
<tr>
<th>Functional Interaction</th>
<th>Functional Roles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter Lubricant</td>
<td>Lubricant in Filtration, Oil Filter System, Removed Solid Contaminant, Removed Water</td>
</tr>
<tr>
<td>Install Filter</td>
<td>Service Person, Filter</td>
</tr>
<tr>
<td>Monitor Filter</td>
<td>Filter, Monitor &amp; Control System</td>
</tr>
<tr>
<td>Prevent Vapor Leakage</td>
<td>Lubricant, Vapor, Filter, Atmosphere</td>
</tr>
<tr>
<td>Prevent Lubricant Leakage</td>
<td>Lubricant, Filter, Local Surface</td>
</tr>
<tr>
<td>Transmit Shock &amp; Vibration</td>
<td>Filter, Mounting System</td>
</tr>
<tr>
<td>Transmit Thermal Energy</td>
<td>Filter, Lubricant, Mounting System, Ambient Air</td>
</tr>
</tbody>
</table>

Every system directly interacting with the Subject System (Oil Filter System) contributes to its Requirements.
An Interaction of Systems, expressed as an external (outcome) relationship in which systems impact each other's states. Interacting systems fill Roles in the Interaction. Interactions technically characterize (model) the behaviors summarized by stakeholder-valued Features.

**Product Functional Interactions, Roles**

<table>
<thead>
<tr>
<th>Functional Interaction</th>
<th>Functional Roles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter Lubricant</td>
<td>Lubricant in Filtration, Oil Filter System, Removed Solid Contaminant, Removed Water</td>
</tr>
<tr>
<td>Change Filter</td>
<td>Service Person, Filter</td>
</tr>
<tr>
<td>Monitor Filter</td>
<td>Filter, Monitor &amp; Control System</td>
</tr>
<tr>
<td>Prevent Vapor Leakage</td>
<td>Lubricant, Vapor, Filter, Atmosphere</td>
</tr>
<tr>
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<td>Lubricant, Filter, Local Surface</td>
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<td>Transmit Shock &amp; Vibration</td>
<td>Filter, Mounting System</td>
</tr>
<tr>
<td>Transmit Thermal Energy</td>
<td>Filter, Lubricant, Mounting System, Ambient Air</td>
</tr>
</tbody>
</table>

Input/Outputs exchanged during these interactions are:
- Energy
- Force
- Mass
- Information
State Models directly address a key SE challenge by discovering and describing all Situations, Modes, or Use Cases (environmental states) that a Subject System will encounter. These are associated with Functional Interactions that lead directly to requirements. State Models can also describe Designs.

Product State Model

States answer the question: "When does each requirement apply?"
States are Situations (Modes, Use Cases, Phases) that will be encountered in the environment of a Subject System, in which it is required to meet certain requirements.
Logical Architecture Models directly address key SE challenges by partitioning the structure of requirements into Logical Roles independent of design, then address more SE challenges by stimulating design ideation and role allocation to physical designs and future technologies.

Product Logical Architecture Model
Directly addressing a key SE challenge, multiple alternate physical architectures are typically supported by a single Logical Architecture! This provides a powerful means for managing across Technologies & Configurations, and enhances Platform Management.

Alternate Technologies, Family Configurations, Roadmaps
What Is the Smallest Model of a System?

William D. Schindel
ICTT System Sciences
schindel@ictt.com

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Abstract. How we represent systems is fundamental to the history of mathematics, science, and engineering. Model-based engineering methods shift the nature of representation of systems from historical prose forms to explicit data structures more directly comparable to those of science and mathematics. However, using models does not guarantee simpler representation—indeed a typical fear voiced about models is that they may be too complex.

Minimality of system representations is of both theoretical and practical interest. The mathematical and scientific interest is that the size of a system’s “minimal representation” is one definition of its complexity. The practical engineering interest is that the size and redundancy of engineering specifications challenge the effectiveness of systems engineering processes. INCOSE thought leaders have asked how systems work can be made 10:1 simpler to attract a 10:1 larger global community of practitioners. And so we ask: What is the smallest model of a system?

Introduction and Background

Representation Size, Purpose, Traditions. This paper explores upper bounds on the sizes of effective representations of systems engineering. Compared to traditional systems on directly on scientific traditions for representing behavior, engineering is still young, and its connections to supporting language and compression. This subject may appear to describe systems, and an interesting thread in the matter of whether minimality is in a sense independent of language. In any case, systems modeling languages such as SysML are valuable assets for the movement to model-based methods is not the machinery of these specific modeling languages models must address. When used for systems modeling, representation described here is subject to significant compression to provide powerful insights about approaches size of SE descriptions and processes, and about ongoing feedback. These dynamics also suggest that such patterns of the interaction rules of the systems engineering process are critical.

