Enabling Improved Digital Transformation of Requirements and Simulation through SysML and MBSE

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Outline

• Introduction
• Model-based Structured Requirements
• Integration of SysML and External Simulation Models
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Introduction

• Digital Transformation, Digital Engineering, Digital Threads, Model-based Systems Engineering (MBSE), etc. — Imperative ideas, but often there are still challenges in releasing their vision to support better engineering practice

• Here, we wanted to highlight briefly two areas of work towards the broad goal of better digital engineering through MBSE and the use of the Systems Modeling Language (SysML)

• The two areas are:
  o Model-based structured requirements that better bring requirements into digital engineering and model-centric practices
  o Digital thread creation between SysML and external simulation models for improved optioneering, program management, and systems engineering
Outline

• Introduction
• **Model-based Structured Requirements**
• Integration of SysML and External Simulation Models
Structured Requirements

- A structured requirement, or a requirements template, defines an orderly requirement structure with specified attribute placeholders
  - Helps capture the precise meaning and communicate the required information to define a complete requirement
- A structured requirement statement may look like:
  - The [Who] shall [What] [How Well] under [Condition].
- Some examples:
  - The [Nuclear Power Plant] shall [have an installation level seismic margin] [greater than 1.5 safety factor] under [SL-1 earthquake definitions from SSG-67].
  - The [Instrumentation & Controls] shall [be protected] [in accordance with the guidance of SSG-64] under [effects of fire & explosion as defined in SSG-64].
  - The [Standby Pump 123-C] shall [deliver water to equipment XYZ-A] [at the rate of at least 150 gpm] under [a loss of primary pumps A and B].
- There is a variety of other potential structured requirement templates for different standards and requirement types

R. Carson (2021). Developing Complete and Validated Requirements
Classical SysML Requirements Modeling

- A classical SysML-based requirement is developed by defining:
  - Some predefined abstract attributes: Name, Id, and Text
  - Some traceability relationships that include attributes such as: Owner, Derived, Derived From, Satisfied By, Refined By, Traced To, and Verified By
  - Hierarchical relationships between requirements

- An identified issue is that many approaches do not fully integrate requirements with the system model, including in classical SysML
  - Many perspectives have less to do with defining the requirements and more with traceability to the system model (an important aspect)

- Therefore, we have been developing model-based structured requirements (MBSRs)
  - Combines the two together textual structured requirements and classical SysML requirements modeling to leverage the advantages of both
**MBSR Example Diagram**

**Context**
- Nuclear Power Plant

**Location**
- SL-1 Earthquake

**Seismic Margin Assessment**
- Peak Ground Acceleration = 0.21 g
- Probability = 1.2e-3

**Constraint**
- SM > 1.5

**Artifact**
- SSG-67: Seismic Design for Nuclear Installations
  - Location = [https://www.iaea.org/publications/14664/seismic-design-for-nuclear-installations](https://www.iaea.org/publications/14664/seismic-design-for-nuclear-installations)

**Structured Requirement**
- Core Damage Frequency Limit
  - Id = "1"
  - Text = "The [Nuclear Power Plant] shall [have an installation level seismic margin] [greater than 1.5 safety factor] under [SL-1 earthquake definitions from SSG-67]."

**System**
- Nuclear Power Plant
  - Parts: Containment Building, Cooling, Power Generation
  - Values: Installation Level Seismic Margin

**testCase**
- Installation Level Seismic Margin values:
  - Power Generation
  - Cooling
  - Containment Building

**testCase**
- Seismic Margin Assessment
  - Test Case

**Abstract Requirement**
- Core Damage Frequency Limit

**Engineer**
- A
- B

**Comment**
- Email: person@abc.gov

**System Context**
- NS-G-2.13

**Artifact**
- ABC Design Spec. Document
  - Location = [server/folder/file]

**Engineer**
- A performs

**Artifact**
- Earthquake Assessment Report 2023-1-3
  - Location = [server/folder/file]
# MBSR Dependency Matrix

<table>
<thead>
<tr>
<th>Legend</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependency</td>
</tr>
<tr>
<td>Dependency (Implied)</td>
</tr>
</tbody>
</table>

