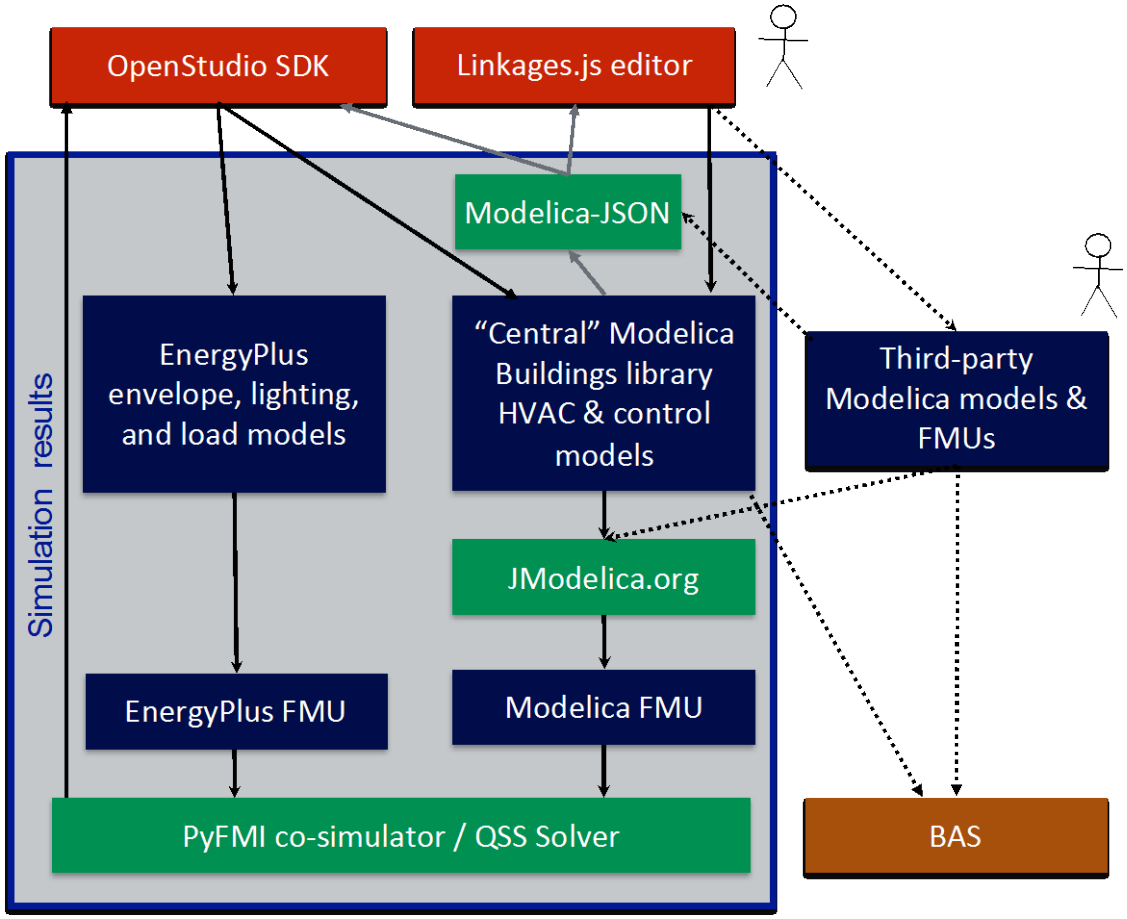
U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Spawn of EnergyPlus



LBNL

NREL
Modelon

Objexx

Michael Wetter

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Project Summary

Timeline:

Start date: Oct. 2015

Planned end date: Sep. 2019
[continuation proposal is currently in review]

Key Milestones:

1. Simulate Modelica HVAC coupled to EnergyPlus; 3/31/18
2. Release Modelica Buildings library for use with EnergyPlus; 8/31/18

Budget:

Total Project $ to Date:

- DOE: $1,500k (since Oct. 2015)
  $200k (since Oct. 2017)
- Cost Share: no direct, but leverage of >100M investment in Modelica/FMI, Modelon compiler & simulator technology, and IEA EBC Annex 60 (42 institutes) and IBPSA Project 1 (26 institutes + 27 individual participants)

Total Project $:

- DOE: $2.2M (Oct. 2015 to Sep. 2018, includes non-SOEP tasks)

Key Partners:

NREL	>41 institutes through IEA EBC Annex 60 and IBPSA Project 1 that jointly develop Modelica & FMI for buildings
Objexx	
Modelon	

Project Outcome:

Next-generation BEM engine that:

- Connects energy simulation with control design, optimization, and implementation
- Closes simulation technology model gap by supporting vendor-defined component, system, and control models, including proprietary models
- Uses open standards (Modelica and FMI) that leverages >$100M in investment along with domain-agnostic expertise in compilation and simulation
- Leverages EnergyPlus for envelope, load, and lighting simulation
- Leverages OpenStudio ecosystem

Team

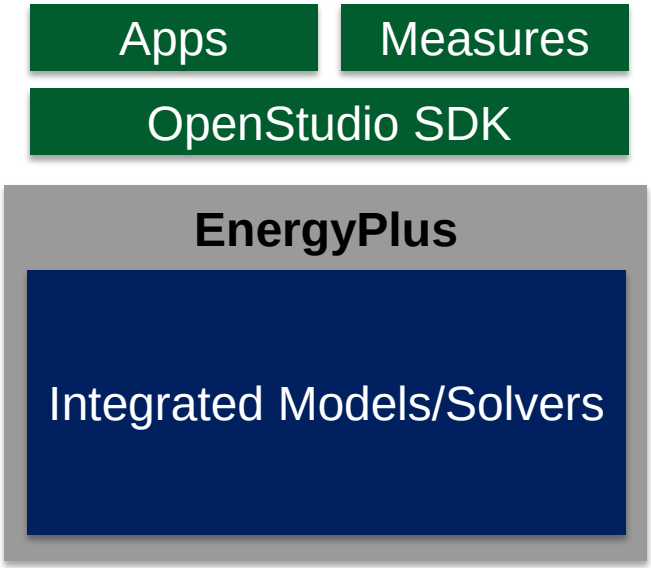
LBNL (Michael Wetter, PI; Thierry S. Nouidui; Jianjun Hu)
- Overall software architecture
- Modelica Buildings Library development
- Specification of FMI extension
- QSS integration
- Lead and coordination with IBPSA Project 1 & Modelica IBPSA Library