Practical representation challenges of traditional system documentation. Concept of operations (CONOPS) specifications, failure mode and effects analysis (FMEA), maintenance procedures, and other task-specific system documentation can exceed thousands of pages. This does not equate to minimal representation. The final question is: What is the smallest model of a system?
The Attribute Coupling Model addresses a key SE challenge to understand the quantitative coupling of stakeholder preferences (Features) to technical requirements (Roles), establishing a Feature-based scoring space for trade-offs.

**Attribute Coupling Model--Requirements**

- The “A” and “B” couplings organize all the quantitative relationships, including first principles math/physics models, design of experiment models, empirical studies, market surveys, etc.
- Organizes trade-off scoring space.
- Provides a uniform way to integrate Team Partner models of Fuel Cell, other systems.
The Attribute Coupling Model addresses a key Challenge to describe the coupling of Design Component attributes to technical requirements (Role) attributes, provide scoring (in Feature Space) of Design Attribute solutions.

Attribute Coupling Model--Designs

• The “A” and “B” couplings organize all the quantitative relationships, including first principles math / physics models, design of experiment models, empirical studies, market surveys, etc.

• Organizes trade-off scoring space.

• Provides a uniform way to integrate Team Partner models of Fuel Cell, other systems.
Attribute couplings cross domains

The Coupling Model is a unifying framework integrating all forms of coupling:
• First principles equations
• Empirical datasets
• Graphical relations
• Data tables
• Prose statements
• Fuzzy relationships
• Other
The capability of the model to represent quantitative (parametric) couplings between stakeholder-valued measures of effectiveness and objective external black box behavior performance measures.

The capability of the model to represent quantitative (parametric) couplings between objective external black box behavior variables and objective internal white box behavior variables.

The capability of the model to represent quantitative (parametric) couplings between objective behavior variables and physical identity (material of construction, part or model number).

The capability of the model to include managed datasets for use as inputs, parametric characterizations, or outputs

The capability of the model to serve as a configurable pattern, representing different modeled system configurations across a common domain, spreading the cost of establishing trusted model frameworks across a community of applications and configurations.

<table>
<thead>
<tr>
<th>Feature Stakeholder</th>
<th>Feature</th>
<th>Attribute</th>
<th>Feature Attribute</th>
<th>Attribute Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model User</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model Developer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model Maintainer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mdl Deployer-Distributor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model Use Supporter</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Regulatory Authority</td>
<td></td>
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<tr>
<td>Mdl Investor-Owner</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Physics Based</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data Driven</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dataset Type: The type(s) of data sets (may be multiple)

Configuration ID: A specific system of interest configuration within the family that the pattern framework can represent

Pattern ID: The identifier of the trusted configurable pattern.
The Family Configurations Model directly addresses a key SE challenge by providing Class Hierarchy Models with Configuration Rules (Gestalt Rules) that govern Platforms and Portfolios of Products, Systems, and Technologies.

Family Configurations Model

- The Family Configurations Model supports multiple configurations, technologies:

- This can be exploited by partitioning the model to integrate with existing Portfolio Roadmaps for Markets, Technologies, and Products.
## Family Configurations Model

