

# Modeling, Simulation and Analysis of Integrated Building Energy and Control Systems

Michael Wetter

Simulation Research Group

Building Technologies Department

Energy and Environmental Technologies Division

Lawrence Berkeley National Laboratory

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# Lawrence Berkeley National Laboratory

- 4000 people – pure and applied science and engineering
- 400 people in Environmental Energy Technologies Division
- 200 people working on buildings:
  - HVAC, lighting, daylighting, IAQ, controls, demand response, ...
- Operated by the University of California for the Department of Energy



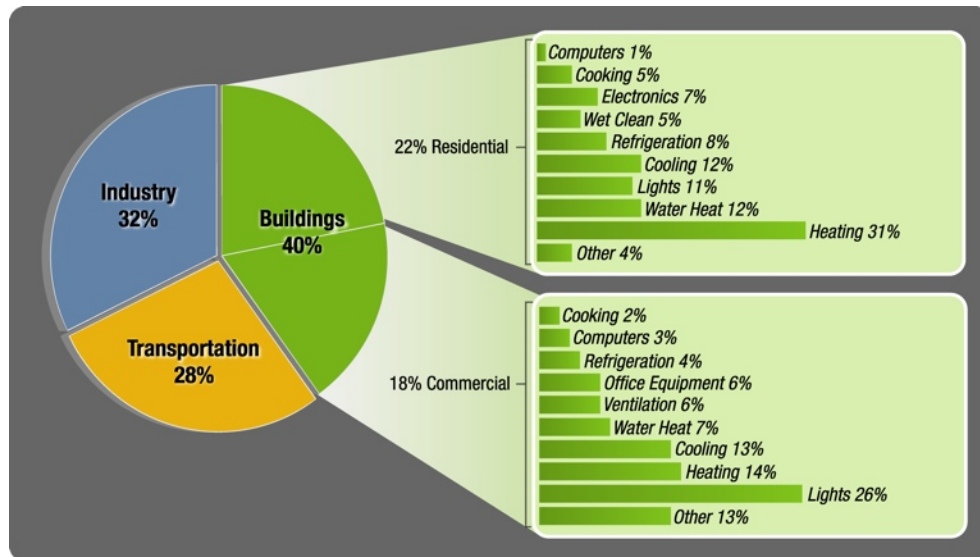
# Overview

- **Introduction**
  - Trends - Problems - Needs
- **Mono-Simulation with Modelica**
  - Modelica Standard Library - LBNL Buildings Library - Applications
- **Co-Simulation with Building Controls Virtual Test Bed**
  - Analysis - Building Controls Virtual Test Bed - Applications
- **R&D Needs**

# Buildings

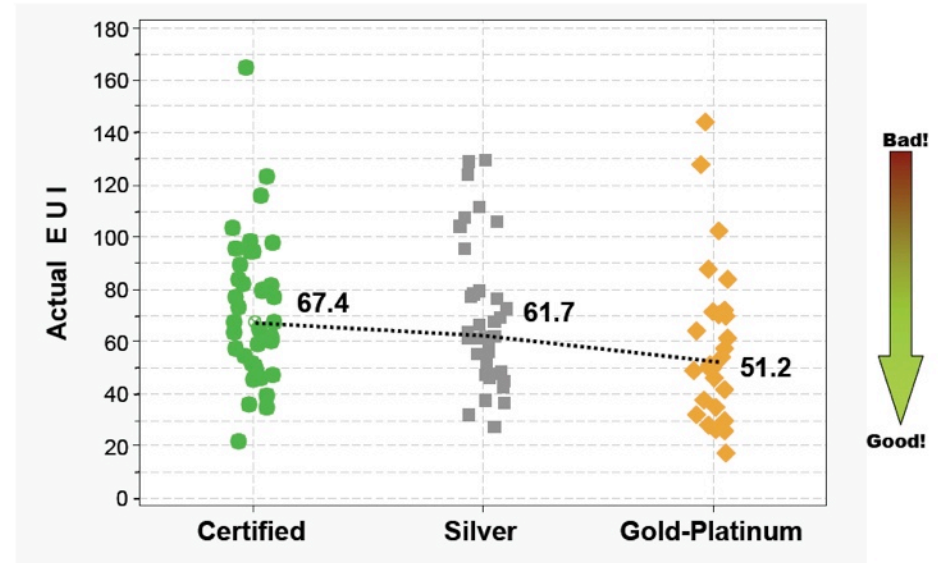
They matter:

US Buildings use **73%** of nation's electricity, **55%** of nation's natural gas.



They don't perform well:

EUI in kBtu/sq.ft.-yr



Note: LEED also includes non-energy aspects.

And....

They are one of the few products

- whose performance doesn't get tested before built.
- whose inefficiencies don't get measured & reported during operation.

They don't get designed as a system.

# Integration to Increase Efficiency

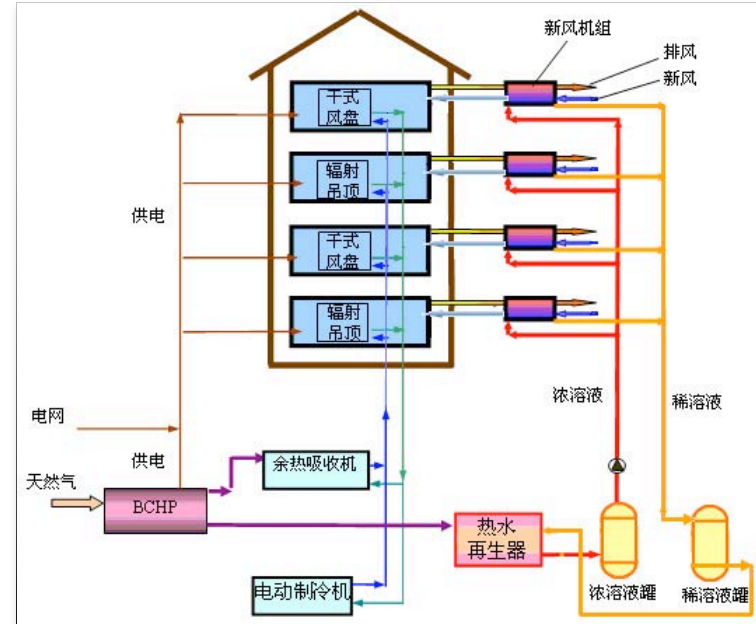
Active facade for natural ventilation



Micro-mirror to redirect sunlight



Decentralized dehumidification with liquid desiccant



Phase change material to increase thermal storage



Cyprus grass to humidify supply air



Web-server at the size of 25 cents



# Trends

Innovation happens at **the interface between disciplines.**

Integrated systems require **system-level analysis.**

**Computational Science and Engineering** reduces cost and time,

- by rapidly analyzing new systems
- by reducing number of full-scale experiments
- by detecting and fixing more mistakes in models and less in real plant

New opportunities through **C<sup>3</sup>:**

**Communication Computation Controls**

# Issues of Building Simulation Programs

- **Monolithic**, lack of modularity
- Large numerical **noise**
  
- **Controls** has wrong semantics
- Typically dynamic building model and **steady-state HVAC**
  
- Many modern building systems cannot be analyzed
- **Adding models** takes months
- **No standard** that allows model exchange
  
- **Limited educational benefits** due to black-box models and outdated technologies
  
- Heavy reliance on expensive and slow **full scale experiments**

# Modeling for Integrated System Design & Operation

## Needs

Freely programmable **modularized** functional objects (thermodynamics, controls, ...)

**Hierarchies** to manage complexity vertically and horizontally

**Code generation** for control hardware

**Different evolutions** within modules

- continuous time (seconds to minute time scale)
- discrete time
- finite state machine

Analysis support through **application programming interfaces (API)**

- **reduced order model extraction**
- **optimization**



# Modeling of Physical Systems

Higher-level of abstraction to

- increase productivity
- facilitate model-reuse
- preserve system topology
- enable analysis
- generate code for target hardware

Procedural modeling  $\approx 1970$

```

program euler
implicit none
double precision, parameter :: tFin = 7200 ! Final time
integer, parameter :: N = 72000 ! Number of steps
integer, parameter :: NCon = 10 ! Communication interval
integer :: iCon

double precision dt ! Time step

double precision, parameter :: T0 = 293.15 ! Initial temp.
double precision :: T1, T2 ! Temperature
double precision :: TBC ! Temp. boundary condition
double precision :: TSur ! Surface temperature
double precision, parameter :: TSet = 293.15 ! Set point temp.
double precision :: derT1, derT2 ! Temperature derivative

double precision :: QSou, QCon1, QCon2 ! Heat Flux

double precision, parameter :: Kp = 100 ! P Gain
double precision, parameter :: h = 5 ! Convective heat transfer coefficient
double precision, parameter :: G = 10 ! Conductivity
double precision, parameter :: C = 10 ! Capacity

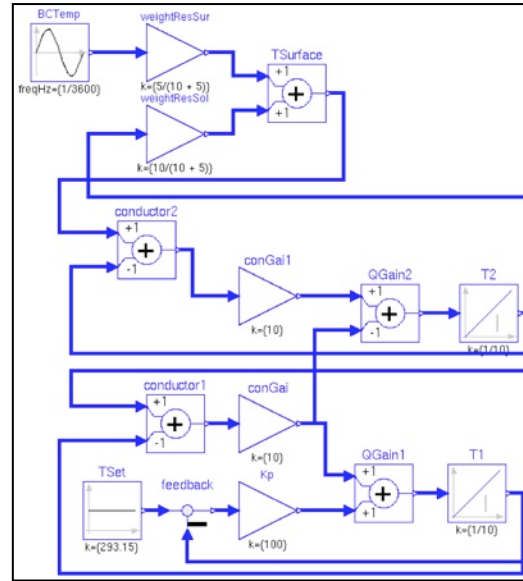
integer :: i ! Loop counter
integer, parameter :: lun = 6 ! logical unit number

double precision, parameter :: amp = 5 ! Amplitude
double precision :: time ! Simulation time

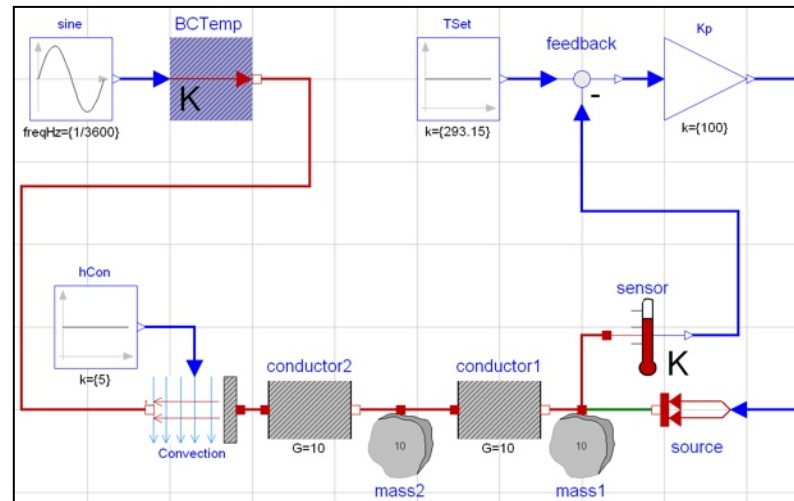
character(len=*) , parameter :: FMT = "(NF14.7)"

! Initialize variables
dt = tFin/N
T1 = T0
T2 = T0
time = 0
iCon = 1
open (lun, FILE='results.txt')
! Perform integration
do i = 1, N, 1
    TBC = T0 + amp * dsin(2*pi*14159*time/3600)
    TSur = T2 + (G / (G+h)) * TBC + (h / (G+h))
    QSou = Kp * (TSet - T1)
    QCon1 = G * (T2 - T1)
    QCon2 = G * (TSur - T2)
    derT1 = 1/C * (QCon1 + QSou)
    derT2 = 1/C * (QCon1 - QCon2)
    if (i.EQ.iCon) then
        write(lun,FMT) time, T1, T2, QSou
        iCon = iCon + NCon
    endif
! Update variables
    T1 = T1 + dt * derT1
    T2 = T2 + dt * derT2
    time = time + dt
end do
write(lun,FMT) time, T1, T2, QSou
close(lun)
write(*,*) 'Program Finished'
end program
    
```

