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

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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

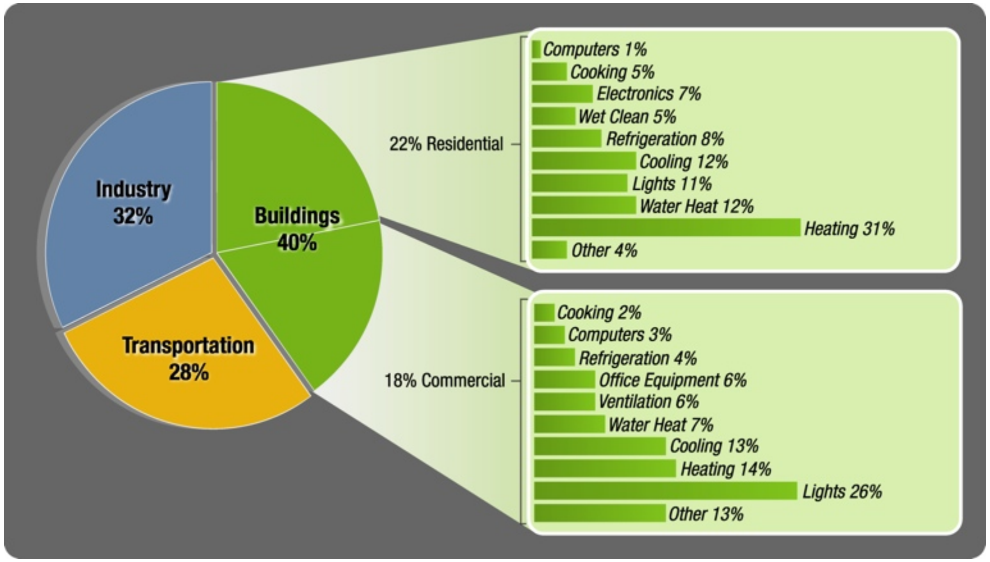
Overview

- 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

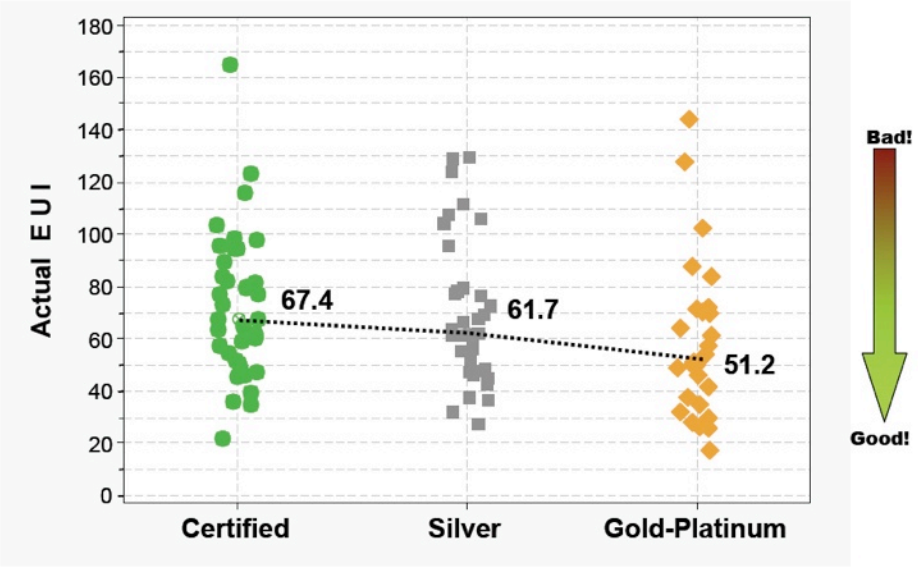
They matter:

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.

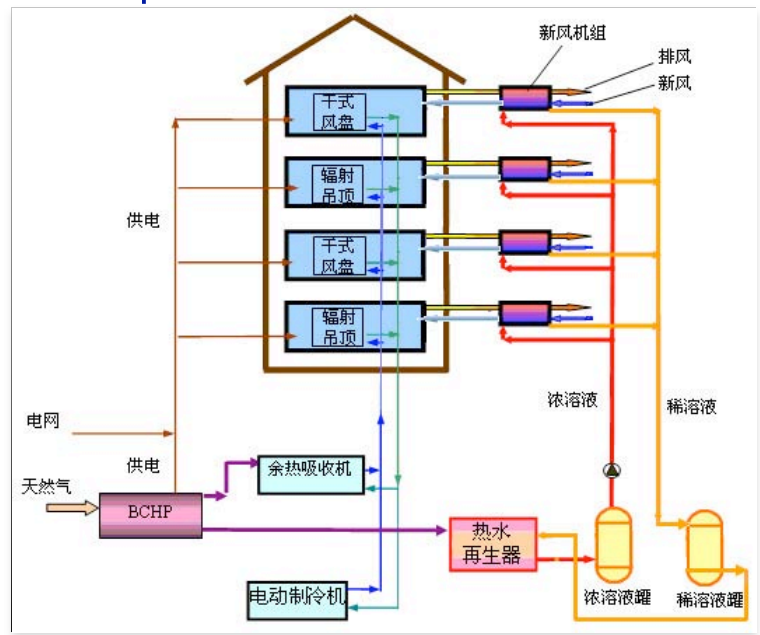
They don't get designed as a system.

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^3:

Communication **C**omputation **C**ontrols

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

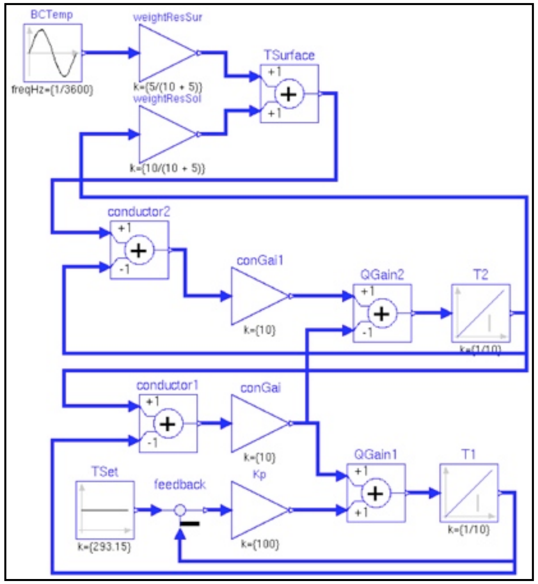
Analysis support through application programming interfaces (API)

- 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

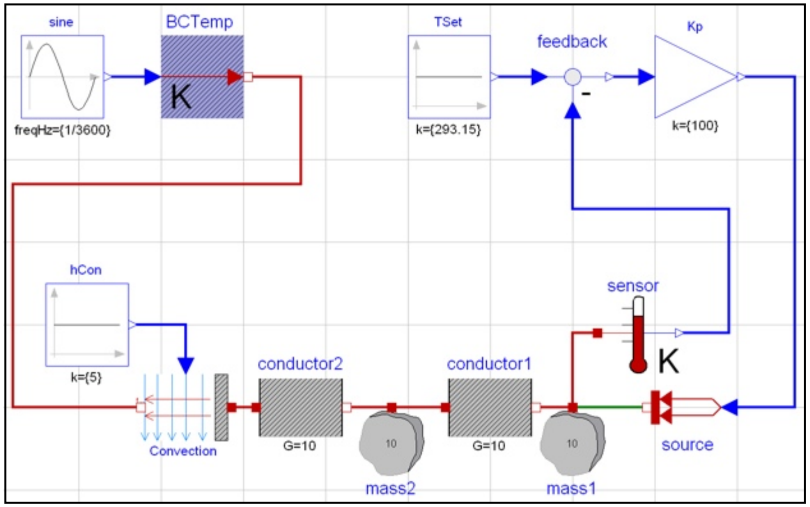
Block diagram modeling ≈ 1990



Procedural modeling ≈ 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                              ! Communication counter

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 = "(4F14.7)"

