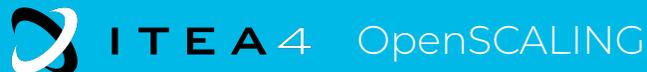


Towards a Common Standard for Uncertainty Quantification

in SSP and FMI

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Overview

- Introduction & Background
- The Layered Standard for Uncertainty Quantification (LS-UQ)
- Work in Progress
 - ◆ Modeling Assumptions
 - ◆ OMUQViz
 - ◆ Use Case: Environmental Control System (ECS)
- Future Work

Introduction

What is UQ and Why it Matters?

- Simulation models approximate reality with varying degrees of accuracy
- UQ is about understanding and quantifying the uncertainties present in models.
- This directly impacts the context in which models are usable
- **Key workflows that rely on UQ:**
 - ◆ Choosing appropriate models for the application scope
 - ◆ Evaluating overall uncertainty from parameter propagation (*Forward UQ*)
 - ◆ Model calibration, validation, and sensitivity analysis

The Need for Standardization

- **Traceability is Vital**
 - ◆ Machine-interoperable traceability is key for transparent model validation and reduces reliance on implicit knowledge.
- **Existing Standards**
 - ◆ **SSP Traceability (SRMD)**: Captures verification activities and operational domains.
 - ◆ **Credible Simulation Process (CSP)**: Formalizes continuous credibility processes using SSP-based layering.
- **The Missing Piece (*Our work aims to fill this gap!*)**
 - ◆ These frameworks require a standardized method for quantifying, propagating, and communicating uncertainty.
- First specification version published: "Towards a Common Standard for UQ"
Modelica Conference 2025

Forward Uncertainty Quantification (Forward UQ)⁶

→ What is Forward UQ?

- ◆ The process of propagating uncertainties from model inputs through the model to quantify the resulting uncertainty in the outputs.

→ Why run forward UQ on real use cases?

- ◆ See the spread, not just a number
 - Understand how results vary across real conditions, how often you'll meet specs, and how much margin you need.
- ◆ Focus where it counts
 - Identify which uncertainties drive outcomes.

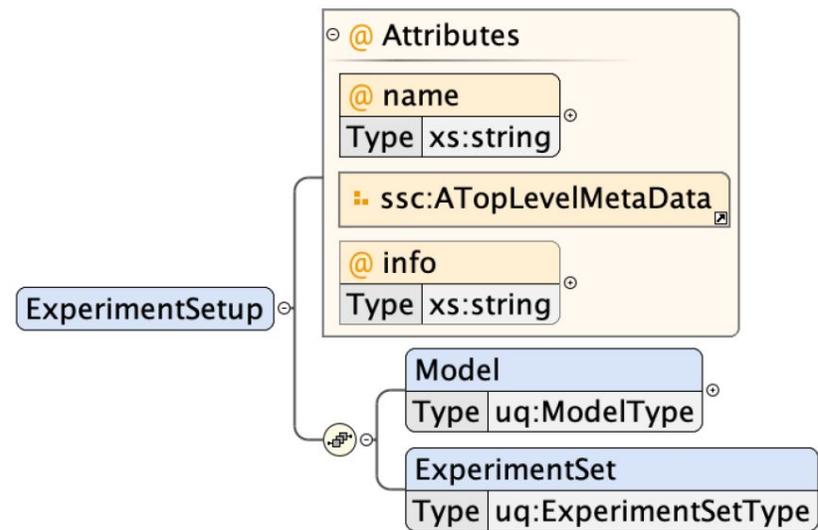
LS-UQ: The Proposed Standard

- A tool-agnostic, machine-readable data model for UQ
- Cross-layer standard for Modelica, FMI, and SSP workflows

