Modelica Model Use During Operations:
Learnings from the Annex 60

Raymond Sterling

Informatics Research Unit for Sustainable Engineering (IRUSE) Galway
Department of Civil Engineering and Ryan Institute
National University of Ireland, Galway

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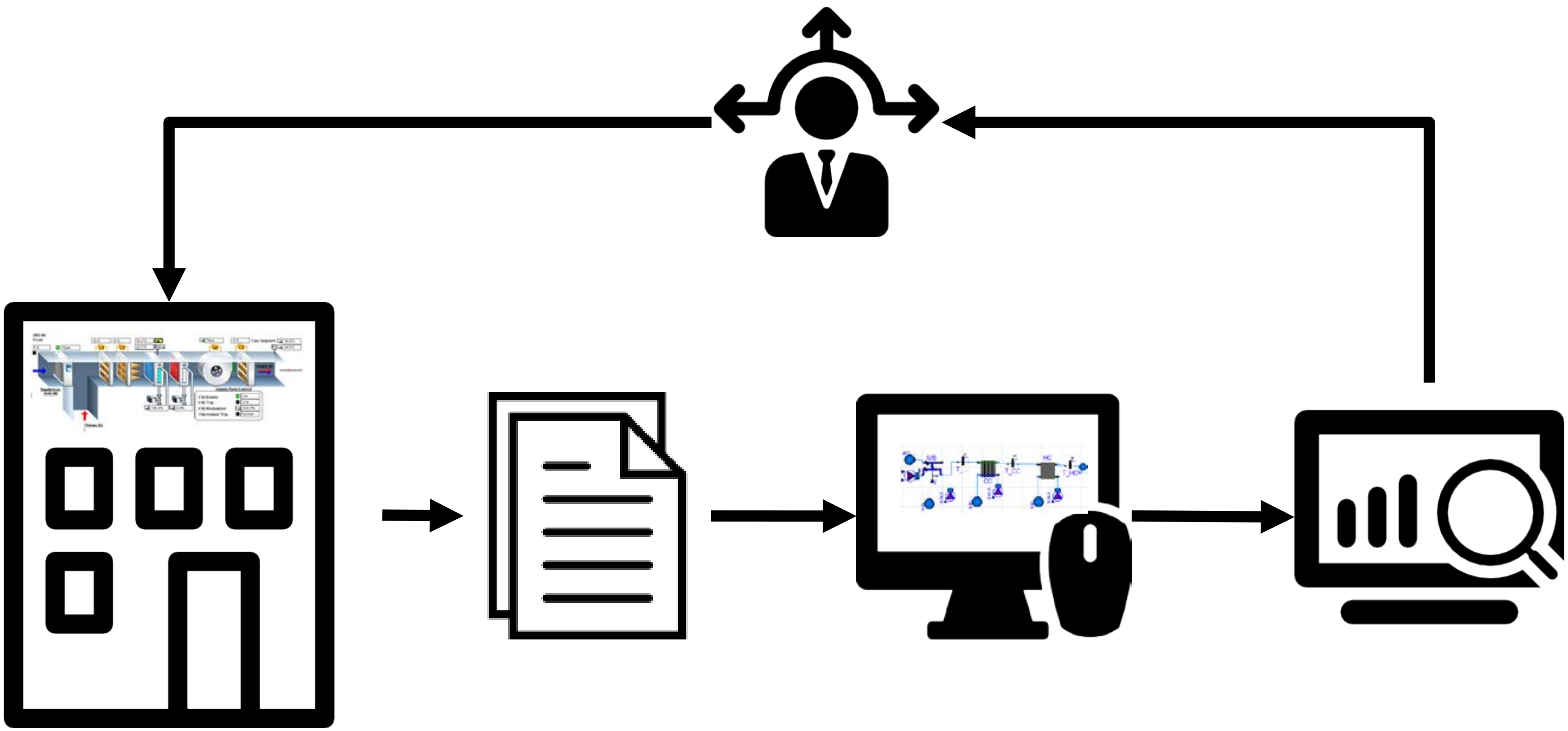
GENSIM Scientific School. Corsica, France

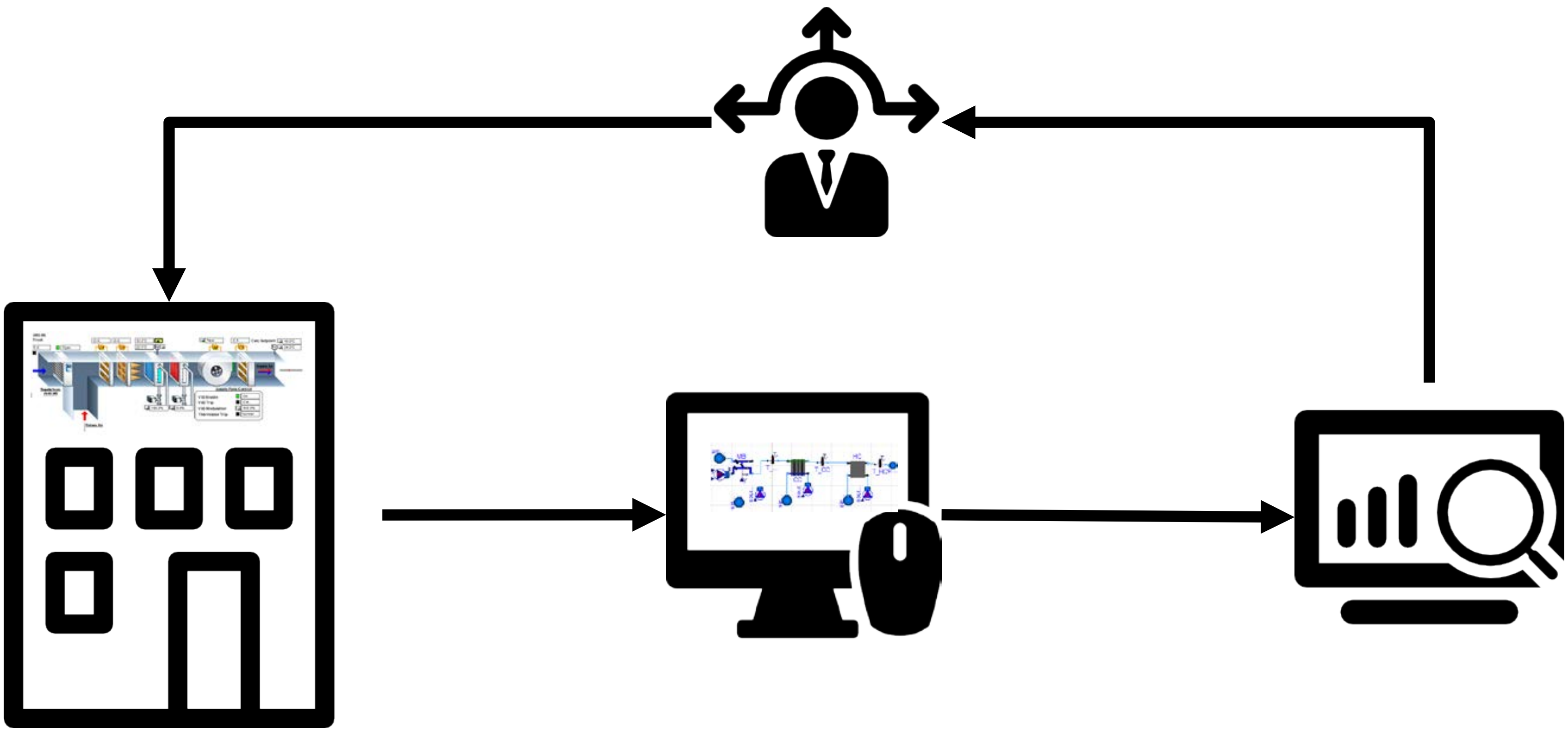
What is model use during operations?

- Use of models in conjunction with real data to understand and/or improve the performance of a system.
  - Model can be used offline, online or inline

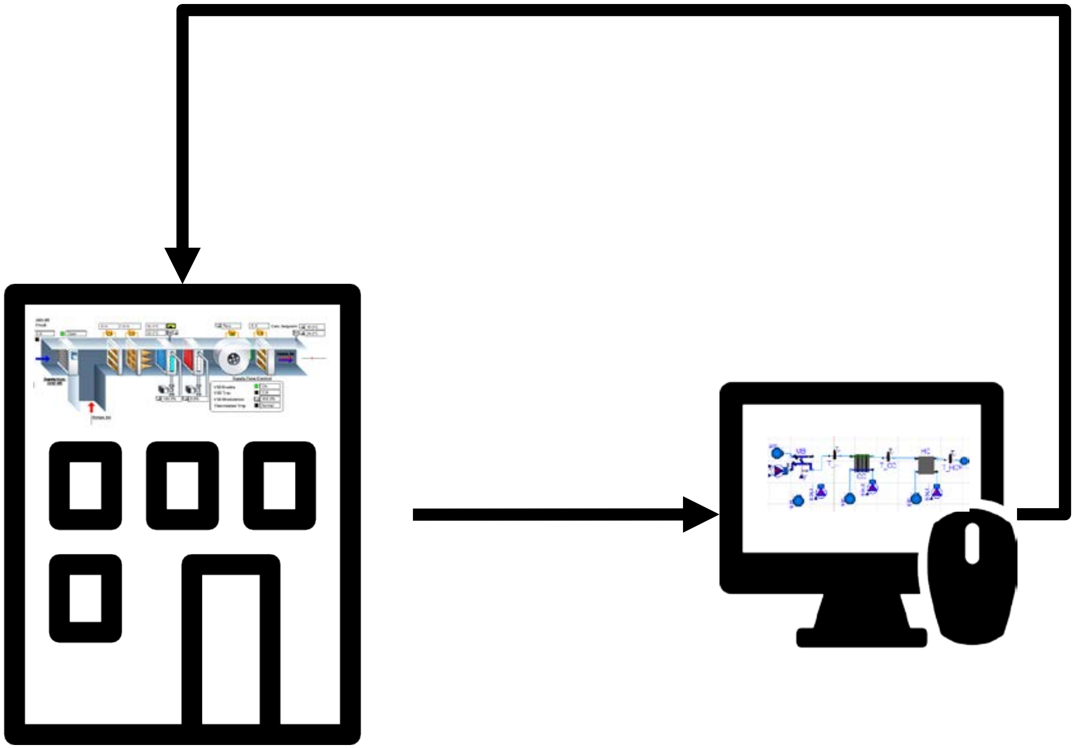
Model use during operations - **offline**