! 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*3.14159*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
```

Equation-based, object-oriented modeling ≈ 2000



Separation of Concerns

Modeling Compilation Simulation

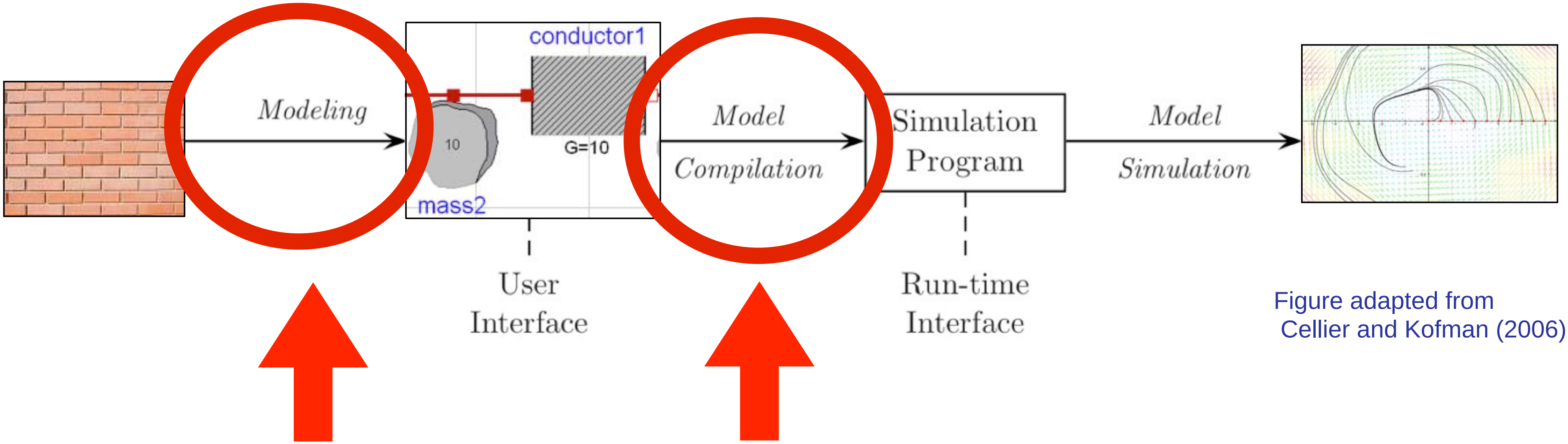


Figure adapted from
Cellier and Kofman (2006)

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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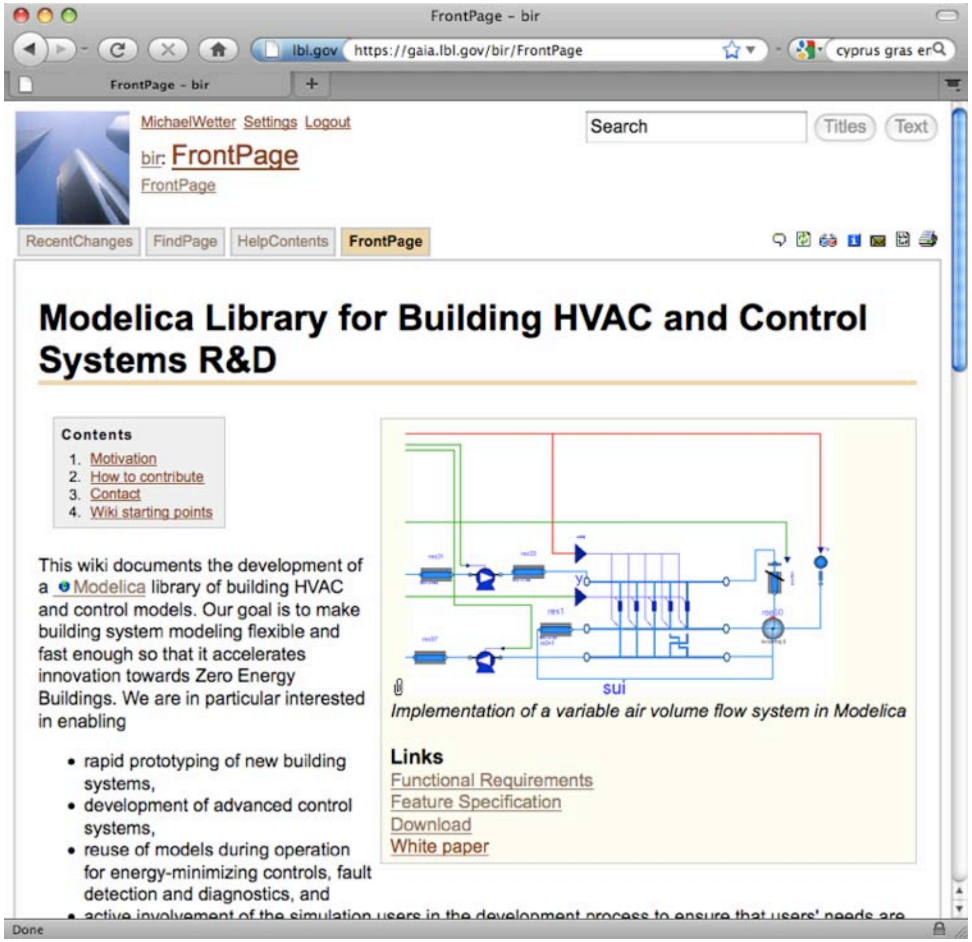
Modelica Buildings Library

Enable

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

Available from

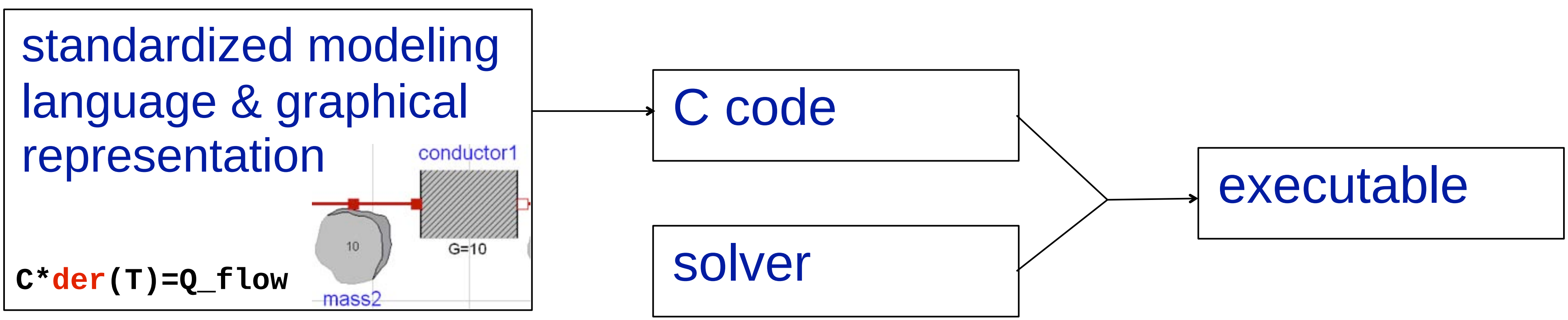
http://simulationresearch.lbl.gov/modelica



What is Modelica

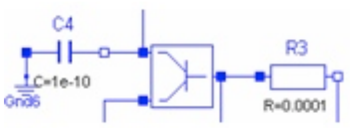
- Object-oriented equation-based language
- Icons with standardized interfaces encapsulate differential, algebraic and discrete equations

- 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.

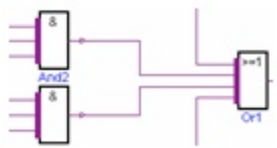


Modelica Standard Library. 1300 models & functions.

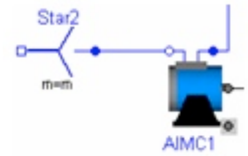
Analog



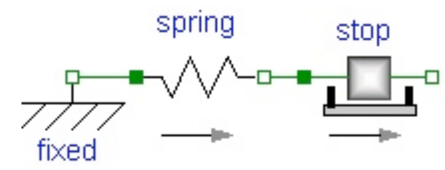
Digital



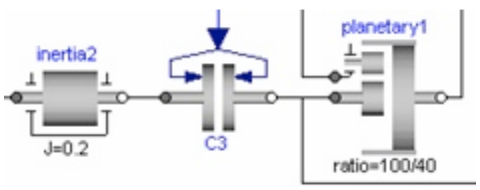
Machines



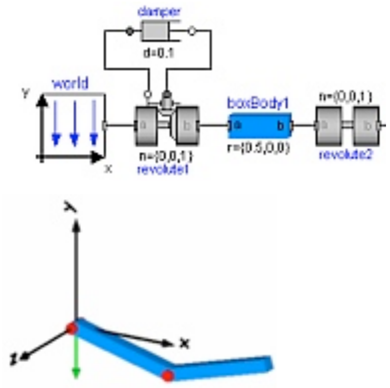
Translational



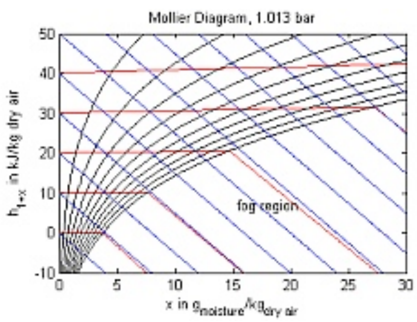
Rotational



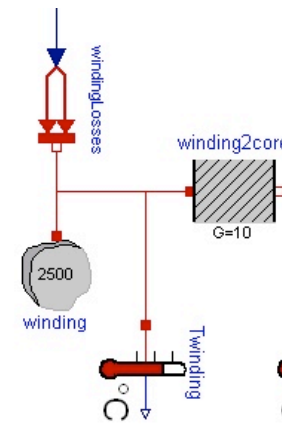
MultiBody



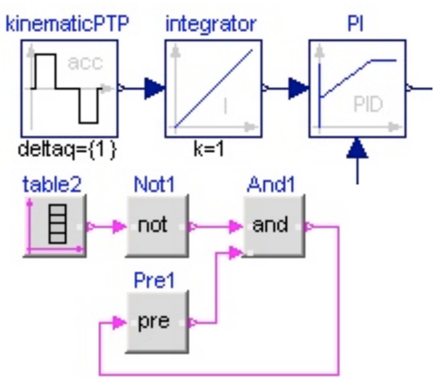
Media



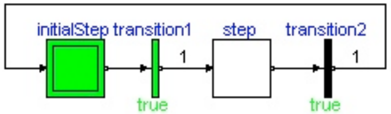
HeatTransfer



Blocks



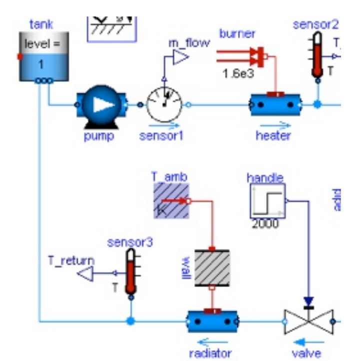
StateGraph



Math

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

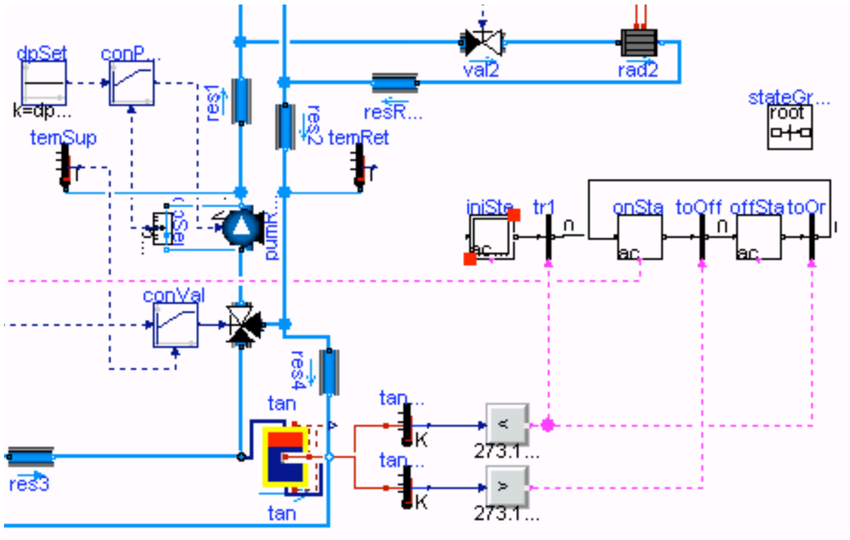
Fluid



Modelica Buildings Library

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

Open-source, free:
https://simulationresearch.lbl.gov/modelica




