GLRC 11

Bill Schindel,

ICTT System Sciences

schindel@ictt.com

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

11th Annual INCOSE Great Lakes Regional Conference

SUPERIOR SYSTEM SOLUTIONS FOR TODAY'S COMPLEX ENVIRONMENTS

11 - 14 October 2017 Twin Cities, Minnesota

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.

Tutorial Summary Outline

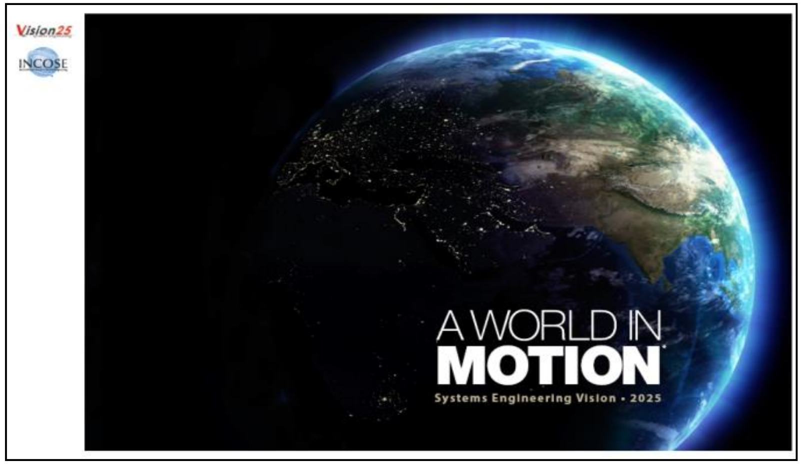
Part I (Morning):

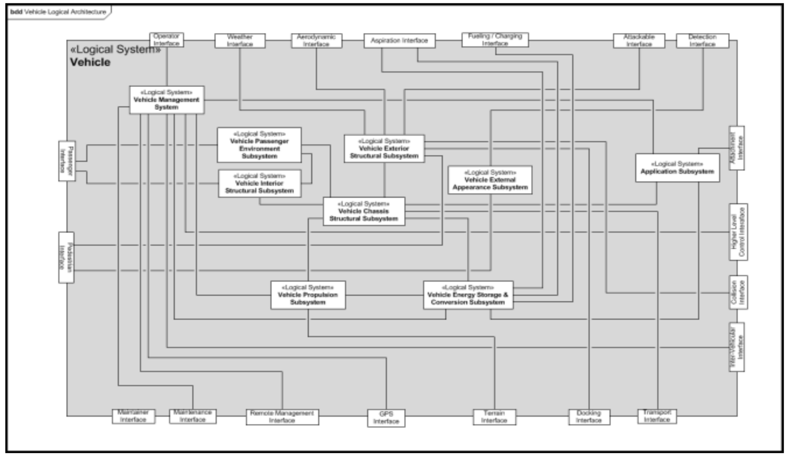
- **<u>Targeting Purpose</u>**: Planning development, use, and life cycle of models based on a standard model planning framework, neutral as to modeling tools, languages, methods
- **<u>Institutionalizing Learning</u>**: Practical steps to improve on organizational learning, using models as a focus of organizational learning and knowledge, based on model-based Learning Systems and Autonomous Systems.
- **<u>Enabling Trust</u>**: Can You Trust Someone Else's Model? Your Model? Planning for Model Verification, Validation, and Uncertainty Quantification (VVUQ)

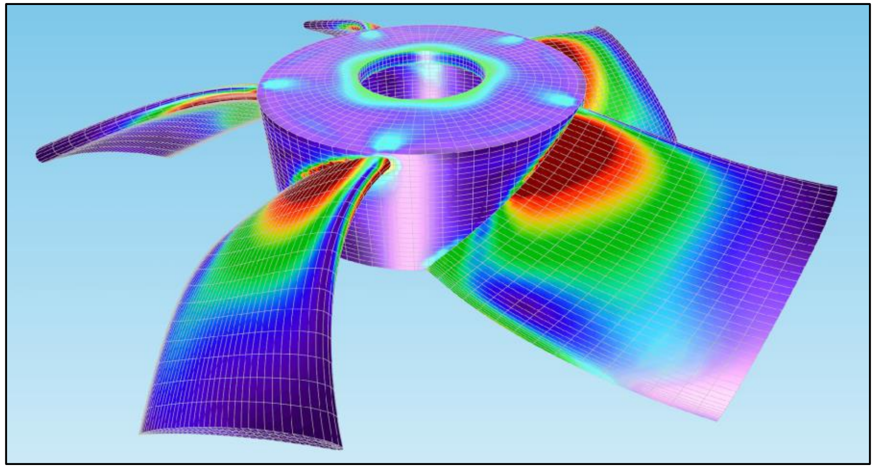
Part II (Afternoon):

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

Enthusiasm for Models



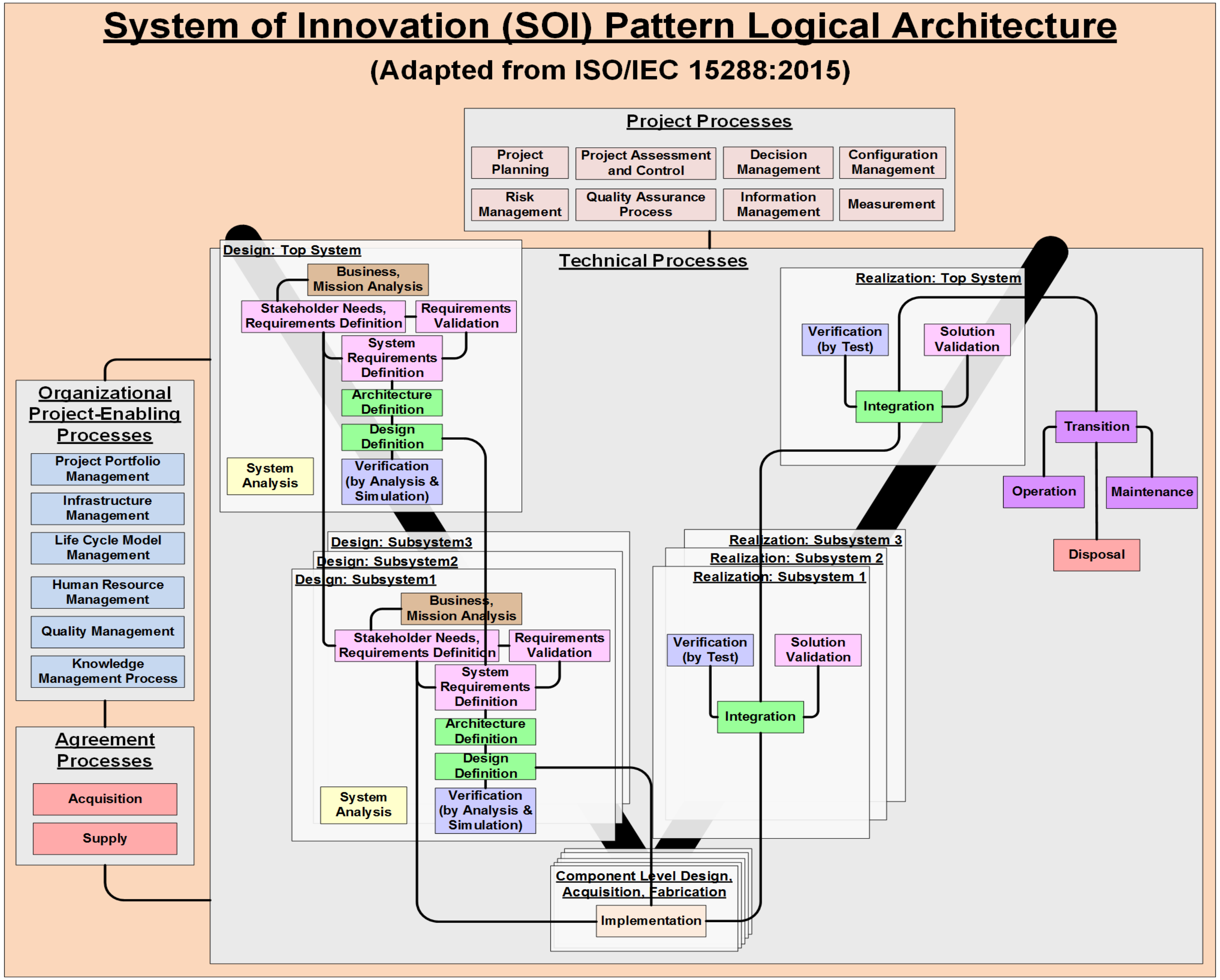




The INCOSE systems community has shown growing enthusiasm for “engineering with models” of all sorts:

- 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

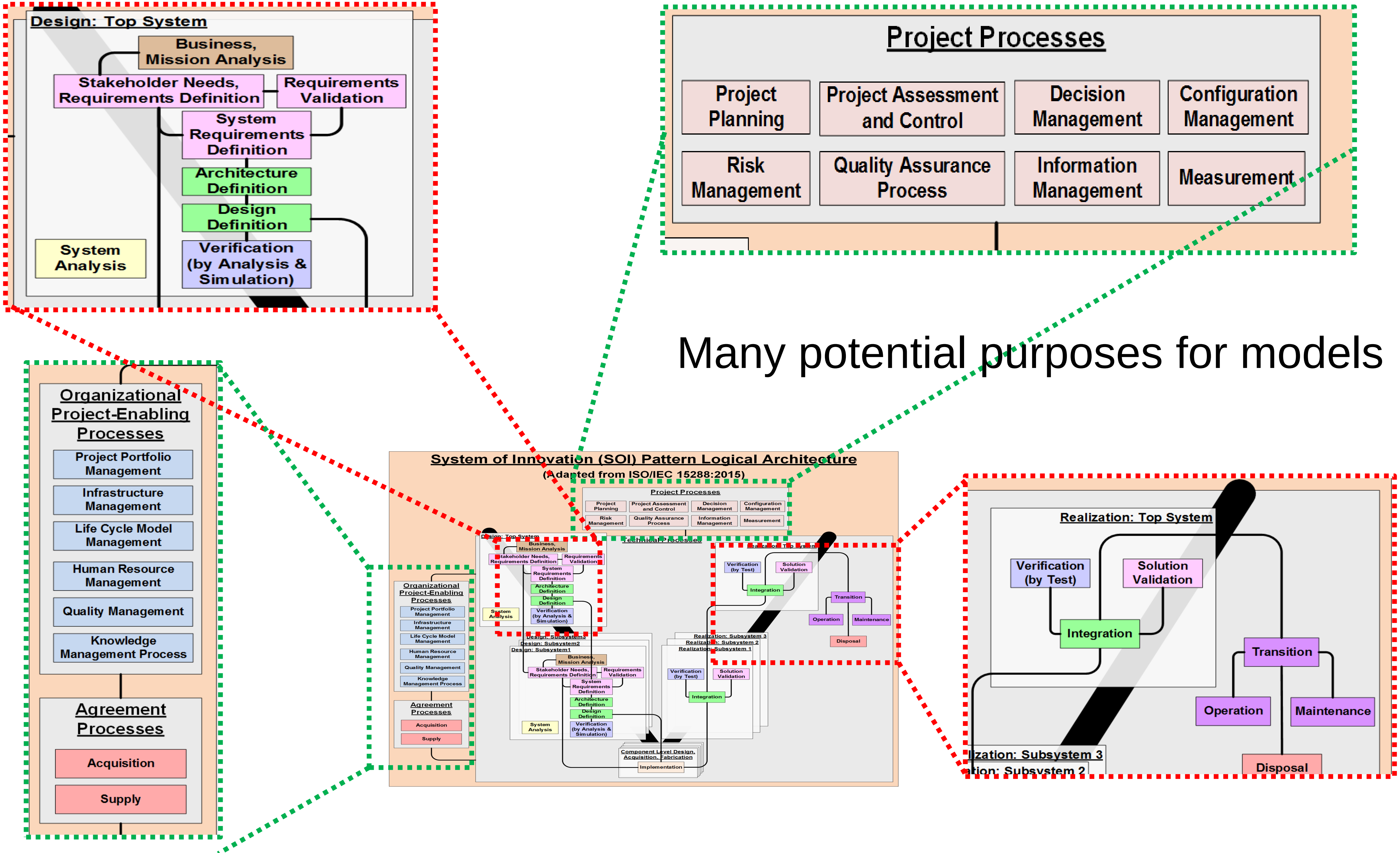
Models for what purposes? Possible ISO15288 answers.



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



Targeting Purpose: Connections to ISO15288

- 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.

Targeting Purpose: Connections to ISO15288

- 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.

INCOSE MB Transformation; planning and 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 . . .

INCOSE MB Transformation; 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 Improvers);
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.

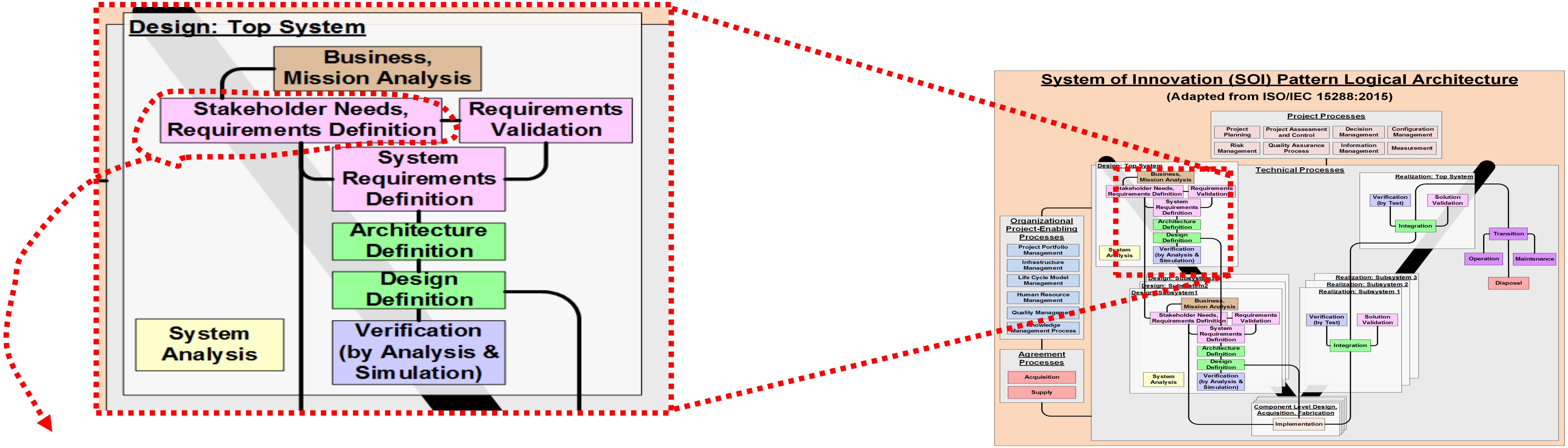
Further analysis of the Transformation Stakeholders

(also shows Energy Tech 2016 Conference ratings of needs, opportunities)

Population <-- Size (Log)	Stakeholders in A Successful MBSE Transformation (showing their related roles and parent organizations)	Industry & Gvmt. Initiatives	Organizations Internalizing MBSE, Including Gvmt Contractors & Commercial	Vendors of MBSE Tooling and Services	Academia and Researchers	Technical Societies, Other Non-Technical Organizations
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.	x	x			x
**	Technical model users, including designers, project leads, production engineers, system installers, maintainers, and users/operators.	x	x			x
*	Leaders responsible to building their organization's MBSE capabilities and enabling MBSE on their projects	x	x			x
Model Creators (including Model Improvers):						
*	Product visionaries, marketers, and other non-technical leaders of thought and organizations	x	x		x	x
*	System technical specifiers, designers, testers, theoreticians, analysts, scientists	x	x		x	x
*	Students (in school and otherwise) learning to describe and understand systems				x	x
*	Educators, teaching the next generation how to create with models	x	x		x	
*	Researchers who advance the practice		x	x	x	
*	Those who translate information originated by others into models	x	x		x	x
*	Those who manage the life cycle of models	x	x		x	x
Complex Idea Communicators (Model "Distributors"):						
**	Marketing professionals	x	x	x		x
**	Educators, especially in complex systems areas of engineering and science, public policy, other domains, and including curriculum developers as well as teachers	x	x	x	x	
**	Leaders of all kinds	x	x	x	x	x
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			x		
*	Methodologists, consultants, others who assist individuals and organizations in being more successful through model-based methods	x	x	x	x	
*	Standards bodies (including those who establish modeling standards as well as others who apply them within other standards)	x				x
INCOSE and other Engineering Professional Societies						
*	As a deliverer of value to its membership					x
*	As seen by other technical societies and by potential members					x
*	As a great organization to be a part of					x
*	As promoter of advance and practice of systems engineering and MBSE					x

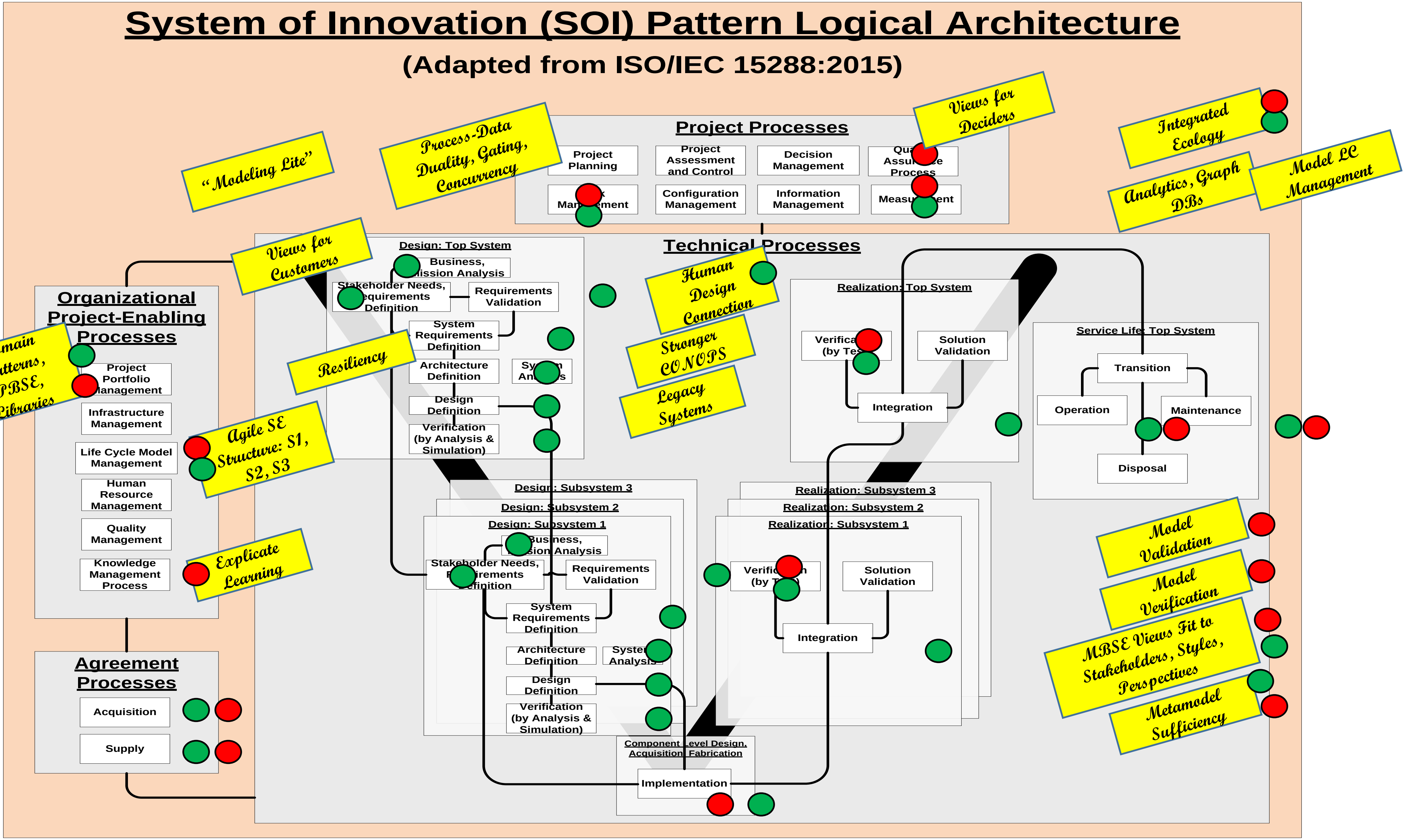
12

Each 15288 process definition suggests potentially assessable model impacts



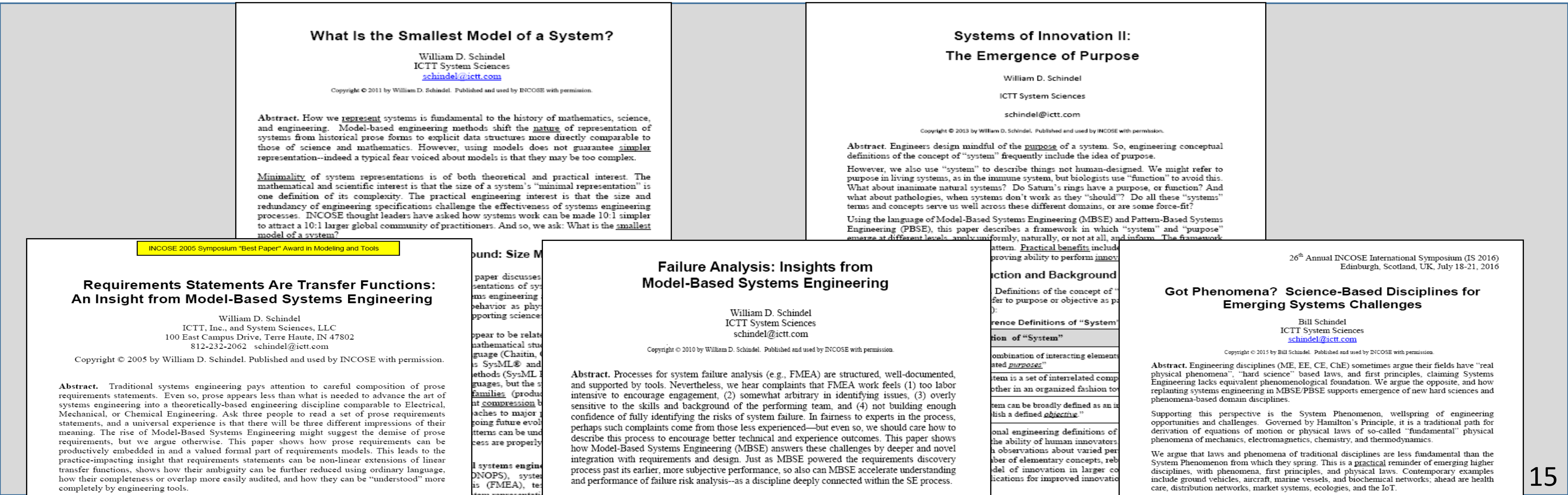
a) “Stakeholders of the system are identified.
b) Required characteristics and context of use of capabilities and concepts in the life cycle stages, including operational concepts, are defined.
c) Constraints on a system are identified.
d) Stakeholder needs are defined.
e) Stakeholder needs are prioritized 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.”

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



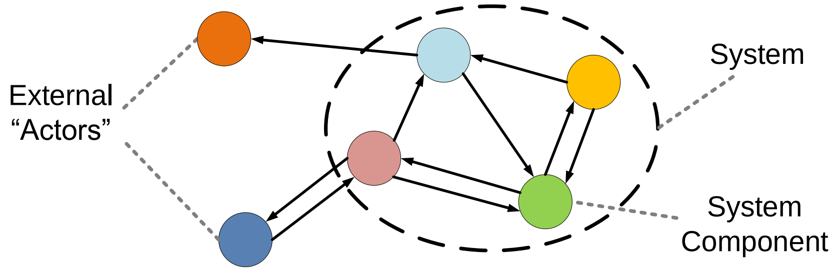
Sufficiency for Purposes; Minimality

- 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.
  - 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)

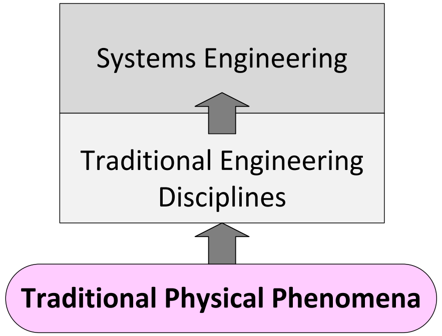


Scientific heritage (~300 years)

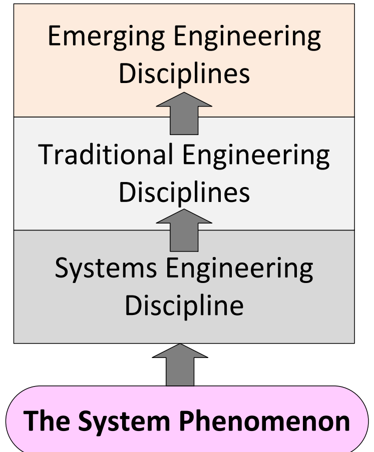
- The eventual flowering of the physical sciences depended upon the emergence of strong enough underlying model constructs (of math, physics) to better represent Nature.
- Specifically, the System Phenomenon (Newton, Lagrange, Hamilton):



A traditional view of systems engineering

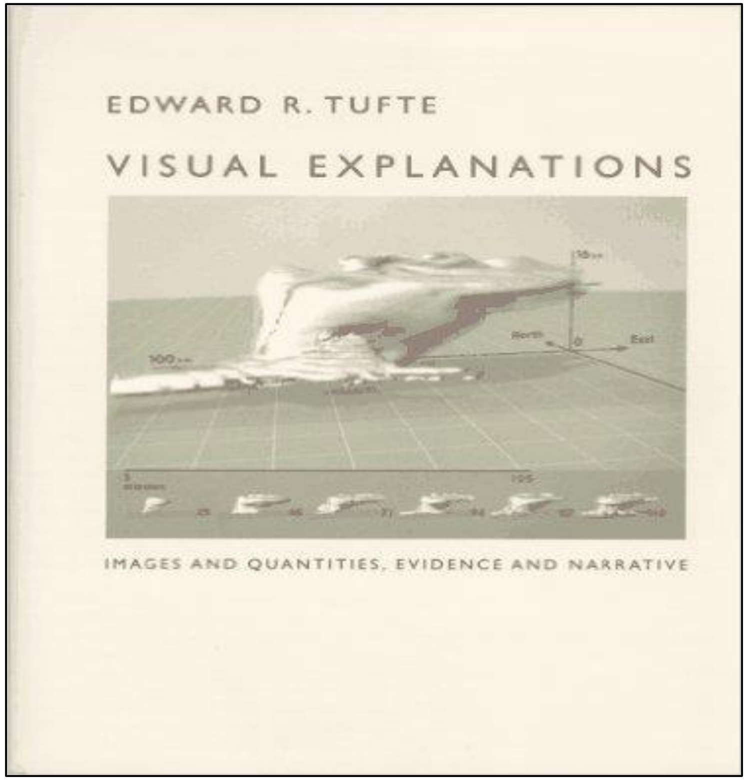


Our view of systems engineering



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

Model Stakeholder Type	Definition
Model User	A person, group, or organization that directly uses a model for its agreed upon purpose. May include technical specialists, non-technical decision-makers, customers, supply chain members, regulatory authorities, or others.
Model Developer	A person who initially creates a model, from conceptualization through implementation, validation, and verification, including any related model documentation. Such a person may or may not be the same as one who subsequently maintains the model.
Model Maintainer	A person who maintains and updates a model after its initial development. In effect, the model maintainer is a model developer after the initial release of a model.
Model Deployer-Distributor	A person or organization that distributes and deploys a model into its intended usage environment, including transport and installation, through readiness for use.
Model Use Supporter	A person who supports or assists a Model User in applying a model for its intended use. This may include answering questions, providing advice, addressing problems, or other forms of support.
Regulatory Authority	An organization that is responsible for generating or enforcing regulations governing a domain.
Model Investor-Owner	A person or organization that invests in a model, whether through development, purchase, licenses, or otherwise, expecting a benefit from that investment.

