The Role of Modelica for Building and Community Energy Systems

—

Progress and Challenges

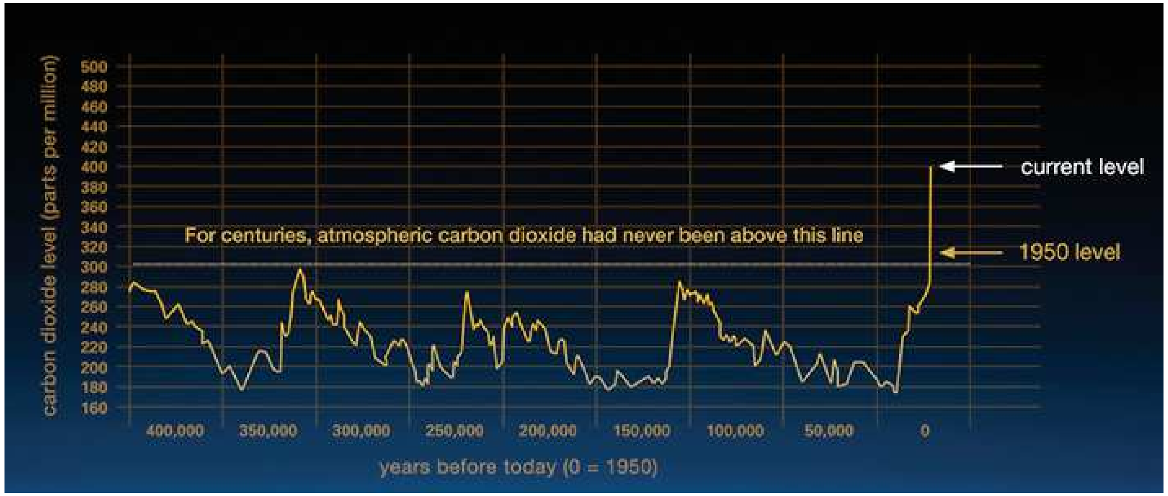
Michael Wetter

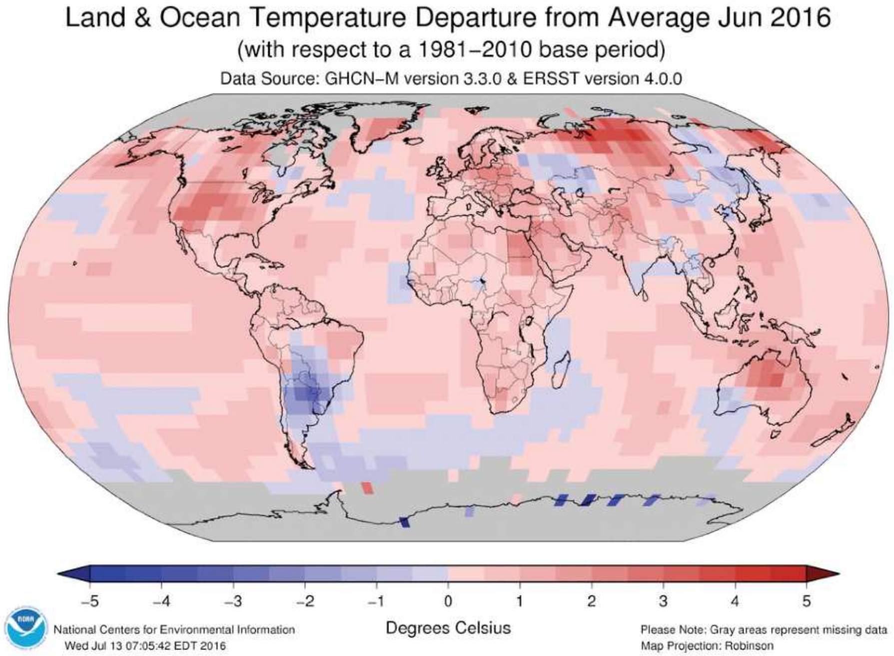
February 8, 2017

BERKELEY LAB

ENERGY TECHNOLOGIES AREA

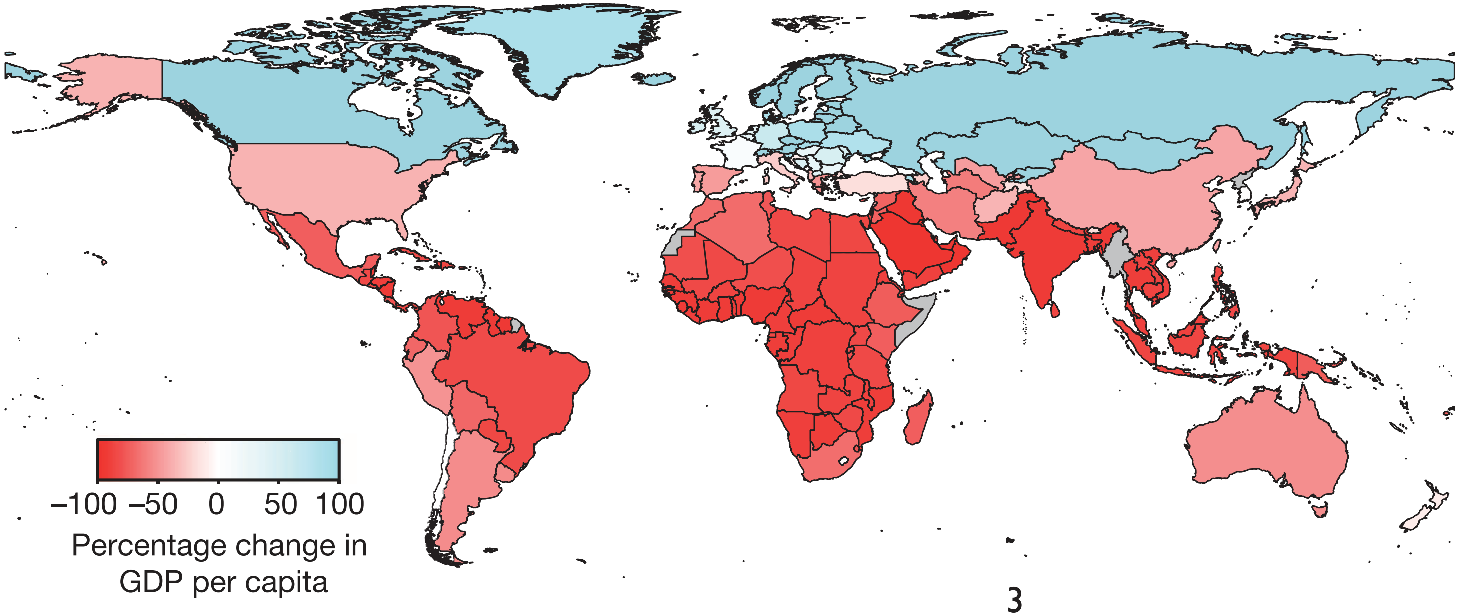
Problem and challenges





http://climate.nasa.gov/climate_resources/24/

https://www.ncdc.noaa.gov/sotc/global/201606



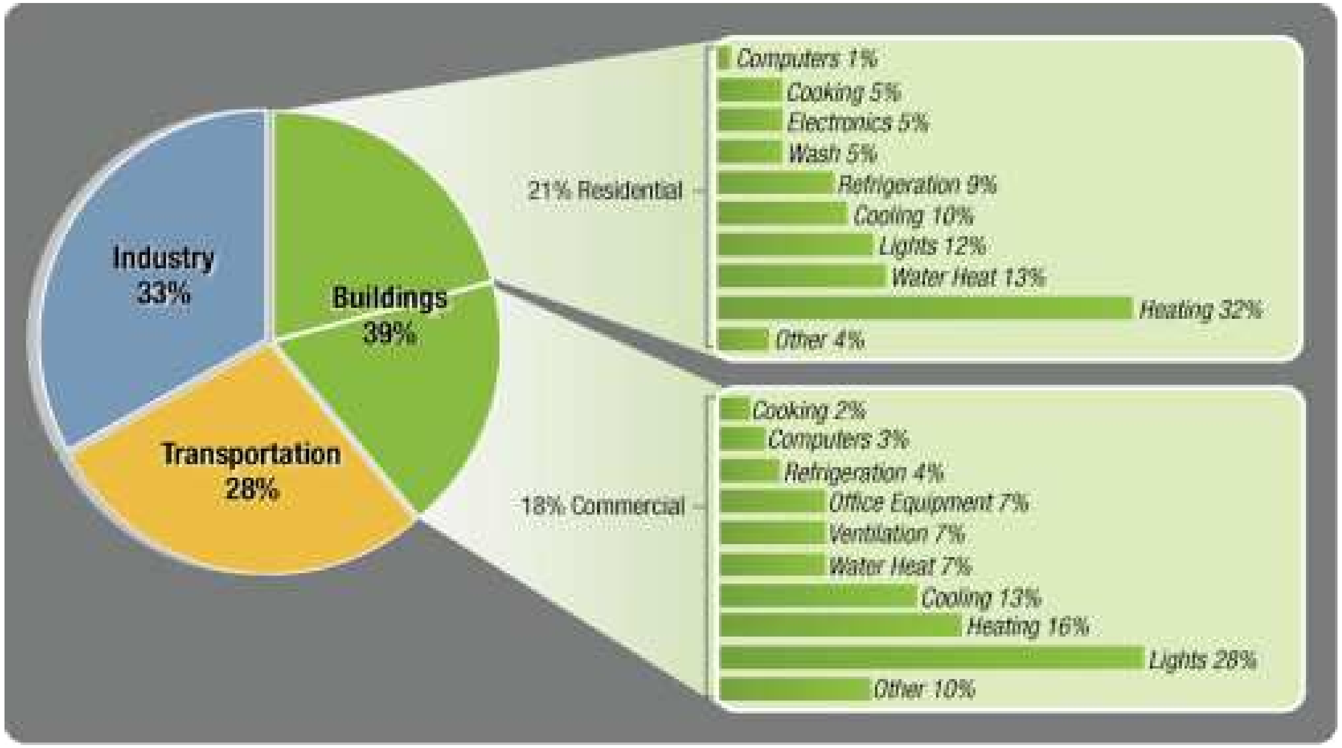
Change in global GDP by 2100 due to nonlinear effects of temperature. doi:10.1038/nature15725

Why buildings?

Buildings use
- 40% of global energy,
- 25% of global water,
- 40% of global resources,

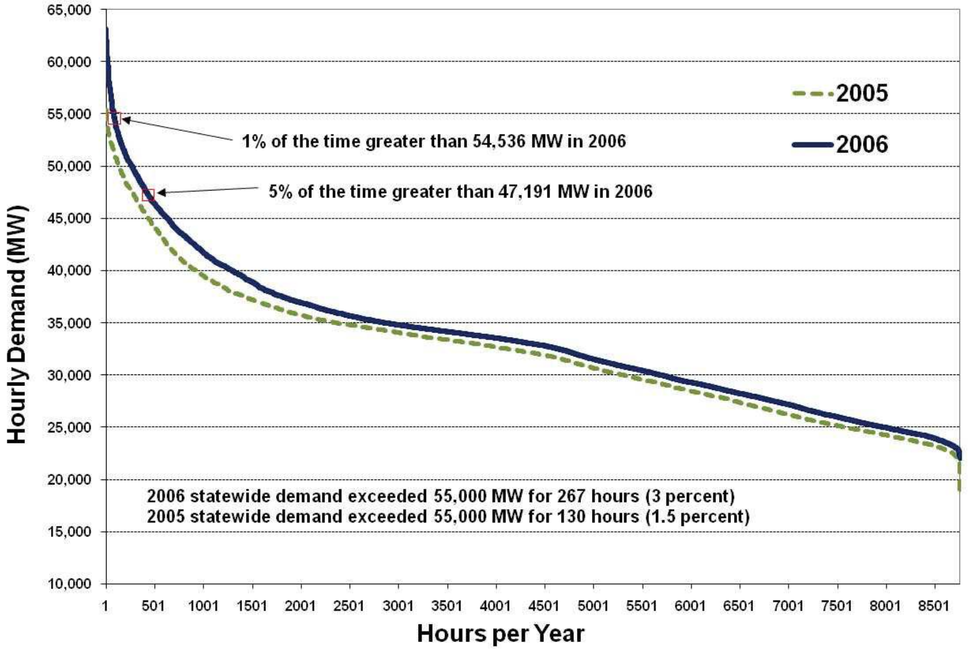
and emit 1/3 of GHG.

The building sector is the largest contributor to global GHG emissions.

