The Model VVUQ Pattern: Input to the Requirements Generation Process for Physics-Based and Data-Driven Computational Models

- What MBSE tells us about requirements for models
- Inputs for the model life cycle writing teams

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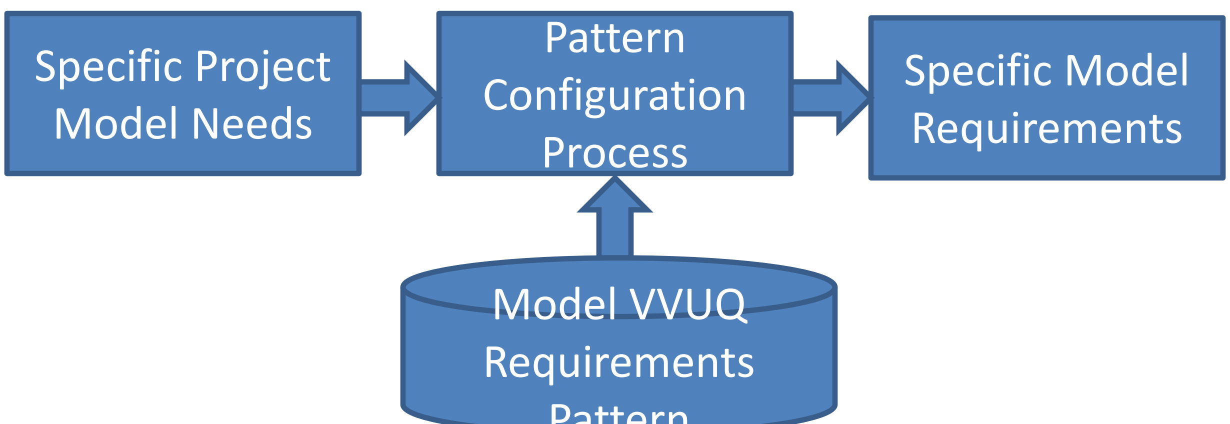
Contents

Vision for a Practical Aid to Model Community

- A computation model is validated and verified with respect to not just the system it represents, but also the Model Requirements, specifying the intended use 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.

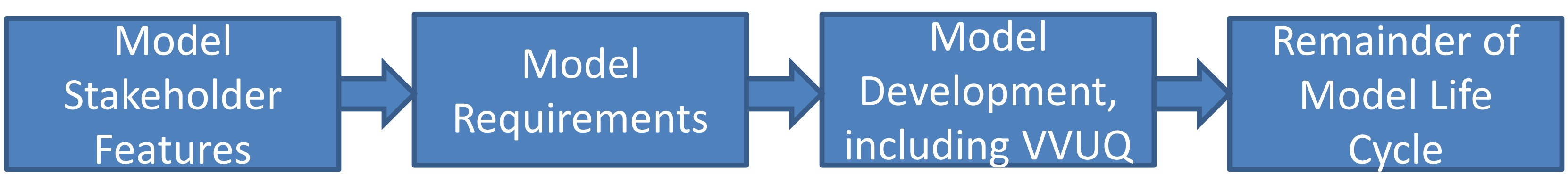
Vision for a Practical Aid to Model Community

- 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:

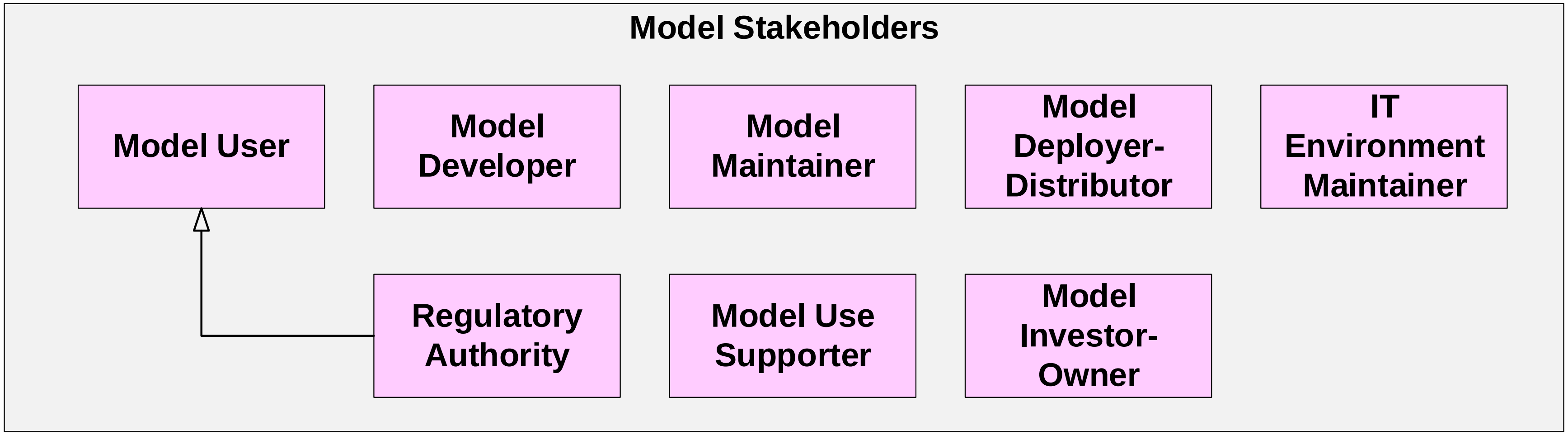


Vision for a Practical Aid to Model Community

- 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 intains 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, 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.

