Supporting Development of Complex System through Modeling & Simulation

Dr. Oscar A Mondragon
Director MS in Software Engineering
Computer Science Department
The University of Texas at El Paso
What is a model?

“Model”

Generally, the term “model” refers to an abstraction or representation of a system, entity, phenomenon, or process of interest.

Types of models

mathematical, logical, physical, or procedural representations of a system.

Intended use of a model

**describe selected aspects** of the entity, e.g., geometry, functions, or performance.

**Software Cost Reduction Event Transition Table**

<table>
<thead>
<tr>
<th>Old Mode</th>
<th>Event</th>
<th>New Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>TooLow</td>
<td>@T(WaterPres ≥ Low)</td>
<td>Permitted</td>
</tr>
<tr>
<td>Permitted</td>
<td>@T(WaterPres ≥ Permit)</td>
<td>High</td>
</tr>
<tr>
<td>Permitted</td>
<td>@T(WaterPres &lt; Low)</td>
<td>TooLow</td>
</tr>
<tr>
<td>High</td>
<td>@T(WaterPres &lt; Permit)</td>
<td>Permitted</td>
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</tbody>
</table>

**Petri Net Model**

**Systems engineers**

- use models to represent a system and its environment
- analyze, specify, design, and verify systems
- Different types of models represent different modeling purposes

**State Transition Machine**
Principles of Modeling

Clearly define the purpose of the model.

Some of the purposes that models can serve throughout the system life cycle include:

- Characterize an existing system
- Mission / concept formulation and evaluation
- System architecture design and requirements flow-down
- systems integration and verification
- Support for training
- Knowledge capture and system design evolution
- Validating your understanding with stakeholders
- Visual representation of abstract concepts

Purpose of Modeling

What is it that models represent?

- **Essential characteristics**
- SOI environment
- SOI interactions.

Models and simulations **support** most system life cycle processes, for example:

- **Business or mission** analysis
- **Requirements** (stakeholder and system) definition
- **Architecture** definition
- **Design** definition
- **System** analysis
- **Verification** and validation
- **Operations**
Model Scope

Scope your model to achieve its intended purpose: breadth, depth, & fidelity

Model breadth: requirements coverage in terms of functional, interface, performance, and nonfunctional requirements.

Model depth: coverage of system decomposition down to the system elements.

Model fidelity: level of detail the model must represent for any given part.

A system may have different types of models.
Forms/types of Models

Start with a **mental model** that is elaborated and translated in several stages to form a **final model or simulation product**.

A model maybe a mental image of selected concepts, and relationships between them, that can be translated to:

- Textual Specifications
- Graphics / Images
- Mock-ups
- Emulations
- Scale models
- Prototypes
- Sketches

Several models are developed for distinct viewpoints:

- functional,
- behavioral,
- performance,
- reliability,
- operational availability,
- cost
Models have syntax and semantics

You must understand the **semantics** and **syntax** of the models that you develop.

**Semantics**

Intended meaning of a model.

It is much like when speaking to someone, what is the meaning of the discussion?

**Syntax**

Components and Rules used to convey the intended meaning.

May use specific shapes to represent specific elements.

- e.g., grammatical rules and spelling in the use of a language.

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**Petri net diagram**

- "Places"
- "Transitions"
- "Tokens"
Selecting a model for use

Many types of models exist across different standards and methodologies, so the big question is:

**What model do I use?**

When developing a model,
**First consider the goals** you are trying to achieve in making that model.

- **What is the purpose** of the model?
- **What knowledge** is it intended to convey?
- **Who is the audience**?

**Is it for validation with a customer or end user?**
**How technical or high level should it be?**
Sample Model Taxonomy

Sample model taxonomy
Provides a useful classification for one instance of models (model classes)

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Provides a useful classification for one instance of models (model classes)

Physical mock-ups
represents an actual system
• a model airplane
• wind tunnel model

Abstract models
• have different expressions to represent a system
• vary in degrees of formalism.

Informal models
• simple drawing or textual description.
• Should have clear agreement on terms’ meaning
• If missing agreement ➔ may lack of precision and have ambiguity in the representation.

Sample model taxonomy
Provides a useful classification for one instance of models (model classes)

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Provides a useful classification for one instance of models (model classes)

Formal models
Further classified as
• Geometric
• Quantitative (i.e., mathematical),
• Logical models.
Systems Engineering Body of Knowledge (SEBoK) model taxonomy.