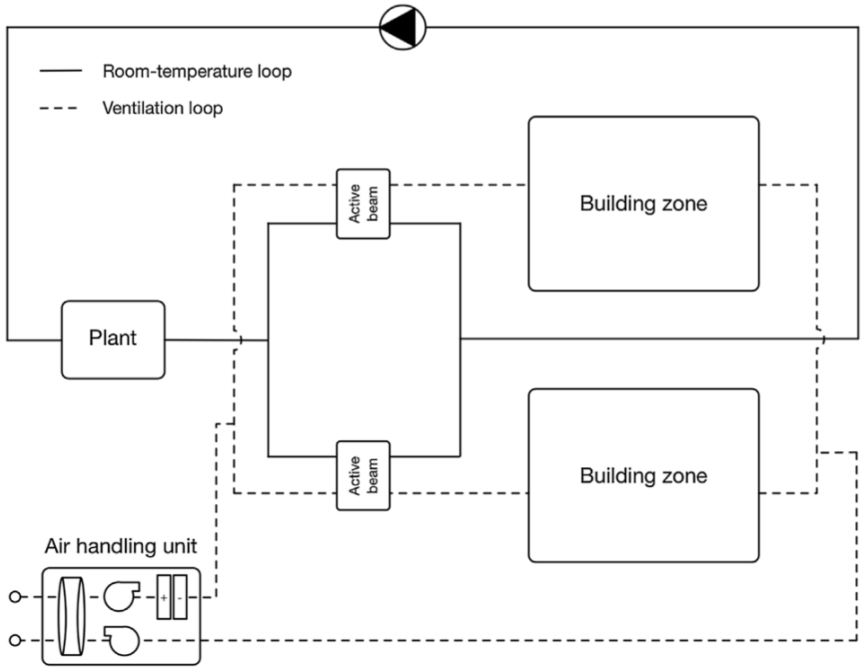
NREL (Kyle Benne)
- Tool-chain for end-to-end distribution
- EnergyPlus envelope model refactoring
- EnergyPlus API integration

Modelon (Hubertus Tummescheit; Christian Winther)
- JModelica.org translator and simulator
- Implementation of FMI extensions for QSS

Objexx (Stuart Mentzer)
- QSS solver development and integration

Challenge





Novel two-pipe system, reducing energy by 12-18% compared to conventional four-pipe system, built based on Modelica virtual prototyping.
http://dx.doi.org/10.1016/j.enbuild.2016.10.051

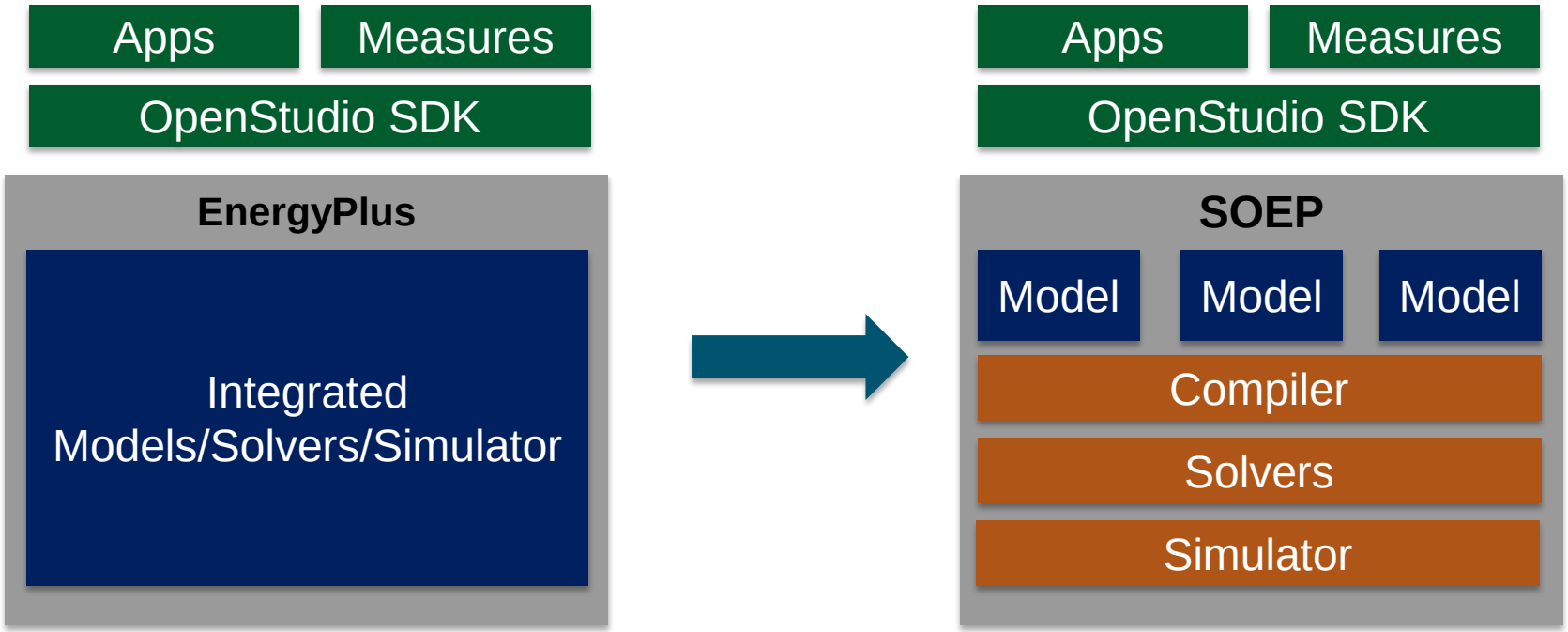
Current BEM engines are "monolithic"