### Lawnmower Product Line: Configurations Table

<table>
<thead>
<tr>
<th>Units</th>
<th>Walk-Behind Mower</th>
<th>Walk-Behind Mower</th>
<th>Walk-Behind Mower</th>
<th>Riding Mower</th>
<th>Riding Mower</th>
<th>Riding Mower</th>
<th>Autonomous Mowing System</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Push Mower</td>
<td>Self-Propelled</td>
<td>Self-Propelled</td>
<td>Rear Engine</td>
<td>Tractor</td>
<td>Tractor</td>
<td>Autonomous Mowing System</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mower</td>
<td>Mower</td>
<td>Rider</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Engine Manufacturer</td>
<td>Briggs 3 Stratton</td>
<td>Briggs 3 Stratton</td>
<td>Tecumseh</td>
<td>Kohler</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horsepower</td>
<td>5</td>
<td>6</td>
<td>13</td>
<td>16</td>
<td>18.5</td>
<td>22</td>
<td>0.5</td>
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<tr>
<td>Mower</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turning Radius</td>
<td>Inches</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>126</td>
<td>185</td>
<td>0</td>
</tr>
<tr>
<td>Fuel Tank Capacity</td>
<td>Hours</td>
<td>1.5</td>
<td>1.5</td>
<td>2.5</td>
<td>2.8</td>
<td>3.2</td>
<td>3.5</td>
</tr>
<tr>
<td>Maximum Mowing Speed</td>
<td>MPH</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>8</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Maximum Mowing Productivity</td>
<td>Acres/Hr</td>
<td>1</td>
<td>1</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Towing Feature</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric Starter Feature</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basic Mowing Feature Group</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Anti-Scalping Rollers</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>Cutting Height Minimum</td>
<td>Inches</td>
<td>1</td>
<td>1.5</td>
<td>1.5</td>
<td>1</td>
<td>1.5</td>
<td>1.2</td>
</tr>
<tr>
<td>Cutting Height Maximum</td>
<td>Inches</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Operator Riding Feature</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grass Bagging Feature</td>
<td>Optional</td>
<td>Optional</td>
<td>Optional</td>
<td>Optional</td>
<td>Optional</td>
<td>Optional</td>
<td></td>
</tr>
<tr>
<td>Mulching Feature</td>
<td>Optional</td>
<td>Optional</td>
<td>Optional</td>
<td>Optional</td>
<td>Optional</td>
<td>Optional</td>
<td></td>
</tr>
<tr>
<td>Aerator Feature</td>
<td>Optional</td>
<td>Optional</td>
<td>Optional</td>
<td>Optional</td>
<td>Optional</td>
<td>Optional</td>
<td></td>
</tr>
<tr>
<td>Autonomous Mowing Feature</td>
<td>Optional</td>
<td>Optional</td>
<td>Optional</td>
<td>Optional</td>
<td>Optional</td>
<td>Optional</td>
<td></td>
</tr>
<tr>
<td>Dethatching Feature</td>
<td>Optional</td>
<td>Optional</td>
<td>Optional</td>
<td>Optional</td>
<td>Optional</td>
<td>Optional</td>
<td></td>
</tr>
<tr>
<td>Physical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheel Base</td>
<td>Inches</td>
<td>18</td>
<td>20</td>
<td>22</td>
<td>48</td>
<td>52</td>
<td>16</td>
</tr>
<tr>
<td>Overall Length</td>
<td>Inches</td>
<td>18</td>
<td>20</td>
<td>23</td>
<td>58</td>
<td>56</td>
<td>69</td>
</tr>
<tr>
<td>Overall Height</td>
<td>Inches</td>
<td>40</td>
<td>42</td>
<td>42</td>
<td>30</td>
<td>32</td>
<td>26</td>
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<tr>
<td>Weight</td>
<td>Pounds</td>
<td>120</td>
<td>160</td>
<td>300</td>
<td>680</td>
<td>705</td>
<td>1020</td>
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<tr>
<td>Self-Propelled Mowing Feature</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Financials</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Retail Price</td>
<td>Dollars</td>
<td>350</td>
<td>460</td>
<td>1800</td>
<td>3300</td>
<td>6100</td>
<td>9690</td>
</tr>
<tr>
<td>Manufacturer Cost</td>
<td>Dollars</td>
<td>120</td>
<td>140</td>
<td>550</td>
<td>950</td>
<td>1500</td>
<td>3500</td>
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<tr>
<td>Maintenance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warranty</td>
<td>Months</td>
<td>12</td>
<td>12</td>
<td>18</td>
<td>24</td>
<td>24</td>
<td>24</td>
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<tr>
<td>Product Service Life</td>
<td>Hours</td>
<td>500</td>
<td>500</td>
<td>800</td>
<td>1100</td>
<td>1350</td>
<td>1500</td>
</tr>
<tr>
<td>Safety</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spark Arrest Feature</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

### Pattern-Based Systems Engineering (PBSE)

- Pattern Class Hierarchy
- Product Lines of System Families
- Configuration Specific Product
- Product Lines of System Configurations
- Pattern Class Families
Family Configurations Model
Family Configurations Model
### Model Credibility

**Model Envelope**
- Quantitative Accuracy Reference
- Function Structure Accuracy Reference
- Uncertainty Quantification (UQ) Reference
- Model Validation Reference

**Validated Conceptual Model Credibility**
- Quantitative Accuracy Reference
- Function Structure Accuracy Reference
- Uncertainty Quantification (UQ) Reference
- Model Validation Reference

**Verified Executable Model Credibility**
- Quantitative Accuracy Reference
- Function Structure Accuracy Reference
- Uncertainty Quantification (UQ) Reference
- Speed
- Quantization
- Stability
- Model Validation Reference