**Descriptive Model**
- Logical relationships (e.g., whole-part)
  - parts tree
  - interconnection between its parts
  - Components functions
  - Test cases to verify requirements

**Analytical Model**
- Mathematical relationships (e.g., differential equations)
  - quantifiable analysis of system parameters.
  - **Dynamic models**: time-varying state of a system.
  - **Static models**: not time-varying state of a system.

**Domain-specific Model**
- Descriptive & Analytical models
  - Their classification, terminology and approach is adapted to a application domain.

**System Model**
- Descriptive and Analytical
  - Span several modeling domains
  - Must be integrated to ensure a consistent and cohesive system representation.

Adapted from the Systems Engineering Body of Knowledge (SEBoK) v1.8
Other classifications of models

- **Functional model**: Captures the system functions and their functional interfaces.
- **Behavioral model**: Captures the overall behavior of the system functions.
- **Temporal model**: Captures the timing-related aspects of the architecture.
- **Structural model**: Captures the system elements and their physical interfaces.
- **Layout model**: Captures the mass-related aspects of the system.
- **Network model**: Captures the flow of resources among the applicable system functions or elements.
- **Mass model**: Captures the absolute and relational spatial placements of the system elements.

ISO/IEC/IEEE 15288
**What is a simulation?**

```
• implementation of a model(s) in a specific environment
• allows the model’s execution over time.
```

**Simulations:** provide a means for analyzing complex dynamic behavior of systems, people, and physical phenomena.

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**EXAMPLE**

A computer simulation includes the **analytical model** that is represented in **executable code**, the **input conditions** and other **input data**, and the **computing infrastructure (CI)**. CI includes the **computational engine** needed to **execute** the **model**, **input** and **output** devices.

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**Run a simulation**

**Analytical Model** (executable code)

**Inputs**
- Conditions
- Data

**Simulation**

Executes the code with the given inputs over a set amount of time.

**Outputs**
- Test report
- Visual Representation
- Other output
Main Goal of Simulations

Simulation Goals

Investigate, verify and validate a system’s behavior in relation to its context

The simulation model and its insights can be used to do:

- Performance evaluation
- Evaluation of design alternatives
- Uncertainty reduction in decision making
- Determine if a performance requirement can be achieved
- Create a rapid prototype
- Validate your understanding with customers and end users
- Risk assessment

Operating simulations

May operate in real-time e.g. there is an operator in the loop.

May operate faster than real-time
- performing thousands of simulation runs
- provide statistically valid simulation results.

May use artificial intelligence to prune the searches.
Physical Simulations

Use physical models and aim to replicate a small number of system attributes to a high degree of accuracy (fidelity).

When would it be used?

- Physical model of environmental attributes with similar levels of fidelity.
  - These simulations are costly* to construct
  - limited number of system and environment attributes restricts the range of questions that can be answered.

EXAMPLE

- Wind tunnels tests,
- Environmental tests,
- Mock-ups of manufacturing processes.
Computer-based Simulations

- Cover a broad scope of system attributes
- Become complex
- Include models of many types of systems
- Interact in many different ways

Further classified based on Models of Computation (MoC):
- Discrete event
- Monte Carlo
- Continuous time solving
- Finite element: numerical method for solving partial differential equations (structural analysis, heat transfer)

Monte Carlo use a repeated random sampling of input data into a model, using randomness to obtain results.
- complex models with coupled degrees of freedom
- significant uncertainty
- unknown correlations
- probabilistic in nature

May use as starting model when not enough data for correlations

Computer-based fluid mechanics simulation of air flow across a jet liner model
Hardware Simulations

Human-in-the-loop simulations
• execute in real-time
• use computer-based models
  • close loop on inputs and outputs
• has hardware and/or human element

• have a high level of fidelity
• costly when physical stimulation is required
  • motion or visual scene generation

A cockpit of a flight simulator used in training pilots.
Within the US defense community, it is common to refer to simulations as **live**, **virtual**, or **constructive**, where you have:

<table>
<thead>
<tr>
<th><strong>Live Simulations</strong></th>
<th><strong>Virtual Simulations</strong></th>
<th><strong>Constructive Simulations</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>live operators</td>
<td>live operators</td>
<td>simulated operators</td>
</tr>
<tr>
<td>operating real systems</td>
<td>operating simulated</td>
<td>operating with</td>
</tr>
<tr>
<td>systems</td>
<td>systems</td>
<td>simulated systems</td>
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Developing Models and Simulations

In developing your models and simulations, apply the SE approach

What does that involve?