- Models mixed with solvers and implicit control

Resulting limitations

- Large, difficult to maintain code bases
- Inability to
  - integrate with external models or analyses
  - extract and reuse models for other use cases (e.g., control implementation)
  - model certain systems with non-conventional flow networks or control sequences
- Poor scalability for large analyses (e.g., district systems)

Approach



Separation of concerns – equation-based modeling language (Modelica)

- Building experts develop domain-specific models
- Numerical/software experts develop domain-neutral compiler/solver/simulator/optimizer

Modularity and inter-operability – use open standard simulation interface (FMI)

- Modular plug-and-play components

OpenStudio layer hides changes from 3rd-party developers and users

Impact – Support New Use Cases

Controls

- Modeling of actual control sequences such as from ASHRAE Guideline 36 that showed 30% reduction in annual HVAC energy (http://obc.lbl.gov/specification/example.html).
- Development and deployment of actual, implementable control sequences, rather than idealized, load-based control.
- Allow users to customize control in a way that allows export of control sequence to control systems, or to functional verification tools (http://obc.lbl.gov/specification/codeGeneration.html)
- Export of models for controls and FDD, including MPC as needed for grid flexible buildings and integrated dynamic systems, possibly after simplifications in tool chains such as developed by LBNL in CERC or by KU Leuven's Modelica team.

FDD

- Quickly insert fault scenarios in equipment models and control sequences.
- Assess how control sequences compensate for equipment faults.

Data-driven modeling

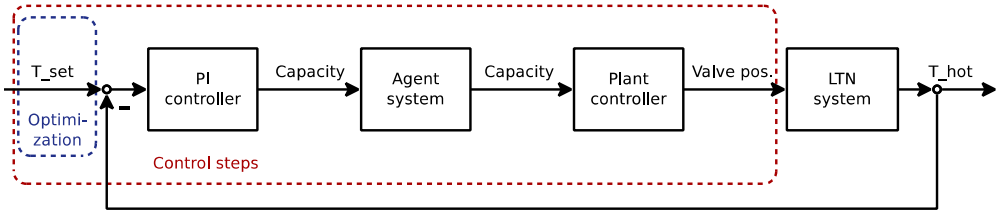
- Combine data-driven and physics-based models, including use of measured data as input to component and system models.

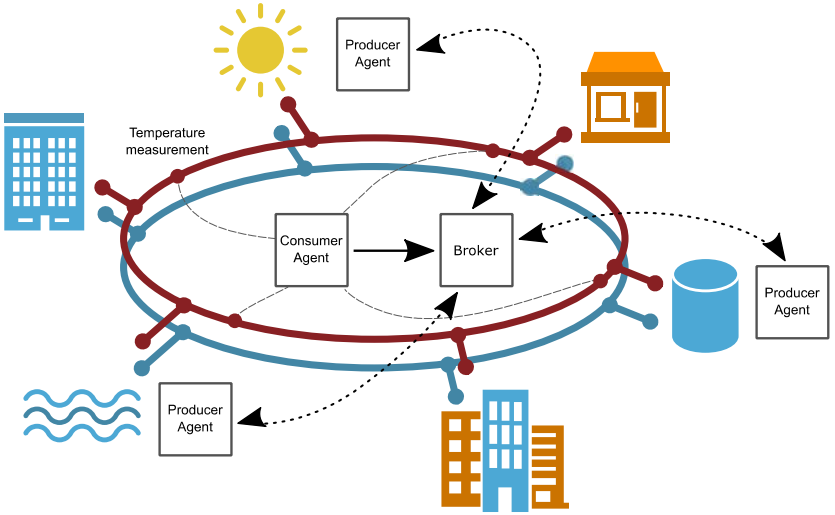
Impact – Expand Scope of Analyzable Systems

Support design, analysis (and hardware-in-the-loop) of systems, including controls, for

- novel HVAC systems
- district energy systems, including 5th generation where buildings share waste heat/cool, and where pumping energy and control sequences are critical for performance
- buildings to grid integration, including coupled building & distribution grid simulation
- cyber-physical systems

