The Modelica Buildings Requirements Library for In-Simulation Requirements Verification for HVAC Applications

American Modelica & FMI Conference 2026

October 12-14, 2026

David Blum
dhblum@lbl.gov

Ettore Zanetti
ezanetti@lbl.gov

Michael Wetter
mwetter@lbl.gov



The Modelica Buildings Requirements Library for In-Simulation Requirements Verification for HVAC Applications

- Motivation
- Library Description
- Example Usage: Commercial Building Central Plant
- Conclusions and Future Work

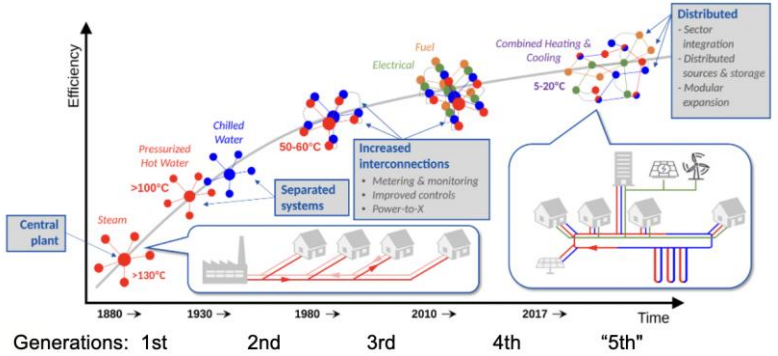
The Modelica Buildings Requirements Library for In-Simulation Requirements Verification for HVAC Applications

- Motivation
- Library Description
- Example Usage: Commercial Building Central Plant
- Conclusions and Future Work

Motivation

Increasingly complex HVAC system designs

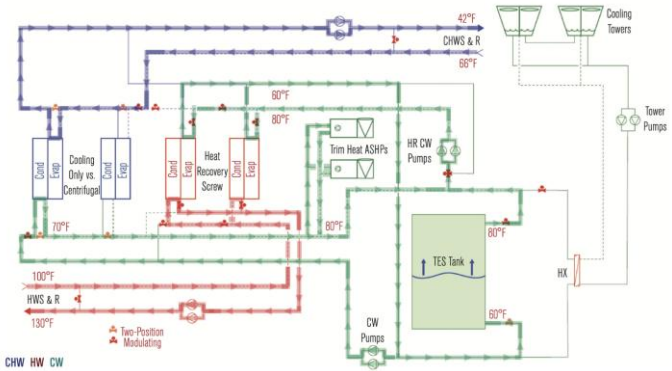
- Heating with heat pumps
- Thermal storage and energy recovery
- District heating and cooling
- Data centers



Evolution of district heating and cooling systems, from unidirectional, high-temperature steam to bidirectional, ambient-temperature loops (Wetter 2023 adapted from Hinkelman 2023)

Increasingly complex control requirements

- Reliable operation
- Responsive to dynamic conditions
- Efficient and affordable
- Enabling demand flexibility



"Time-Independent Energy Recovery (TIER)" central plant, designed by Taylor Engineers (Gill 2021)

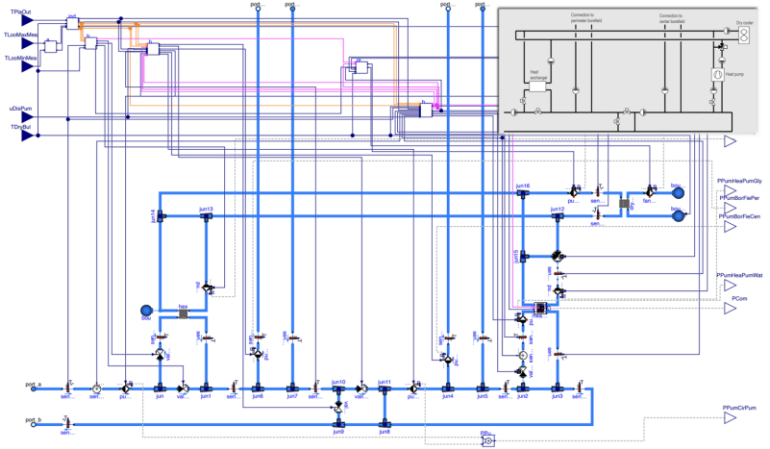
Motivation

Growing model-based design ecosystem

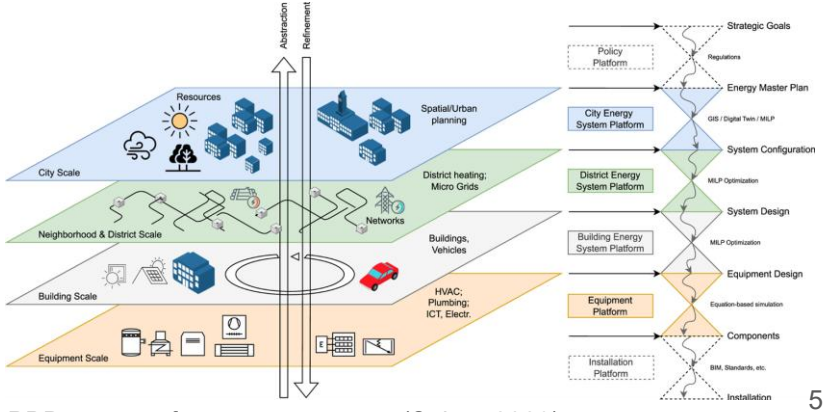
- Reduce system deployment risk
- Optimize control performance
- Reduce development time and costs

Examples

- Modelica for dynamic systems simulation
- ASHRAE S231 for digital control workflows
- Platform-Based Design (PBD) for a model- and verification-based design process
- AI for assisted modeling workflows



District heating & cooling central plant model in Modelica (Wetter 2026)



PBD concept for energy systems (Sulzer 2023)

Motivation

Importance of requirements specification and verification

- Common in automotive, aerospace, and power plants
- Growing need in HVAC energy systems
- In particular, operational and control requirements

Examples from a district system (Wetter 2026)

- ➢ O-201: At system-wide level, the heat pumps must operate at least 30 min when activated, and remain off for at least 10 min.
- ➢ O-202: At system-wide level, all control valves must show stable operation.
- ➢ O-303: At energy transfer station level: The space heating water supply temperature set point must be tracked within 1 K once the system is in space heating mode for 10 min.
- ➢ O-503: At central plant level: The mixing water temperature in the district loop after the central plant must be between 10.5 C and 24.0 C.

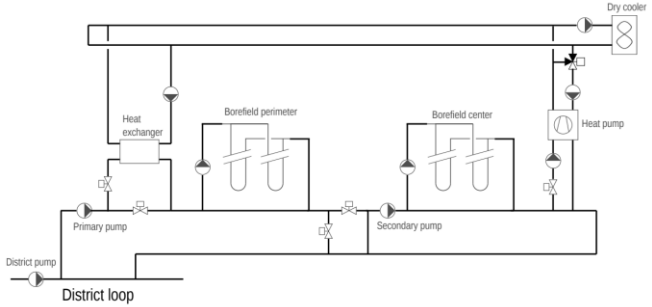


Figure 32. Schematic diagram of central plant. (Wetter 2026)

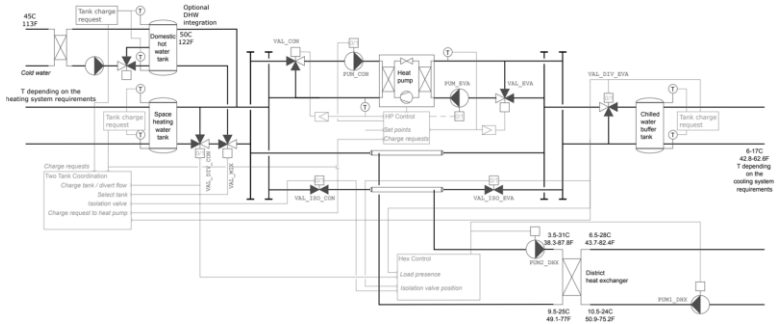


Figure 34. Schematic diagram of the ETS. (Wetter 2026)