Block diagram modeling  $\approx 1990$



Equation-based, object-oriented modeling  $\approx 2000$



# Separation of Concerns

## Modeling

## Compilation

## Simulation

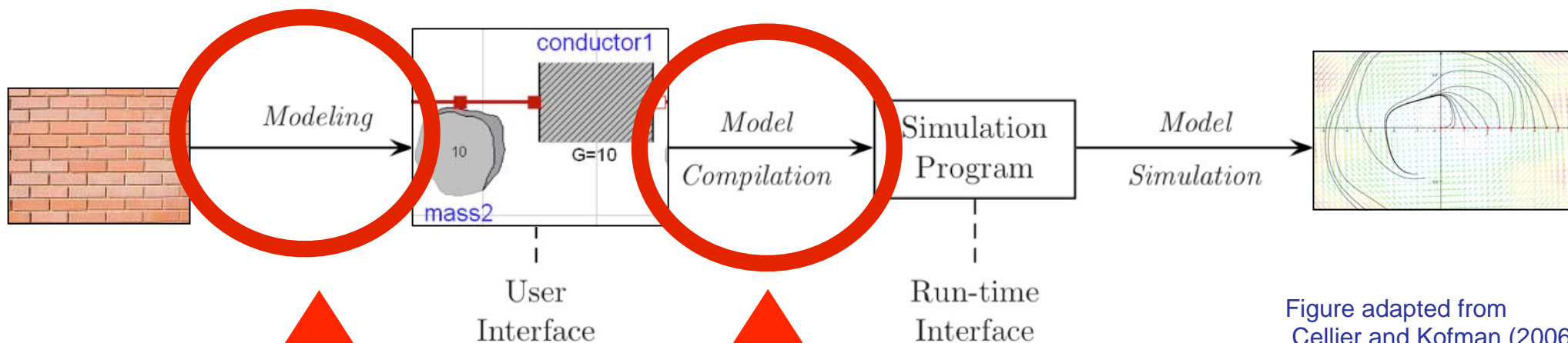


Figure adapted from  
Cellier and Kofman (2006)

### Different coupled domains

- heat transfer
- thermodynamics
- airflow
- controls
- batteries...

### Different states

- continuous time
- discrete time
- finite state machine

### Different code

- simulation
- real-time simulation
- optimization w. analytic gradients

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- R&D Needs

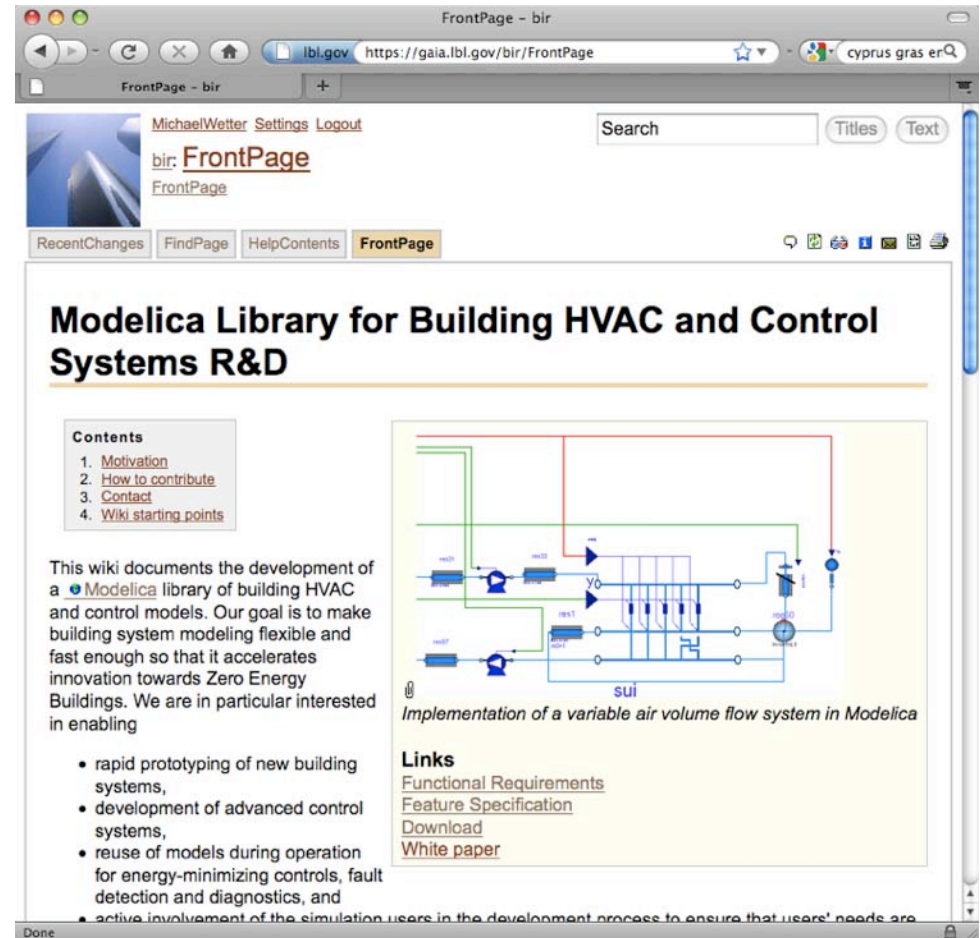
# Modelica Buildings Library

## Enable

- Rapid prototyping of innovative systems
- Controls design
- Model-based operation

Available from

<http://simulationresearch.lbl.gov/modelica>

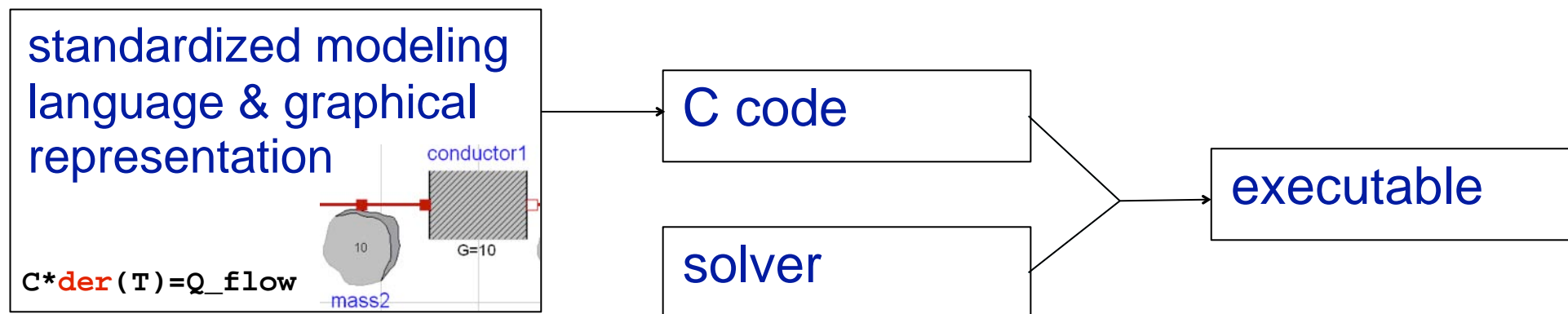


The screenshot shows a web browser window titled "FrontPage - bir" with the URL "https://gaia.lbl.gov/bir/FrontPage". The page content includes a navigation bar with "MichaelWetter Settings Logout", a search box, and a "FrontPage" button. The main heading is "Modelica Library for Building HVAC and Control Systems R&D". Below this is a "Contents" section with links to "Motivation", "How to contribute", "Contact", and "Wiki starting points". The main text describes the development of a Modelica library for building HVAC and control models, aiming for flexible and fast modeling to accelerate innovation towards Zero Energy Buildings. A diagram titled "Implementation of a variable air volume flow system in Modelica" shows a complex HVAC system with various components and connections. Below the diagram is a "Links" section with links to "Functional Requirements", "Feature Specification", "Download", and "White paper".

# What is Modelica

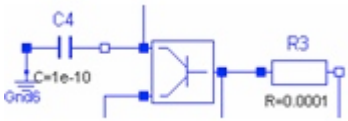


- Object-oriented equation-based language
- Icons with standardized interfaces encapsulate differential, algebraic and discrete equations
- Developed since 1996
- Conventional approach for modeling was inadequate for integrated systems
- Well positioned to become de-facto **open standard** for modeling multi-engineering systems
  - ITEA2: 370 person-years investment over next three years.