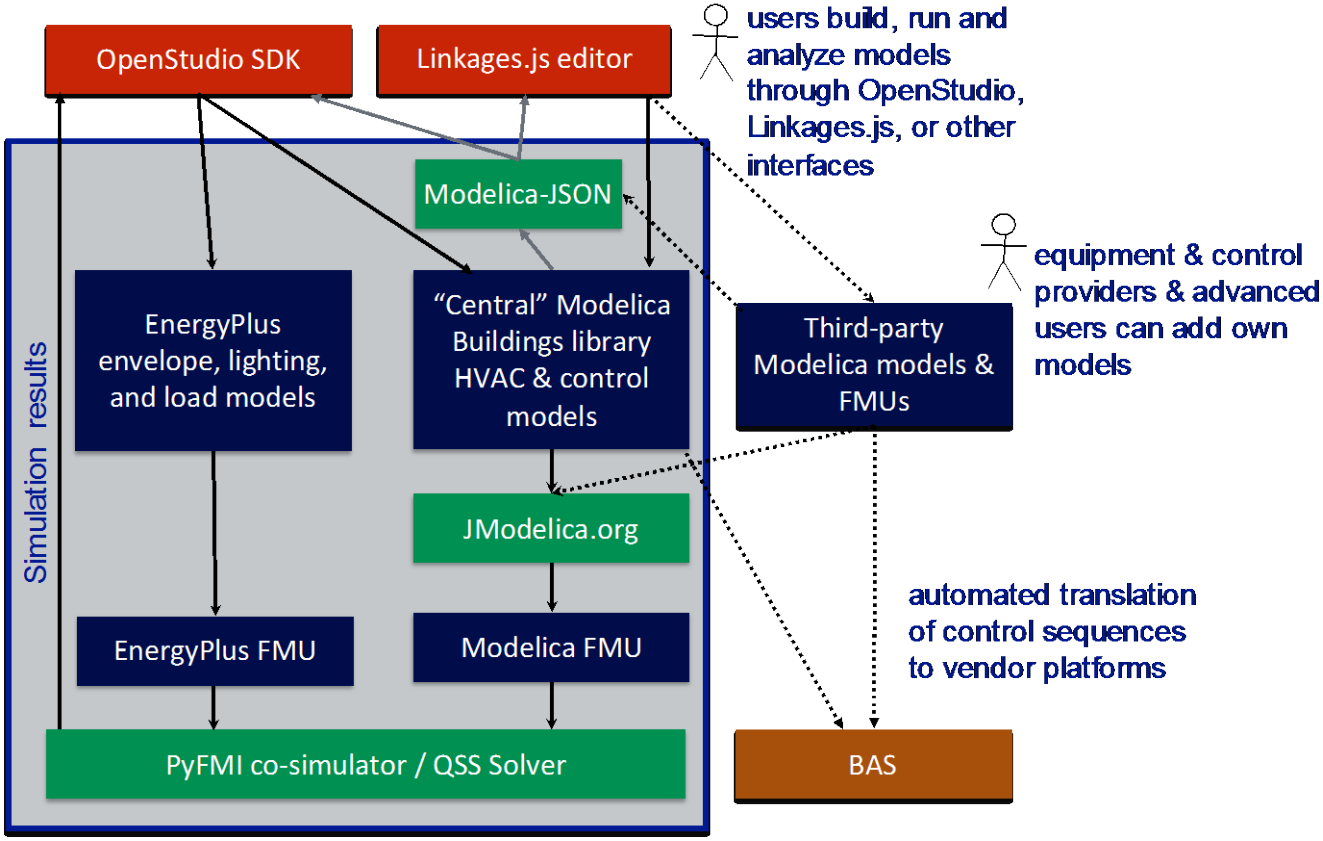
Reduce effort and complexity of developing models for these systems.





5th generation bidirectional DHC system that allows buildings to share waste heat, cold and storage capacity through agent-based control, modelled with Modelica.
Buenning et al., 2017
https://doi.org/10.1016/j.apenergy.2017.10.072

Progress: Architecture



Developed, and started implementation of, modular Spawn architecture

- Reuses EnergyPlus envelope, load, and lighting models
- Built leveraging open, industry-driven standards (Modelica and FMI)
- See https://lbl-srg.github.io/soep/softwareArchitecture.html for more details.

Foundational Standards – Modelica and FMI

https://modelica.org/

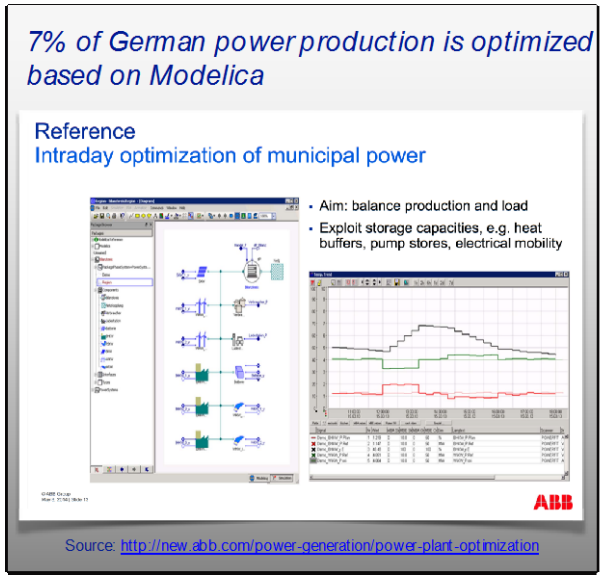
- Open, industry-driven standard for multi-physics modeling
- Developed since 1996
- Large ecosystem of free and commercial libraries and tools
- Large LBNL/RWTH Aachen led collaborations on Modelica for building and district energy systems:
  - IEA EBC Annex 60: 42 institutes (2012-2017)
  - IBPSA Project 1: 26 institutes + 27 individual participants (2017-2022)

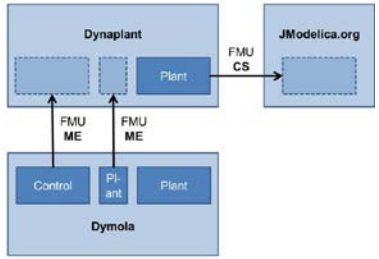
https://www.fmi-standard.org/

- API standard to exchange simulators or models
- Developed since 2008
- Supported by >100 tools.

Why standards?

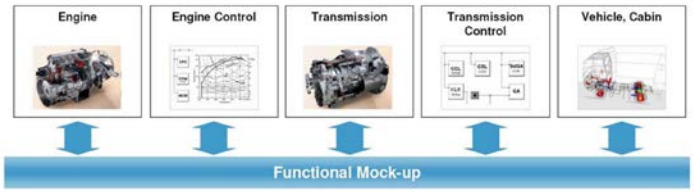
- Leverages investments in related industries.
- Provides well-tested APIs for software integration.
- Provides to industry a stable basis for investment.
- Avoids vendor lock-in.





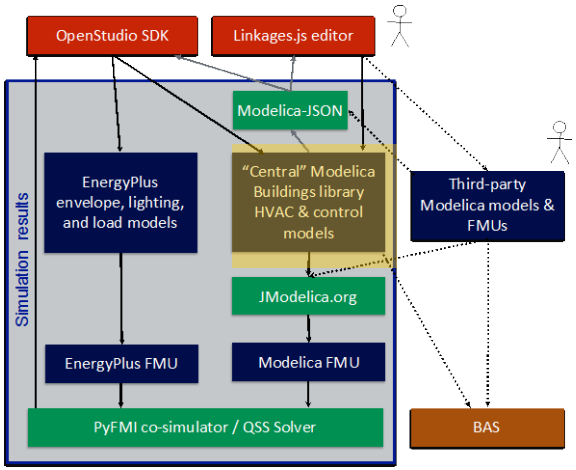
Powerplant simulation with Modelica (Dymola) coupled to in-house simulator (Dynaplant).