```
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
```

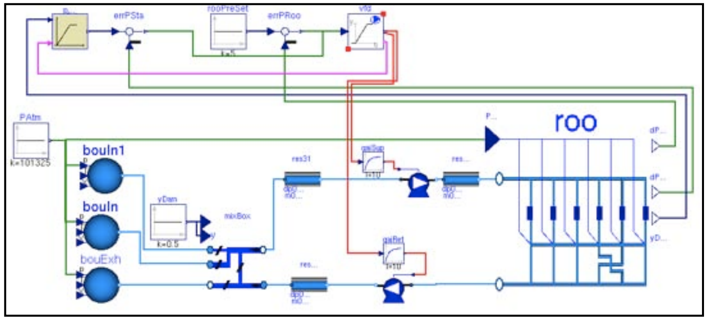
Applications

1) Hydronic system: Rapid prototyping

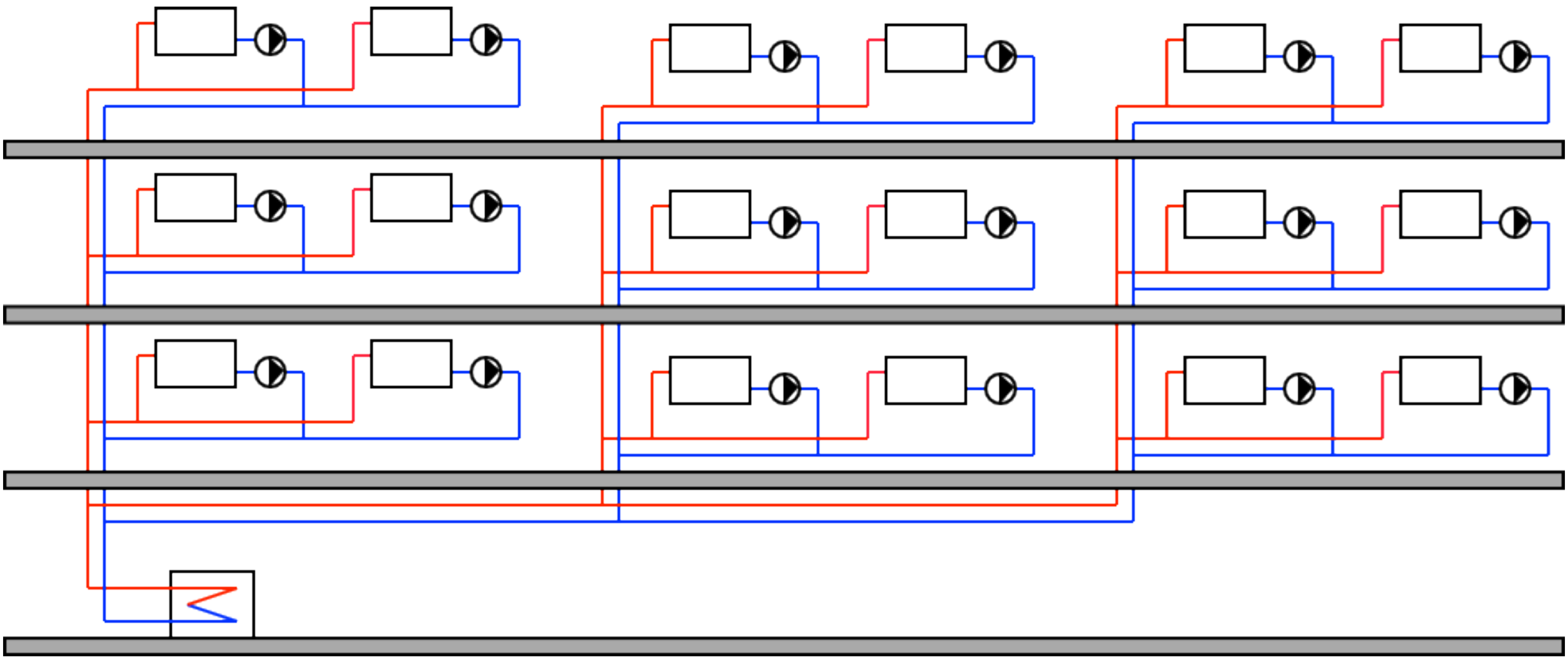
Analyzed novel hydronic heating system with radiator pumps and hierarchical system controls.

2) Air-based system: Supervisory controls

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

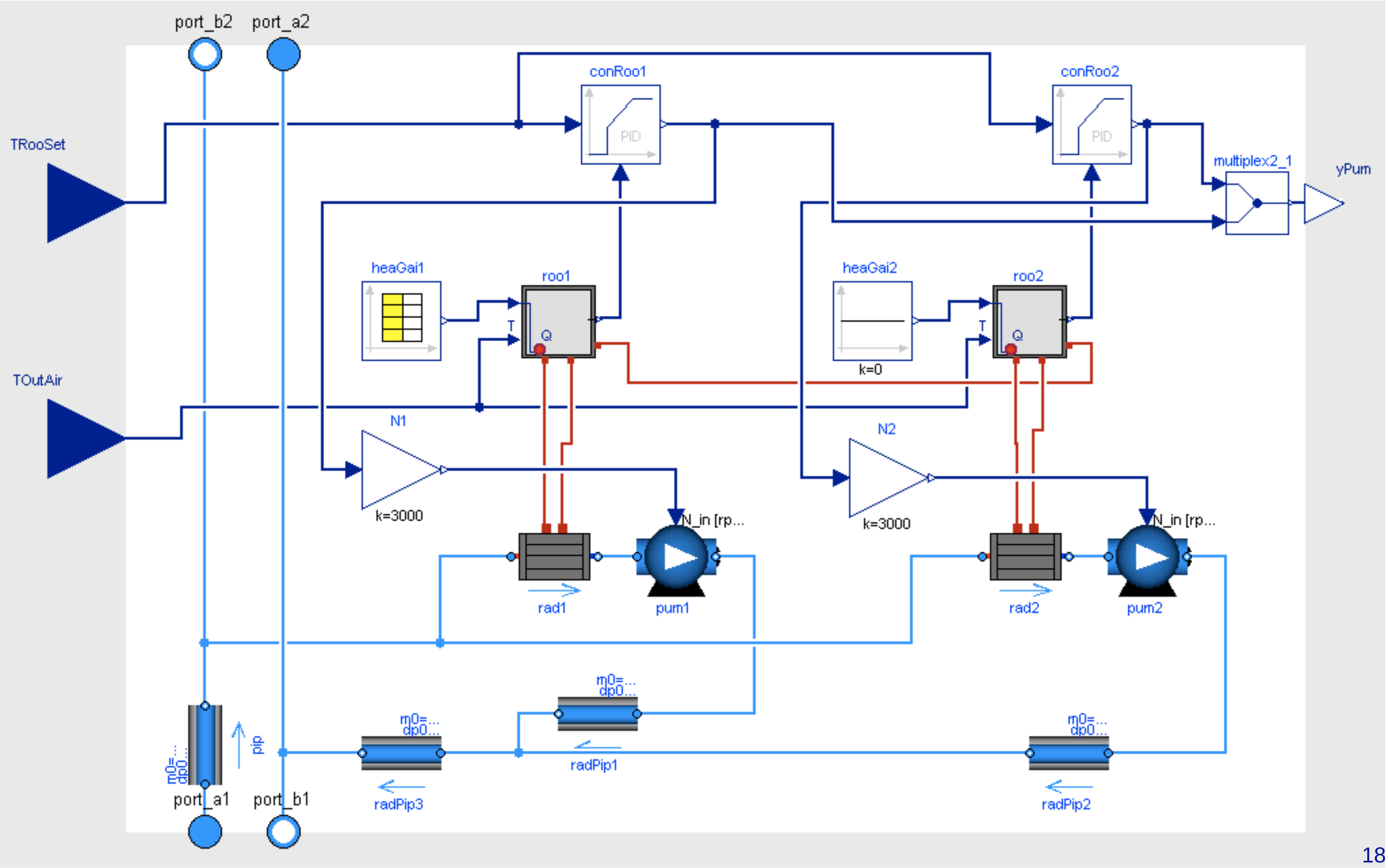


Rapid Prototyping: Wilo GENIAX (Introduction 2009)



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

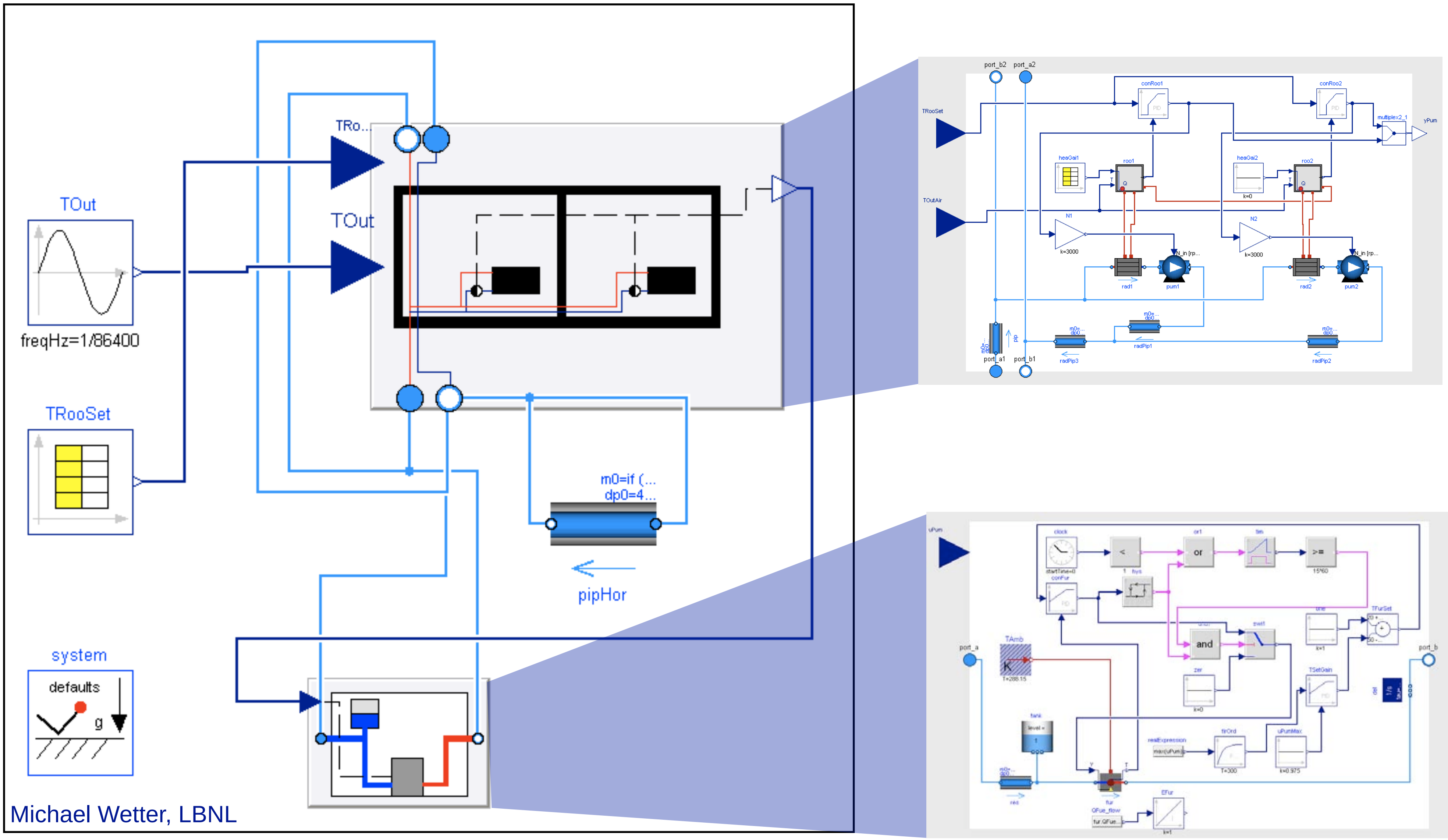
Rapid Prototyping: Wilo GENIAX (Introduction 2009)