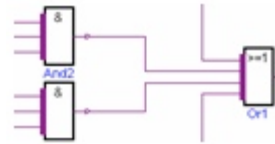


# Modelica Standard Library. 1300 models & functions.

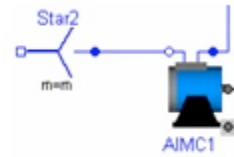
## Analog



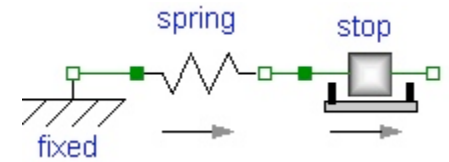
## Digital



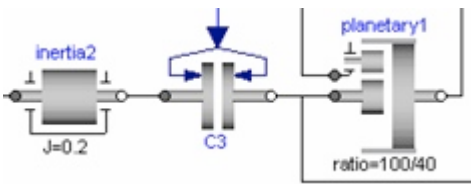
## Machines



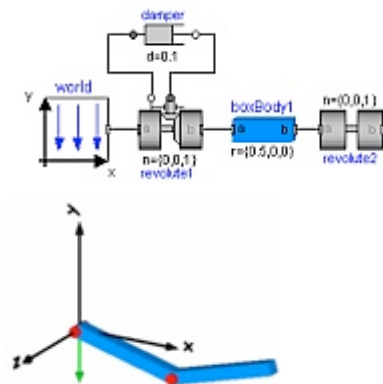
## Translational



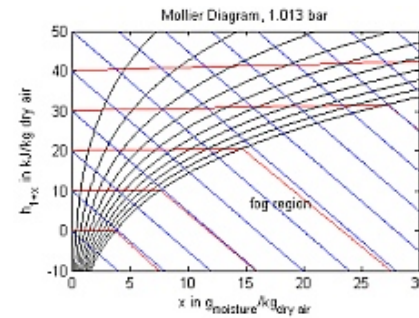
## Rotational



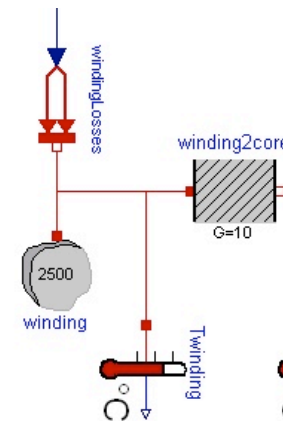
## MultiBody



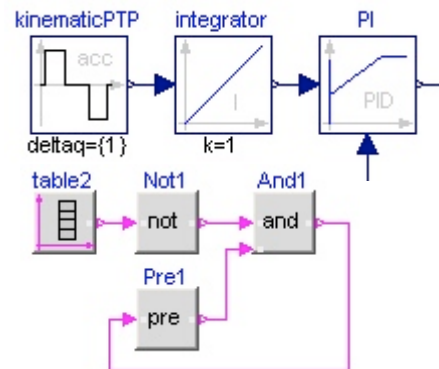
## Media



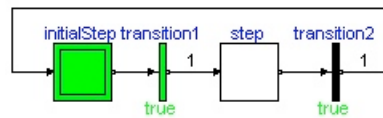
## HeatTransfer



## Blocks



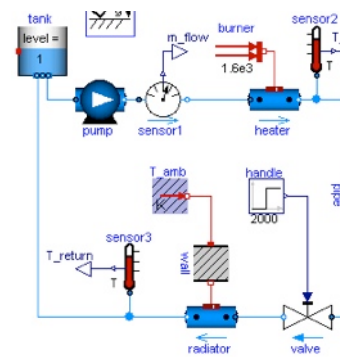
## StateGraph



## Math

$$\|v\|_p = \left( \sum_{i=1}^n |v[i]|^p \right)^{1/p}, \quad 1 \leq p \leq \infty$$

## Fluid

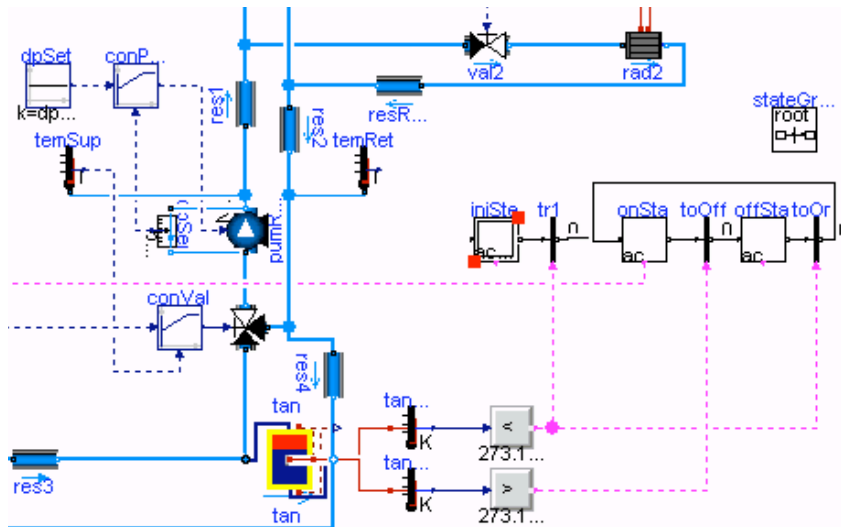


# Modelica Buildings Library

Provides 100+ models and functions for HVAC applications, based on Modelica.Fluids library

**Open-source, free:**

[https://simulationresearch  
.lbl.gov/modelica](https://simulationresearch.lbl.gov/modelica)



- Controls -- Continuous
- Discrete
- SetPoints
- Fluids -- Actuators -- Dampers
- Motors
- Valves
- Boilers
- Chillers
- Delays
- HeatExchangers
- MassExchangers
- Media
- MixingVolumes
- Movers
- Sensors
- Storage
- HeatTransfer
- Utilities -- Diagnostics
- IO
- Math
- Psychrometrics
- Reports

# Applications

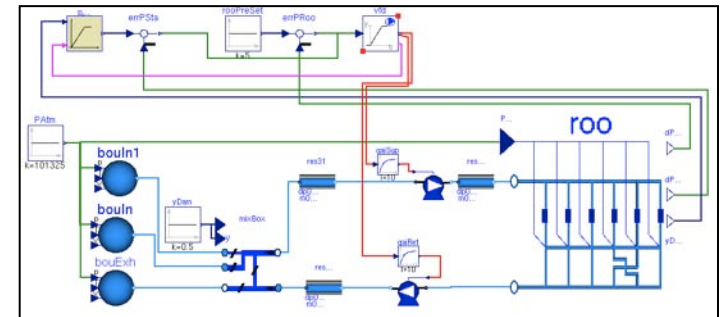
## 1) Hydronic system: Rapid prototyping

Analyzed novel hydronic heating system with radiator pumps and hierarchical system controls.



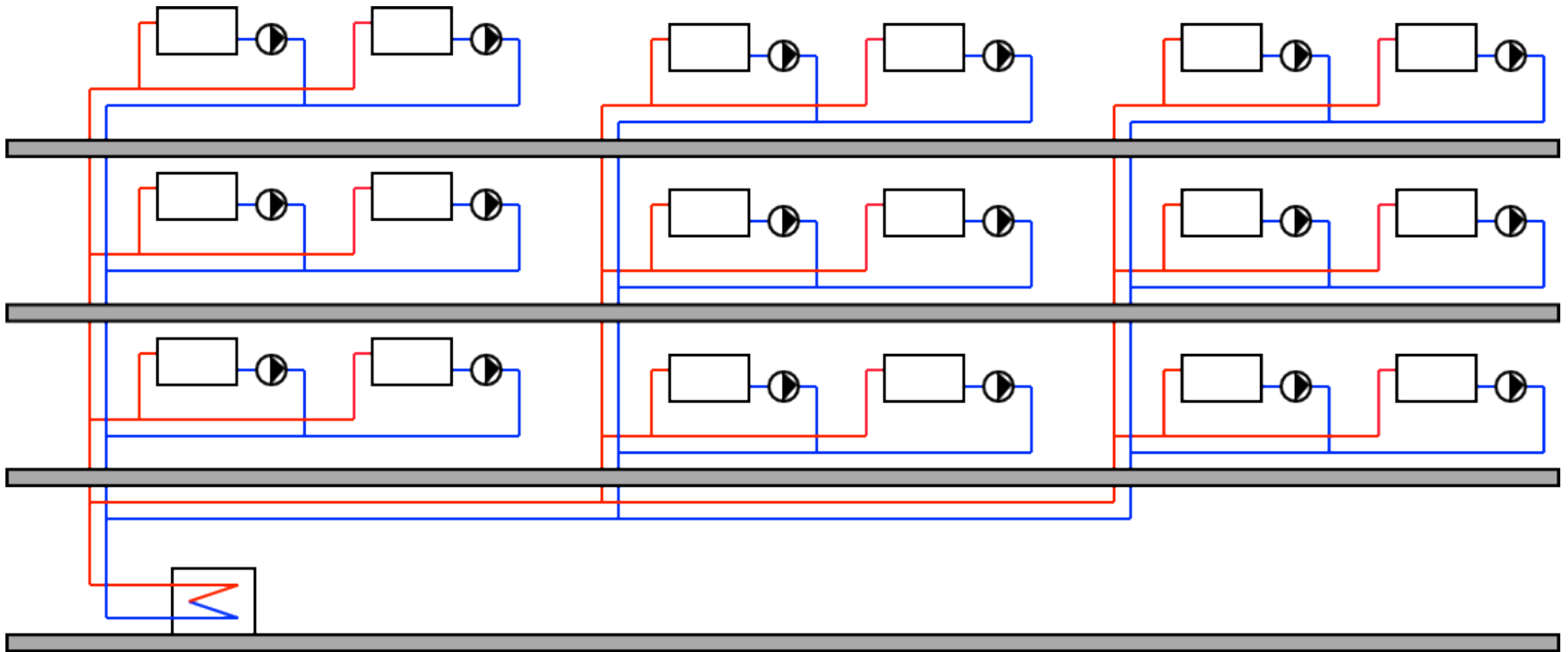
## 2) Air-based system: Supervisory controls

Simulated & auto-tuned “trim and response” sequence for variable air volume flow systems.