Source: Siemens, doi:10.3384/ecp1511817



Cosimulation of the behavioral models and the embedded controller software

Progress: Modelica Buildings Library

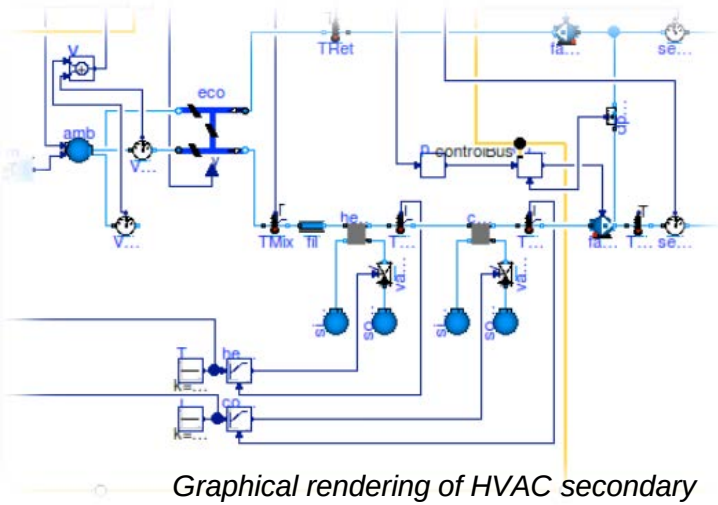


Modelica Buildings Component Library

- http://simulationresearch.lbl.gov/modelica/
- 600+ open-source component models
- Used for US-China project, DOE/BENEFIT projects, by major control vendors and equipment manufacturers
- Validated with BESTEST, EnergyPlus, TRNSYS and measured data
- Continuous integration testing with JModelica & Dymola, with 1000 tests for each

Past year accomplishments

- Reduced computing time up to 20% for large models with discrete time control
- Improved automated continuous integration & verification of results
- Added new models
  - Data center equipment & systems [UC Boulder & Schneider Electric data center project]
  - Pipe with transport delay, heat loss and friction [IBPSA Project 1]
  - ASHRAE Guideline 36 control sequences [OpenBuildingControl project]
  - Humidifiers [IBPSA Project 1]
  - Idealized heater/cooler [IBPSA Project 1]

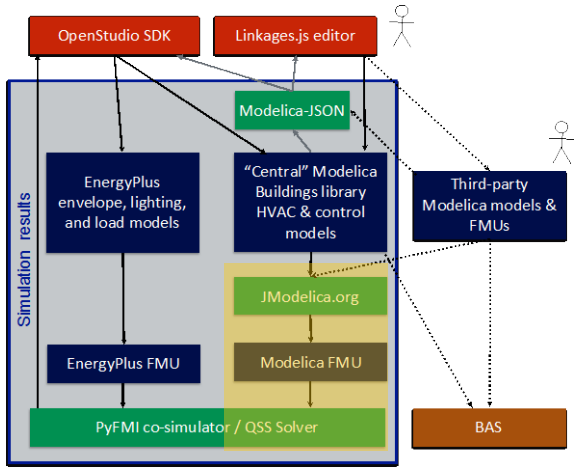


Graphical rendering of HVAC secondary system in Modelica.

Progress: QSS Validation

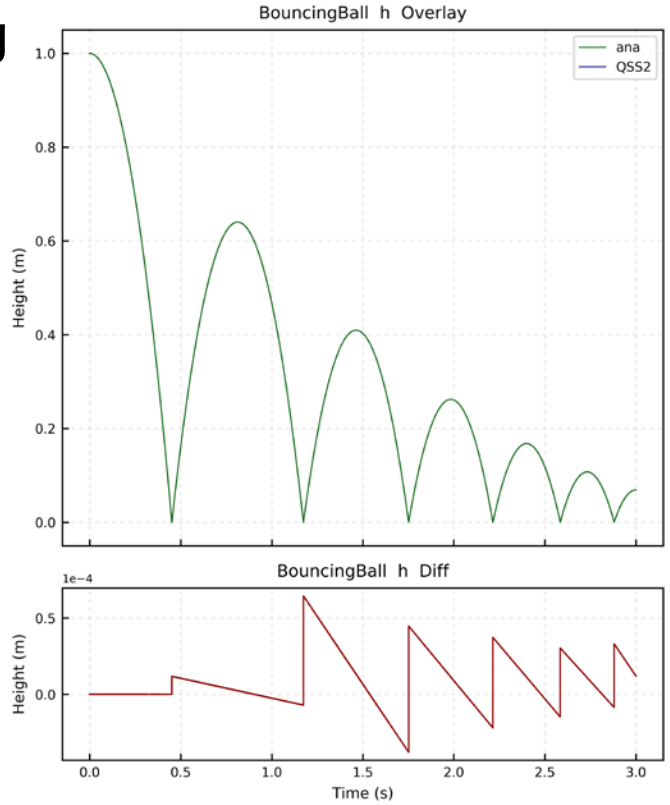
QSS solver validated through cross-comparison with analytical solution

- QSS solvers discretize the state variables (e.g., room temperature), allowing for explicit, efficient simulation of switched control systems (e.g., thermostats) and systems with coupled fast and slow dynamics.