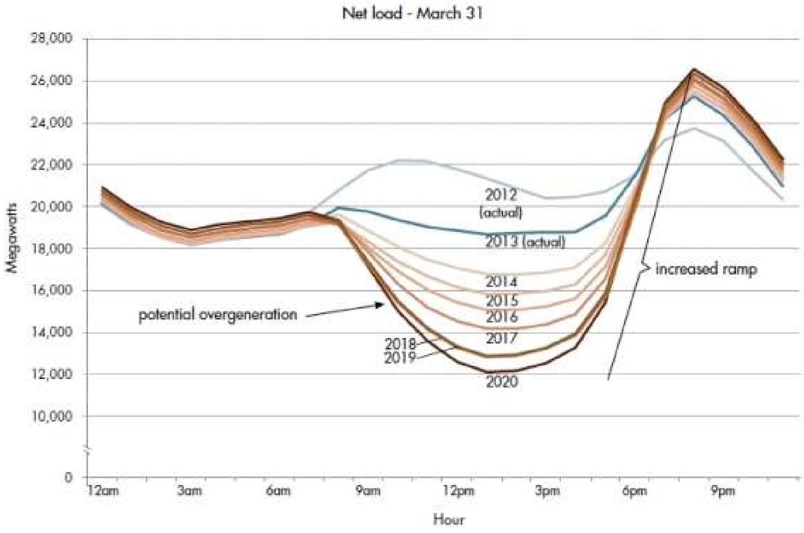


Source: http://www.unep.org/sbci/AboutSBCI/Background.asp

The problems:
Green house gas emissions, peak capacity and steep ramps

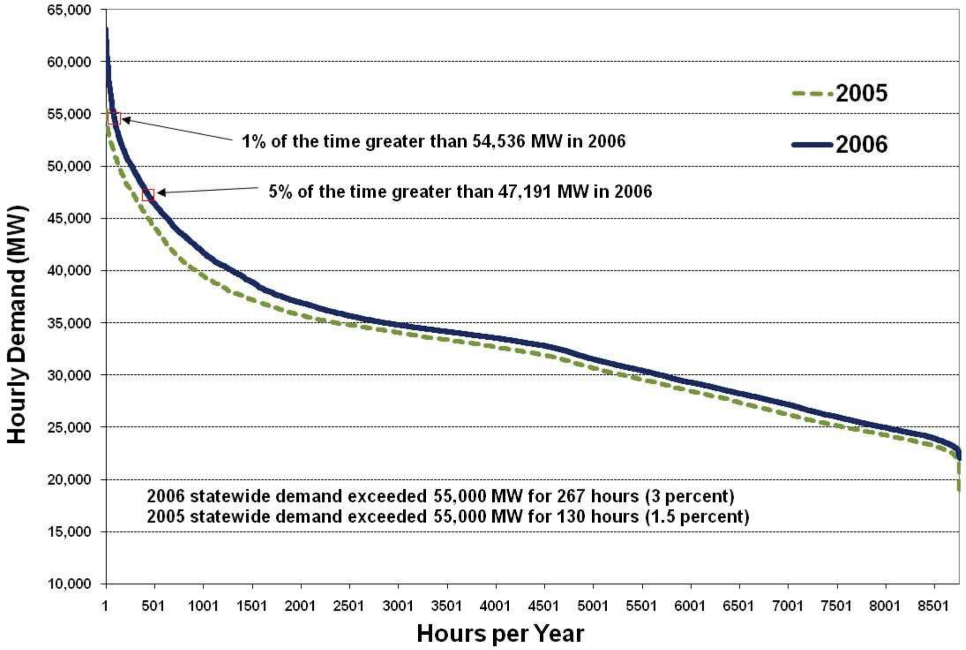


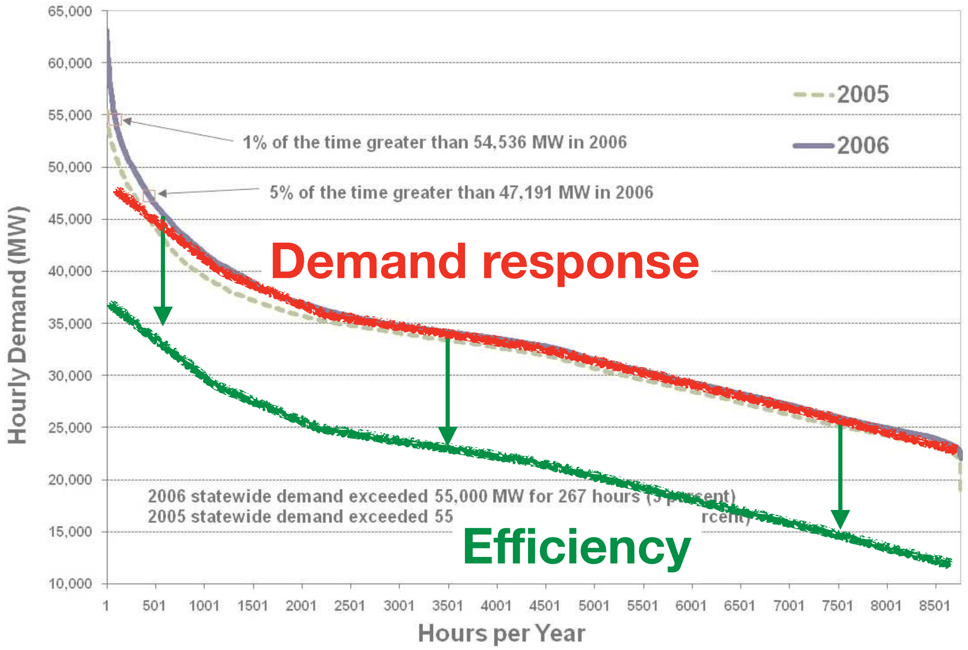
Source: CEC-400-2008-027-CTD



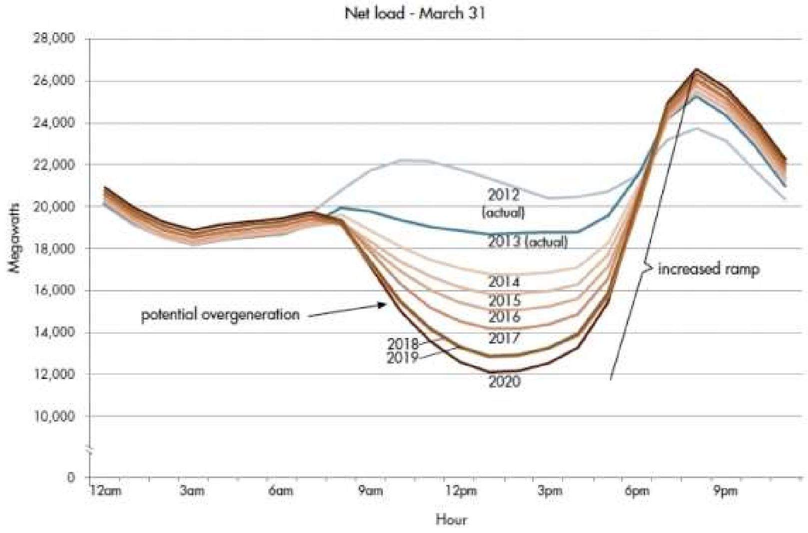
Source: http://insideenergy.org

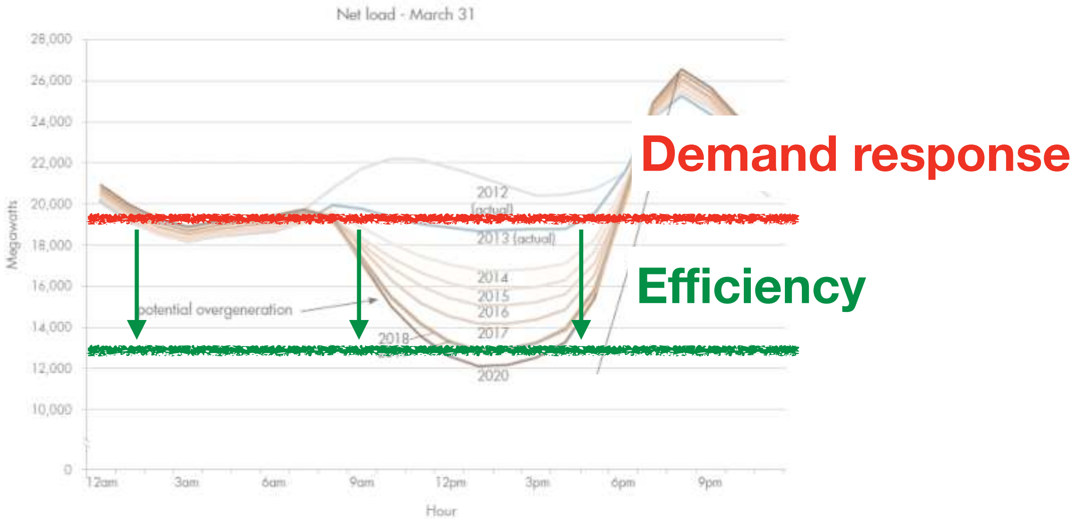
The problems:
Green house gas emissions, peak capacity and steep ramps





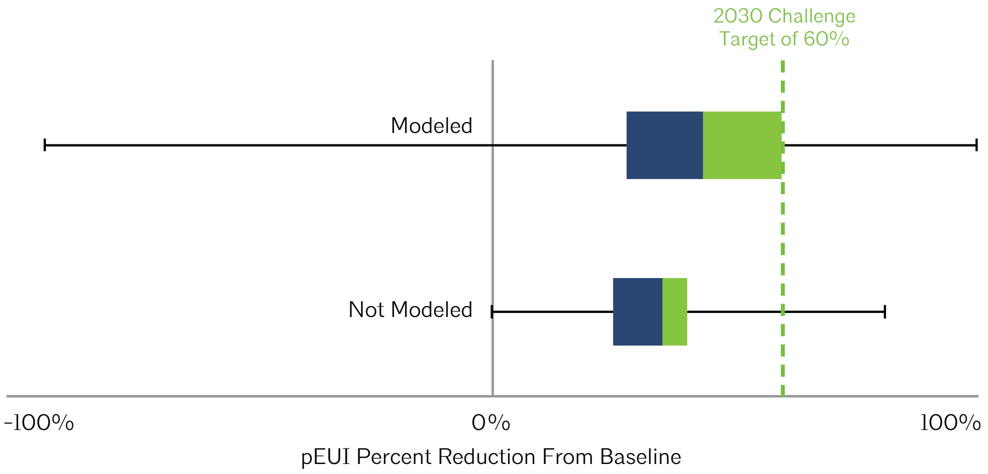
Source: CEC-400-2008-027-CTD

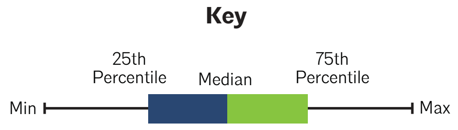




Source: http://insideenergy.org

Buildings that are modeled during design are more efficient, and payback for modeling fees are a few months



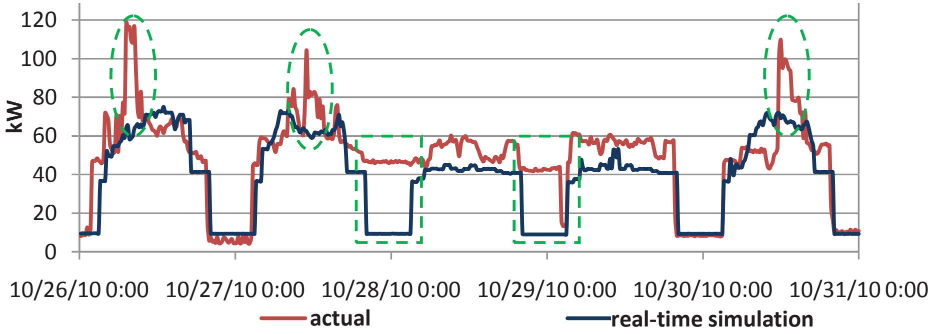


Source: AIA 2030 commitment, 2014

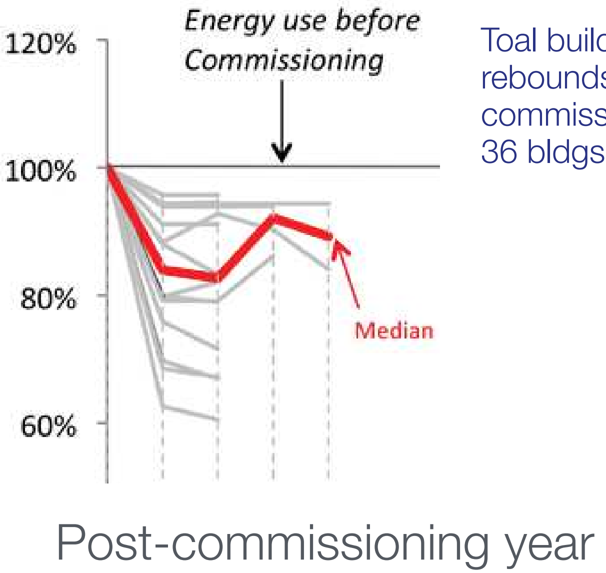
Project Name	% Modeling Fees vs Gross Fees	Annual Modeled Energy Cost Savings	Payback on Modeling Fees in MONTHS
Office Building	0.7%	$122,876	2
Office Building	0.5%	$306,692	1
Justice Center	0.8%	$350,000	3
Convention Hotel	0.6%	$233,791	1
Regional Hospital	2.4%	$3,300,000	1
Government Office Building	3.3%	$186,000	4
Government Building 20	1.1%	$224,276	2
Cancer & Critical Care Tower	0.6%	$853,013	3
Institutional Research Center	0.6%	$340,000	3
Energy Institute	2.5%	$169,432	7
Institutional Research Facility	1.0%	$302,169	1
Science Teaching and Research Facility	0.8%	$419,599	1
Corporate Headquarters	1.0%	$239,835	4

Source: HOK/DOE 2016

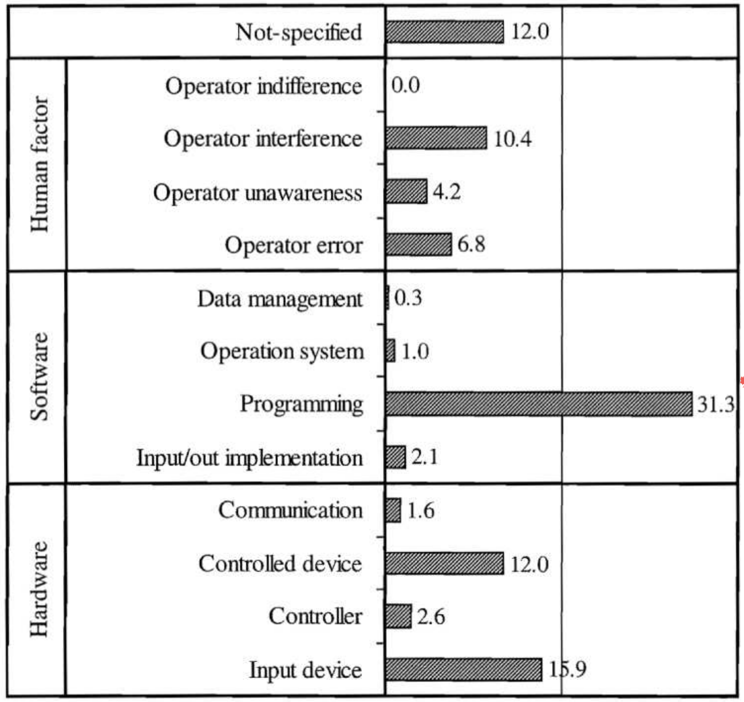
Building operation needs to be improved



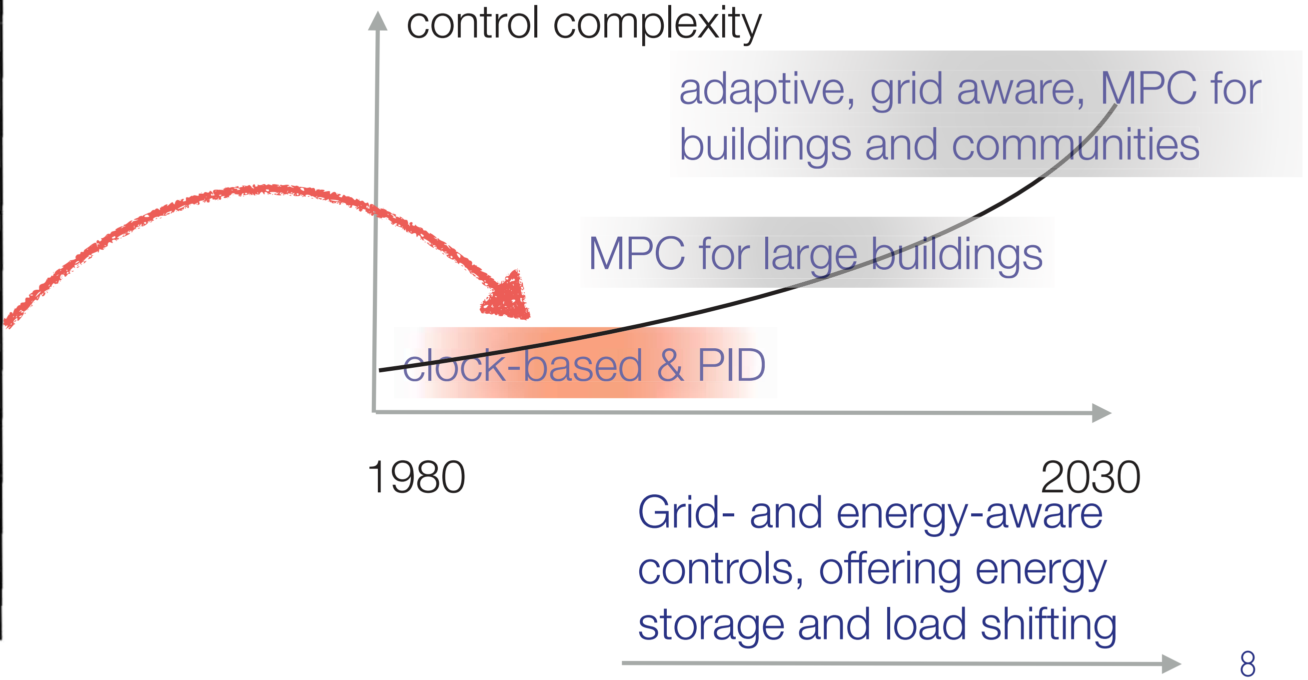
Monitored vs. real-time simulated total building electricity use (Pang et al, 2011)



Toal building energy use rebounds a few years after commissioning (Mills 2009, 36 bldgs.)