# Rapid Prototyping: Wilo GENIAX (Introduction 2009)

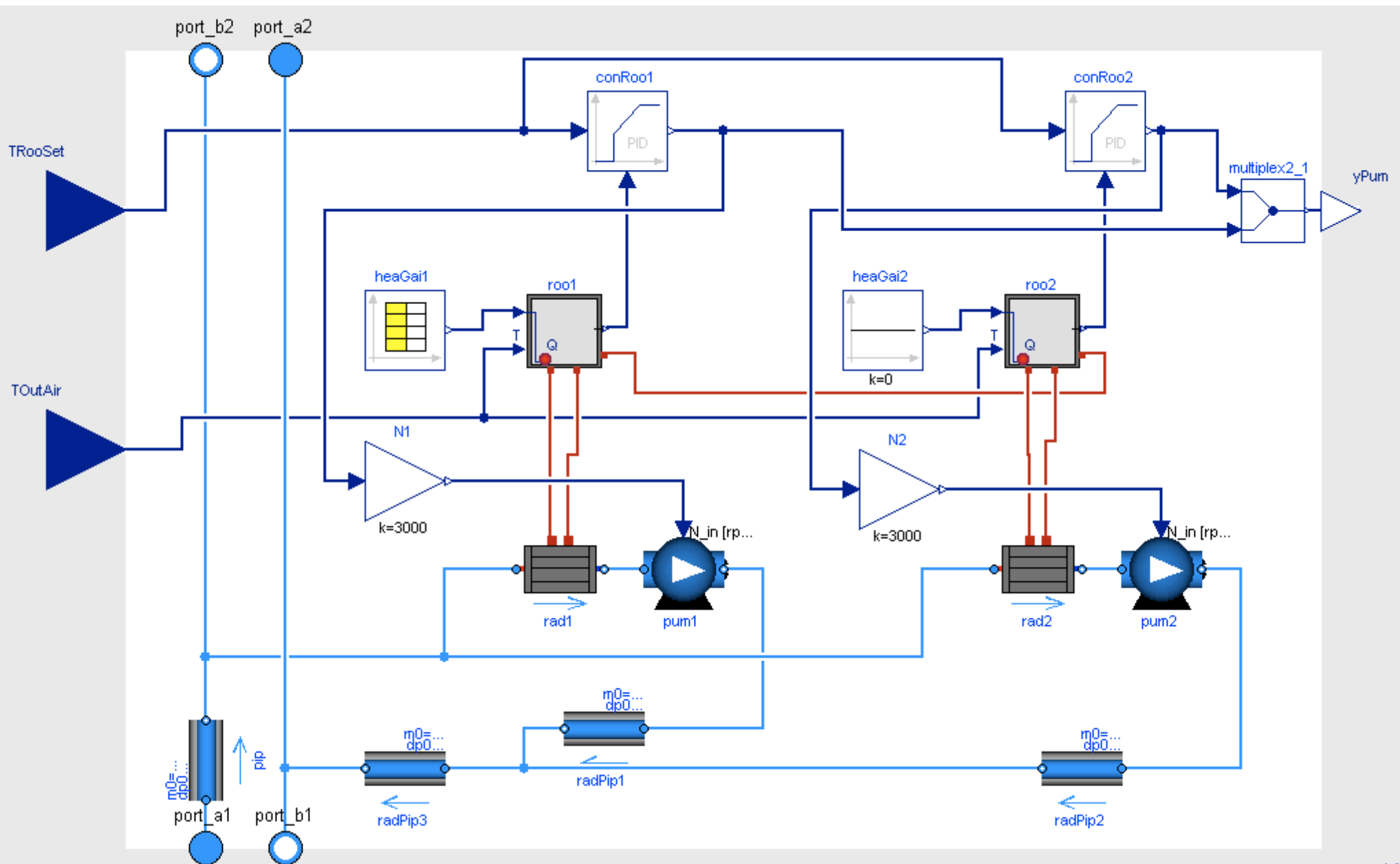


## Goal

Demonstrate rapid prototyping of new building energy and control system that is outside the capabilities of conventional building simulation programs.



# Rapid Prototyping: Wilo GENIAX (Introduction 2009)



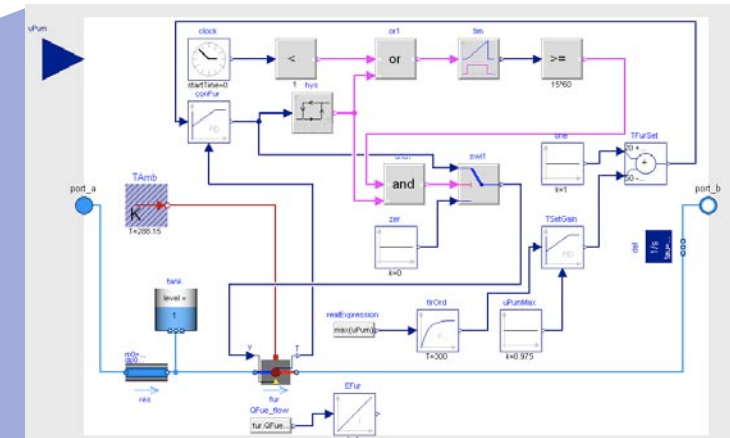
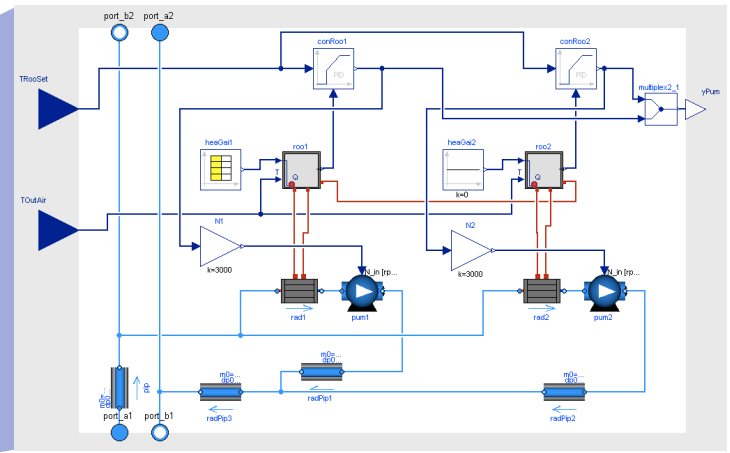
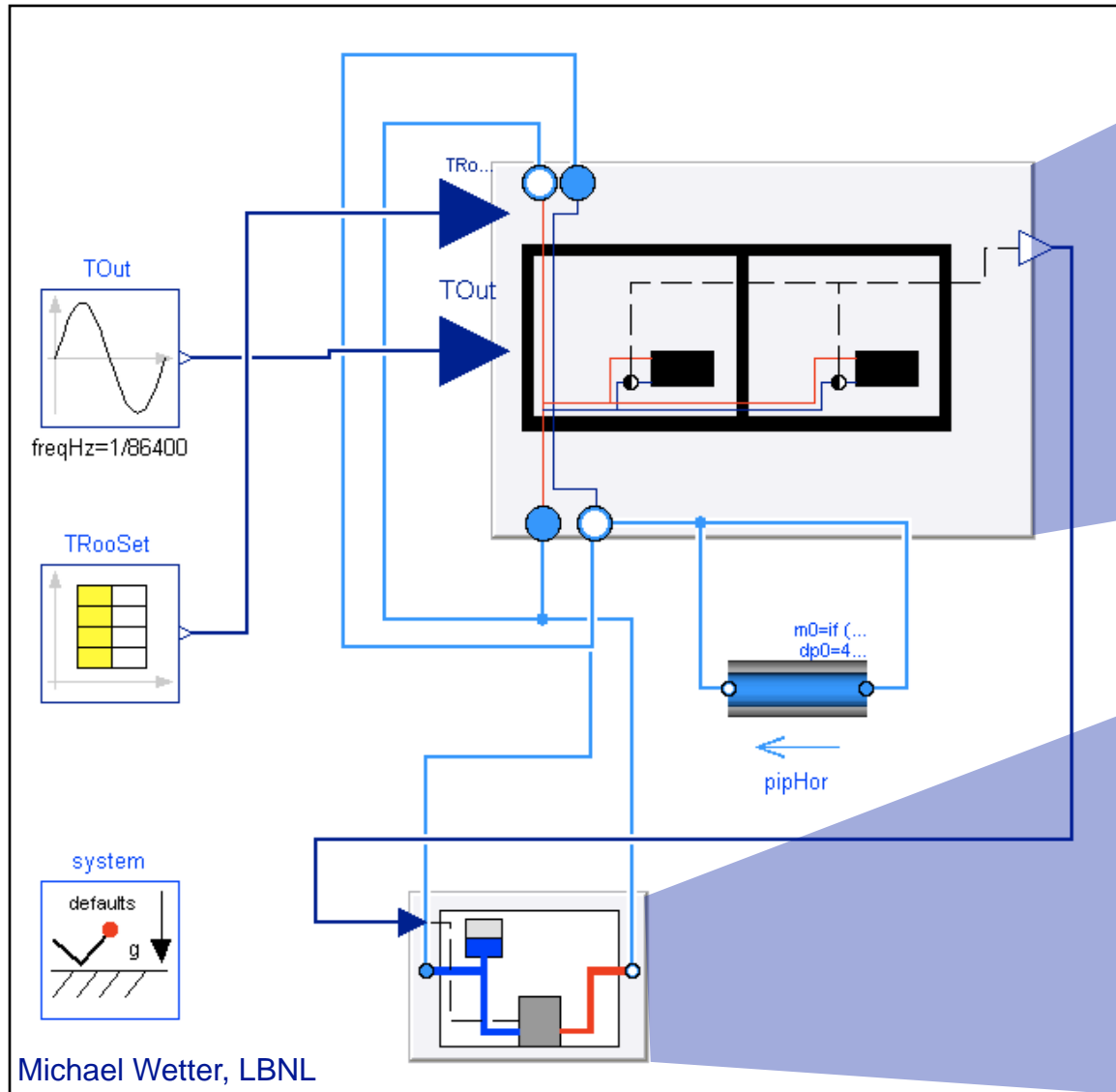
# Rapid Prototyping: Wilo GENIAX (Introduction 2009)