Rapid Prototyping: Wilo GENIAX (Introduction 2009)

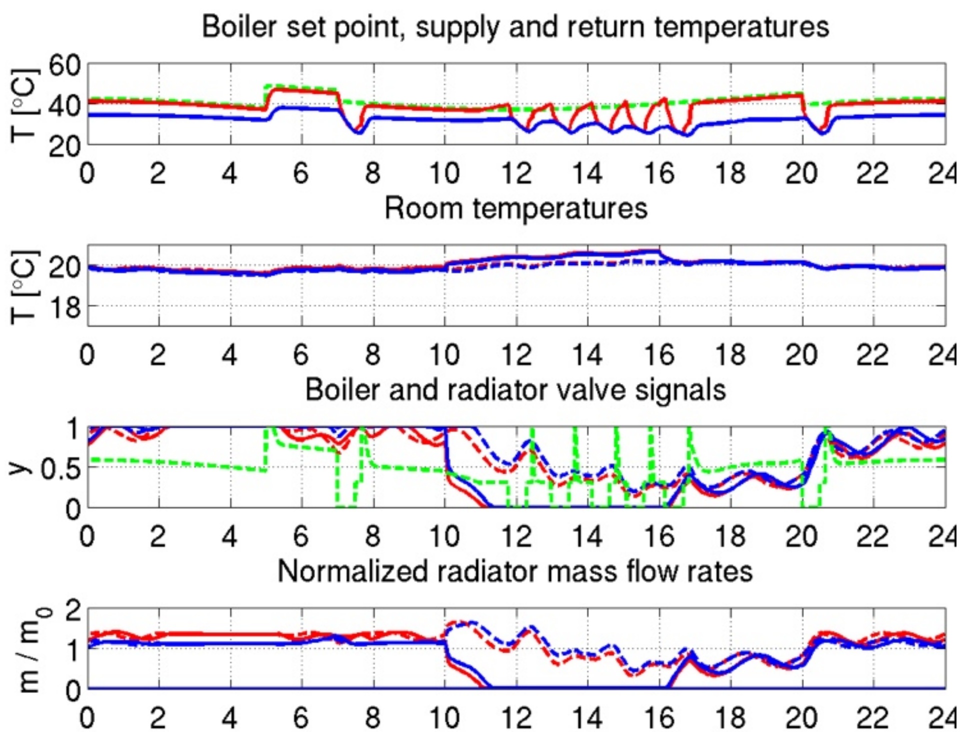
Original system model
2400 components
13,200 equations

After symbolic manipulations
300 state variables
8,700 equations

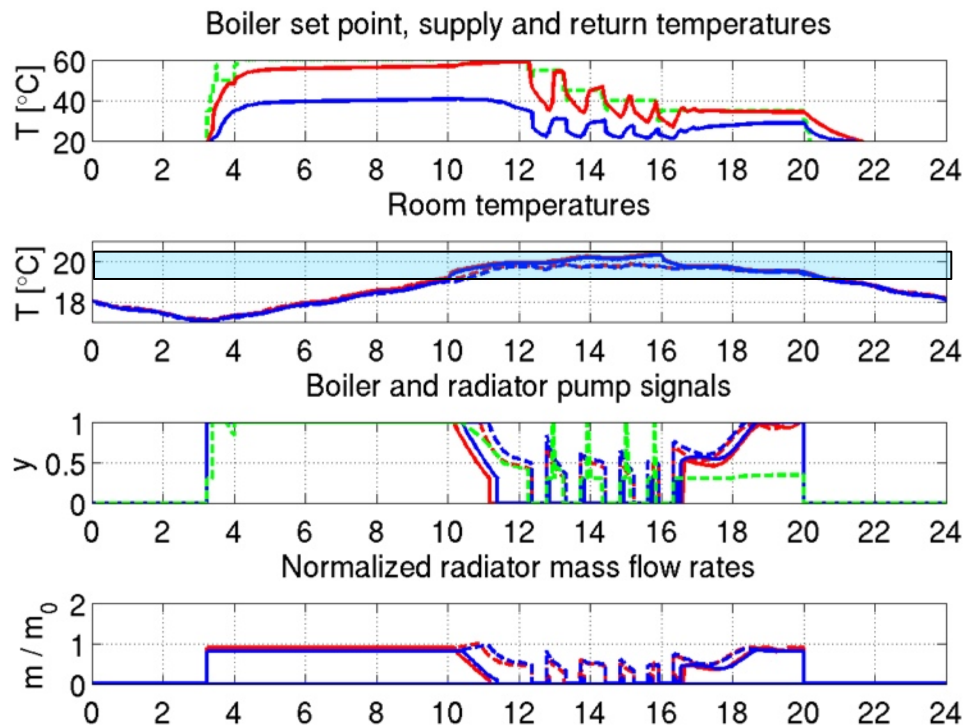


Rapid Prototyping: Wilo GENIAX (Introduction 2009)

Thermostatic radiator valves



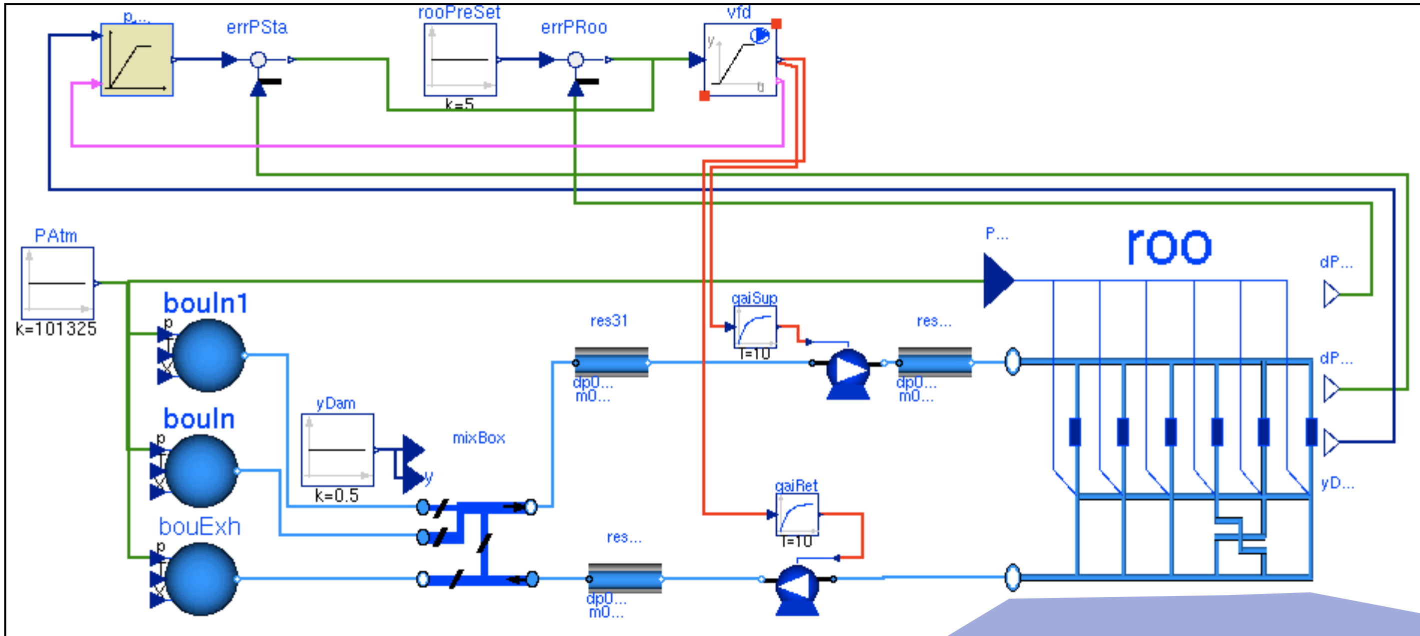
Radiator pumps



Reproduced trends published by Wilo.

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

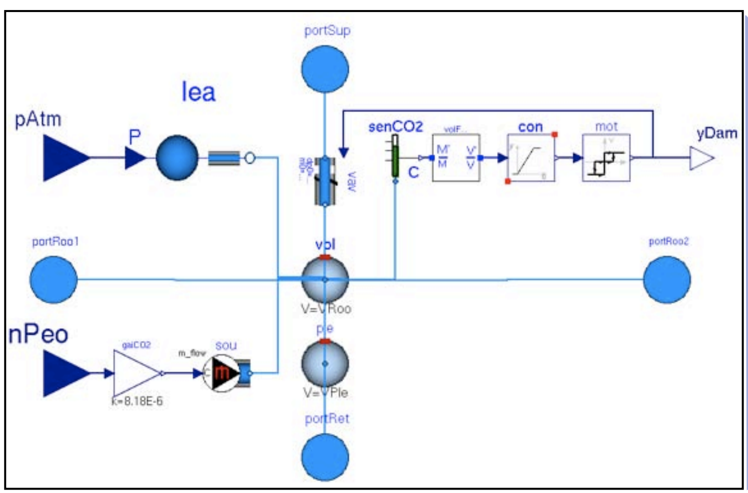
Applications – VAV System Controls

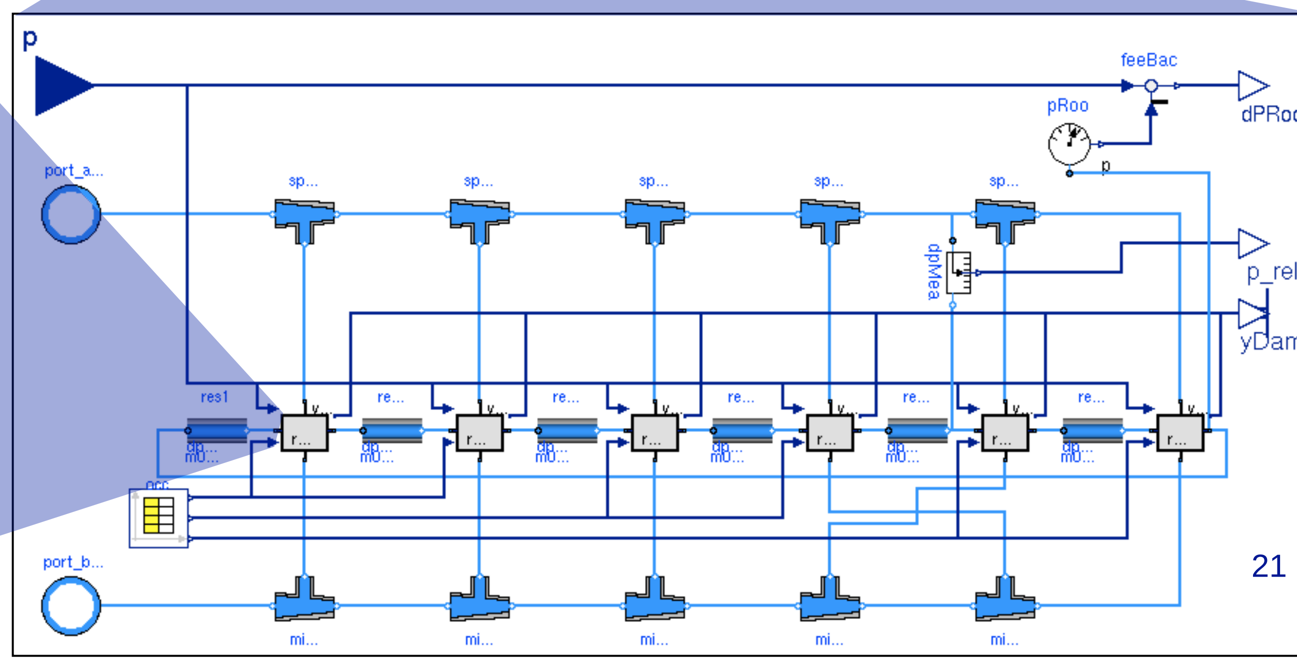


VAV System
(ASHRAE 825-RP)