Control-related problems (Ardehali, Smith 2002)



control complexity

adaptive, grid aware, MPC for buildings and communities

MPC for large buildings

clock-based & PID

1980

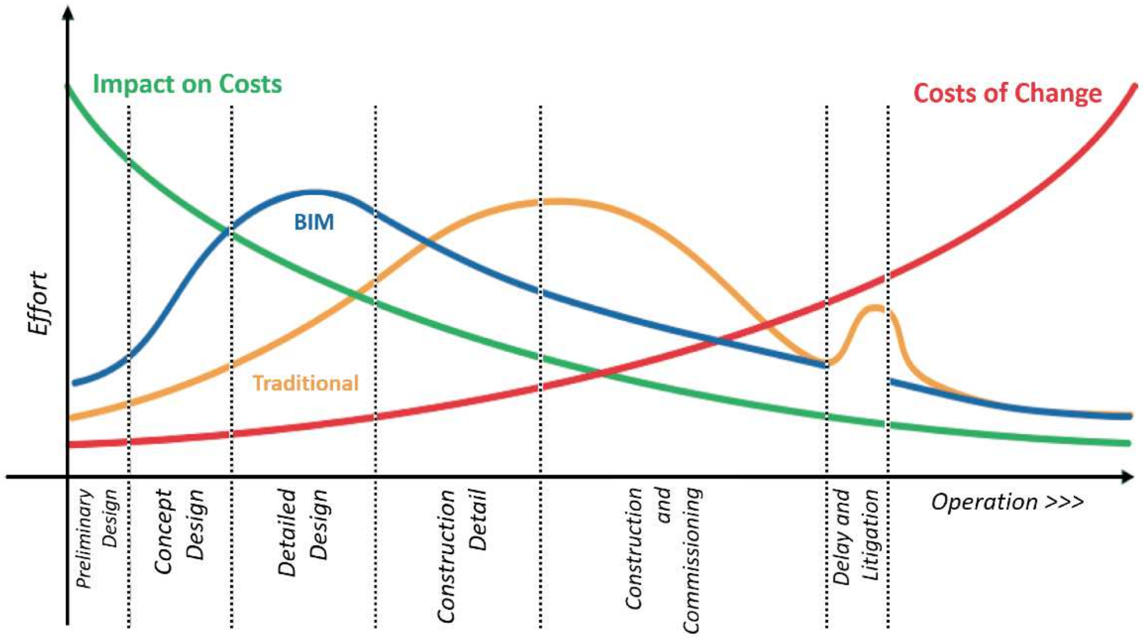
2030

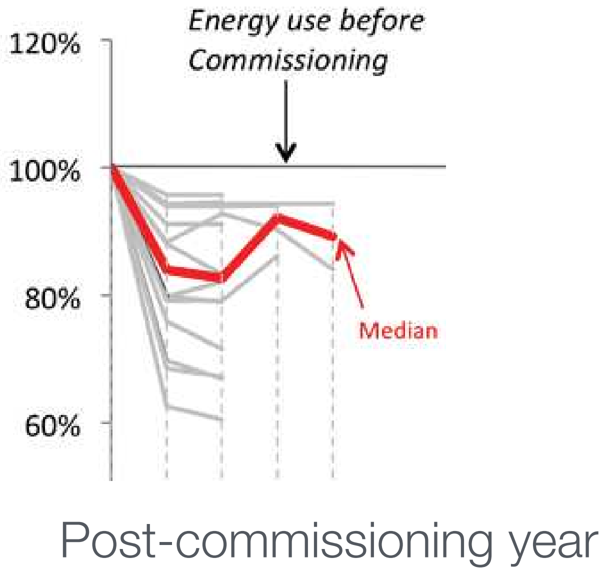
Grid- and energy-aware controls, offering energy storage and load shifting

Who are the users? — and how are they paid?

Typical users are civil, architectural, mechanical engineer with bachelor or master.

Typical cost for modeling per building: $30k to $200k [energy, daylight, CFD].





https://energy.gov/eere/buildings/articles/shockingly-short-payback-energy-modeling

Use cases

Typical use cases

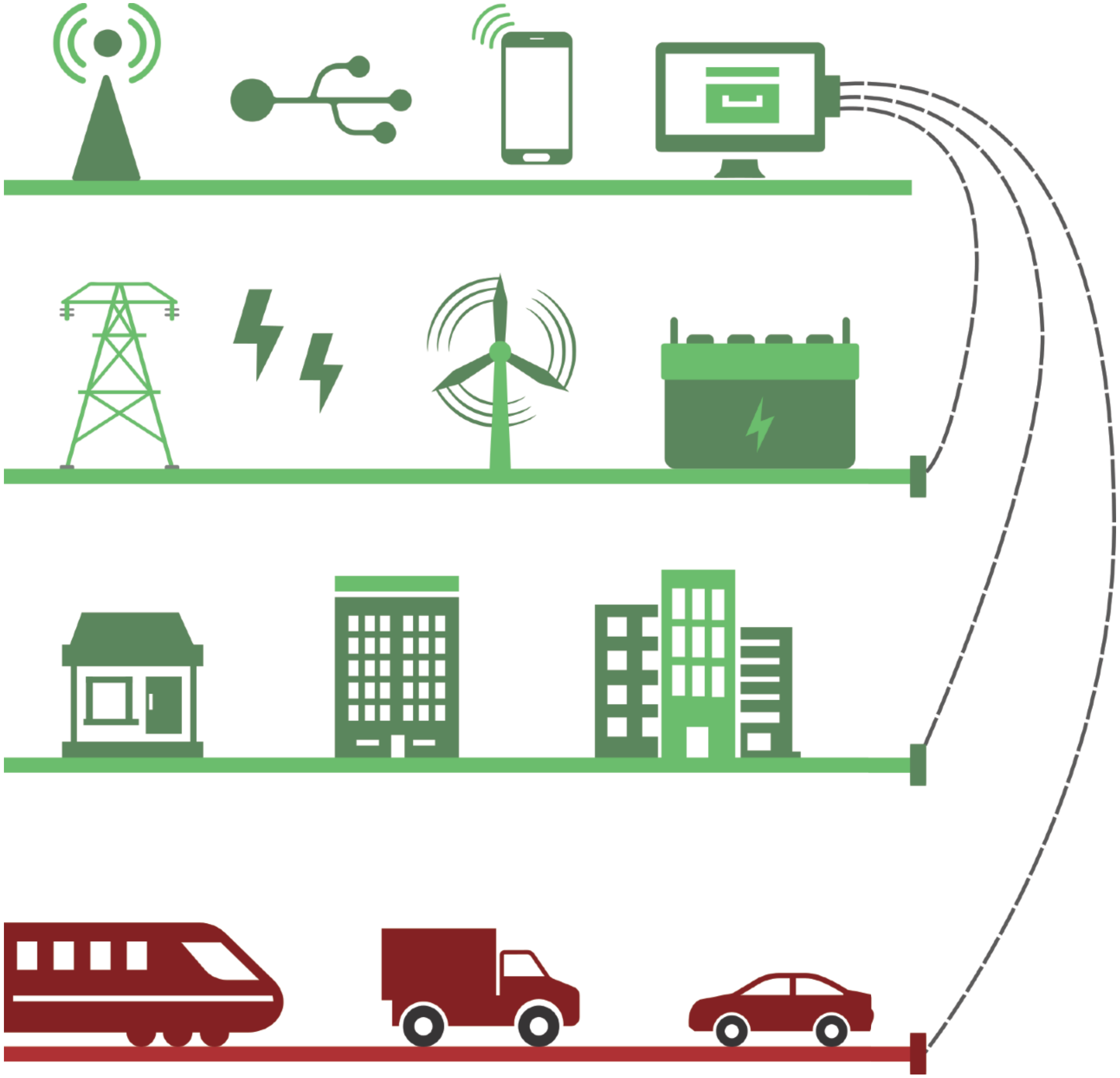
- Select optimal system architecture.
- Evaluate competing energy conservation measures.
- Assess comfort.
- Size system.

Need to support during lifetime of HVAC system: Use open-standards to provide a stable basis for industry to invest in.

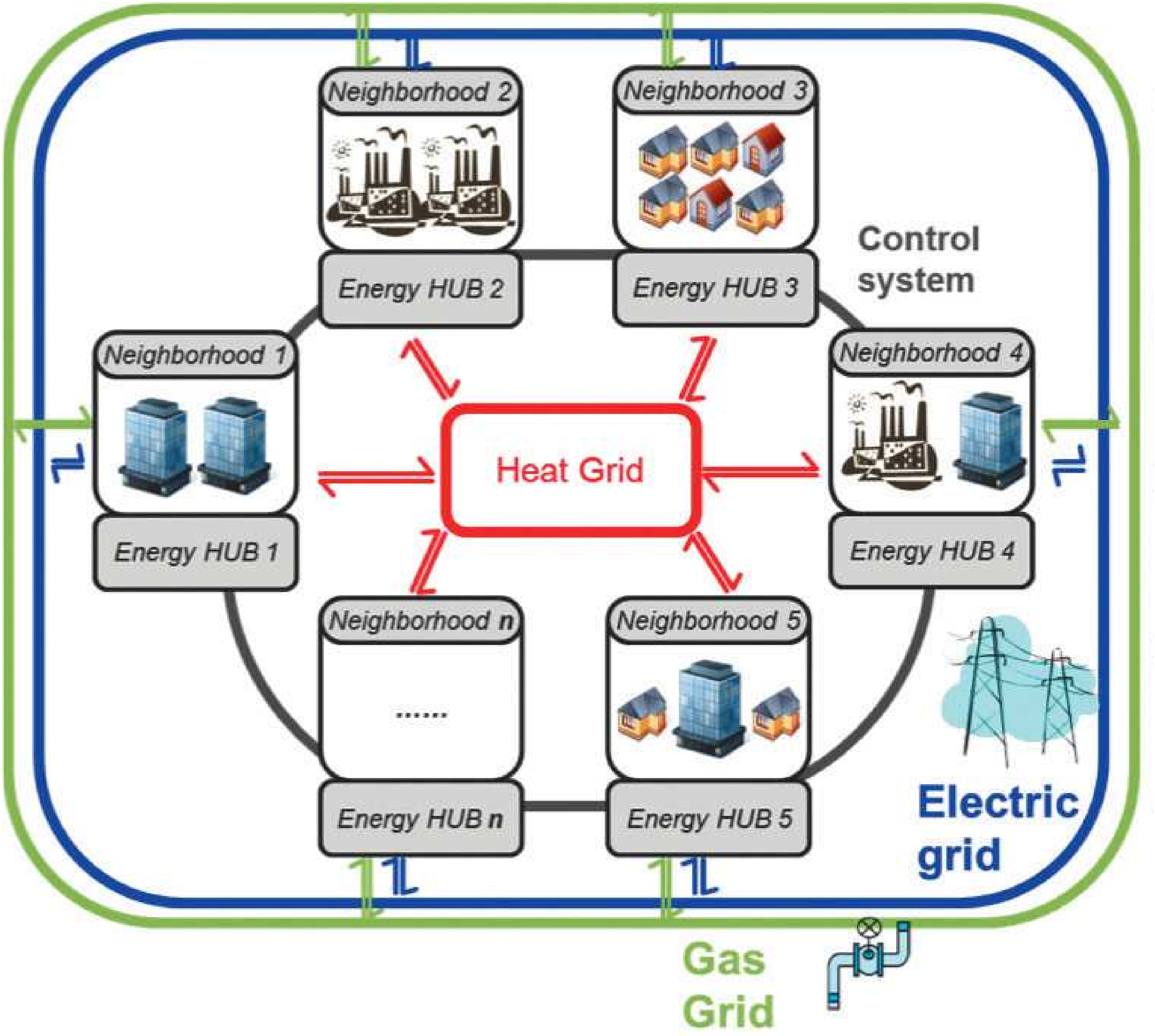
Largely untapped opportunities:

- controls design
- verify correct installation
- verify correct operation
- sustain low energy operation
- integrate with grid & environment (MPC)
- fault detection and diagnostics