Model use during operations - **online**



Model use during operations - **inline**



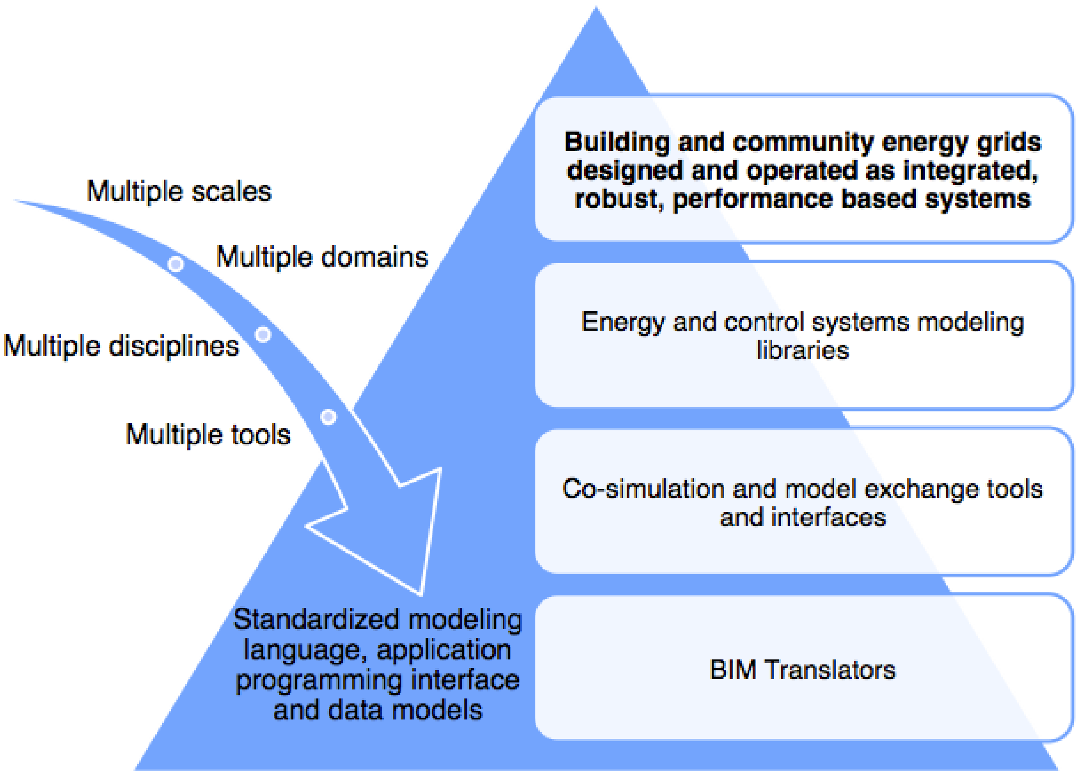
Typical issues

- Data quality
- Data quantity
- Access to data
- Access to documentation
- Availability for experimentation
- Cost of experimentation
- ...

The Annex 60

- The IEA EBC Annex 60 is developing and demonstrating new generation computational tools for building and community energy systems based on the non-proprietary Modelica modelling language and Functional Mock-up Interface standards.

- Activity 2.3 focuses on the use of models during building operations to augment monitoring, implement control algorithms and fault detection, and diagnostics methods



Activity 2.3 focus areas & projects

MPC

- UNIVPM
- KU Leuven
- University of Miami

HIL

- University of Alabama

FDD

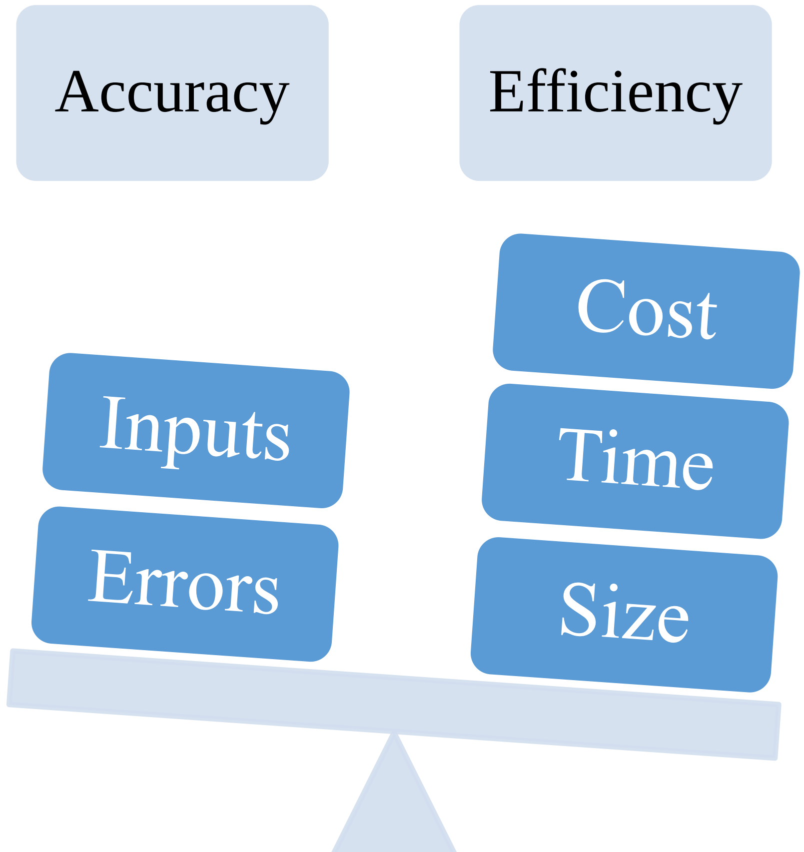
- Fraunhofer ISE
- LBNL
- NUI Galway
- KU Leuven

Model Predictive Control

- Use the model of the system to predict the future evolution. Some advantages:

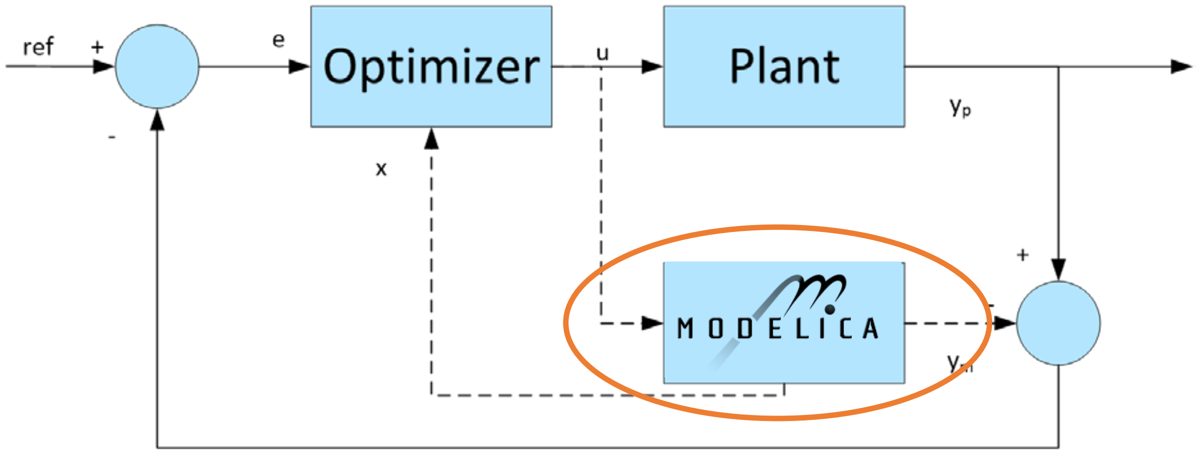
  - Explicitly formulates constrains
  - Explicitly uses a Model
  - Well understood tuning parameters
  - Less development time for complex systems
  - Improved prediction capability
  - Adaptability to varying conditions