- must have a project
- Manage it as a project
- Create a plan
- Use a lifecycle process
- apply configuration management
- enforce change management
- Involve experts to collect knowledge

So, the completed model or simulation can be considered a system in its own right.

Therefore...

- Follow SE life cycle processes.
- Model/simulation development need to be planned and tracked,
  - as any other developmental effort.
Validation & Verification of Models

Developing the model

How many characteristics are being modeled?
Can you verify the model using these characteristics?

Verifying the model

Can you verify the model using these characteristics?

Validating the model

Who provided the information to create the model?
How much information was provided by experts versus non-experts?

Taking important questions into consideration, such as...
Can you trust the experts that were consulted?
Model and Simulation Integration

A key activity is to facilitate the integration of models and simulations across multiple domains and disciplines.

**Example**

System models can be used to specify the elements of the system.

**Logical model**
define their interconnection or other relationships among the elements.

**Executable system models**
for the for interaction of system elements to validate behavioral requirements.

**Quantitative models**
for performance, physical, and other quality characteristics, such as reliability

These models represent **different facets** of the same system.

The different engineering disciplines for **electrical**, **mechanical**, and **software** each create their own models representing **different facets** of the same system.

The different models must be sufficiently integrated to ensure a cohesive system solution.
Prototyping

- enhance the likelihood of providing a system that will meet the user's need.
- facilitate both the awareness and understanding of user needs and stakeholder requirements.

The original use of a prototype...

As the first-of-a-kind product from which all others were replicated.
Not “the first draft” of production entities.

The intent in using a prototype...

- Only intended to enhance learning (validation)
- Only intended to determine if a technical aspect, function, quality attribute is feasible (verification)

Two types of prototyping are commonly used: rapid and traditional.
Rapid Prototyping

Rapid prototyping
• easiest and fastest ways to get user performance data
• evaluate alternate concepts

What is it?
• A particular type of simulation quickly assembled from a menu of existing physical, graphical, or mathematical elements

Used to investigate:
• form and fit,
• human–system interface,
• operations,
• feasibility considerations.

Should be discarded after achieving its purpose
Additive Manufacturing

Additive Manufacturing (3D printing)
- provides a rapid and low cost alternative for physical simulations
- creates parts by adding material in a layer-by-layer manner
- include various types of materials
  - plastics, polymers,
  - elastic polymers, and metals
- May create complex geometry models
  - very hard to produce with subtractive techniques

Additive manufacturing preferred over subtractive manufacturing:
- Using less material
- Built on reasonable period of time
Traditional Prototyping - 1

May reduce risk or uncertainty through either partial or full higher-fidelity interactive prototypes.

Partial prototype:
- verify critical elements of SOI

Full prototype
- complete representation of the system.
- must be complete and accurate in the aspects of concern.

Benefit of traditional prototyping?
- Collect objective and quantitative data on performance times and error rates
- Identify changes to improve performance, reduce production costs, quality, ...

Engineer Jonathan Kuniholm wears a full prototype of the prosthetic arm created by the DARPA Revolutionizing Prosthetics project. Source: www.spectrum.ieee.org
A maglev train system is developed for the purpose of testing: form, fit, and function.

- not intended to provide transportation
- test within an established short-distance

Is it a prototype?

*may be considered a prototype*
proof of concept for longer distance systems

engineers evaluate modifications needed for long distance system
Modeling & Simulation Tool

A modeling tool

- Verifies and enforces compliance to the syntax & semantics
- helps the modeler to create a well-formed model.

Checking the model

Tool support

Modeling and simulation tools support the system development environment.

emphasis to promote information exchange among different tools.

Error checking of a given Stateflow diagram produces an alert to detected errors in the model.
Model and Simulation-Based Metrics

- provide technical and management metrics
- assess modeling and simulation efforts

Types of metrics:

- Assess progress
- Estimate effort and cost
- Assess technical quality and risk
- Determine if a performance requirement can be achieved
- Assess model quality
- Predict Number of defects in system testing based on peer reviews **
A Model is ...

A representation of the essential characteristics of a system, its intended environment, and the its interactions with other systems and user.

Simulation is...

- The implementation of a model in a specific environment
- allows the model’s execution over time.
- Considering the goals of the model’s use
- Reviewing audience, purpose, and knowledge to be conveyed

Selecting a model or simulation involves...

Use M&S to enhance the learning of a system.

- M&S are good for verification and validation
- M&S are abstraction and not the actual real system

Measure the quality of your M&S ensure you have a usable / trustable product.
References


• Communication of simulation and modelling activities in early SE (Journal)


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