Needs - Technology Integration



Increased integration, increased electrification



http://www.sccer-feebd.ch/

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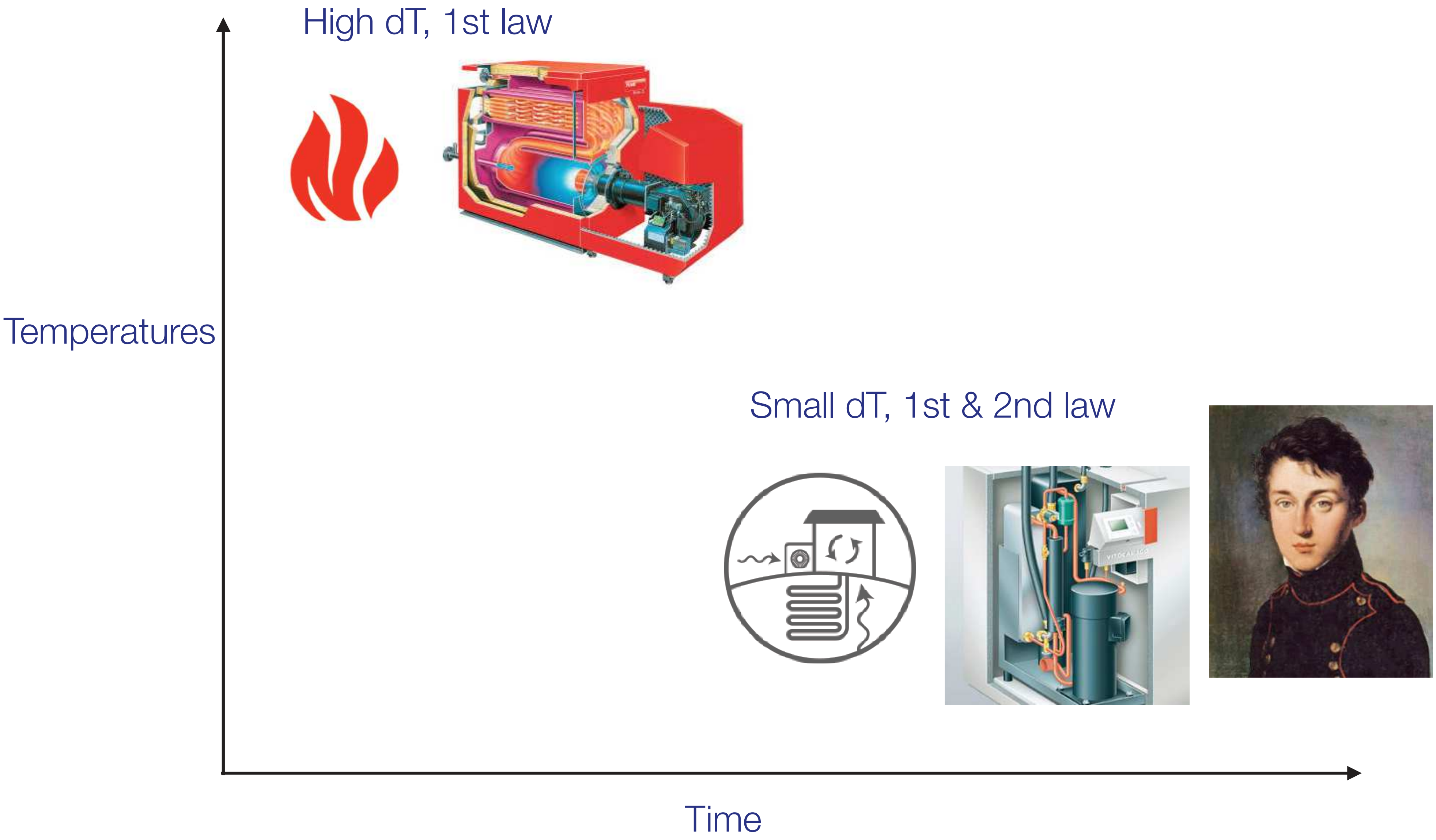
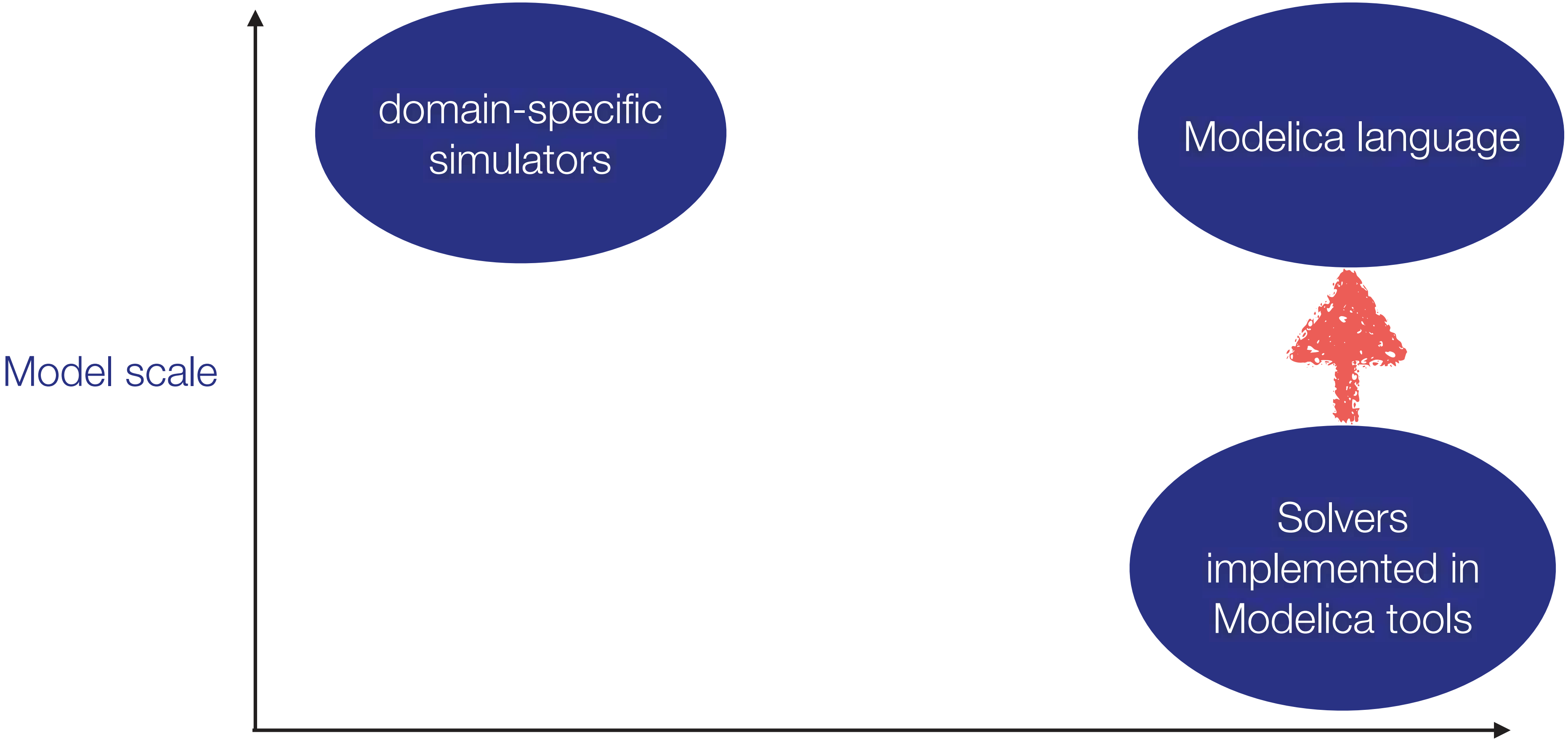


The challenge for this community



Number of domains (or use cases)

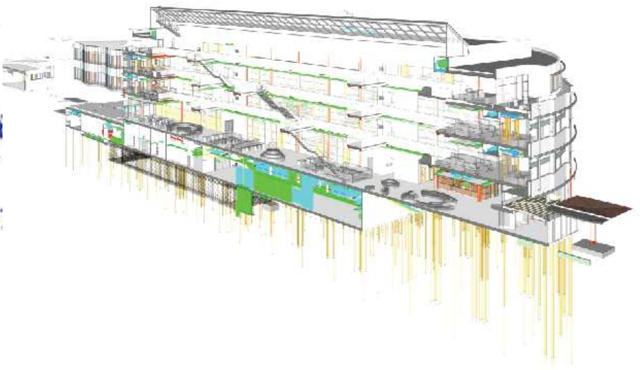
Physical: Controls, thermal, fluid, electrical.
Numerical: Continuous time, discrete time, events.

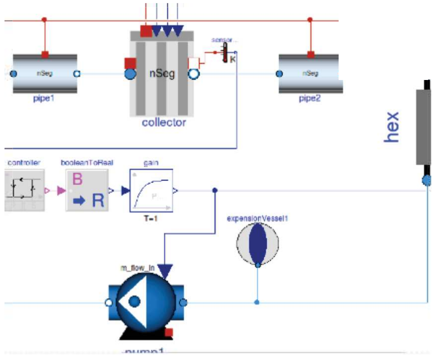
Use cases: Design, optimization, hardware-in-the-loop

Progress

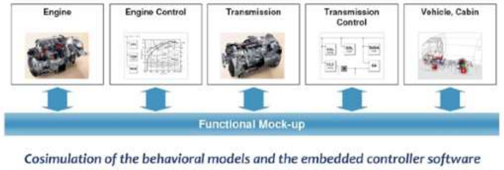
With Modelica and FMI, we have now IT standards for interoperability that go beyond static data

Semantics	Standard
static data	CityGML
mathematics (behavioral models)	MODELICA
computations (simulators)	fmi FUNCTIONAL MOCK-UP INTERFACE





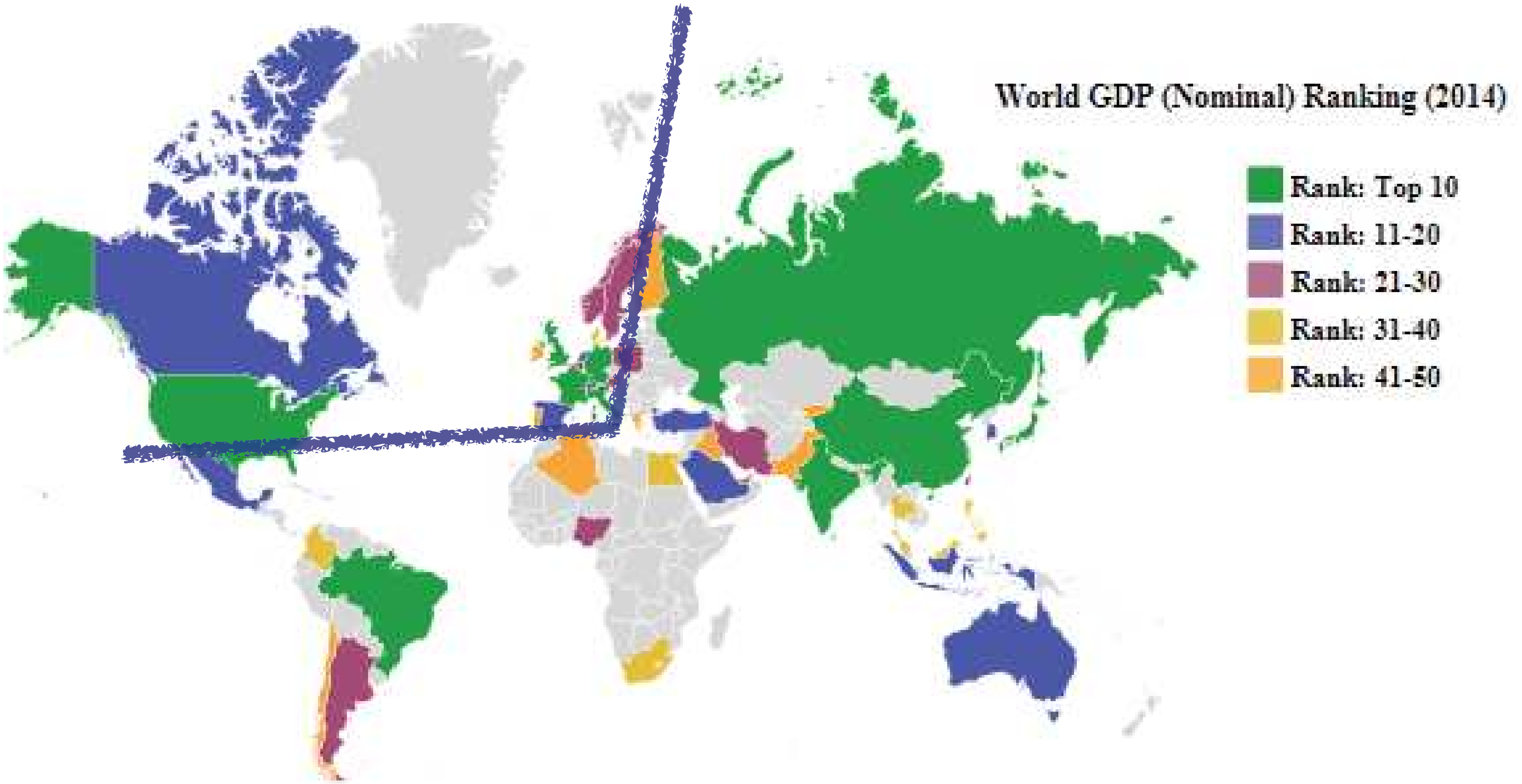
> 75M Euro investment during 2007-15



Cosimulation of the behavioral models and the embedded controller software

Supported by 90 tools

Geographical spread



http://statisticstimes.com/economy/world-gdp-ranking.php

IEA EBC Annex 60

New generation computational tools for buildings and community energy systems

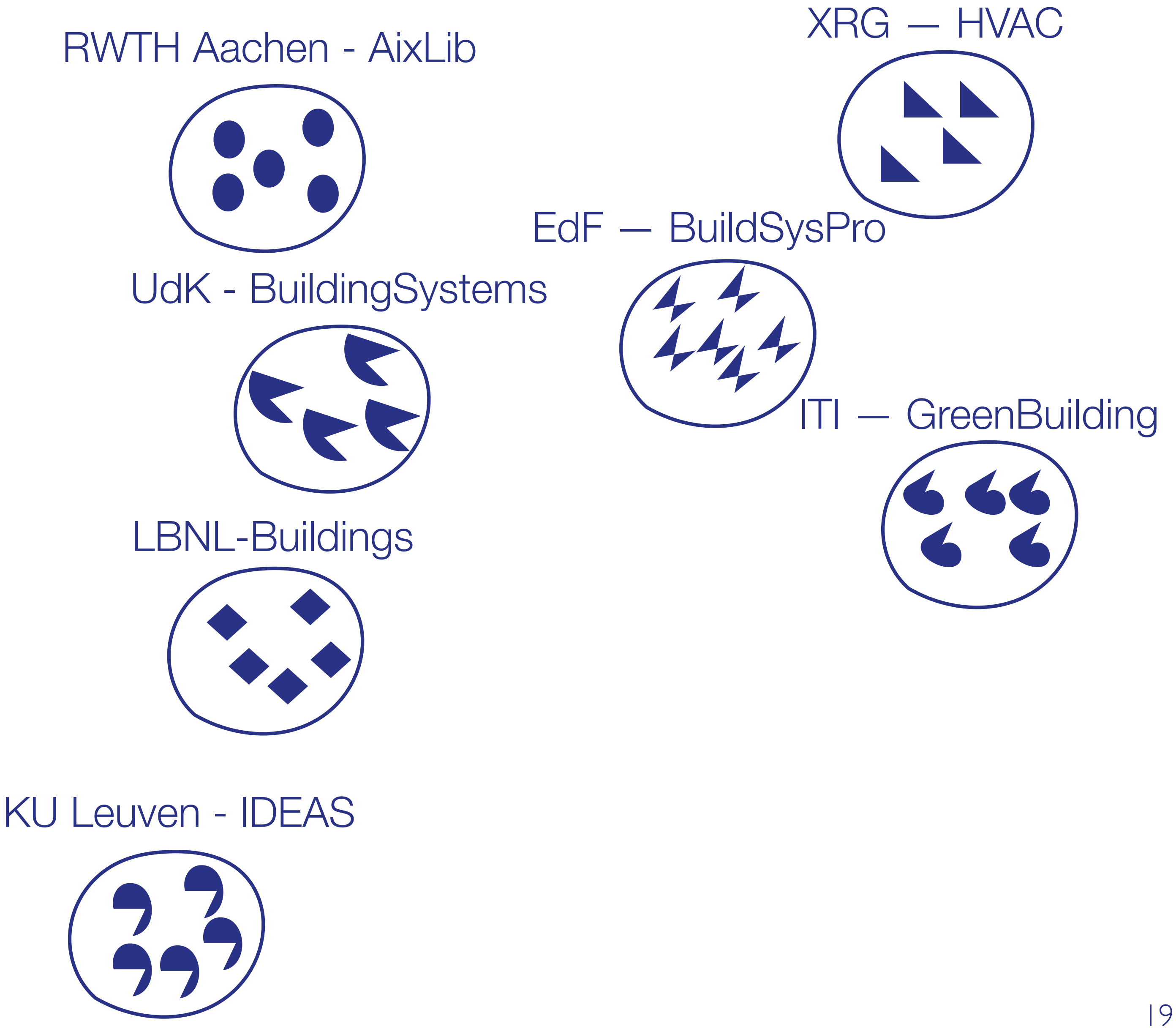
Duration: 2012-2017

Operating agents:
Michael Wetter (LBNL) and
Christoph van Treeck (RWTH Aachen).