Modelling for MPC – A balance

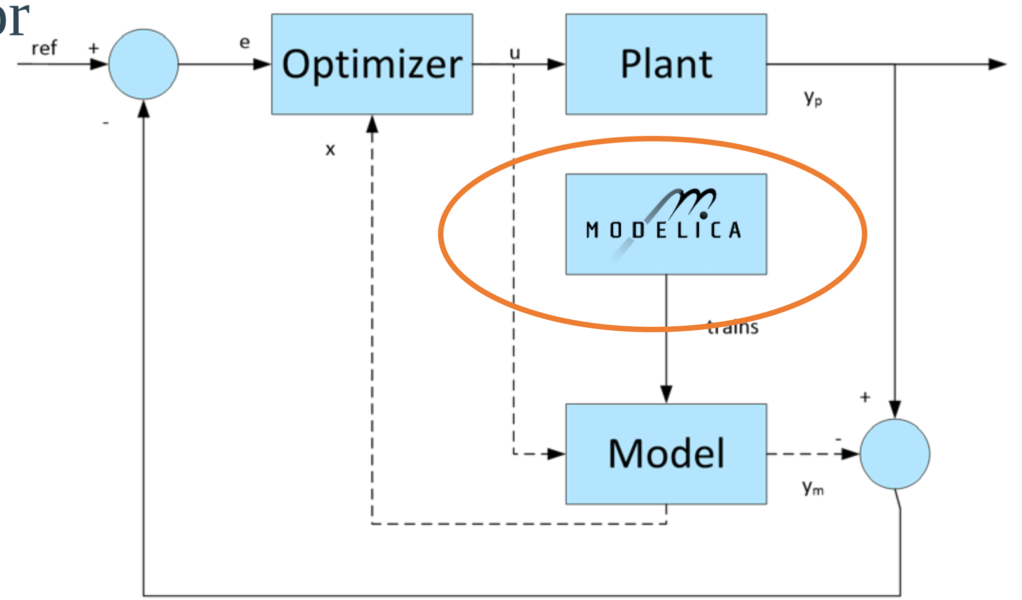


Modelica in the MPC Workflow Options

- Modelica model inline use

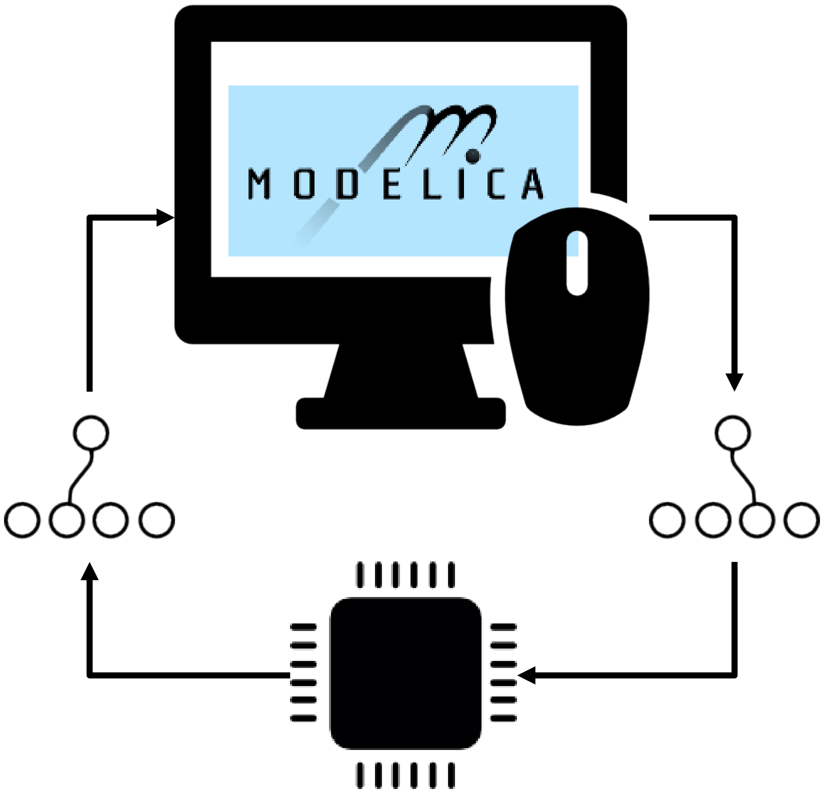


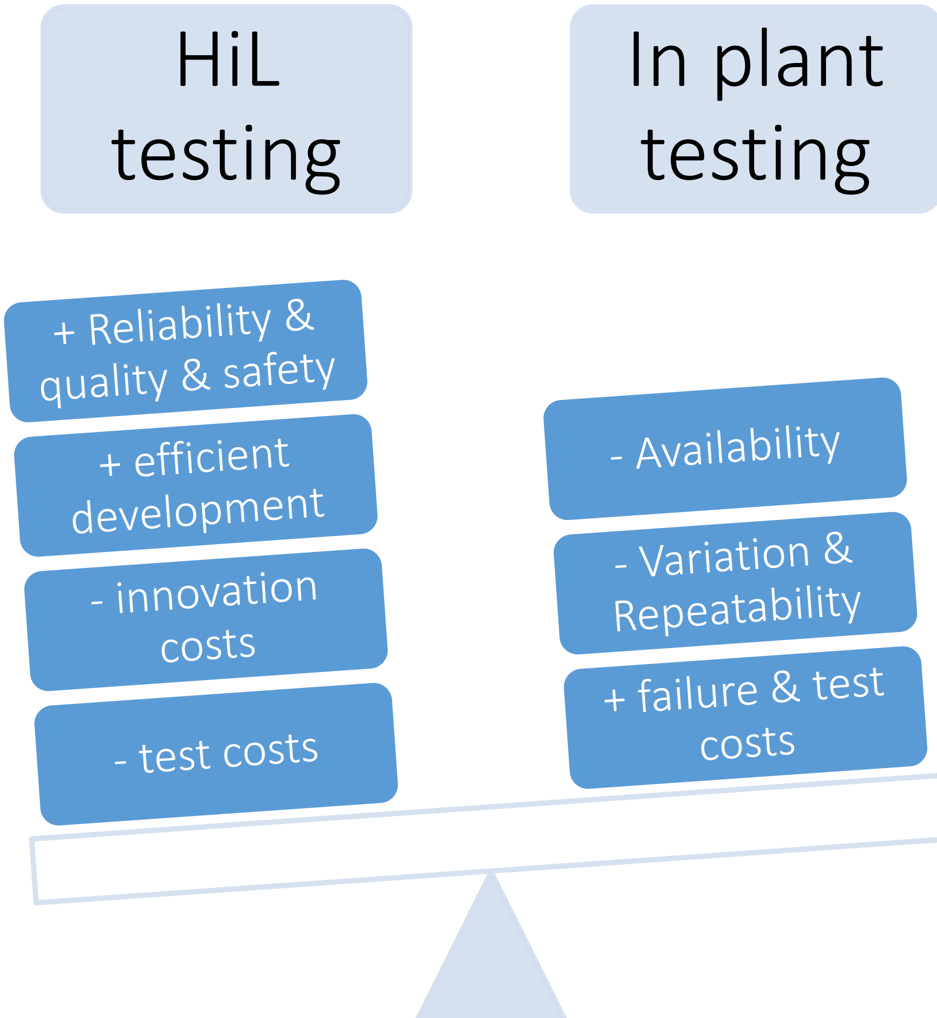
- Model as data generator for offline training



Hardware in the Loop (inline)

- Is a form of real time simulation that connects a model to hardware normally to test performance on emulated behaviour



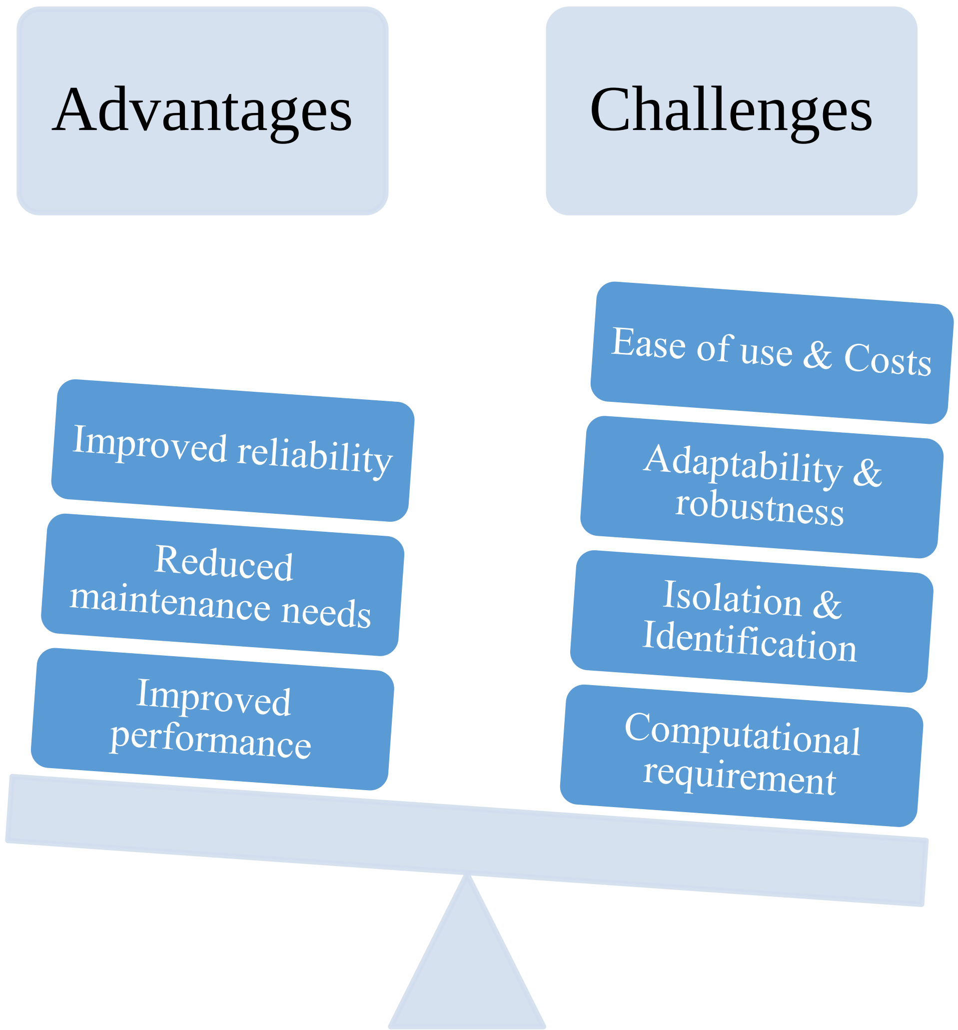


Fault Detection and Diagnosis

- (Automated) Realisation of performance lost and determination of root causes.
- The FDD process

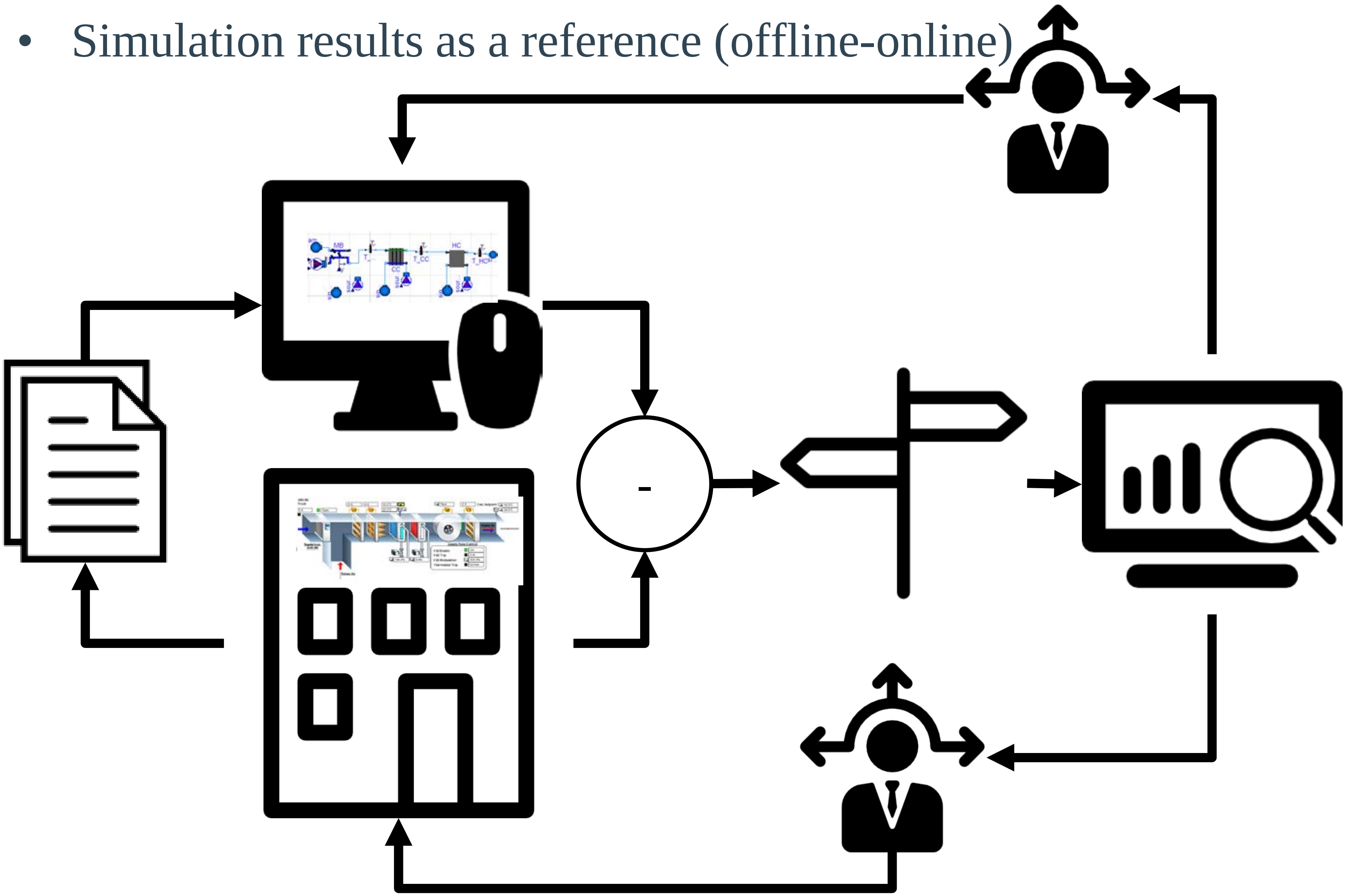
  - Measured values are different from model predicted ones
  - Each component is checked for intended operation
  - The ‘localized’ component is checked against a set of possible fault (covering the whole set of possible misbehaviours is normally non-practical)