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

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





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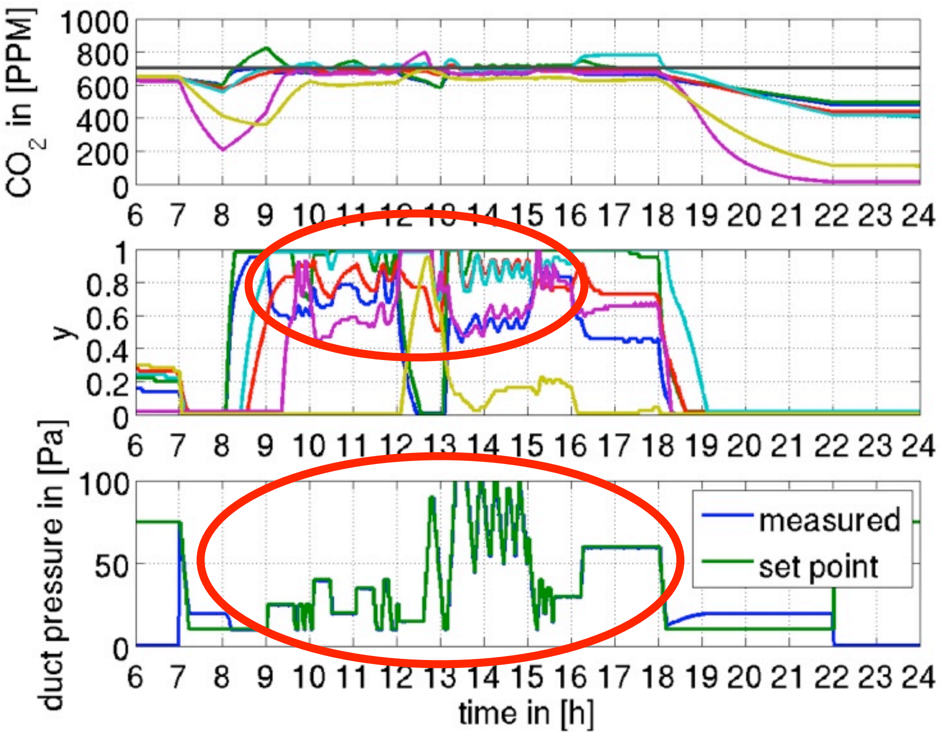
Applications – VAV System Controls

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



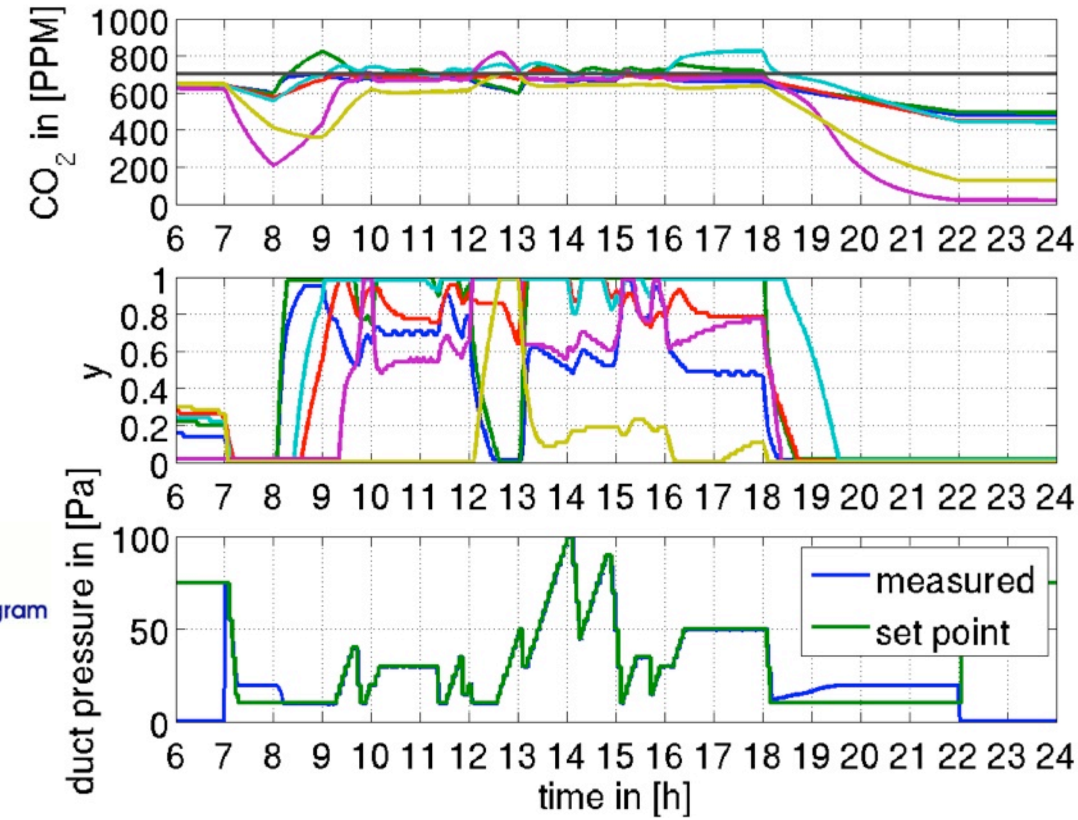
$$\min_{x \in \mathbf{X}} \{ f(x) \,|\, g(x) = 0 \},$$

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

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

GenOpt

Generic Optimization Program



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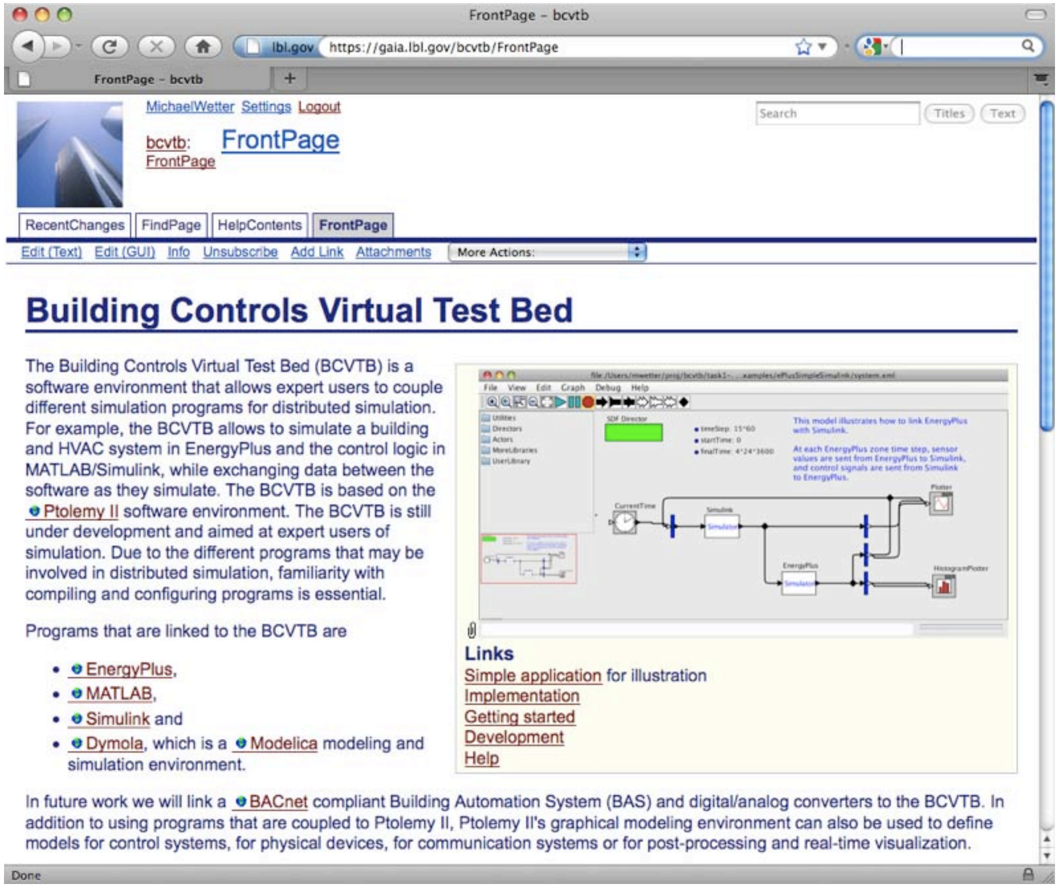
Building Controls Virtual Test Bed (BCVTB)