## Original system model

2400 components  
13,200 equations

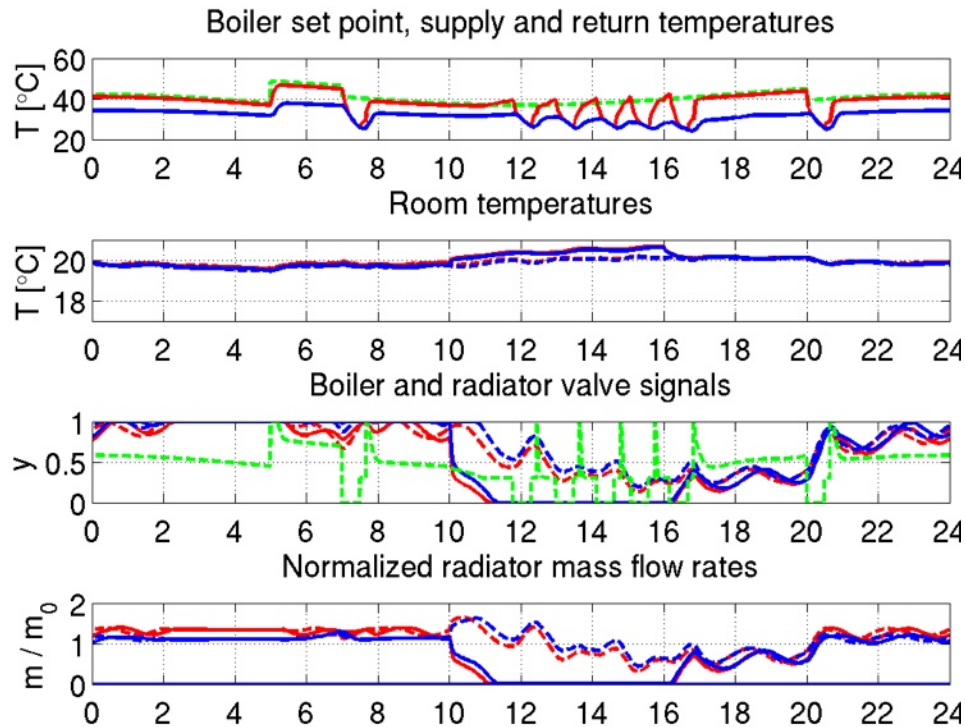
## After symbolic manipulations

300 state variables  
8,700 equations

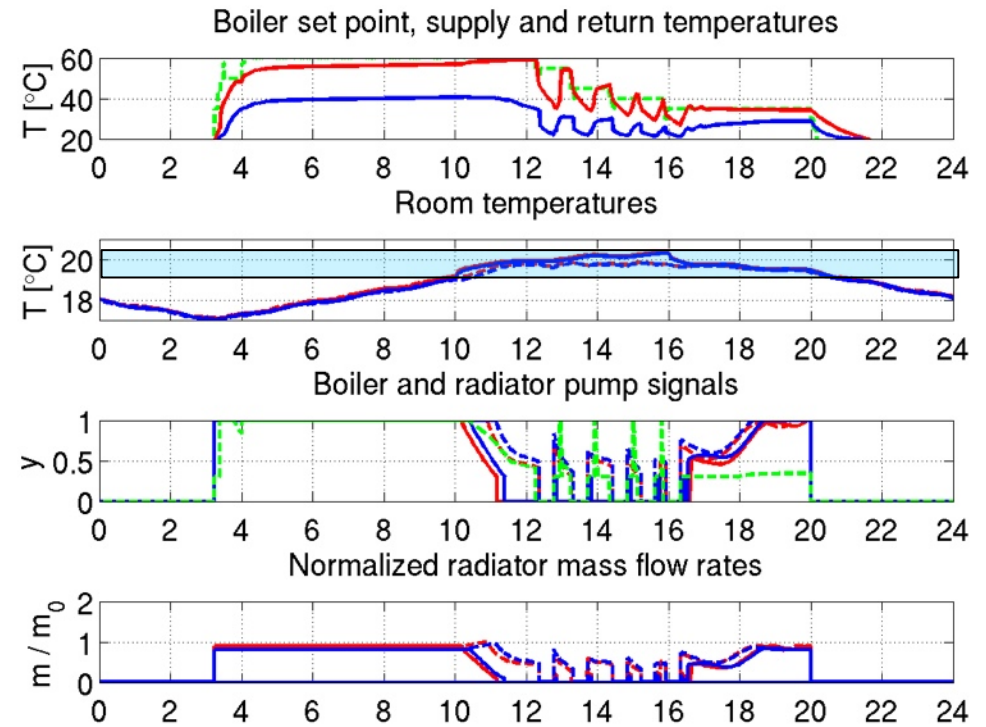


# Rapid Prototyping: Wilo GENIAX (Introduction 2009)

## Thermostatic radiator valves



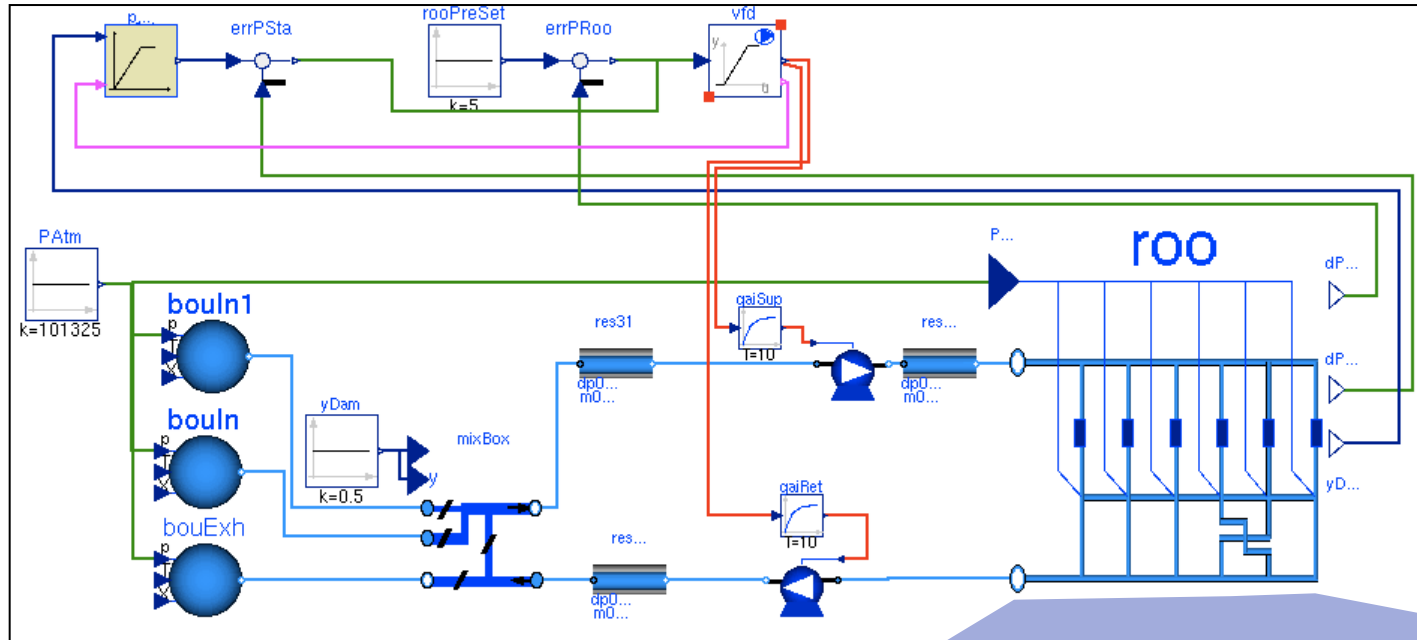
## Radiator pumps



Reproduced trends published by Wilo.

Required one week to develop boiler model, radiator model, simple room model and both system models.

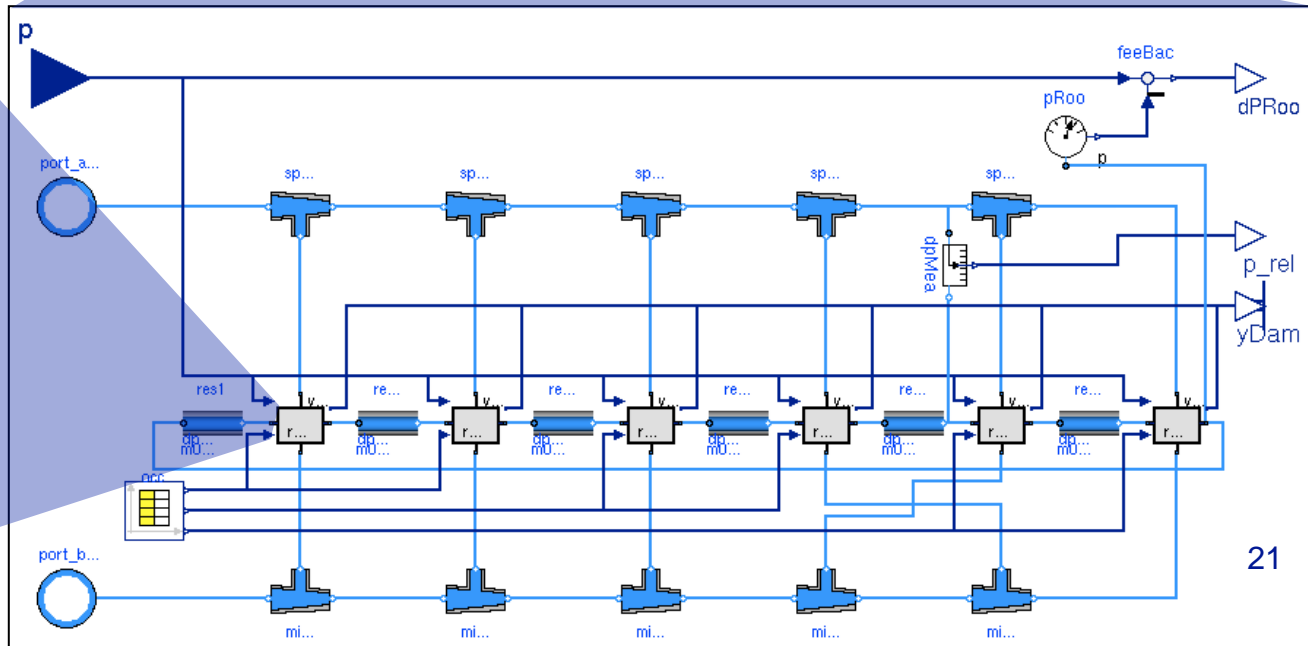
# Applications – VAV System Controls



VAV System  
(ASHRAE 825-RP)