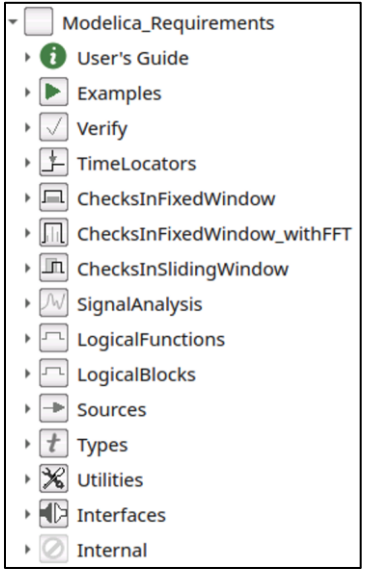
Motivation

Problem: Tedious manual verification of simulation results

- Can take many hours
- Repetitive work to inspect trajectories and verify against requirements
- Not systematically integrated into model-based workflows, limiting true scalability

Solution: Modelica Buildings Requirements Library

- Defines requirements in Modelica model and verify during simulation
- Extends existing *Modelica Requirements Library* for common HVAC applications (Martin 2015)
- Creates template blocks that implement common operational requirements in a consistent manner
- Combines requirements often grouped together or with other functionality as-needed



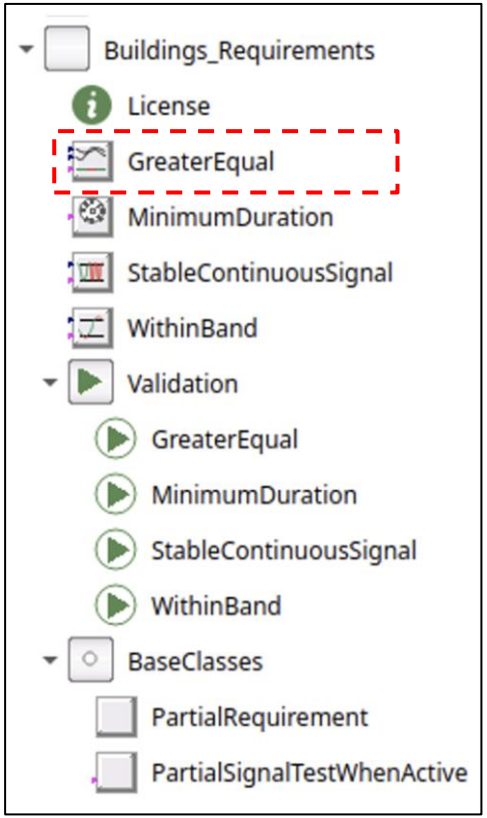
Modelica Requirements Library provides foundational functionality (Martin 2015)

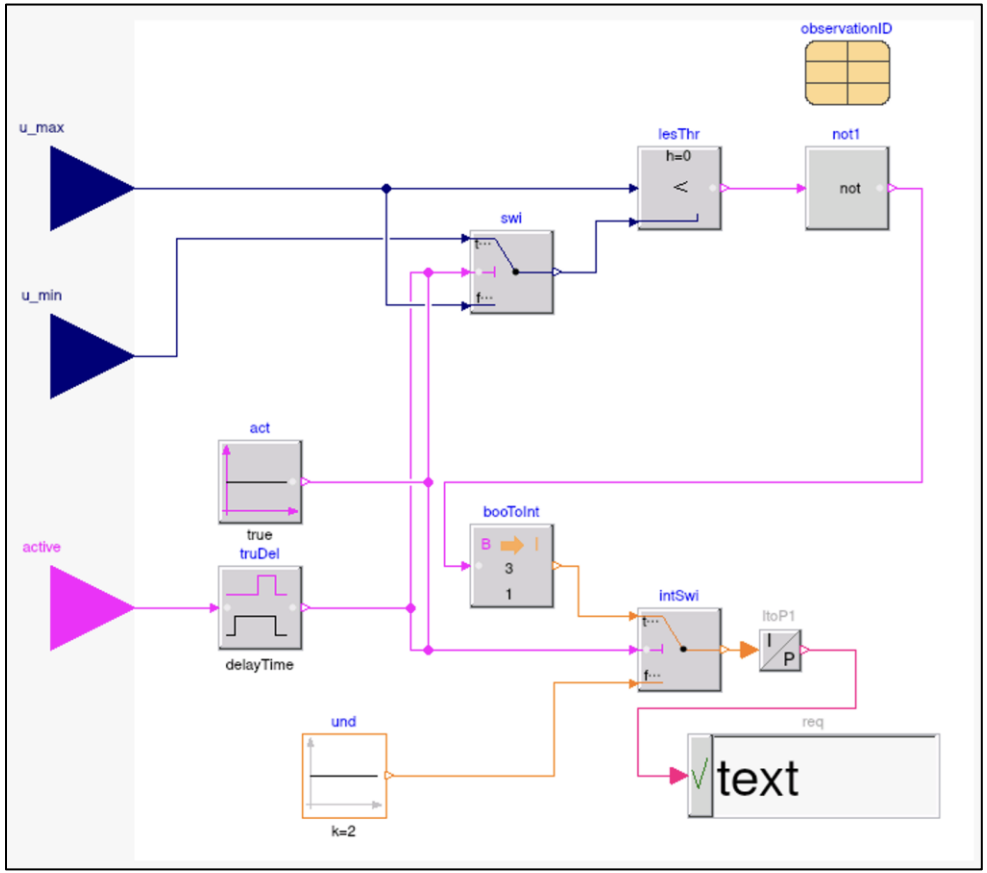
The Modelica Buildings Requirements Library for In-Simulation Requirements Verification for HVAC Applications

- Motivation
- **Library Description**
- Example Usage: Commercial Building Central Plant
- Conclusions and Future Work