---

### Feature Table

<table>
<thead>
<tr>
<th>Feature Group</th>
<th>Feature Name</th>
<th>Feature Definition</th>
<th>Feature Attribute</th>
<th>Attribute Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Envelope</td>
<td>Model Application Envelope</td>
<td>The capability of the model to meet its Model Credibility requirements over a stated range (envelope) of dynamical inputs, outputs, and parameter values.</td>
<td>Model</td>
<td>The range over which the model is intended for use.</td>
</tr>
<tr>
<td>Validated Conceptual Model Credibility</td>
<td>Quantitative Accuracy Reference</td>
<td>The specification reference describing the quantitative accuracy of the conceptual model compared to the system of interest.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Function Structure Accuracy Reference</td>
<td>The specification reference describing the structural (presence or absence of behaviors) accuracy of the conceptual model compared to the system of interest.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Uncertainty Quantification (UQ) Reference</td>
<td>The specification reference describing the degree of uncertainty of the Credibility of the conceptual model to the system of interest.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Model Validation Reference</td>
<td>The reference documenting the validation of the conceptual model’s Credibility to the system of interest.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**Feature Stakeholder**
- Model User
- Model Developer
- Model Maintainer
- Mali
- Model Use Safety Authority
- Mali
- Military

**Model Type**
- Physics
- Executive
- Data Division
<table>
<thead>
<tr>
<th>Feature Group</th>
<th>Feature Name</th>
<th>Feature Definition</th>
<th>Feature Attribute</th>
<th>Attribute Definition</th>
<th>Feature Stakeholder</th>
<th>Model Type</th>
<th>Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verified Executable</td>
<td>Model Credibility</td>
<td>The verified capability of the executable portion of the model to represent the system of interest with acceptable Credibility.</td>
<td>Quantitative Accuracy Reference</td>
<td>The specification reference describing the quantitative accuracy of the executable model to the conceptual model.</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Validated Conceptual</td>
<td>Structural Accuracy Reference</td>
<td>The specification reference describing the structural (presence or absence of elements) accuracy of the executable model to the conceptual model.</td>
<td>Structural Accuracy Reference</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Model Credibility</td>
<td>Uncertainty Quantification (UQ) Reference</td>
<td>The specification reference describing the degree of uncertainty of the Credibility of the executable model to the conceptual model.</td>
<td>Uncertainty Quantification (UQ) Reference</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Speed</td>
<td>The specification reference describing the execution run time (speed) for the executable model.</td>
<td>Speed</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Quantization</td>
<td>The specification reference describing the quantization error of the executable model.</td>
<td>Quantization</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stability</td>
<td>The specification reference describing the level of stability of the accuracy and uncertainty of the executable model error characteristics.</td>
<td>Stability</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Model Validation Reference</td>
<td>The reference documenting the verification of the executable model’s Credibility to the conceptual model.</td>
<td>Model Validation Reference</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>
# Model Life Cycle Management

## Model Versioning and Configuration Management
- **CM Capability Type**: The capability of the model to provide for version and configuration management.
- **Feature**: The type(s) of CM capabilities included (may be multiple).
- **Stakeholder**: X X X X X X

## Executable Model Environmental Compatibility
- **IT Environmental Component**: The capability of the model to be compatibly supported by specified information technology environment(s), indicating compatibility, portability, and interoperability.
- **Feature**: The type(s) of IT environments or standards supported.
- **Stakeholder**: X X X X X X

## Model Design Life Cycle and Retirement
- **Design Life**: The capability of the model to be sustained over an indicated design life, and retired on a planned basis.
- **Feature**: The planned retirement date.
- **Stakeholder**: X X X X X X

## Model Maintainability
- **Maintenance Method**: The relative ease with which the model can be maintained over its intended life cycle and use, based on capable maintainers, availability of effective model documentation, and degree of complexity of the model.
- **Feature**: The type of maintenance methodology used to maintain the model's capability and availability for the intended purposes over the intended life cycle.
- **Stakeholder**: X X X X X X

## Model Deployability
- **Deployment Method**: The capability of the model to support deployment into service on behalf of intended users, in its original or subsequent updated versions.
- **Feature**: The type of method used to deploy (possibly in repeating cycles) the model into its intended use environment.
- **Stakeholder**: X X X X X X

## Model Cost
- **Development Cost**: Operational Cost
- **Maintenance Cost**: Deployment Cost
- **Retirement Cost**: Life Cycle Financial Risk