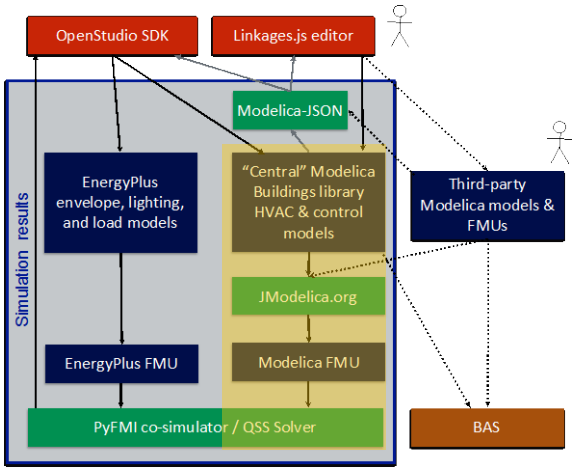
This bouncing ball model validates handling of "zero-crossing" events

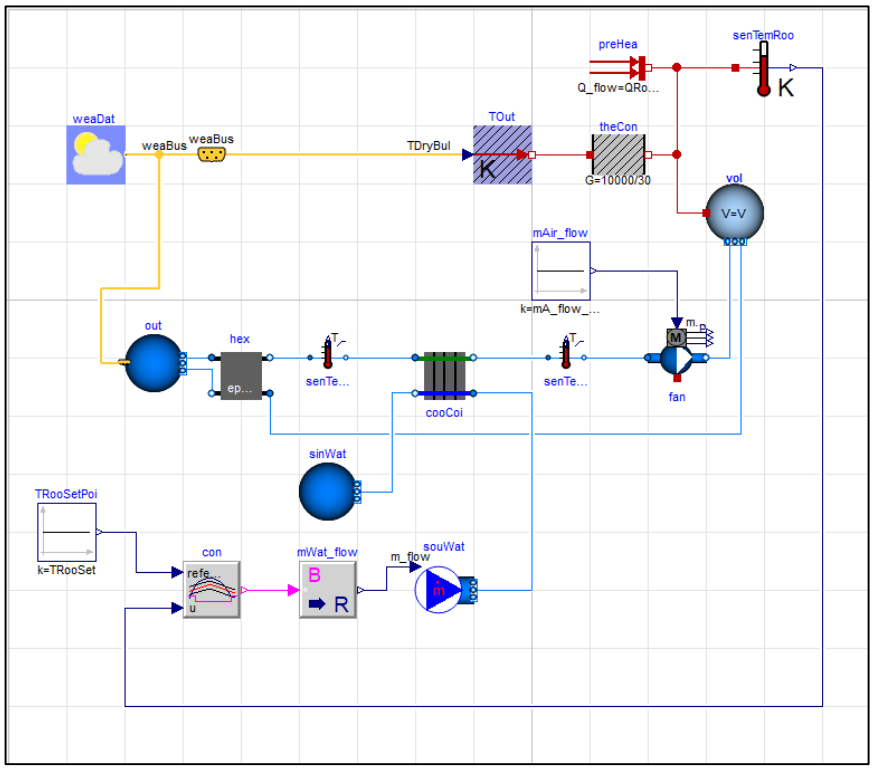
```
model BouncingBall
  "This model simulates the bouncing ball"
  extends Modelica.Icons.Example;
  type Height = Real (unit="m");
  type Velocity = Real (unit="m/s");
  parameter Real e=0.8 "Coefficient of restitution";
  parameter Height h0=1.0 "Initial height";
  Height h;
  Velocity v(start=0.0, fixed=true);
  Modelica.Blocks.Interfaces.RealOutput __zc_z
    "Zero crossing function";
  Modelica.Blocks.Interfaces.RealOutput __zc_der_z
    "Derivative of zero crossing function";
initial equation
  h = h0;
equation
  v = der(h);
  der(v) = -9.81;
  __zc_z = h;
  __zc_der_z = v;
  when h < 0 then
    reinit(v, -e*pre(v));
  end when;
end BouncingBall;
```

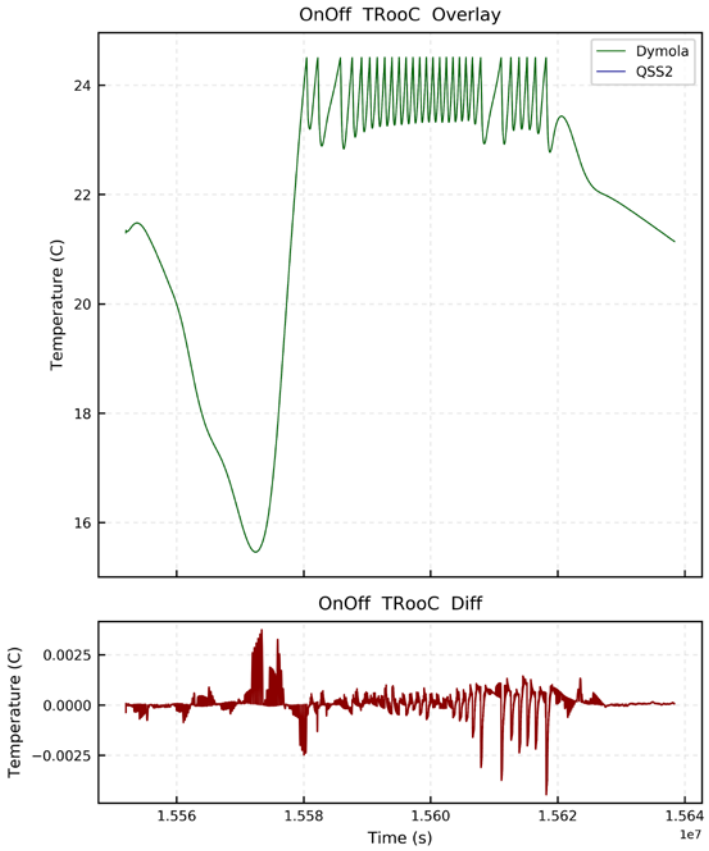


Progress: QSS on Buildings

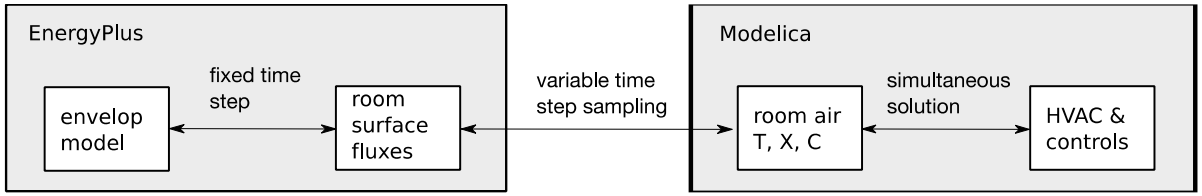
For a Modelica system model consisting of a room air coupled to an air-based HVAC system with on/off control, QSS and Dymola compute the same solution within the solver tolerance.