FDD Advantages and Disadvantages



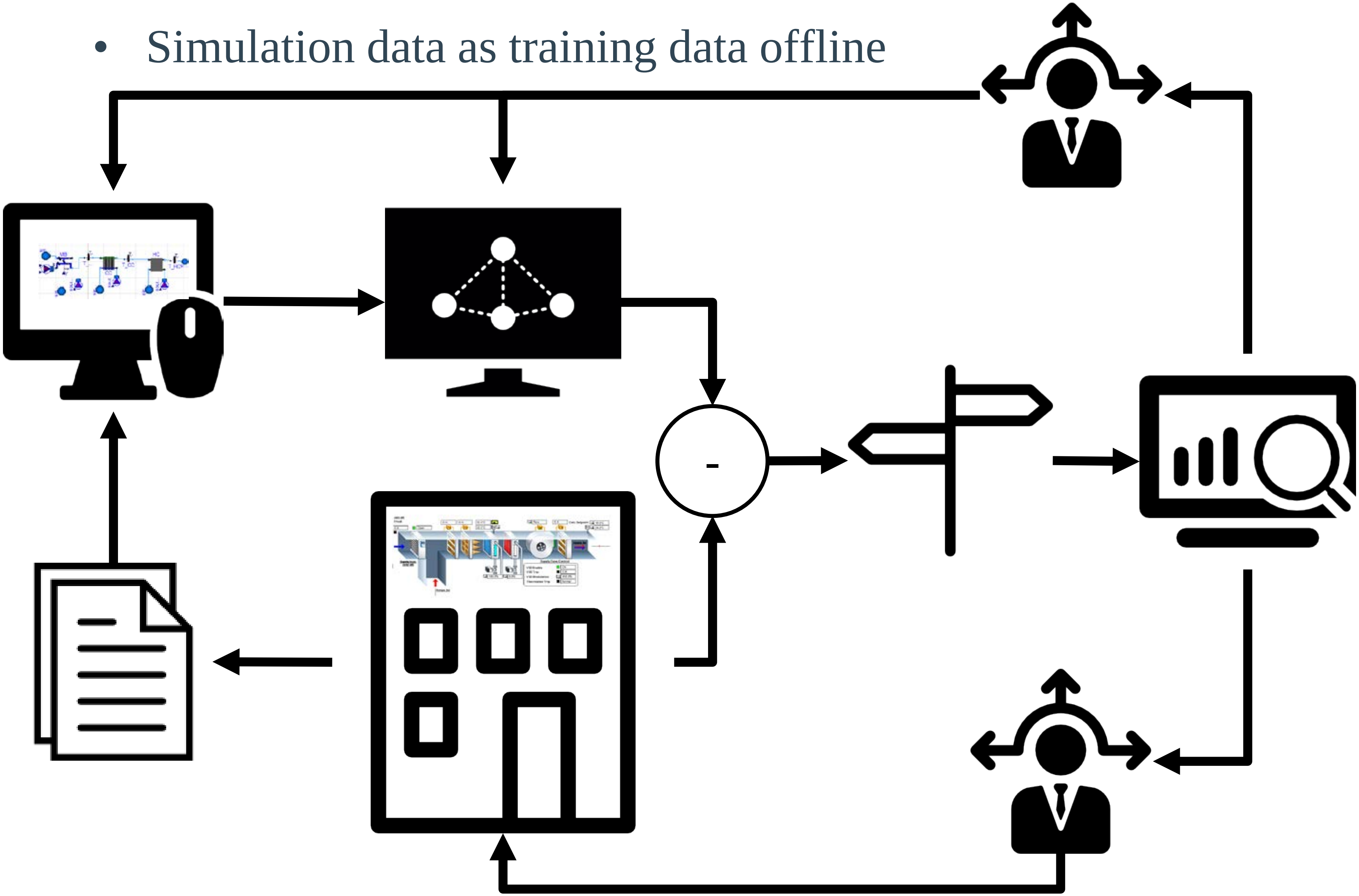
Modelica in the FDD workflow

- Simulation results as a reference (offline-online)

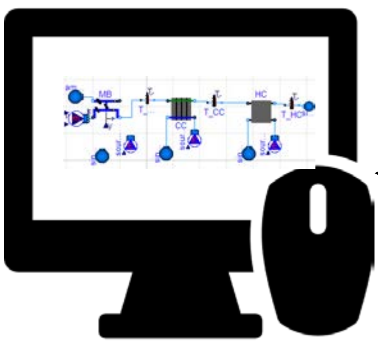


Modelica in the FDD workflow

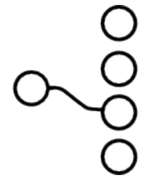
- Simulation data as training data offline

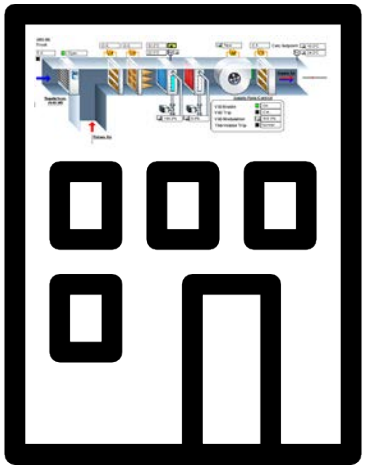


Some Modelica Interfacing Options



- FMI
- BCVTB
- Python
- C-code
- Matlab
- Simulink





Case Studies

MPC

- Energy Control Underground Public Spaces
- Chiller Plant
- Heat Pumps

HIL

- HVAC close-loop control

FDD

- AHU FD
- Chillers in District Cooling
- AHU FDD Automated Reasoning
- AHU FDD Grey Box

Università Politecnica delle Marche (Italy)

MPC

Energy Control Underground Public Spaces

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AHU FD

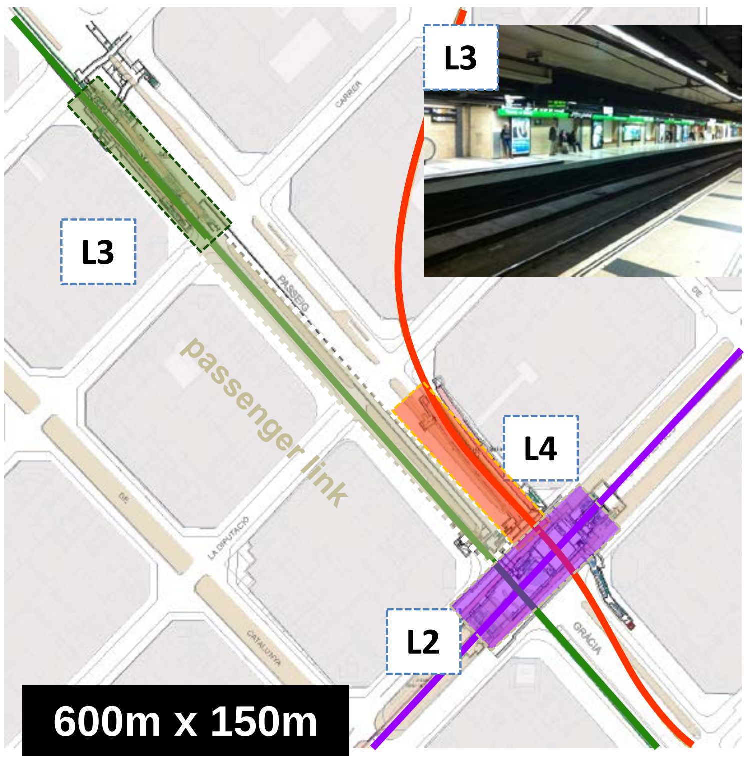
Chillers in District Cooling

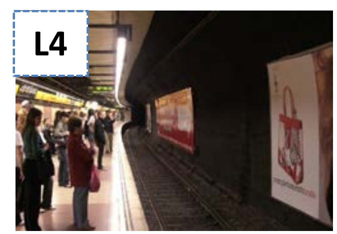
AHU FDD Automated Reasoning

AHU FDD Grey Box

Energy control of underground public spaces

This case study concerns the SEAM4US EU FP7 project (SEAM4US, 2014) pilot that has been deployed, since August 2014, in the Passeig de Gracia (PdG) Line 3 metro Station in Barcelona, Spain.





Train Platform levels

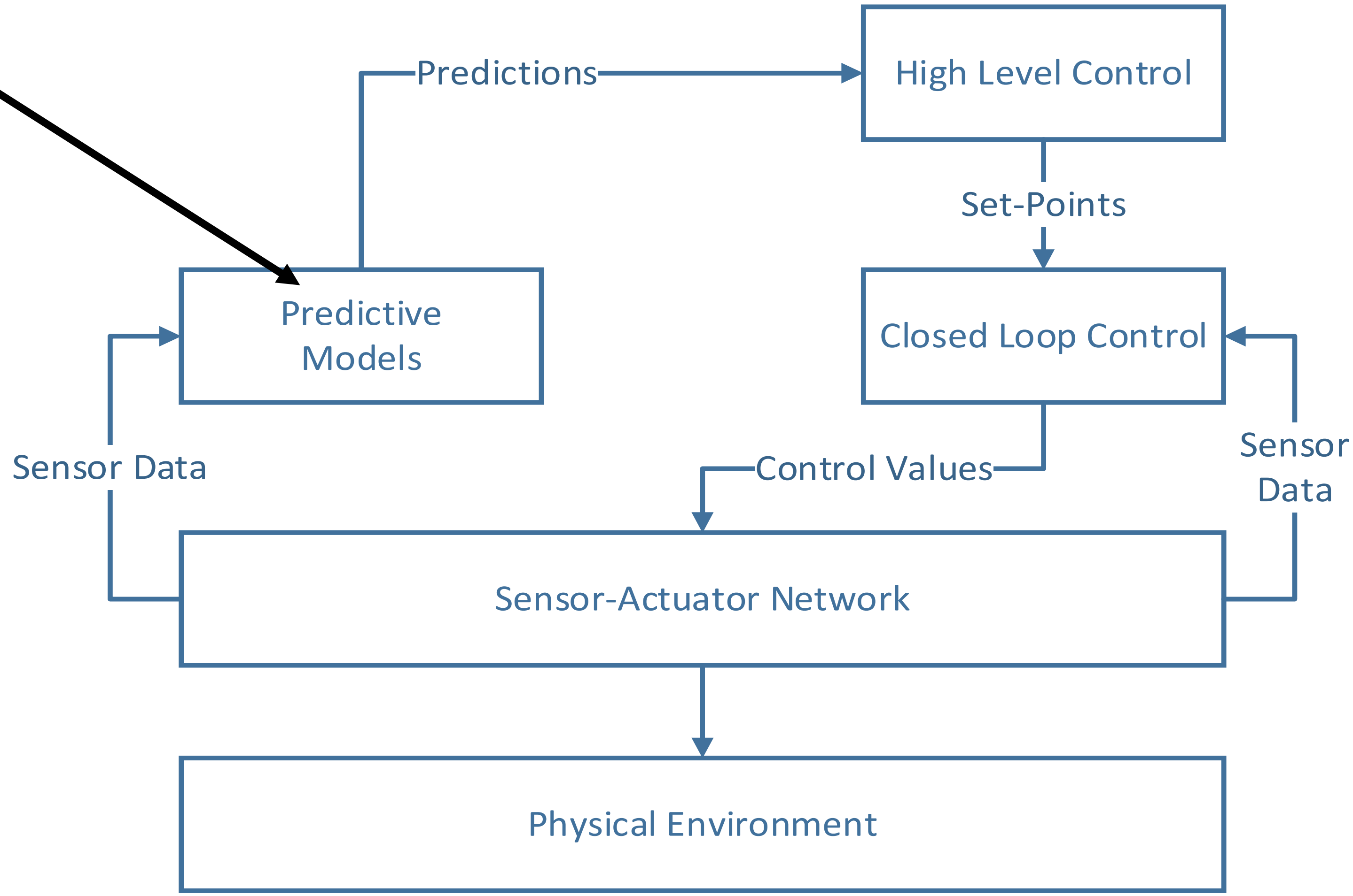
Platform L3 (h= -12m)

Platform L2 (h= -9 m)

Platform L4 (h= -14m)