Library Description

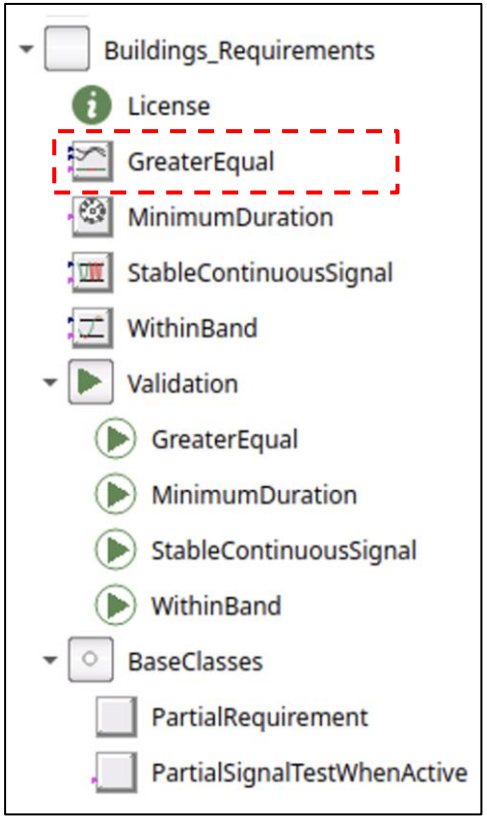
Structure and Models

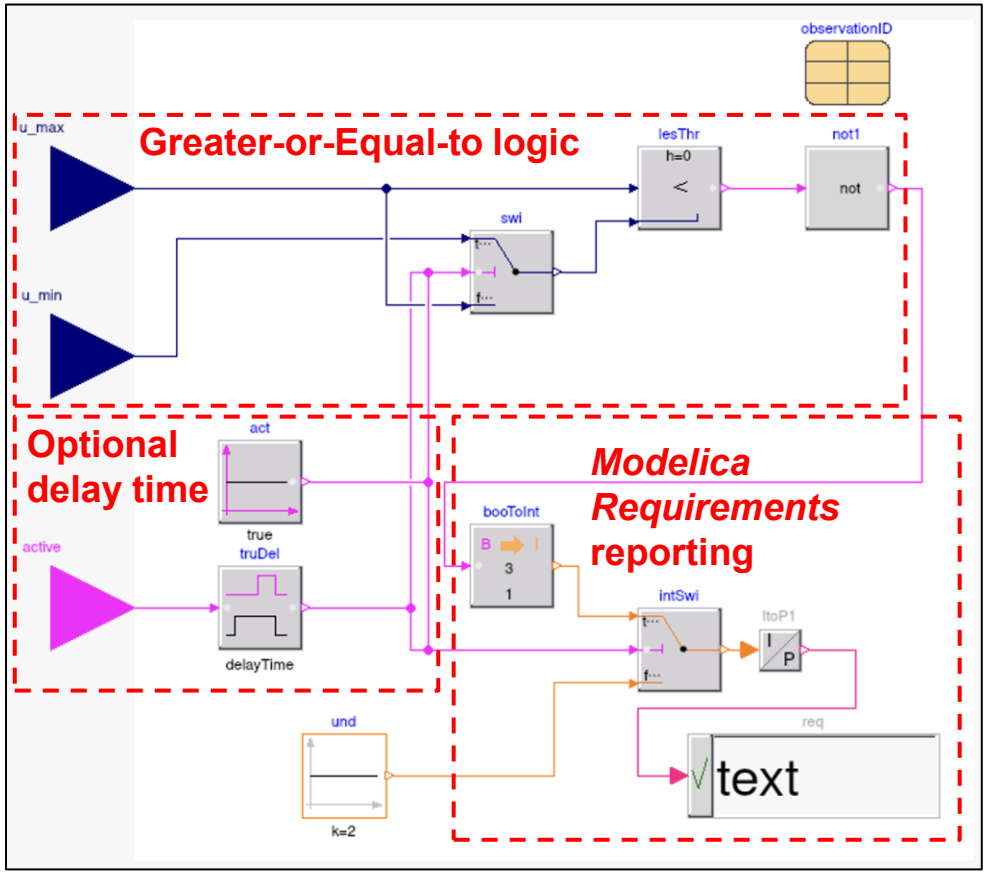




Library Description

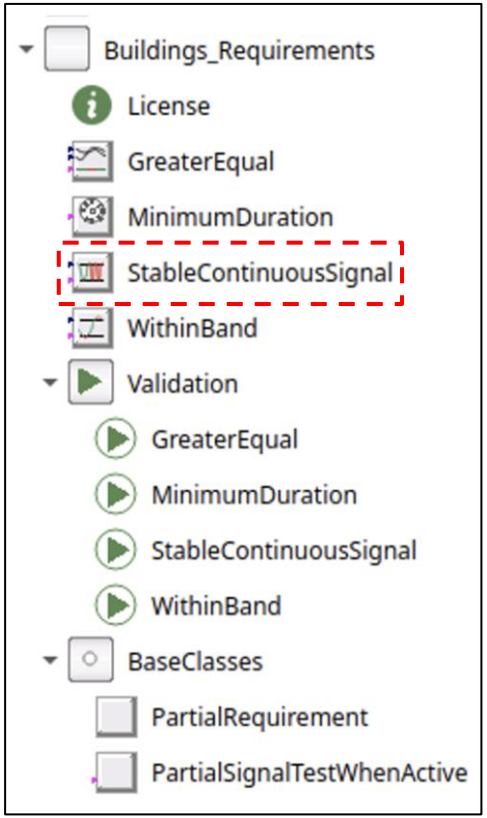
Structure and Models

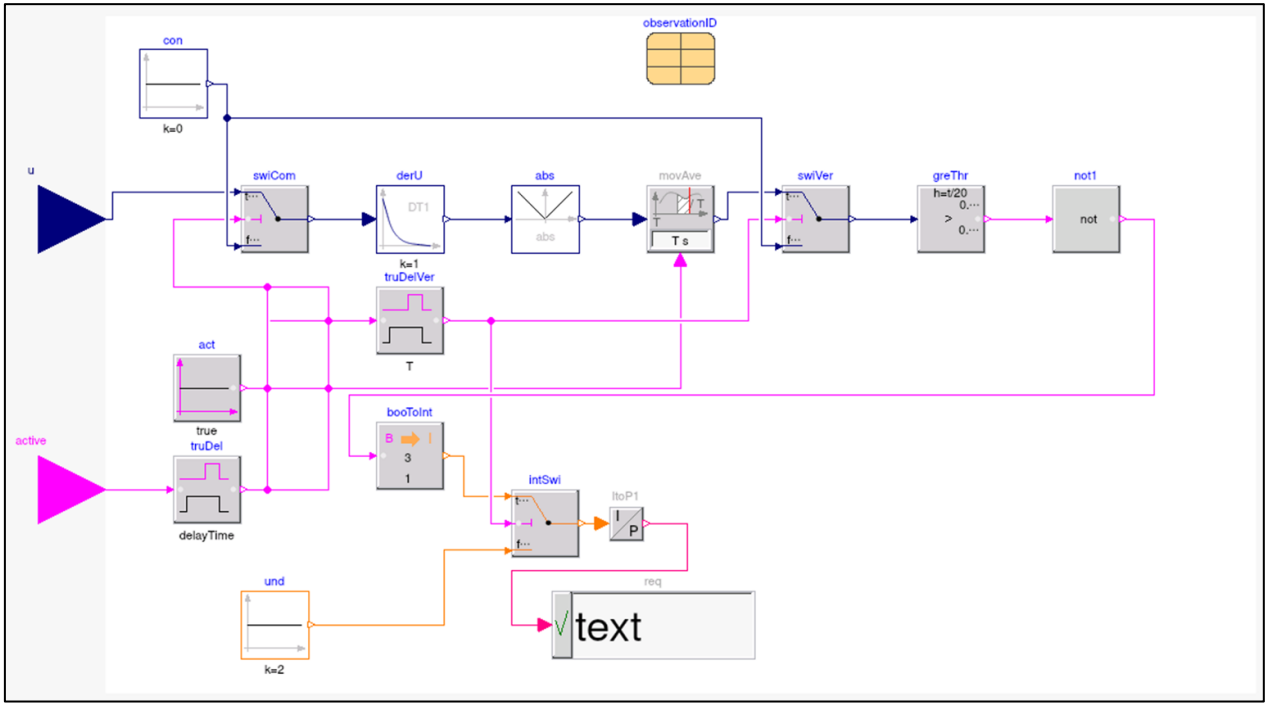




Library Description

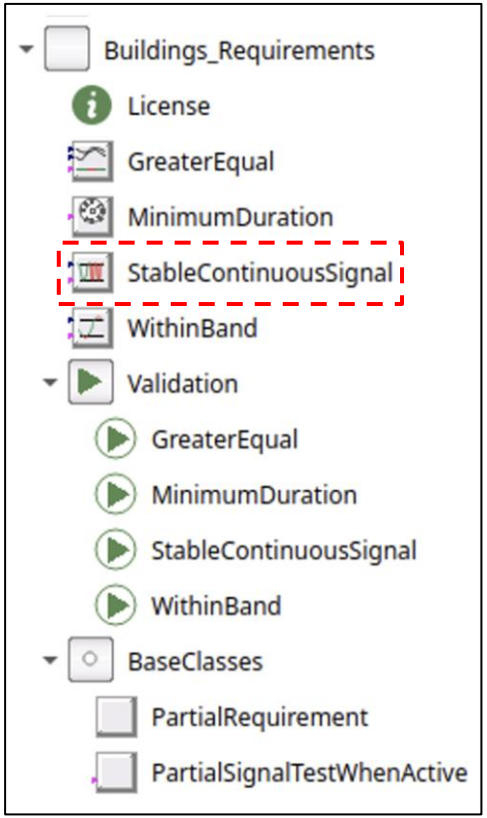
Structure and Models

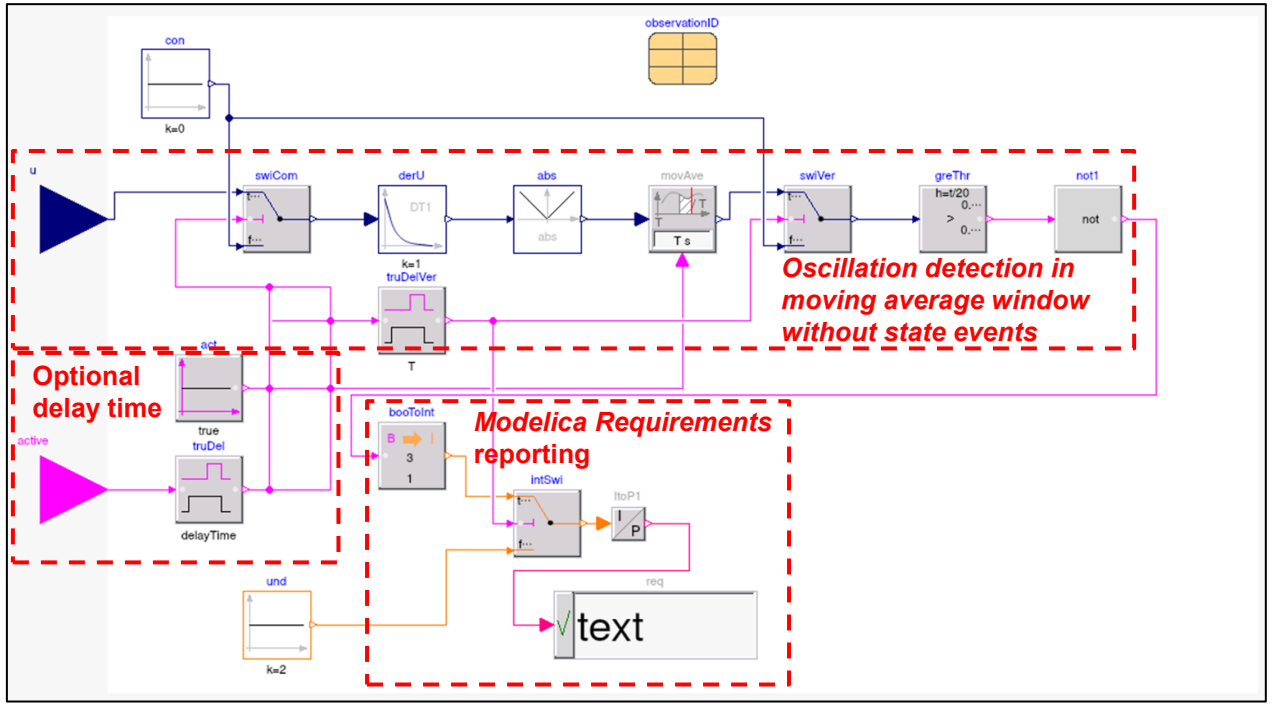




Library Description

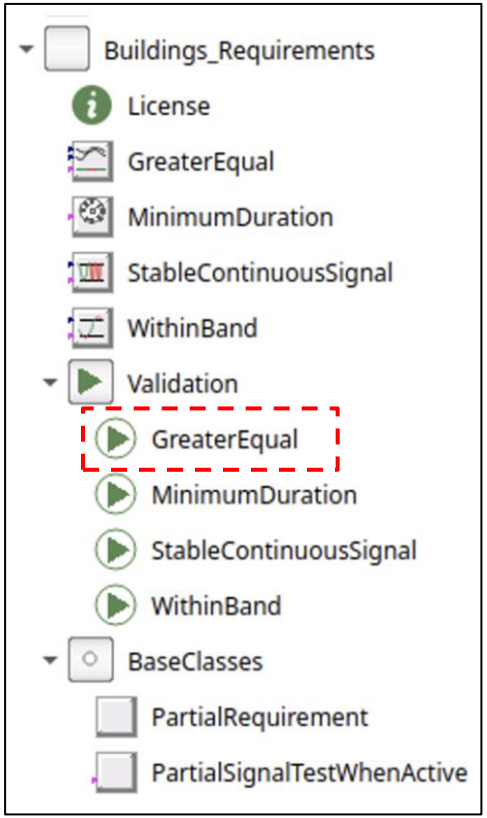
Structure and Models

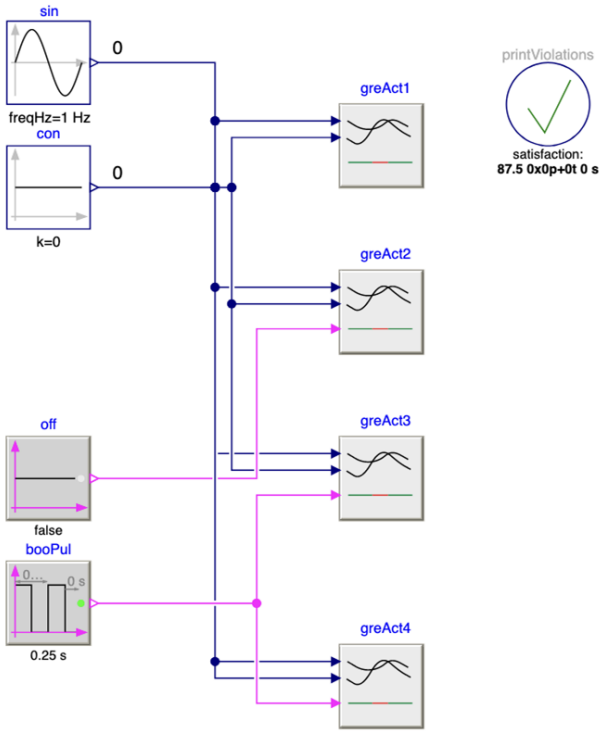


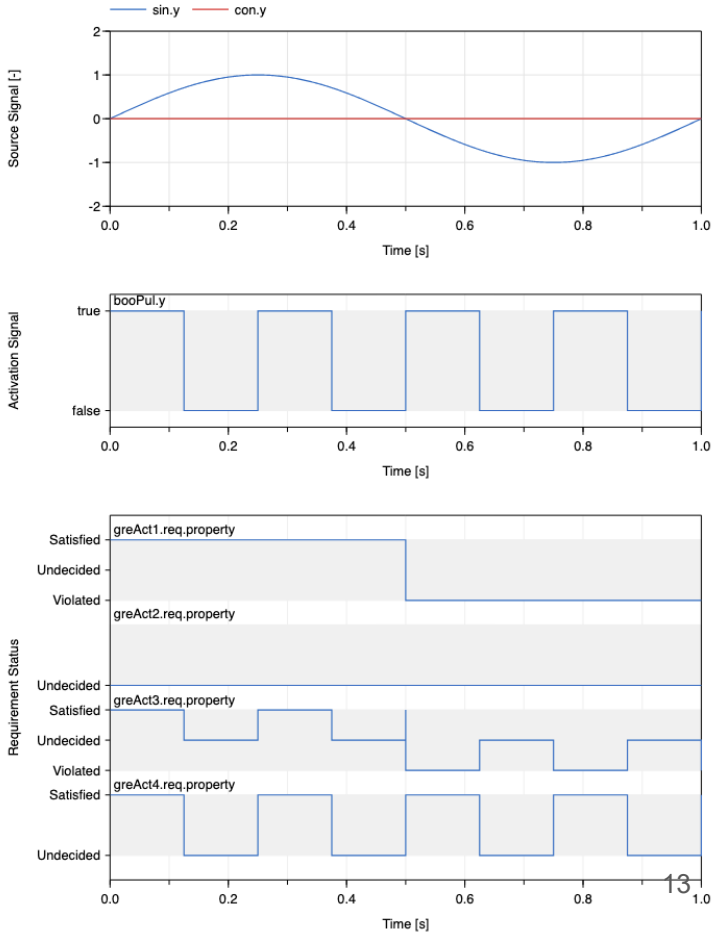


Library Description

Example

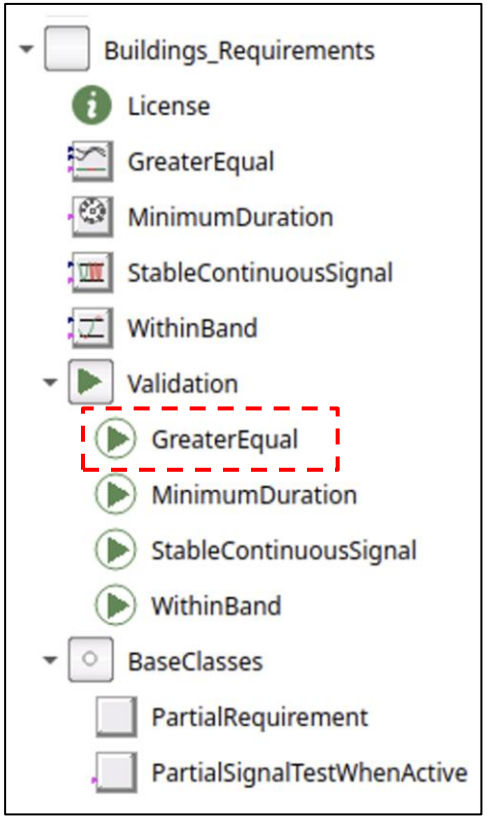


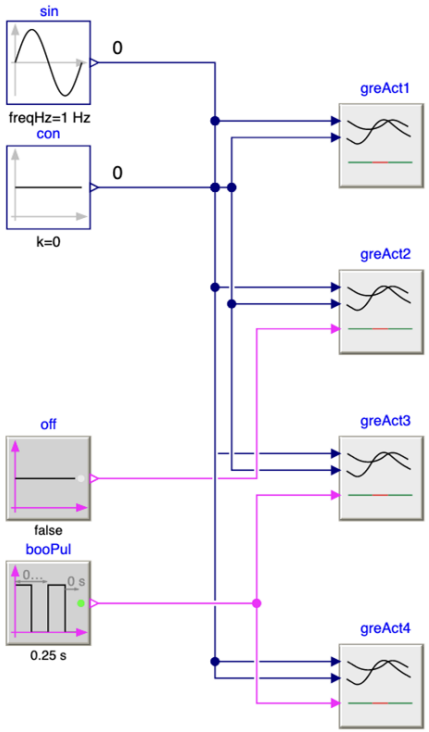




Library Description

Example







Requirements violated (2 of 4)

Observation	Requirement	First violation at	Description