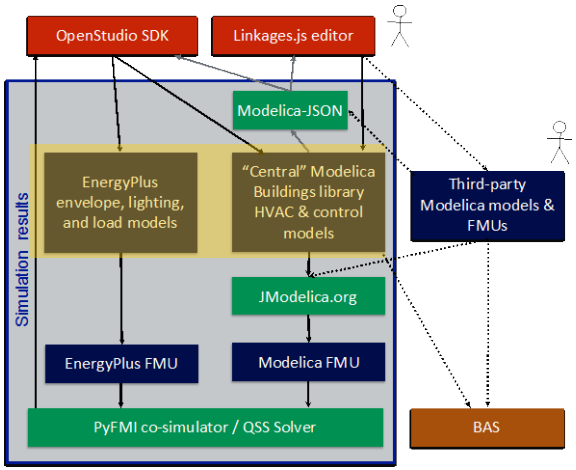






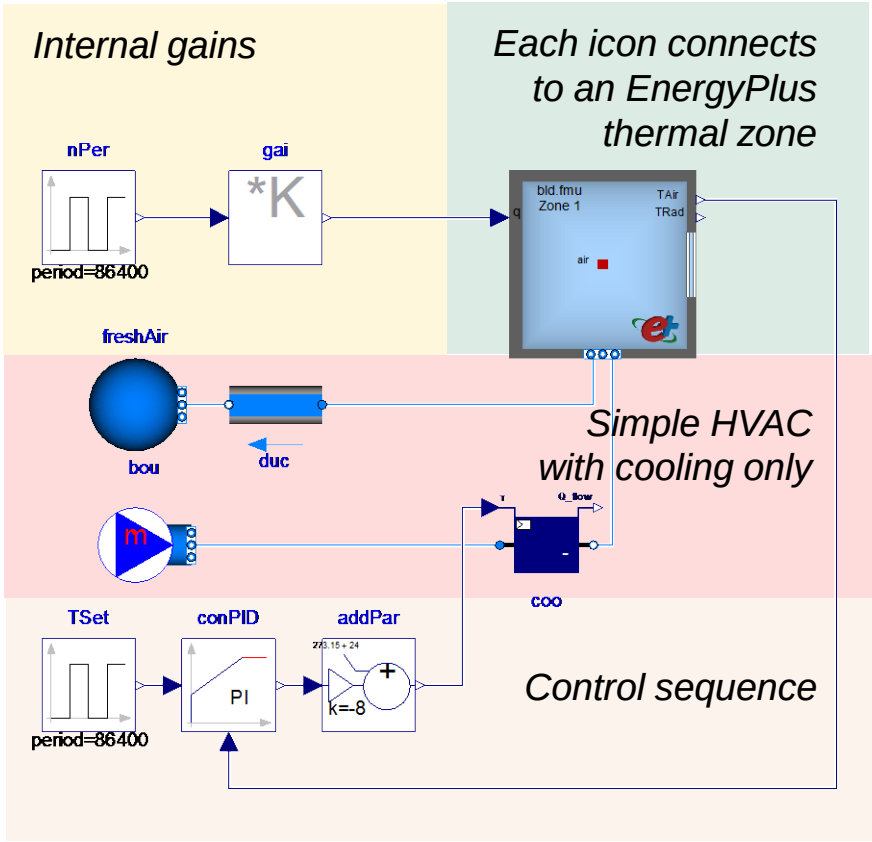
Progress: EnergyPlus + Modelica



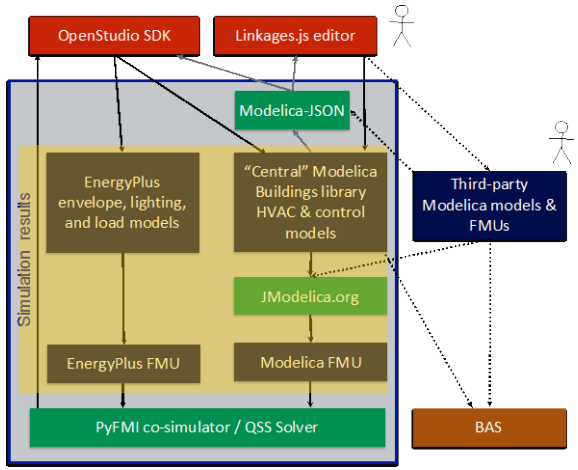


Coupling EnergyPlus & Modelica: Modelica computes room air, allowing

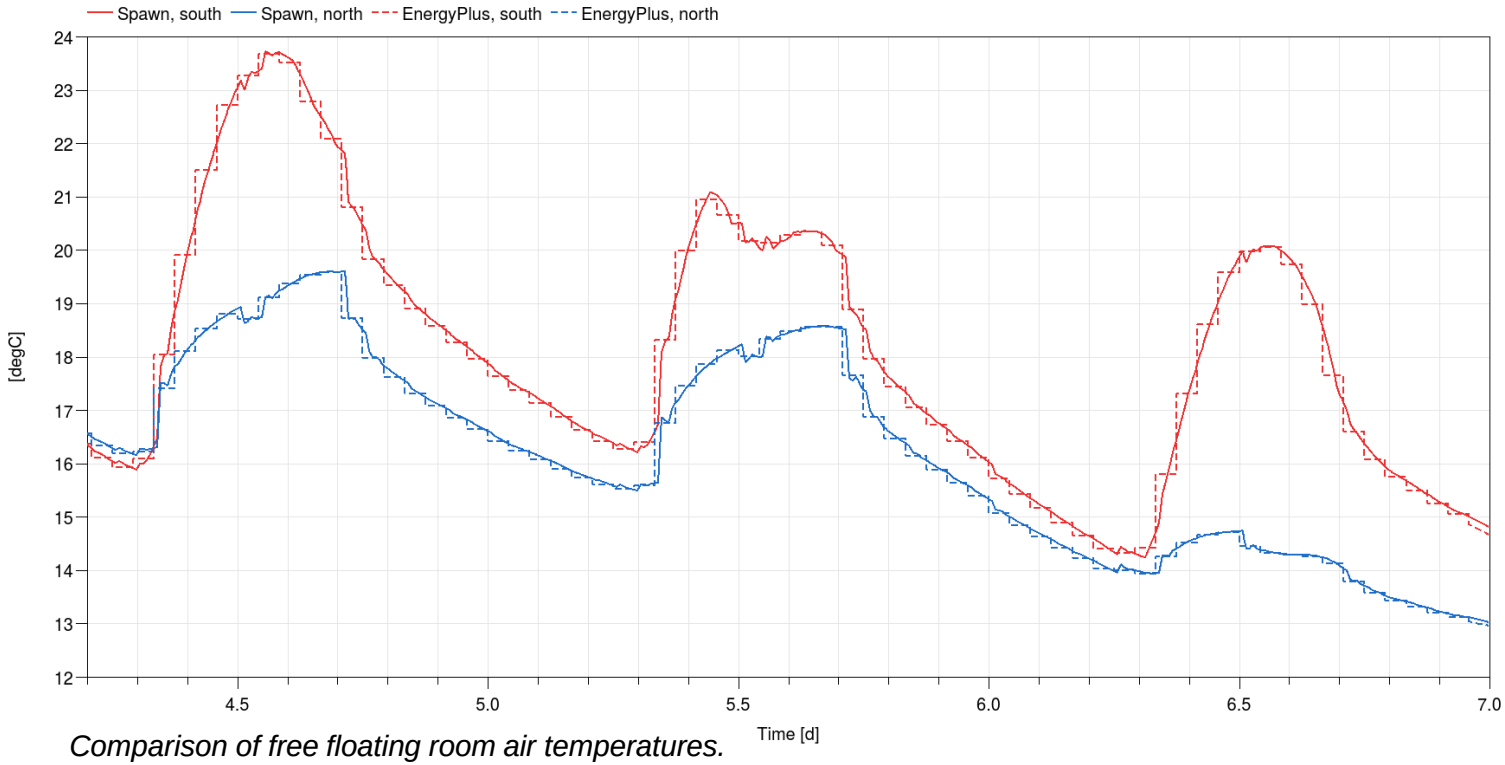
- Adaptive time step with high order ODE solvers for fast changing
  - room air
  - HVAC
  - airflow network
- Coupling of EnergyPlus using slowly time-varying surface temperatures
- Simulation can include of any number of air trace substances (VoC, CO2, …)



Progress: EnergyPlus + Modelica



Coupling EnergyPlus & Modelica for DOE Commercial Reference Building (Small Office): First preliminary Spawn simulations show that free floating temperatures between Spawn (solid lines) and original EnergyPlus (dashed lines) match.



Comparison of free floating room air temperatures.

Stakeholder Engagement

Spawn integrates with OpenStudio ecosystem, and other DOE projects

- OpenBuildingControl,
- Data Center Toolkit,
- Adaptive Control (PNNL) and
- Grid Modernization (PNNL).

IBPSA (International Building Performance Simulation Association) Project 1 2017-22

- https://ibpsa.github.io/project1
- BIM/GIS and Modelica Framework for building and community energy system design and operation
- Continues successful IEA EBC Annex 60 (42 institutes from 18 countries).
- 26 institutes + 27 individual participants, with > 80 FTE, 2017-22.

Training workshops

- American Modelica Conference 2018 (NAMUG sponsored)
- Building Simulation 2017 (NAMUG sponsored)

User support

- Mailing list
- unmethours.com
- Direct collaboration with key companies

Participants of IBPSA Project 1 Expert Meeting 2018

Remaining Project Work

Long term (FY19-22)

Develop and release Spawn, integrated into OS, capable of simulating buildings with 1000s of thermal zones at run-time comparable to EnergyPlus.