---

### Describes related model life cycle management capabilities

<table>
<thead>
<tr>
<th>Feature Group</th>
<th>Feature Name</th>
<th>Feature Definition</th>
<th>Feature Attribute</th>
<th>Attribute Definition</th>
<th>Feature Stakeholder</th>
<th>Model Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Versioning and Configuration Management</td>
<td>The capability of the model to provide for version and configuration management</td>
<td>CM Capability Type</td>
<td>The type(s) of CM capabilities included (may be multiple)</td>
<td>X X X X X X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Executable Model Environmental Compatibility</td>
<td>The capability of the model to be compatibly supported by specified information technology environment(s), indicating compatibility, portability, and interoperability.</td>
<td>IT Environmental Component</td>
<td>The type(s) of IT environments or standards supported</td>
<td>X X X X X X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model Design Life Cycle and Retirement</td>
<td>The capability of the model to be sustained over an indicated design life, and retired on a planned basis.</td>
<td>Design Life</td>
<td>The planned retirement date</td>
<td>X X X X X X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model Maintainability</td>
<td>The relative ease with which the model can be maintained over its intended life cycle and use, based on capable maintainers, availability of effective model documentation, and degree of complexity of the model</td>
<td>Maintenance Method</td>
<td>The type of maintenance methodology used to maintain the model's capability and availability for the intended purposes over the intended life cycle.</td>
<td>X X X X X X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model Deployability</td>
<td>The capability of the model to support deployment into service on behalf of intended users, in its original or subsequent updated versions</td>
<td>Deployment Method</td>
<td>The type of method used to deploy (possibly in repeating cycles) the model into its intended use environment.</td>
<td>X X X X X X</td>
<td></td>
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</table>
### Model Life Cycle Management

#### Model Life Cycle Management

<table>
<thead>
<tr>
<th>Feature Group</th>
<th>Feature Name</th>
<th>Feature Definition</th>
<th>Feature Attribute</th>
<th>Attribute Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model Cost</td>
<td>Development Cost</td>
<td>The financial cost of the model, including development, operating, and maintenance cost for its intended use, including date of its first availability and the degree of ongoing availability thereafter.</td>
<td>Development Cost</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Operational Cost</td>
<td>The cost to execute and otherwise operate the model, in standardized execution load units.</td>
<td>Operational Cost</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Maintenance Cost</td>
<td>The cost to maintain the model.</td>
<td>Maintenance Cost</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Deployment Cost</td>
<td>The cost to deploy, and redeploy updates, per cycle.</td>
<td>Deployment Cost</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Retirement Cost</td>
<td>The cost to retire the model from service, in a planned fashion.</td>
<td>Retirement Cost</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>First Availability Date</td>
<td>Date when version will first be available.</td>
<td>First Availability Date</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>First Availability Risk</td>
<td>Risk to the scheduled date of first availability.</td>
<td>First Availability Risk</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Life Cycle Availability Risk</td>
<td>Risk to ongoing availability after introduction.</td>
<td>Life Cycle Availability Risk</td>
<td></td>
</tr>
</tbody>
</table>

#### Feature Stakeholder

- Model User
- Model Developer
- Model Maintainer
- Mdl Deployer-
- Distributor
- Model Use Supporter
- Regulatory Authority
- Mdl Investor-
- Owner
- Physics Based
- Data Driven

#### Model Type

- Development Cost
- Operational Cost
- Maintenance Cost
- Deployment Cost
- Retirement Cost
- Life Cycle Financial Risk

---

**Describes related model life cycle management capabilities**

- **Model Cost**
  - Development Cost
  - Operational Cost
  - Maintenance Cost
  - Deployment Cost
  - Retirement Cost
  - Life Cycle Financial Risk

- **Model Availability**
  - First Availability Date
  - First Availability Risk
  - Life Cycle Availability Risk
## Model Life Cycle Management

### Executable Model
- Environmental Compatibility

### Model
- Design Life Cycle and Retirement
- Maintainability
- Deployability

### Model Cost
- Development Cost
- Operational Cost
- Maintenance Cost
- Deployment Cost
- Retirement Cost
- Life Cycle Financial Risk

### VVUQ Pattern Learning
- VVUQ Pattern Exception
- Impacted VVUQ Feature
- VVUQ Pattern Version

### Feature Table

<table>
<thead>
<tr>
<th>Feature Group</th>
<th>Feature Name</th>
<th>Feature Definition</th>
<th>Feature Attribute</th>
<th>Attribute Definition</th>
<th>Feature Stakeholder</th>
<th>Model Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>VVUQ Pattern Learning</td>
<td>VVUQ Pattern Exception</td>
<td>The ability to accumulate new discoveries about model-based methods into the VVUQ Pattern, as it is applied over model life cycles. These discoveries are exceptions to the existing VVUQ Pattern, and candidates for inclusion into future versions of that pattern.</td>
<td>VVUQ Pattern</td>
<td>A summary of the exception noted to the current VVUQ Pattern (may be multiple exceptions)</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
## Model Representation