INCOSE
International Council on Systems Engineering

INCOSE MBSE Assessment and Planning Pattern: Model Stakeholder Features Overview

Model Identity and Focus

- **Modeled System of Interest**
  - System of Interest
- **Modeled Environmental Domain**
  - Domain Type

Model Utility

- **Model Intended Use**
  - LIFE CYCLE PROCESS SUPPORTED (ISO15288)
- **Perceived Model Value and Use**
  - USER GROUP SEGMENT
  - Level of Annual Use
  - Value Level
- **Third Party Acceptance**
  - ACCEPTING AUTHORITY
- **Model Ease of Use**
  - Perceived Model Complexity

Model Scope and Content

- **Modeled Stakeholder Value**
  - STAKEHOLDER TYPE
- **Modeled System External (Black Box) Behavior**
- **Explanatory Decomposition**
- **Failure Modes and Effects**
- **Parametric Couplings--Fitness**
- **Parametric Couplings--Decomposition**
- **Parametric Couplings--Characterization**
- **Trusted Configurable Pattern**
  - CONFIGURATION ID
  - Pattern Type
- **Physical Architecture**
- **Managed Model Datasets**
  - DATASET TYPE

Model Credibility

- **Model Envelope**
  - MODEL APPLICATION ENVELOPE
- **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

Model Representation

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

Model Life Cycle Management

- **Model Versioning and Configuration Management**
  - CM CAPABILIY TYPE
- **Model Maintainability**
  - Maintenance Method
- **Model Deployability**
  - Deployment Method
- **Model Cost**
  - Development Cost
  - Operational Cost
  - Maintenance Cost
  - Deployment Cost
  - Retirement Cost
  - Life Cycle Financial Risk
- **Executable Model Environmental Compatibility**
  - IT ENVIRONMENTAL COMPONENT
- **Model Design Life Cycle and Retirement**
  - Design Life
- **Model Availability**
  - First Availability Date
  - First Availability Risk
  - Life Cycle Availability Risk
- **VVUQ Pattern Learning**
  - VVUQ PATTERN EXCEPTION
  - Impacted VVUQ Feature
  - VVUQ Pattern Version
  - Project
  - Person

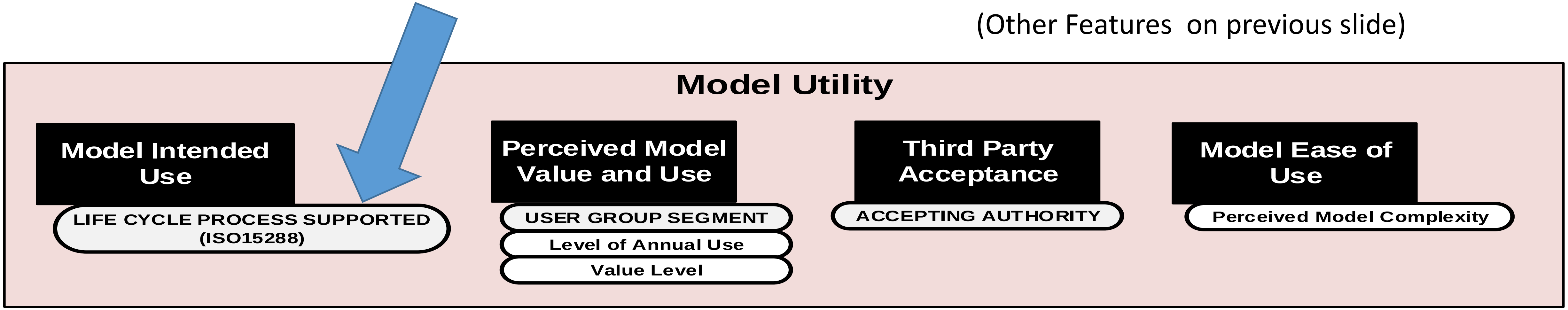
Legend:

- **STAKEHOLDER FEATURE**
  - FEATURE PK ATTRIBUTE
  - Other Feature Attribute
  - Other Feature 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

(Other Features on previous slide)



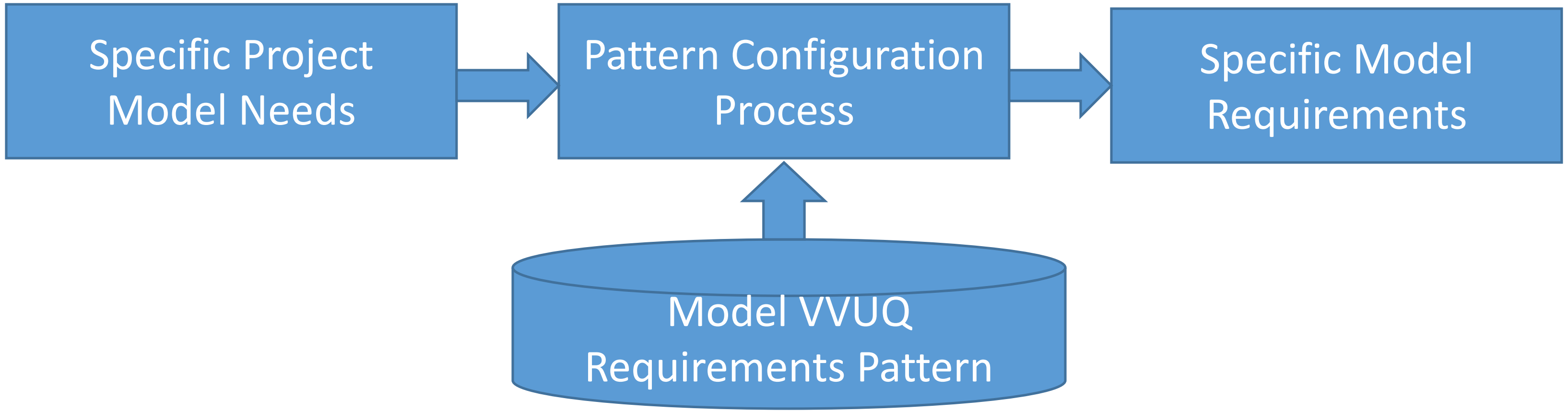
Feature Group	Feature Name	Feature Definition	Feature Attribute	Attribute Definition	Feature Stakeholder: Model User	Model Developer	Model Maintainer	Mdl Deployer-Distributor	Model Use Supporter	Regulatory Authority	Mdl Investor-Owner	Model Type: Physics Based	Data Driven
Describes the intended use, utility, and value of the model													
Model Utility	Model Intended Use	The intended purpose(s) or use(s) of the model.	Life Cycle Process Supported	The intended life cycle management process to be supported by the model, from the ISO15288 process list. More than one value may be listed.	X					X	X	x	x
	Perceived Model Value and Use	The relative level of value ascribed to the model, by those who use it for its stated purpose.	User Group Segment	The identify of using group segment (multiple)	X					X	X	x	x
			Level of Annual Use	The relative level of annual use by the segment	X					X	X	x	x
			Value Level	The value class associated with the model by that segment	X					X	X	x	x
	Third Party Acceptance	The degree to which the model is accepted as authoritative, by third party regulators, customers, supply chains, and other entities, for its stated purpose.	Accepting Authority	The identity (may be multiple) of regulators, agencies, customers, supply chains, accepting the model	X					X	X	x	x
	Model Ease of Use	The perceived ease with which the model can be used, as experienced by its intended users	Perceived Model Complexity	High, Medium Low	X					X		x	x

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.

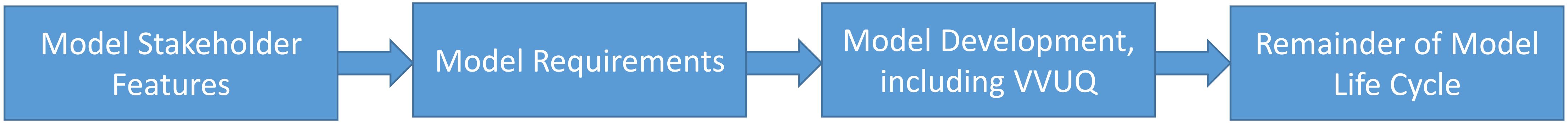
Vision for a Practical Aid to Model Community

- 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:

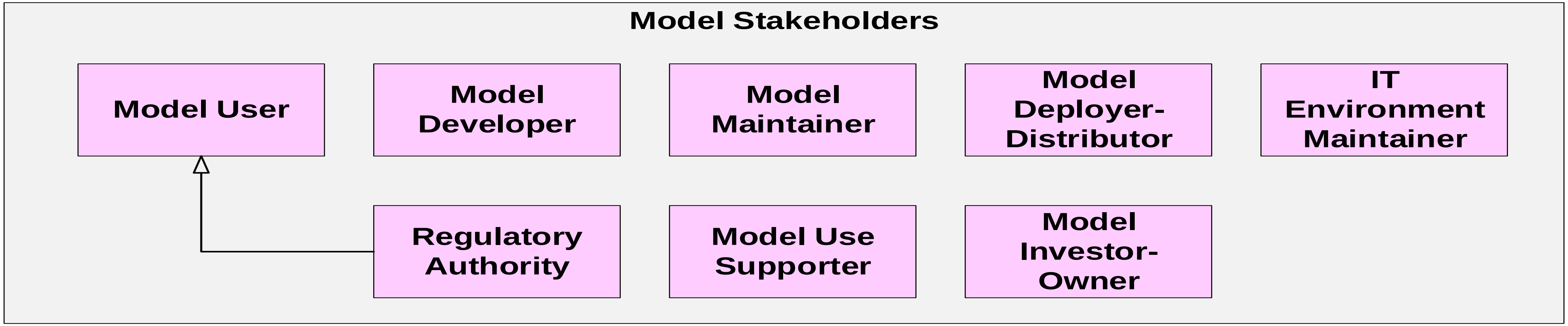


Vision for a Practical Aid to Model Community

- The foundation of this capability are the computational model’s Stakeholder Features and the computational model’s Requirements . . .



Stakeholders for Models



Model Stakeholder Type	Definition
Model User	A person, group, or organization that directly uses a model for its agreed upon purpose. May include technical specialists, non-technical decision-makers, customers, supply chain members, regulatory authorities, or others.
Model Developer	A person who initially creates a model, from conceptualization through implementation, validation, and verification, including any related model documentation. Such a person may or may not be the same as one who subsequently maintains the model.
Model Maintainer	A person who maintains and updates a model after its initial development. In effect, the model maintainer is a model developer after the initial release of a model.
Model Deployer-Distributor	A person or organization that distributes and deploys a model into its intended usage environment, including transport and installation, through readiness for use.
Model Use Supporter	A person who supports or assists a Model User in applying a model for its intended use. This may include answering questions, providing advice, addressing problems, or other forms of support.
Regulatory Authority	An organization that is responsible for generating or enforcing regulations governing a domain.
Model Investor-Owner	A person or organization that invests in a model, whether through development, purchase, licenses, or otherwise, expecting a benefit from that investment.
IT Environment Maintainer	A person or organization that maintains the IT environment utilized by a computational model.

Computational Model Feature Groups: Configurable for Specific Models

Model Identity and Focus

Identifies the main subject or focus of the model.

Model Utility

Describes the intended use, user, utility, and value of the model.

Model Scope and Content

Describes the scope of content of the model.

Model Credibility

Describes the credibility of the model.

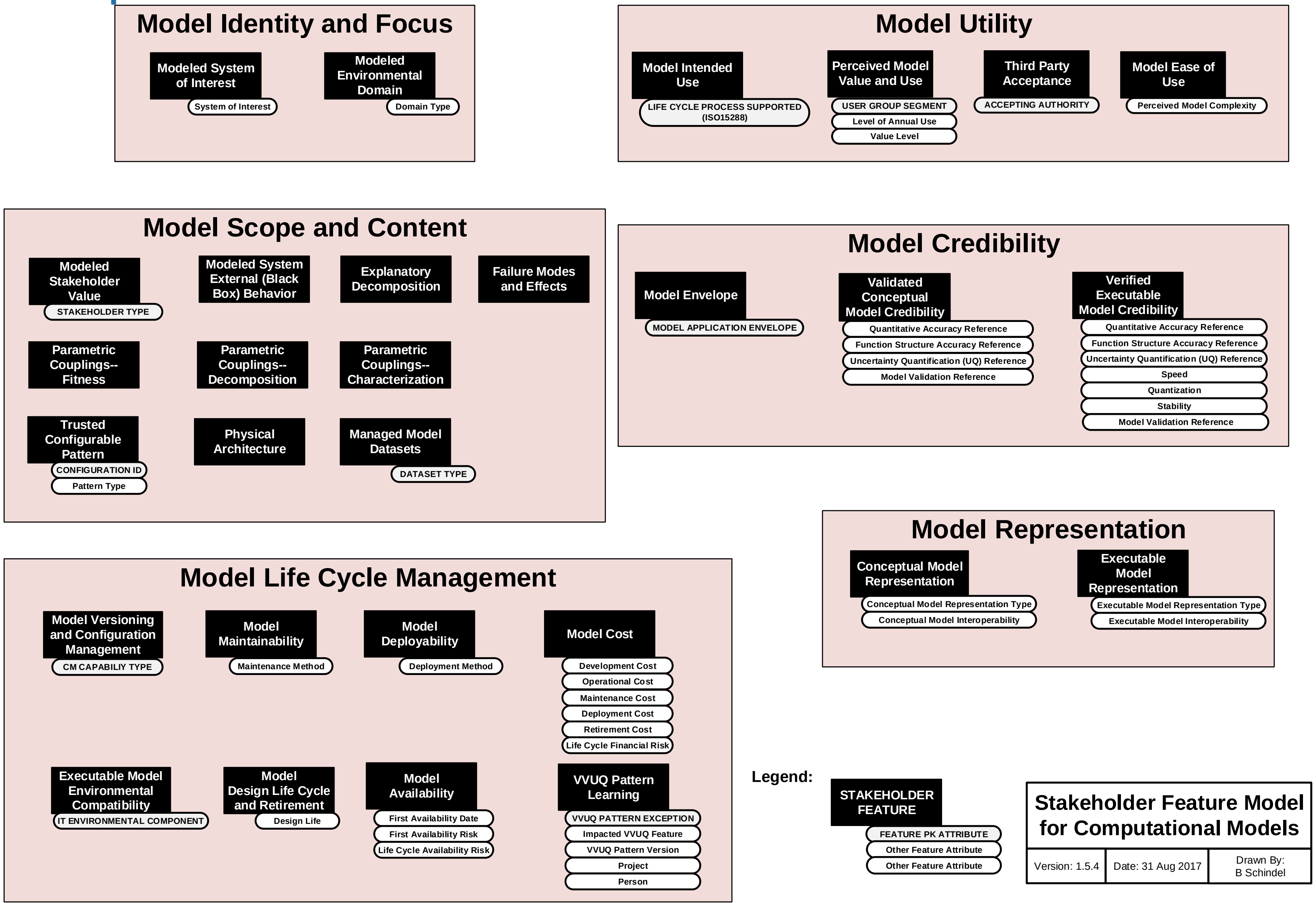
Model Representation

Describes the representation used by the model.

Model Life Cycle Management

Describes the related model life cycle management capabilities.

Computational Model Feature Groups: 27 Features, in 6 Feature Groups, Configurable for Specific Models

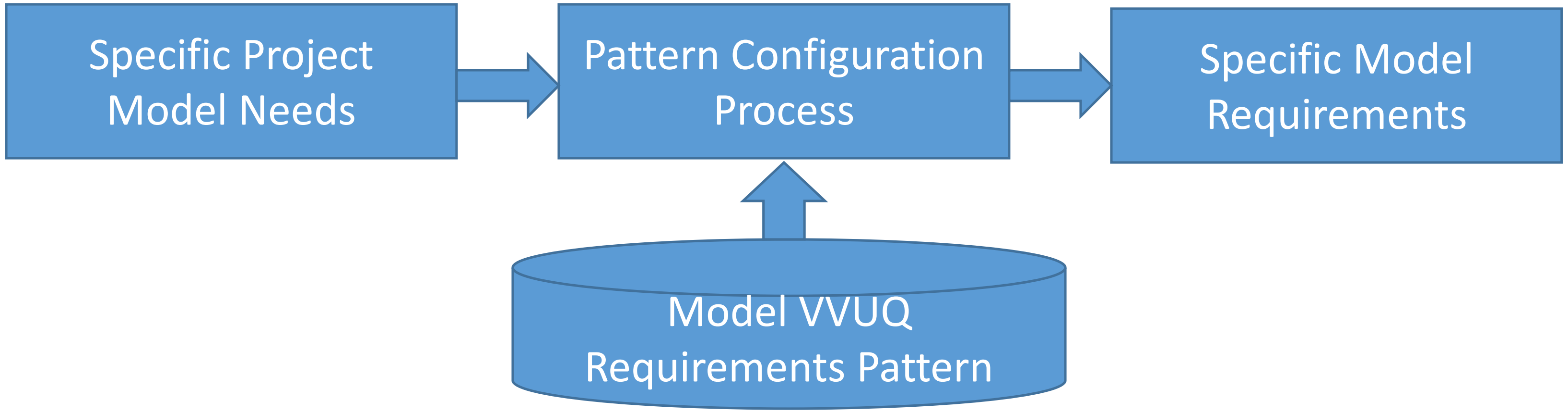


Computational Model Feature Groups: Configurable for Specific Models

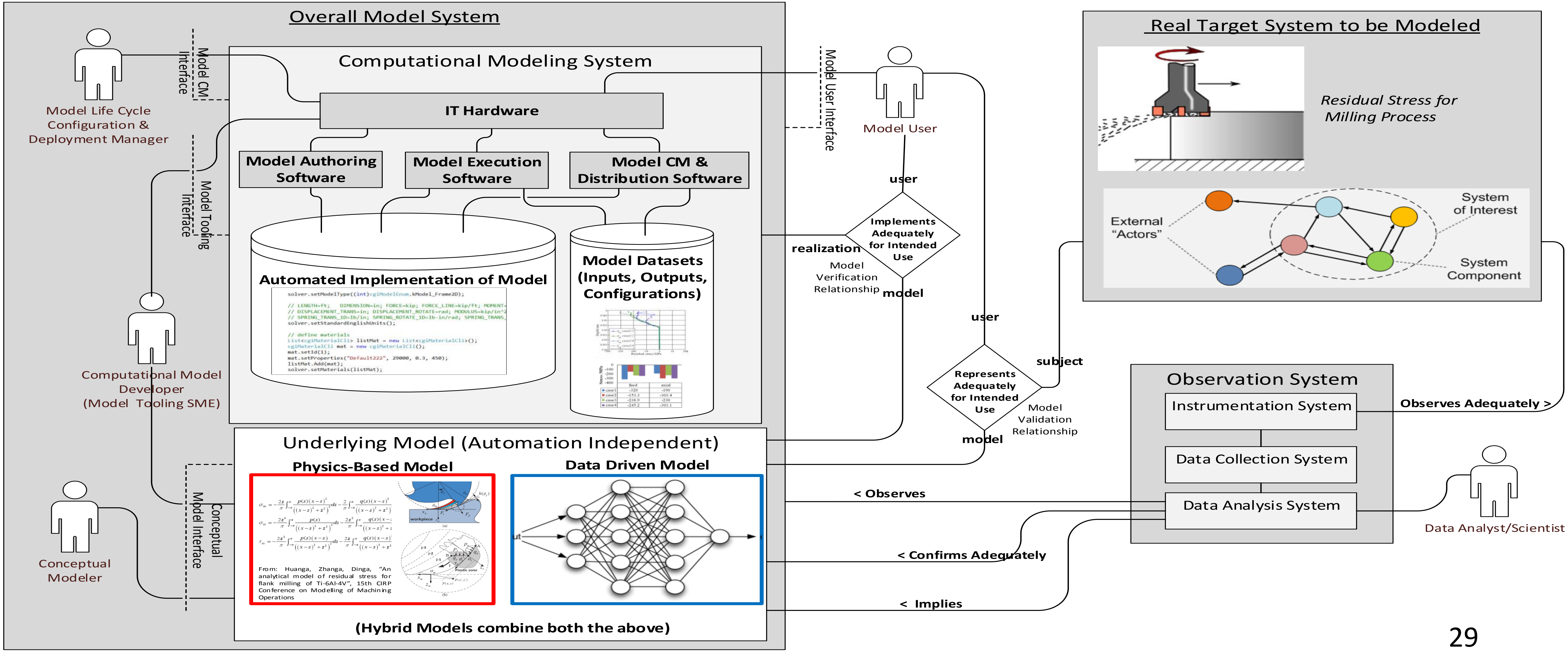
- The Stakeholder Features are configurable Stakeholder expectations, intentions, and valued aspects for a computational model:
  - These can be “configured” like Lego® blocks, as a form of checklist to rapidly create the stakeholder-level expectations for a computational model.
  - And from them, the 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:

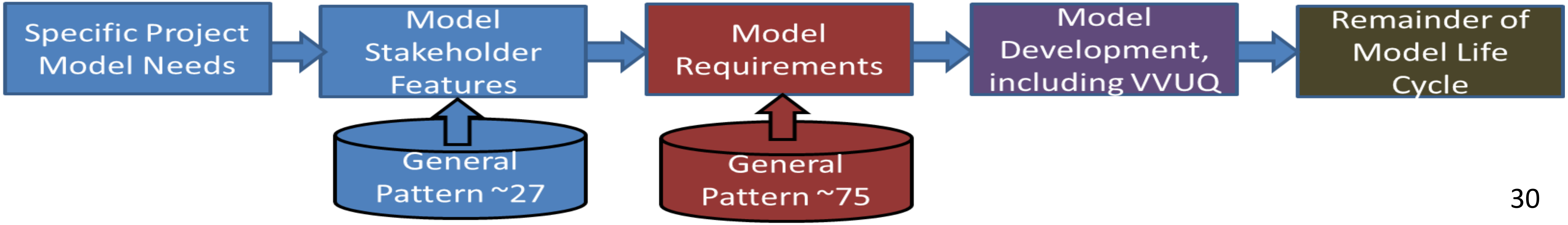


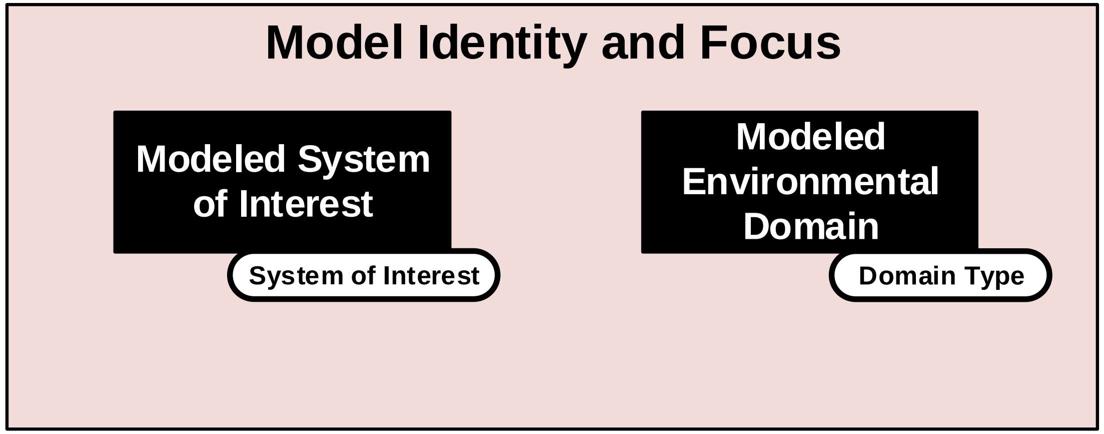
System Reference Boundaries: Computational Modeling Domain



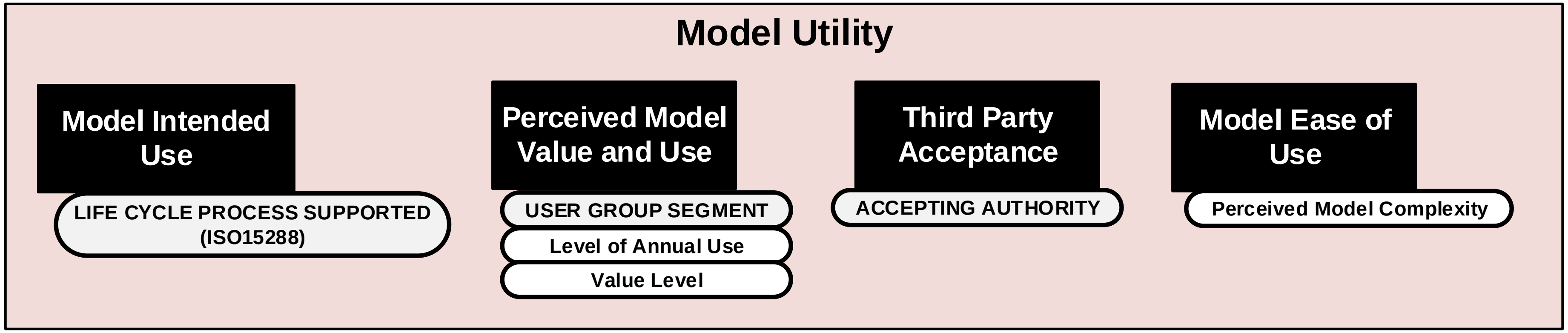
Requirements for Models

- 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.

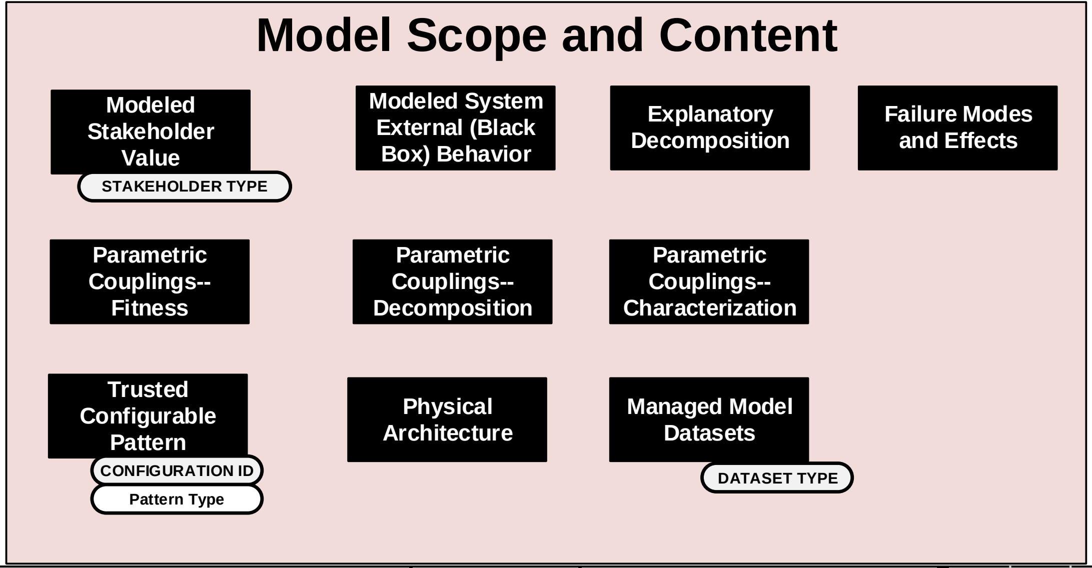




Feature Group	Feature Name	Feature Definition	Feature Attribute	Attribute Definition	Feature Stakeholder: Model User	Feature Stakeholder: Model Developer	Feature Stakeholder: Model Maintainer	Feature Stakeholder: Mdl Deployer-Distributor	Feature Stakeholder: Model Use Supporter	Feature Stakeholder: Regulatory Authority	Feature Stakeholder: Mdl Investor-Owner	Model Type: Physics Based	Model Type: Data Driven
Identifies the main subject or focus of the model													
Model Identity and Focus	Modeled System of Interest	Identifies the type of system this model describes.	System of Interest	Name of system of interest, or class of systems of interest	**X**					**X**	**X**	X	X
	Modeled Environmental Domain	Identifies the type of external environmental domain(s) that this model includes.	Domain Type(s)	Name(s) of modeled domains (manufacturing, distribution, use, etc.)	**X**					**X**	**X**	X	X

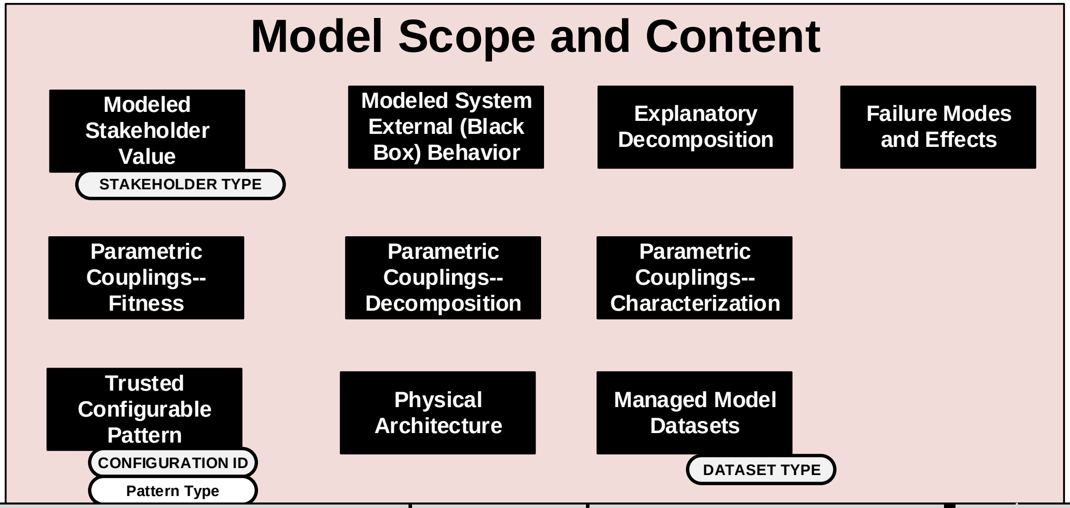


Feature Group	Feature Name	Feature Definition	Feature Attribute	Attribute Definition	Feature Stakeholder							Model Type	
					Model User	Model Developer	Model Maintainer	Mdl Deployer-Distributor	Model Use Supporter	Regulatory Authority	Mdl Investor-Owner	Physics Based	Data Driven
Describes the intended use, utility, and value of the model													
Model Utility	Model Intended Use	The intended purpose(s) or use(s) of the model.	Life Cycle Process Supported	The intended life cycle management process to be supported by the model, from the ISO15288 process list. More than one value may be listed.	**X**					**X**	**X**	X	X
	Perceived Model Value and Use	The relative level of value ascribed to the model, by those who use it for its stated purpose.	User Group Segment	The identify of using group segment (multiple)	**X**					**X**	**X**	X	X
			Level of Annual Use	The relative level of annual use by the segment	**X**					**X**	**X**	X	X
			Value Level	The value class associated with the model by that segment	**X**					**X**	**X**	X	X
	Third Party Acceptance	The degree to which the model is accepted as authoritative, by third party regulators, customers, supply chains, and other entities, for its stated purpose.	Accepting Authority	The identity (may be multiple) of regulators, agencies, customers, supply chains, accepting the model	**X**					**X**	**X**	X	X
	Model Ease of Use	The perceived ease with which the model can be used, as experienced by its intended users	Perceived Model Complexity	High, Medium Low	**X**					**X**		X	X



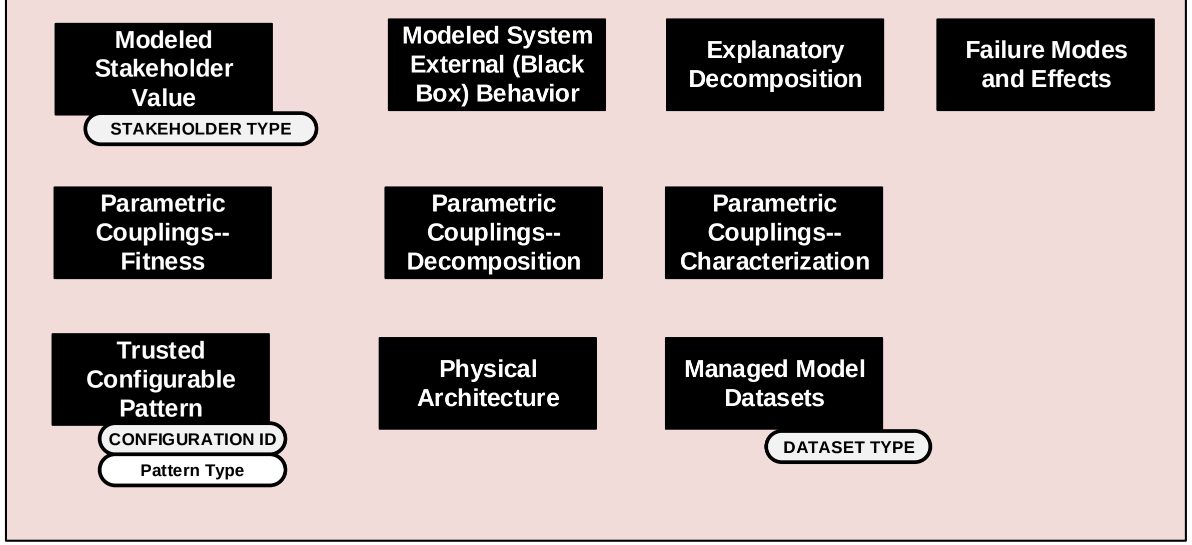
Feature Group	Feature Name	Feature Definition	Feature Attribute	Attribute Definition	Feature Stakeholder: Model User	Model Developer	Model Maintainer	Mdl Deployer-Distributor	Model Use Supporter	Regulatory Authority	Mdl Investor-Owner	Model Type: Physics Based	Data Driven
Describes the scope of content of the model													
Model Scope of Content	Modeled Stakeholder Value	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.	Stakeholder Type	Classes of covered stakeholders (may be multiple)	X					X	X	X	X
	Modeled System External (Black Box) Behavior	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.			X					X		X	X
	Explanatory Decomposition	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.			X					X		X	
	Physical Architecture	The capabiliy 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.			X					X		X	