Near future (FY 18)

Modelica Buildings Library development

- Refactor into more intuitive package structure (addressing feedback from IBPSA Project 1)
- Extend Modelica to JSON parser towards use for OpenStudio integration

Specification of FMI extension and QSS integration

- Package QSS solver with FMU to export model exchange for discrete event simulation

Tool-chain for end-to-end distribution

- Set up distribution for developers/early testers

EnergyPlus envelope model refactoring

- Add moisture and internal load coupling, integrate into CI validation cases
- Validate and test larger cases

JModelica.org compiler

- Finalize addition of QSS-specific information in FMU
- Further reduce translation and simulation time

Thank You

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NREL

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REFERENCE SLIDES

Project Budget

Project Budget: 700k annual funding for SOEP, Modelica, and FMI, including support of legacy tools.

Variances: None.

Cost to Date: $200k

Additional Funding:

* Cost share shown as 0, although we leverage significant resources through

- Modelica and FMI (>$100M private and public investment),
- IEA EBC Annex 60 (42 partners)
- IBPSA Project 1 (26 institutes, 27 indiv. participants, >80 FTE), and
- working with Modelon which has private investments in their tools such as from ANSYS and Ricardo.

** Proposal for continuation submitted to DOE.

Budget History

FY 2017 (past)		FY 2018 (current)		FY 2019 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
675k	0*	700k	0*	1800k**	0*

Project Plan and Schedule

FY 18 focuses on expanding model library, addressing performance bottlenecks and implementing a more efficient coupling between EnergyPlus envelope and Modelica HVAC by exploiting slow dynamics of surface states rather than room air.