## Nuclear Power Plant

<table>
<thead>
<tr>
<th>Item</th>
<th>Dependencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS-G-2.13</td>
<td>1</td>
</tr>
<tr>
<td>1 Core Damage Frequency Limit</td>
<td>6</td>
</tr>
<tr>
<td>ABC Design Spec. Document</td>
<td>1</td>
</tr>
<tr>
<td>Context</td>
<td>1</td>
</tr>
<tr>
<td>Earthquake Assessment Report</td>
<td>1</td>
</tr>
<tr>
<td>Engineer A</td>
<td>1</td>
</tr>
<tr>
<td>Engineer B</td>
<td>1</td>
</tr>
<tr>
<td>Location XYZ: SL-1 Earthquake</td>
<td>2</td>
</tr>
<tr>
<td>Nuclear Power Plant</td>
<td>1</td>
</tr>
<tr>
<td>Installation Level Seismic Margin</td>
<td>1</td>
</tr>
<tr>
<td>Seismic Margin Assessment</td>
<td>5</td>
</tr>
<tr>
<td>Seismic Margin Limit</td>
<td>4</td>
</tr>
<tr>
<td>SL-1 Earthquake</td>
<td>2</td>
</tr>
<tr>
<td>SSG-67: Seismic Design for Nuclear Power Plants</td>
<td>1</td>
</tr>
</tbody>
</table>
# MBSR Attribute Matrix

MBSRs also support summarizing views for how the system model relates to the requirement definitions

<table>
<thead>
<tr>
<th>#</th>
<th>Id</th>
<th>Name</th>
<th>Requirement Type</th>
<th>Text</th>
<th>Who</th>
<th>What</th>
<th>How Well</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M1</td>
<td>M1 Overall TRAS Requirements</td>
<td>Overall System Requirement Specification</td>
<td>TRAS</td>
<td>TRAS</td>
<td>Initial Deploy Time</td>
<td>Normal Landing Scenario</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>M1.1</td>
<td>M1.1 Initial Time to Deploy</td>
<td>Performance</td>
<td>TRAS</td>
<td>TRAS</td>
<td>Initial Deploy Time</td>
<td>Normal Landing Scenario</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>M1.2</td>
<td>M1.2 Overall Reliability</td>
<td>Non-Functional</td>
<td>TRAS</td>
<td>TRAS</td>
<td>Overall Reliability</td>
<td>Normal Landing Scenario</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>M1.3</td>
<td>M1.3 Probability of Failure</td>
<td>Non-Functional</td>
<td>TRAS</td>
<td>TRAS</td>
<td>Probability of Failure</td>
<td>Normal Landing Scenario</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>M1.4</td>
<td>M1.4 TRAS Average Power Consumption During Deploy Operation</td>
<td>Interface</td>
<td>TRAS</td>
<td>TRAS</td>
<td>TRAS Average Power Consumption During Deploy Operation</td>
<td>Normal Landing Scenario</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>M1.5</td>
<td>M1.5 Unlocking for TR Deployment</td>
<td>Functional</td>
<td>TRAS</td>
<td>TRAS</td>
<td>Overall Reliability</td>
<td>Normal Landing Scenario</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>M1.6</td>
<td>M1.6 Total Mass</td>
<td>Physical</td>
<td>TRAS</td>
<td>TRAS</td>
<td>Total Mass</td>
<td>Normal Landing Scenario</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>M1.7</td>
<td>M1.7 Tertiary Lock Relocking</td>
<td>Design Constraint</td>
<td>TRAS</td>
<td>TRAS</td>
<td>Prevent Relocking</td>
<td>TR Deployment Scenario</td>
<td></td>
</tr>
</tbody>
</table>

Example here is a thrust reverser actuation system (TRAS)

D. R. Herber, et al. Model-based structured requirements in SysML
MBSR Conclusion

• The MBSR approach is more aligned with the model-centric philosophy of system development through its more broad use of elements in a system model
  o The model then contains further information need to effectively understand, satisfy, and verify our requirements
• MBSR restricts us to create and define the right elements and relationships (or readily see that they are missing)
  o Completeness metrics can be defined and automated
• MBSRs simplify activities such as dynamic change impact assessment (e.g., if this block changed, what requirement definitions depended on it?)