Model Scope and Content



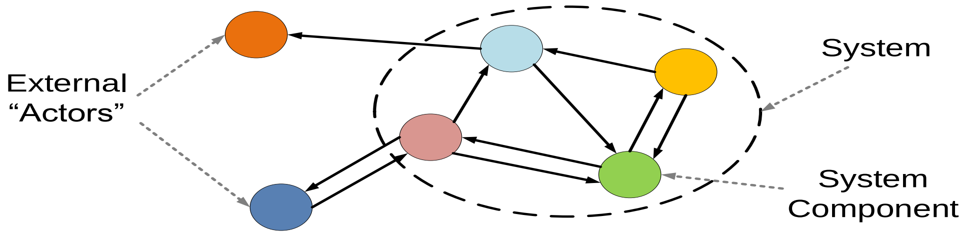
Feature Group	Feature Name	Feature Definition	Feature Attribute	Attribute Definition	Feature Stakeholder: Model User	Model Developer	Model Maintainer	Mdl Deployer-Distributor	Model Use Supporter	Regulatory Authority	Mdl Investor-Owner	Model Type: Physics Based	Data Driven
Describes the scope of content of the model													
	Parametric Couplings--Fitness	The capability of the model to represent quantitative (parametric) couplings between stakeholder-valued measures of effectiveness and objective external black box behavior performance measures.			X					X		X	X
	Parametric Couplings--Decomposition	The capability of the model to represent quantitative (parametric) couplings between objective external black box behavior variables and objective internal white box behavior variables.			X					X		X	X
	Parametric Couplings--Characterization	The capability of the model to represent quantitative (parametric) couplings between objective behavior variables and physical identity (material of construction, part or model number).			X					X		X	
	Managed Model Datasets	The capability of the model to include managed datasets for use as inputs, parametric characterizations, or outputs	Dataset Type	The type(s) of data sets (may be multiple)	X		X			X		X	X
	Trusted Configurable Pattern	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.	Configuration ID	A specific system of interest configuration within the family that the pattern framework can represent.	X		X			X	X	X	X
			Pattern ID	The identifier of the trusted configurable pattern.	X		X			X	X	X	X

Model Scope and Content

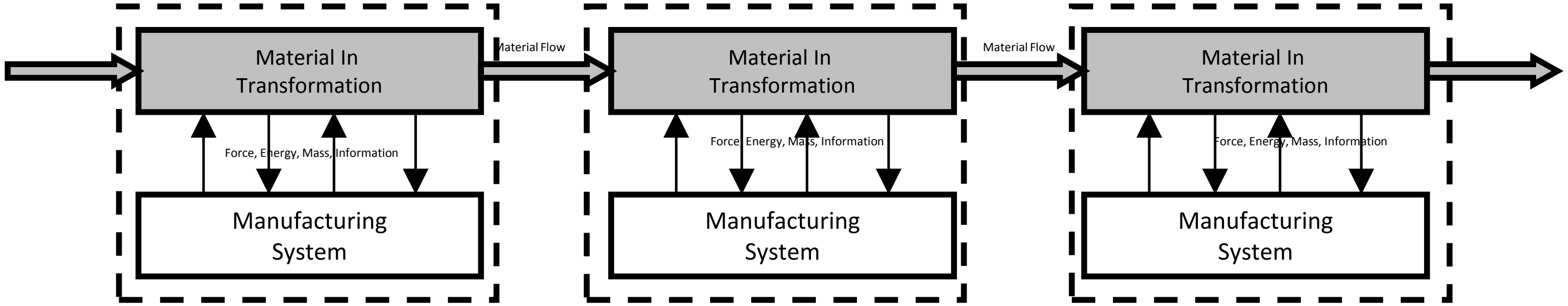


Feature Group	Feature Name	Feature Definition	Feature Attribute	Attribute Definition	Feature Stakeholder							Model Type	
					Model User	Model Developer	Model Maintainer	Mdl Deployer-Distributor	Model Use Supporter	Regulatory Authority	Mdl Investor-Owner	Physics Based	Data Driven
Describes the scope of content of the model													
Model Scope of Content	Failure Modes and Effects	The capability of the model to include identification and analysis of system failure modes, their impact effects, causes, and liklihoods of occurrence.			X					X	X	X	

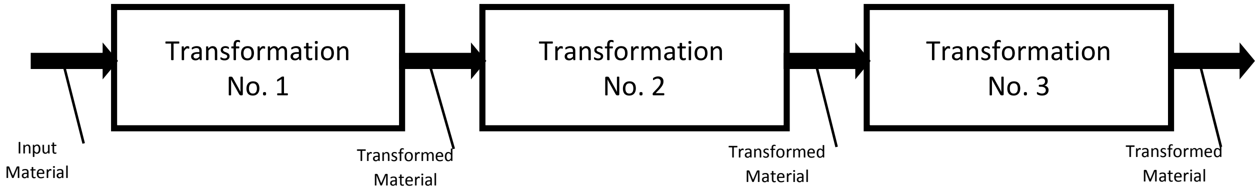
- A System is a set of interacting components:
  - By "interact", we mean exchanging energy, forces, mass flows, or information, resulting in changes of state:



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



- The "Black Box" view of a system sees only its <u>external</u> behavior
- The "White Box" view of a system sees its <u>internal</u> interactions

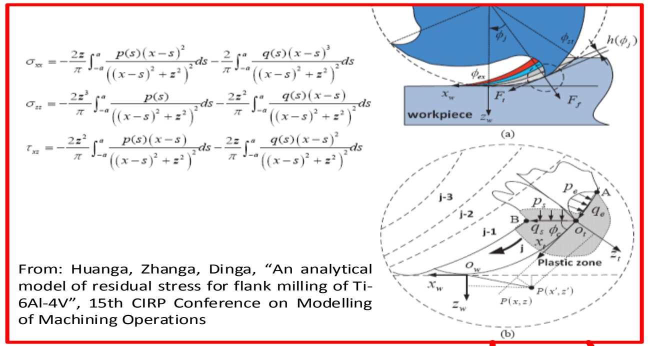


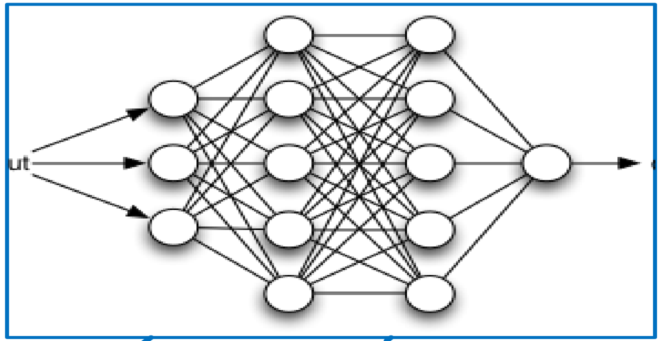
Physics-Based Model

- 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.





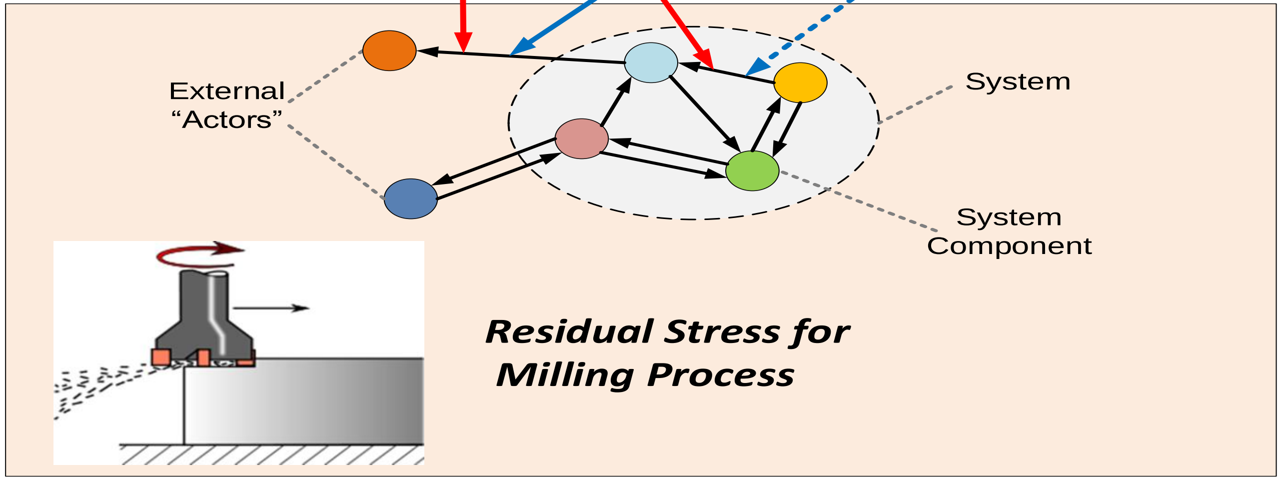
- **Physical scientists and phenomena models from their disciplines can apply here.**
- **The hard sciences physical laws, and how they can be used to explain the externally visible behavior of the system of interest.**

predicts, explains

predicts

optional

- **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.**



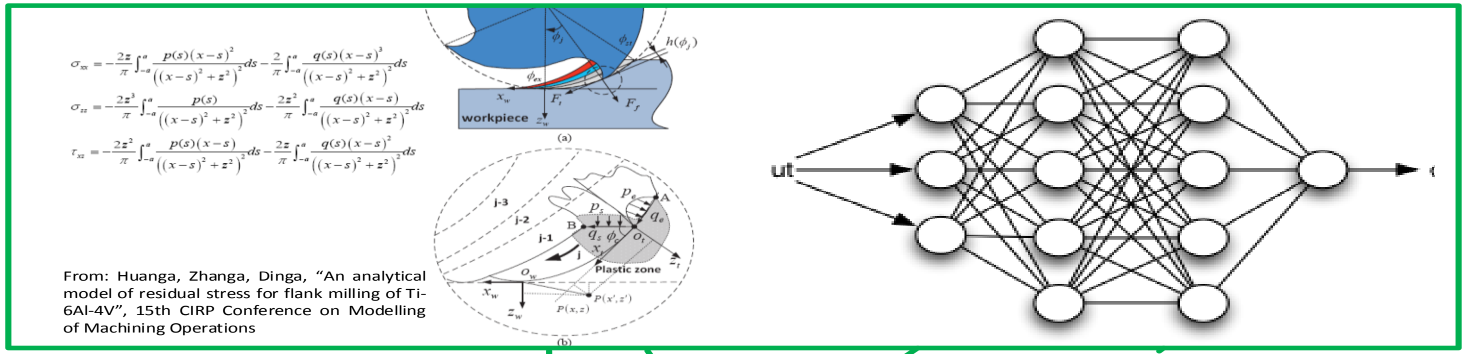
Real System Being Modeled

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.

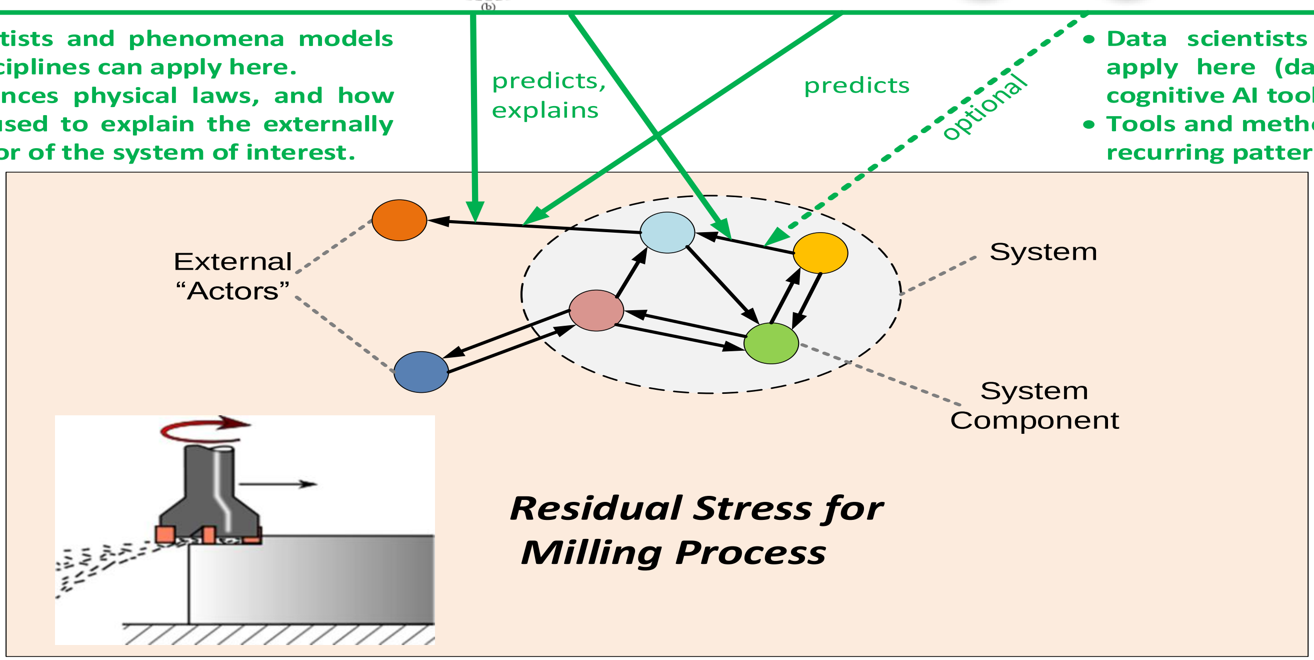
- Models (some aspects of) internal physical interactions of the System of Interest, and how they combine to cause/explain (some aspects of) externally visible behavior.
- Model has both external predictive value and (some) phenomena-based internal-to-external explanatory value.

- (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.



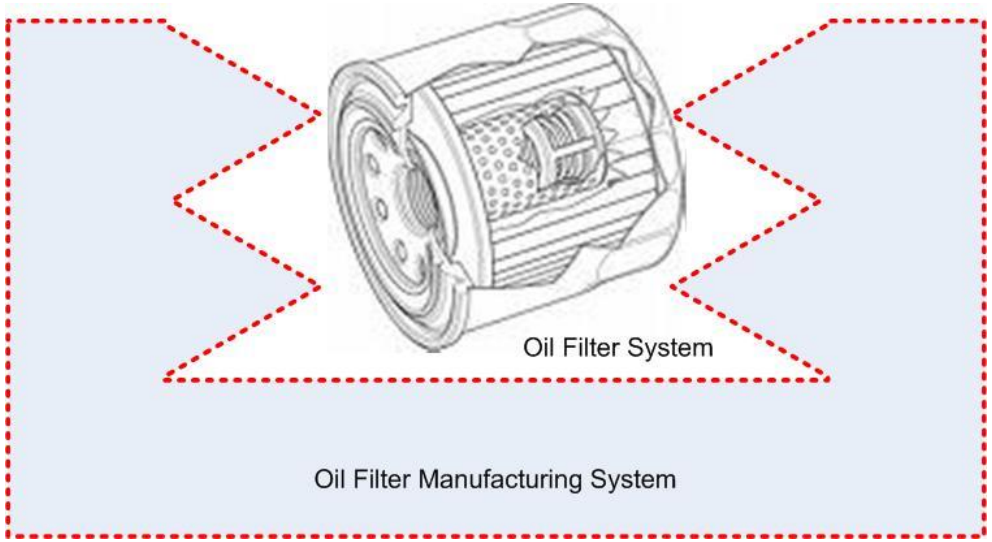
- **Physical scientists and phenomena models from their disciplines can apply here.**
- **The hard sciences physical laws, and how they can be used to explain the externally visible behavior of the system of interest.**

- **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.**



Real System Being Modeled

Samples from a simple illustrative example

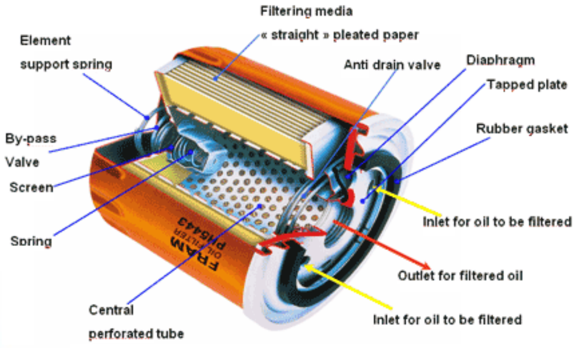


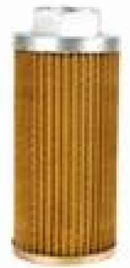
- Product: Oil Filter
- Manufacturing System: Oil Filter Mfg System

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



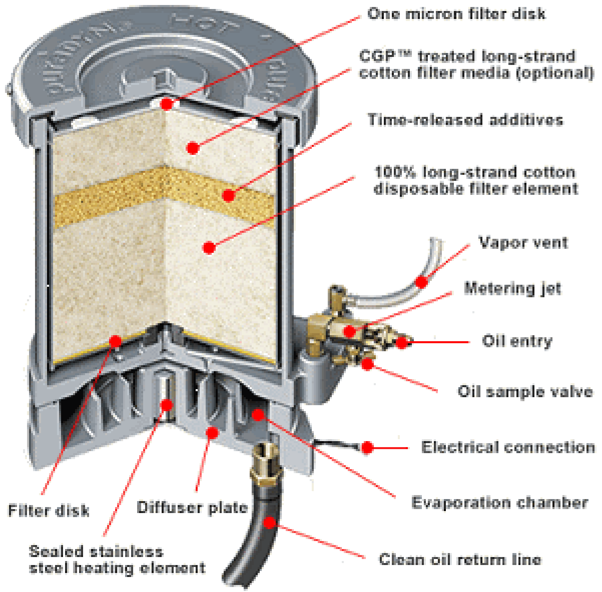


Paper
Filter Media

Synthetic
Filter Media

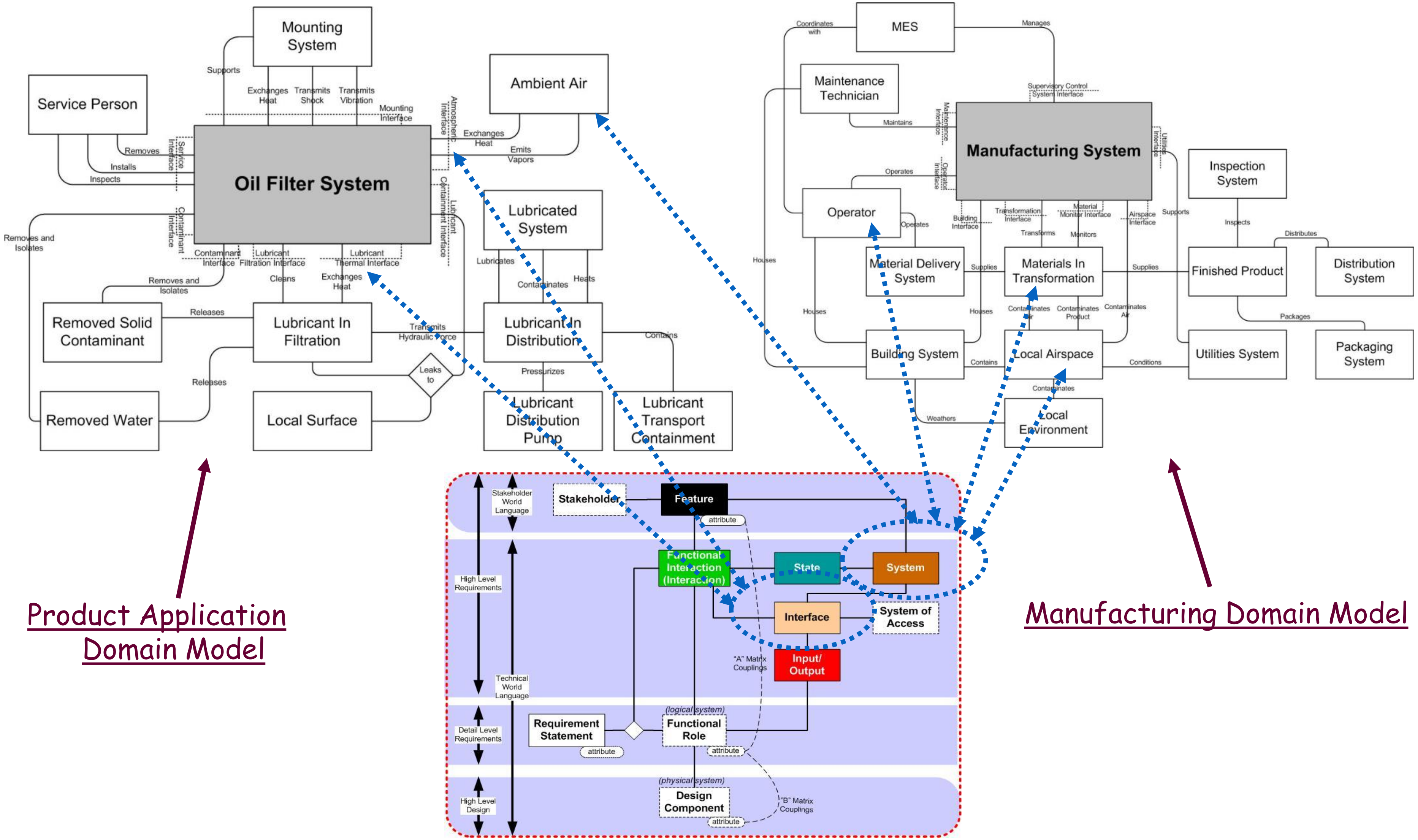
Stainless Steel
Filter Media

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 <u>source of all Functional Requirements</u>.

Domain Models



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

Microsoft Excel - Oil Filter Pattern V1.1.1.xls

I12 — The feature of providing services with a specified level of reliability over the normal operating life of a system.

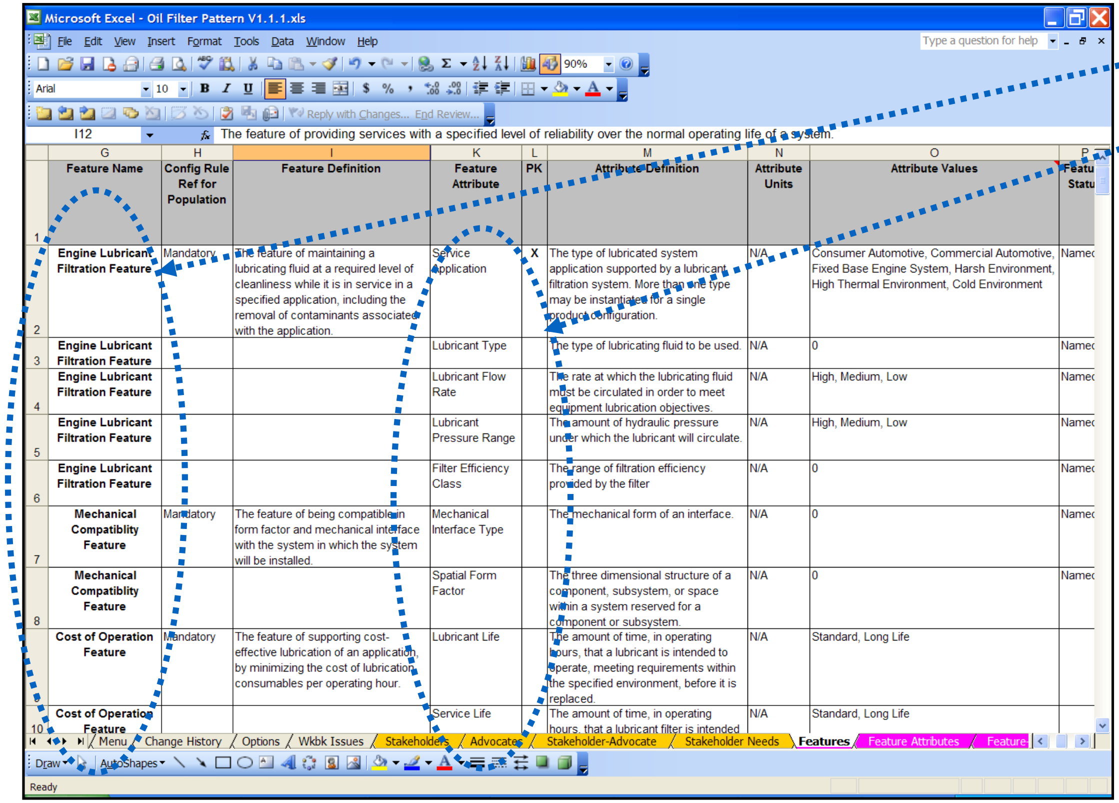
	Feature Name	Config Rule Ref for Population	Feature Definition	Feature Attribute	PK	Attribute Definition	Attribute Units	Attribute Values	Featu Statu
2	**Engine Lubricant Filtration Feature**	Mandatory	The feature of maintaining a lubricating fluid at a required level of cleanliness while it is in service in a specified application, including the removal of contaminants associated with the application.	Service Application	X	The type of lubricated system application supported by a lubricant filtration system. More than one type may be instantiated for a single product configuration.	N/A	Consumer Automotive, Commercial Automotive, Fixed Base Engine System, Harsh Environment, High Thermal Environment, Cold Environment	Namec
3	**Engine Lubricant Filtration Feature**			Lubricant Type		The type of lubricating fluid to be used.	N/A	0	Namec
4	**Engine Lubricant Filtration Feature**			Lubricant Flow Rate		The rate at which the lubricating fluid must be circulated in order to meet equipment lubrication objectives.	N/A	High, Medium, Low	Namec
5	**Engine Lubricant Filtration Feature**			Lubricant Pressure Range		The amount of hydraulic pressure under which the lubricant will circulate.	N/A	High, Medium, Low	Namec
6	**Engine Lubricant Filtration Feature**			Filter Efficiency Class		The range of filtration efficiency provided by the filter	N/A	0	Namec
7	**Mechanical Compatiblity Feature**	Mandatory	The feature of being compatible in form factor and mechanical interface with the system in which the system will be installed.	Mechanical Interface Type		The mechanical form of an interface.	N/A	0	Namec
8	**Mechanical Compatiblity Feature**			Spatial Form Factor		The three dimensional structure of a component, subsystem, or space within a system reserved for a component or subsystem.	N/A	0	Namec
9	**Cost of Operation Feature**	Mandatory	The feature of supporting cost-effective lubrication of an application, by minimizing the cost of lubrication consumables per operating hour.	Lubricant Life		The amount of time, in operating hours, that a lubricant is intended to operate, meeting requirements within the specified environment, before it is replaced.	N/A	Standard, Long Life	
10	**Cost of Operation Feature**			Service Life		The amount of time, in operating hours, that a lubricant filter is intended	N/A	Standard, Long Life	

Menu / Change History / Options / Wkbk Issues / Stakeholders / Advocates / Stakeholder-Advocate / Stakeholder Needs / **Features** / Feature Attributes / Feature

Ready

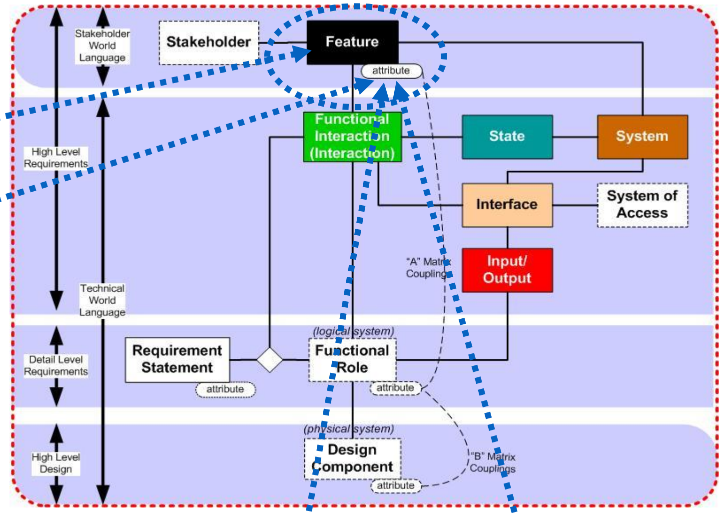
Features are collections of Functional Interactions (behaviors) having value to Stakeholders; their Attributes quantify that value impact. Features are in language of Stakeholders.

Product Stakeholder Features, Feature Attributes

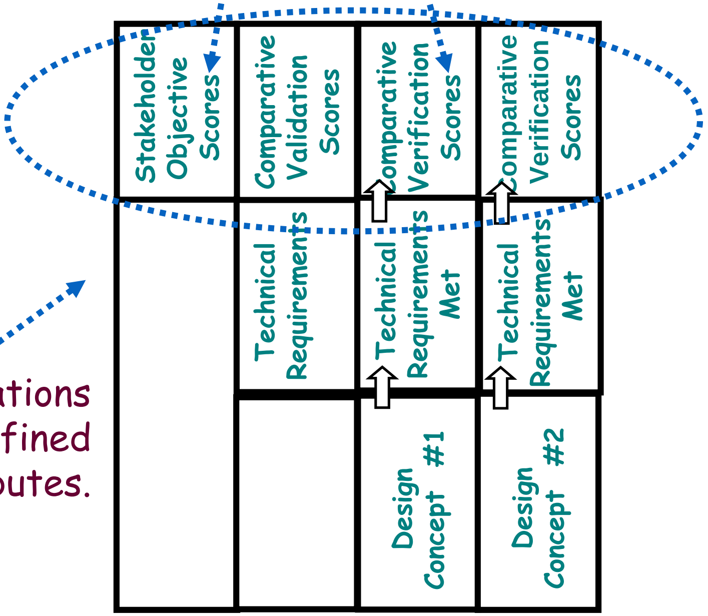

Microsoft Excel - Oil Filter Pattern V1.1.1.xls

I12 — The feature of providing services with a specified level of reliability over the normal operating life of a system.