Enable

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



Available from

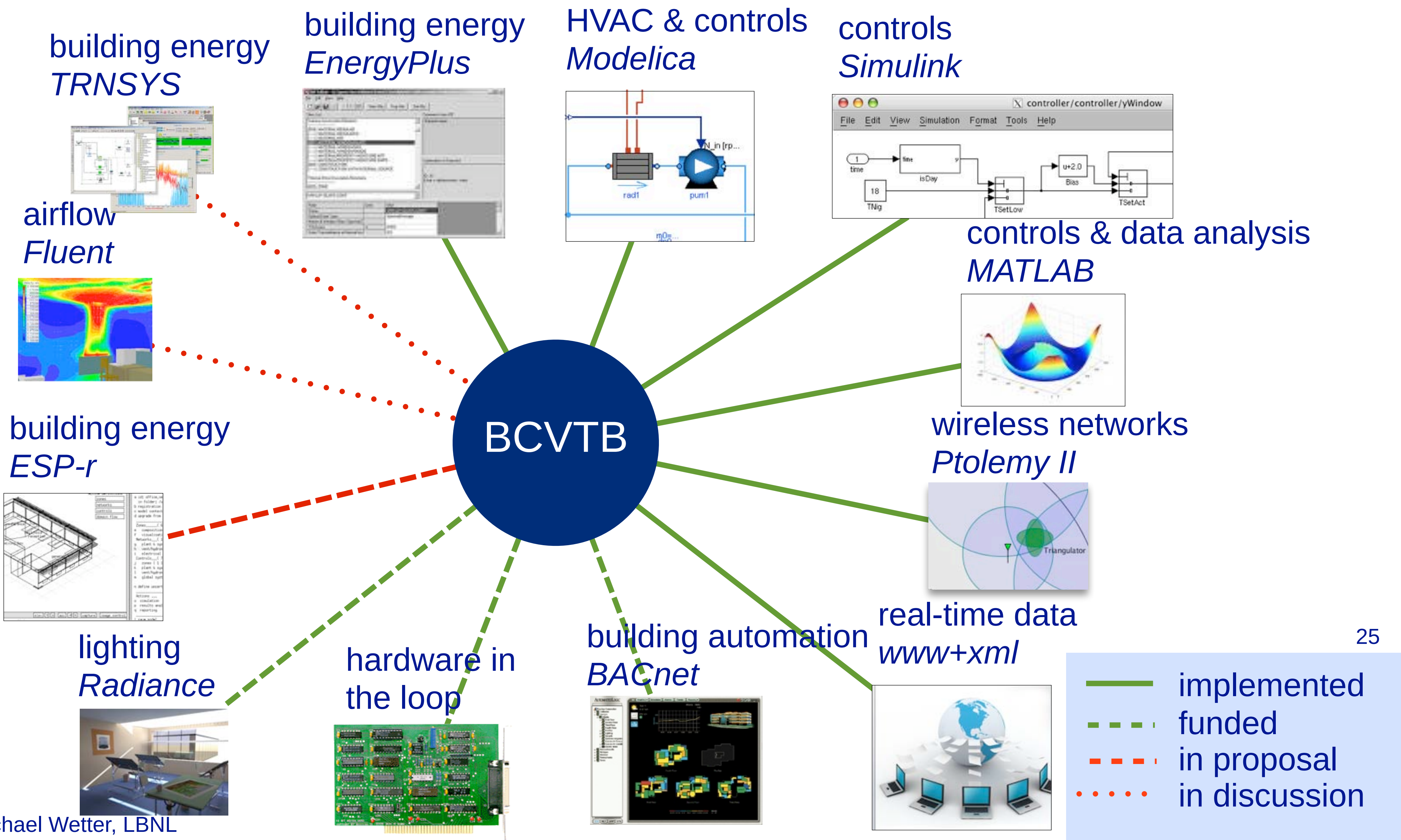
http://simulationresearch.lbl.gov/bcvtb

Based on Ptolemy II from UC Berkeley.

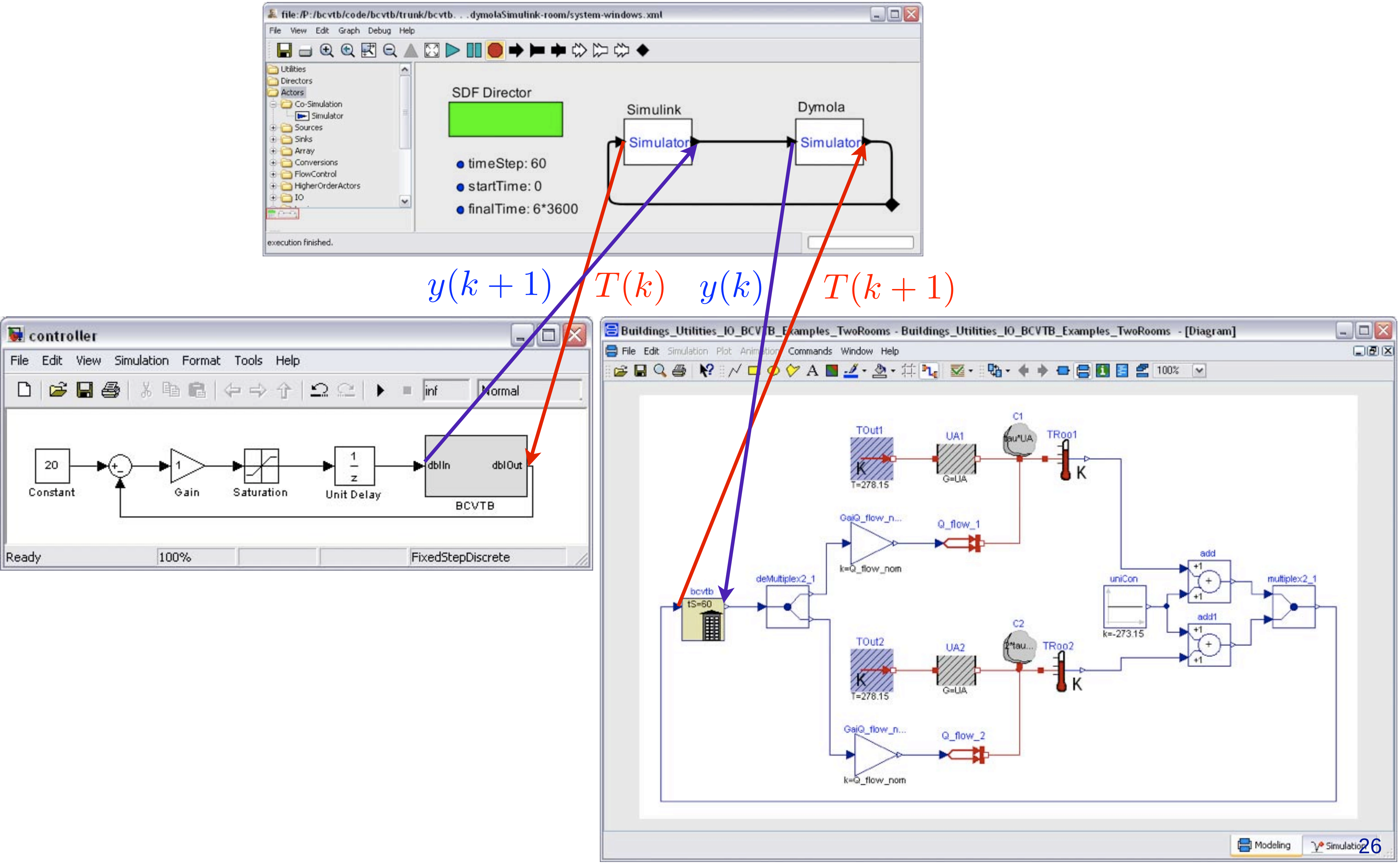
Building Controls Virtual Test Bed

Open-source middle-ware based on UC Berkeley's Ptolemy II program.

Synchronizes and exchanges data as (simulation-)time progresses.



Simple Example: Room Heater



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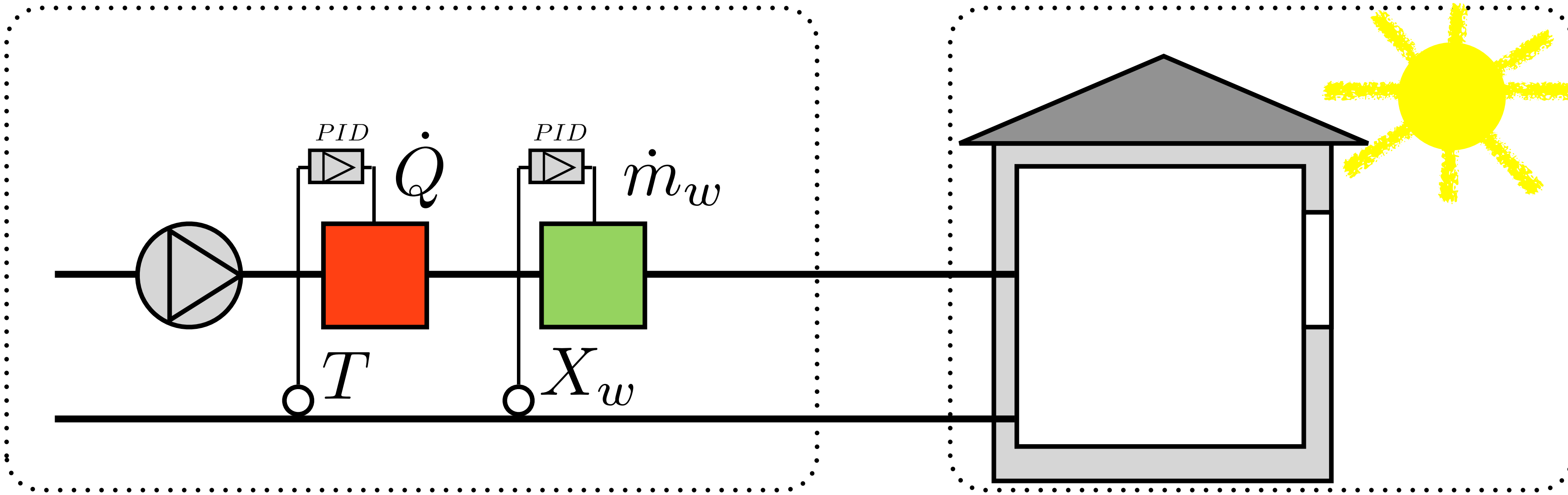
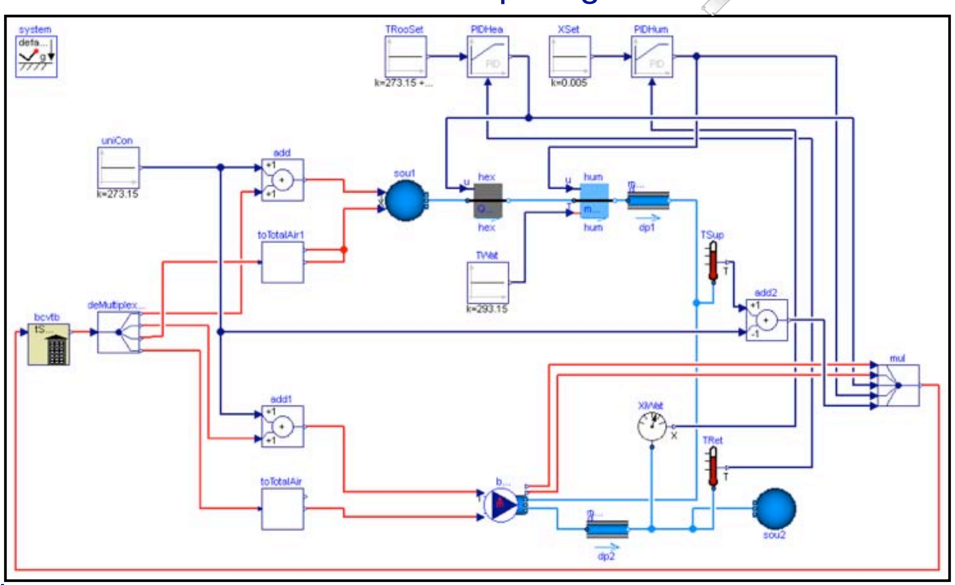
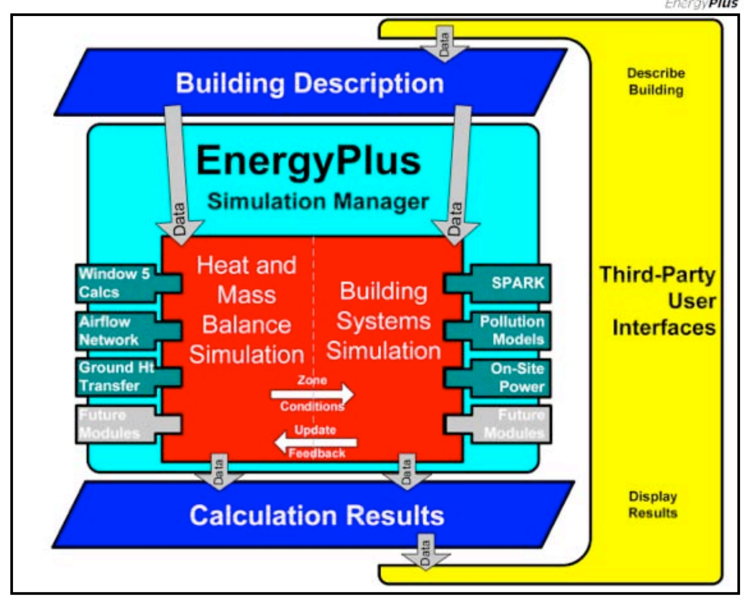