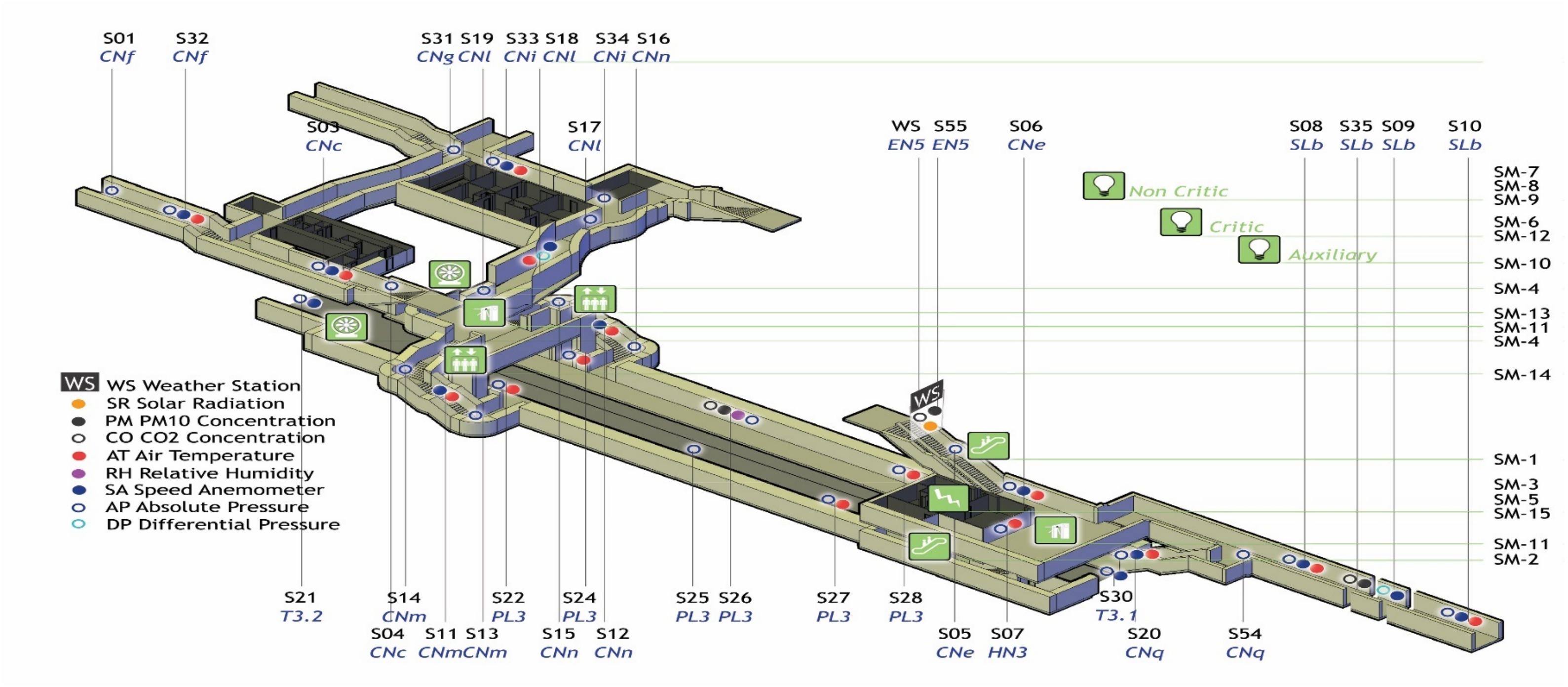
SEAM4US MPC Framework - offline

Bayesian Networks Trained from Modelica Model

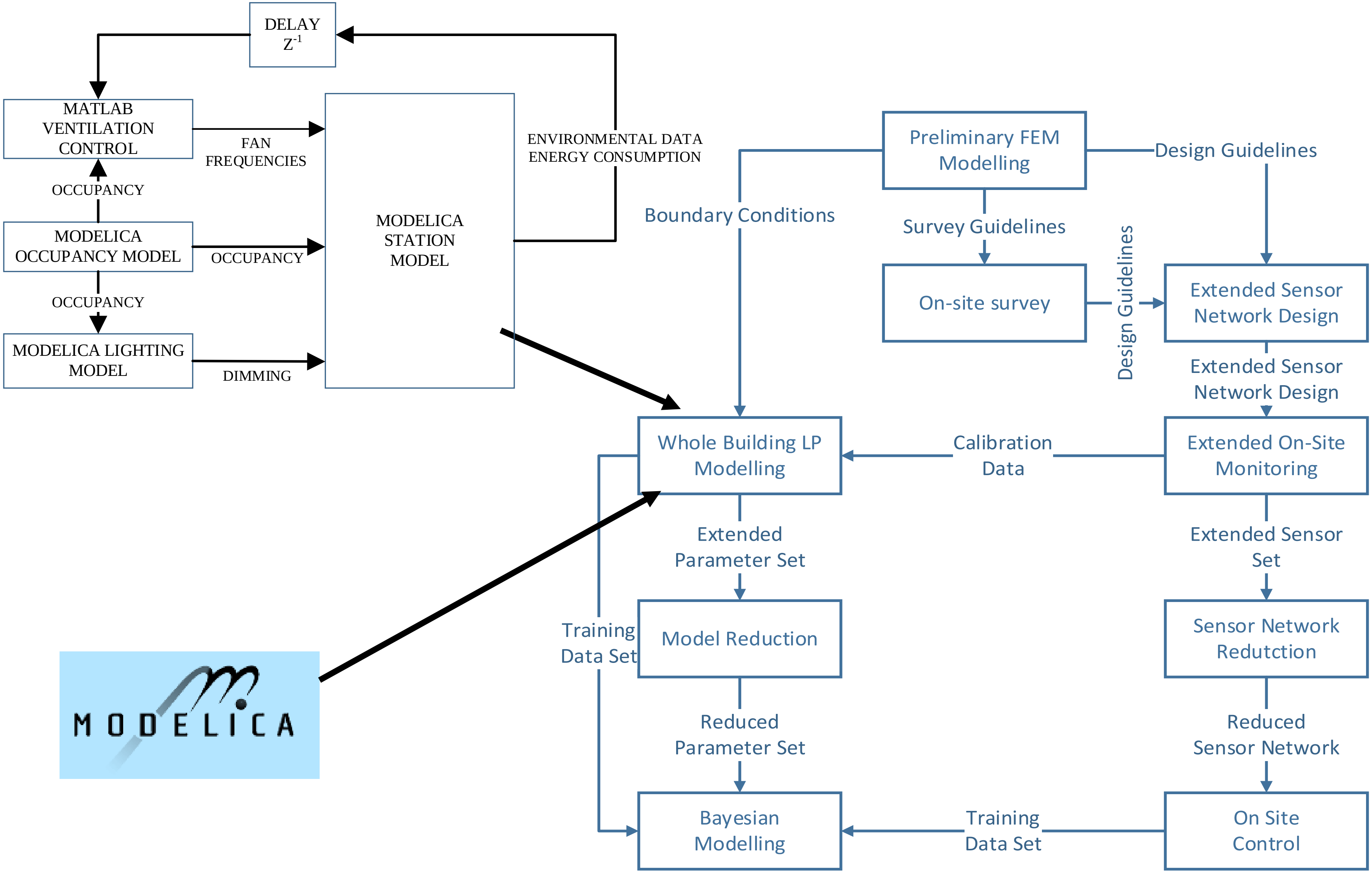


SEAM4US Monitoring Framework

- The deployed environmental sensor network amounts at 80 sensors, including air and surface temperatures, air speed, air pressure, humidity, CO2 and PM10 concentration, and a weather station.
- 35 will be used for controlling the station equipment, the others provide redundancy and calibration support

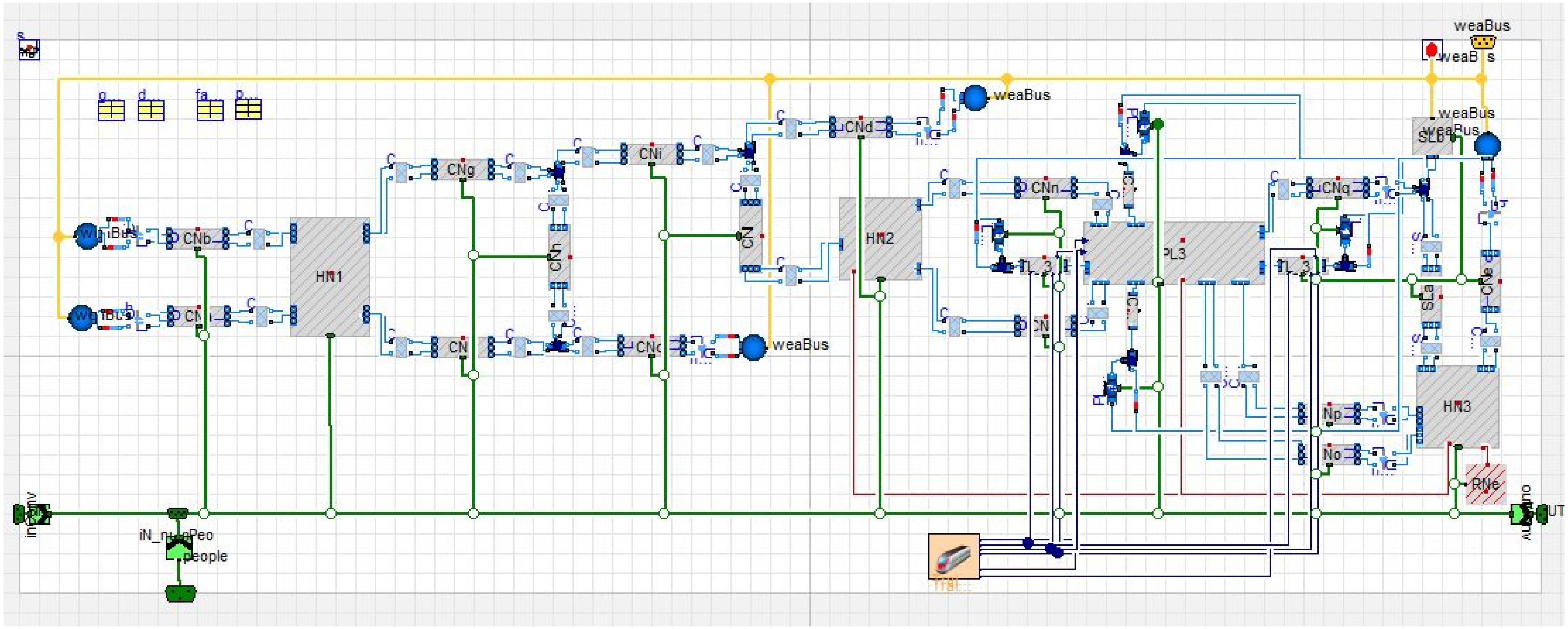


The SEAM4US model-engineering framework



The SEAM4US Modelica Model

- The Modelica Station Model is a large model, the integration generates 38384 unknowns /equations based on Buildings Library
- The model is used to produce scenarios for training the reduced statistical model and for decision support.