Participation:
41 institutes from 16 countries:
Austria, Belgium, Brazil, China, Denmark, France, Germany, Ireland, Italy, the Netherlands,
Slovakia, Spain, Sweden, Switzerland, United Arab Emirates and the USA.

http://iea-annex60.org/

10 years ago, Modelica for buildings was very fragmented. Incompatible interfaces for models that sometimes complement and more often replicate each other



RWTH Aachen - AixLib

XRG — HVAC

EdF — BuildSysPro

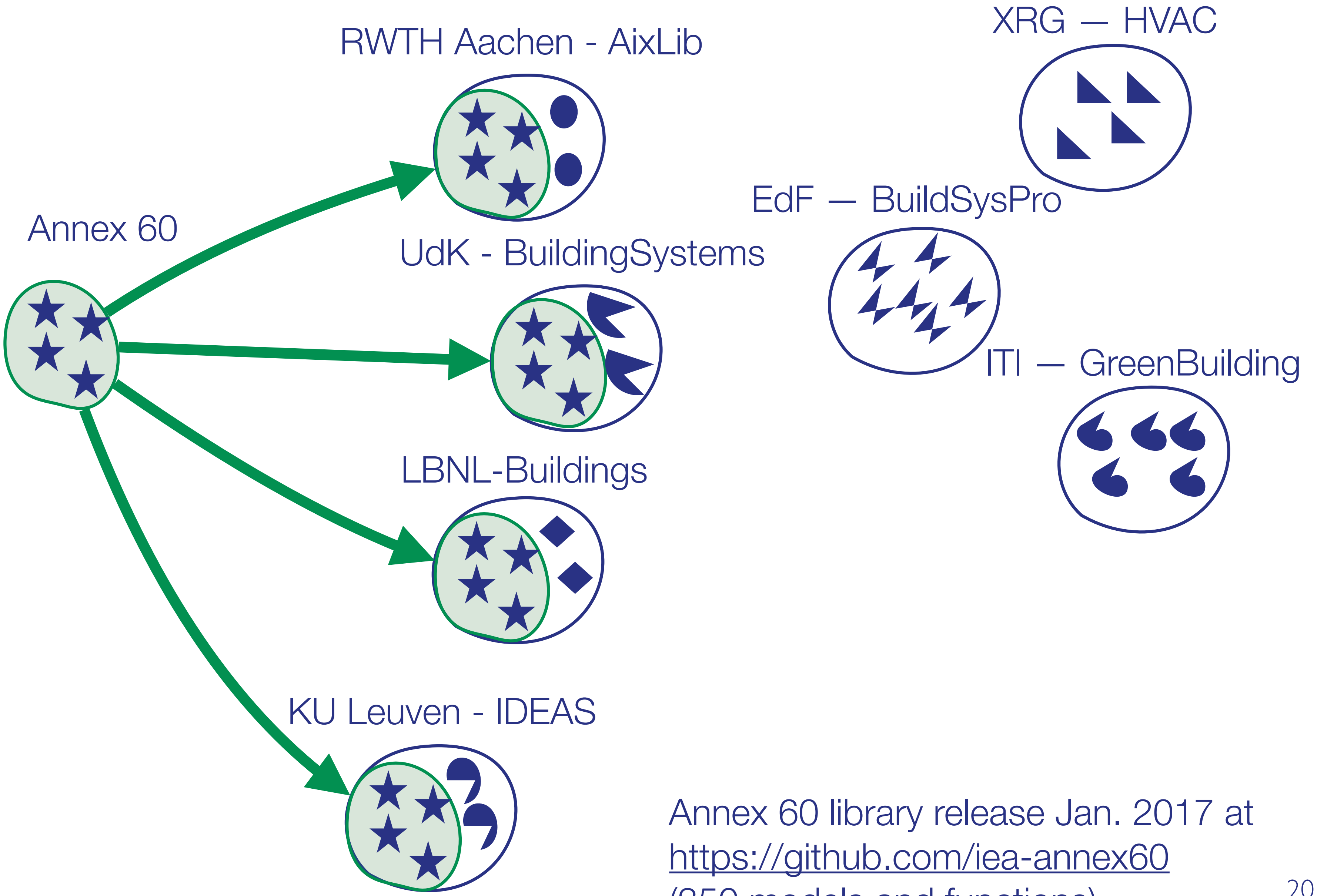
UdK - BuildingSystems

ITI — GreenBuilding

LBNL-Buildings

KU Leuven - IDEAS

At Building Simulation 2011, a joint effort started to avoid fragmentation, collaborate on development, implement best practices and share everything open-source and free



RWTH Aachen - AixLib

XRG — HVAC

EdF — BuildSysPro

Annex 60

UdK - BuildingSystems

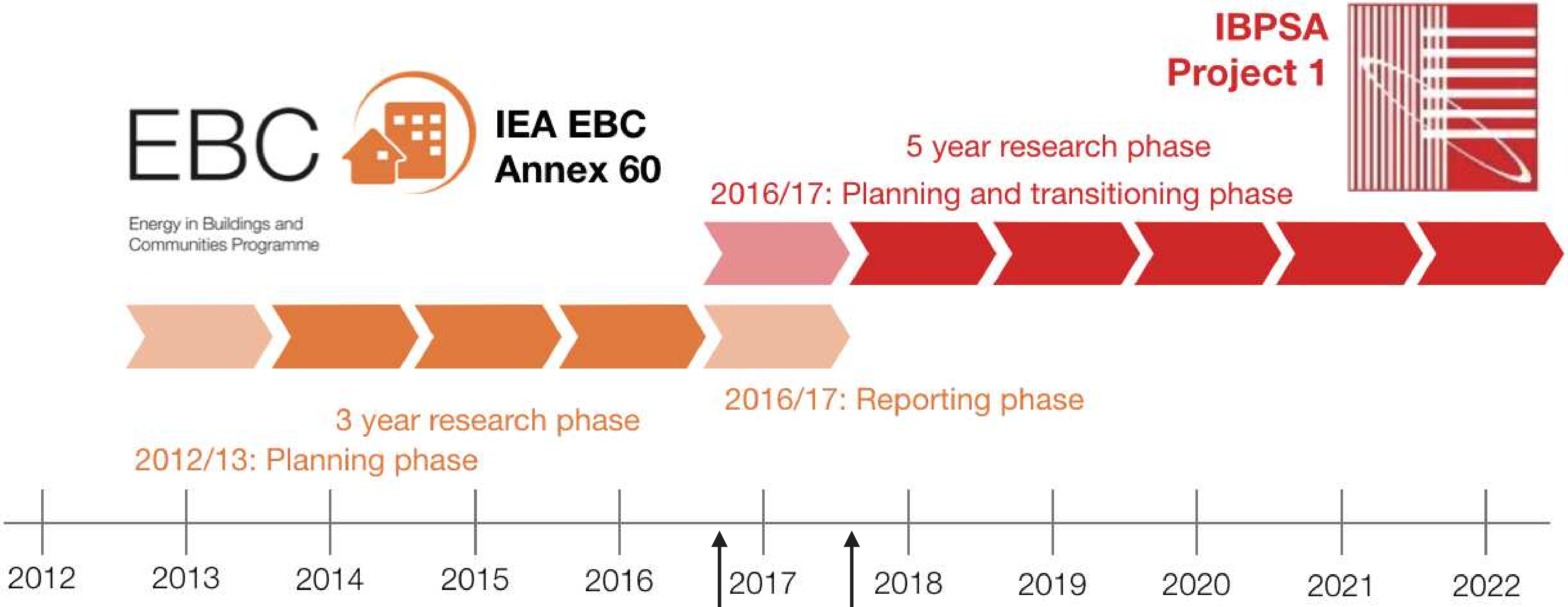
ITI — GreenBuilding

LBNL-Buildings

KU Leuven - IDEAS

Annex 60 library release Jan. 2017 at
https://github.com/iea-annex60
(350 models and functions)

Continue for next 5 years as an IBPSA project



08/17: Kick-off meeting at San Francisco, CA

10/16: Workshop, training and planning session
at Corsica, France.
65 attendees for 5 days.

https://ibpsa.github.io/project1/

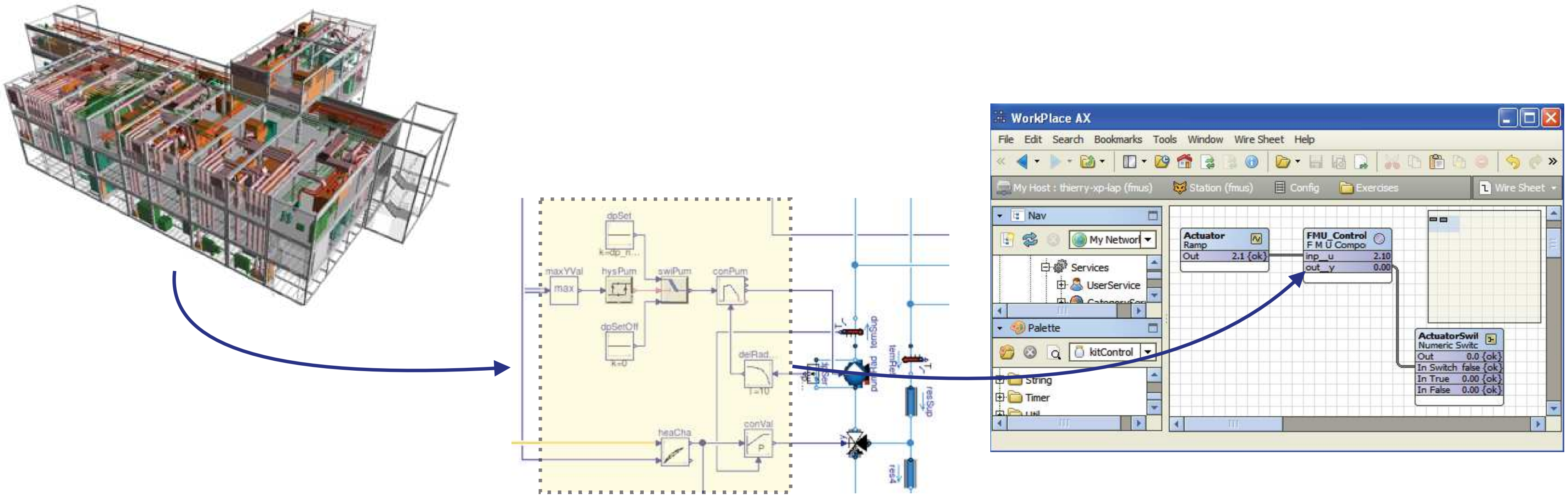
The vision of IBPSA Project 1 is to create open-source software that builds the basis of next generation computing tools for the buildings industry

Allow engineers and scientists to

1) drag and drop preconfigured, modifiable and scalable component models,

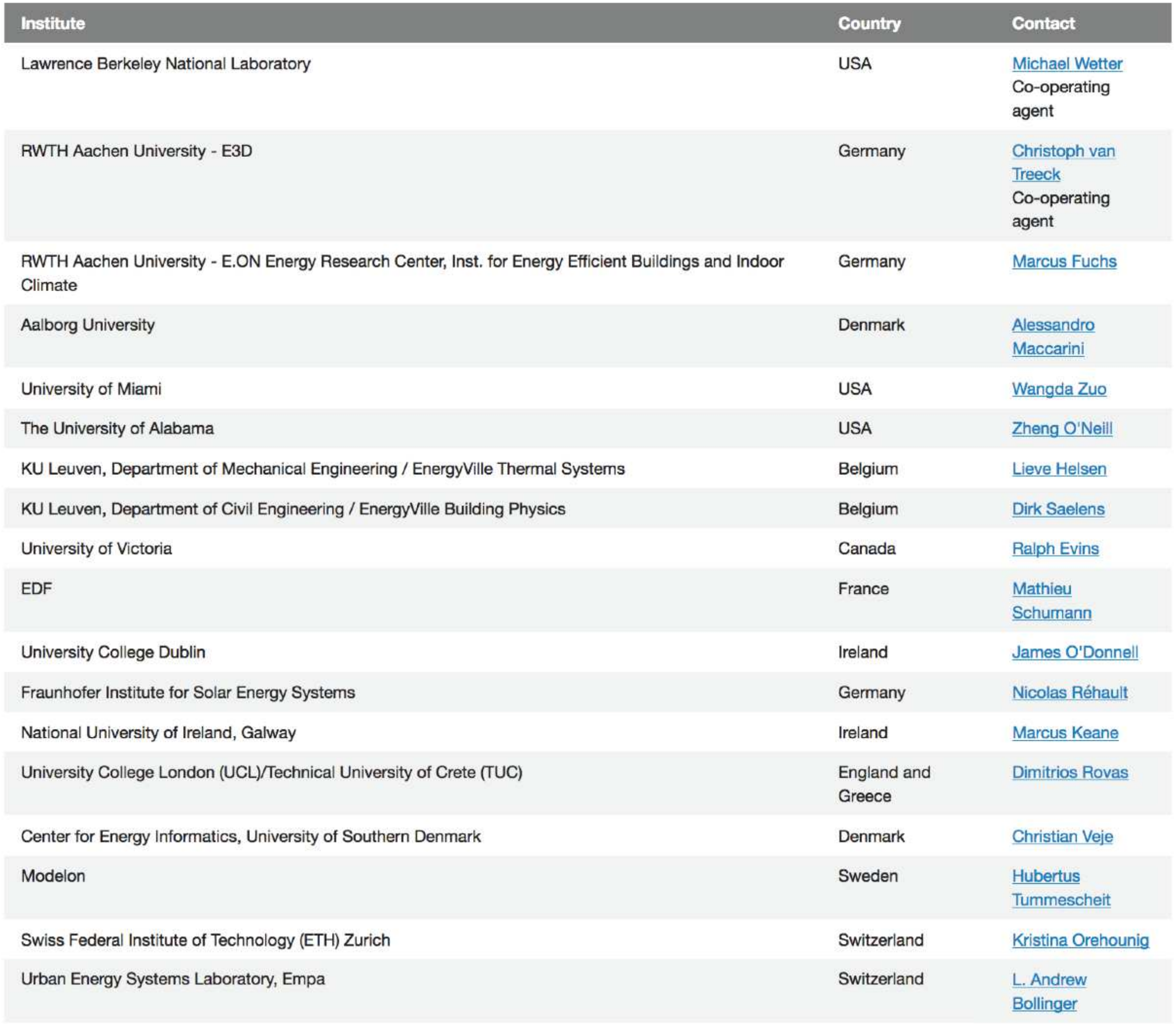
2) optimize the performance of technology options and control strategies, and

3) export models and control algorithms for co-simulation and operation.