AlwaysActive	greAct.req	0.5 s	Sine signal is greater or equal to contant signal
SometimesActive	greAct2.req	0.5 s	Sine signal is greater or equal to contant signal subject to activation

Requirements untested (1 of 4)

Observation	Requirement	Description
NeverActive	greAct1.req	Sine signal is greater or equal to contant signal subject to activation

Requirements satisfied (1 of 4)

Observation	Requirement	Description
AlwaysSatisfied	greAct3.req	Sine signal is greater or equal to contant signal subject to activation

HTML report generated by *Modelica Requirements Library* components

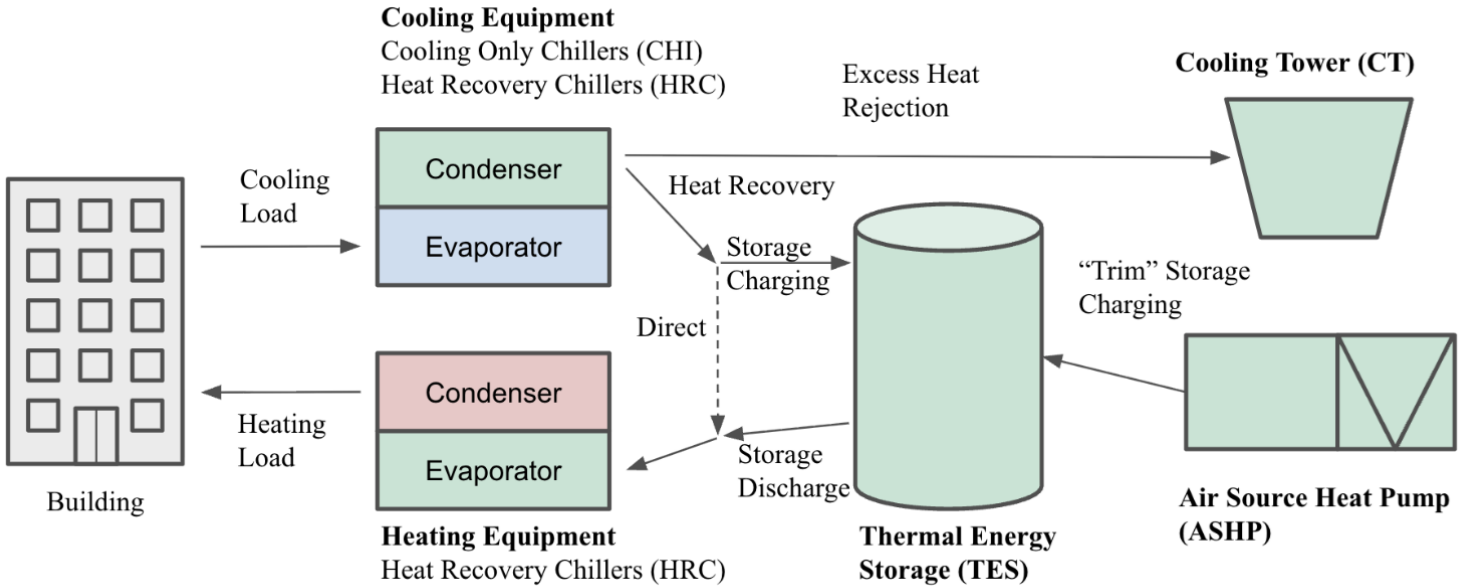
The Modelica Buildings Requirements Library for In-Simulation Requirements Verification for HVAC Applications

- Motivation
- Library Description
- **Example Usage: Commercial Building Central Plant**
- Conclusions and Future Work

Example Usage: Commercial Building Central Plant

Context: Time Independent Heat Recovery (TIER) Plant

- Integrates heat recovery chillers with storage
- Enables heat recovery even without simultaneous heating and cooling loads



TIER Concept (Zanetti 2026)

Example Usage: Commercial Building Central Plant

Context: Time Independent Heat Recovery (TIER) Plant

- Complex, multilayered control due to plant design complexity (44-page document)
- Many operating modes based on building loads, weather, and TES SOC:
  - HRCs: Cascade Cooling or Direct Heat Recovery
  - CW Loop: Charge Assist or Heat Rejection or Tank Charge/Discharge,
- Need to avoid short cycling, unstable temperatures, and catastrophic failures