Please consider engaging with the open-sourced model on GitHub at https://github.com/danielrherber/model-based-structured-requirements
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Digital Threads with MBSE Tools

- Creation of effective digital threads means using the “best-of-breed” tools to complete specific engineering tasks and having different tool inputs and outcomes formally linked.

- Many MBSE tools support integration and execution of external models:
  - For example, Cameo Systems Modeler supports Matlab/Simulink, Python, etc.

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**Cloud/server location with necessary data**

**Modelica Simulation**

**Requirements**

**Requirements list defined in Excel**

**Structure**

**Behavior**

**Matlab/Simulink script/simulation**

**Parametrics**

**Python script**

**Cloud/server location with necessary data**

**Modelica Simulation**

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- **Perform Cooling**: owned behaviors
  - Actuation : Temp
- **Take Off**: owned behaviors
  - : Perform Mission
- **Perform Mission**: Propulsion
- **Land**: owned behaviors
  - : Perform Cooling
- **Limit Actuation Temperature**:
  - Satisfies
  - Requirement
  - «requirement»
  - System
  - Id = "2"
  - Text = "The UAV shall be adequately cooled."

- **Check All Thermals**: constraint
  - Requirement : System
  - Id = "r = constraint defn"
  - Text = "Check All Thermals for temperatures below 60 F during mission operations"

- **Check Other Temps**: constraint
  - Requirement : System
  - Id = "r = constraint defn"
  - Text = "Check Other Temps for temperatures below 60 F during mission operations"

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A primary goal here is to develop more effective, stable pathways for different individuals to interact with the digital system models.
Variant-based Design

• In this work on aircraft design, the four subsystems are 1) Aerodynamics, 2) Engine, 3) Thermal Management System (TMS), 4) and Electrical Power System (EPS)

• A critical aspect considered in this work is when multiple different modeling options (termed variants) are available for a given piece of a system

• As an example, consider the following sets of variants for the four subsystems:
  o \{Aero\} × \{Engine-A, Engine-B\} × \{TMS-A, TMS-B, TMS-C\} × \{EPS-A, EPS-B\}
  o 12 unique complete variant architectures with one specific architecture being \{Aero, Engine-A, TMS-C, EPS-B\}

• The Simulink models were created to support different variant definitions

• Then, we change the variant selections through the SysML-based model

• Finally, requirement verification is completed in the SysML model using the simulation results

Results Summary

Results visualized and captured within the MBSE tool as well as the external tool (Matlab/Simulink)
Many other potential applications, including a microgrid controller

Simulink

SysML

Stateflow

Key Performance Tradeoffs

Borky & Bradley. Effective Model-Based Systems Engineering
Integrating SysML and Simulation Conclusion

• Supported the definition and simulation of 16 distinct configurations (with the potential of 100+ configurations soon) within a digitally-linked SysML and Simulink modeling paradigm

• Other general realized advantages included:
  o Standardization of organizational practices
  o Documentation
  o Stakeholder dialog and artifacts (e.g., automatic generation of presentations and diagrams for reviews)

• Future work remains to explore the added value of the SysML-informed development process formally in the context of the simulation-heavy research group (at AFRL in Dayton, OH)
References

1. R. Carson (2021). Developing Complete and Validated Requirements. INCOSE Seattle-Metropolitan Chapter Monthly Meeting. DOI: 10.13140/RG.2.2.28526.74561

2. D. R. Herber, J. B. Narsinghani, K. Eftekhari-Shahroudi. 'Model-based structured requirements in SysML.' In IEEE 2022 International Systems Conference (SysCon), Apr 2022. DOI: 10.1109/SysCon53536.2022.9773813


Herber Research Group Publications
https://www.engr.colostate.edu/~drherber/publications
Enabling Improved Digital Transformation of Requirements and Simulation through SysML and MBSE

Questions?
CSU Systems Engineering

• My contact info:
  o daniel.herber@colostate.edu

• Many other faculty doing work at CSU in Systems Engineering in a variety of areas related to digital engineering and energy systems:
  o Marie Vans in augmented/virtual reality for energy system maintenance
  o Tim Coburn in analytics and data science in energy
  o Tom Bradley in energy system management and optimization along with MBSE
  o And many others…

• We offer both distance and on-campus degrees (MS, ME, PhD, Deng)
  o Please see the link below

[CSU Systems Engineering](https://www.engr.colostate.edu/se)