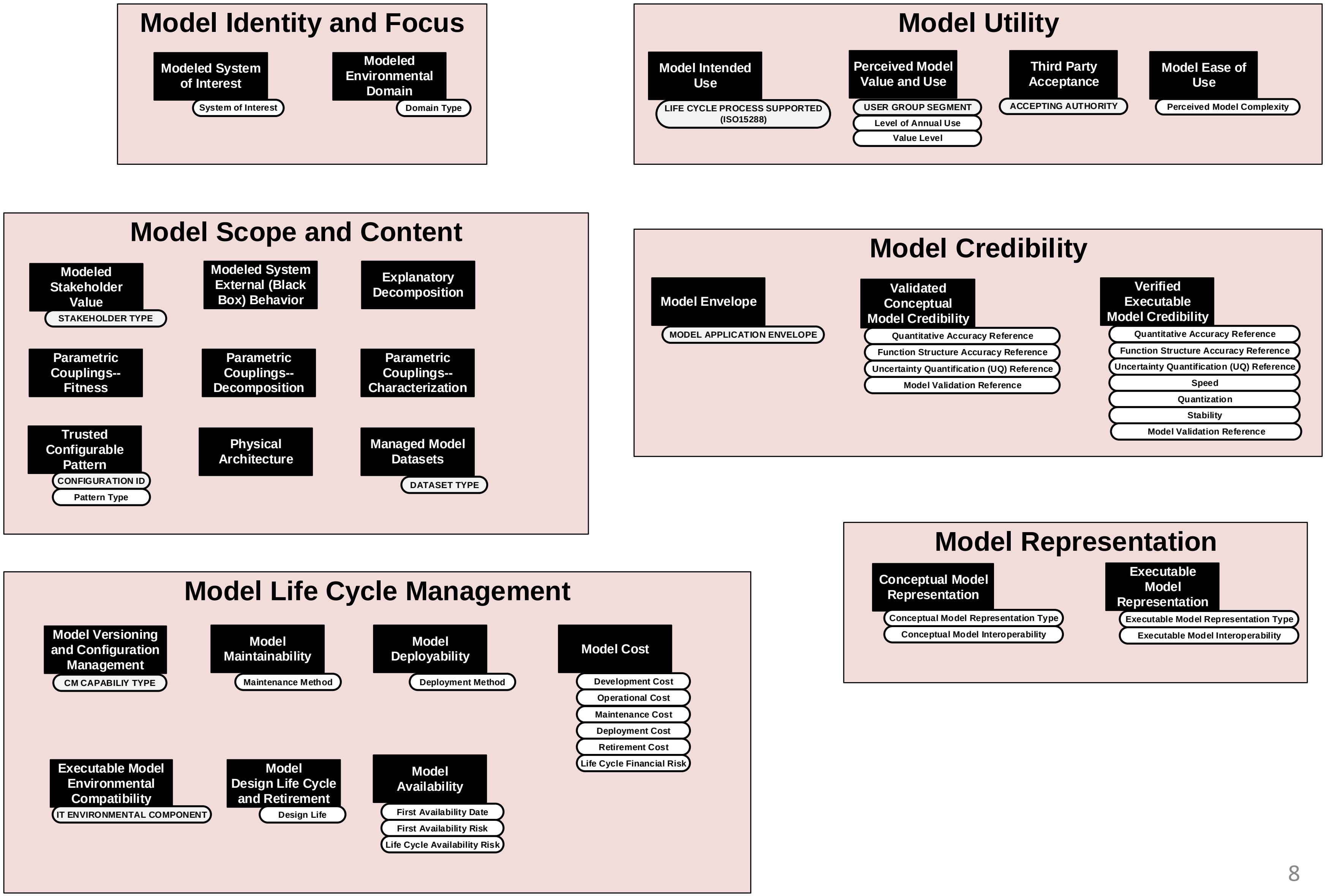
Model Representation

Describes the representation used by the model.

Model Life Cycle Management

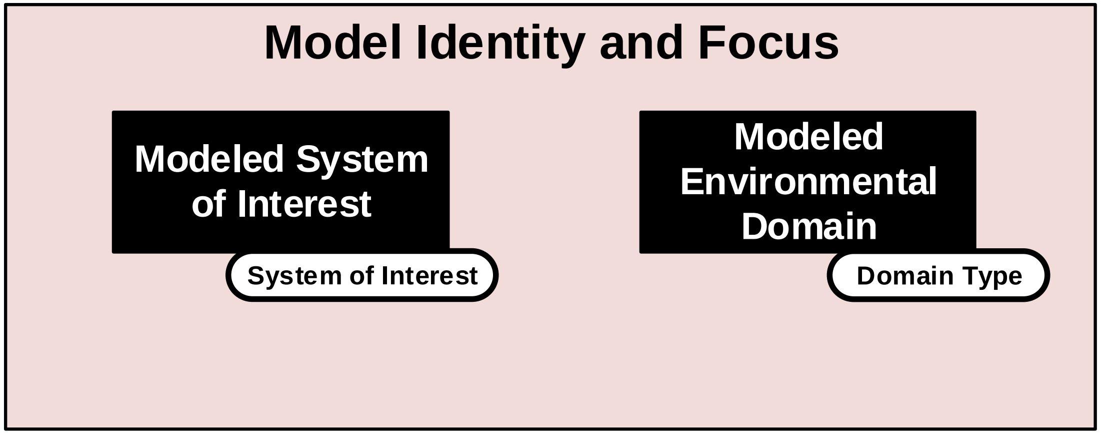
Describes the related model life cycle management capabilities.

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



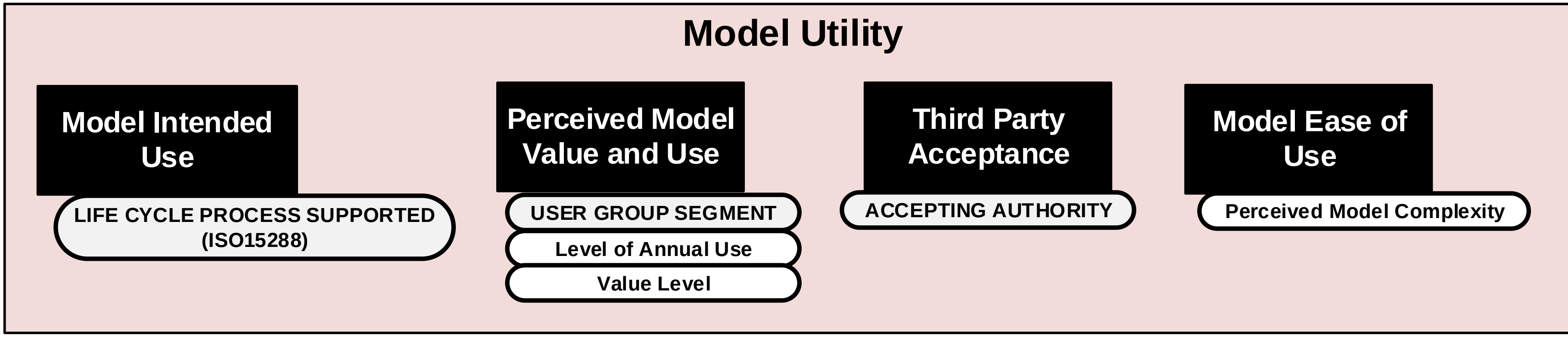
Computational Model Feature Groups: Configurable for Specific Models

- 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.



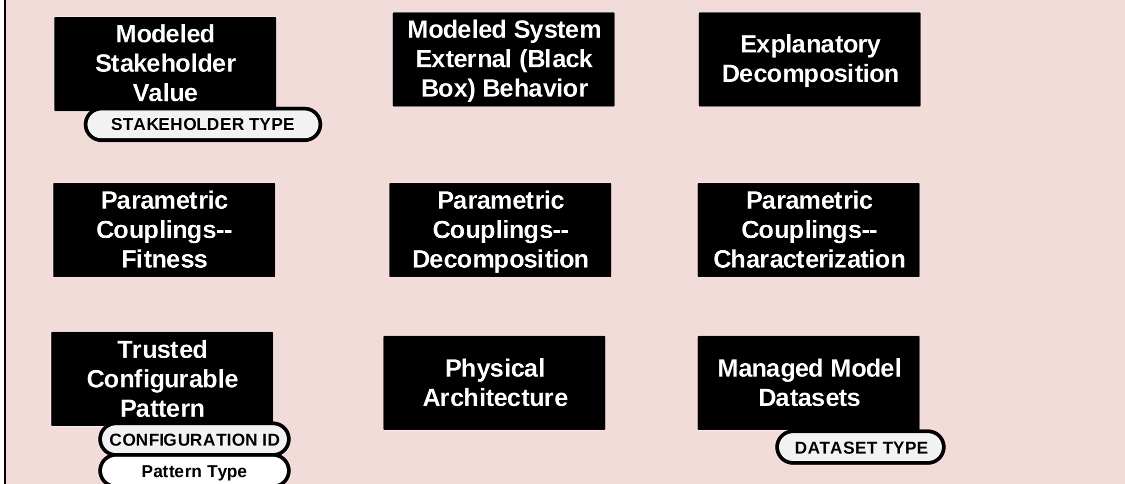
Feature Group	Feature Name	Feature Definition	Feature Attribute	Attribute Definition	Feature Stakeholder							Model Type	
					Model User	Model Developer	Model Maintainer	Mdl Deployer-Distributor	Model Use Supporter	Regulatory Authority	Mdl Investor-Owner	Physics Based	Data Driven
Identifies the main 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

Refer to Slides 21, 27: In this V&V50 work, the Modeled System of Interest above typically focuses on a manufacturing process (including material in process), related to some manufactured product.