### Conceptual Model Representation

**Conceptual Model Representation Type**
- Conceptual Model Interoperability

**Feature**
- Identifies the type of representation used by the model

**Feature Group**
- Conceptual Model Representation
- Executable Model Representation

<table>
<thead>
<tr>
<th>Feature Group</th>
<th>Feature Name</th>
<th>Feature Definition</th>
<th>Feature Attribute</th>
<th>Attribute Definition</th>
<th>Feature Stakeholder</th>
<th>Model Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conceptual Model Representation</td>
<td>The capability of the conceptual portion of the model to represent the system of interest, using a specific type of representation.</td>
<td>Conceptual Model Representation Type</td>
<td>The type of conceptual modeling language or metamodel used.</td>
<td>Model User, Model Developer, Model Maintainer, Mdl Investor-Owner</td>
<td>Physics Based, Data Driven</td>
<td></td>
</tr>
<tr>
<td>Executable Model Representation</td>
<td>The capability of the executable portion of the model to represent the system of interest, using a specific type of representation</td>
<td>Executable Model Representation Type</td>
<td>The type of executable modeling language or metamodel used.</td>
<td>Model User, Model Developer, Model Maintainer, Mdl Investor-Owner</td>
<td>Physics Based, Data Driven</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Executable Model Interoperability</td>
<td>The degree of interoperability of the executable model, for exchange with other environments</td>
<td>Model User, Model Developer, Model Maintainer, Mdl Investor-Owner</td>
<td>Physics Based, Data Driven</td>
<td></td>
</tr>
</tbody>
</table>

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Exercise 1: Model Planning, Targeting Business Values

1. For a (real or hypothetical) use by your enterprise of a model-based approach, configure the VVUQ Model Features Pattern to describe your targeted outcomes – use the Model Features Pattern Form.

2. Did the VVUQ Features Pattern cover all your targeted improvement issues and concerns? Are there others?

3. What model credibility issues would have to be addressed by Model VVUQ?
Learning, versus Lessons Not Learned

• Practical steps to improve on organizational learning, using models as a focus of organizational learning and knowledge, based on model-based Learning Systems and Autonomous Systems.
The System of Innovation (SOI) MBSE Pattern
(Used for INCOSE Agile SE Project, INCOSE CIPR WG, etc.
Innovation reference model: Not prescriptive, but descriptive.)

1. Target System
   LC Manager of Target System
   Learning & Knowledge Manager for LC Managers of Target System

2. Target System (and Component) Life Cycle Domain System
   Life Cycle Manager of LC Managers
   Learning & Knowledge Manager for Target System
   LC Manager of Target System

3. System of Innovation (SOI)
   Learning & Knowledge Manager for LC Managers of Target System
   Target Environment
   (Substantially all the ISO15288 processes are included in all four Manager roles)

- System 1: Target system of interest, to be engineered or improved.
- System 2: The environment of (interacting with) S1, including all the life cycle management systems of S1, including learning about S1.
- System 3: The life cycle management systems for S2, including learning about S2.
ISO 15288 processes appear 4 times, whether we recognize or not.
System Requirements Definition

Arrows show flow of data, not flow of control. Processes can be concurrent.

- Generate Domain Model
- Generate State Model
- Review System Interactions
- Generate System Requirements Statements & Measures of Performance
- Generate Design Constraints
- Classify, Categorize, and Allocate Requirements
- Generate Baseline Document Package
- Approve Baseline Document Package

Design: Top System

- Stakeholder Needs & Requirements Definition
- Requirements Validation
- System Requirements Definition
- Architecture Definition
- Design Definition
- Verification (by Analysis & Simulation)

System of Innovation (SOI) Pattern Logical Architecture

(Adapted from ISO/IEC 15288:2015)
- System 1: Target system of interest, to be engineered or improved.
- System 2: The environment of (interacting with) S1, including all the life cycle management systems of S1, including learning about S1.
- System 3: The life cycle management systems for S2, including learning about S2.
• System 1: Target system of interest, to be engineered or improved.
• System 2: The environment of (interacting with) S1, including all the life cycle management systems of S1, including learning about S1.
• System 3: The life cycle management systems for S2, including learning about S2.

(Substantially all the ISO15288 processes are included in all four Manager roles)
Both System 1 and System 2 are potentially subject to learning.

System 2: Each of the ISO15288 Processes Appears repeatedly in the ASELCM Pattern:

They appear repeatedly, in different ways in the SOI & ASELCM Patterns . . . . . .
From Systems Engineering to Systems Innovation:
Shifting the emphasis from traditional focus on procedure, to greater emphasis on the state of the web of information passing through the process.
When is immaturity valued?