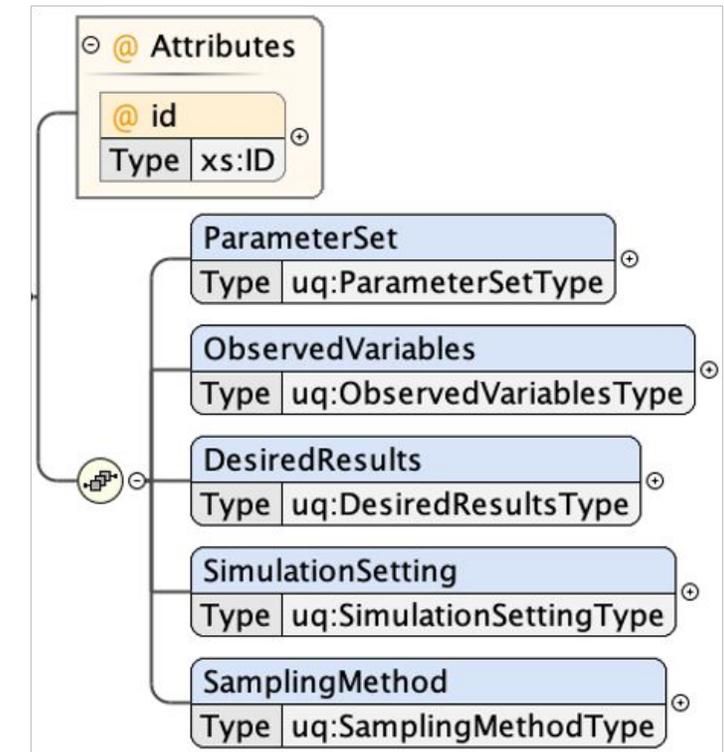
- Design principles:
 - ◆ **Flexible:** Many elements optional, declare only what you need
 - ◆ **Extensible:** Predefined + user-defined distributions
 - ◆ **Lightweight to Comprehensive:** Simple to complex experiments and supporting incremental adaptation in modeling process.

LS-UQ in Practice: XML Format

- LS-UQ structured in XML Schema
- Portable and interoperable
- Possible to combine with other layered standards (SSP Traceability)
- Import/export in Modelica tools



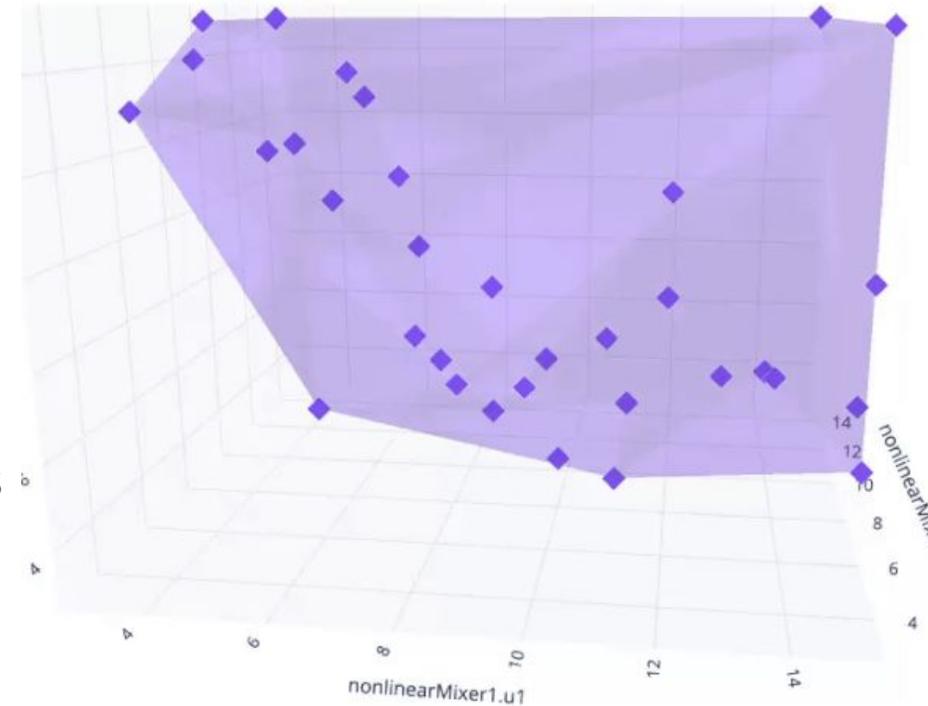
Root Element



ForwardUncertaintyQuantification

Domain of Operation (OD)