	Feature Name	Config Rule Ref for Population	Feature Definition	Feature Attribute	PK	Attribute Definition	Attribute Units	Attribute Values	Featu Statu
2	Engine Lubricant Filtration Feature	Mandatory	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.	Service Application	X	The type of lubricated system application supported by a lubricant filtration system. More than one type may be instantiated for a single product configuration.	N/A	Consumer Automotive, Commercial Automotive, Fixed Base Engine System, Harsh Environment, High Thermal Environment, Cold Environment	Named
3	Engine Lubricant Filtration Feature			Lubricant Type		The type of lubricating fluid to be used.	N/A	0	Named
4	Engine Lubricant Filtration Feature			Lubricant Flow Rate		The rate at which the lubricating fluid must be circulated in order to meet equipment lubrication objectives.	N/A	High, Medium, Low	Named
5	Engine Lubricant Filtration Feature			Lubricant Pressure Range		The amount of hydraulic pressure under which the lubricant will circulate.	N/A	High, Medium, Low	Named
6	Engine Lubricant Filtration Feature			Filter Efficiency Class		The range of filtration efficiency provided by the filter	N/A	0	Named
7	Mechanical Compatiblity Feature	Mandatory	The feature of being compatible in form factor and mechanical interface with the system in which the system will be installed.	Mechanical Interface Type		The mechanical form of an interface.	N/A	0	Named
8	Mechanical Compatiblity Feature			Spatial Form Factor		The three dimensional structure of a component, subsystem, or space within a system reserved for a component or subsystem.	N/A	0	Named
9	Cost of Operation Feature	Mandatory	The feature of supporting cost-effective lubrication of an application, by minimizing the cost of lubrication consumables per operating hour.	Lubricant Life		The amount of time, in operating hours, that a lubricant is intended to operate, meeting requirements within the specified environment, before it is replaced.	N/A	Standard, Long Life	
10	Cost of Operation Feature			Service Life		The amount of time, in operating hours, that a lubricant filter is intended	N/A	Standard, Long Life	



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



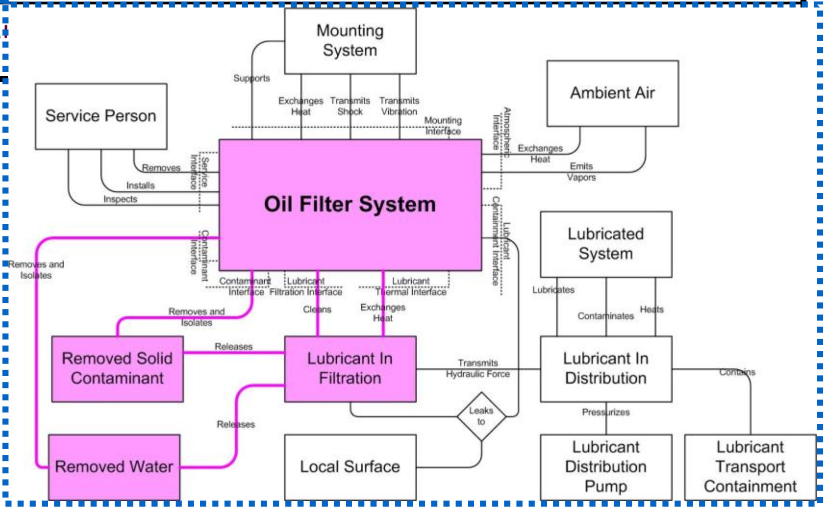
Configuration Score Sheet

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

Functional Interaction	Functional Roles
Filter Lubricant	Lubricant in Filtration, Oil Filter System, Removed Solid Contaminant, Removed Water
Install Filter	Service Person, Filter
Monitor Filter	Filter, Monitor & Control System
Prevent Vapor Leakage	Lubricant, Vapor, Filter, Atmosphere
Prevent Lubricant Leakage	Lubricant, Filter, Local Surface
Transmit Shock & Vibration	Filter, Mounting System
Transmit Thermal Energy	Filter, Lubricant, Mounting System, Ambient Ai

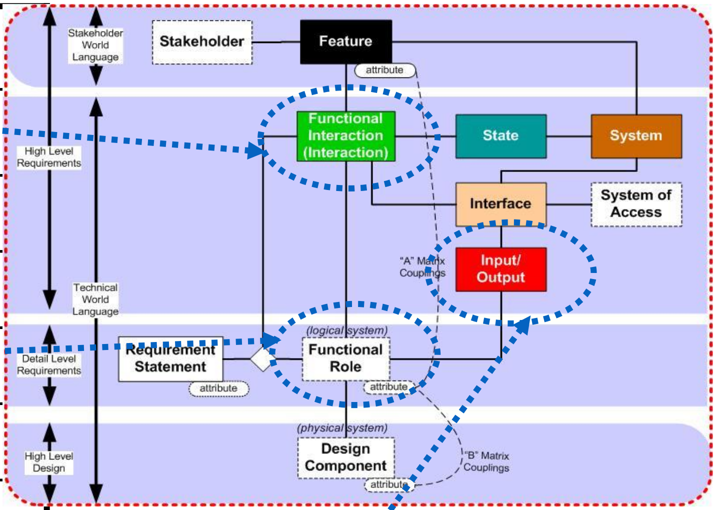


Every system directly interacting with the Subject System (Oil Filter System) contributes to its Requirements.

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

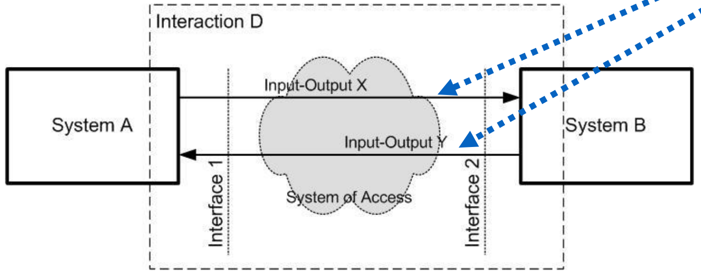
Functional Interaction	Functional Roles
Filter Lubricant	Lubricant in Filtration, Oil Filter System, Removed Solid Contaminant, Removed Water
Change Filter	Service Person, Filter
Monitor Filter	Filter, Monitor & Control System
Prevent Vapor Leakage	Lubricant, Vapor, Filter, Atmosphere
Prevent Lubricant Leakage	Lubricant, Filter, Local Surface
Transmit Shock & Vibration	Filter, Mounting System
Transmit Thermal Energy	Filter, Lubricant, Mounting System, Ambient Air



Input/Outputs exchanged during these interactions are:

- Energy
- Force
- Mass
- Information

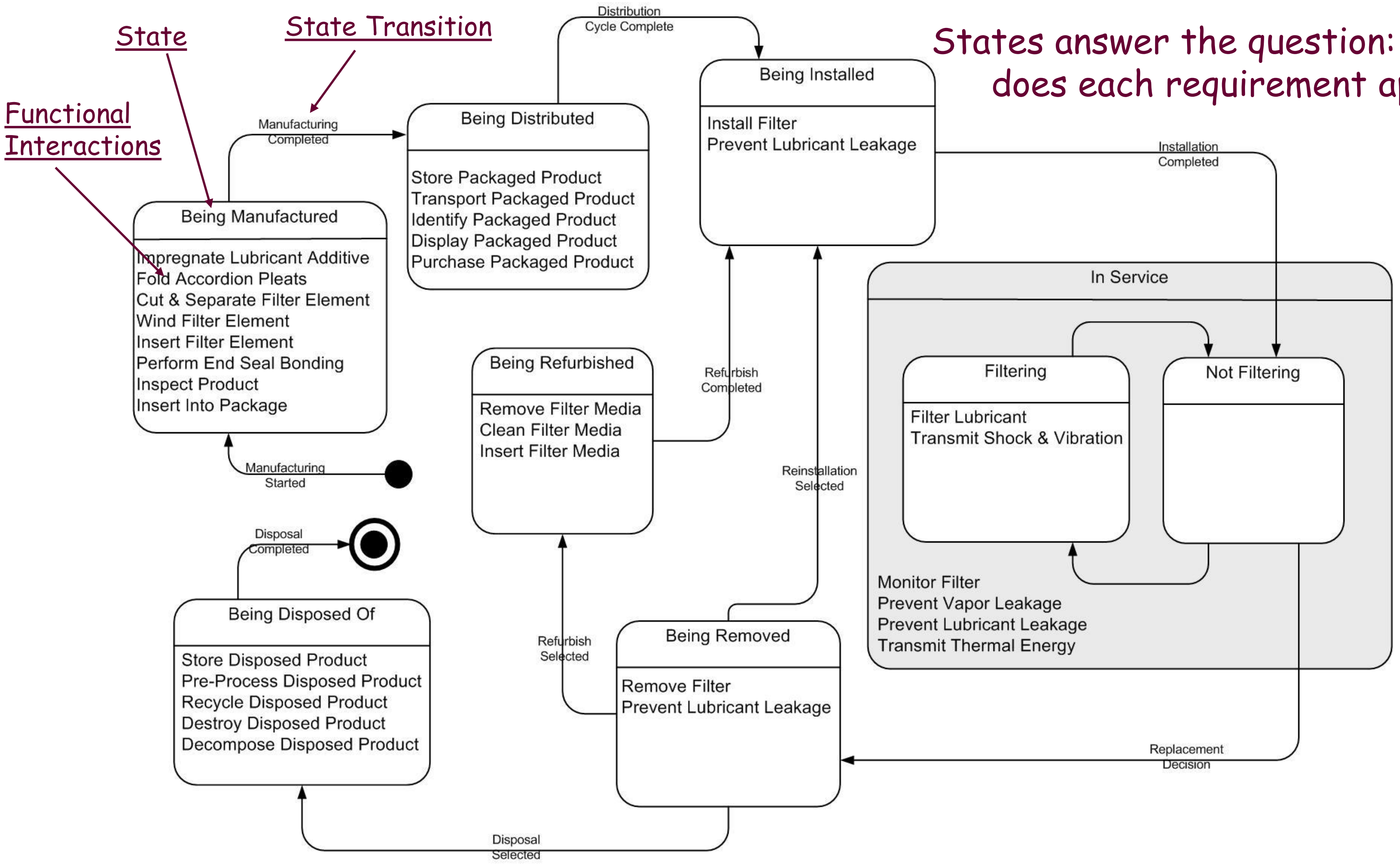
Interactions involve two or more systems.



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.

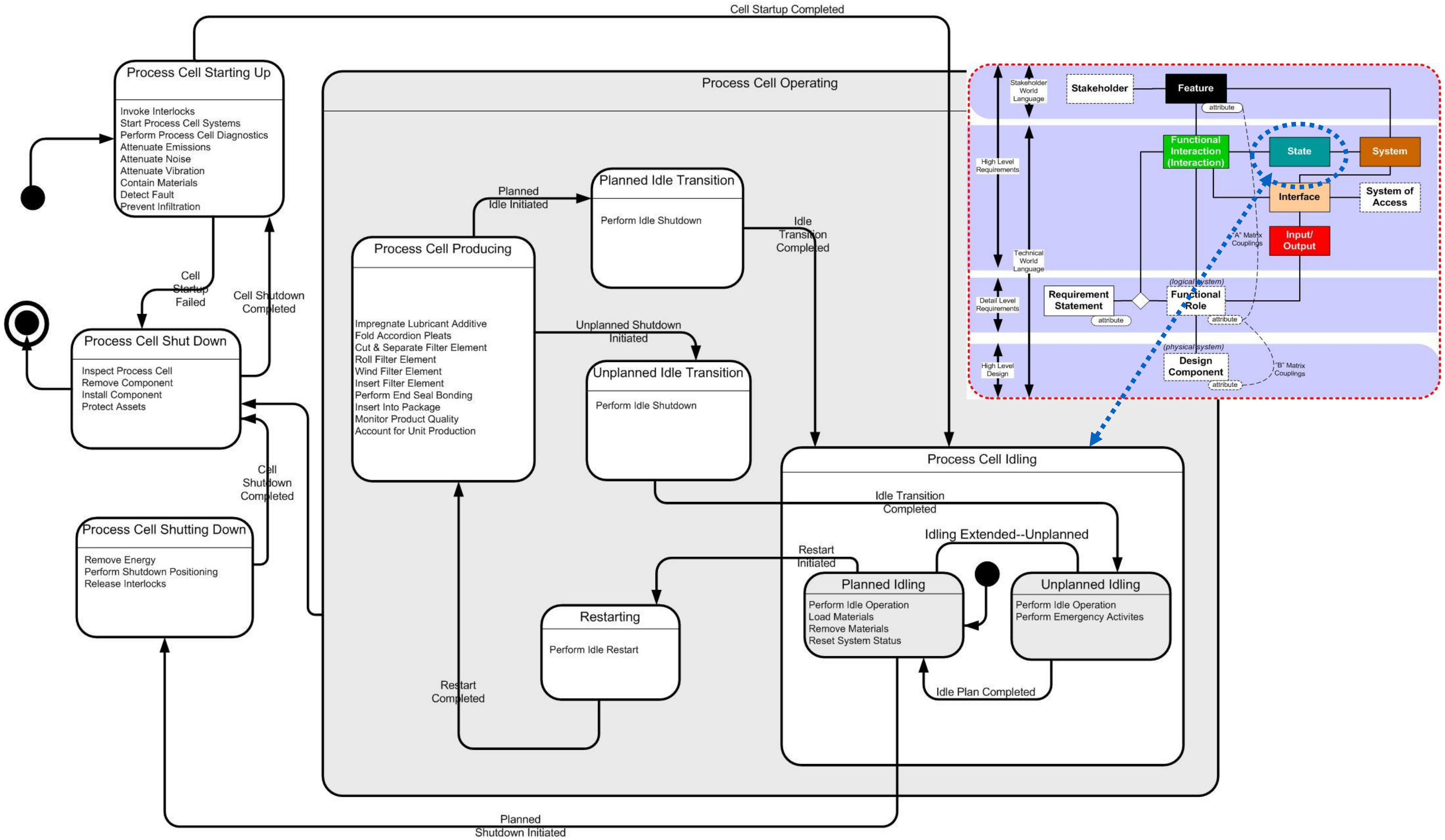
Product State Model

States answer the question: "When does each requirement apply?"



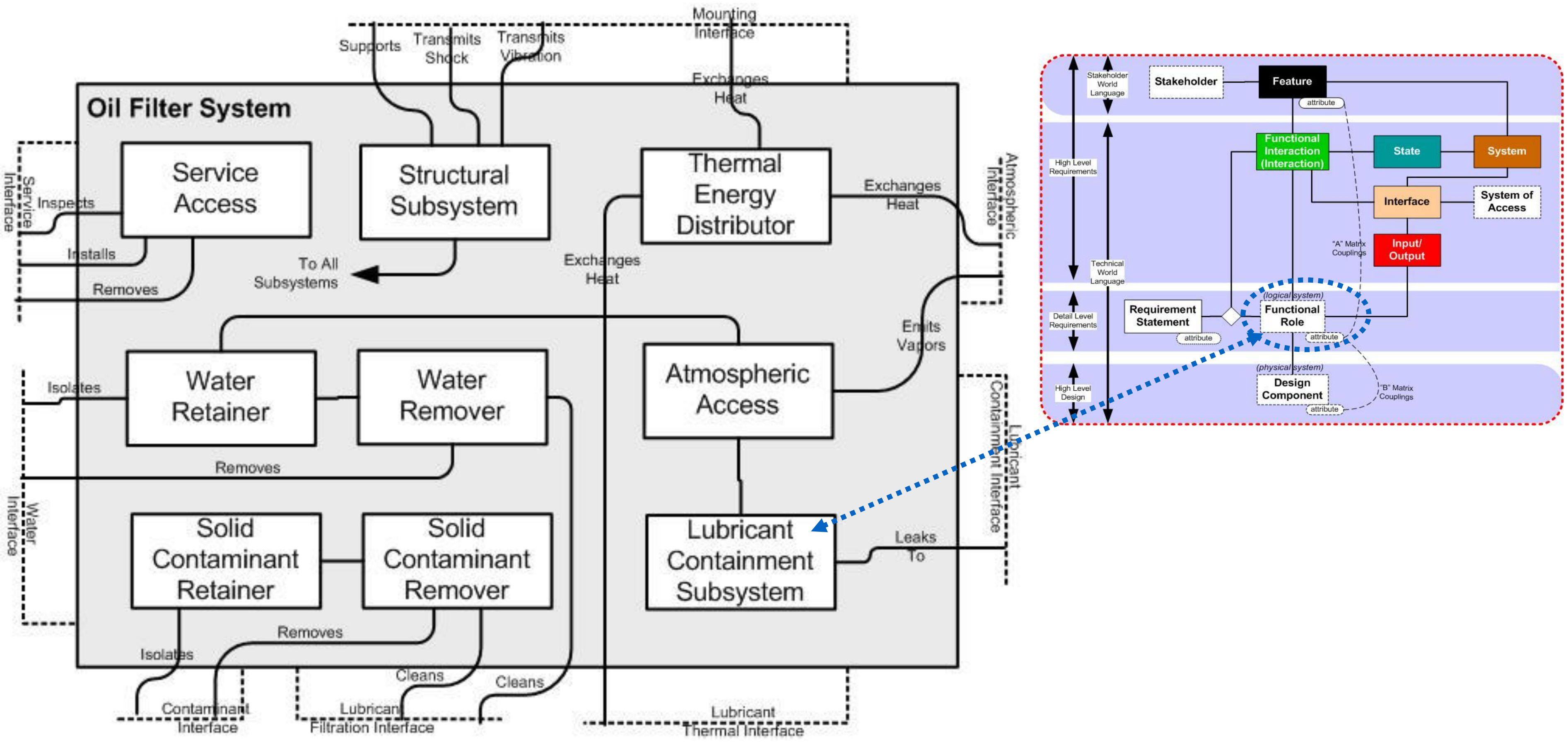
States are Situations (Modes, Use Cases, Phases) that will be encountered in the environment of a Subject System, in which it is required to meet certain requirements.

Manufacturing System State Model



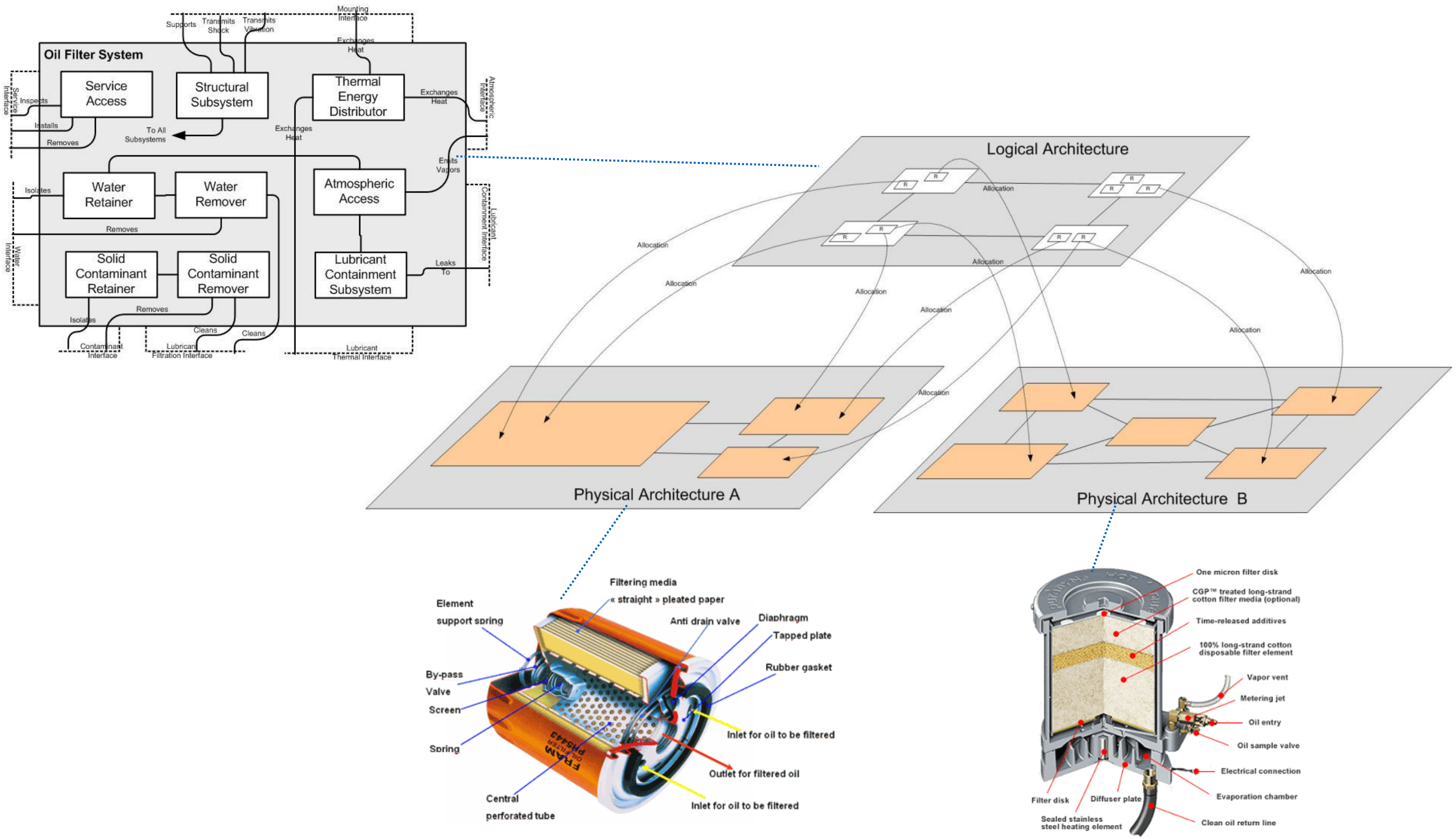
Logical Architecture Models directly address key SE challenges by partitioning the structure of requirements into Logical Roles independent of design, then address more SE challenges by stimulating design ideation and role allocation to physical designs and future technologies.

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

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 least) upper bounds on the sizes of effective representati *systems engineering*. Compared to traditional systems en directly on scientific traditions for representing behavi engineering is still young, and its connections to supportir

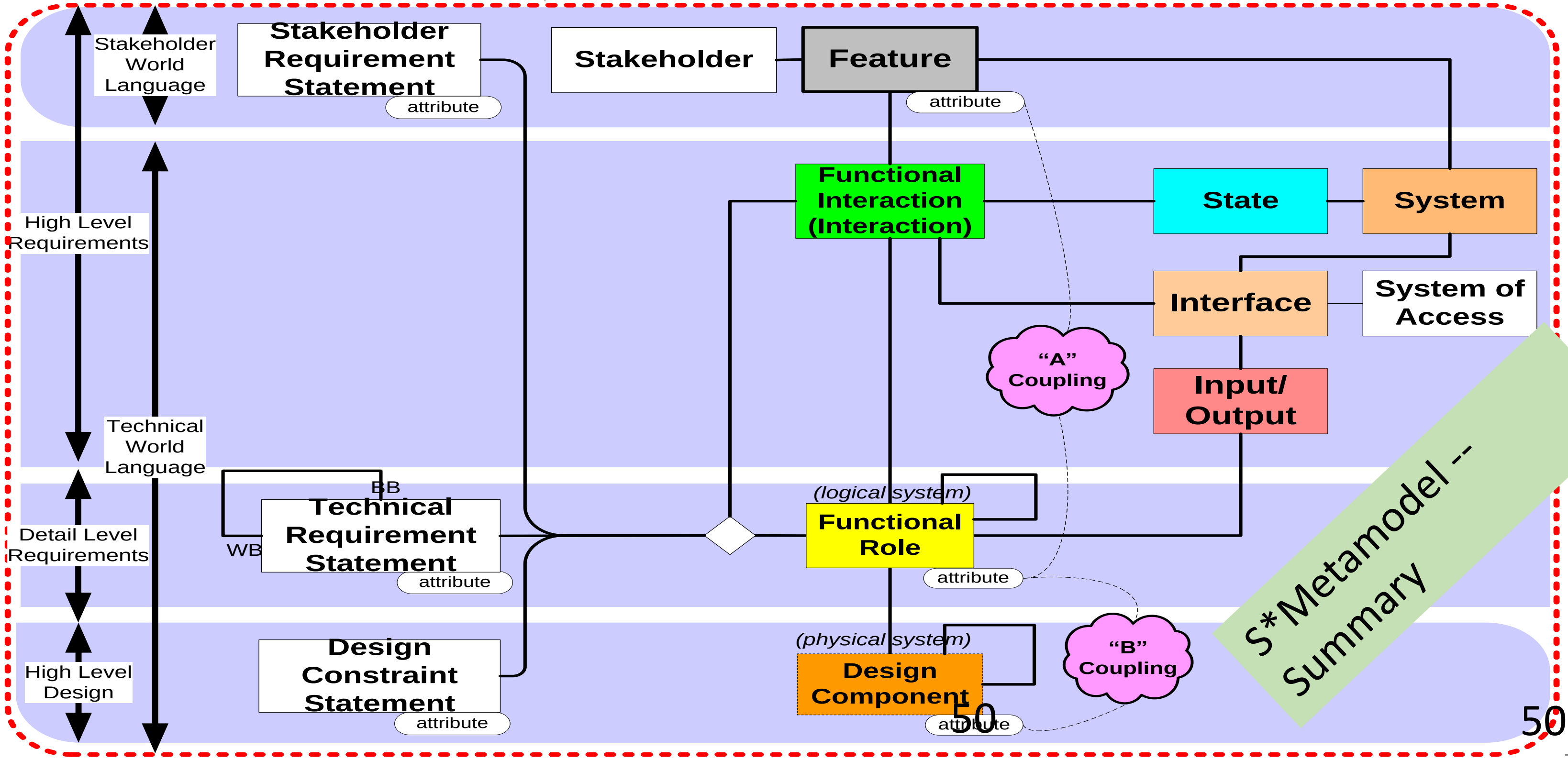
Language and Compression. This subject may appear t describe systems, and an interesting thread in the mathem whether minimality is in a sense independent of language In any case, systems modeling languages such as SysI valuable assets for the movement to model-based methods is not the machinery of these specific modeling languages models must address. When used for system familic representation described here is subject to significant com turns out to provide powerful insights about approaches size of SE descriptions and processes, and about ongoing f over time. These dynamics also suggest that such patterns the interaction rules of the systems engineering process ar

Practical representation challenges of traditional syste documentation of concept of operations (CONOPS specifications, failure mode and effects analysis (FM maintenance procedures, and other task-specific system re system can exceed thousands of pages. This does not e

INCOSE 2005 Symposium "Best Paper" Award in Modeling and Tools

Requirements Statements Are Transfer Functions: An Insight from Model-Based Systems Engineering

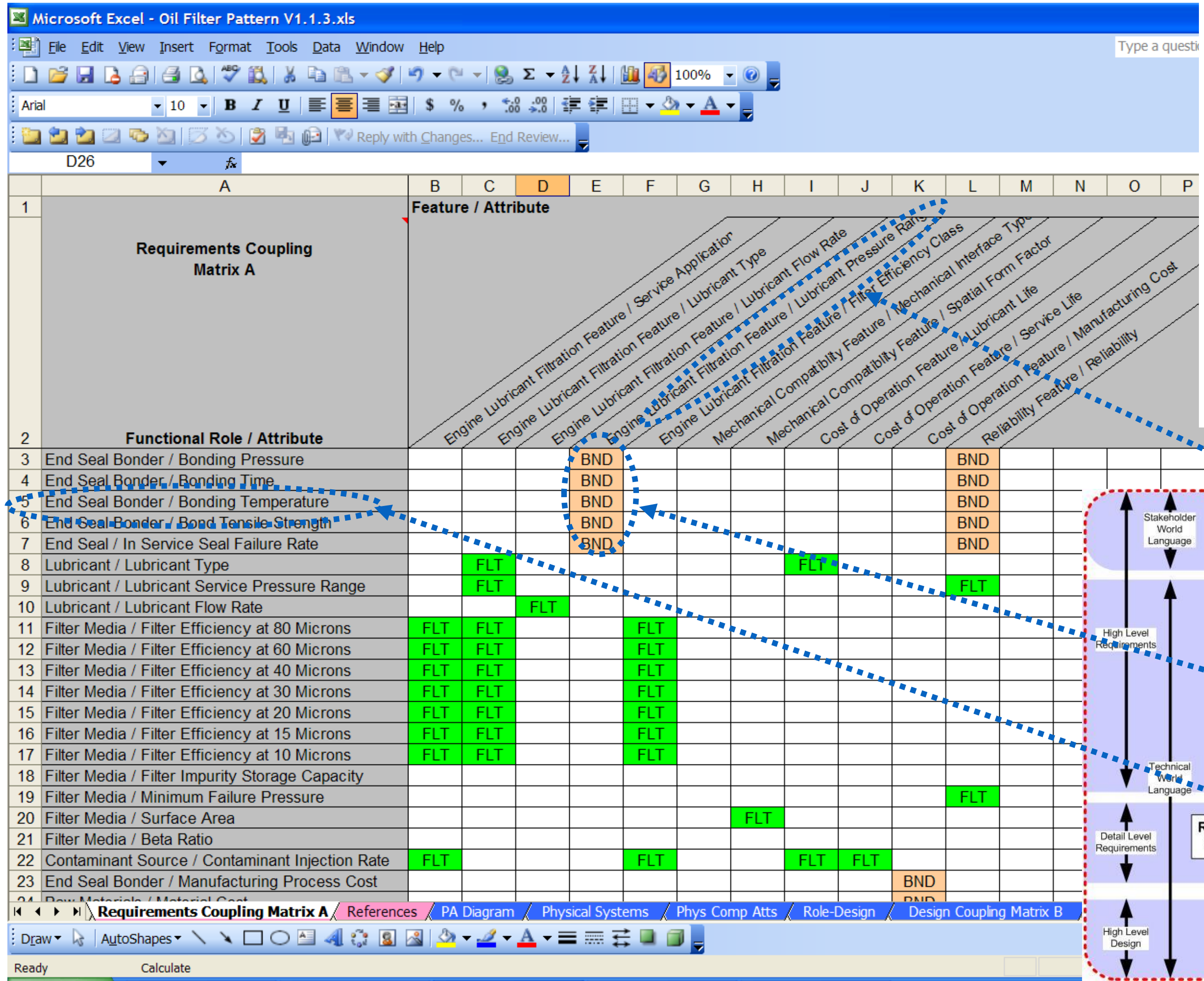
William D. Schindel
ICTT, Inc., and System Sciences, LLC
100 East Campus Drive, Terre Haute, IN 47802
812-232-2062 schindel@ictt.com



S*Metamodel -- Summary

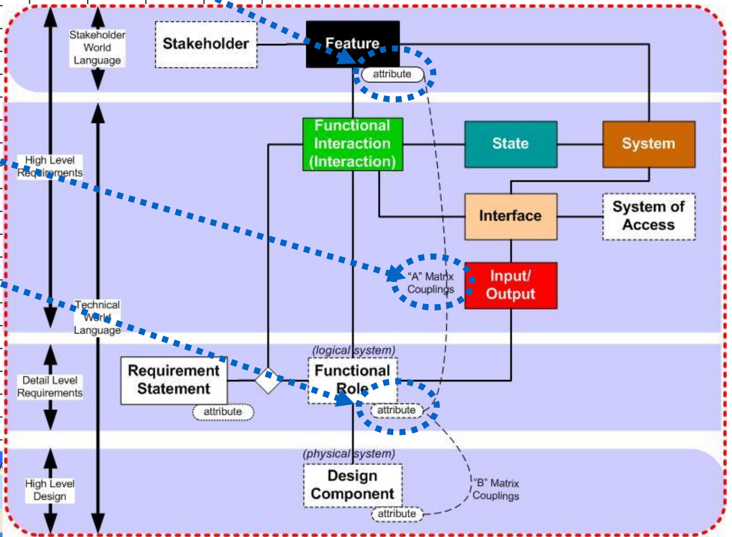
The Attribute Coupling Model addresses a key SE challenge to understand the quantitative coupling of stakeholder preferences (Features) to technical requirements (Roles), establishing a Feature-based scoring space for trade-offs.