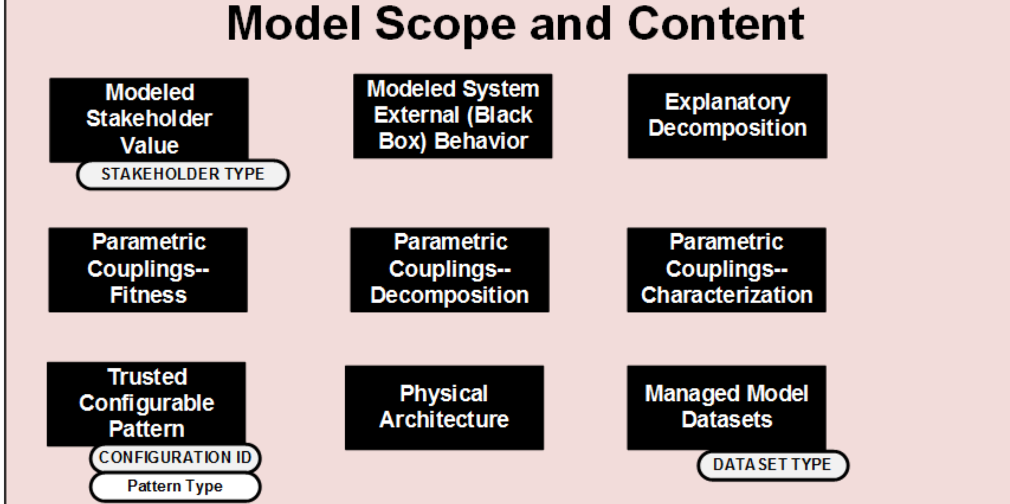


Feature Group	Feature Name	Feature Definition	Feature Attribute	Attribute Definition	Feature Stakeholder: Model User	Model Developer	Model Maintainer	Mdl Deployer-Distributor	Model Use Supporter	Regulatory Authority	Mdl Investor-Owner	Model Type: Physics Based	Data Driven
Describes the intended use, 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

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	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	



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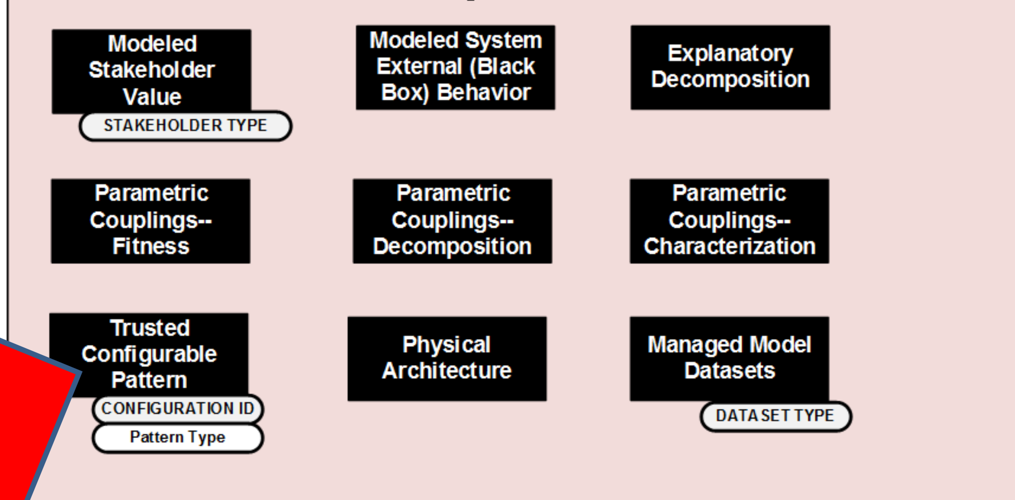
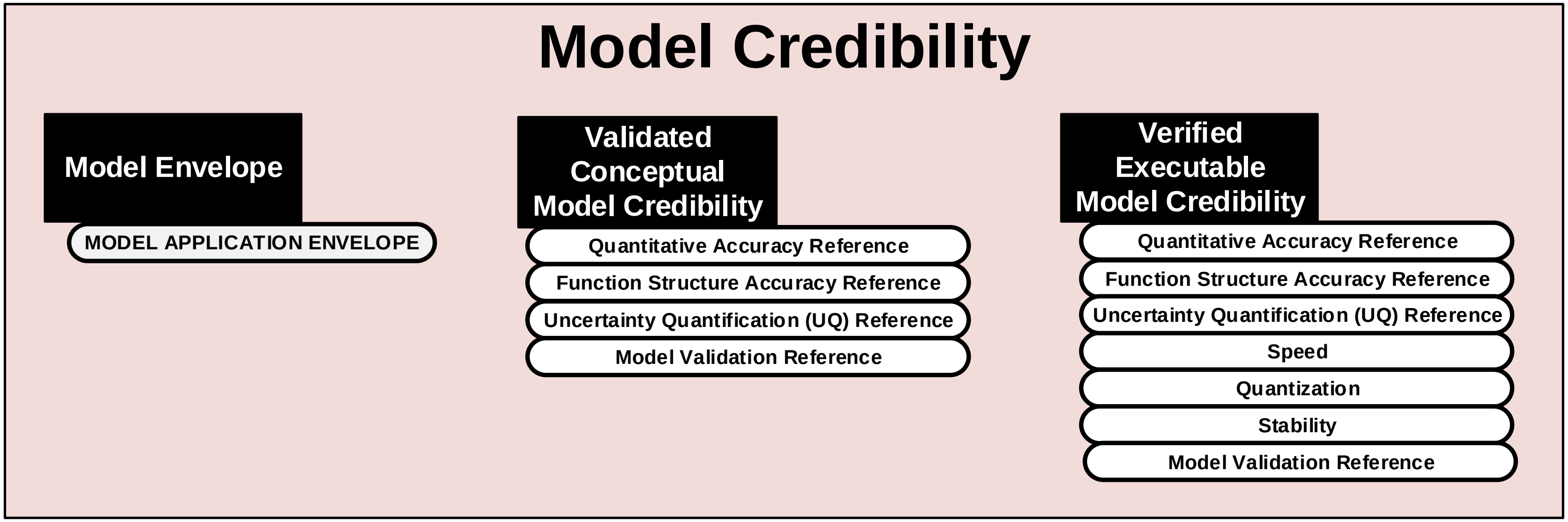
					Model User	Model Developer	Model Maintainer	Mdl Deployer-Distributor	Model Use Supporter	Regulatory Authority	Mdl Investor-Owner	Physics Based	Data Driven
Describes the scope of content of the model													
	Parametric Couplings--Fitness	The capability of the model to represent quantitative (parametric) 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



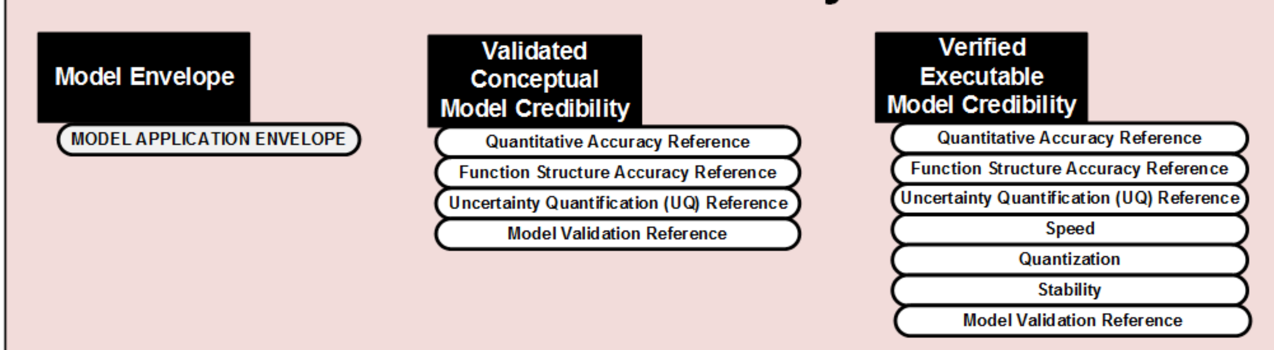
Of special importance to the economics of trust and VVUQ