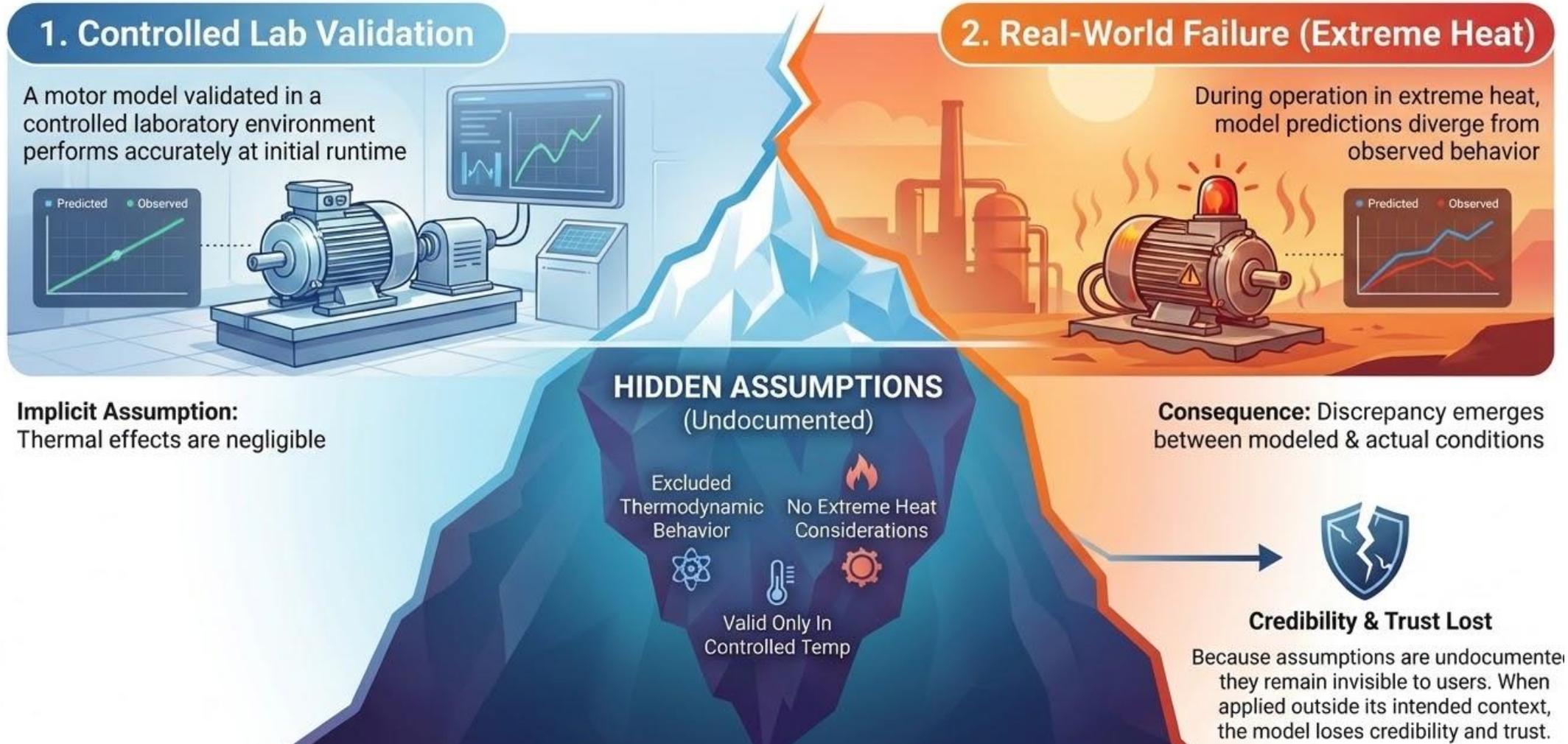
- The space of all possible combinations of model inputs that define where the model is intended to be used.
 - Defined as a geometric boundary (e.g., convex hull) through a set of coordinate points.
-
- **Why Include OD in a Standard Workflow?**
 - ◆ Supports automated model suitability evaluations
 - ◆ Enables traceability for transparent model validation
 - ◆ Essential for evaluating model credibility