- The progressive “S Curves” of waves of new technologies, paradigms, product families, scientific, and other discoveries represent learning.
- In this context, “maturity” is the flat part at the top of each generation of learning.
- The earlier, “steep” part of the curve represents higher rates of change, as we learn more rapidly and exploit discovery.

- So, where do we want to be on this curve?
- Notice the challenging trade-off!
- Applies to learning about System 2 (e.g., methodology) as well as Learning about System 1 (engineered system).
Lessons Learned: Effective Learning?

• In many enterprises, recording “lessons learned” is institutionalized as good practice:
  • At least, at the end of a project;
  • Often, in the form of a report or memorandum to file.

• Likewise, “Knowledge Management” efforts are noted, focusing on encoding what is deemed important for future work of others.

• Measuring effectiveness of such practices:
  • Instead of how often the data is referred to, how about . . .
  • how frequently related future work that could be impacted is effectively impacted, versus repeating similar work or problem consequences.
Lessons Learned Report


“We should write that spot down.”
Lessons Effectively Learned?

Lessons Learned Report


“Well, what the? ... I thought I smelled something.”

Copyright Gary Larson, The Far Side
3. System of Innovation (SOI)
2. Target System (and Component) Life Cycle Domain System
1. Target System

Learning & Knowledge Manager for Target System

LC Manager of Target System

(Substantially all the ISO 15288 processes are included in all four Manager roles)

Copyright Gary Larson, The Far Side

“Didn’t get the meme”

Copyright Gary Larson, The Far Side

“Well, what the? ... I thought I smelled something.”
Lessons Learned: Effective Learning?

• Where are the “lessons learned” encoded? What would cause them to be accessed?

• Compare to biology:
  • “Muscle Memory” builds “motor” learning directly into a future situation, for future unconscious use, vs. syllogistic reasoning that may not be remembered fast enough, or at all
  • This is about “effective learning” for future agile use
  • Just having a growing file of “lessons learned”, even if text searchable, is not the same as building what we learn directly in line with the path of future related work that will have to access it in order to be executed.

• Just because we label a report “lessons learned” does not mean that those who will need this information in the future will have access to it.
Learned models from STEM (~300 years) offer the most dramatic example of positive collaborative impact of effectively **shared** and **validated** models

- **Effective Model Sharing:**
  - We cannot view MBSE as mature if we perform modeling “from scratch”, instead of building on what we (*including others*) already know.
  - This is the basis of MBSE Patterns, Pattern-Based Systems Engineering (PBSE), and the work of the INCOSE MBSE Patterns Working Group.
  - S1 Patterns are built directly into future S2 project work of other people—effective sharing only occurs to extent it impacts future tasks performed by others.
  - This sharing may occur across individuals, departments, enterprises, domains, markets, society.
  - It applies not only to models of S1 (by S2), but also models of S2 (by S3).

- **Effective Model Validation:**
  - Especially when shared, models demand that we **trust** them.
  - This is the motivation for Model Validation, Verification, and Uncertainty Quantification (Model VVUQ) being pursued with ASME standards committees.
  - Effectiveness of Model VVUQ is essential to MBSE Maturity.
  - Because Model VVUQ adds significantly to the cost of a trusted model, MBSE Patterns are all the more important—they IP of enterprises, industries.
An emerging special case: Regulated markets

- Increasing use of computational models in safety-critical, other regulated markets is driving development of methodology for Model VVUQ:
  - See, for example, ASME V&V 10, 20, 30, 40, 50, 60.

- Models have economic advantages, but the above can add new costs to development of models for regulatory submission of credible evidence:
  - Cost of evidentiary submissions to FDA, FAA, NRC, NTSB, EPA, OSHA, when supported by models—includes VVUQ of those models.

- This suggests a vision of collaborative roles for engineering professional societies, along with regulators, and enterprises:
  - Trusted shared MBSE Patterns for classes of systems
  - Configurable for vendor-specific products
  - With Model VVUQ frameworks lowering the cost of model trust for regulatory submissions

- Further emphasizes the issue of trust in models...
An emerging special case: Regulated markets

- Trusted shared MBSE Patterns for classes of systems
- Configurable for vendor-specific products
- With Model VVUQ frameworks lowering the cost of model trust for regulatory submissions

(Substantially all the ISO15288 processes are included in all four Manager roles)
1. Identify and list the opportunities in your enterprise and process to capture what is learned in system patterns used as the basis of future projects.