		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													
	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

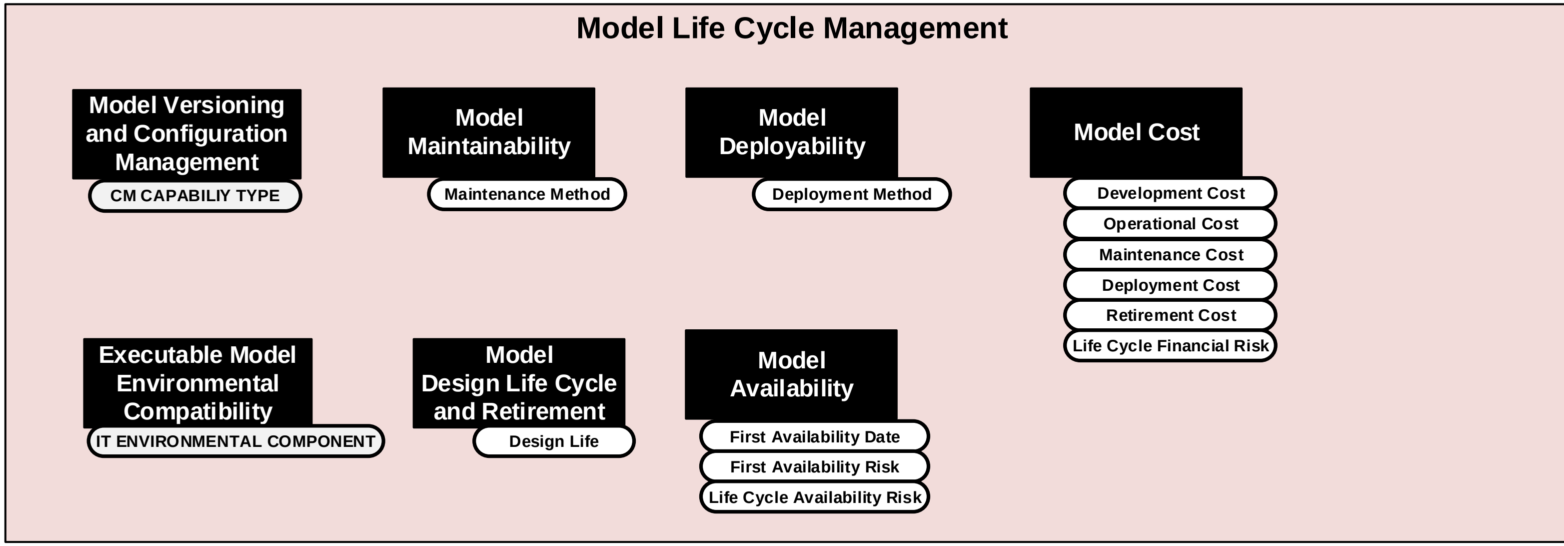


Feature Group	Feature Name	Feature Definition	Feature Attribute	Attribute Definition	Feature Stakeholder							Model Type	
					Model User	Model Developer	Model Maintainer	Mdl Deployer–	Model Use Supporter	Regulatory Authority	Mdl Investor–	Physics Based	Data Driven
Describes the credibility of the model													
	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

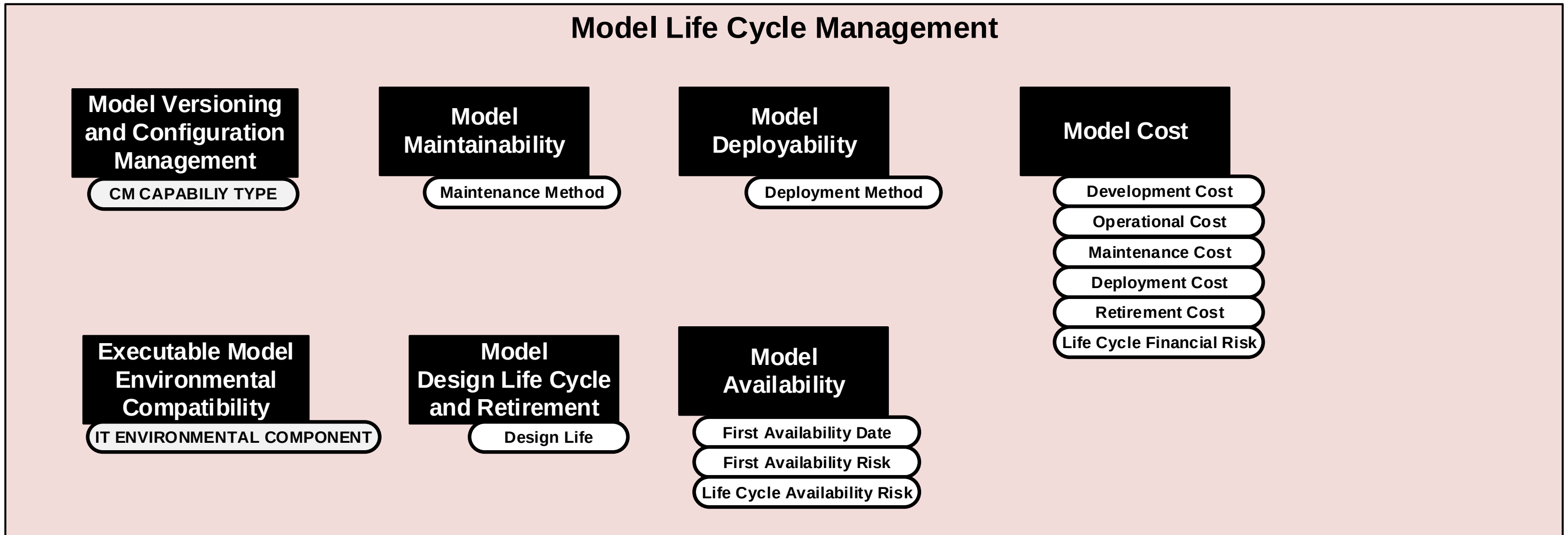
Model Credibility



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
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 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 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



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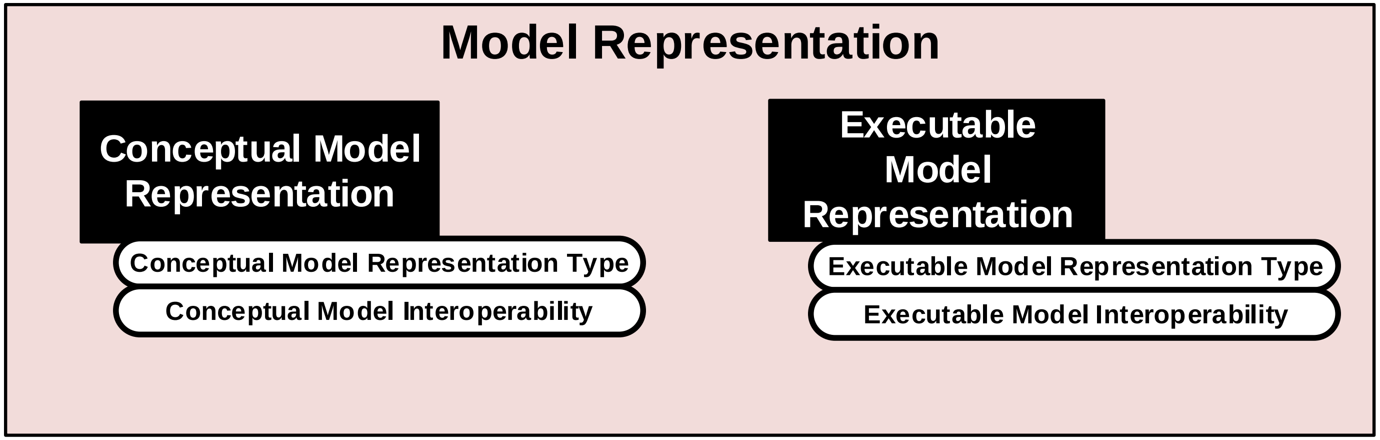
Describes related model life cycle management capabilities													
Model Life Cycle Management	Model Cost	The financial cost of the model, including development, operating, and maintenance cost	Development Cost	The cost to develop the model, including its validation and verification, to its first 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