Levels of participation

Organizational participants



Institute	Country	Contact
Lawrence Berkeley National Laboratory	USA	Michael Wetter Co-operating agent
RWTH Aachen University - E3D	Germany	Christoph van Treeck Co-operating agent
RWTH Aachen University - E.ON Energy Research Center, Inst. for Energy Efficient Buildings and Indoor Climate	Germany	Marcus Fuchs
Aalborg University	Denmark	Alessandro Maccarini
University of Miami	USA	Wangda Zuo
The University of Alabama	USA	Zheng O'Neill
KU Leuven, Department of Mechanical Engineering / EnergyVille Thermal Systems	Belgium	Lieve Helsen
KU Leuven, Department of Civil Engineering / EnergyVille Building Physics	Belgium	Dirk Saelens
University of Victoria	Canada	Ralph Evins
EDF	France	Mathieu Schumann
University College Dublin	Ireland	James O'Donnell
Fraunhofer Institute for Solar Energy Systems	Germany	Nicolas Réhault
National University of Ireland, Galway	Ireland	Marcus Keane
University College London (UCL)/Technical University of Crete (TUC)	England and Greece	Dimitrios Rovas
Center for Energy Informatics, University of Southern Denmark	Denmark	Christian Veje
Modelon	Sweden	Hubertus Tummescheit
Swiss Federal Institute of Technology (ETH) Zurich	Switzerland	Kristina Orehounig
Urban Energy Systems Laboratory, Empa	Switzerland	L. Andrew Bollinger

Individual participants

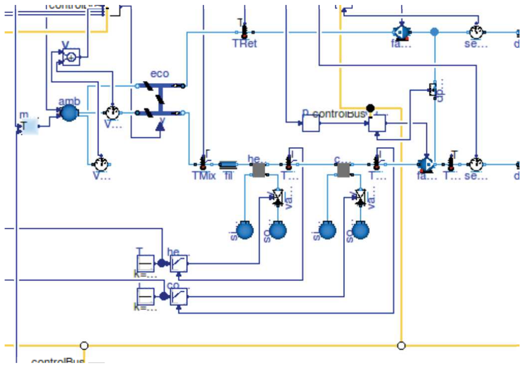
Name	Affiliation	Country
Ruben Baetens	3E	Belgium
Susana Lopez	IK4-TEKNIKER	Spain

Sponsoring participants

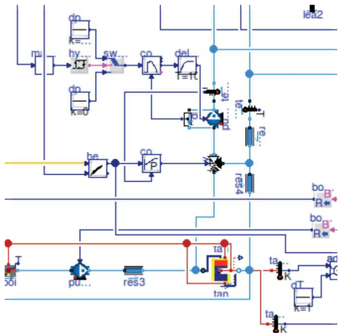
Company	Country	Contact
Mitsubishi Electric Research Laboratories	USA	Scott Bortoff

Buildings library: 500+ validated, free, open-source models

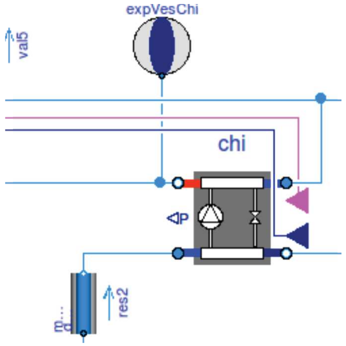
Air-based HVAC



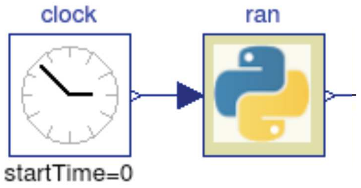
Hydronic heating



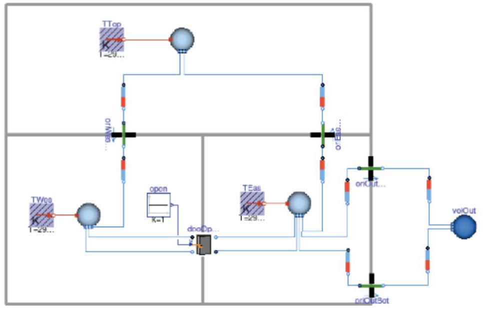
Chiller plants



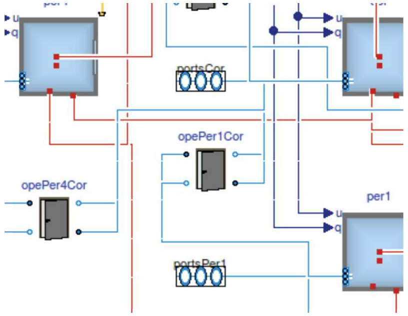
Embedded Python



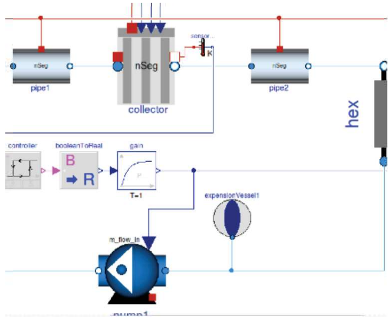
Natural ventilation,
multizone air exchange,
contaminant transport



Room heat transfer,
incl. window (TARCOG)

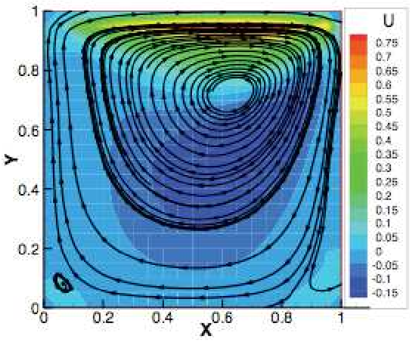


Solar collectors

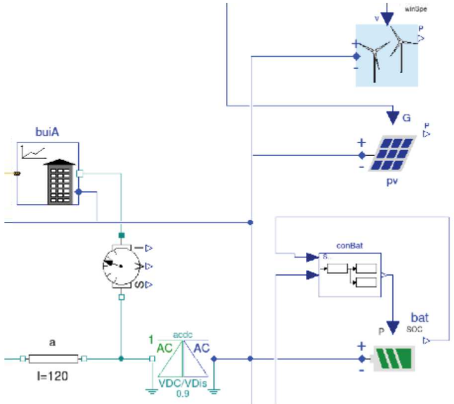


FLEXLAB

Room air flow



Electrical systems



Next release

Reduced order building models for city-scale simulation.

Heating/cooling piping networks for districts.

Heat pump models

Current development:

Make it the core of the Spawn of EnergyPlus.

Develop building control design, specification, deployment and verification tool.

simulationresearch.lbl.gov/modelica

Michael Wetter, Wangda Zuo, Thierry S. Nouidui and Xiufeng Pang. Modelica Buildings library. Journal of Building Performance Simulation, 7(4):253-270, 2014.

Challenges & Needs:
EnergyPlus whole building energy simulation program

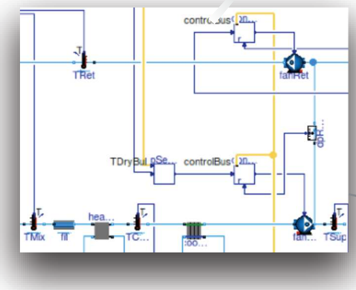
750,000+ lines of C++ code & 4,500+ pages of documentation

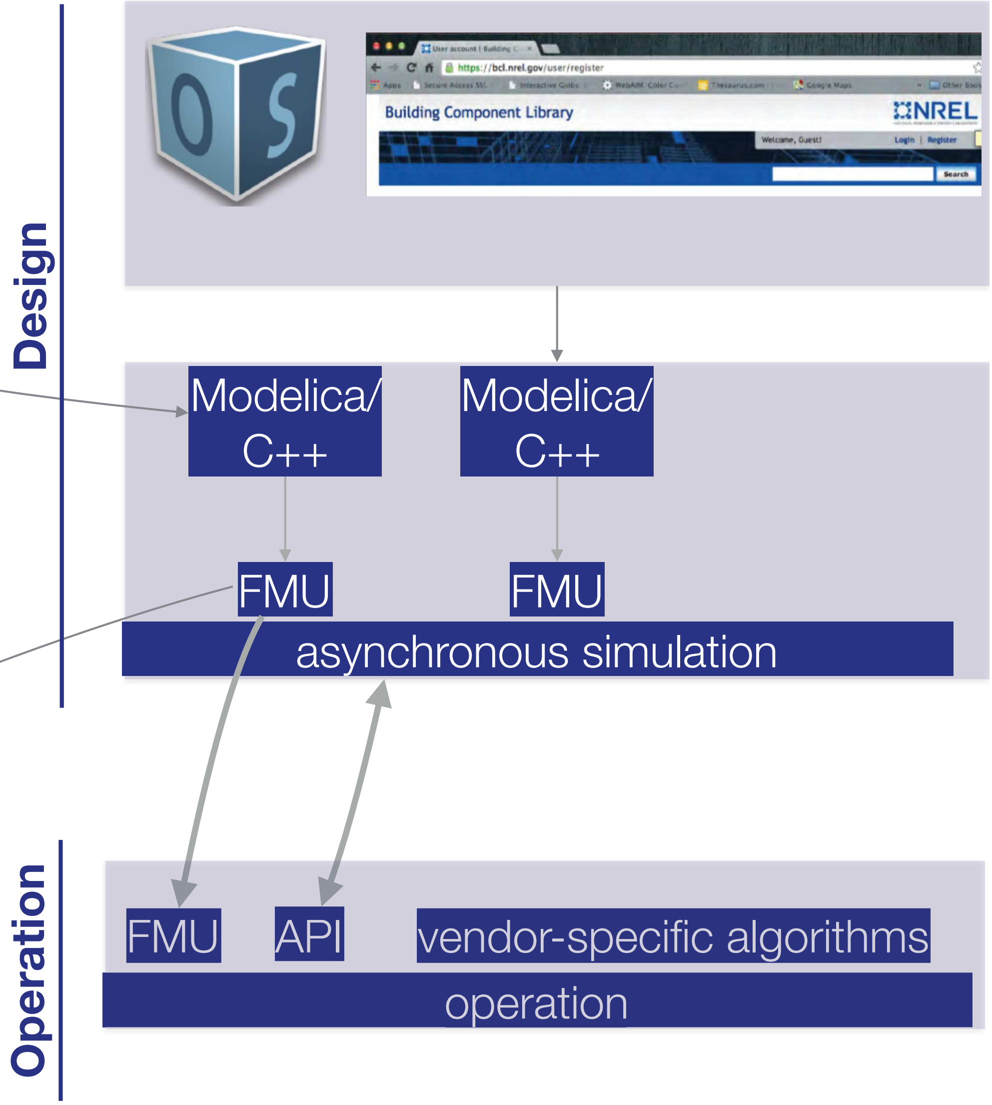
Still more than 20x slower than DOE-2, how much of this is detailed physics?

Catching up to, then keeping up with, HVAC, refrigeration & controls advances

Design (and towards operation):
Spawn of EnergyPlus —
Modularize EnergyPlus using open standards

Buildings library





Design

Modelica/ C++

Modelica/ C++

FMU

FMU

asynchronous simulation

Operation

FMU

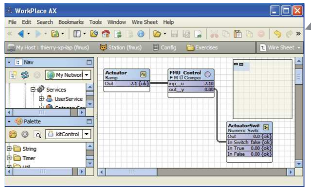
API

vendor-specific algorithms

operation

Spawn-of-EnergyPlus

- Modular
- Standard interfaces (FMUs)
- Support insertion of custom models and computing modules
- Inter-operability with control workflows and product development

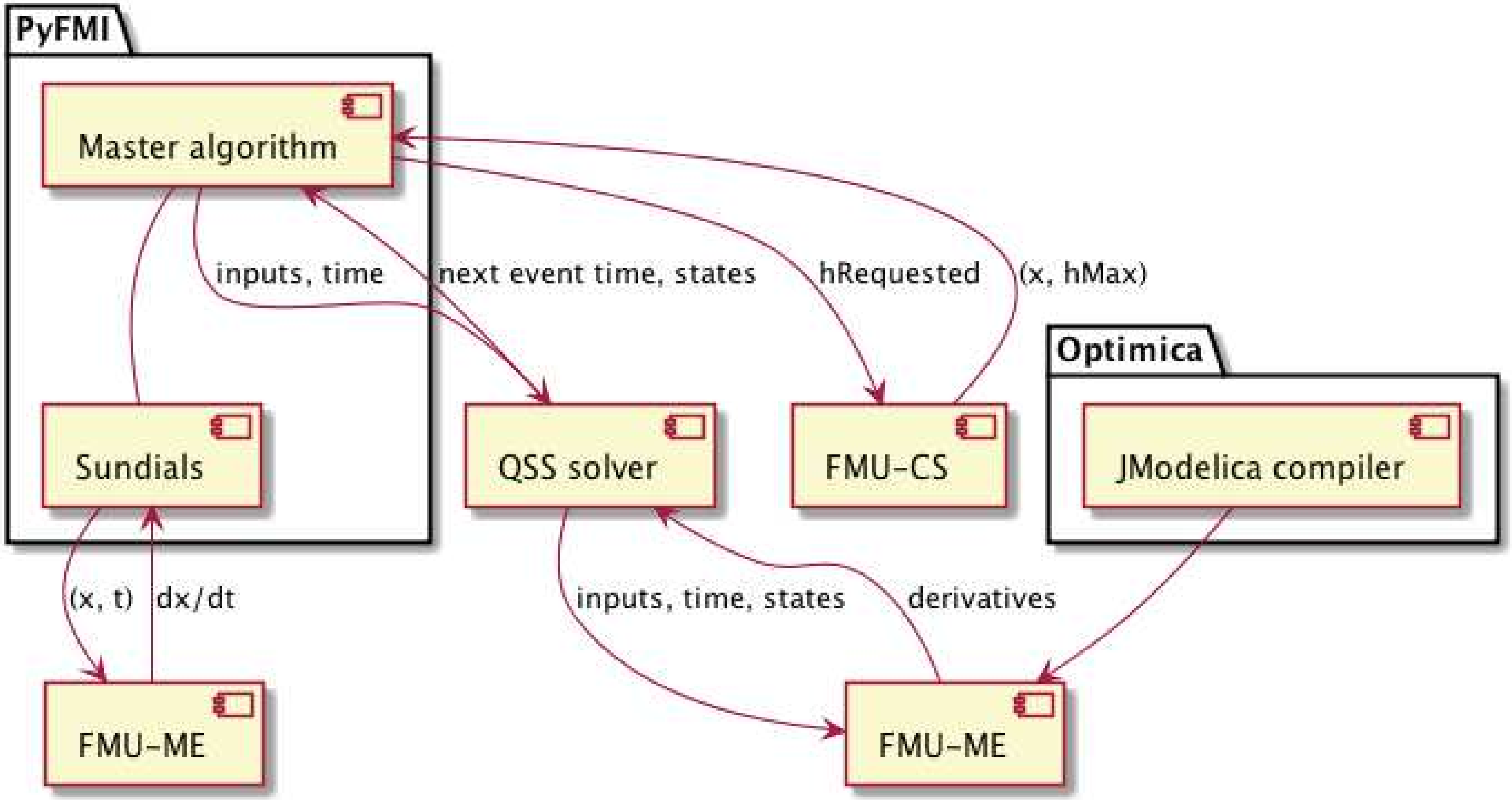


Automatic code generation from Modelica to, e.g., Niagara

https://lbl-srg.github.io/soep/

Design (and towards operation): Spawn of EnergyPlus — Modularize EnergyPlus using open standards