Progress Since Publication

Assumptions, OMUQViz, and New Use Cases

The Problem: Hidden Assumptions



The Problem: Hidden Assumptions

1. A motor model validated in a controlled laboratory environment performs accurately at initial runtime
2. During operation in extreme heat, model predictions diverge from observed behavior
3. Thermal effects were implicitly assumed to be negligible
4. Thermodynamic behavior was excluded from the model formulation
5. A discrepancy emerges between modeled conditions and actual operating conditions
6. Because assumptions are undocumented, they remain invisible to users
7. When applied outside its intended context, the model loses credibility and trust

The Solution: Explicit Assumptions

→ Make model assumptions explicit, formal, and traceable

→ Key capabilities:

- ◆ Associate assumptions with defined ODs
- ◆ Record assumption sources (standards, empirical evidence, expert judgment)
- ◆ Specify time- or condition-dependent validity (e.g., valid for first 60 seconds)
- ◆ Bind assumptions to specific model parameters to ensure traceability and auditability

```
<ModelingAssumptions id="thermal_v1">

  <Assumption
    name="linearCooling"
    origin="empirical"
    originRef="test_report_2024.pdf">
    <OperationalDomainRef ref="od_normal_operation"/>
    <Text>Cooling follows Newton's law</Text>
  </Assumption>

  <Assumption
    name="startOperatingTemperature"
    origin="empirical"
    validFrom="0"
    validTo="50"
    timeUnit="s">
    <RealRange low="-5" high="70" unit="C"/>
  </Assumption>

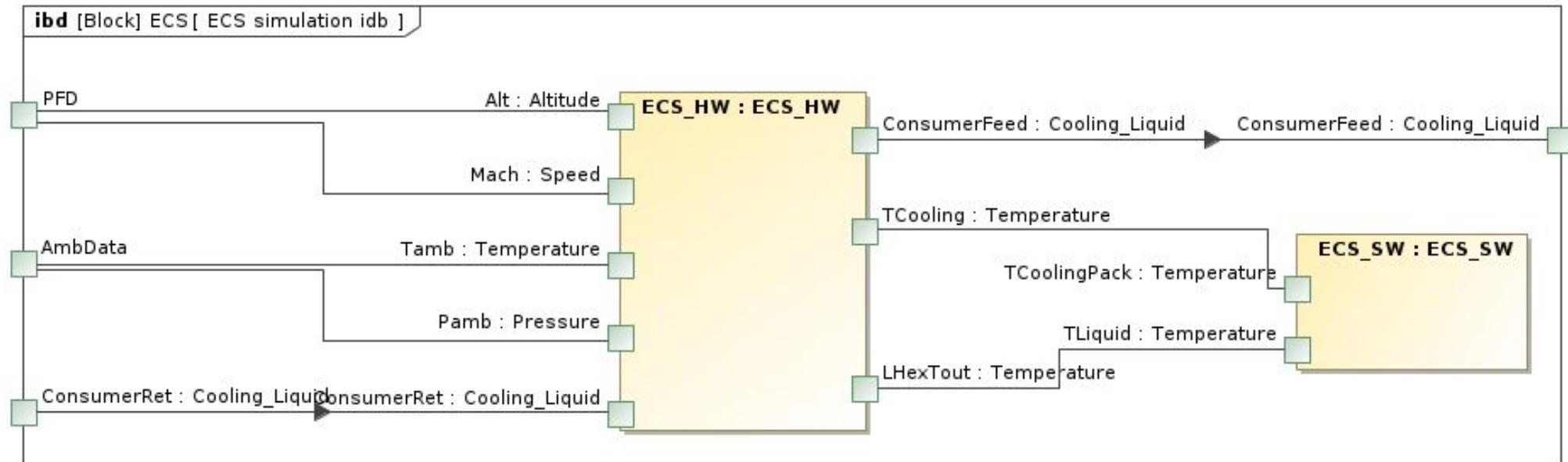
</ModelingAssumptions>
```