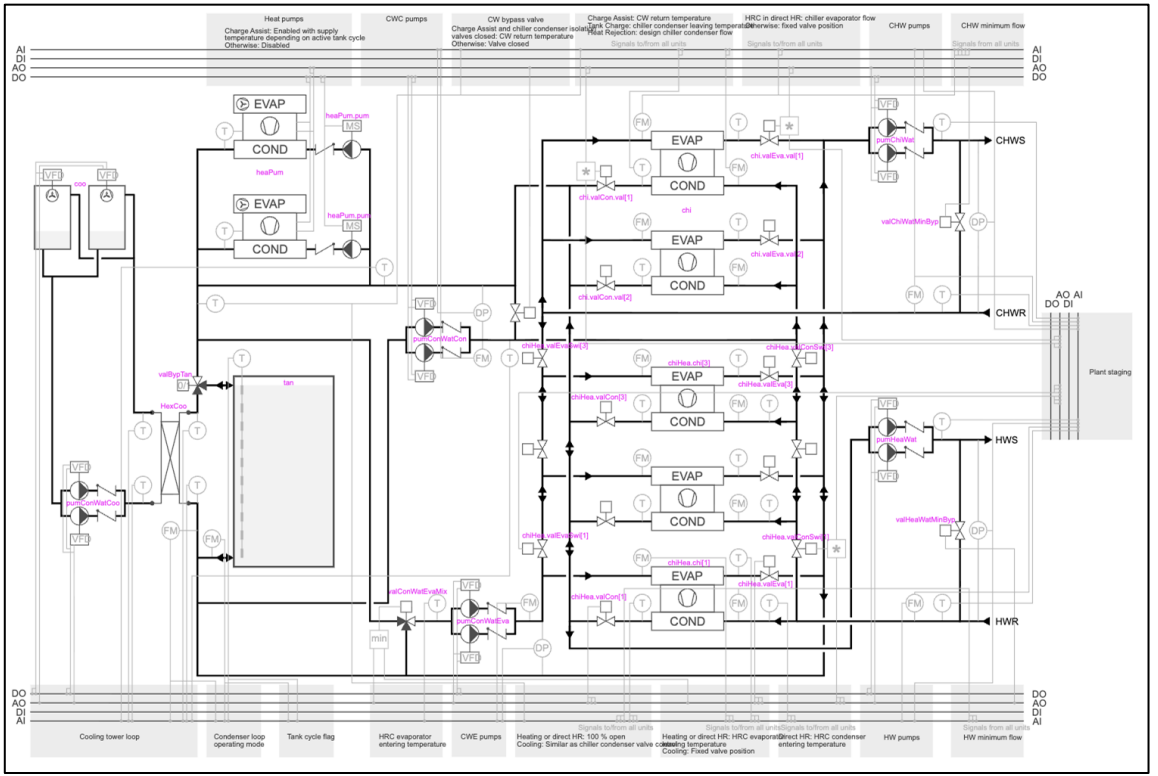
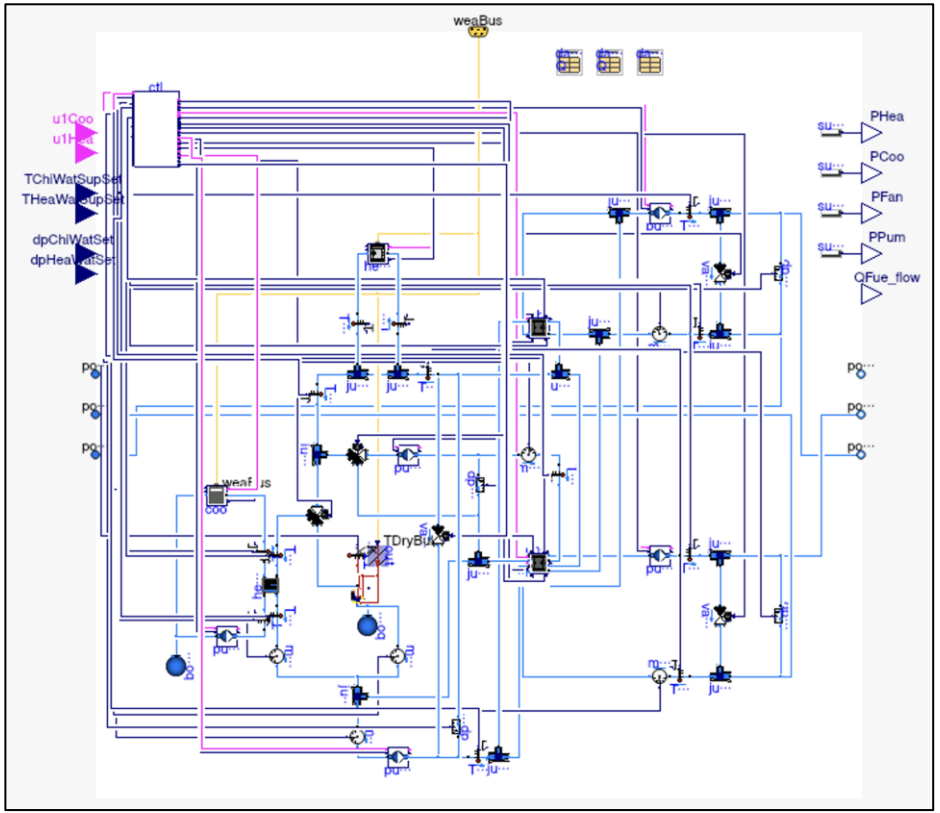


Image from Modelica Buildings Library documentation at https://simulationresearch.lbl.gov/modelica/releases/v12.0.0/help/Buildings_DHC_Plants_Combined.html#Buildings.DHC.Plants.Combined.AllElectricCWStorage

Example Usage: Commercial Building Central Plant

Context: Time Independent Heat Recovery (TIER) Plant

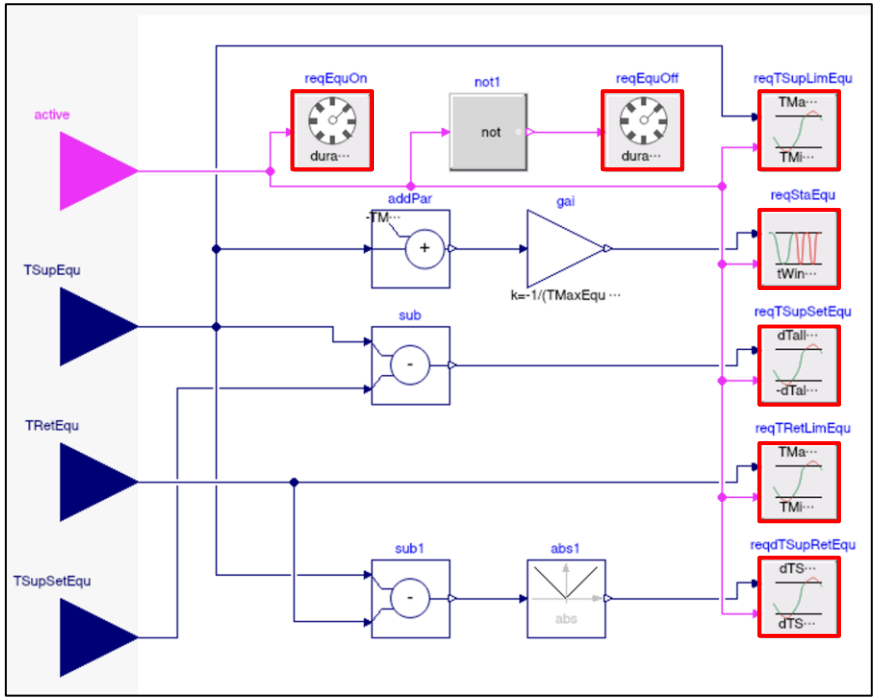
- Modeled using Modelica Buildings Library v12.0.0 (Buildings.DHC.Plants.Combined.AllElectricCWStorage)
- Annual simulations with pre-generated building heating and cooling load timeseries and corresponding TMY3 weather data (San Francisco)