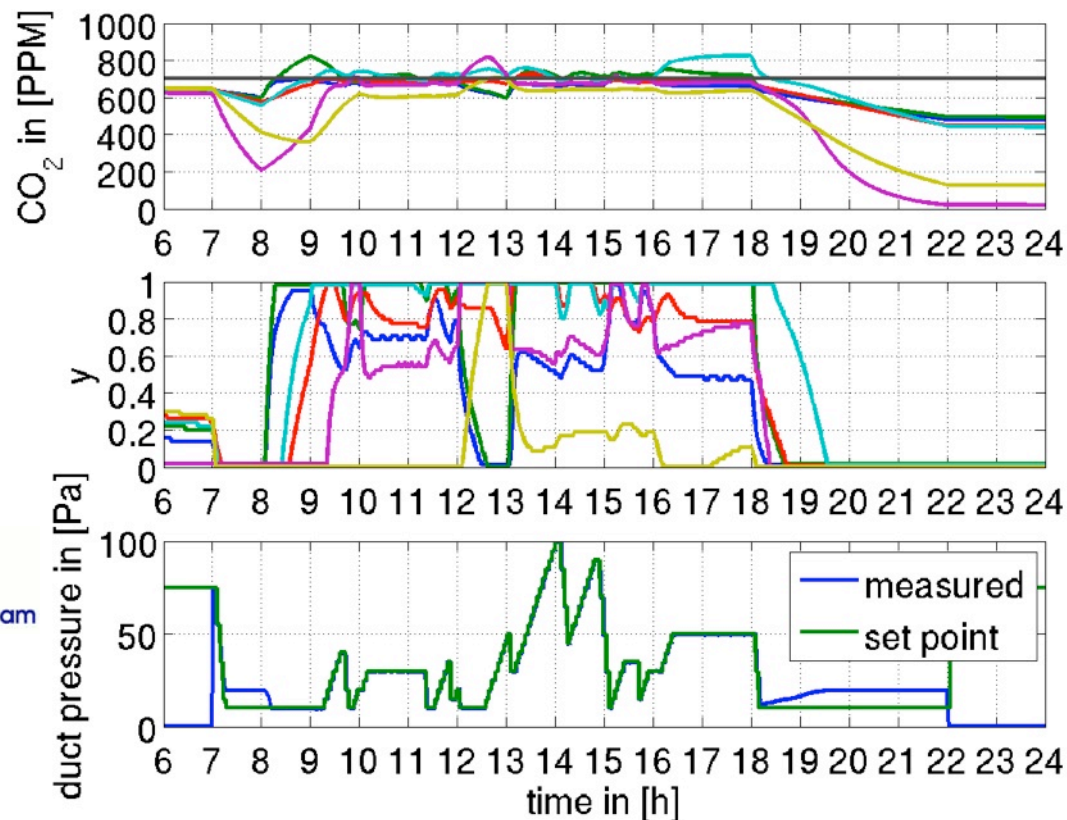
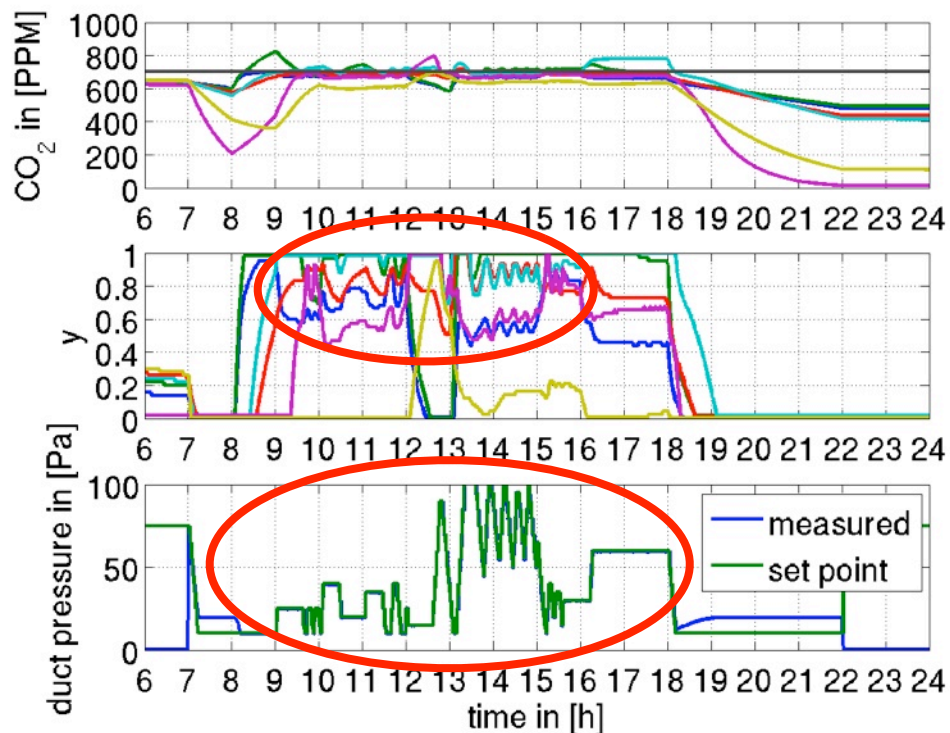
Trim & response control for fan  
static pressure reset  
(Taylor, 2007)

**Original system model**  
730 components  
4,420 equations  
40 state variables



# Applications – VAV System Controls

Stabilized control and reduced energy by solving optimization problem with state constraints



$$\min_{x \in \mathbf{X}} \{f(x) \mid g(x) = 0\},$$

$$f(x) = \frac{1}{E_0} \int_0^T P_f(x, t) dt,$$

$$g(x) = \frac{1}{T} \int_0^T \left( \max\{0, (y_j(x, t)/\hat{x}_s) - 1/(2K_p) - 1 \mid j \in \mathbf{J}(x, t)\} \right)^2 dt$$

**GenOpt**  
Generic Optimization Program



# Overview

- Introduction

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- Mono-Simulation with Modelica

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- **Co-Simulation with Building Controls Virtual Test Bed**

  - Analysis - Building Controls Virtual Test Bed - Applications

- R&D Needs

# Building Controls Virtual Test Bed (BCVTB)

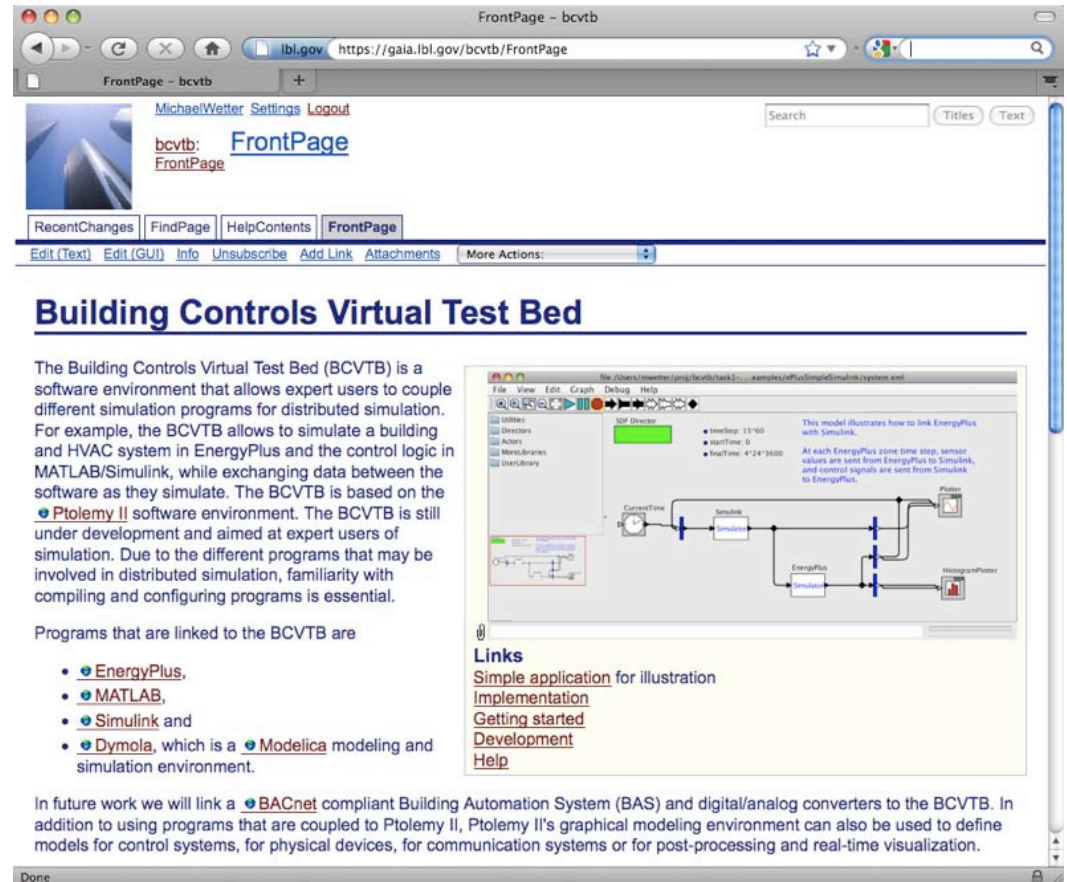
## Enable

- Co-simulation for integrated multi-disciplinary analysis
- Use of domain-specific tools
- Model-based system-level design
- Model-based operation

## Available from

<http://simulationresearch.lbl.gov/bcvtb>

Based on Ptolemy II from UC Berkeley.



The screenshot shows a web browser window displaying the BCVTB website. The website has a navigation menu with links for 'RecentChanges', 'FindPage', 'HelpContents', and 'FrontPage'. Below the menu, there is a search bar and a 'More Actions' dropdown. The main content area is titled 'Building Controls Virtual Test Bed' and contains a detailed description of the BCVTB software environment. It explains that BCVTB is a software environment for distributed simulation, coupling different simulation programs like EnergyPlus and MATLAB/Simulink. The text mentions that BCVTB is based on the Ptolemy II software environment and is still under development. A list of programs linked to BCVTB is provided, including EnergyPlus, MATLAB, Simulink, and Dymola. A 'Links' section offers further resources like 'Simple application for illustration', 'Implementation', 'Getting started', 'Development', and 'Help'. At the bottom, it mentions future work involving BACnet compliant BAS and digital/analog converters. To the right of the text is a screenshot of a simulation interface showing a block diagram with components like 'CurrentTime', 'Simulink', 'EnergyPlus', and 'HistogramPower'. The interface includes a 'UI Director' window with simulation parameters like 'TimeStep: 15:00', 'StartTime: 0', and 'EndTime: 4:24:3600'. A text box explains that the model illustrates how to link EnergyPlus with Simulink, and that sensor values are sent from EnergyPlus to Simulink, while control signals are sent from Simulink to EnergyPlus.

FrontPage - bcvtb  
https://gaia.lbl.gov/bcvtb/FrontPage

MichaelWetter Settings Logout

bcvtb: FrontPage

RecentChanges FindPage HelpContents FrontPage

Edit (Text) Edit (GUI) Info Unsubscribe Add Link Attachments More Actions:

## Building Controls Virtual Test Bed

The Building Controls Virtual Test Bed (BCVTB) is a software environment that allows expert users to couple different simulation programs for distributed simulation. For example, the BCVTB allows to simulate a building and HVAC system in EnergyPlus and the control logic in MATLAB/Simulink, while exchanging data between the software as they simulate. The BCVTB is based on the Ptolemy II software environment. The BCVTB is still under development and aimed at expert users of simulation. Due to the different programs that may be involved in distributed simulation, familiarity with compiling and configuring programs is essential.

Programs that are linked to the BCVTB are

- EnergyPlus,
- MATLAB,
- Simulink and
- Dymola, which is a Modelica modeling and simulation environment.