Ex: HVAC in Modelica, Building in EnergyPlus



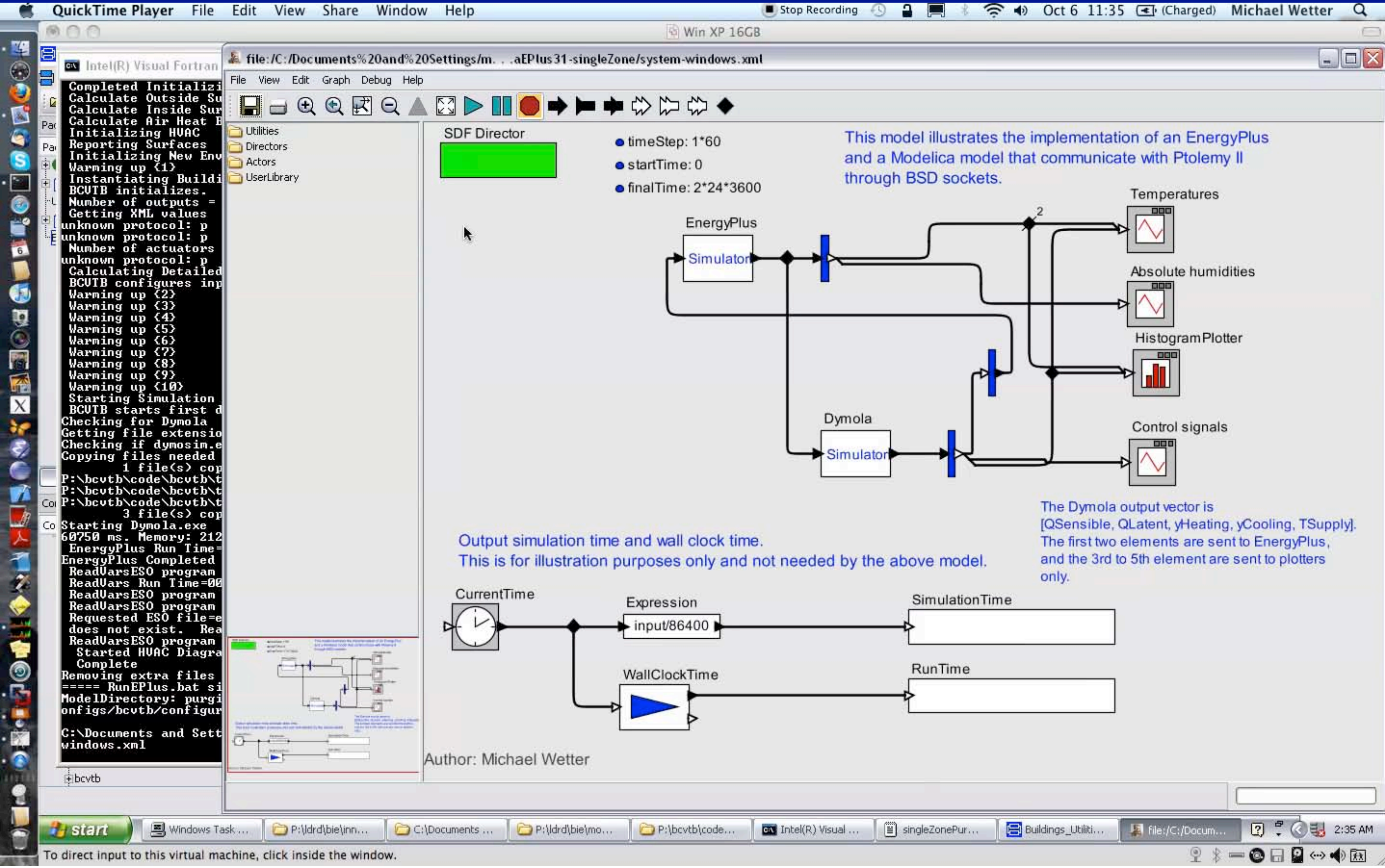
Rapid virtual prototyping.
Path towards embedded computing.



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



Ex: HVAC in Modelica, Building in EnergyPlus

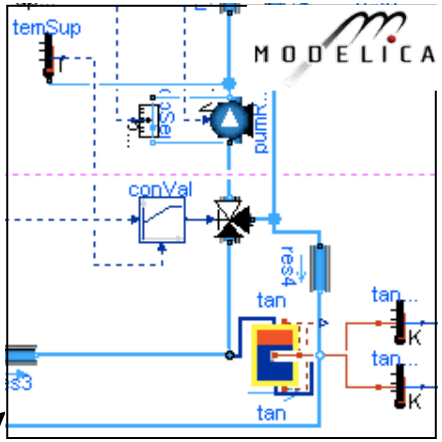


Reusable modules for model-based operation

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

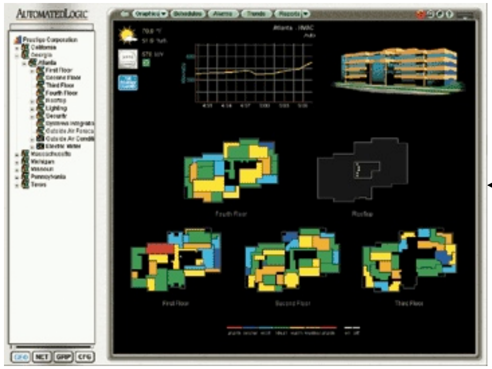
Tool selection depends on
- required model resolution
    - emulation of controls
    - dynamics of equipment
- analysis capabilities
    - smoothness
    - state initialization

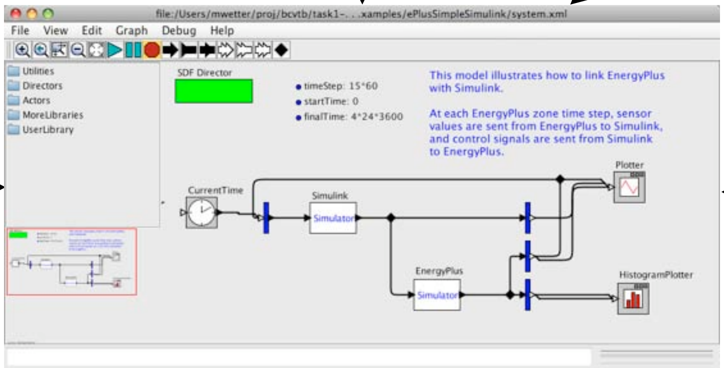