Attribute Coupling Model--Requirements



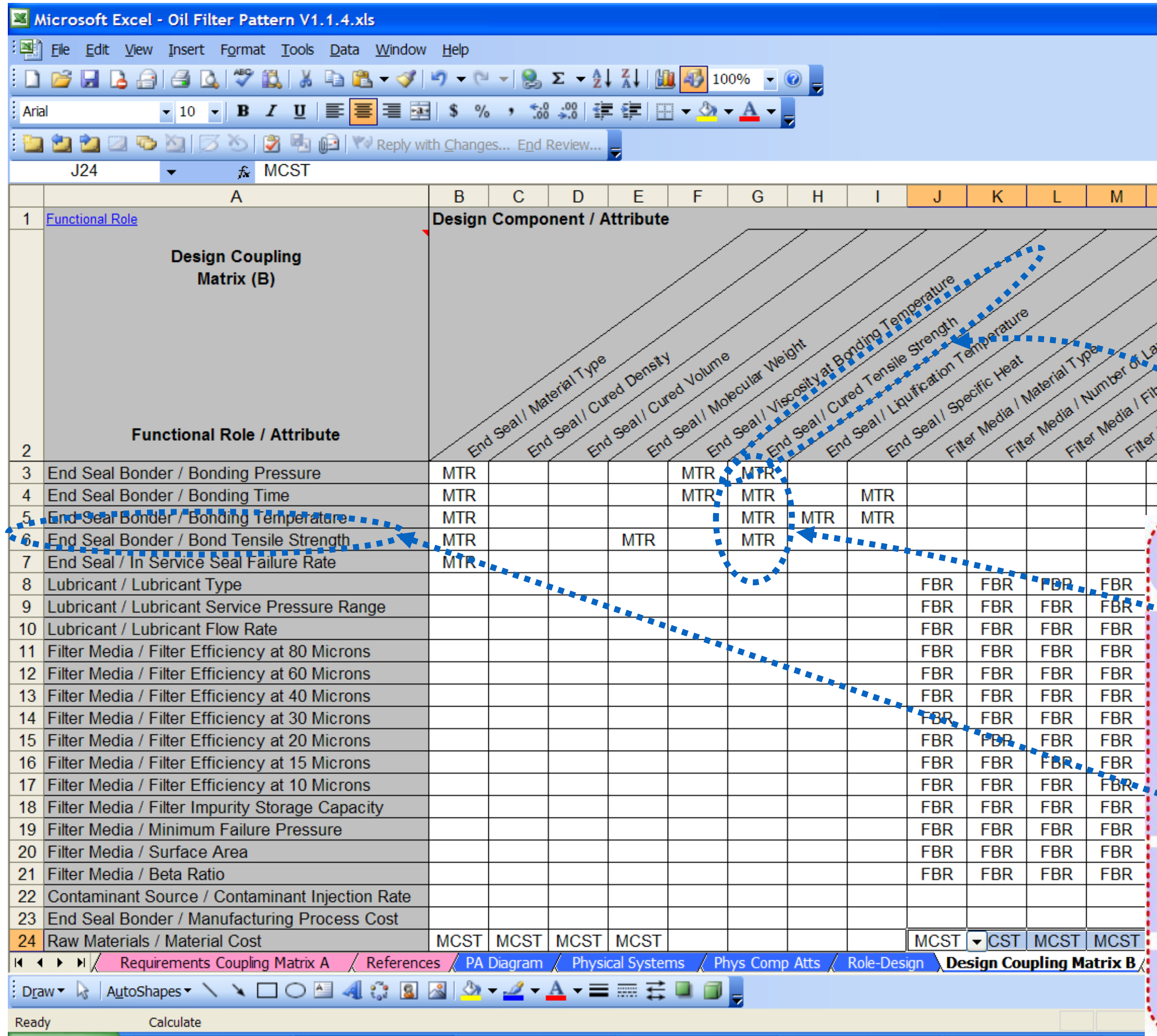
	Functional Role / Attribute	Engine Lubricant Filtration Feature / Service Application	Engine Lubricant Filtration Feature / Lubricant Type	Engine Lubricant Filtration Feature / Lubricant Flow Rate	Engine Lubricant Filtration Feature / Lubricant Pressure Rang	Engine Lubricant Filtration Feature / Filter Efficiency Class	Mechanical Compatibility Feature / Mechanical Interface Typ	Mechanical Compatibility Feature / Spatial Form Factor	Cost of Operation Feature / Lubricant Life	Cost of Operation Feature / Service Life	Cost of Operation Feature / Manufacturing Cost	Reliability Feature / Reliability
3	End Seal Bonder / Bonding Pressure				BND							BND
4	End Seal Bonder / Bonding Time				BND							BND
5	End Seal Bonder / Bonding Temperature				BND							BND
6	End Seal Bonder / Bond Tensile Strength				BND							BND
7	End Seal / In Service Seal Failure Rate				BND							BND
8	Lubricant / Lubricant Type		FLT						FLT			
9	Lubricant / Lubricant Service Pressure Range		FLT									FLT
10	Lubricant / Lubricant Flow Rate			FLT								
11	Filter Media / Filter Efficiency at 80 Microns	FLT	FLT			FLT						
12	Filter Media / Filter Efficiency at 60 Microns	FLT	FLT			FLT						
13	Filter Media / Filter Efficiency at 40 Microns	FLT	FLT			FLT						
14	Filter Media / Filter Efficiency at 30 Microns	FLT	FLT			FLT						
15	Filter Media / Filter Efficiency at 20 Microns	FLT	FLT			FLT						
16	Filter Media / Filter Efficiency at 15 Microns	FLT	FLT			FLT						
17	Filter Media / Filter Efficiency at 10 Microns	FLT	FLT			FLT						
18	Filter Media / Filter Impurity Storage Capacity											
19	Filter Media / Minimum Failure Pressure											FLT
20	Filter Media / Surface Area							FLT				
21	Filter Media / Beta Ratio											
22	Contaminant Source / Contaminant Injection Rate	FLT				FLT			FLT	FLT		
23	End Seal Bonder / Manufacturing Process Cost										BND	

- 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



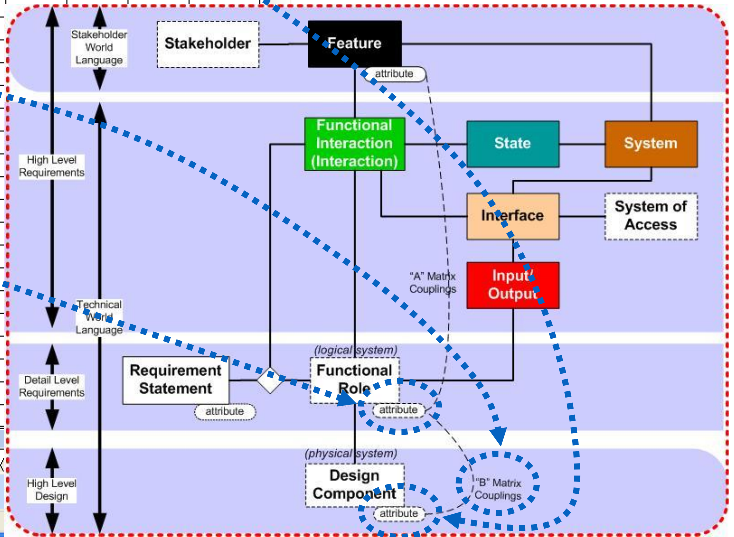
Microsoft Excel - Oil Filter Pattern V1.1.4.xls

J24 MCST

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Functional Role	Design Component / Attribute													
2	Design Coupling Matrix (B) Functional Role / Attribute	End Seal / Material Type	End Seal / Cured Density	End Seal / Cured Volume	End Seal / Molecular Weight	End Seal / Viscosity at Bonding Temperature	End Seal / Cured Tensile Strength	End Seal / Liquification Temperature	End Seal / Specific Heat	Filter Media / Material Type	Filter Media / Number of Layers	Filter Media / Fiber Density	Filter Media / Fiber Size	Filter Media / M	End
3	End Seal Bonder / Bonding Pressure	MTR				MTR	MTR								X
4	End Seal Bonder / Bonding Time	MTR				MTR	MTR		MTR						
5	End Seal Bonder / Bonding Temperature	MTR					MTR	MTR	MTR						
6	End Seal Bonder / Bond Tensile Strength	MTR			MTR		MTR								
7	End Seal / In Service Seal Failure Rate	MTR													
8	Lubricant / Lubricant Type									FBR	FBR	FBR	FBR		
9	Lubricant / Lubricant Service Pressure Range									FBR	FBR	FBR	FBR		
10	Lubricant / Lubricant Flow Rate									FBR	FBR	FBR	FBR		
11	Filter Media / Filter Efficiency at 80 Microns									FBR	FBR	FBR	FBR		
12	Filter Media / Filter Efficiency at 60 Microns									FBR	FBR	FBR	FBR		
13	Filter Media / Filter Efficiency at 40 Microns									FBR	FBR	FBR	FBR		
14	Filter Media / Filter Efficiency at 30 Microns									FBR	FBR	FBR	FBR		
15	Filter Media / Filter Efficiency at 20 Microns									FBR	FBR	FBR	FBR		
16	Filter Media / Filter Efficiency at 15 Microns									FBR	FBR	FBR	FBR		
17	Filter Media / Filter Efficiency at 10 Microns									FBR	FBR	FBR	FBR		
18	Filter Media / Filter Impurity Storage Capacity									FBR	FBR	FBR	FBR		
19	Filter Media / Minimum Failure Pressure									FBR	FBR	FBR	FBR		
20	Filter Media / Surface Area									FBR	FBR	FBR	FBR		
21	Filter Media / Beta Ratio									FBR	FBR	FBR	FBR		
22	Contaminant Source / Contaminant Injection Rate														
23	End Seal Bonder / Manufacturing Process Cost														
24	Raw Materials / Material Cost	MCST	MCST	MCST	MCST					MCST	CST	MCST	MCST		

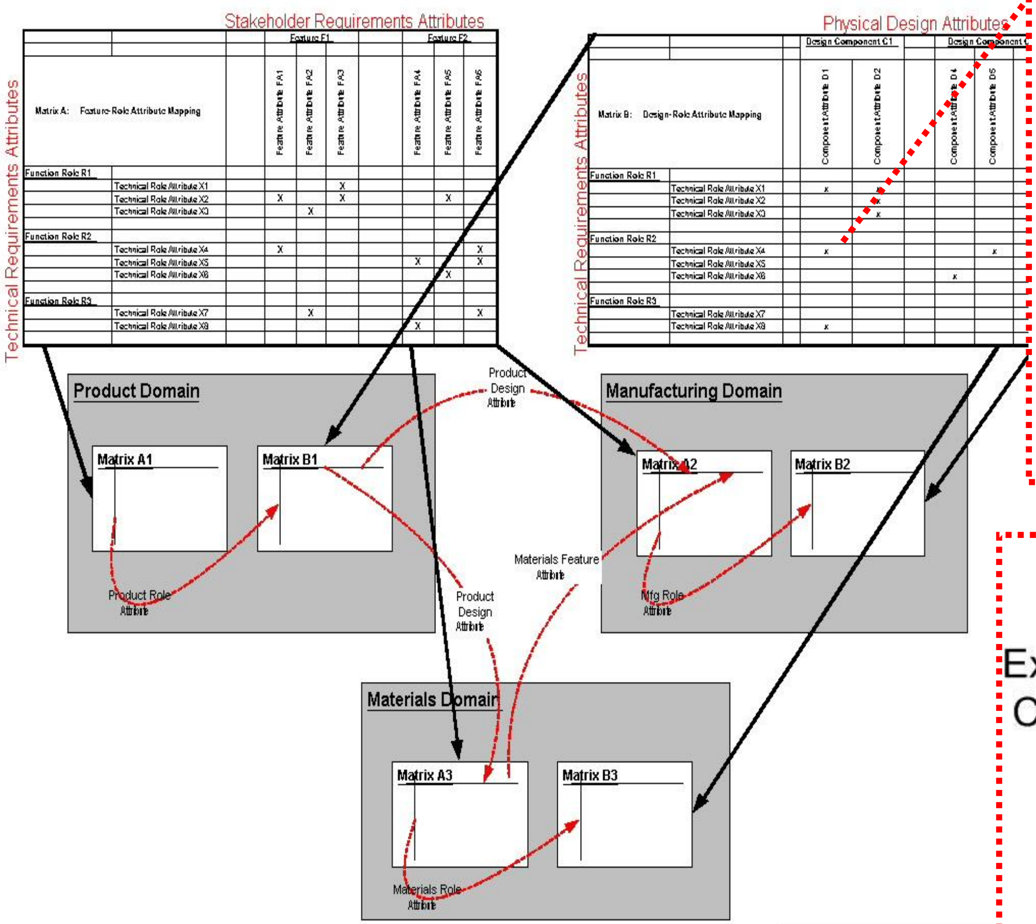
Requirements Coupling Matrix A / References / PA Diagram / Physical Systems / Phys Comp Atts / Role-Design / Design Coupling Matrix B

Ready Calculate



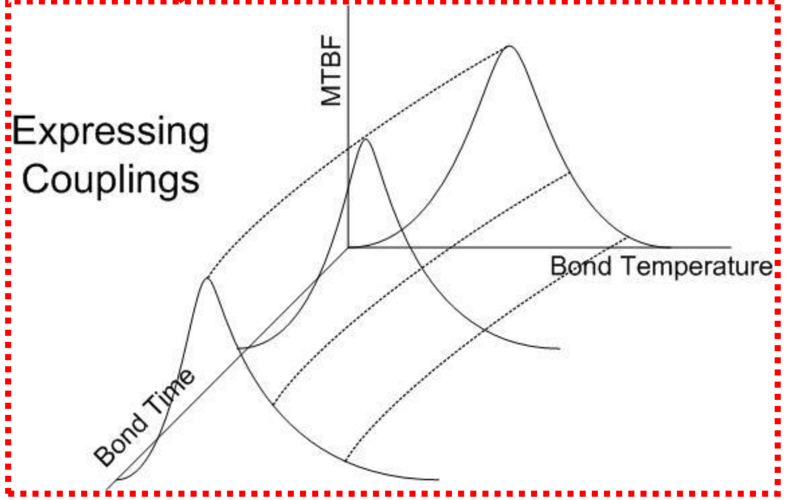
- The "A" and "B" couplings organize all the quantitative relationships, including first principles math / physics models, design of experiment models, empirical studies, market surveys, etc.
- Organizes trade-off scoring space.
- Provides a uniform way to integrate Team Partner models of Fuel Cell, other systems.

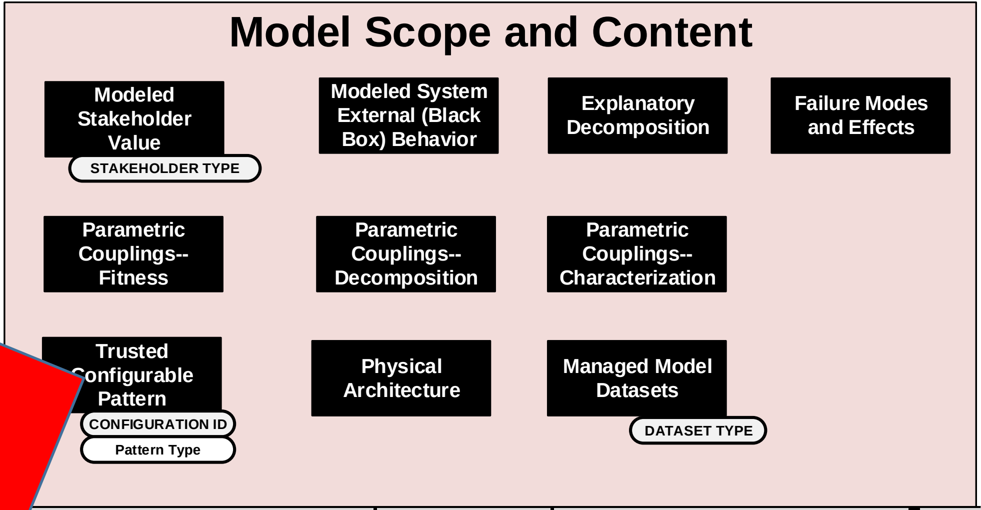
Attribute couplings cross domains



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





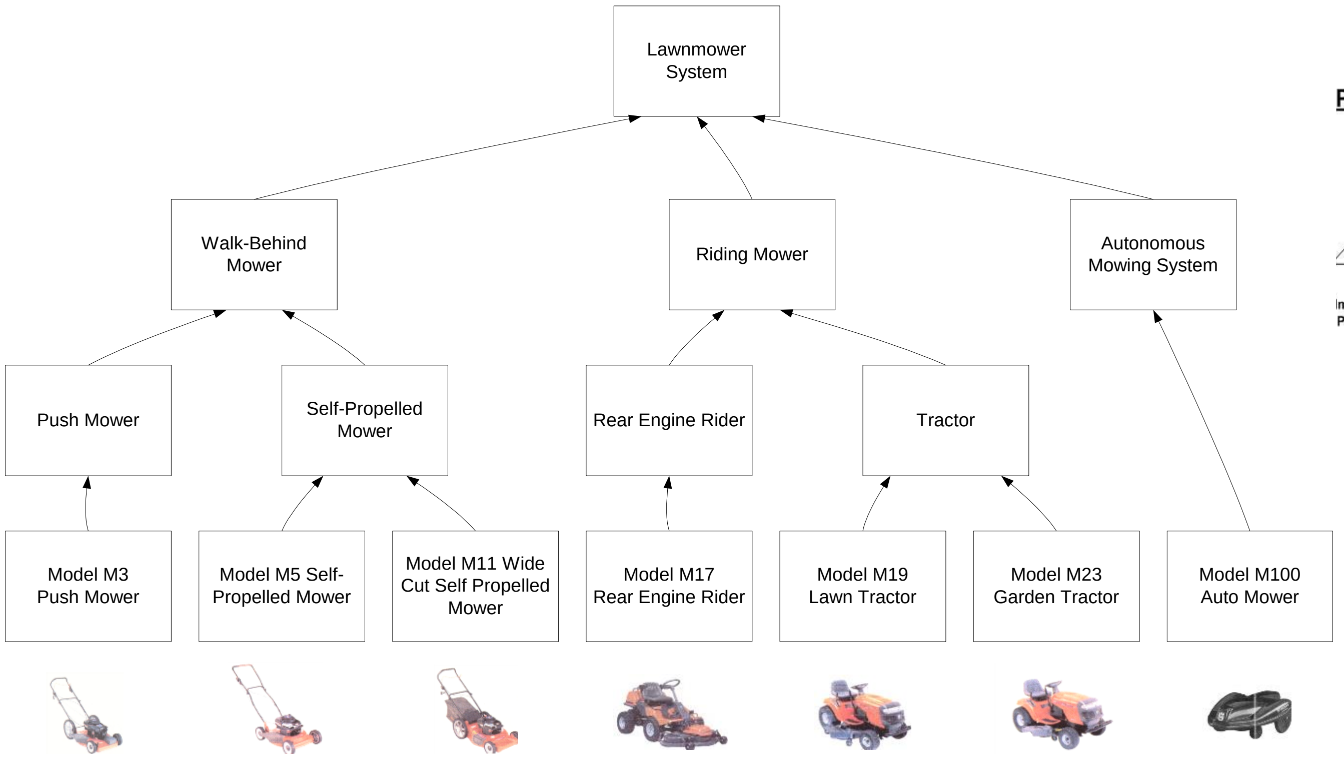
Of special importance to the economics of trust and VVUQ

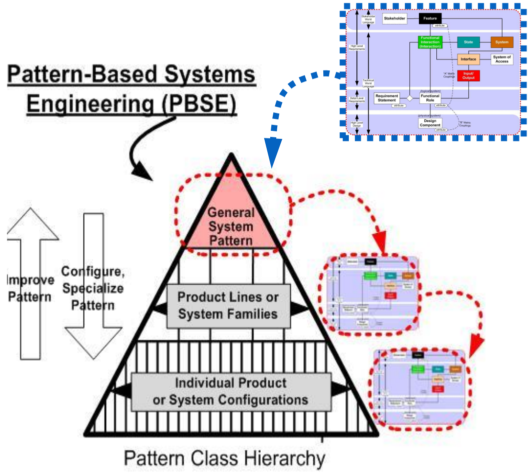
	ame	Feature Definition	Feature Attribute	Attribute Definition	Feature Stakeholder: Model User	Model Developer	Model Maintainer	Mdl Deployer-Distributor	Model Use Supporter	Regulatory Authority	Mdl Investor-Owner	Model Type: Physics Based	Data Driven
Describes the scope of content of the model													
	Parametric Couplings--Fitness	The capability of the model to represent quantitative (parametric) couplings between stakeholder-valued measures of effectiveness and objective external black box behavior performance measures.			X					X		X	X
	Parametric Couplings--Decomposition	The capability of the model to represent quantitative (parametric) couplings between objective external black box behavior variables and objective internal white box behavior variables.			X					X		X	X
	Parametric Couplings--Characterization	The capability of the model to represent quantitative (parametric) couplings between objective behavior variables and physical identity (material of construction, part or model number).			X					X		X	
	Managed Model Datasets	The capability of the model to include managed datasets for use as inputs, parametric characterizations, or outputs	Dataset Type	The type(s) of data sets (may be multiple)	X		X			X		X	X
	Trusted Configurable Pattern	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.	Configuration ID	A specific system of interest configuration within the family that the pattern framework can represent.	X		X			X	X	X	X
			Pattern ID	The identifier of the trusted configurable pattern.	X		X			X	X	X	X

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:

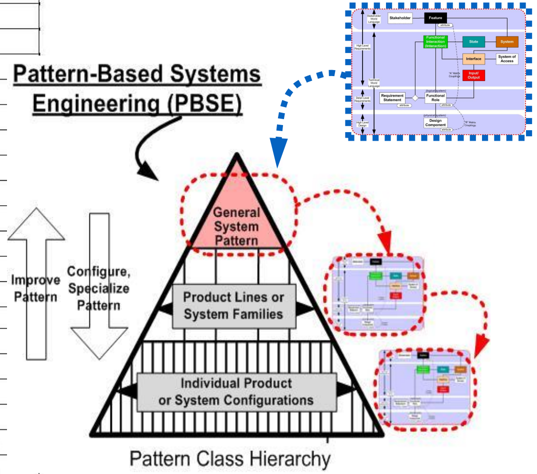




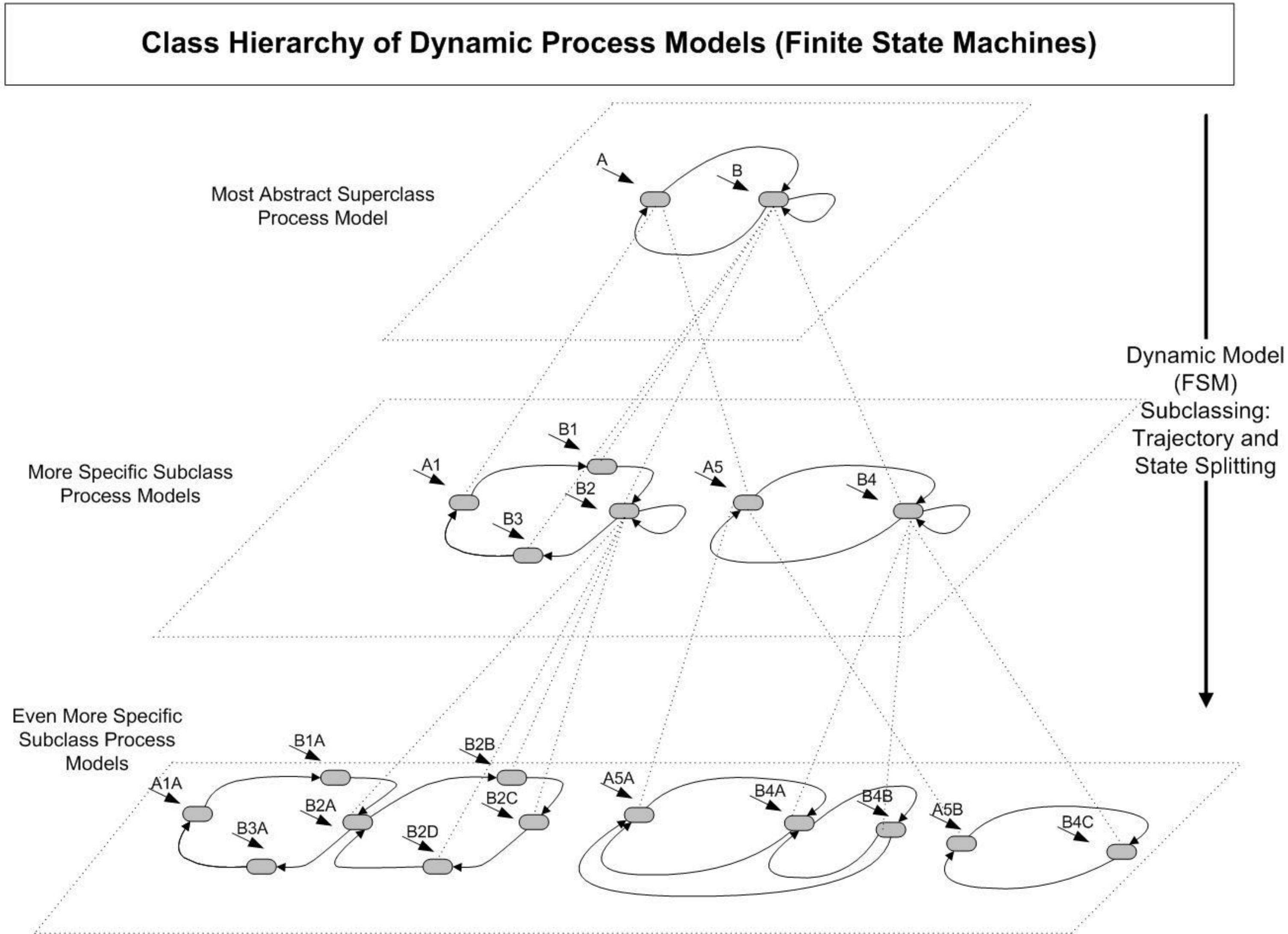
- This can be exploited by partitioning the model to integrate with existing Portfolio Roadmaps for Markets, Technologies, and Products

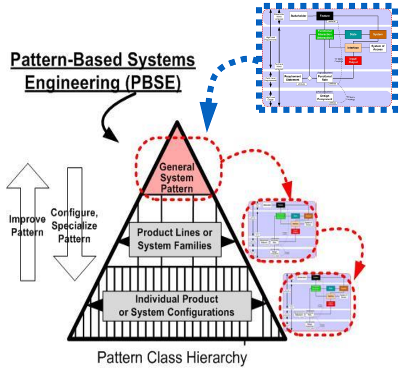
Family Configurations Model

Lawnmower Product Line: Configurations Table									
		Units							
			Walk-Behind Mower	Walk-Behind Mower	Walk-Behind Mower	Riding Mower	Riding Mower	Riding Mower	Autonomous Mowing System
			Push Mower	Self-Propelled Mower	Self-Propelled Mower	Rear Engine Rider	Tractor	Tractor	Autonomous Mowing System
			Push Mower	Self-Propelled	Wide Cut Self Propelled Mower	Rear Engine Rider	Lawn Tractor	Garden Tractor	Auto Mower
	Model Number		M3	M5	M11	M17	M19	M23	M100
	Market Segment		Small Residential	Medium Residential	Medium Residential	Large Residential	Large Residential	Home Garden	High End Suburban
Power	Engine Manufacturer		Briggs & Stratton	Briggs & Stratton	Tecumseh	Tecumseh	Kohler	Kohler	Elektroset
	Horsepower	HP	5	6.5	13	16	18.5	22	0.5
Production	Cutting Width	Inches	17	19	36	36	42	48	16
	Maximum Mowing Speed	MPH	3	3	4	8	10	12	2.5
	Maximum Mowing Productivity	Acres/Hr			1.6				
	Turning Radius	Inches	0	0	0	0	126	165	0
	Fuel Tank Capacity	Hours	1.5	1.7	2.5	2.8	3.2	3.5	2
	Towing Feature						x	x	
	Electric Starter Feature				x	x	x	x	
	Basic Mowing Feature Group		x	x	x	x	x	x	x
Mower	Number of Anti-Scalping Rollers		0	0	1	2	4	6	0
	Cutting Height Minimum	Inches	1	1.5	1.5	1.5	1	1.5	1.2
	Cutting Height Maximum	Inches	4	5	5	6	8	10	3.8
	Operator Riding Feature					x	x	x	
	Grass Bagging Feature		Optional	Optional	Optional	Optional	Optional	Optional	
	Mulching Feature		Standard	Factory Installed	Dealer Installed				
	Aerator Feature					Optional	Optional	Optional	
	Autonomous Mowing Feature								x
	Dethatching Feature					Optional	Optional	Optional	
Physical	Wheel Base	Inches	18	20	22	40	48	52	16
	Overall Length	Inches	18	20	23	58	56	68	28.3
	Overall Height	Inches	40	42	42	30	32	36	10.3
	Width	Inches	18	20	22	40	48	52	23.6
	Weight	Pounds	120	160	300	680	705	1020	15.6
	Self-Propelled Mowing Feature			x	x	x	x	x	x
	Fully Automatic Transmission Feature							x	
Financials	Retail Price	Dollars	360	460	1800	3300	6100	9990	1799
	Manufacturer Cost	Dollars	120	140	550	950	1800	3500	310
Maintenance	Warranty	Months	12	12	18	24	24	24	12
	Product Service Life	Hours	500	500	600	1100	1350	1500	300
	Time Between Service	Hours	100	100	150	200	200	250	100
Safety	Spark Arrest Feature		x	x	x	x	x	x	