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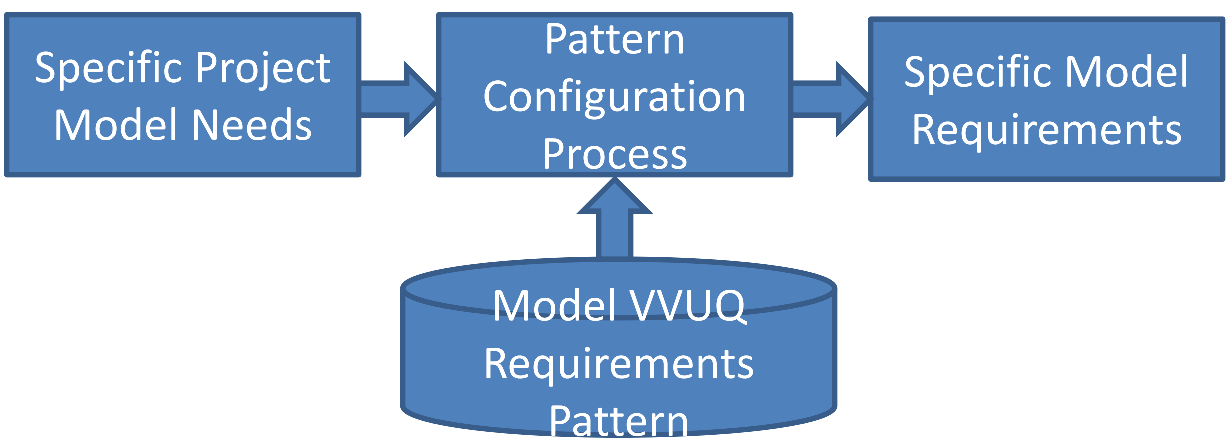
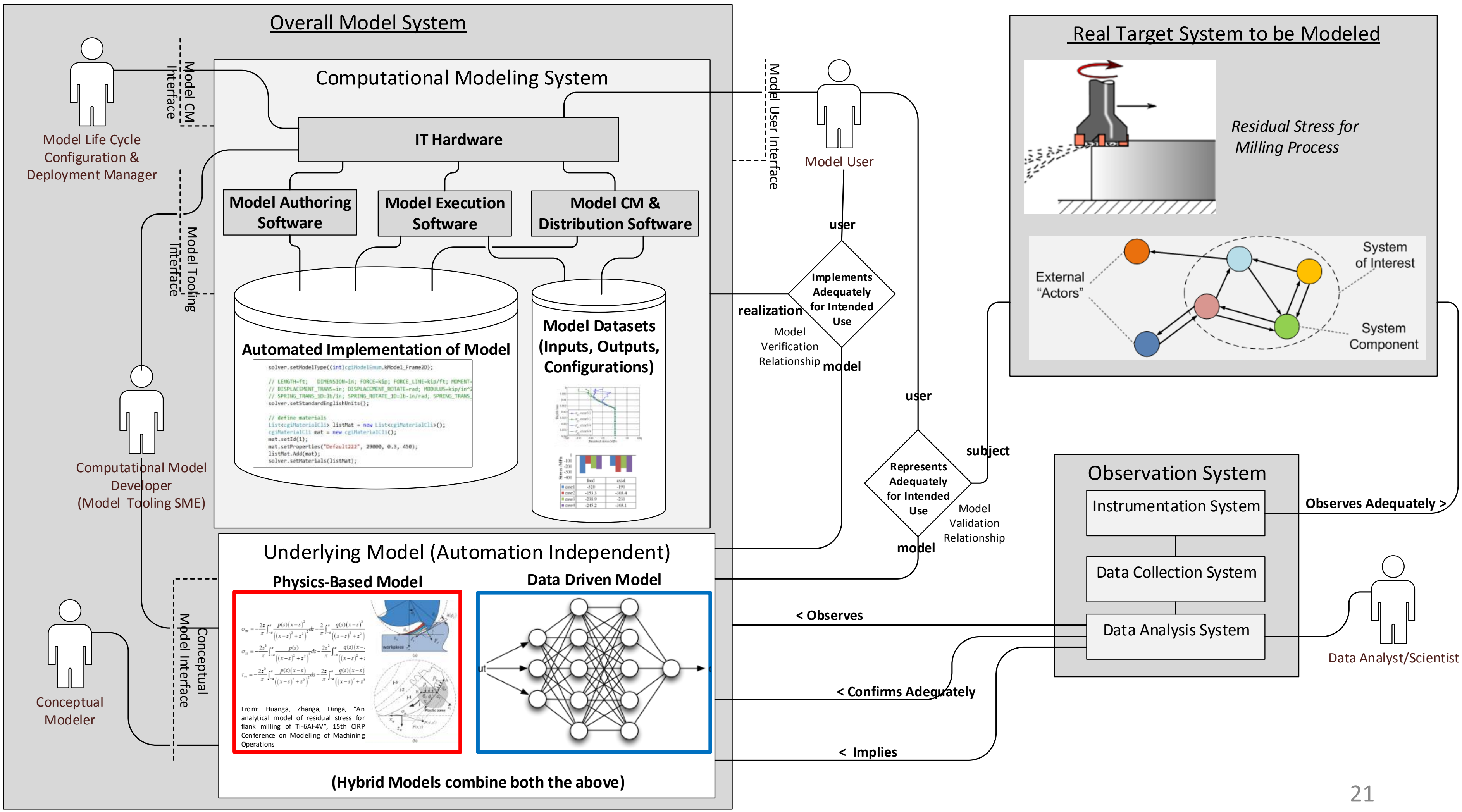
					Model User	Model Developer	Model Maintainer	Mdl Deployer-Distributor	Model Use Supporter	Regulatory Authority	Mdl Investor-Owner	Physics Based	Data Driven
Identifies the type of representation used by the model													
Model Representation	Conceptual Model Representation	The capability of the conceptual 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

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:

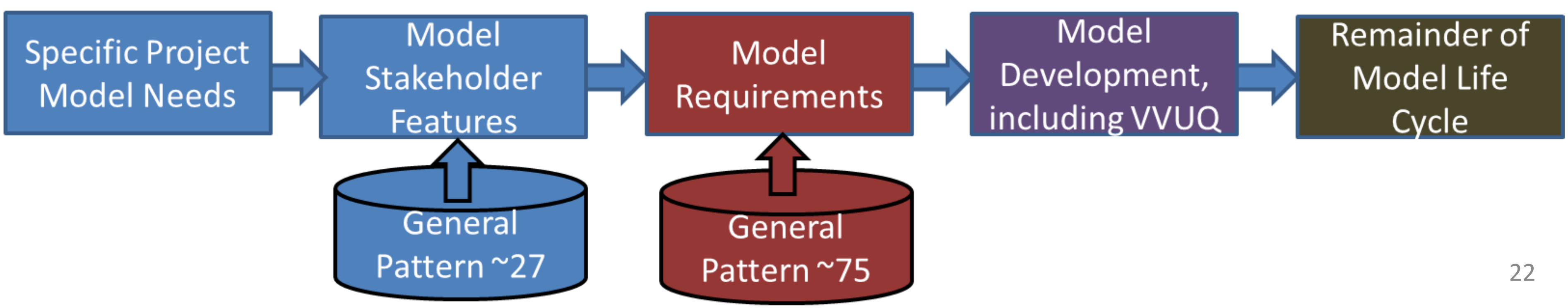


System Reference Boundaries: Computational Modeling Domain



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.