2. Which are System 1 and which are System 2?
Can You Trust Someone Else’s Model? Your Model?

• Planning for Model Verification, Validation, and Uncertainty Quantification (Model VVUQ)
Requirements for **trustable** models

We cannot discuss maturity in development or use of models without discussing whether we can **trust** those models . . .
If we expect to use models to support critical decisions, then we are placing *increased trust in models*:

- Critical financial, other business decisions
- Human life safety
- Societal impacts
- Extending human capability

MBSE Maturity requires that we *characterize the structure of that trust* and manage it:

- The Validation, Verification, and Uncertainty Quantification (VVUQ) *of the models themselves.*
What is meant by VVUQ of a model?

- Model Validation (V)
- Model Verification (V)
- Model Uncertainty Quantification (UQ)
- Not just for numerical grid (FEA, CFD, Thermal) models—extension to system models at all levels.
- Bayesian Network aspects of UQ
V&V of Models, Per Emerging ASME Model V&V Standards

Does the Model adequately describe what it is intended to describe?

- Model Validation
- Model validated?
- Model verified?
- Model Verification

Does the Model implementation adequately represent what the Model says?

V&V of Systems, Per ISO 15288 & INCOSE Handbook

Do the System Requirements describe what stakeholders need?

- System Validation
- Requirements validated?
- Design verified?
- System Verification

Does the System Design define a solution meeting the System Requirements?

Don’t forget: A model (on the left) may be used for system verification or validation (on the right!)
Quantitative Fidelity, including Uncertainty Quantification (UQ)

- There is a large body of literature on a mathematical subset of the UQ problem, in ways viewed as the heart of this work.
- But, some additional systems work is needed, and in progress, as to the more general VVUQ framework, suitable for general standards or guidelines.

General structure of uncertainty / confidence tracing:

- Do the modeled external Interactions qualitatively cover the modeled Stakeholder Features over the range of intended S1 situations of interest?
- Quantify confidence / uncertainty that the modeled Stakeholder Feature Attributes quantitatively represent the real system concerns of the S1 Stakeholders with sufficient accuracy over the range of intended situation envelopes.
- Quantify confidence / uncertainty that the modeled Technical Performance Attributes quantitatively represent the real system external behavior of the S1 system with sufficient accuracy over the range of intended situation envelopes.
Related ASME activities and resources

• ASME, has an active set of teams writing guidelines and standards on the Verification and Validation of Computational Models.
  • Inspired by the proliferation of computational models (FEA, CFD, Thermal, Stress/Strain, etc.)
  • It could fairly be said that this historical background means that effort was not focused on what most systems engineers would call “system models”
• Also conducts annual Symposium on Validation and Verification of Computational Models, in May.
• To participate in this work, in 2016 the speaker joined the ASME VV50 Committee:
  • With the idea that the framework ASME set as foundation could apply well to systems level models; and . . .
  • with a pre-existing belief that system level models are not as different from discipline-specific physics models as believed by systems community.
• Also invited sub-team leader Joe Hightower (Boeing) to address the INCOSE IW2017 MBSE Workshop, on our related ASME activity.
ASME Verification & Validation Standards Committee

- V&V 10: Verification & Validation in Computational Solid Dynamics
- V&V20: Verification & Validation in Computational Fluid Dynamics and Heat Transfer
- V&V 30: Verification and Validation in Computational Simulation of Nuclear System Thermal Fluids Behavior
- V&V 40: Verification and Validation in Computational Modeling of Medical Devices
- V&V 50: Verification & Validation of Computational Modeling for Advanced Manufacturing
- V&V 60: Verification and Validation in Modeling and Simulation in Energy Systems and Applications

https://cstools.asme.org/csconnect/CommitteePages.cfm?Committee=100003367
Requirements for trustable, impactful models, as a basis for MBSE maturity

MBSE Maturity in general, and VVUQ for Models in particular, mean we have to understand:

• Stakeholders for Models
• Stakeholder Features of Models
• Technical Requirements for Models
• We are capturing these in an MBSE Pattern

(Substantially all the ISO15288 processes are included in all four Manager roles)
Opportunities--what you can do

• Think larger about intended uses and users of MBSE, and judge its maturity in that light.
• Include how well MBSE enables group learning.
• Include the full breadth of model types in your thinking.
• Consider why you think a model should be trusted.
• Join the INCOSE MBSE Patterns Working Group, to advance practice.
• Join the ASME Computational VVUQ effort, to advance model trust.
• Exercise the emerging MBSE Planning and Assessment Framework, in your own company and work, and provide feedback.
Exercise 3: Identifying Credibility Needs for Trusted System Patterns

1. Where and when, in your enterprise organization and process, could a trusted system pattern be consulted as the basis for configuring system Requirements, Designs, Failure Analysis, Manufacturing, Distribution, Support, or otherwise? (Hint: Consider your answers to Exercise 2.)

2. What would be the model credibility issues that would need to be addressed? What could be the benefits of a trustable model?
End of Part I