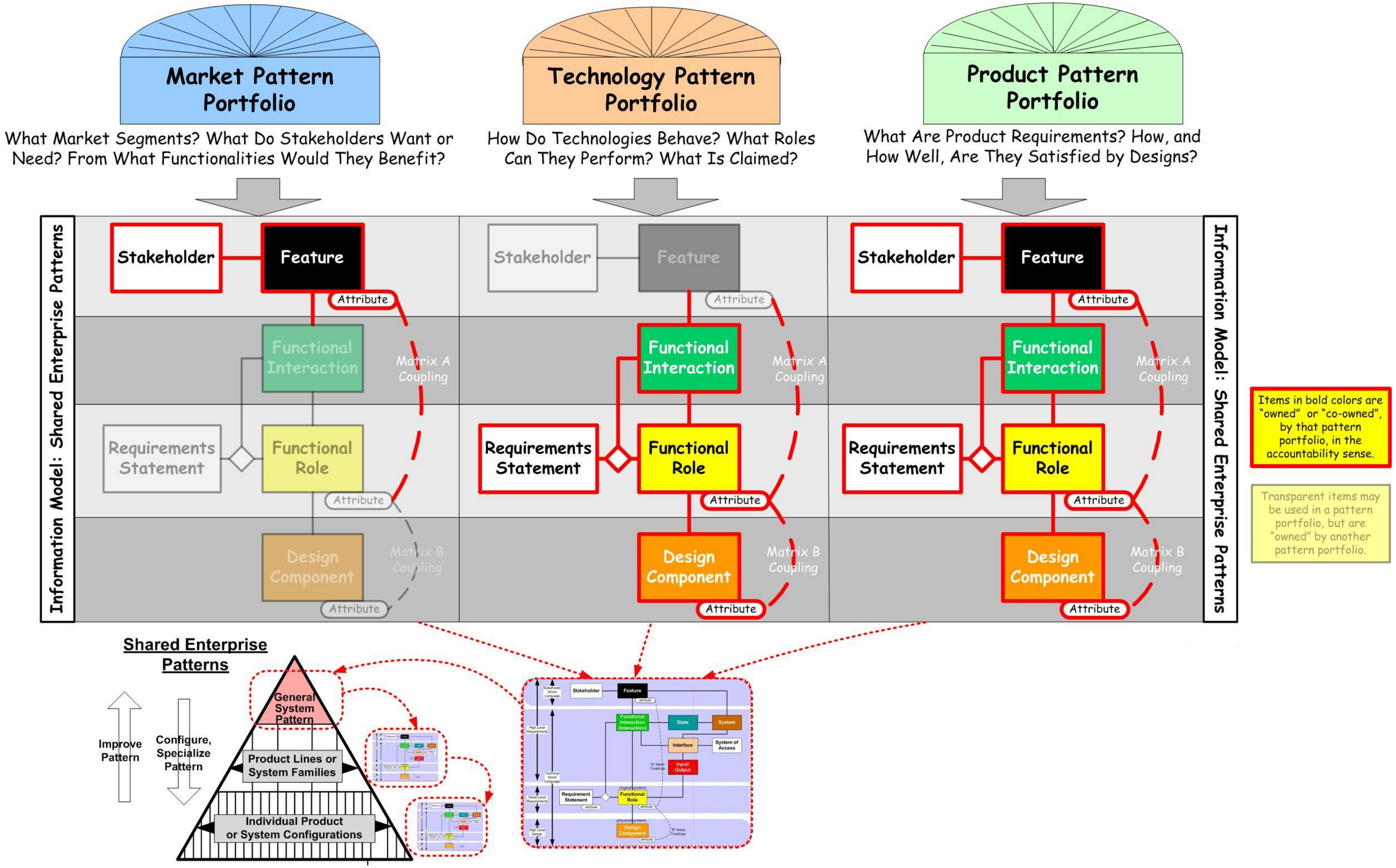


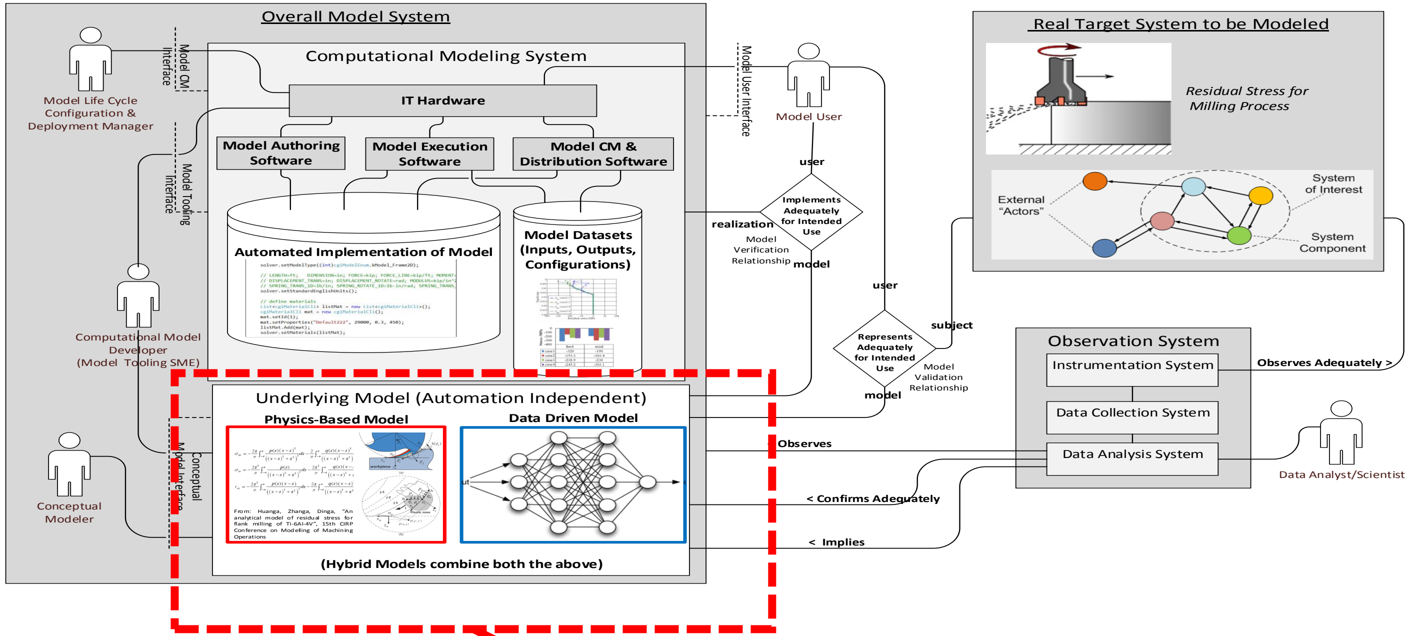
Family Configurations Model





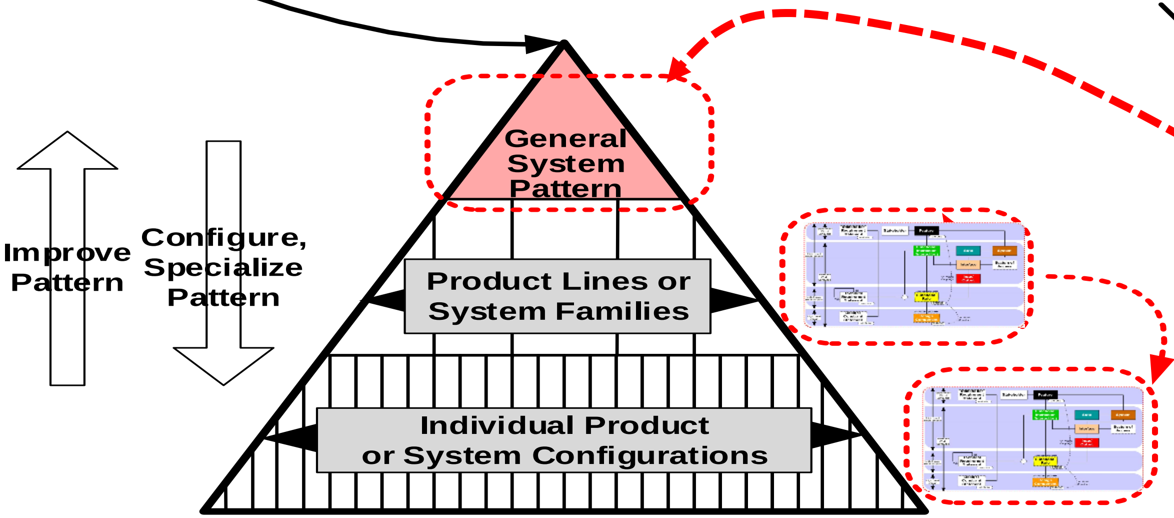
Family Configurations Model



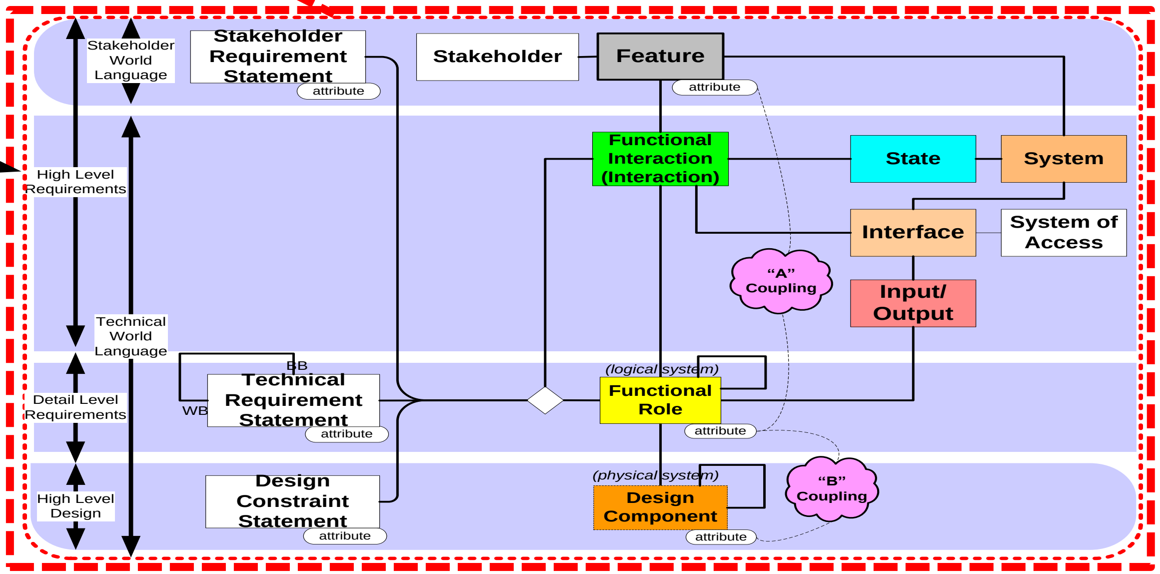


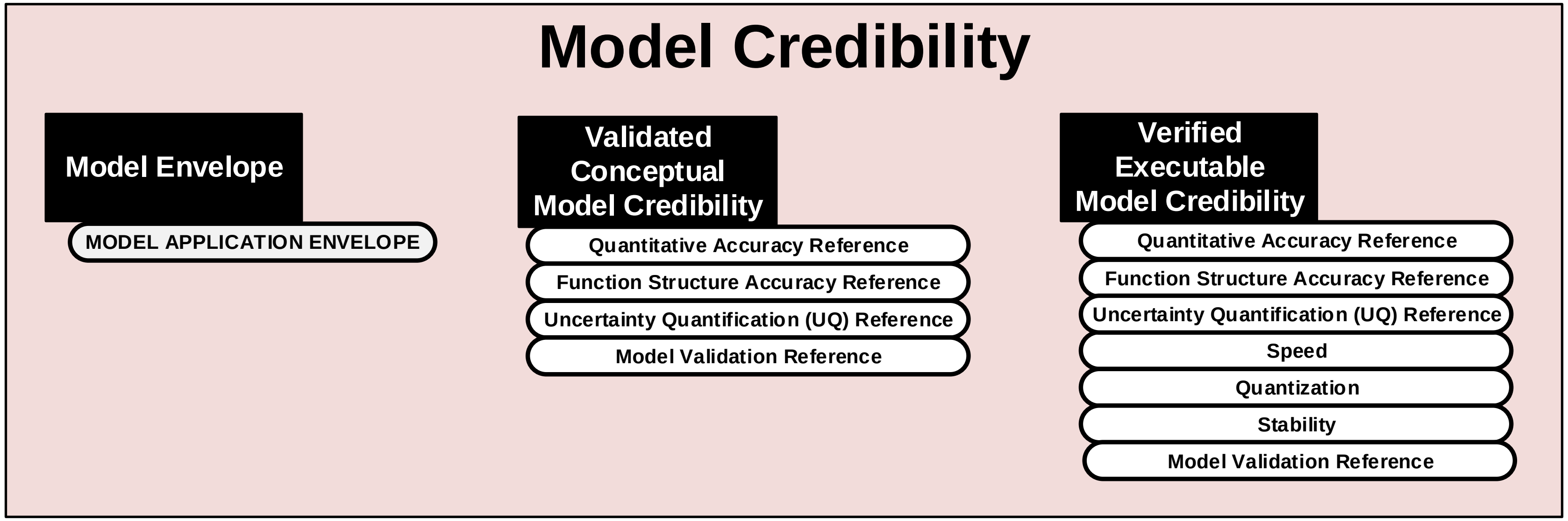
S*Pattern Hierarchy for Pattern-Based Systems Engineering (PBSE)

S*Metamodel for Model-Based Systems Engineering (MBSE)

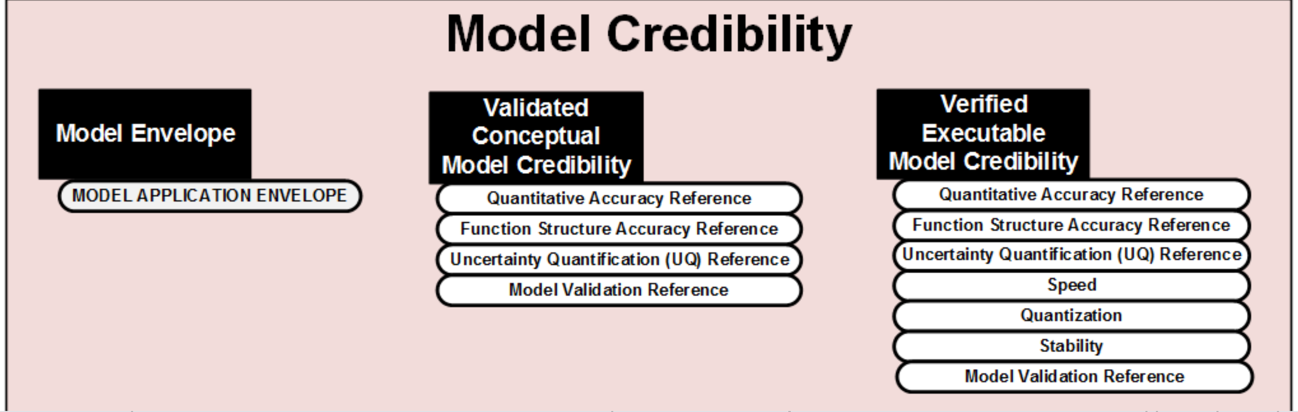


System Pattern Class Hierarchy

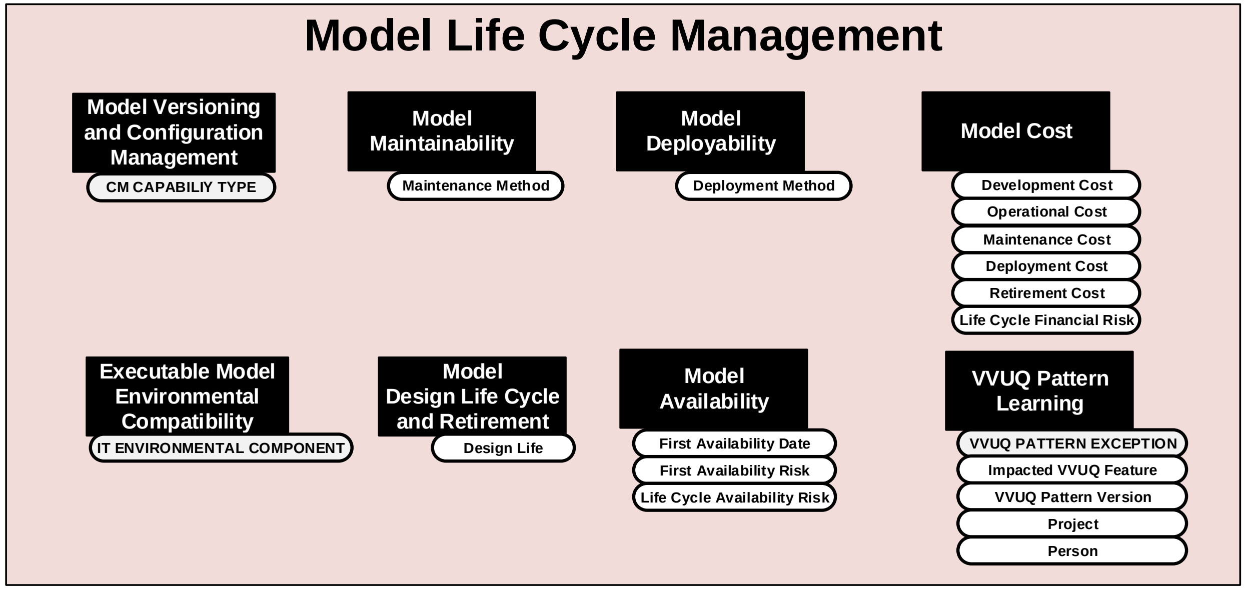




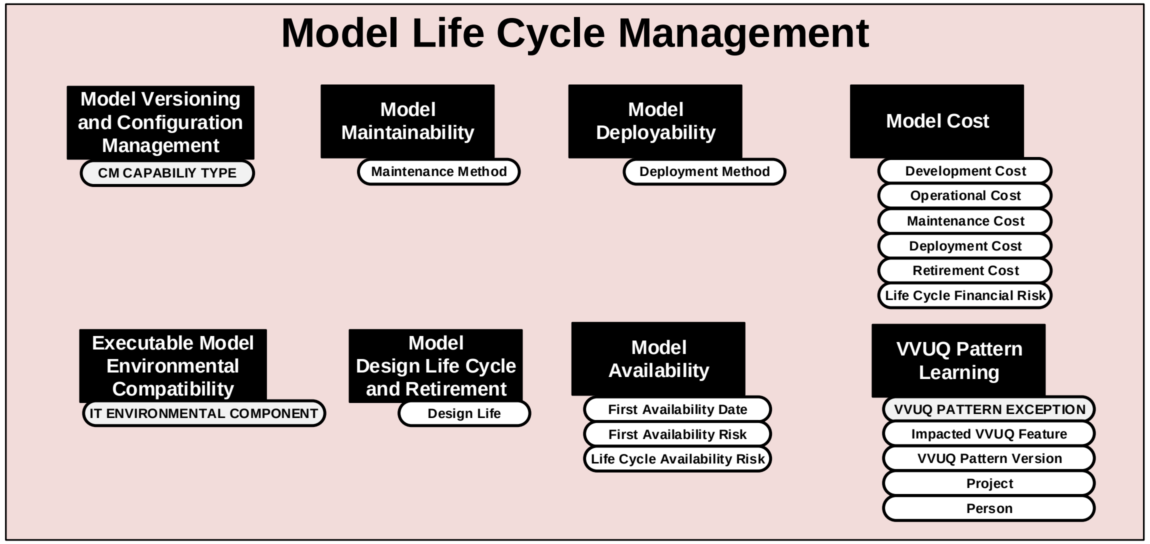
Feature Group	Feature Name	Feature Definition	Feature Attribute	Attribute Definition	Feature Stakeholder: Model User	Model Developer	Model Maintainer	Mdl Deployer	Model Use Supporter	Regulatory Authority	Mdl Investor	Model Type: Physics Based	Data Driven
Describes the credibility of the model													
	Model Envelope	The capability of the model to meet its Model Credibility requirements over a stated range (envelope) of dynamical inputs, outputs, and parameter values.	Model Application Envelope	The range over which the model is intended for use.	X		X			X	X	X	X
	Validated Conceptual Model Credibility	The validated capability of the conceptual portion of the model to represent the System of Interest, with acceptable Credibility.	Quantitative Accuracy Reference	The specification reference describing the quantitative accuracy of the conceptual model compared to the system of interest.	X					X	X	X	X
			Function Structure Accuracy Reference	The specification reference describing the structural (presence or absence of behaviors) accuracy of the conceptual model compared to the system of interest.	X		X			X	X	X	X
			Uncertainty Quantification (UQ) Reference	The specification reference describing the degree of uncertainty of the Credibility of the conceptual model to the system of	X		X			X	X	X	X
			Model Validation Reference	The reference documenting the validation of the conceptual model's Credibility to the system of	X		X			X	X	X	X



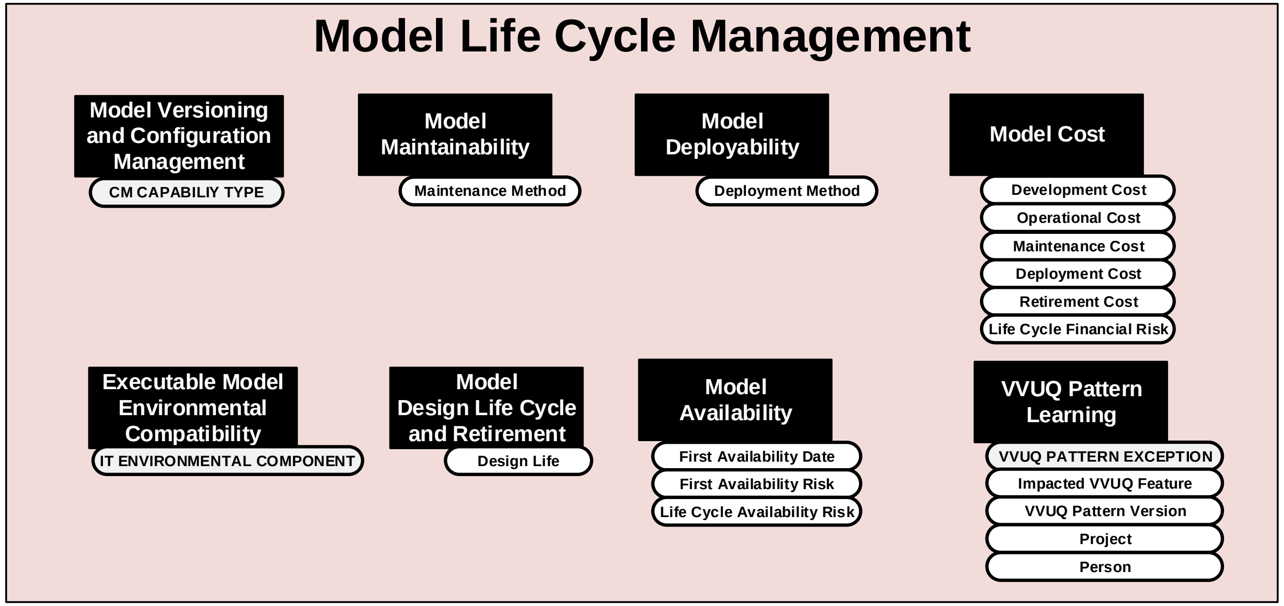
Feature Group	Feature Name	Feature Definition	Feature Attribute	Attribute Definition	Feature Stakeholder							Model Type	
					Model User	Model Developer	Model Maintainer	Mdl Deployer	Model Use Supporter	Regulatory Authority	Mdl Investor	Physics Based	Data Driven
Model Credibility	Verified Executable Model Credibility	The verified capability of the executable portion of the model to represent the System of Interest, with acceptable Credibility.	Quantitative Accuracy Reference	The specification reference describing the quantitative accuracy of the executable model to the conceptual model.	X		X			X	X	X	X
			Structural Accuracy Reference	The specification reference describing the structural (presence or absence of elements) accuracy of the executable model to the conceptual model.	X		X			X	X	X	X
			Uncertainty Quantification (UQ) Reference	The specification reference describing the degree of uncertainty of the Credibility of the executable model to the conceptual model.	X		X			X		X	X
			Speed	The specification reference describing the execution run time (speed) for the executable model.	X		X			X	X	X	X
			Quantization	The specification reference describing the quantization error of the executabl e model.	X		X			X	X	X	X
			Stability	The specification reference describing the level of stability of the accuracy and uncertainty of the executable model error characteristics.	X		X			X	X	X	X
			Model Validation Reference	The reference documenting the verification of the executable model's Credibility to the conceptual model.	X		X			X	X	X	X



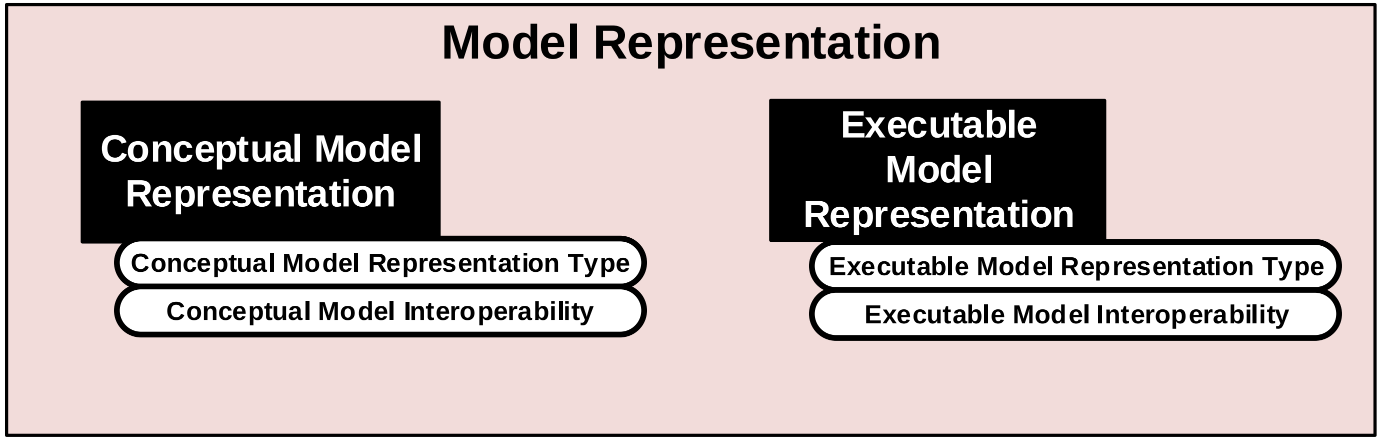
Feature Group	Feature Name	Feature Definition	Feature Attribute	Attribute Definition	Feature Stakeholder							Model Type	
					Model User	Model Developer	Model Maintainer	Mdl Deployer-Distributor	Model Use Supporter	Regulatory Authority	Mdl Investor-Owner	Physics Based	Data Driven
Describes related model life cycle management capabilities													
Model Life Cycle Management	Model Versioning and Configuration Management	The capability of the model to provide for version and configuration management.	CM Capability Type	The type(s) of CM capabilities included (may be multiple)	X		X			X		X	X
	Executable Model Environmental Compatibility	The capability of the model to be compatibly supported by specified information technology environment(s), indicating compatibility, portability, and interoperability.	IT Environmental Component	The type(s) of IT environments or standards supported	X		X			X		X	X
	Model Design Life and Retirement	The capability of the model to be sustained over an indicated design life, and retired on a planned basis.	Design Life	The planned retirement date	X		X			X		X	X
	Model Maintainability	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	Maintenance Method	The type of maintenance methodology used to maintain the model's capability and availability for the intended purposes over the intended life cycle.	X		X			X	X	X	X
	Model Deployability	The capability of the model to support deployment into service on behalf of intended users, in its original or subsequent updated versions	Deployment Method	The type of method used to deploy (possibly in repeating cycles) the model into its intended use environment.	X			X			X	X	X



Feature Group	Feature Name	Feature Definition	Feature Attribute	Attribute Definition	Feature Stakeholder: Model User	Model Developer	Model Maintainer	Mdl Deployer-Distributor	Model Use Supporter	Regulatory Authority	Mdl Investor-Owner	Model Type: Physics Based	Data Driven
Describes related model life cycle management capabilities													
Model Life Cycle Management	Model Cost	The financial cost of the model, including development, operating, and maintenance cost	Development Cost	The cost to develop the model, including its validation and verification, to its first availability for service date		**X**					**X**	X	X
			Operational Cost	The cost to execute and otherwise operate the model, in standardized execution load units	**X**						**X**	X	X
			Maintenance Cost	The cost to maintain the model			**X**				**X**	X	X
			Deployment Cost	The cost to deploy, and redeploy updates, per cycle				**X**			**X**	X	X
			Retirement Cost	The cost to retire the model from service, in a planned fashion	**X**						**X**	X	X
			Life Cycle Financial Risk	Risk to the overall life cycle cost of the model							**X**	X	X
	Model Availability	The degree and timing of availability of the model for its intended use, including date of its first availability and the degree of ongoing availability thereafter.	First Availability Date	Date when version will first be available	**X**						**X**	X	X
			First Availability Risk	Risk to the scheduled date of first availability	**X**						**X**	X	X
			Life Cycle Availability Risk	Risk to ongoing availability after introduction	**X**						**X**	X	X



Feature Group	Feature Name	Feature Definition	Feature Attribute	Attribute Definition	Feature Stakeholder: Model User	Model Developer	Model Maintainer	Mdl Deployer–	Model Use Supporter	Regulatory Authority	Mdl Investor–	Model Type: Physics Based	Data Driven
	VVUQ Pattern Learning	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.	VVUQ Pattern Exception	A summary of the exception noted to the current VVUQ Pattern (may be multiple exceptions)		X					X	X	X
			Impacted VVUQ Feature	The impacted existing, modified, or additional feature of the VVUQ Pattern.		X					X	X	X
			VVUQ Pattern Version	The version of the VVUQ Pattern in current use before change.		X					X	X	X
			Project	Identifies the project in which the exception was noted		X					X	X	X
			Person	Identifies the person describing the exception		X					X	X	X



Feature Group	Feature Name	Feature Definition	Feature Attribute	Attribute Definition	Feature Stakeholder: Model User	Model Developer	Model Maintainer	Mdl Deployer-Distributor	Model Use Supporter	Regulatory Authority	Mdl Investor-Owner	Model Type: Physics Based	Data Driven
Identifies the type of representation used by the model													
Model Representation	Conceptual Model Representation	The capability of the conceptual portion of the model to represent the system of interest, using a specific type of representation.	Conceptual Model Representation Type	The type of conceptual modeling language or metamodel used.	X		X			X		X	X
			Conceptual Model Interoperability	The degree of interoperability of the conceptual model, for exchange with other environments	X		X			X		X	X
	Executable Model Representation	The capability of the executable portion of the model to represent the system of interest, using a specific type of representation	Executable Model Representation Type	The type of executable modeling language or metamodel used.	X		X			X		X	X
			Executable Model Interoperability	The degree of interoperability of the executable model, for exchange with other environments	X		X			X		X	X

Exercise 1: Model Planning, Targeting Business Values

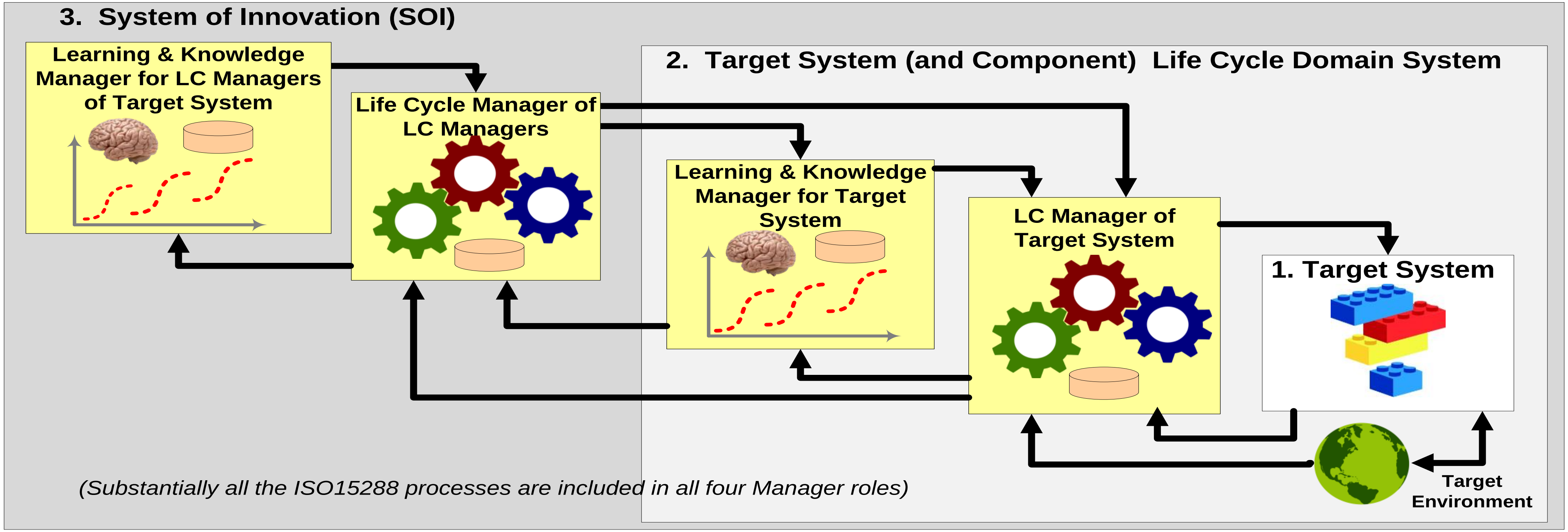
1. For a (real or hypothetical) use by your enterprise of a model-based approach, configure the VVUQ Model Features Pattern to describe your targeted outcomes – use the Model Features Pattern Form.
2. Did the VVUQ Features Pattern cover all your targeted improvement issues and concerns? Are there others?
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.