Software architecture for QSS integration with JModelica with extended FMI API

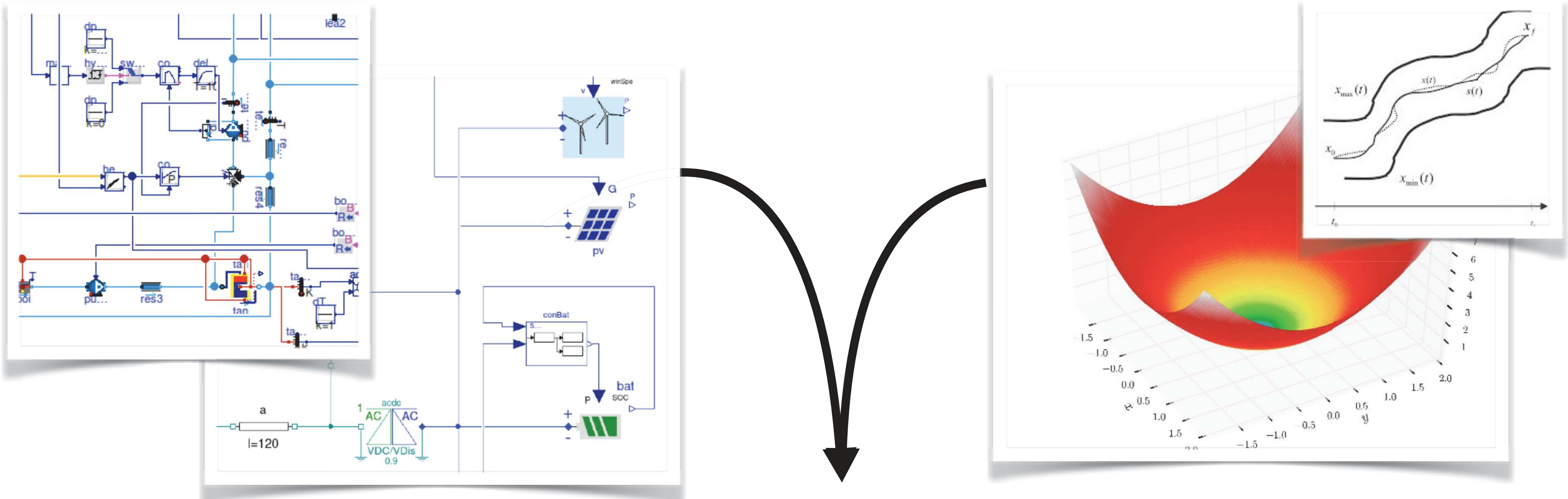


https://lbl-srg.github.io/soep/

Operation:
Bridging the gap between the silos of modeling and optimization

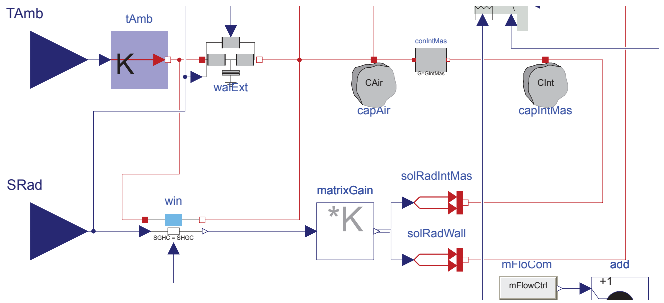
Repository of models

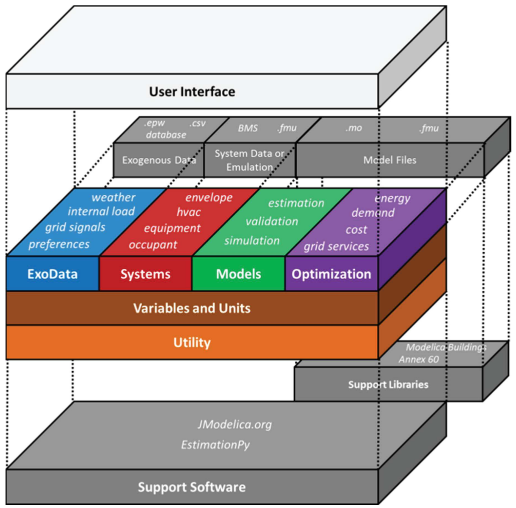
Repository of optimization algorithms

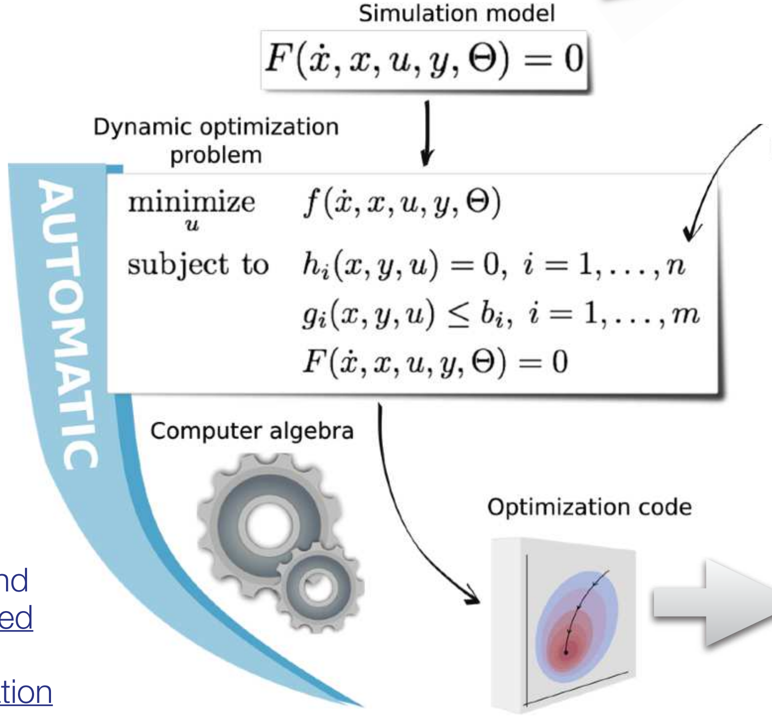


Framework for combining models and optimization

Operation:
Bridging the gap between the silos of modeling and optimization to improve building operation







$$F(\dot{x}, x, u, y, \Theta) = 0$$

$$\begin{aligned} \underset{u}{\text{minimize}} \quad & f(\dot{x}, x, u, y, \Theta) \\ \text{subject to} \quad & h_i(x, y, u) = 0, \; i = 1, \dots, n \\ & g_i(x, y, u) \le b_i, \; i = 1, \dots, m \\ & F(\dot{x}, x, u, y, \Theta) = 0 \end{aligned}$$

Define cost function and constraints

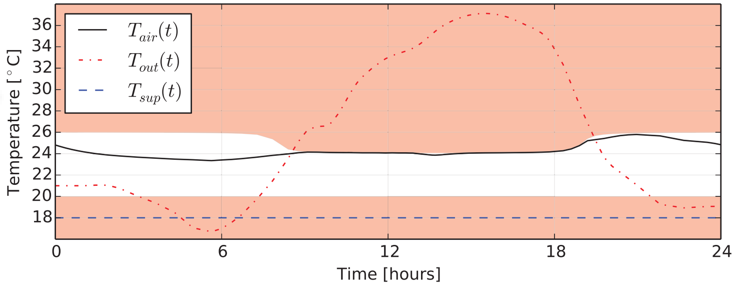
MPCPy: An Open-Source Software Platform for Model Predictive Control in Buildings. David Blum and Michael Wetter. In review.

Michael Wetter, Marco Bonvini and Thierry S. Nouidui. Equation-based languages - A new paradigm for building energy modeling, simulation and optimization. Energy and Buildings, 117(1), p. 290-300, 2016. doi: 10.1016/j.enbuild.2015.10.017

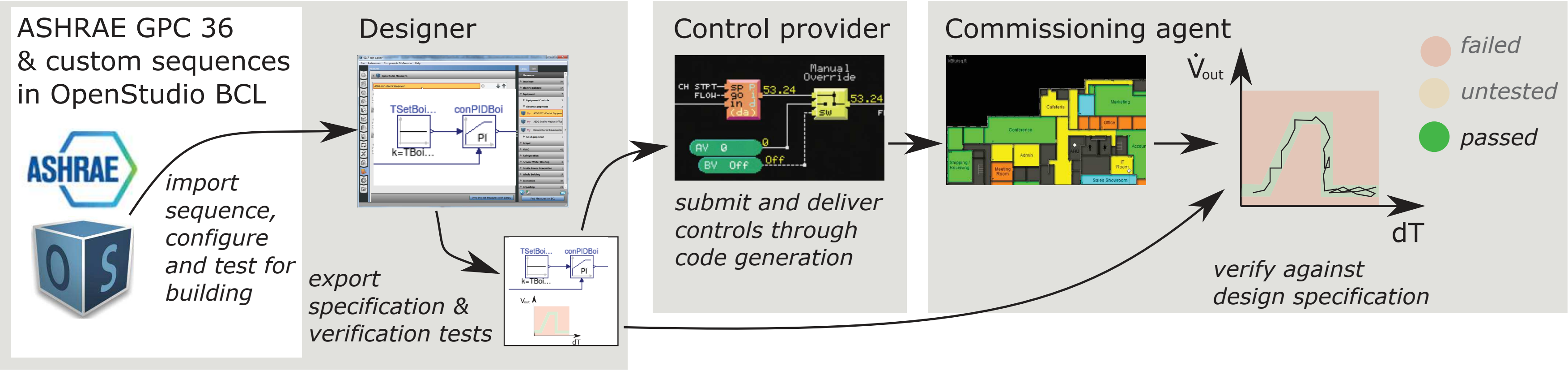
Time required to compute optimal control function:

JModelica with collocation: 8 seconds

Nelder Mead: 5 hours



Design to operation:
Bridging the gap through formal design, deployment and verification



ASHRAE GPC 36
& custom sequences
in OpenStudio BCL

import sequence, configure and test for building

Designer

export specification & verification tests

Control provider

submit and deliver controls through code generation

Commissioning agent

verify against design specification

Codify best practice

Design

Implement

Verify against original design intent

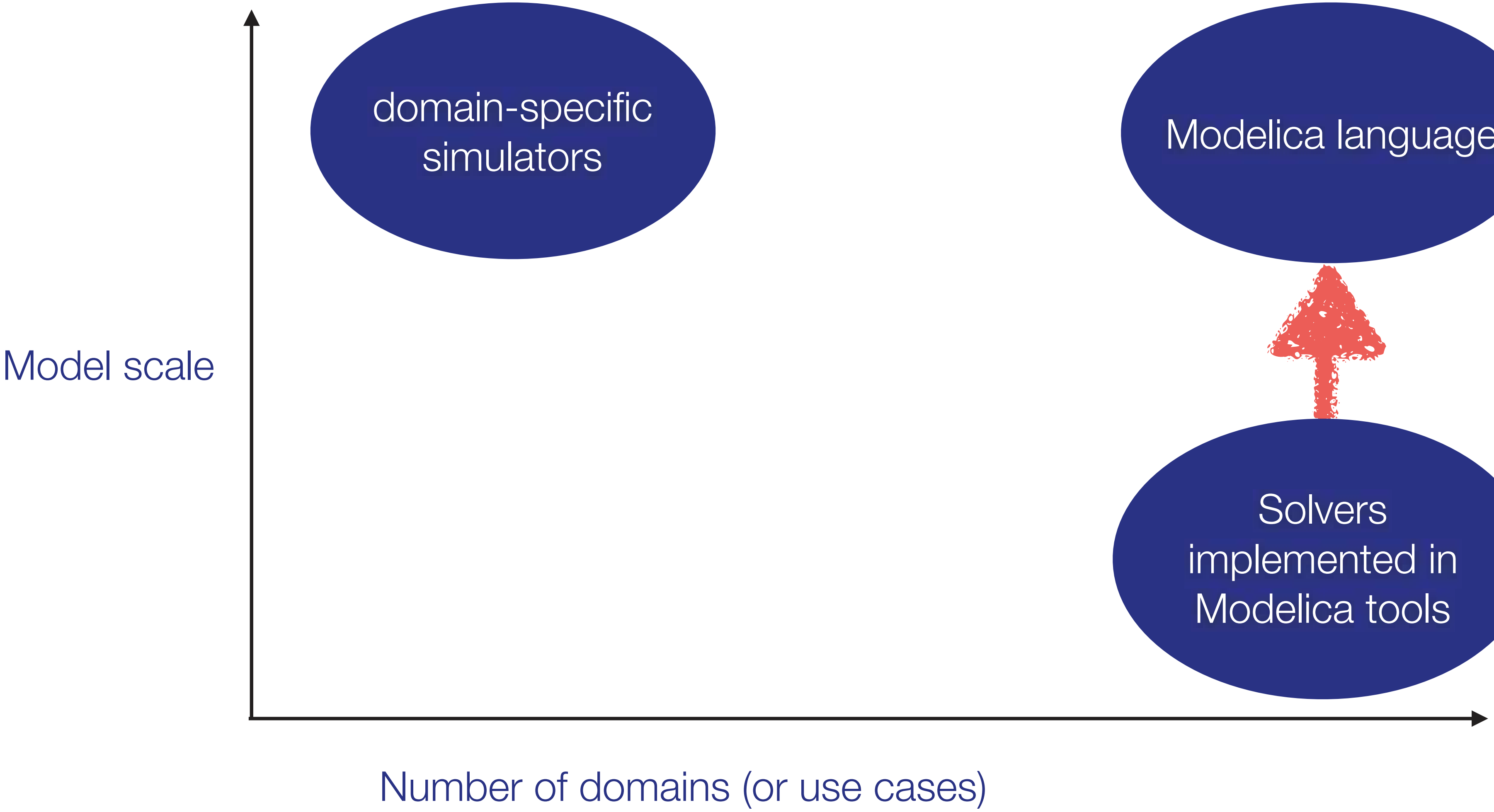
BACnet standardizes communication.

OpenBuildingControl will standardize expressing control sequences and functional tests for bidding, automatic implementation and automated functional testing.

http://obc.lbl.gov

Gaps

Scalability of simulation backend



domain-specific simulators

Modelica language

Solvers implemented in Modelica tools

Model scale

Number of domains (or use cases)

Physical: Controls, thermal, fluid, electrical.
Numerical: Continuous time, discrete time, events.