KU Leuven (Belgium)

MPC

- Energy Control Underground Public Spaces
- Chiller Plant
- **Heat Pumps**

HIL

- HVAC close-loop control

FDD

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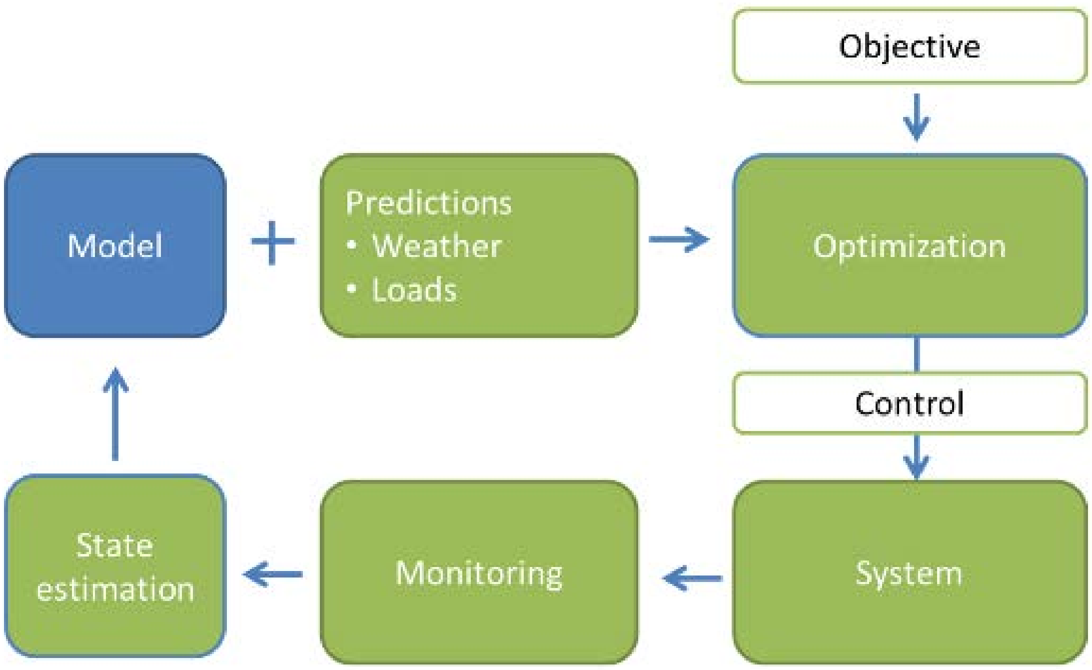
- AHU FDD Grey Box

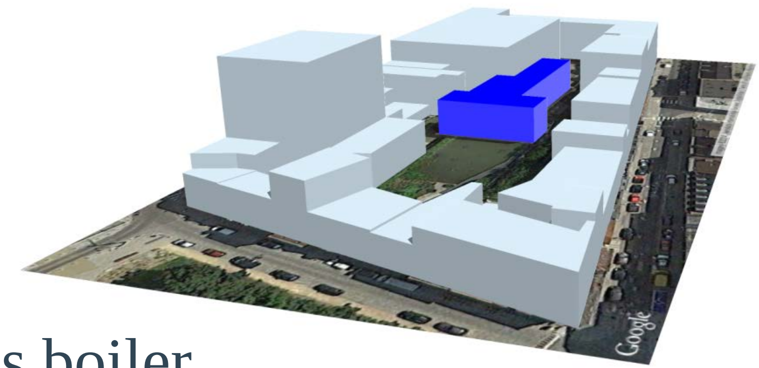
MPC for heat pumps - online

- In this case study, we developed an MPC approach to optimize the heat production of two identical heat pumps and a gas boiler. We have implemented and tested the MPC (using the Modelica environment) at the headquarters office building of 3E which is located in the center of Brussels, Belgium.

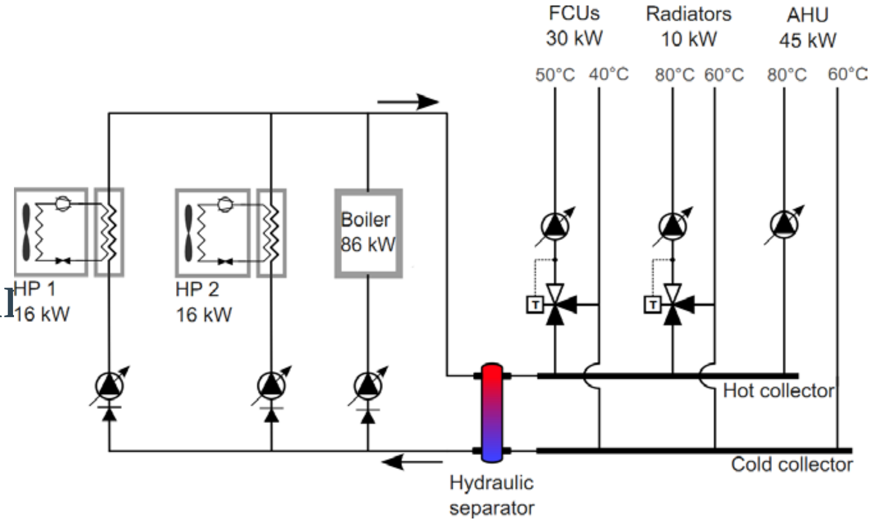


Cascade heat production to heat office building

- Office building, Brussels
- 50-70 occ
- ~1000m² conditioned surface



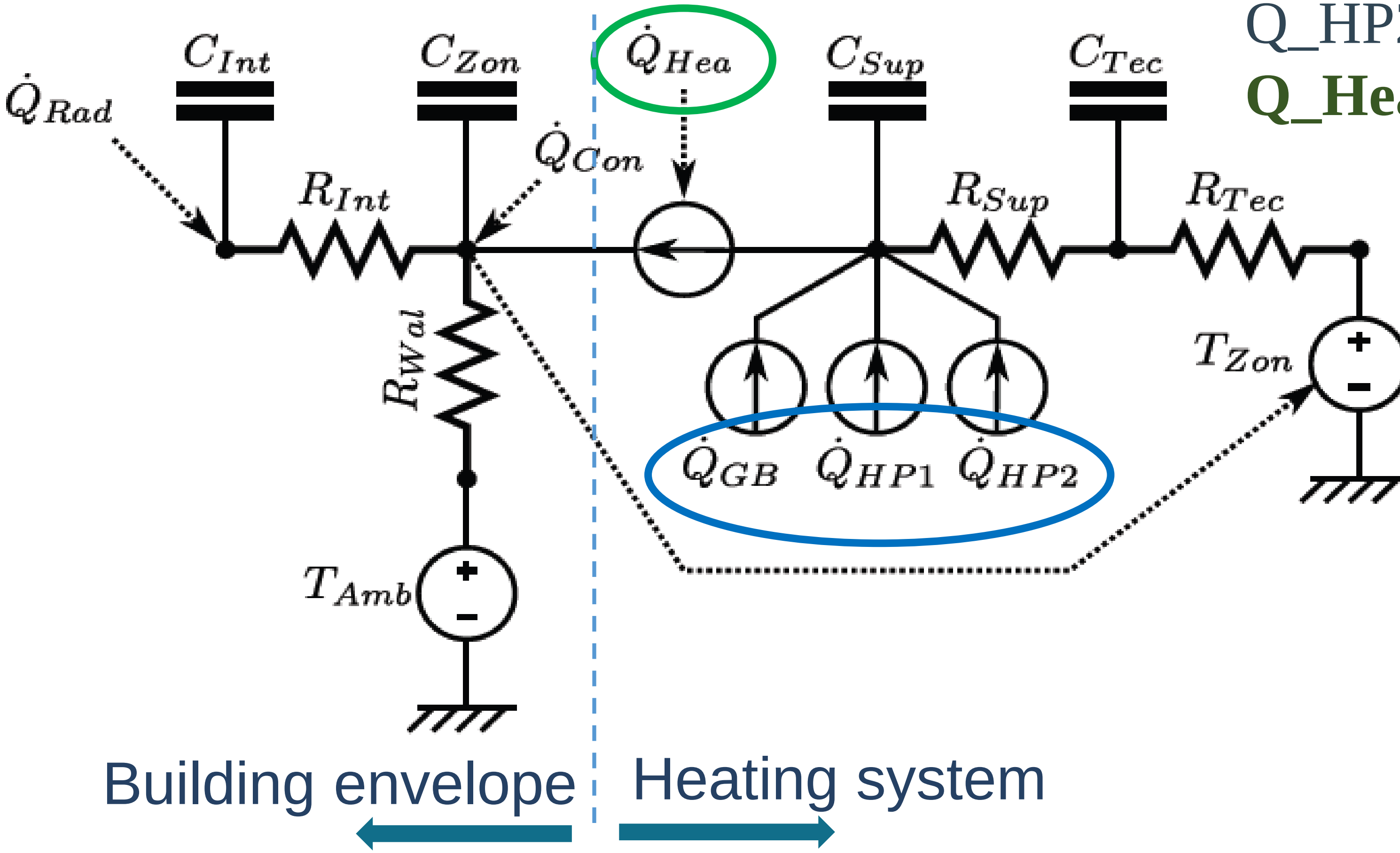
- PRODUCTION:
  16 kWth heat pump (2x) 87kW gas boiler
- EMISSION:
  FCU units in zones
  AHU unit
- Zone temperatures: comfort bour



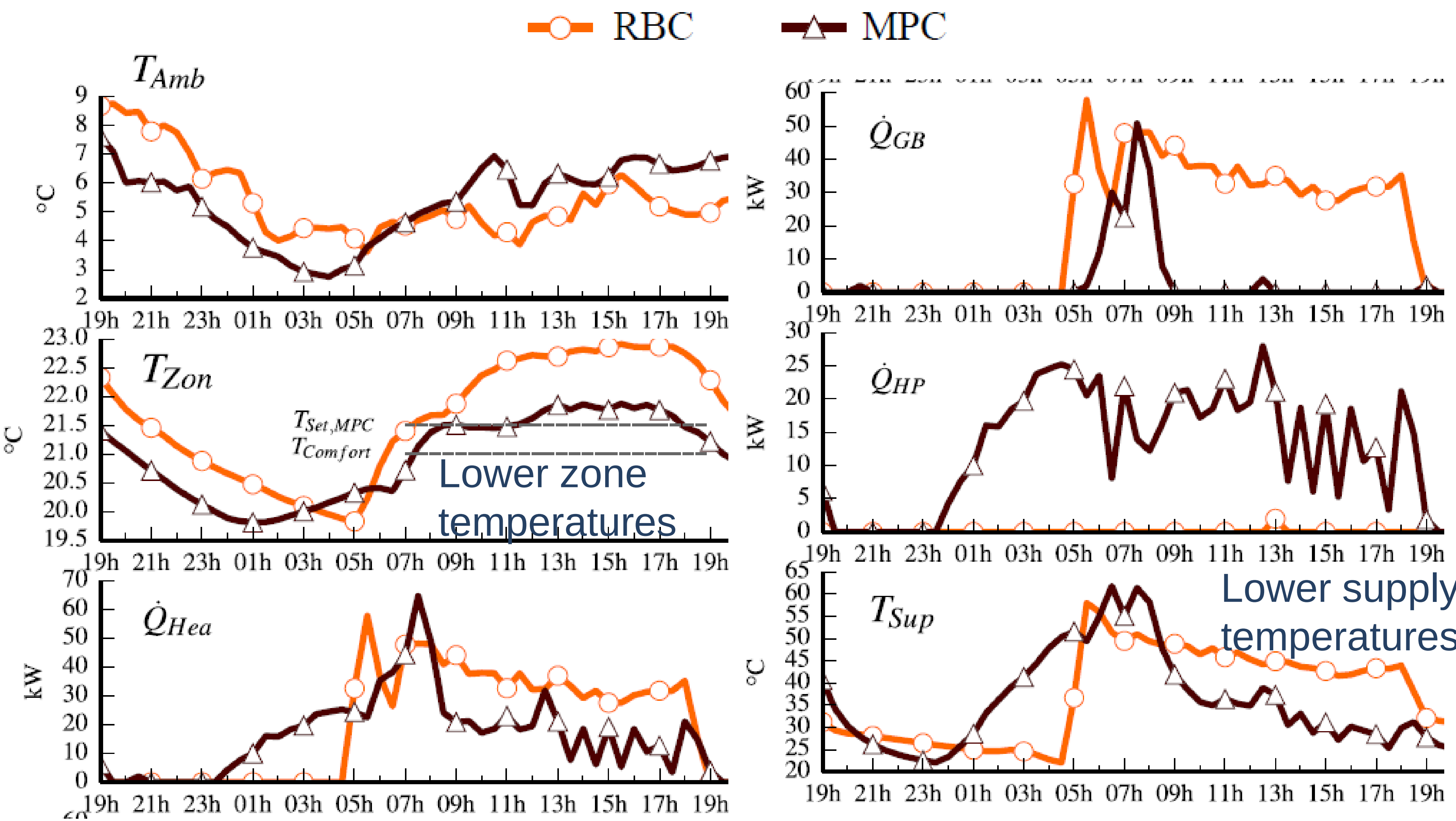
Control model building envelope

- 4 control variables in optimal control problem (OCP)