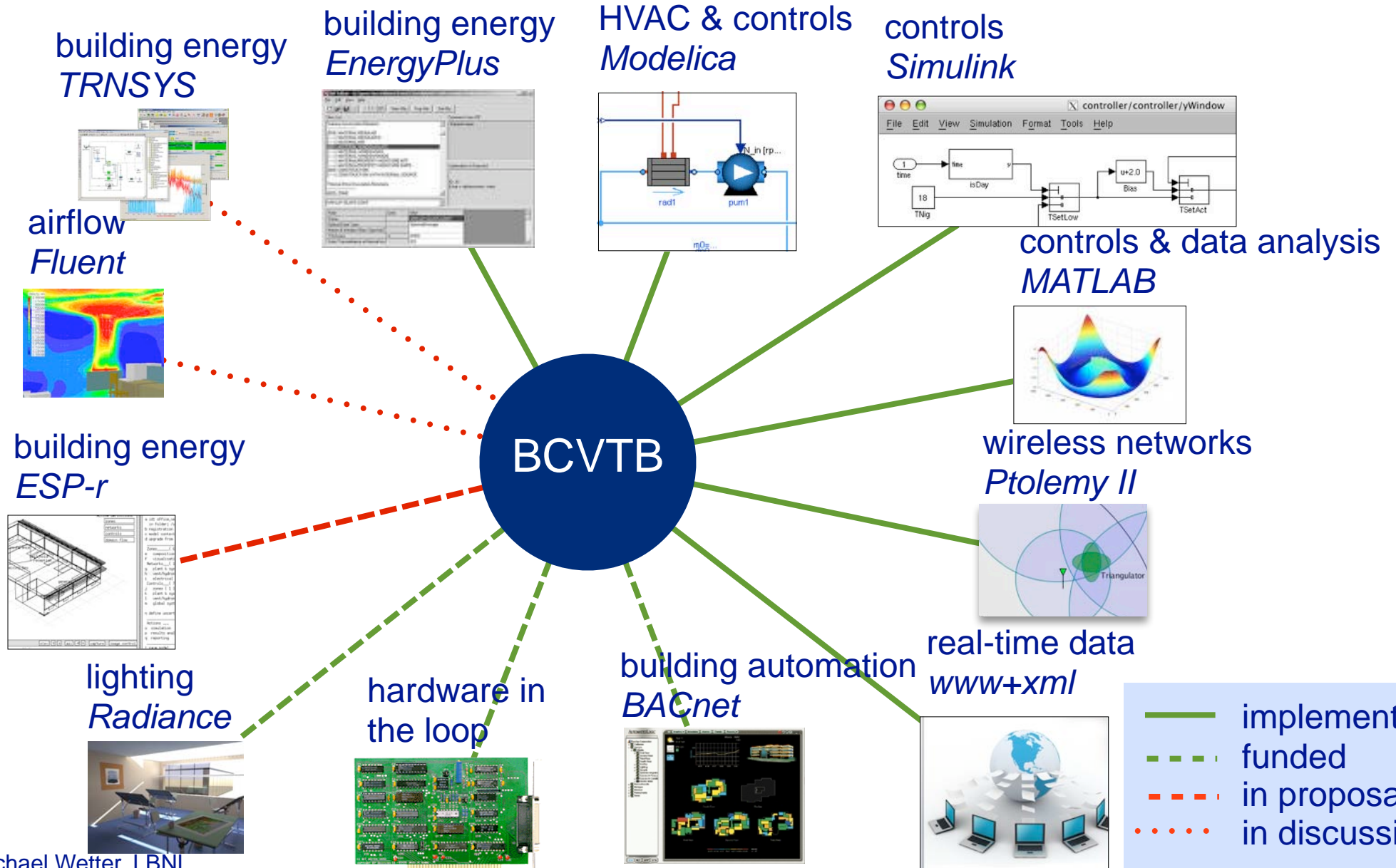
**Links**  
[Simple application](#) for illustration  
[Implementation](#)  
[Getting started](#)  
[Development](#)  
[Help](#)

In future work we will link a BACnet compliant Building Automation System (BAS) and digital/analog converters to the BCVTB. In addition to using programs that are coupled to Ptolemy II, Ptolemy II's graphical modeling environment can also be used to define models for control systems, for physical devices, for communication systems or for post-processing and real-time visualization.

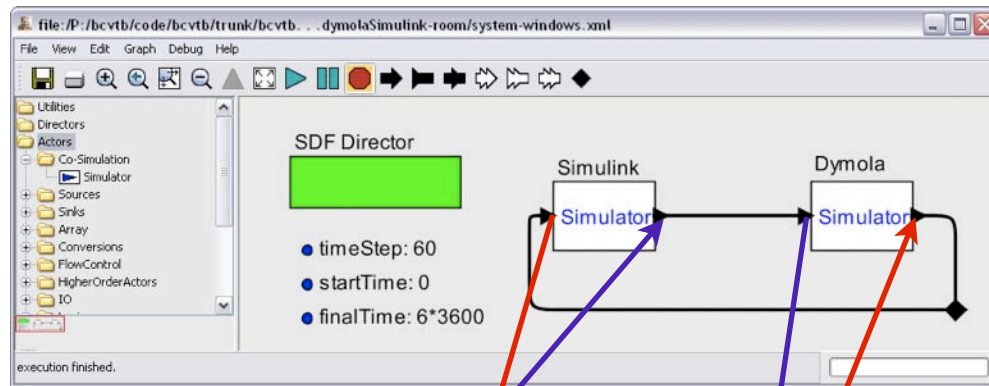


# Building Controls Virtual Test Bed

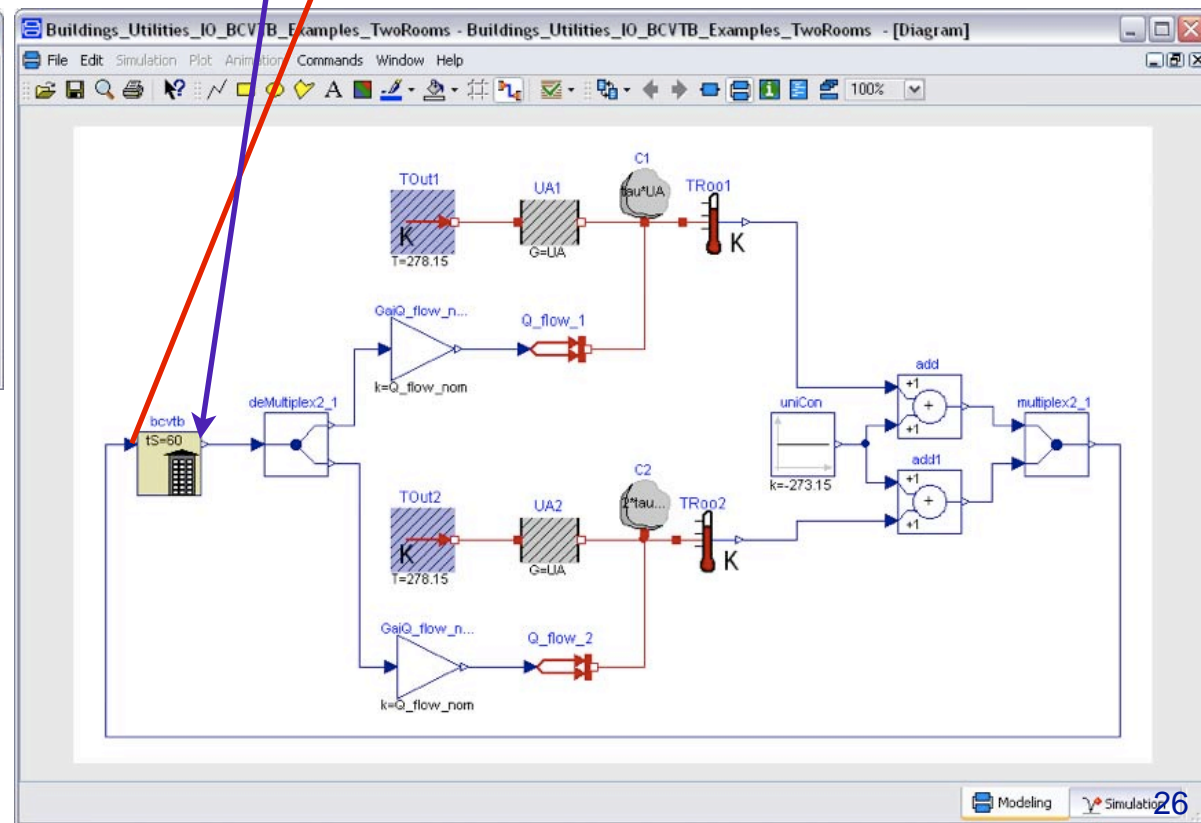
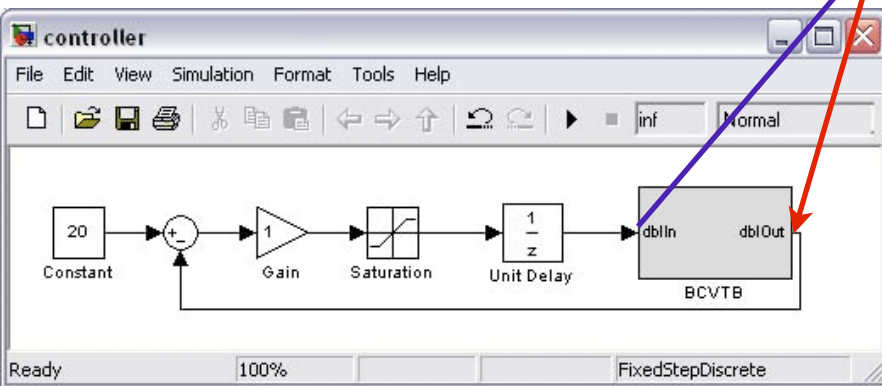
Open-source middle-ware based on UC Berkeley's Ptolemy II program.  
Synchronizes and exchanges data as (simulation-)time progresses.