Hybrid systems, emulate actual feedback control

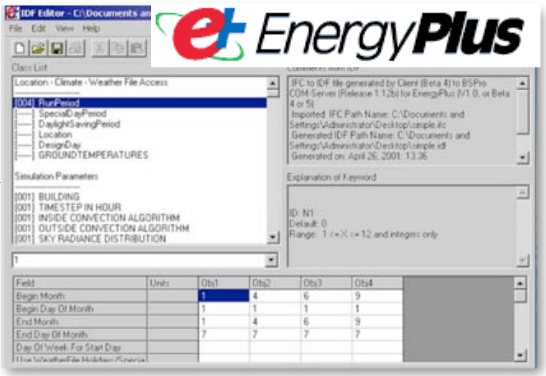


www/xml

Discrete time, idealized controls







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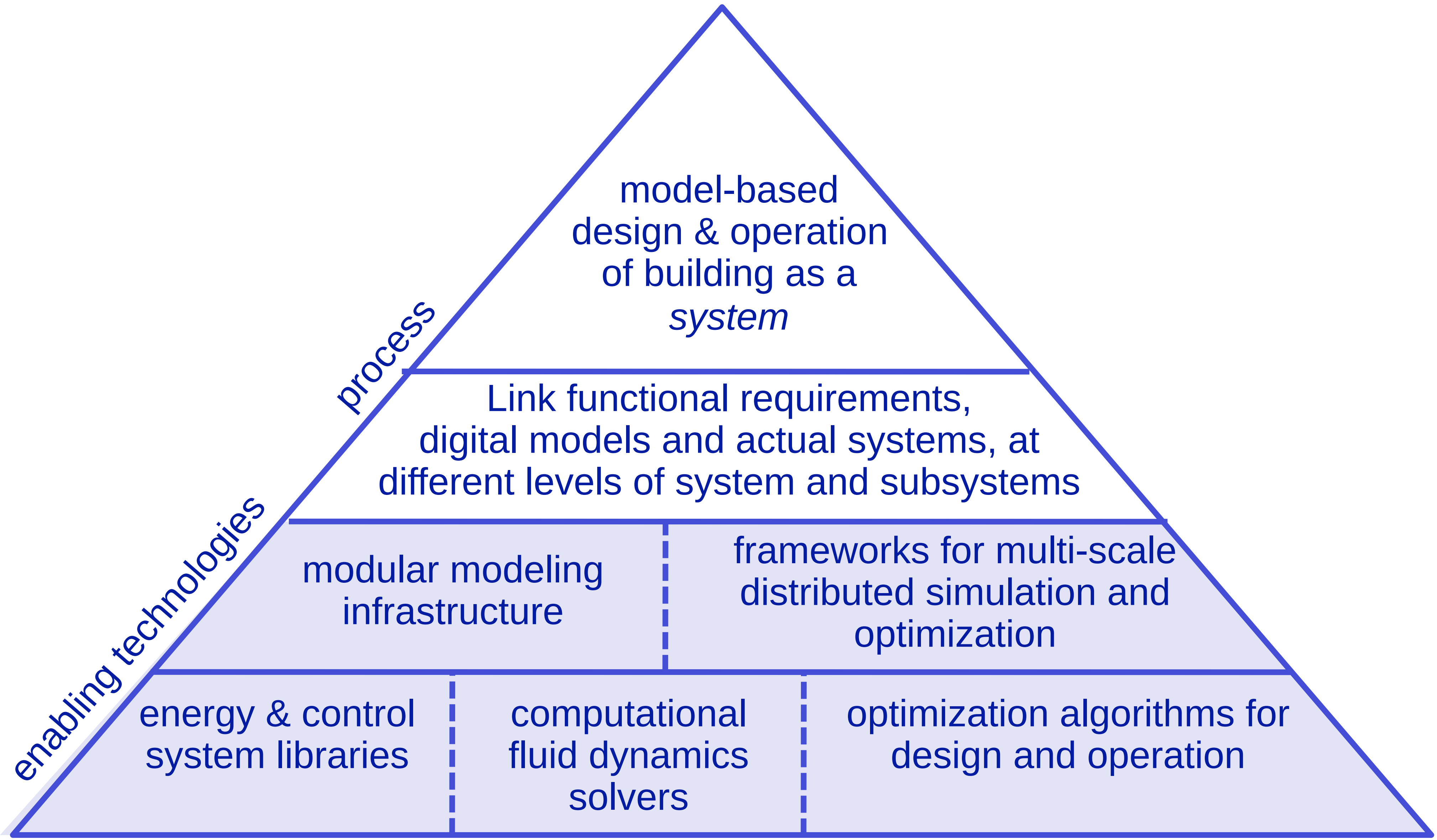
model-based
design & operation
of building as a
system
Link functional requirements,
digital models and actual systems, at
different levels of system and subsystems
modular modeling
infrastructure
frameworks for multi-scale
distributed simulation and
optimization
energy & control
system libraries
computational
fluid dynamics
solvers
optimization algorithms for
design and operation
process
enabling technologies