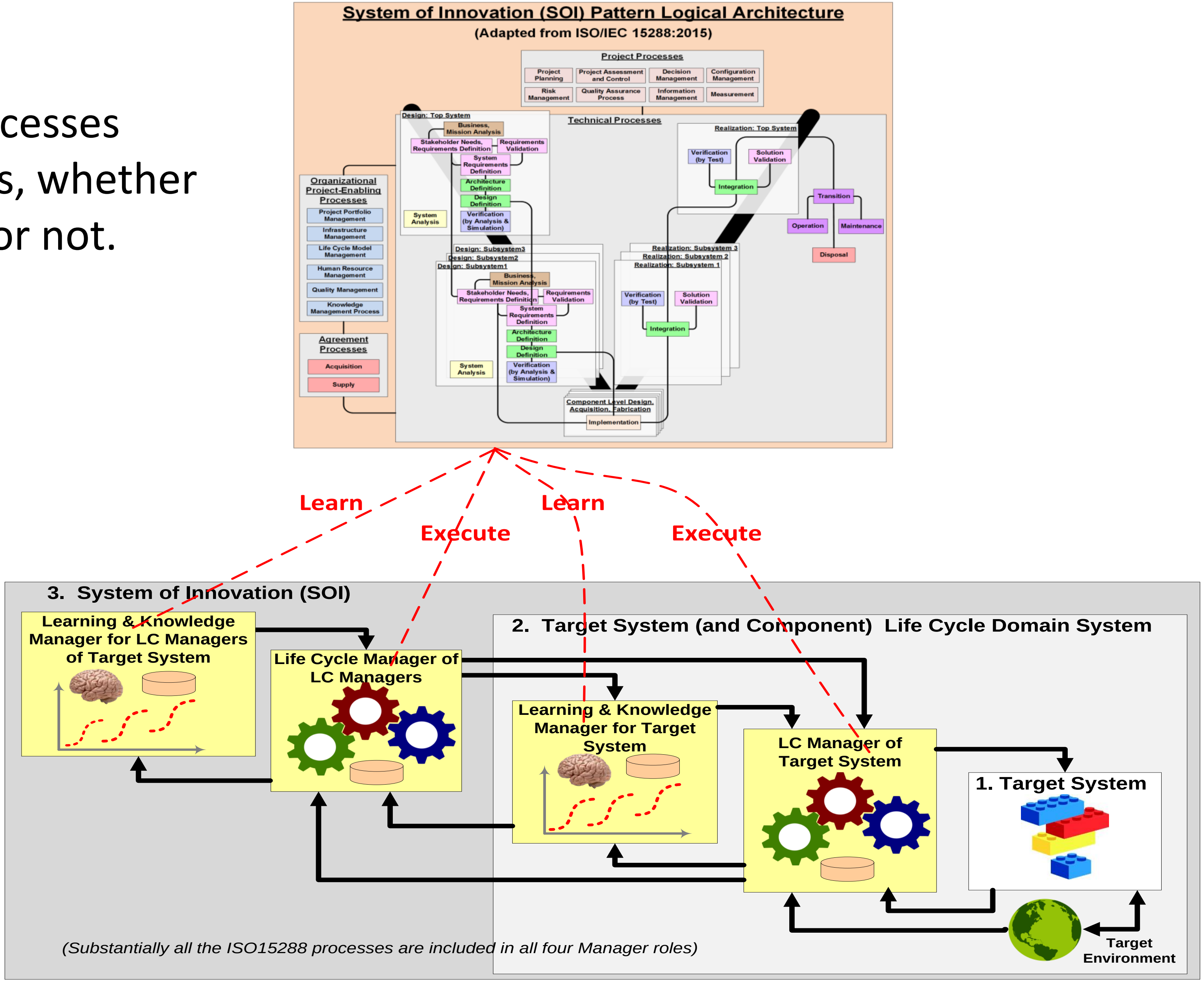
The System of Innovation (SOI) MBSE Pattern

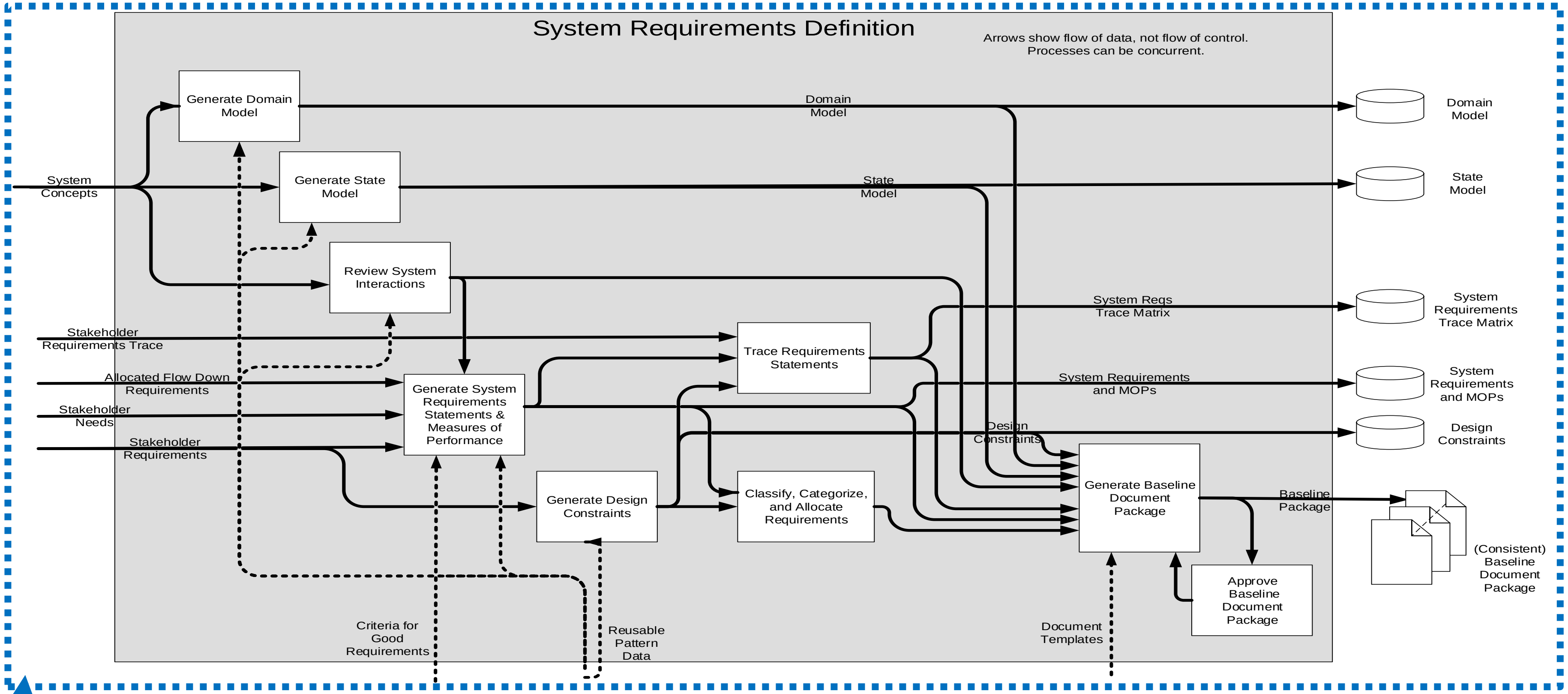
(Used for INCOSE Agile SE Project, INCOSE CIPR WG, etc.
Innovation reference model: Not prescriptive, but descriptive.)



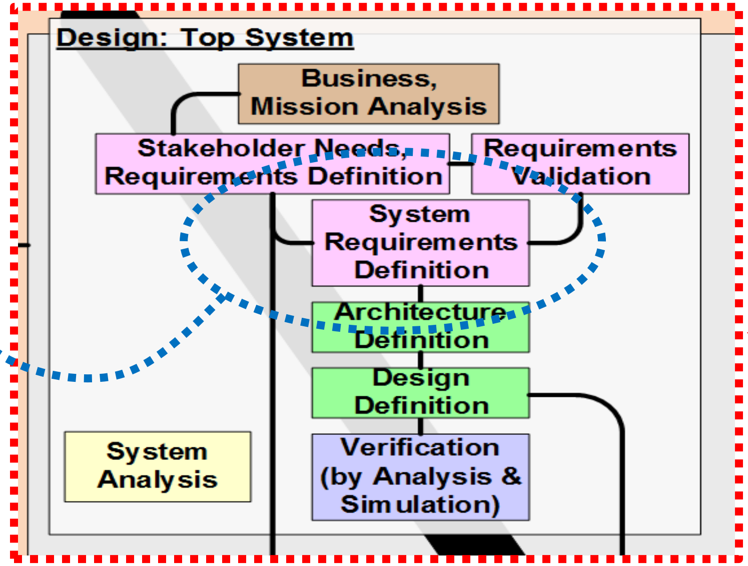
- System 1: Target system of interest, to be engineered or improved.
- System 2: The environment of (interacting with) S1, including all the life cycle management systems of S1, including learning about S1.
- System 3: The life cycle management systems for S2, including learning about S2.

ISO 15288 processes appear 4 times, whether we recognize or not.

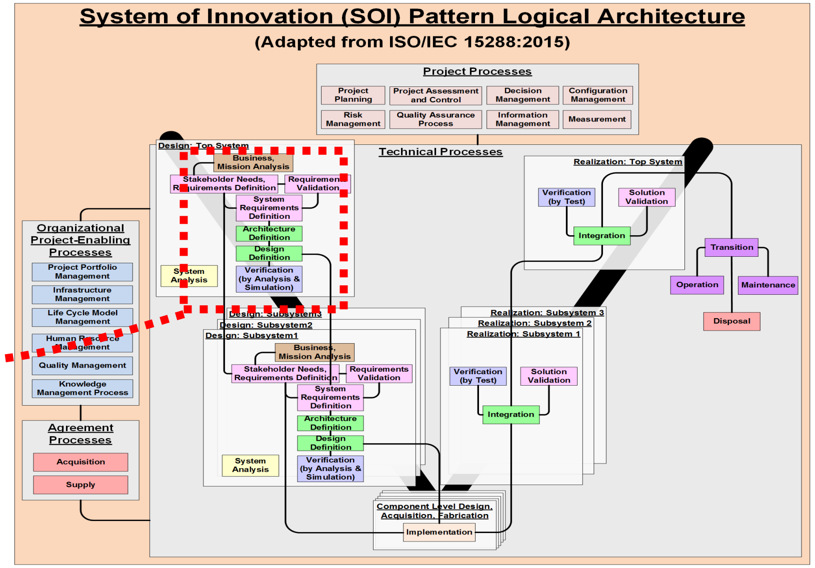




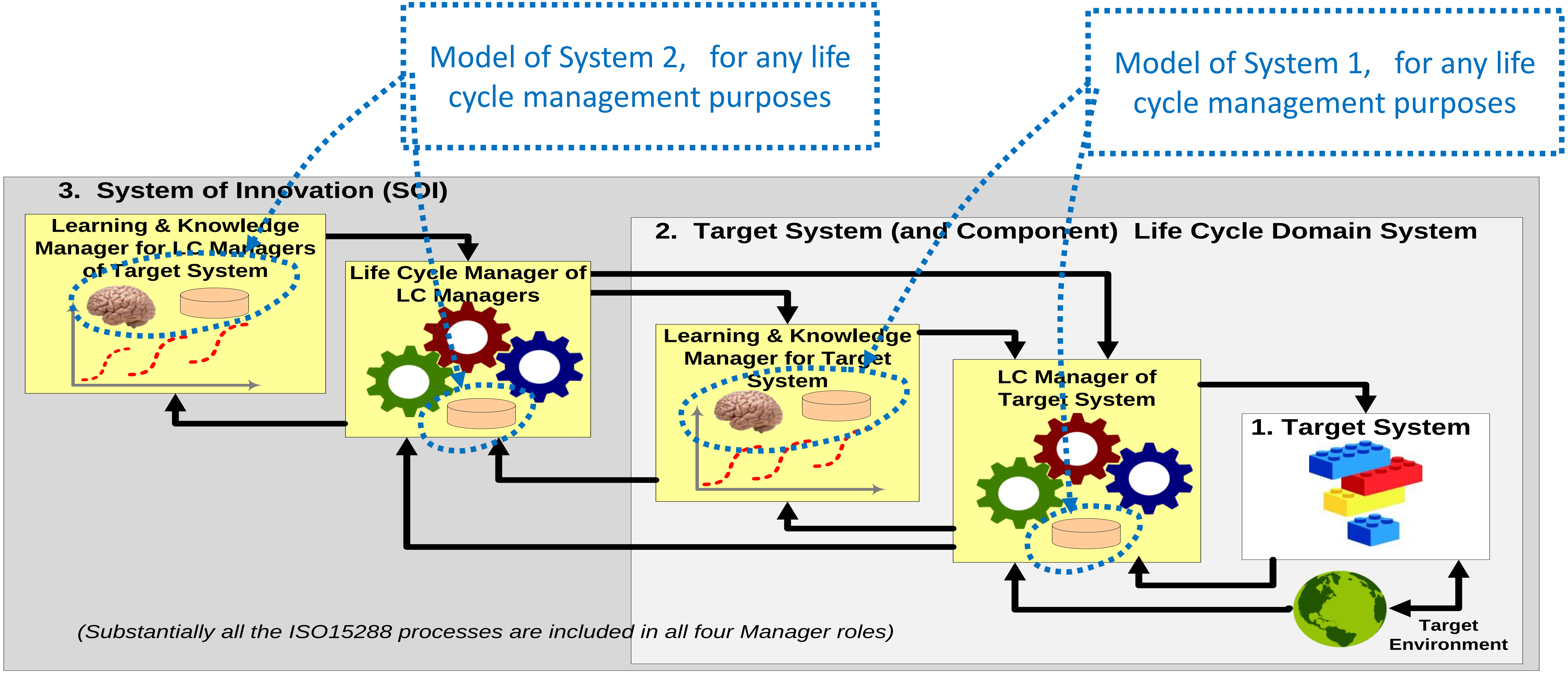
System Requirements Definition
Arrows show flow of data, not flow of control.
Processes can be concurrent.
Generate Domain Model
Generate State Model
Review System Interactions
Trace Requirements Statements
Generate System Requirements Statements & Measures of Performance
Generate Design Constraints
Classify, Categorize, and Allocate Requirements
Generate Baseline Document Package
Approve Baseline Document Package
System Concepts
Stakeholder Requirements Trace
Allocated Flow Down Requirements
Stakeholder Needs
Stakeholder Requirements
Domain Model
State Model
System Reqs Trace Matrix
System Requirements and MOPs
Design Constraints
Baseline Package
Criteria for Good Requirements
Reusable Pattern Data
Document Templates
Domain Model
State Model
System Requirements Trace Matrix
System Requirements and MOPs
Design Constraints
(Consistent) Baseline Document Package



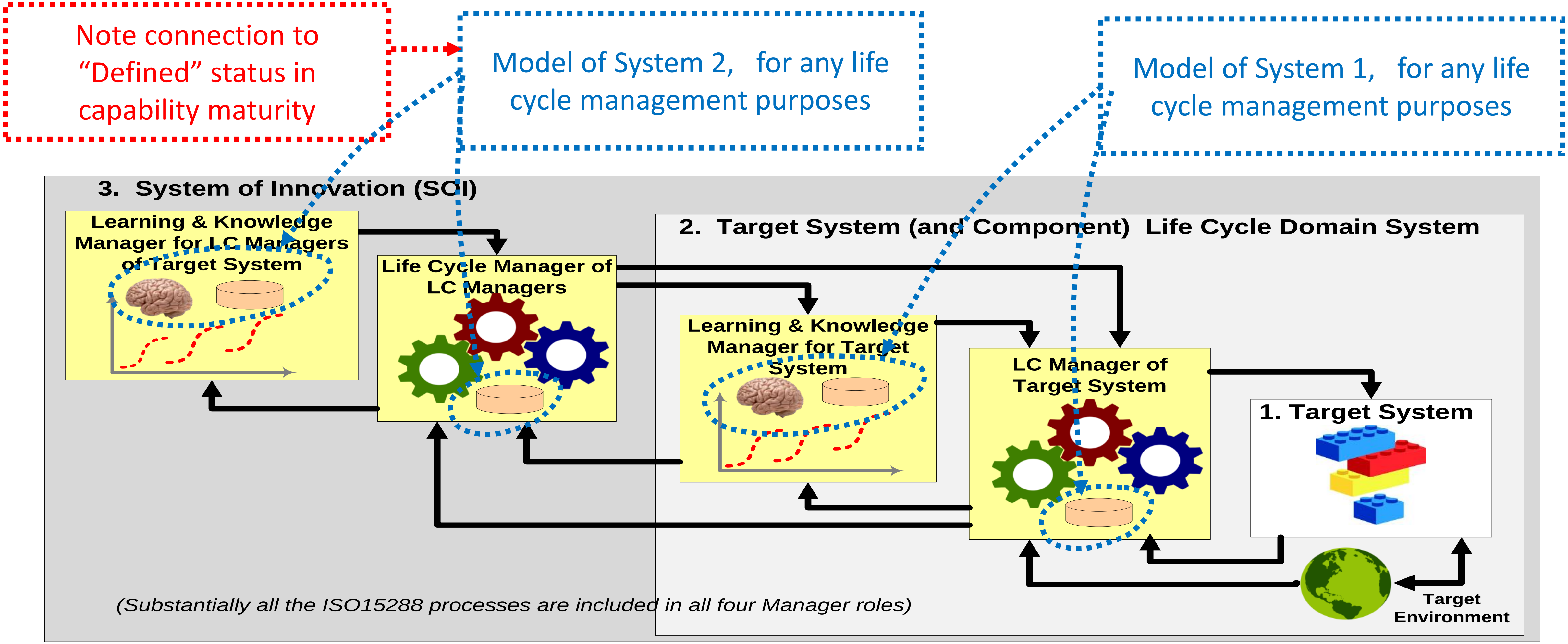
Design: Top System
Business, Mission Analysis
Stakeholder Needs, Requirements Definition
Requirements Validation
System Requirements Definition
Architecture Definition
Design Definition
Verification (by Analysis & Simulation)
System Analysis



System of Innovation (SOI) Pattern Logical Architecture
(Adapted from ISO/IEC 15288:2015)
Project Processes
Project Planning
Project Assessment and Control
Decision Management
Configuration Management
Risk Management
Quality Assurance Process
Information Management
Measurement
Technical Processes
Organizational Project-Enabling Processes
Project Portfolio Management
Infrastructure Management
Life Cycle Model Management
Human Resource Management
Quality Management
Knowledge Management Process
Agreement Processes
Acquisition
Supply
Design: Top System
Business, Mission Analysis
Stakeholder Needs, Requirements Definition
Requirements Validation
System Requirements Definition
Architecture Definition
Design Definition
Verification (by Analysis & Simulation)
System Analysis
Design: Subsystem3
Design: Subsystem2
Design: Subsystem1
Realization: Top System
Verification (by Test)
Solution Validation
Integration
Transition
Operation
Maintenance
Disposal
Realization: Subsystem 3
Realization: Subsystem 2
Realization: Subsystem 1
Component Level Design, Acquisition, Fabrication
Implementation



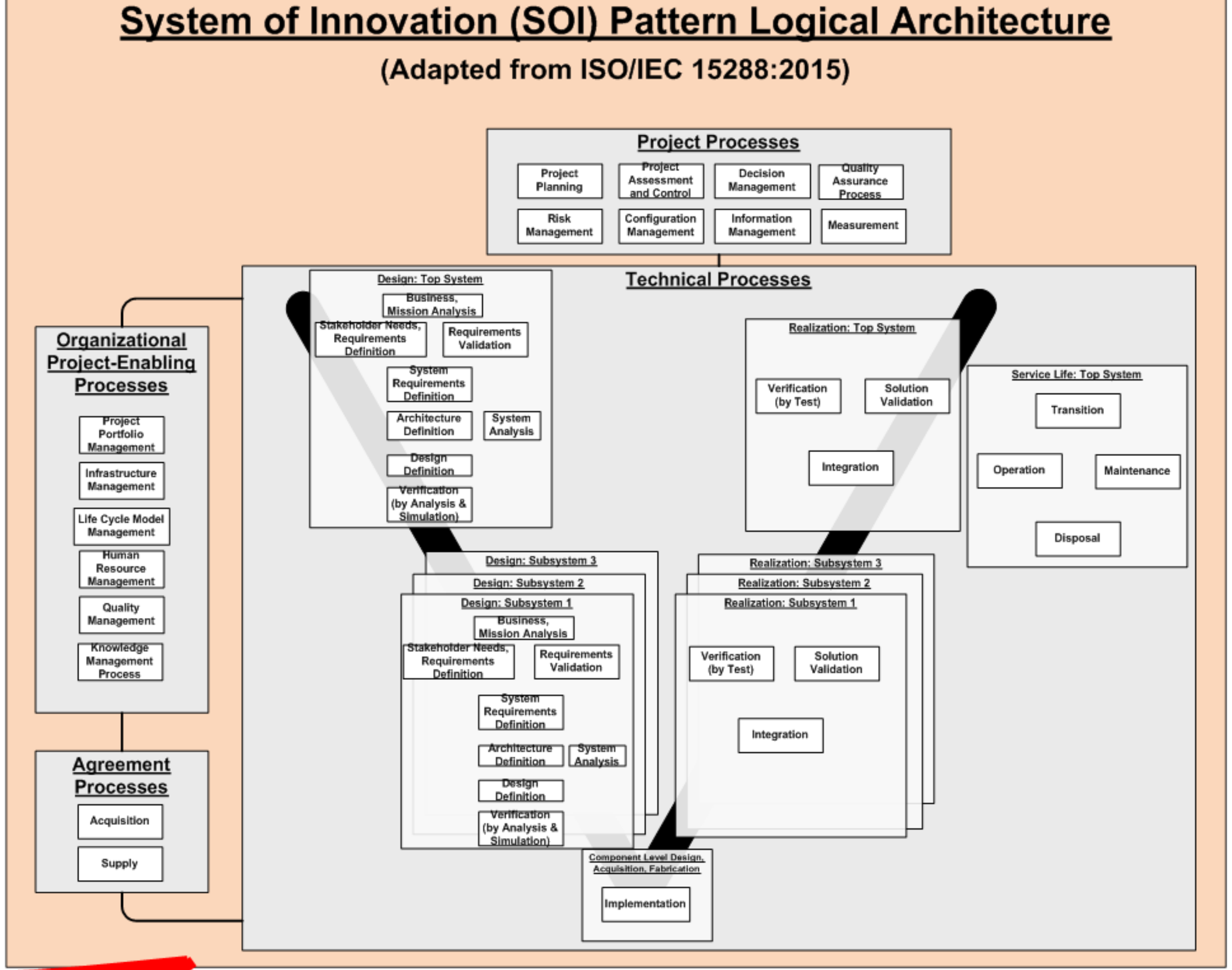
- System 1: Target system of interest, to be engineered or improved.
- System 2: The environment of (interacting with) S1, including all the life cycle management systems of S1, including learning about S1.
- System 3: The life cycle management systems for S2, including learning about S2.

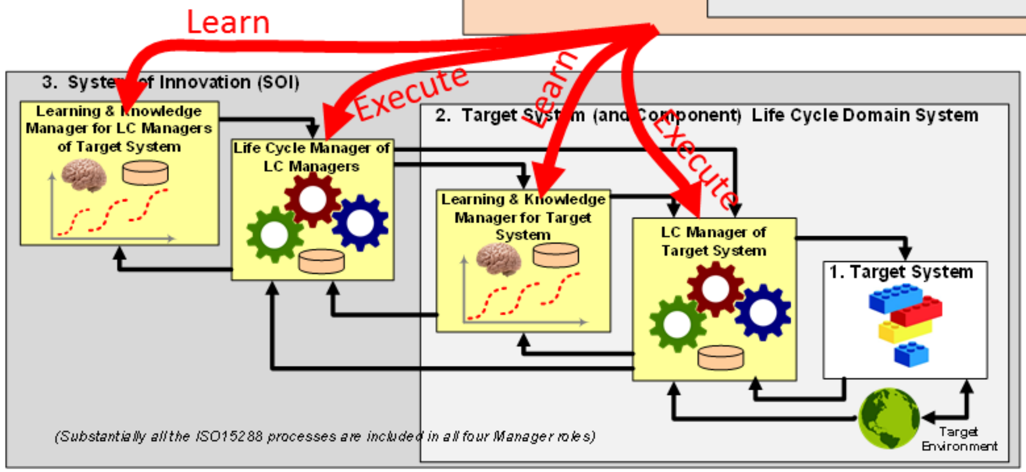


- System 1: Target system of interest, to be engineered or improved.
- System 2: The environment of (interacting with) S1, including all the life cycle management systems of S1, including learning about S1.
- System 3: The life cycle management systems for S2, including learning about S2.

Both System 1 and System 2 are potentially subject to learning.

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

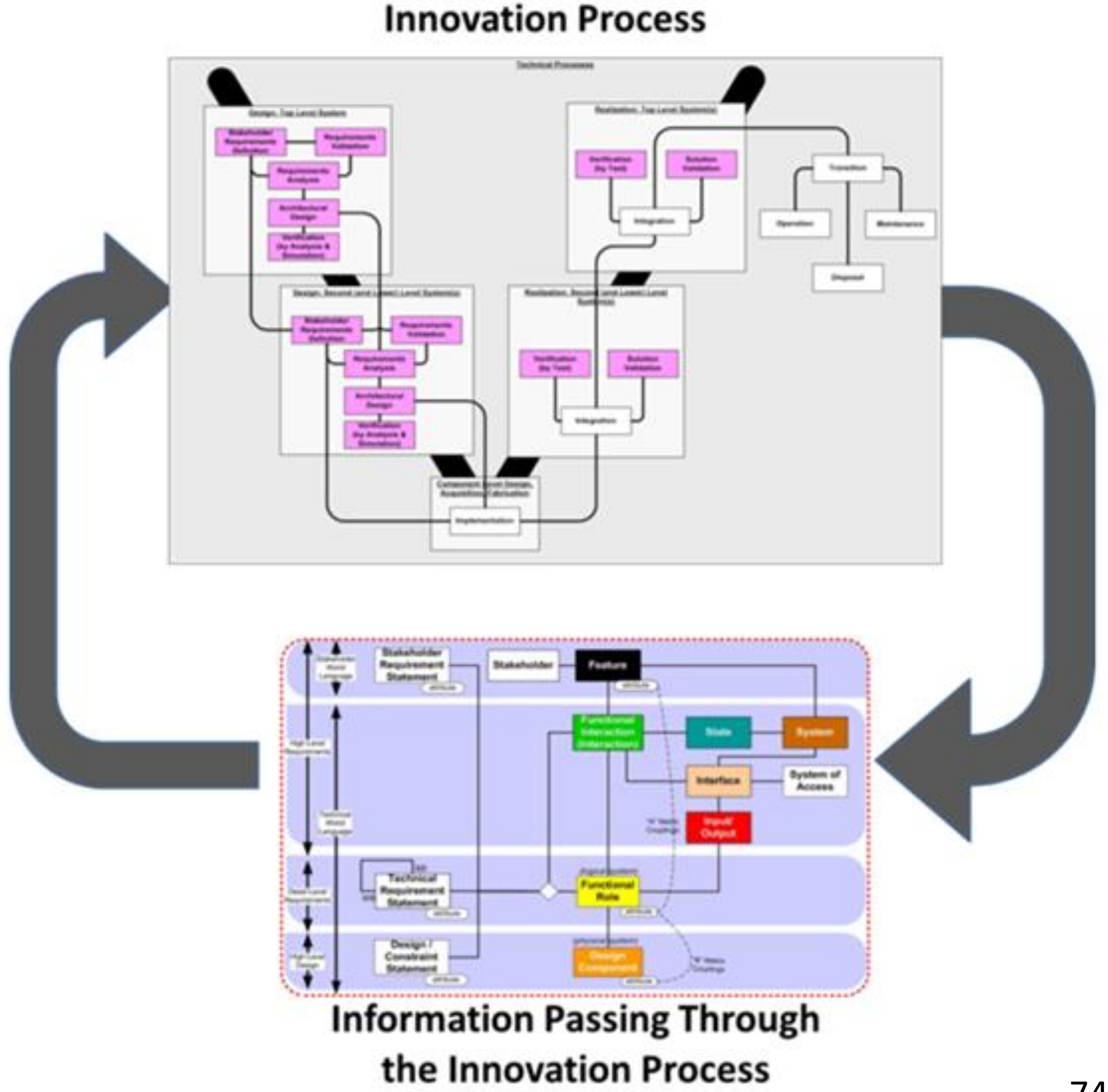




They appear repeatedly, in different ways in the SOI & ASELCM Patterns . . . . . .

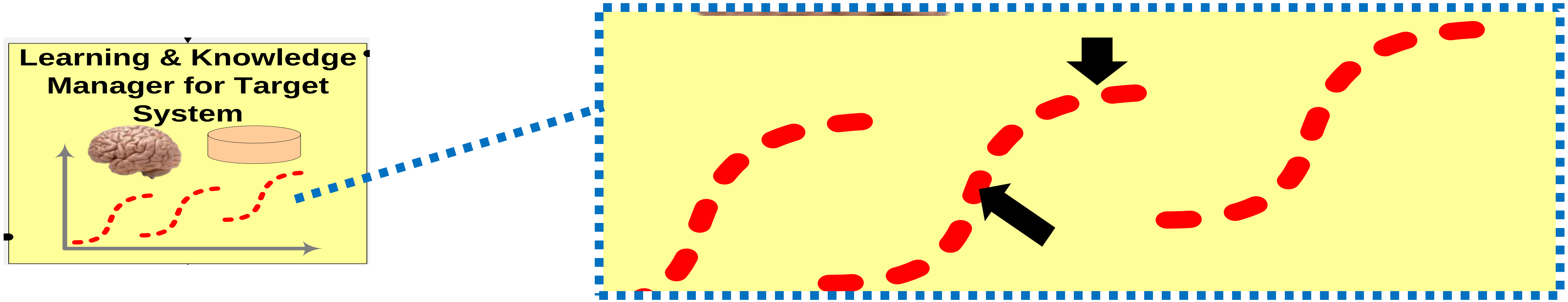
From Systems Engineering to Systems Innovation:

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).