Requirements for Models: Example Extract

Requirement Group	Model Requirement Name	Model Requirement (configure further as needed)	Explanation, discussion
2.2 External Behavior Model			
	External Interfaces	The Model shall represent the external Input-Outputs exchanged during interactions with Domain Actors, and the external Interfaces through which they are exchanged.	Input-Outputs are flows of energy, force, mass, or information, exchanged during the interactions noted above. These flow through Interfaces. Examples of Interfaces include radiating or absorbing surfaces, mechanical connections or fasteners, hydraulic connections, electrical connectors, liquid-liquid or liquid-solid boundaries, keyboards, displays, chemically active interfaces, sensors, actuators, biologically active interfaces, etc.
	External Interactions	The model shall represent all the significant external interactions that the system of interest has with its listed environmental actors, listing which actors are involved in each interaction.	All behavior, and all the laws of the physical sciences, is in the context of Interactions, consisting of the exchange of energy, force, mass flow, or information, leading to state change in the interacting entities. Representing Interactions is accordingly central to Physics-Based Models. In addition, Data-Driven Models represent discovered and compressed description of the external appearance of those interactions, even though no underlying physics-based cause may be included. So, both types of models require that the models include identification of all the external interactions that the subject system has with its environmental actors. "Significant" in this requirement is always evaluated in terms of its impact on the modeled system stakeholder measures of effectiveness. Note that this requirement is not about interactions that are internal to the system of interest. Those are only of interest for certain types of models, and covered in another section later below.
	Parasitics--External	The modeled external interactions shall include any parasitic aspects which arise from choice of internal design, materials, technologies, or solution approach but which were not otherwise required by the primary intended system purpose, where significant from a stakeholder perspective.	These are in principle a subset of the External Interactions referred to in the preceding section, but are noted here so that they are not overlooked. Some interactions that a system has with its environment may be "accidents" of its design, selected technology, or the environment itself. For example, a mechanical structural member (a part) may contribute parasitic or "stray" electrical capacitance that impacts the electronic behavior of the system. In engineered (human designed) systems, these interactions might be considered to fall in the category of "unintended" interactions, but they are just as real as those intended, and may have large technical and stakeholder impacts. Failure modes are a part of this behavior.
	Dynamical Variables--External	For each identified Interaction, the model shall include the dynamically changing quantities significant to the interaction, for both the System of Interest and the External Actors in the Interaction.	The external behavior Interactions identified above are further parameterized by technical Measures of Performance, providing numerical or other measures that quantify the external behavior of the system objectively, without regard to stakeholder-judged "goodness". Typical measures of this type include position, temperature, pressure, rates of change of those variables, mass flow rate, timing, or other technical measures. These parameters include the variables of physics and what technical instrumentation tries to measure. They are further divided into "fast changing dynamic variables" that describe system dynamics, and "slow changing static parameters" such as heat capacity, power ratings, mechanical dimensions or geometry, etc.
	Static Parameters--External	For each identified Interaction, the model shall include the static or slow changing quantities characterizing the system's performance of the interaction, for both the System of Interest and the External Actors in the Interaction.	

Backup, References

- From INCOSE/OMG MBSE Patterns Working Group

http://www.incose.org/ChaptersGroups/WorkingGroups/transformational/mbse-patterns

http://www.omgwiki.org/MBSE/doku.php?id=mbse:patterns:patterns

An Old Subject, Renewed

- Guidance on generating Requirements for any system is a decades-old subject, with lots of literature, so might seem to be settled.
- However, the rise of Model-Based Engineering (MBE, MBSE, etc.) has dramatically changed our understanding and related practices for the better, as we describe systems with the language of science and mathematics, not just structured prose alone.
- This has reminded us what all models, computational or otherwise, must tell us for purposes of engineering or science.

What Is the Smallest Model of a System?

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

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

Introduction and Background

Representation Size, Purpose, Traditions. This paper
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 Sys
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 familie
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 (CONOP
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

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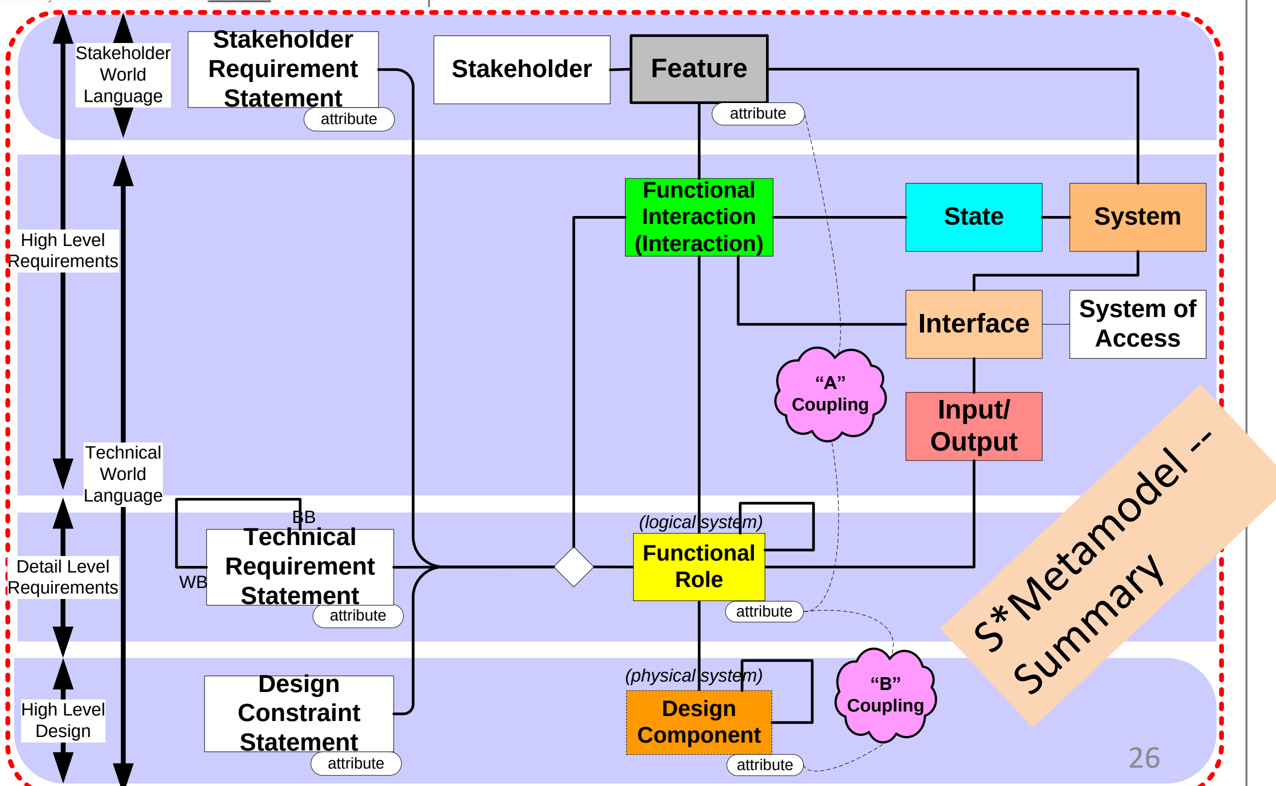
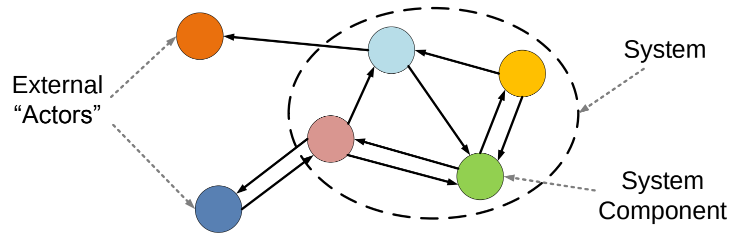
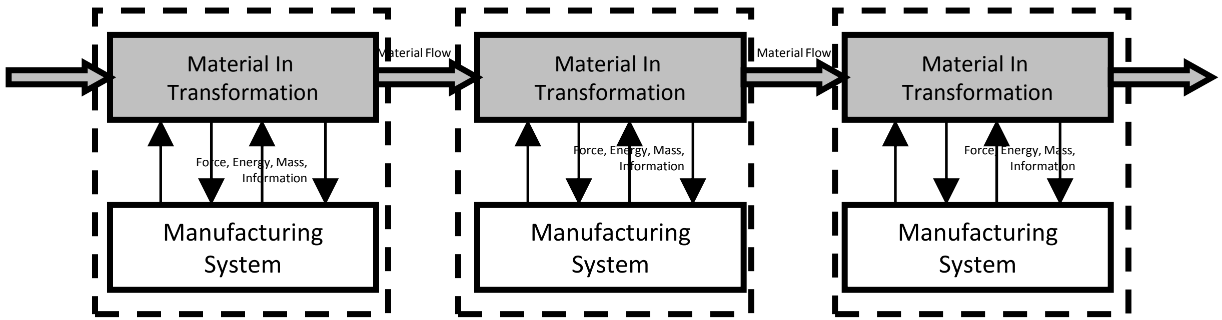