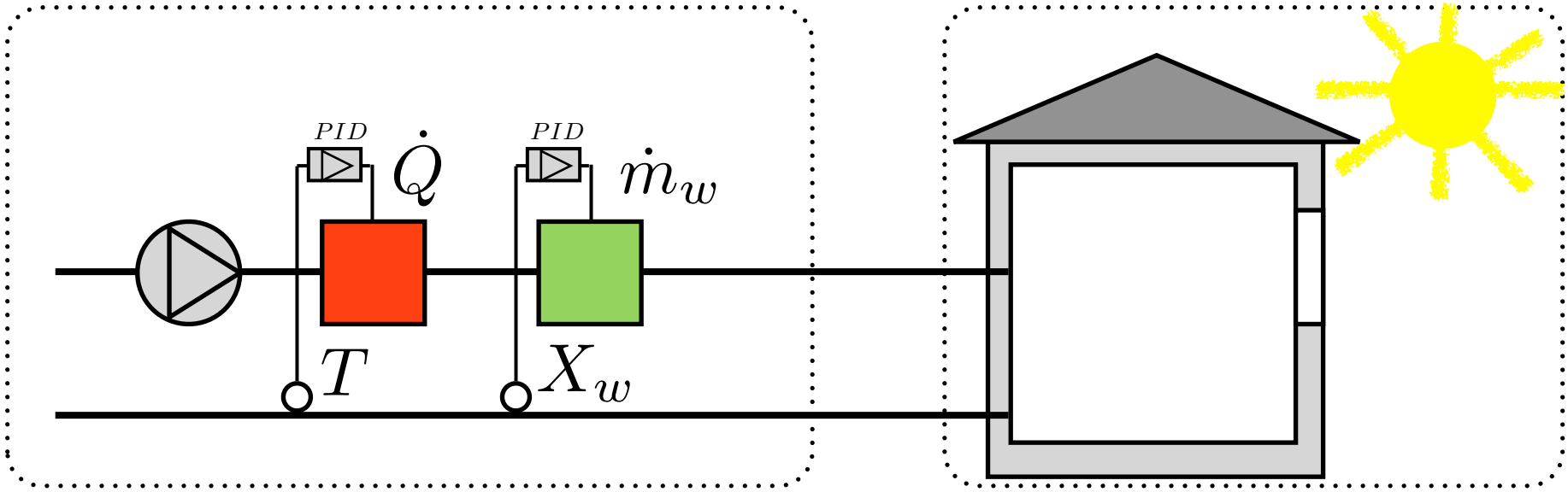
# Simple Example: Room Heater



$y(k+1)$   $T(k)$   $y(k)$   $T(k+1)$



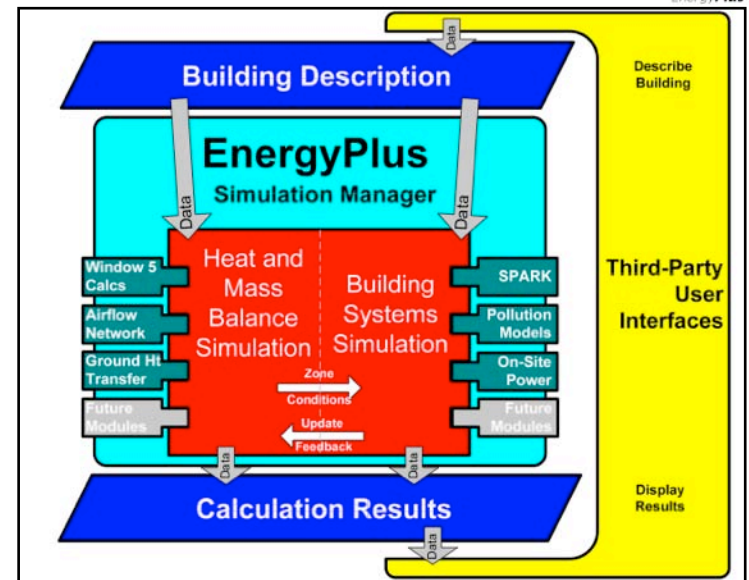
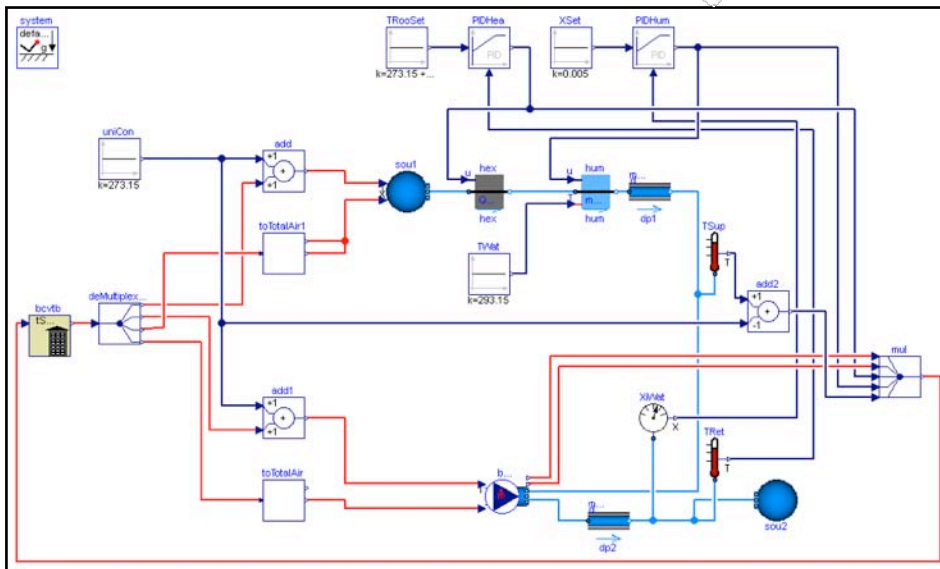
# Ex: HVAC in Modelica, Building in EnergyPlus



Rapid virtual prototyping.  
Path towards embedded computing.



Whole building energy analysis.  
Reuse of 500,000 lines of code.



# Ex: HVAC in Modelica, Building in EnergyPlus

QuickTime Player File Edit View Share Window Help Stop Recording Oct 6 11:35 (Charged) Michael Wetter

Win XP 16GB

file:/C:/Documents%20and%20Settings/m...aEPlus31-singleZone/system-windows.xml

File View Edit Graph Debug Help

Utilities  
Directors  
Actors  
UserLibrary

SDF Director

- timeStep: 1\*60
- startTime: 0
- finalTime: 2\*24\*3600

This model illustrates the implementation of an EnergyPlus and a Modelica model that communicate with Ptolemy II through BSD sockets.

Temperatures

Absolute humidities

HistogramPlotter

Control signals

EnergyPlus Simulator

Dymola Simulator

The Dymola output vector is [QSensible, QLatent, yHeating, yCooling, TSupply]. The first two elements are sent to EnergyPlus, and the 3rd to 5th element are sent to plotters only.

Output simulation time and wall clock time.  
This is for illustration purposes only and not needed by the above model.

CurrentTime

Expression input/86400

SimulationTime

WallClockTime

RunTime

Author: Michael Wetter

```
Completed Initializ
Calculate Outside Su
Calculate Inside Sur
Calculate Air Heat B
Initializing HUAC
Reporting Surfaces
Initializing New Env
Warming up <1>
Instantiating Build
BCUTB initializes.
Number of outputs =
Getting XML values
unknown protocol: p
unknown protocol: p
Number of actuators
unknown protocol: p
Calculating Detailed
BCUTB configures inp
Warming up <2>
Warming up <3>
Warming up <4>
Warming up <5>
Warming up <6>
Warming up <7>
Warming up <8>
Warming up <9>
Warming up <10>
Starting Simulation
BCUTB starts first d
Checking for Dymola
Getting file extensio
Checking if dymosim.e
Copying files needed
1 file(s) cop
P:\bcvth\code\bcvth\t
P:\bcvth\code\bcvth\t
P:\bcvth\code\bcvth\t
3 file(s) cop
Starting Dymola.exe
607750 ms. Memory: 212
EnergyPlus Run Time=
EnergyPlus Completed
ReadVarsESO program
ReadVars Run Time=00
ReadVarsESO program
ReadVarsESO program
Requested ESO file=e
does not exist. Rea
ReadVarsESO program
Started HUAC Diagra
Complete
Removing extra files
==== RunEPlus.bat si
ModelDirectory: purgi
onfigs/bcvth/configur
C:\Documents and Sett
windows.xml
```

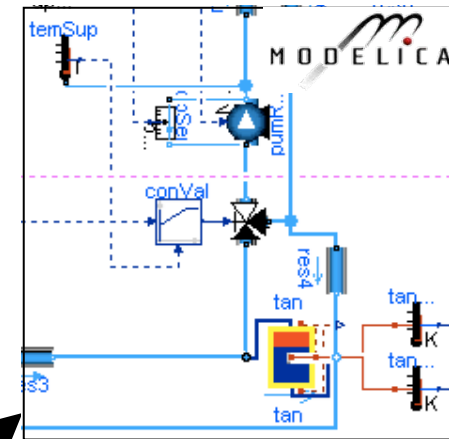
# Reusable modules for model-based operation

Use models in real-time for optimal control, fault detection and diagnostics.

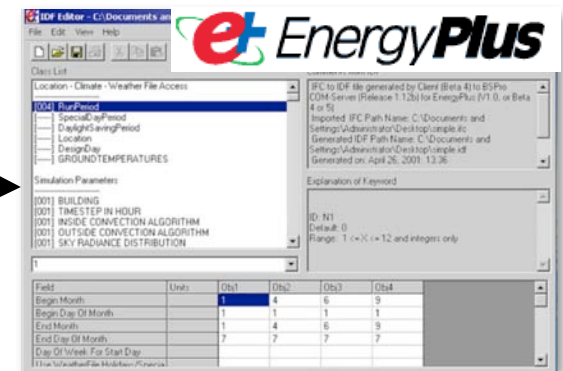
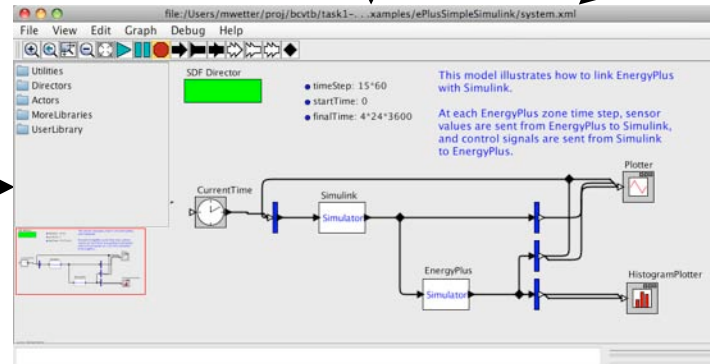
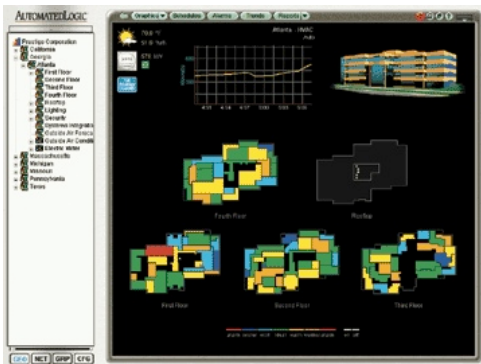
- Tool selection depends on
- required model resolution
  - emulation of controls
  - dynamics of equipment
  - analysis capabilities
  - smoothness
  - state initialization

Hybrid systems, emulate actual feedback control

www/xml



Discrete time, idealized controls



# Overview

- Introduction

  - Trends - Problems - Needs

- Mono-Simulation with Modelica

  - Modelica Standard Library - LBNL Buildings Library - Applications

- Co-Simulation with Building Controls Virtual Test Bed

  - Analysis - Building Controls Virtual Test Bed - Applications

- **R&D Needs**

# R&D Needs