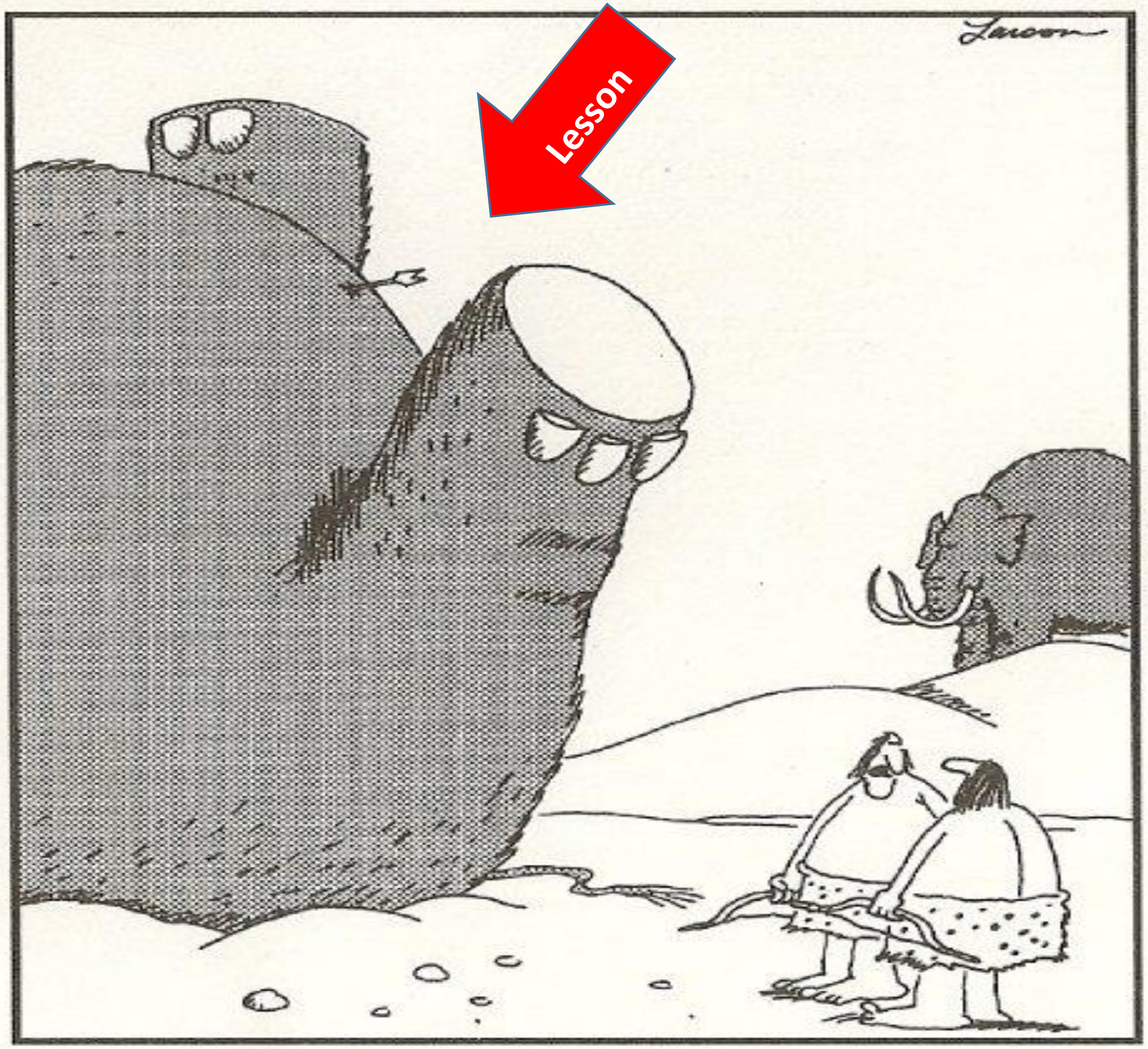
Lessons Learned: <u>Effective</u> Learning?

- 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 <u>could</u> be impacted <u>is</u> effectively impacted, versus repeating similar work or problem consequences.

Lessons Learned?

Lessons Learned Report

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Sed aliquam odio eget massa feugiat, at tincidunt quam ullamcorper. Nullam ac purus tortor. Duis a ullamcorper augue. Pellentesque eu eros hendrerit, tempor tellus vitae, suscipit.

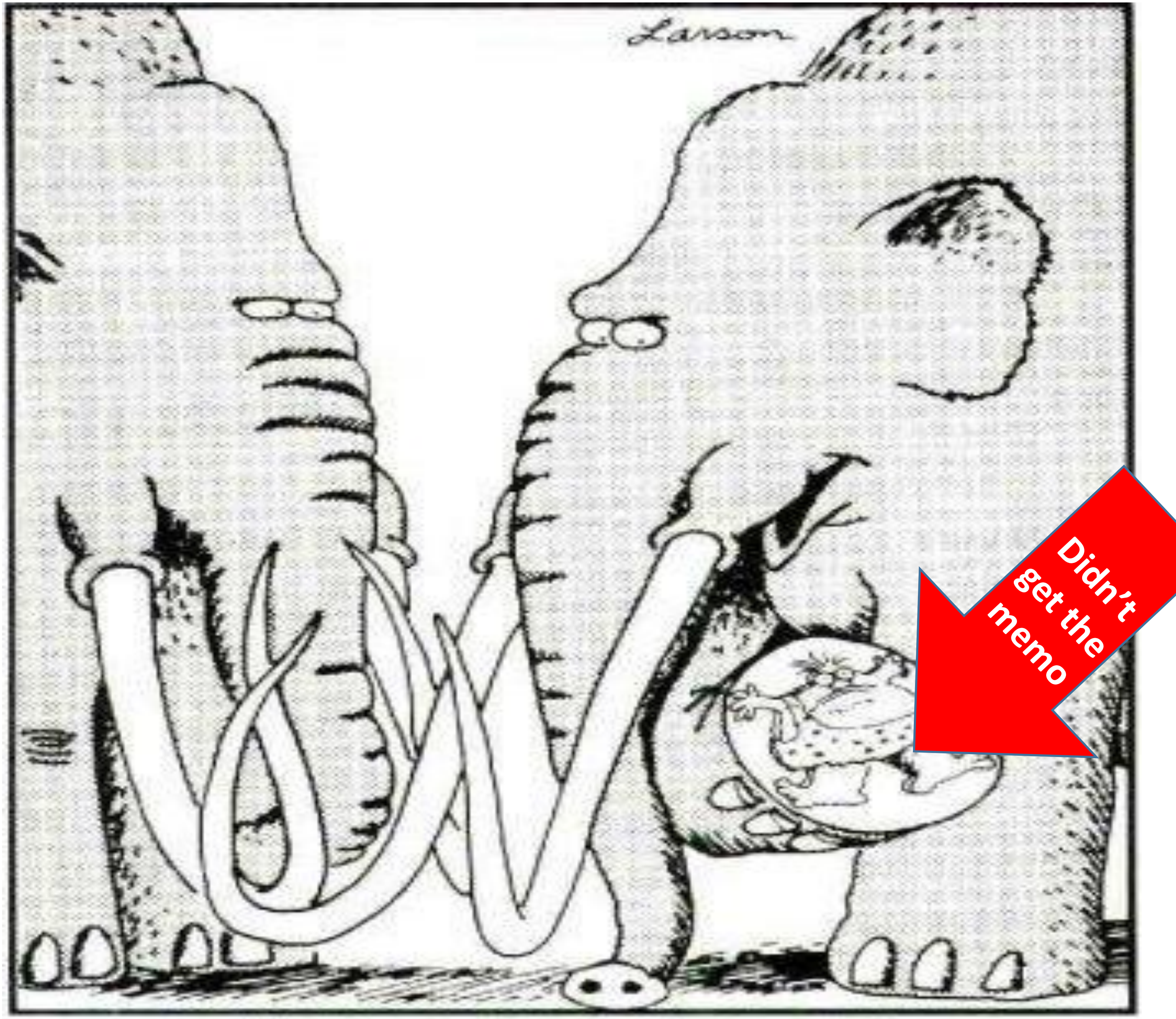


"We should write that spot down."

Lessons Effectively Learned?

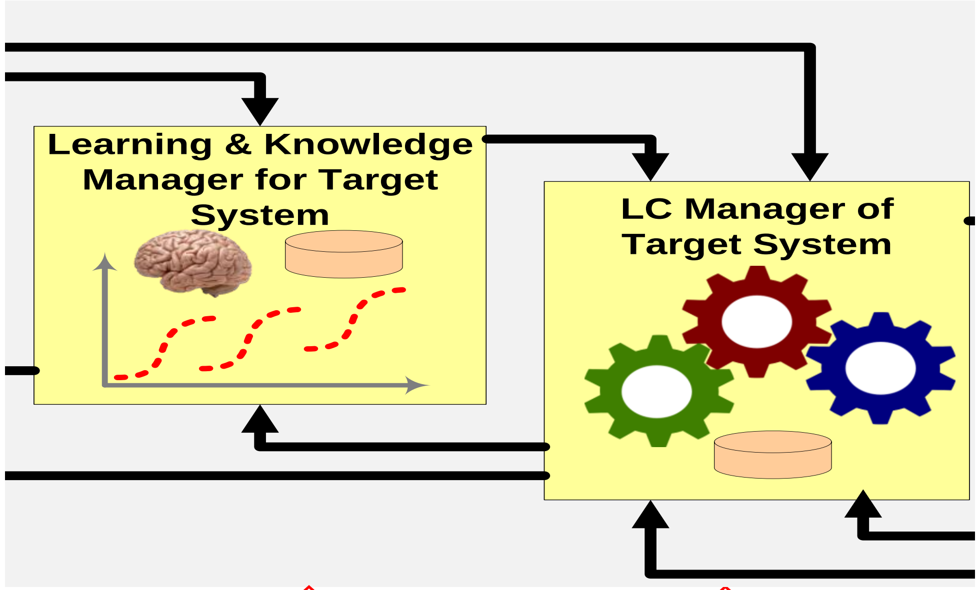
Lessons Learned Report

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Sed aliquam odio eget massa feugiat, at tincidunt quam ullamcorper. Nullam ac purus tortor. Duis a ullamcorper augue. Pellentesque eu eros hendrerit, tempor tellus vitae, suscipit.

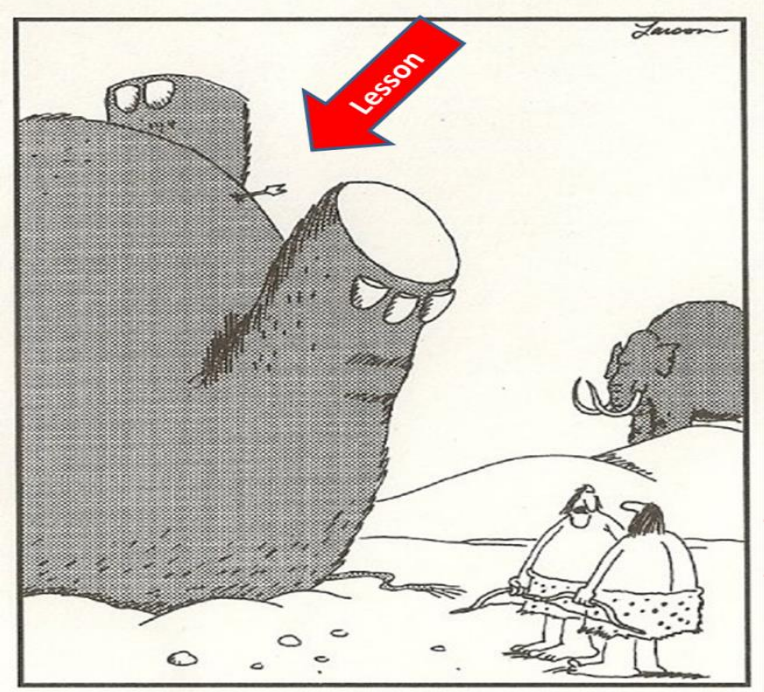


"Well, what the? ... I *thought* I smelled something."

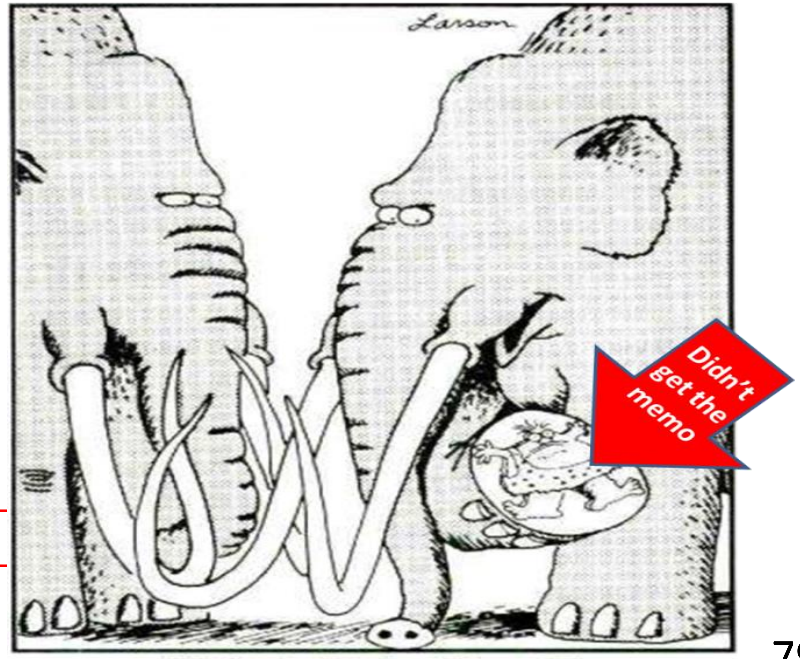
Learning



Executing



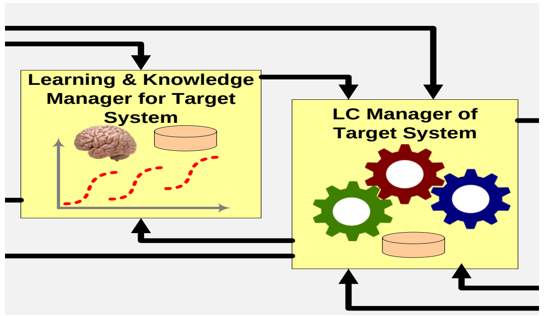
"We should write that spot down."



"Well, what the? ... I *thought* I smelled something."

Lessons Learned: Effective Learning?

- Where are the "lessons learned" encoded? What 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.

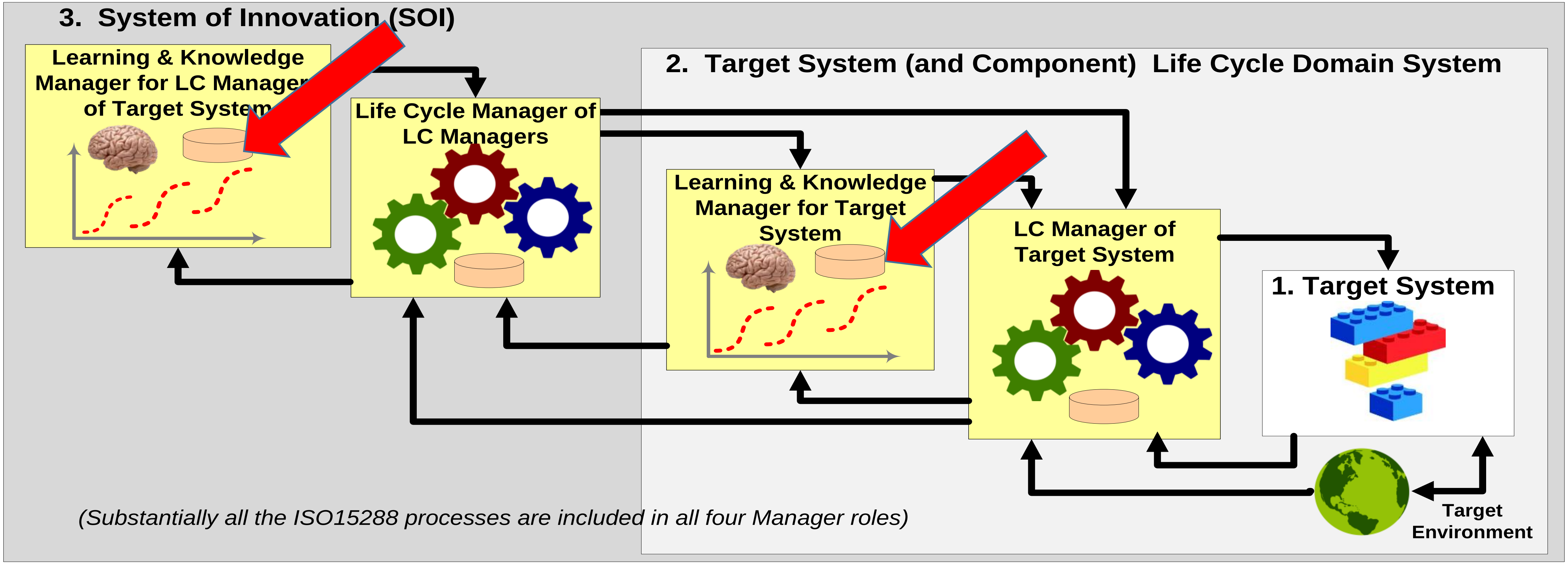
Learned models from STEM (~300 years) offer the most dramatic example of positive collaborative impact of effectively <u>shared</u> and <u>validated</u> models

- Effective Model <u>Sharing</u>:
  - 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 <u>Validation</u>:
  - Especially when shared, models demand that we <u>trust</u> 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



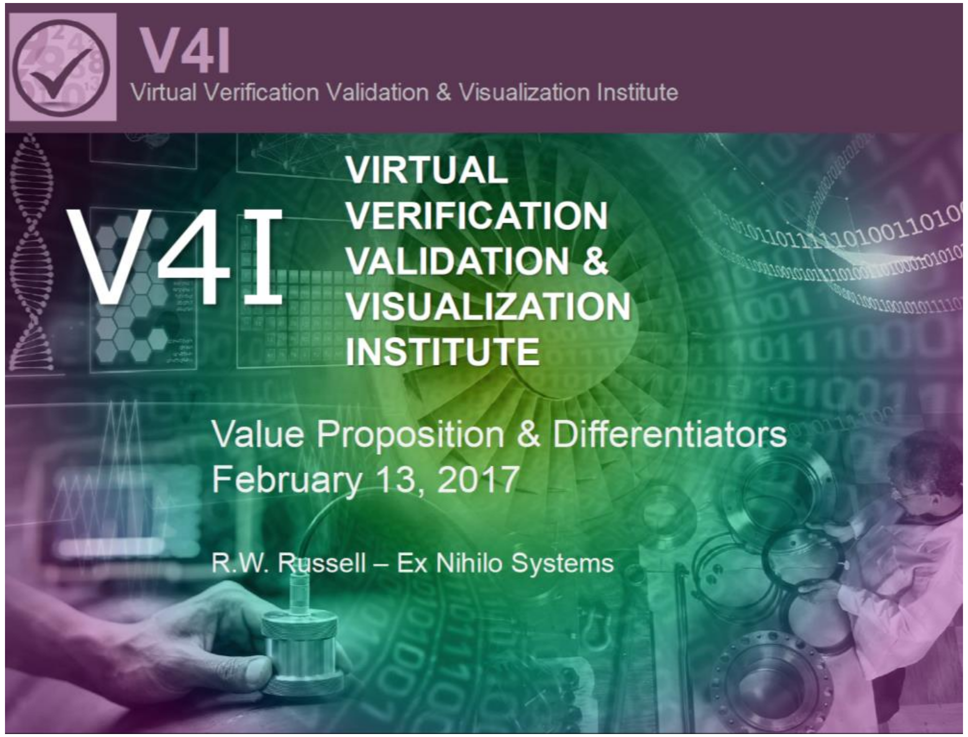
- Trusted shared MBSE Patterns for classes of systems
- Configurable for vendor-specific products
- With Model VVUQ frameworks lowering the cost of model trust for regulatory submissions

Exercise 2: Targeted Learning Areas

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?

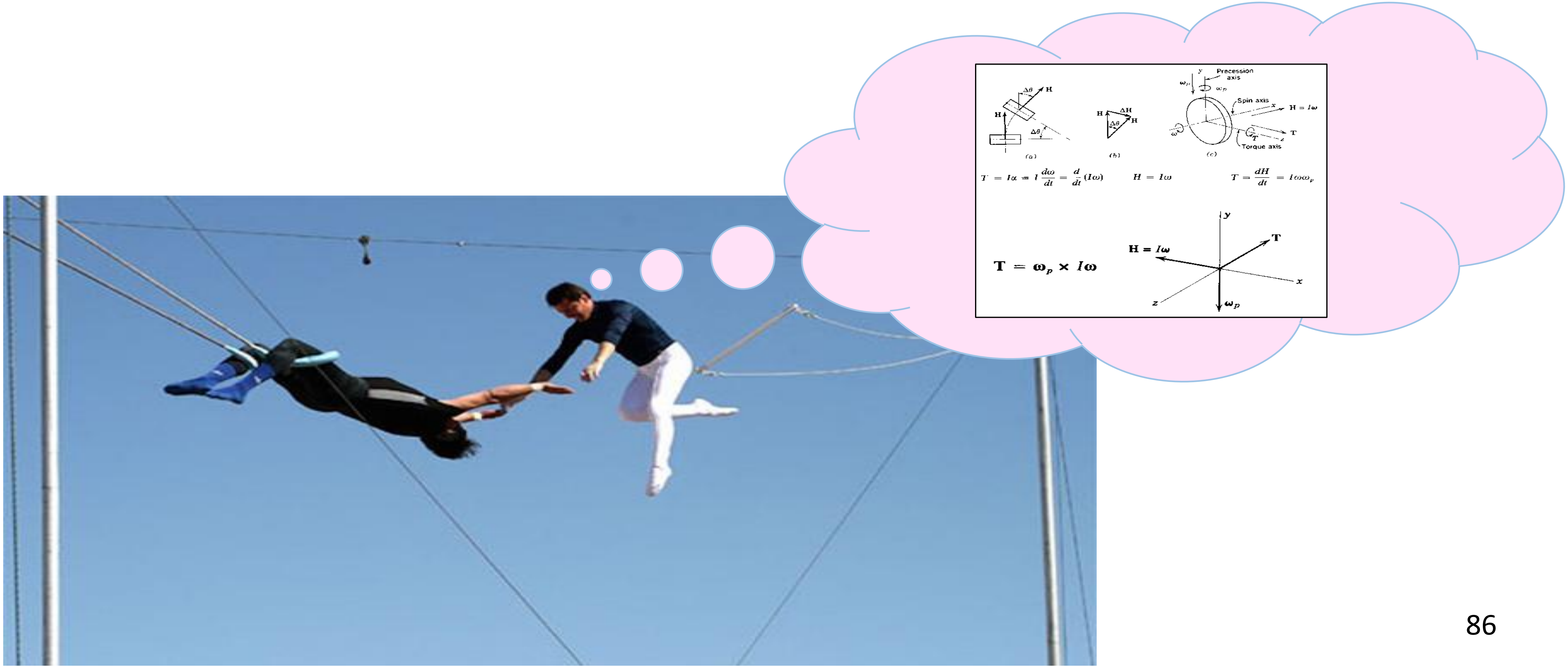
Can You Trust Someone Else's Model? Your Model?

- Planning for Model Verification, Validation, and Uncertainty Quantification (Model VVUQ)



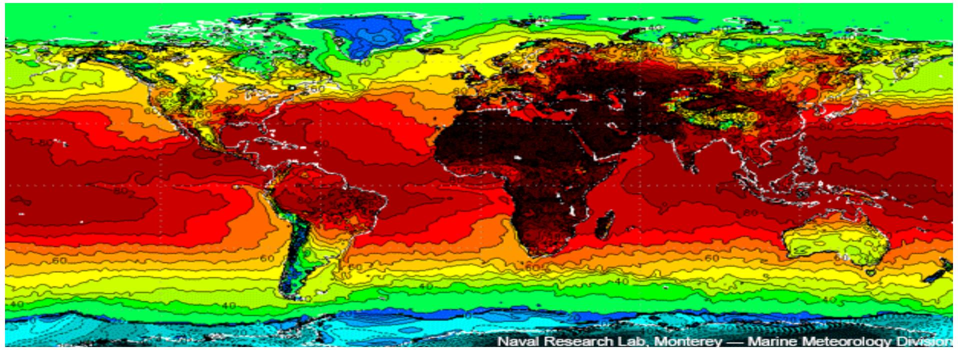
Requirements for trustable models

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?

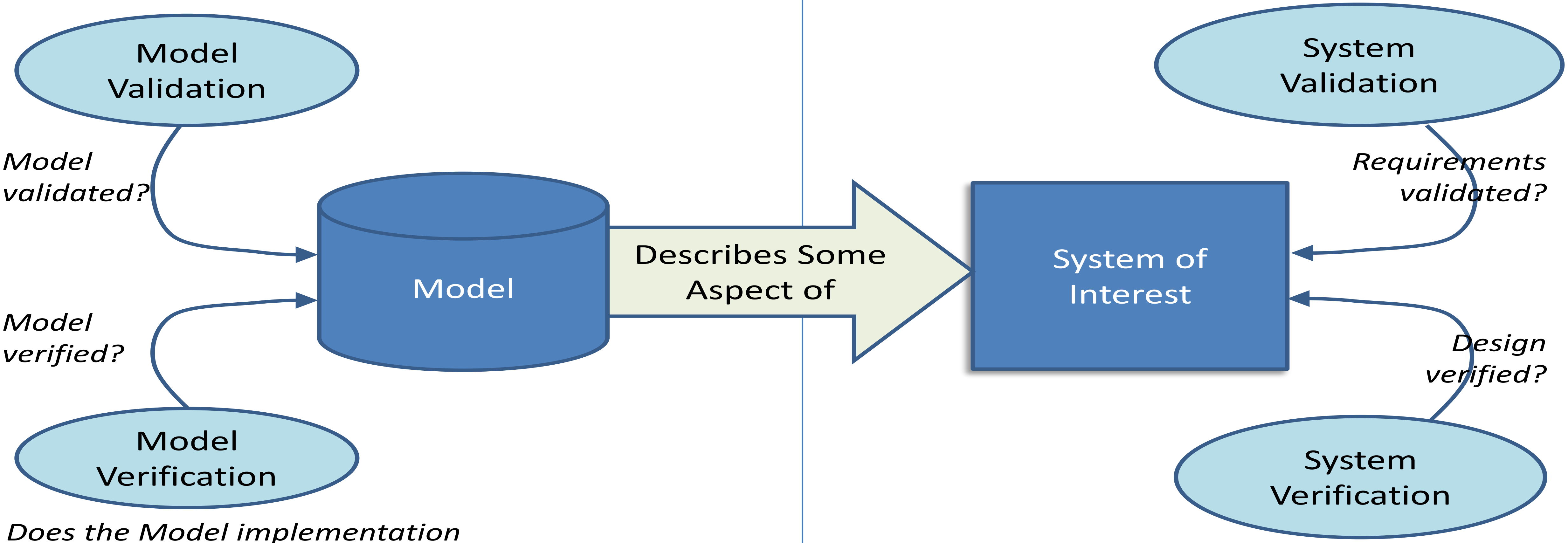
- Model Validation (V)
- Model Verification (V)
- Model Uncertainty Quantification (UQ)
- Not just for numerical grid (FEA, CFD, Thermal) models—extension to system models at all levels.
- Bayesian Network aspects of UQ

V&V of *Models*, Per Emerging ASME Model V&V Standards

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

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

Do the System Requirements describe what stakeholders need?

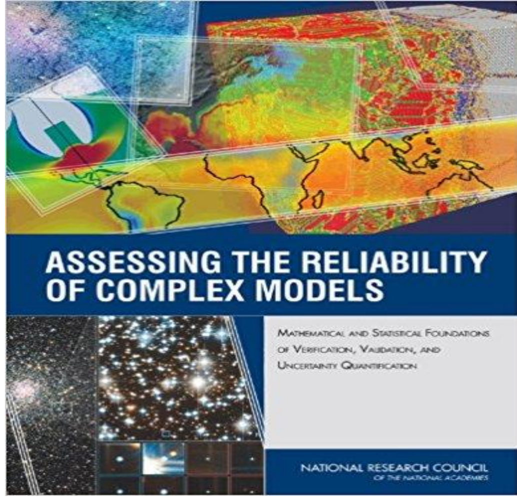


Does the Model implementation adequately represent what the Model says?

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

Don't forget: A model (on the left) <u>may</u> 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

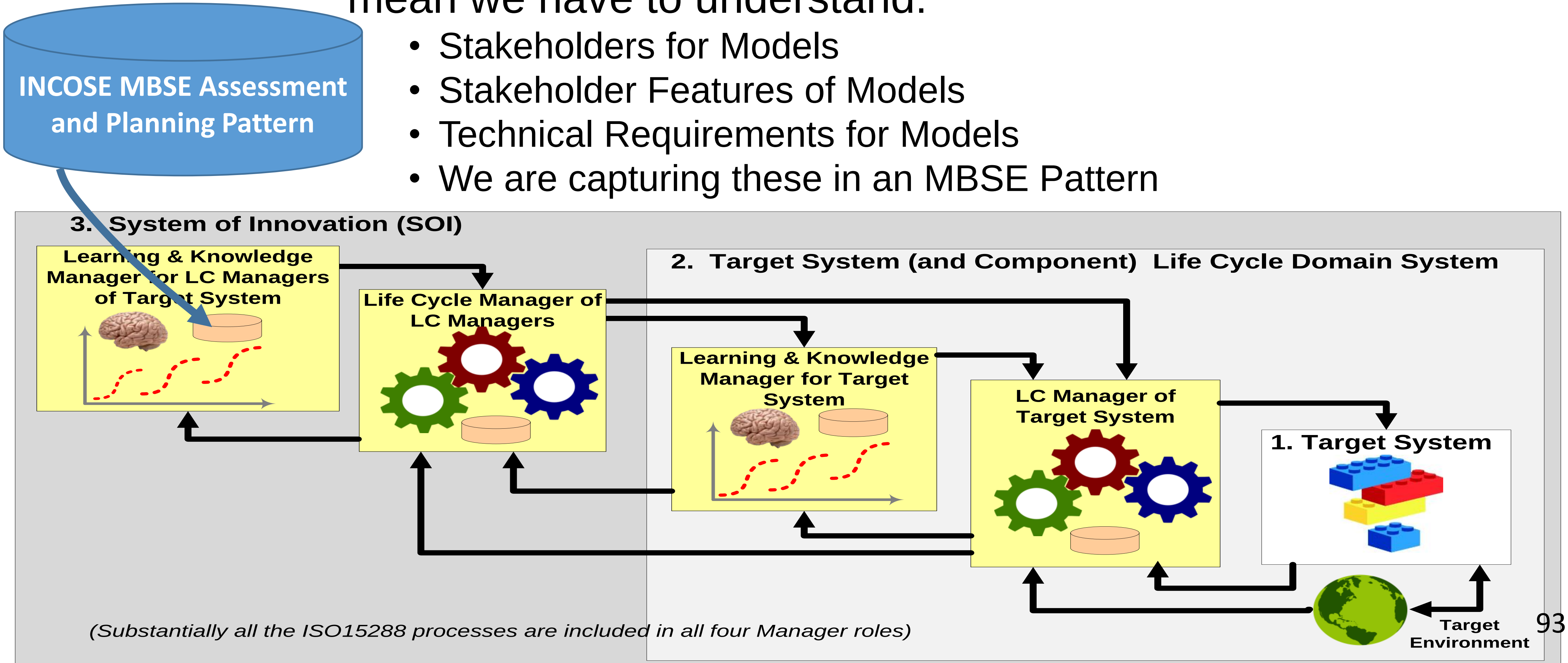
https://cstools.asme.org/csconnect/CommitteePages.cfm?Committee=100003367

ASME SETTING THE STANDARD

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



Opportunities--what you can do

- Think larger about <u>intended uses and users of MBSE</u>, 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?

You are here.

End of Part I