Use cases: Design, optimization, hardware-in-the-loop

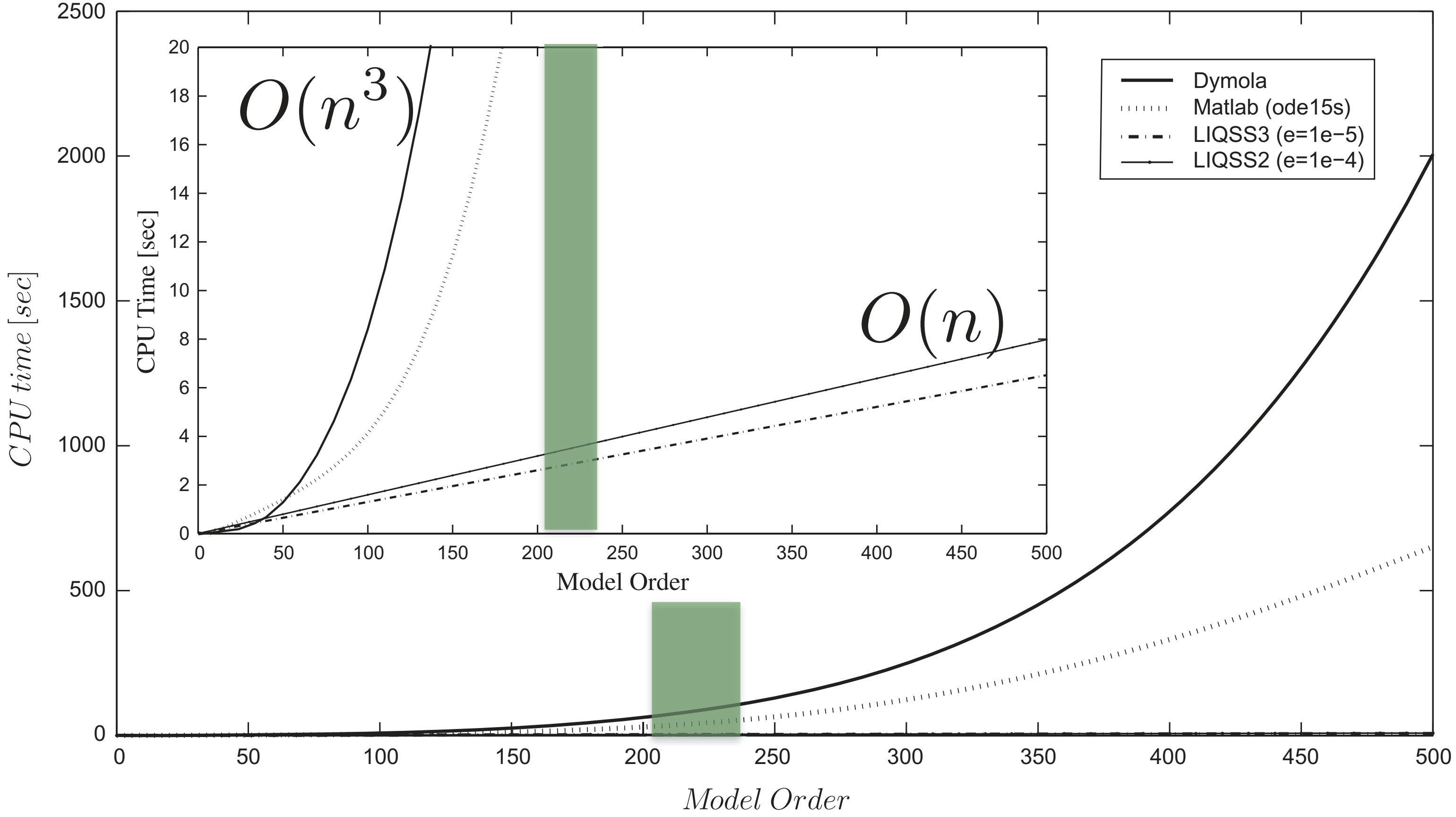
Typical building simulations VAV system serving 5 zones

	Dymola	EnergyPlus (idealized control & steady-state HVAC)
Translation time	30 s	
Compilation time	15 s	
CPU time	2 hours	40 seconds
# of states	220	
# time-varying variables	3800	
time constants	seconds to hours	

Why

- Using the same time step for each state?
- Translating and recompiling the whole model each time?
- Flattening the model, thereby removing structural information that could aid decomposition?

Scalability — Ordinary differential equations: QSS integration method is promising for our application domain



Migoni et al., Simulation Modelling Practice and Theory, 2013

Floros et al., Modelica conf. 2014:

- QSS was more than **2 orders of magnitude** faster than DASSL and Runge-Kutta
- QSS allowed to simulate **1000 times bigger models** than DASSL.

Scalability

Compilation

- Exploit repetitive structures and common subexpressions. [Bergero et al., 2015]
- Use of pre-compiled models?
- Compile large junks separately, and recompile only when needed.

Simulation [Casella 2015]

- Exploit sparsity
- Use different time steps for subsystems
- Handle events locally (Modelica language definition asks for global event handling)
- Address large scale algebraic constraints (e.g., electrical grid models, [Vanretti 2016])
- Infinite fast processes [Zimmer 2014]

- Automatically switch solvers & tearing set?

Model exchange

- FMI with array size determined at initialization.

Bergero, Botta, Campostrini, Kofman (2015): “Efficient Compilation of Large Scale Dynamical Systems“, Proc. of the 11th Int. Modelica Conf., doi: 0.3384/ecp15118449

Casella, Francesco (2015). "Simulation of Large-Scale Models in Modelica: State of the Art and Future Perspectives", Proc. of the 11th Int. Modelica Conf., doi:10.3384/ecp15118459

Vanretti, Rabuzin, Baudette, Murad (2016): “iTesla Power Systems Library (iPSL): A Modelica library for phasor time-domain simulations”, Software X, p.84-88, doi:10.1016/j.softx.2016.05.001

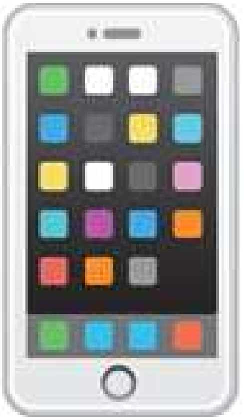
Deployment

User

- Modeling & simulation environment that don't cost 1,000s of Euros to just get started.

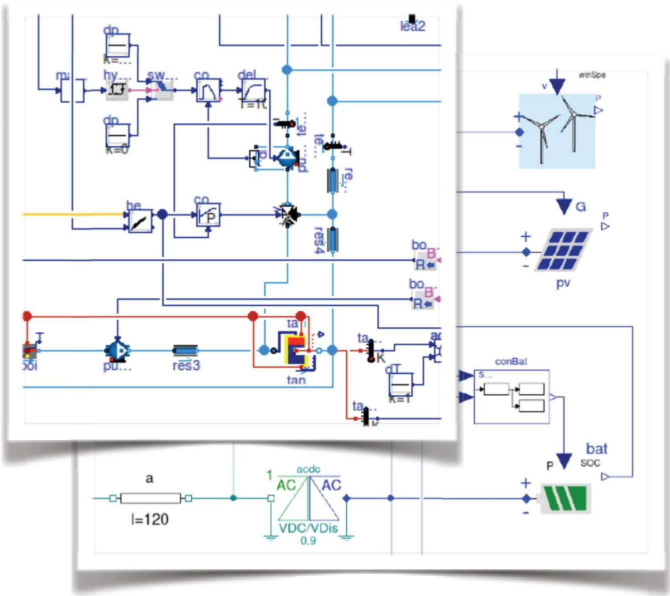
Tool developer

- Modelica parser and compiler that is easy to ship with other tools.
    - License
    - Installation
    - Code size

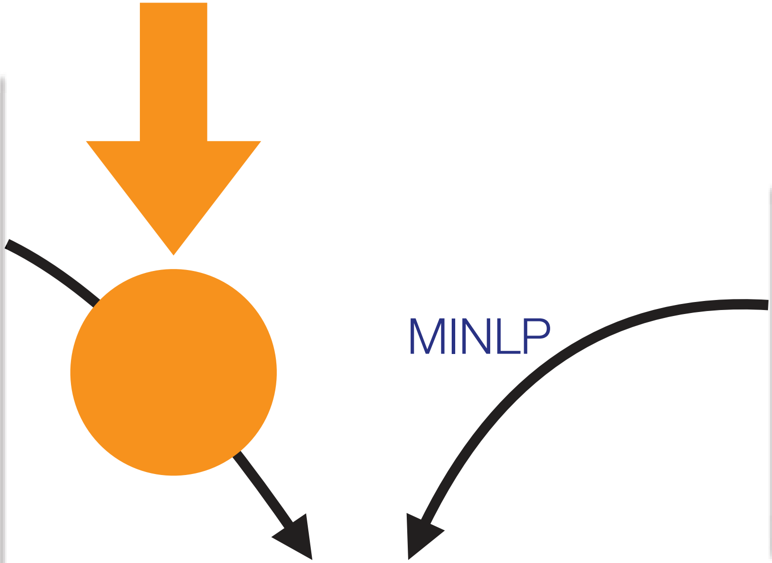


Optimization

Repository of models

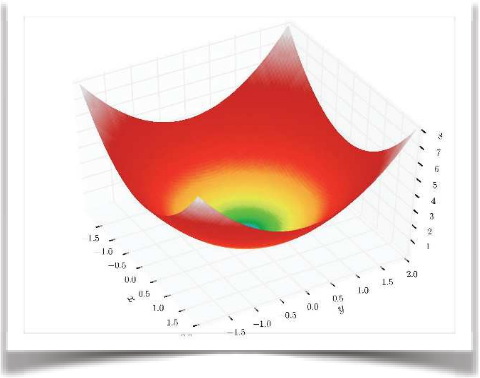


How do you transform models to fit optimization algorithms, and provide diagnostics to modeler?



MINLP

Repository of optimization algorithms



Framework for combining models and optimization

Fast translation, robust and fast simulators for large scale energy systems

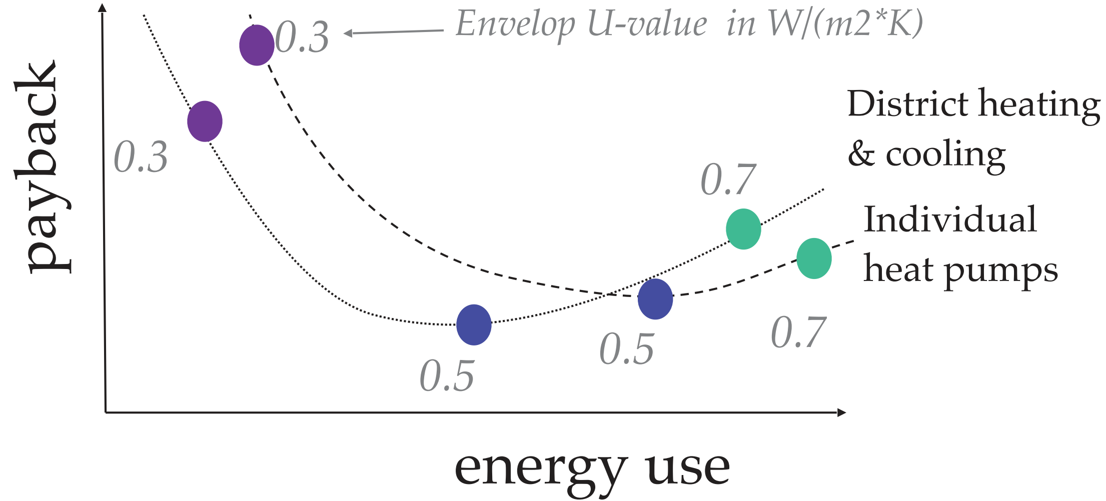
CityGML

Tool loads building stock data

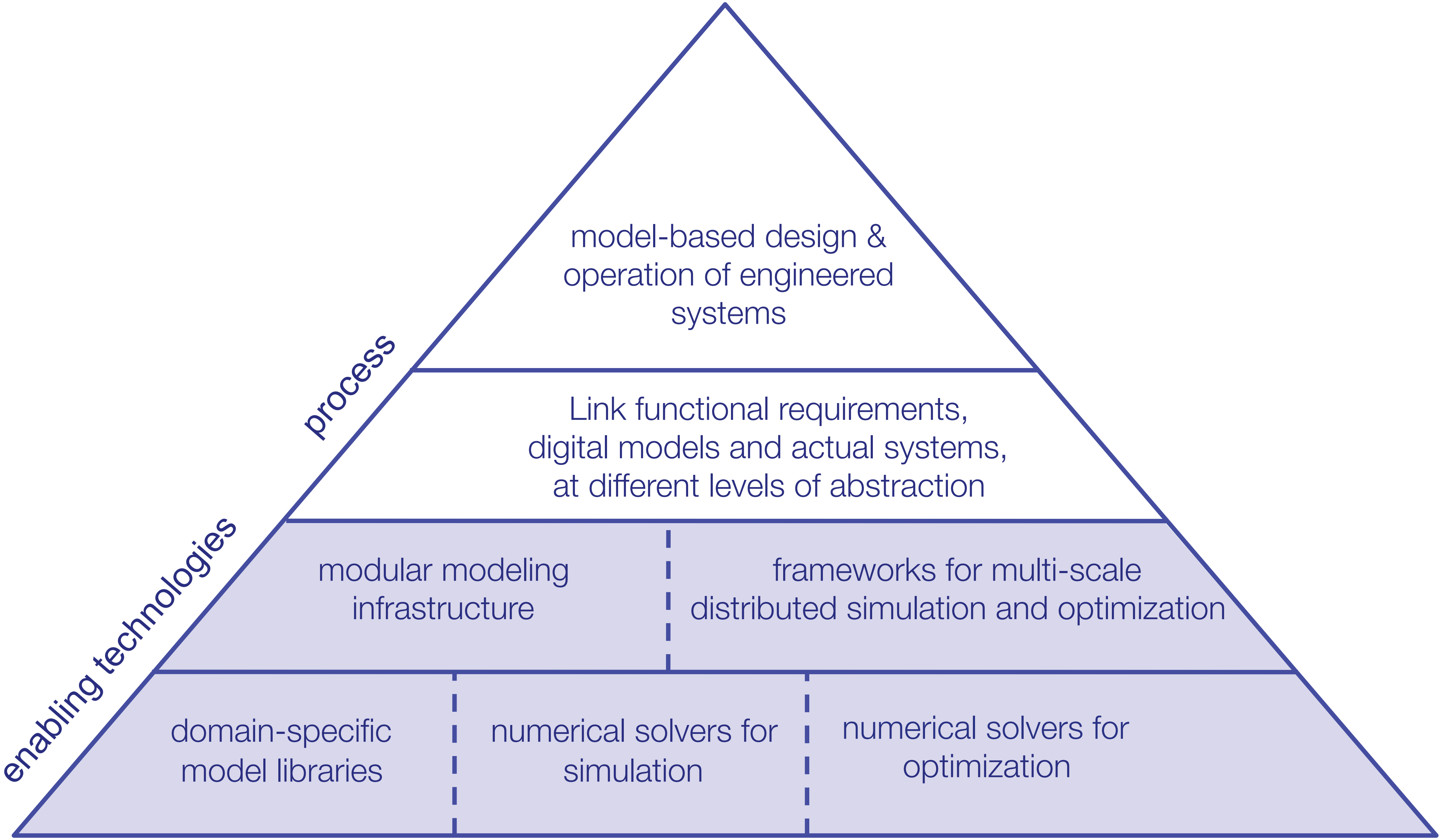
Tool optimizes system design & quantify performance

Energy consultant draws district energy system architecture

Tool outputs payback vs. energy reduction target for different architectures to inform design or incentive programs



R&D Needs



model-based design & operation of engineered systems

Link functional requirements, digital models and actual systems, at different levels of abstraction

modular modeling infrastructure

frameworks for multi-scale distributed simulation and optimization

domain-specific model libraries

numerical solvers for simulation

numerical solvers for optimization