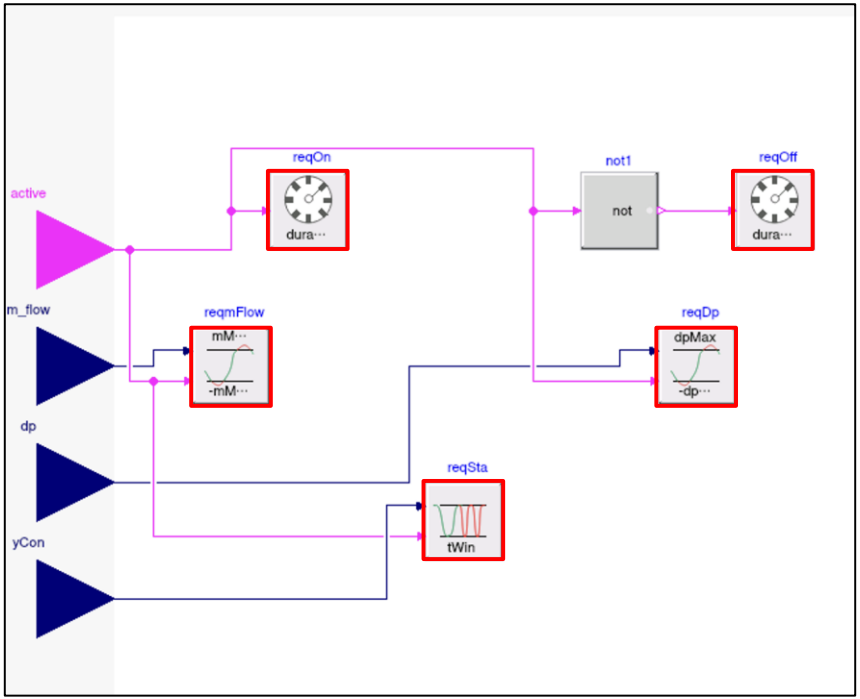
Model of the TIER system in the Modelica Buildings Library

Example Usage: Commercial Building Central Plant

Modelica Buildings Requirements Usage



Heating and cooling equipment requirements:
min on/off time, min/max supply & return temperature, set point tracking for supply temperature and supply-return temperature difference, and stability of supply temperature



Pump equipment requirements: min on/off time, min/max flow rate, min/max pressure difference, and stability of pump control signal

Example Usage: Commercial Building Central Plant

Results

Requirements violated (15 of 80)

Observation	Requirement	First violation at	Description
chiller	plantRequirement.chiReq[1].reqdTSupRetEqu.req	404246 s	This chiller supply and return temperature difference should be between 4K and 20K once the equipement is active for 10 min.
cooling plant	plantRequirement.cooPlaReq[1].reqTSupSetEqu.req	394654 s	This cooling plant supply temperature set point must be tracked within ± 0.5K once the equipement is active for 10 min.
cooling plant	plantRequirement.cooPlaReq[1].reqdTSupRetEqu.req	394654 s	This cooling plant supply and return temperature difference should be between 4K and 20K once the equipement is active for 10 min.
heat recovery chiller	plantRequirement.heaChiReq[1].reqTSupSetEqu.req	1.12877e+07 s	This heat recovery chiller supply temperature set point must be tracked within ± 0.5K once the equipement is active for 10 min.
heat recovery chiller	plantRequirement.heaChiReq[1].reqdTSupRetEqu.req	174000 s	This heat recovery chiller supply and return temperature difference should be between 4K and 20K once the equipement is active for 10 min.
heat recovery chiller	plantRequirement.heaChiReq[2].reqTSupSetEqu.req	1.12865e+07 s	This heat recovery chiller supply temperature set point must be tracked within ± 0.5K once the equipement is active for 10 min.
heat recovery chiller	plantRequirement.heaChiReq[2].reqdTSupRetEqu.req	290216 s	This heat recovery chiller supply and return temperature difference should be between 4K and 20K once the equipement is active for 10 min.
heating plant	plantRequirement.heaPlaReq[1].reqEquOn.req	3.1536e+07 s	This heating plant must operate at least 10 min when activated.
heating plant	plantRequirement.heaPlaReq[1].reqTSupSetEqu.req	1.12877e+07 s	This heating plant supply temperature set point must be tracked within ± 0.5K once the equipement is active for 10 min.
heating plant	plantRequirement.heaPlaReq[1].reqdTSupRetEqu.req	174000 s	This heating plant supply and return temperature difference should be between 4K and 20K once the equipement is active for 10 min.
heat pump	plantRequirement.heaPumReq[1].reqEquOn.req	192464 s	This heat pump must operate at least 10 min when activated.
heat pump	plantRequirement.heaPumReq[1].reqdTSupRetEqu.req	394236 s	This heat pump supply and return temperature difference should be between 2K and 20K once the equipement is active for 10 min.
heat pump	plantRequirement.heaPumReq[2].reqEquOn.req	192464 s	This heat pump must operate at least 10 min when activated.
heat pump	plantRequirement.heaPumReq[2].reqdTSupRetEqu.req	394236 s	This heat pump supply and return temperature difference should be between 2K and 20K once the equipement is active for 10 min.
tank	plantRequirement.tanReq[1].greTUpp.req	174000 s	This tank average temperature is above the upper bound once the equipement is active for 10 minutes.

Requirements untested (0 of 80)

None

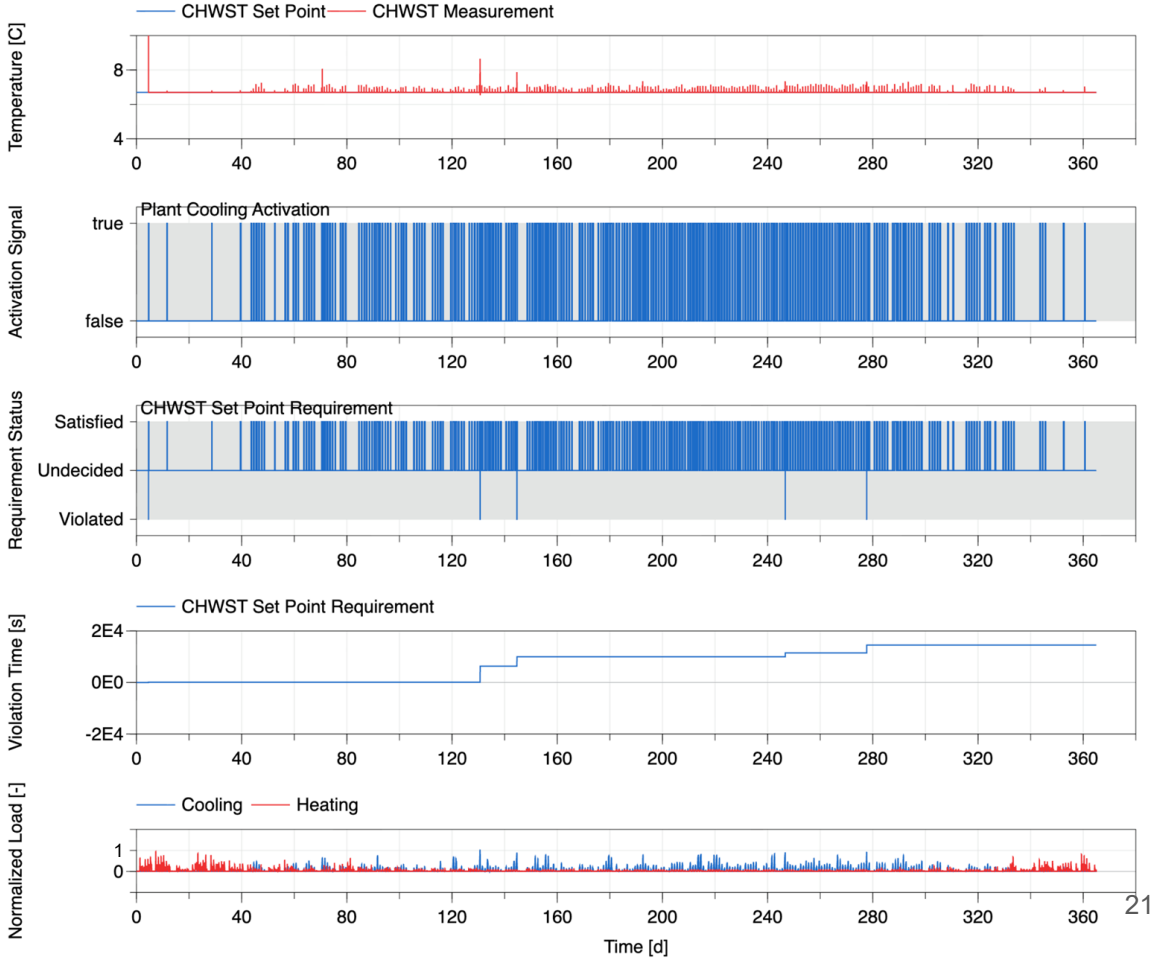
Requirements satisfied (65 of 80)