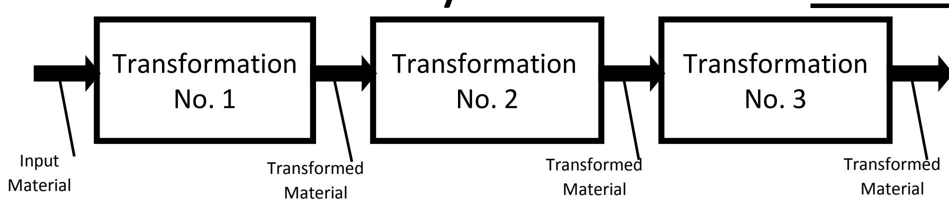
- A System is a set of interacting components:
  - By "interact", we mean exchanging energy, forces, mass flows, or information, resulting in changes of state:



  - 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

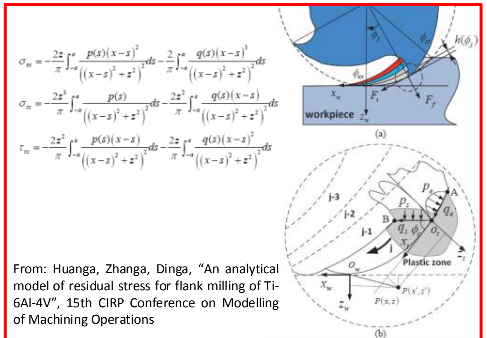


Physics-Based Model

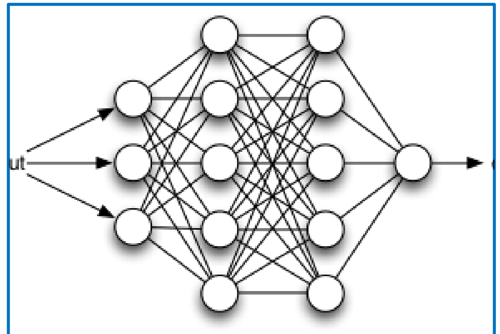
- Predicts the external behavior of the System of Interest, visible externally to the external actors with which it interacts.
- Models internal physical interactions of the System of Interest, and how they combine to cause/explain externally visible behavior.
- Model has both external predictive value 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.



From: Huanga, Zhanga, Dinga, "An analytical model of residual stress for flank milling of Ti-6Al-4V", 15th CIRP Conference on Modelling of Machining Operations



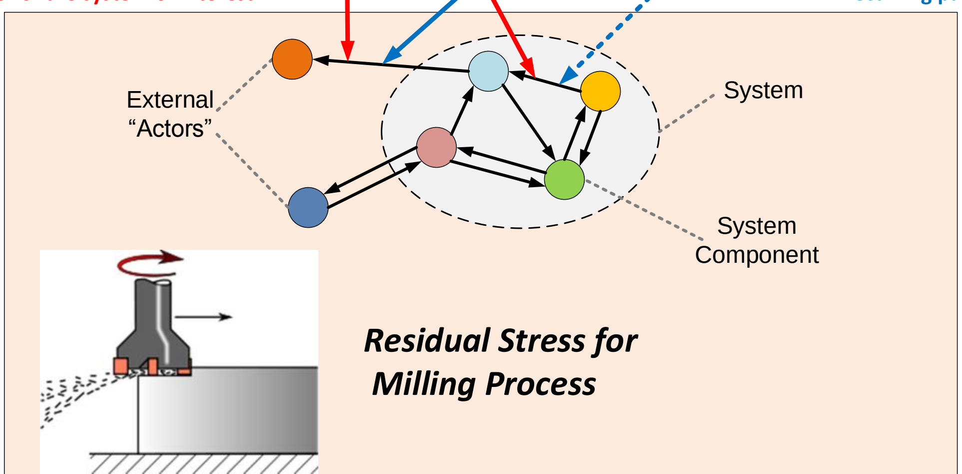
- **Physical scientists and phenomena models from their disciplines can apply here.**
- **The hard sciences physical laws, and how they can be used to explain the externally visible behavior of the system of interest.**

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.**



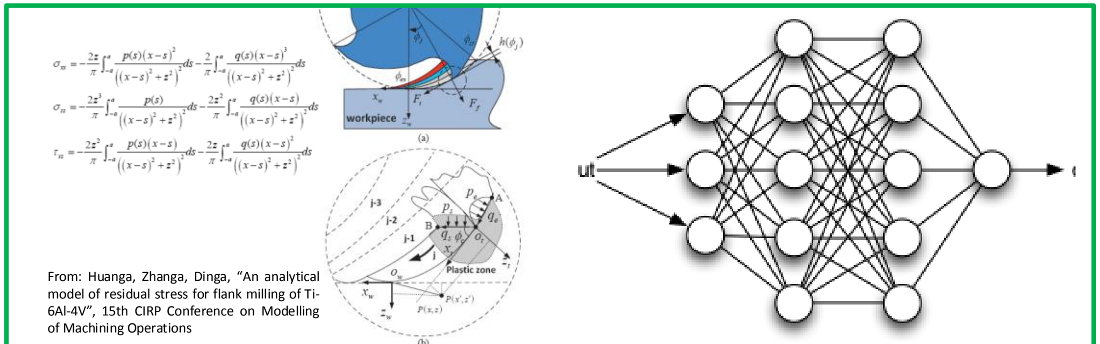
Real System Being Modeled

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.