Progress: OMUQViz Tool

- Standalone tool for working with LS-UQ
- Core Features:
 - ◆ Create and modify LS-UQ at multiple system layers
 - ◆ Run simulations and monitor parameters/variables in real-time
 - ◆ Visualize envelopes for Domain of Validity (DoV) and OD
- Integration:
 - ◆ Currently standalone python web application
 - ◆ Planned integration with OMEdit for seamless workflow
- Work in Progress:
 - ◆ SDK for users to build custom visualization tools
 - ◆ Support for external result analysis pipelines

Use Case: Environmental Control System (ECS)

- Part of the OpenSCALING aerospace demonstrator
- Critical aircraft subsystem that regulates cabin temperature, cooling, and pressure control
- Complex system with multiple interacting components



ECS: Applying LS-UQ

- Operational Domain: Altitude & Mach number
 - ◆ Boundary defined as convex hull
- Observed variables: *inlet/outlet* temperatures
- Validation experiments: Executed at experiment points within the domain

- Complete study in single portable XML file

```
<uq:ExperimentSetup xmlns:uq="http://openscaling.org/UQ1/UncertaintyQuantification">
  <uq:Model name="ECS" file="resources/example.fmu"/>
  <uq:ExperimentSet>
    <uq:ValidationExperiment>
      <uq:ParameterSet>
        <uq:OperationalDomain>
          <uq:Axes>
            <uq:Axis name="ALT" unit="m"/> <uq:Axis name="MACH" unit="1"/>
          </uq:Axes>
          <uq:Boundary>
            <uq:ConvexHull>
              <uq:Point coordinates="0.0 0.0" />
              <!-- ... -->
              <uq:Point coordinates="1.0 1.0" />
            </uq:ConvexHull>
          </uq:Boundary>
          <uq:ExperimentPoints>
            <uq:PointSet id="DoV_1">
              <uq:Points>
                <uq:Point coordinates="0.001 0.0028" id="P1"/>
                <uq:Point coordinates="0.172 0.415" id="P2"/>
              </uq:Points>
              <uq:Parameters/>
            </uq:PointSet>
          </uq:ExperimentPoints>
        </uq:OperationalDomain>
      </uq:ParameterSet>
      <uq:ObservedVariables>
        <uq:ObservedVariable name="outletTemp" />
        <uq:ObservedVariable name="inletTemp" />
      </uq:ObservedVariables>
    </uq:ValidationExperiment>
    <uq:ValidationResults validationMetric="relativeError">
      <uq:ValidationResult point="P1" result="0.295 0.292" />
      <uq:ValidationResult point="P2" result="0.293 0.289" />
    </uq:ValidationResults>
  </uq:ExperimentSet>
</uq:ExperimentSetup>
```

Future Work

- SDK for custom visualization in OMUQViz
- Extend the standard
- Complex workflow support

Thanks!

©Bajand, A., Larsson, L. V., Buffoni, L., Nahodovic, E., Hällqvist, R., Lenord, O., Olsson, H., Otter, M., Vandamme, A., & Pop, A. (2025). Towards a Common Standard for Uncertainty Quantification. In *Linköping Electronic Conference Proceedings (Vol. 218)*. Linköping University Electronic Press. The 16th International Modelica&FMI Conference, September 8 – 10, 2025, Lucerne University of Applied Sciences and Arts (HSLU).
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