HTML report generated by *Modelica Requirements Library* components

Example Usage: Commercial Building Central Plant

Results

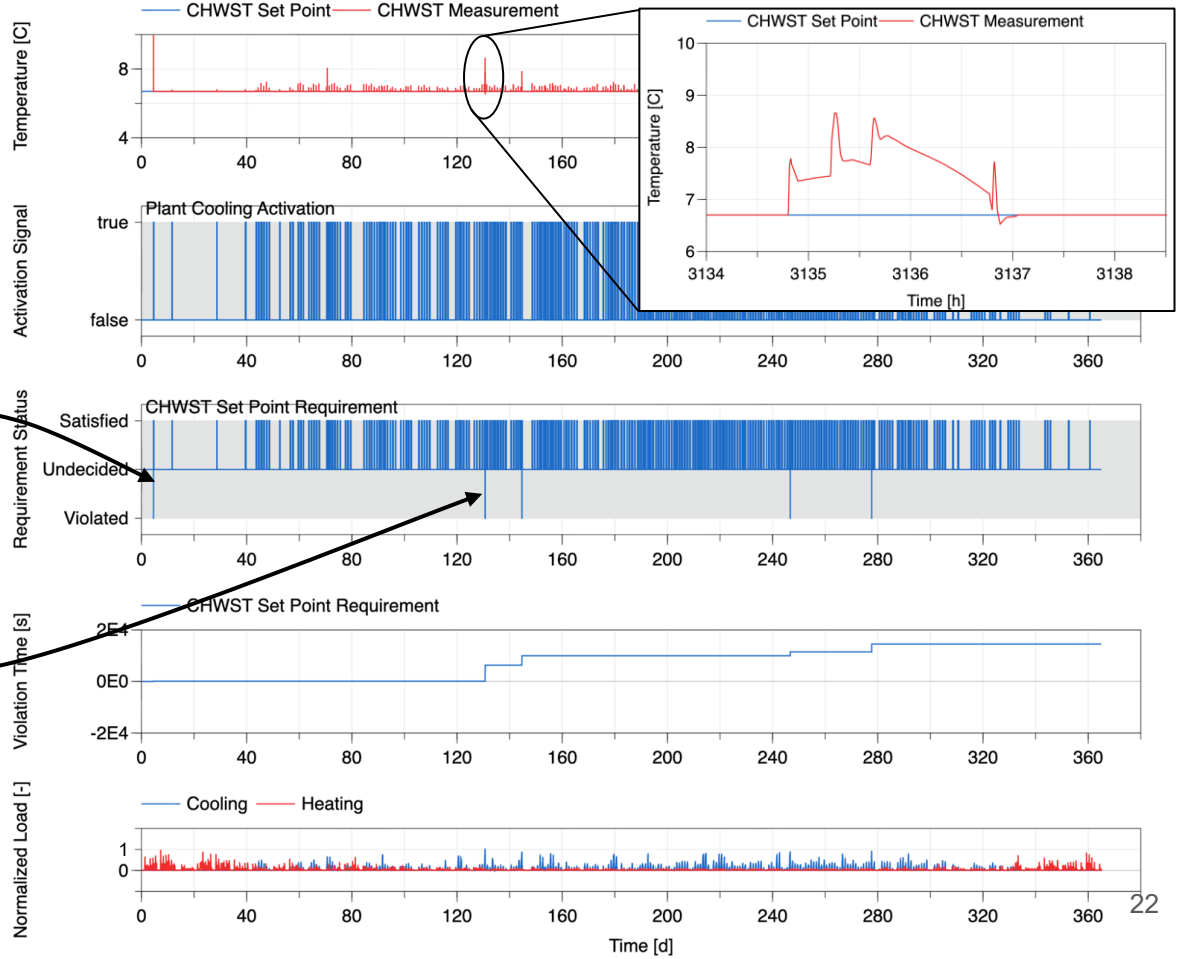
- **Example Requirement:** “Maintain the plant-wide chilled water supply temperature within 0.5 K of the set point.”



Example Usage: Commercial Building Central Plant

Results

- **Example Requirement:** “Maintain the plant-wide chilled water supply temperature within 0.5 K of the set point.”
- Violated 5 times total, for example:
  - **1st violation:** Plant turns on for first time, leading to extra time for water in loop to cool down to set point from initial condition
  - **2nd violation:** Set point excursion of ~2 C for two-hour window during peak cooling load



The Modelica Buildings Requirements Library for In-Simulation Requirements Verification for HVAC Applications

- Motivation
- Library Description
- Example Usage: Commercial Building Central Plant
- **Conclusions and Future Work**

Conclusions and Future Work

Conclusions

- The library proved useful to define and observe any operational requirements violations
  - Eliminated the need for tedious examination of large result files
  - Streamlined verification across batches of simulation scenarios (30 total)
- Use of the library increases system simulation time, depending on system model and solver choice (1.3x for the TIER system)

Limitations and Future Work

- The library indicates when requirements are violated, but not how long, how often, nor by how much, which would help prioritization
- No ability to formally define criteria of short/limited violations which may actually be acceptable (especially as tradeoff to increased costs)
- Develop more equipment and system-specific requirements templates

Acknowledgments

This research was developed by Lawrence Berkeley National Laboratory, operated for the U.S. Department of Energy (DOE) under Contract No. DE-AC02-05CH11231.

This research was supported by the Environmental Security Technology Certification Program (ESTCP) of the U.S. Department of Defense (DoD), under Contract No. EW23-BB-7686.

The California Energy Commission Electric Program Investment Charge Program (EPC-23-023) provided funding for this research.

References

- B. Gill (2021). “Solving the Large Building All-Electric Heating Problem.” ASHRAE Journal, 63(10). October. Available online at https://www.techstreet.com/standards/solving-the-large-building-all-electric-heating-problem?product_id=2235471.
- K. Hinkelman (2023). “Modelica Modeling And Ecosystem Biomimicry Of District Energy Systems.” PhD Dissertation, The Pennsylvania State University. https://etda.libraries.psu.edu/catalog/27446kgh5244.
- M. Otter et al. (2015). “Formal Requirements Modeling for Simulation-Based Verification”. In *Proc. of the 11th International Modelica Conference*, Sep 21-23, Versailles, France. http://dx.doi.org/10.3384/ecp15118625.
- M. Sulzer, M. Wetter, R. Mutschler, and A. Sangiovanni-Vincentelli (2023). “Platform-based design for energy systems”. *Applied Energy,* 352, 121955. https://doi.org/10.1016/j.apenergy.2023.121955.
- M. Wetter (2023). “Spawn and Modelica Buildings Library.” 2023 DOE BTO Peer Review Presentation. https://www.energy.gov/sites/default/files/2023-05/bto-peer-2023-35511-spawn-lbnl-wetter.pdf.
- M. Wetter et al. (2026). Thermal Reservoir Networks for Modularly Expandable Thermal Microgrids. Tech. rep. ESTCP Project EW23-7686. URL: https://escholarship.org/uc/item/6r42g2pt.
- E. Zanetti, D. Blum, A. Gautier, P. Raftery, and H. Cheng (2026). “Optimizing Heat Recovery with Storage: Control Validation and Sensitivity Analysis of the Time-Independent Energy Recovery Plant Using Modelica.” In *Proc. of the 2026 Summer Study on Energy Efficiency in Buildings (ACEEE)*, Aug 2-7, Pacific Grove, CA.

The Modelica Buildings Requirements Library for In-Simulation Requirements Verification for HVAC Applications

Thank you!

David Blum
dhblum@lbl.gov

Ettore Zanetti
ezanetti@lbl.gov

Michael Wetter
mwetter@lbl.gov

Find the library here: https://github.com/lbl-srg/modelica-buildings-requirements

BERKELEY LAB