Q_GB
Q_HP1
Q_HP2
Q_Hea



Zone temperature is controlled better and gas boiler is used less



University of Miami (USA)

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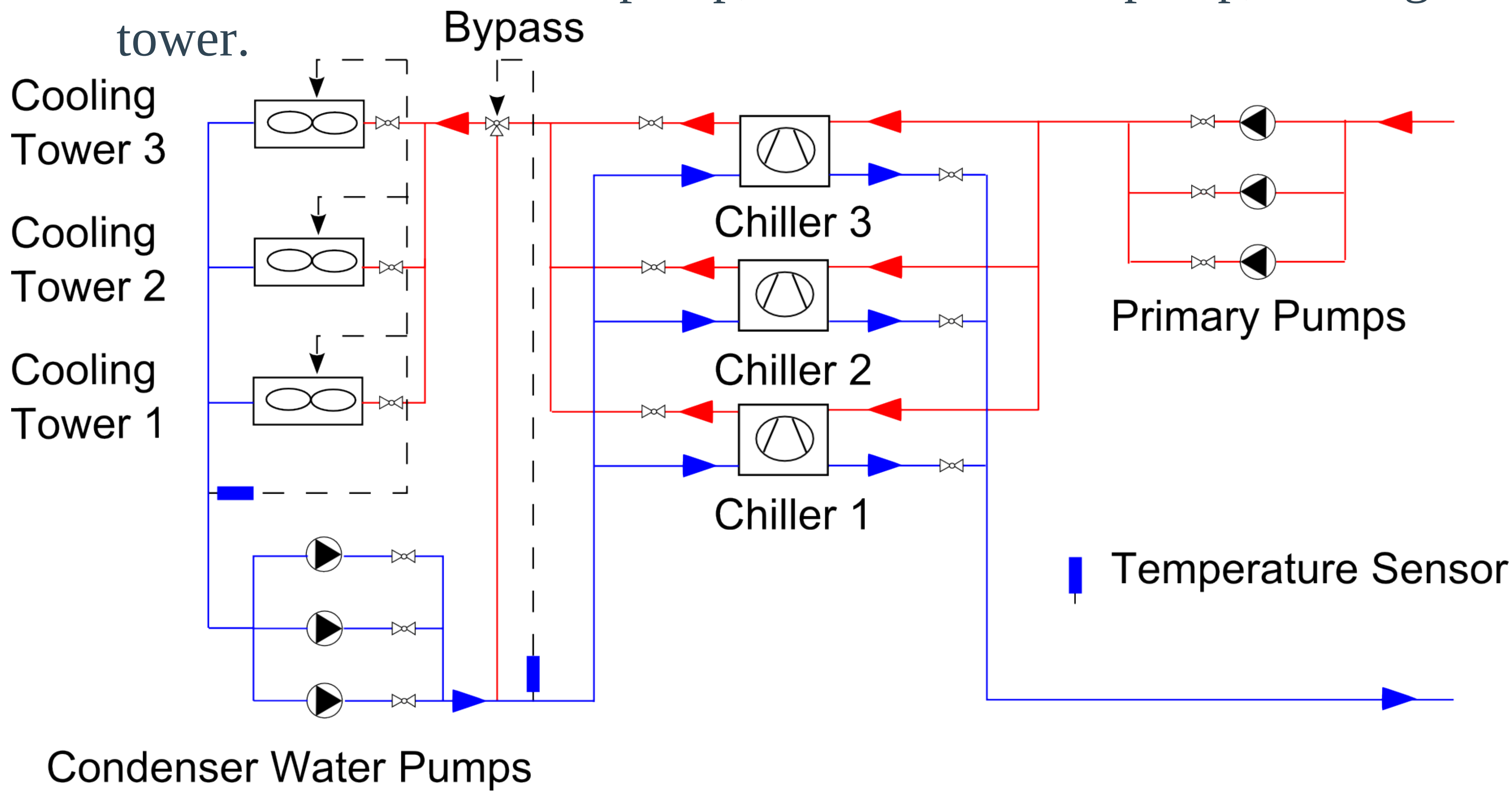
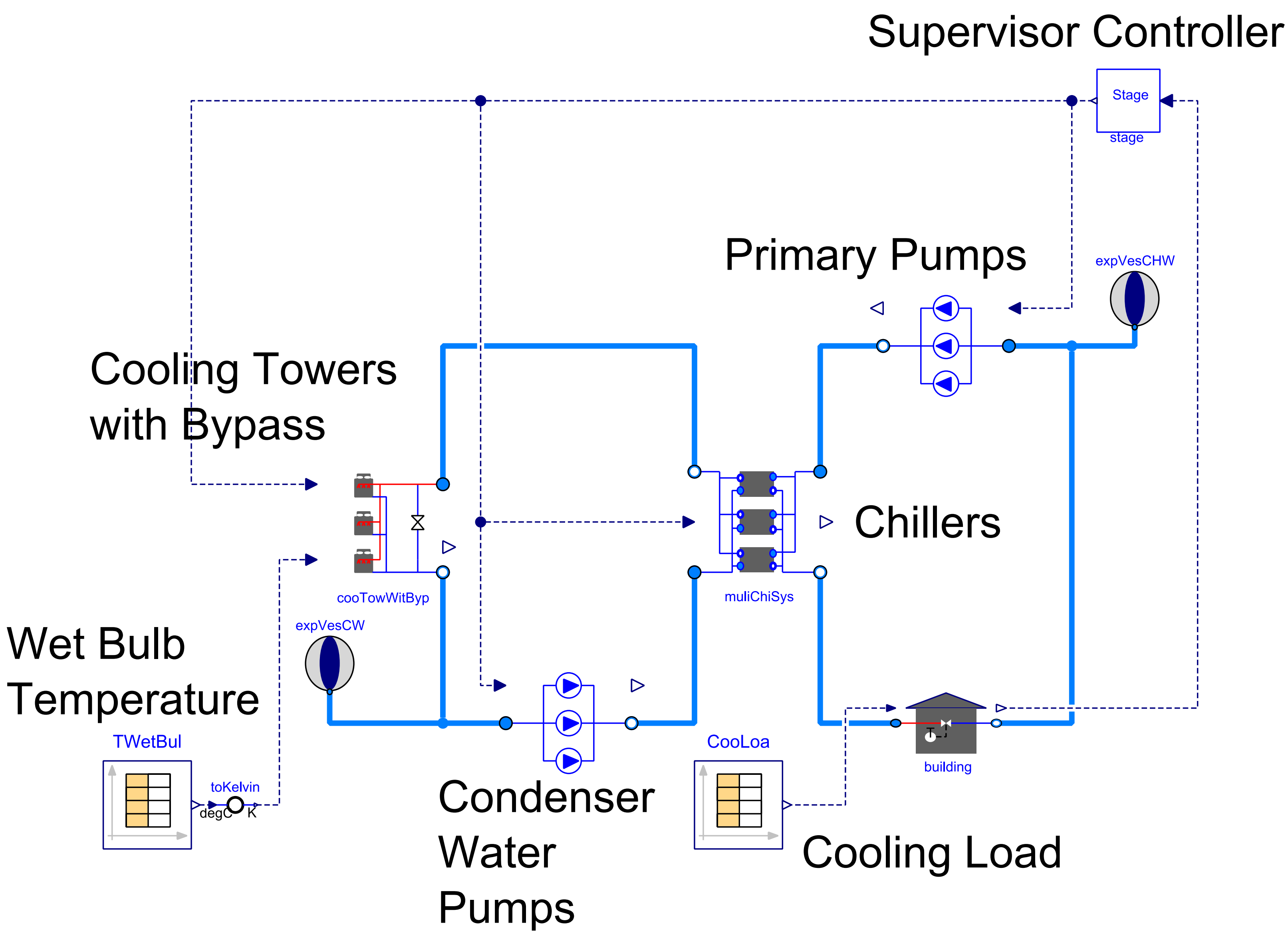
MPC approach for chiller plants - offline

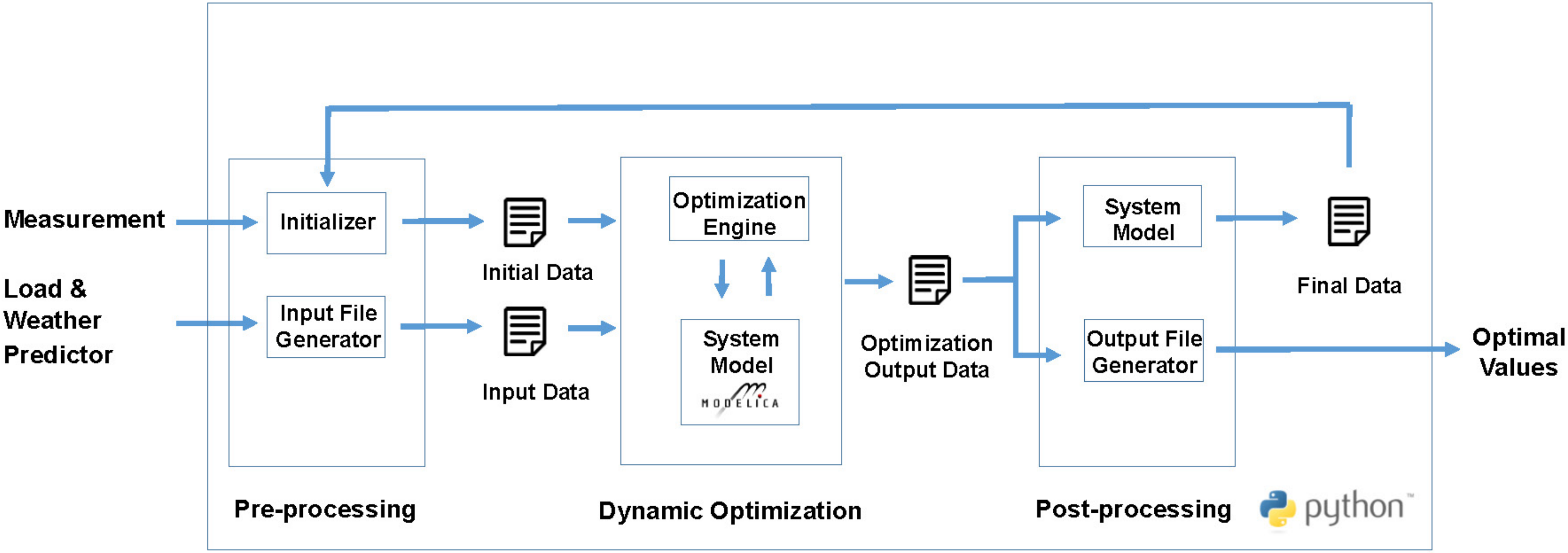
- The studied case is a chiller plant with 3 identical chillers, 3 identical chilled water pumps, 3 identical condenser water pumps, and three identical cooling towers. Each chiller has dedicated chilled water pump, condenser water pump, cooling tower.