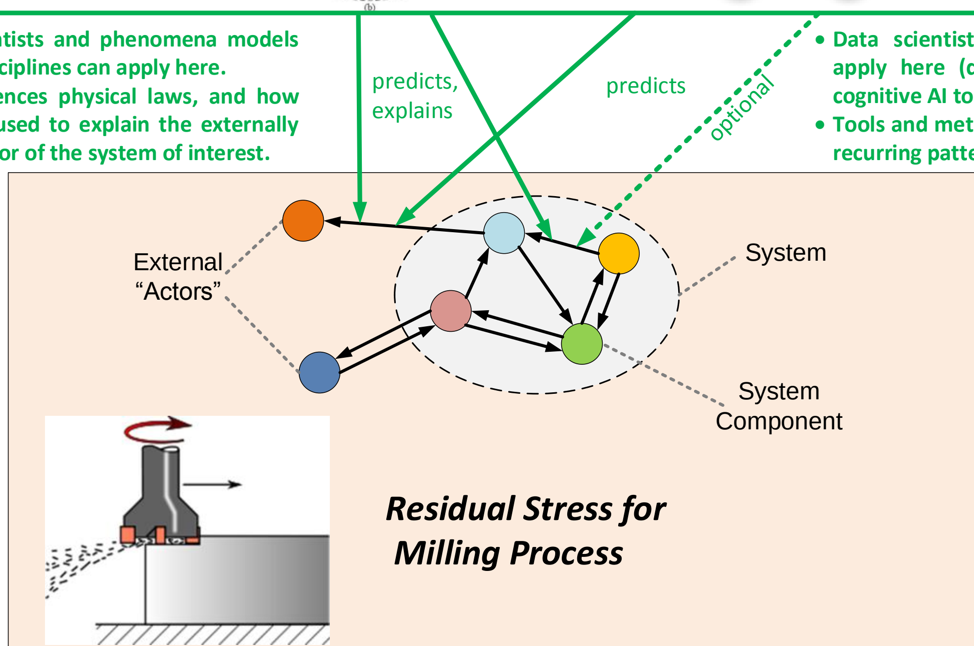
- Models (some aspects of) internal physical interactions of the System of Interest, and how they combine to cause/explain (some aspects of) externally visible behavior.
- Model has both external predictive value and (some) phenomena-based internal-to-external explanatory value.

- (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.

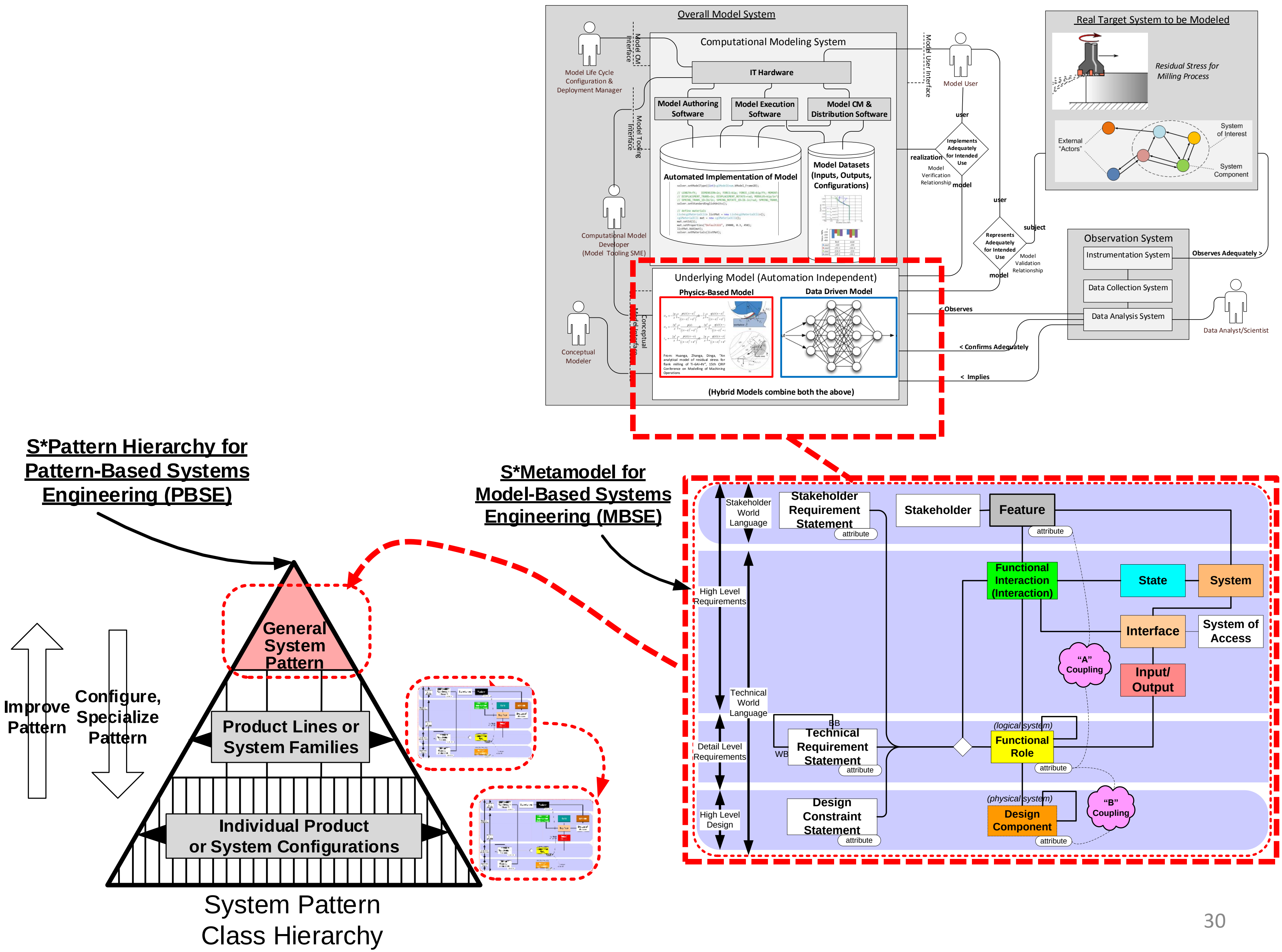


- **Physical scientists and phenomena models from their disciplines can apply here.**
- **The hard sciences physical laws, and how they can be used to explain the externally visible behavior of the system of interest.**

- **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



Overall Model System
Computational Modeling System
IT Hardware
Model Authoring Software
Model Execution Software
Model CM & Distribution Software
Automated Implementation of Model
Model Datasets (Inputs, Outputs, Configurations)
Model Life Cycle Configuration & Deployment Manager
Model CM Interface
Model Tooling Interface
Computational Model Developer (Model Tooling SME)
Conceptual Modeler
Conceptual Model Interface
Model User Interface
Model User
user
Implements Adequately for Intended Use
realization
Model Verification Relationship
model
Represents Adequately for Intended Use
subject
Model Validation Relationship
Real Target System to be Modeled
Residual Stress for Milling Process
External "Actors"
System of Interest
System Component
Observation System
Instrumentation System
Data Collection System
Data Analysis System
Observes Adequately >
Data Analyst/Scientist
Underlying Model (Automation Independent)
Physics-Based Model
Data Driven Model
< Observes
< Confirms Adequately
< Implies
(Hybrid Models combine both the above)
S*Pattern Hierarchy for Pattern-Based Systems Engineering (PBSE)
S*Metamodel for Model-Based Systems Engineering (MBSE)
General System Pattern
Product Lines or System Families
Individual Product or System Configurations
Improve Pattern
Configure, Specialize Pattern
System Pattern Class Hierarchy
Stakeholder World Language
Stakeholder Requirement Statement
attribute
Stakeholder
Feature
High Level Requirements
Functional Interaction (Interaction)
State
System
Interface
System of Access
"A" Coupling
Input/ Output
Technical World Language
Detail Level Requirements
BB
WB
Technical Requirement Statement
(logical system)
Functional Role
High Level Design
Design Constraint Statement
(physical system)
Design Component
"B" Coupling