Modelica Model – Top Level

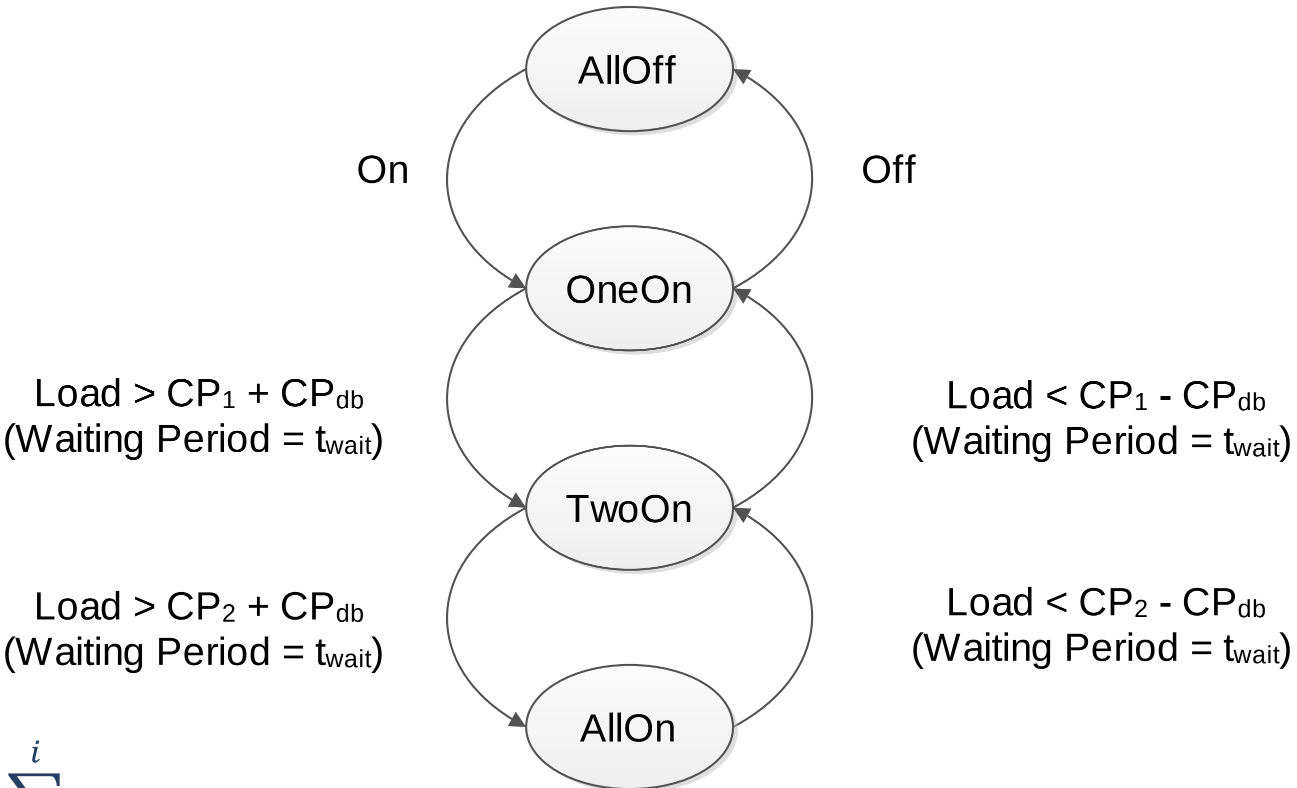


Modelica in the Process - offline



Sen Huang, Wangda Zuo, Michael D. Sohn. Amelioration of the Cooling Load based Chiller Sequencing Control. *Applied Energy,* 168, pp. 204-215, 2016

Rule based Control For Chiller Staging



$$CP_i = \eta \sum_{j=1}^{i} CC_{nom,j}$$

$CC_{nom,j}$: the nominal capacity of the jth chiller

η : the safety factor

Model Predictive Control For Chiller Staging

$$J = \min\left(E_{tot}\Big|_{t_0}^{t_0+\Delta t}\right)$$

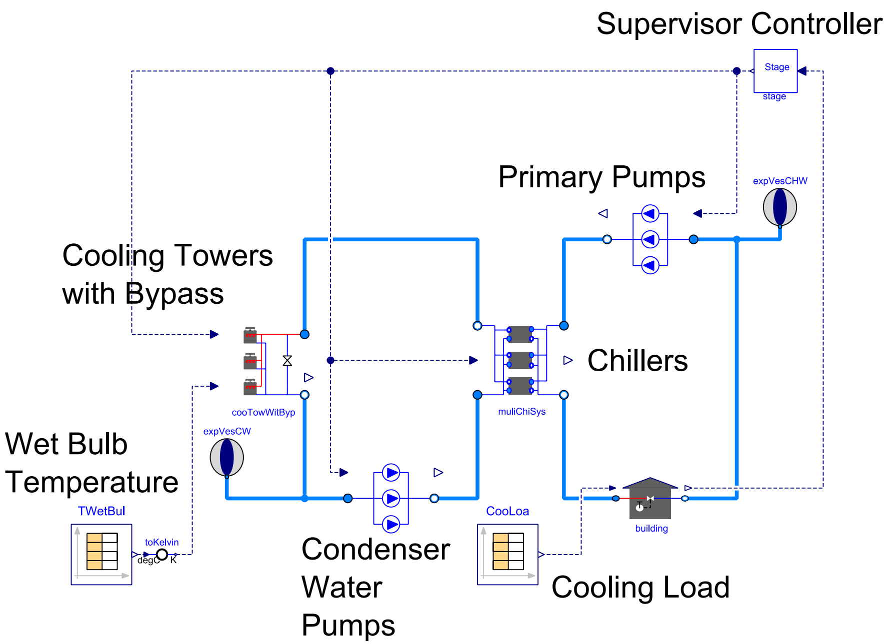
s.t.

$$T_{cw,set,L} \le T_{cw,set}(t_0) \le T_{cw,set,H}$$

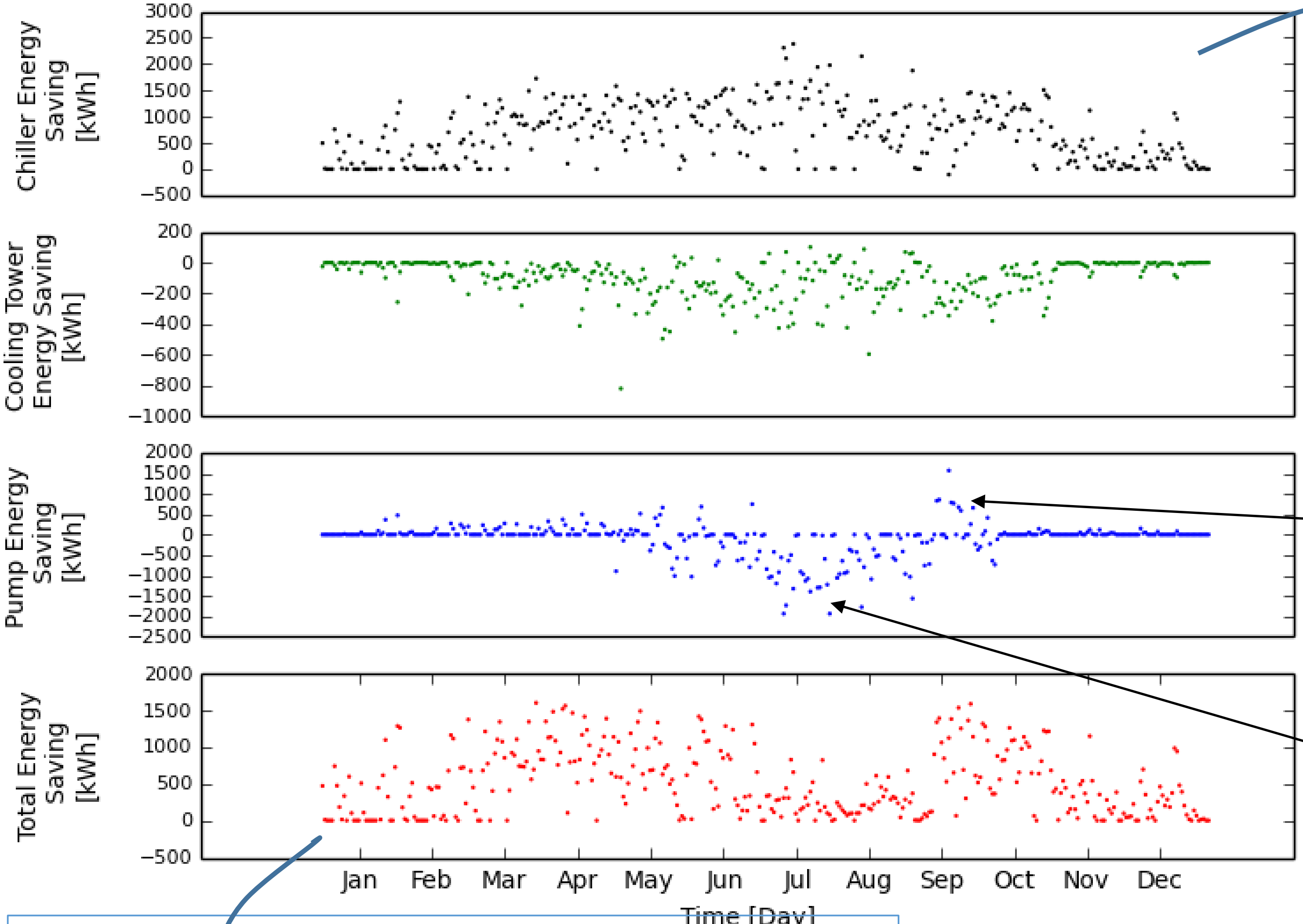
$$CP_1^{min} < CP_1(t_0) \le CP_1^{max}$$

$$CP_{i-1}(t_0) < CP_i(t_0) \le CP_i^{max}\ (i > 1)$$

$$\int_{t_0}^{t_0+\Delta t} \left|T_{chw,lea}(t) - T_{chw,set}\right| dt \le \int_{t_0}^{t_0+\Delta t} \left|T_{chw,lea,base}(t) - T_{chw,set}\right| dt$$



Offline Simulation Results



11.8% energy saving

Less Pumps Operating

More Pumps Operating (summer)

5.6% annual total energy saving

University of Alabama (USA)

MPC

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HIL

- **HVAC close-loop control**

FDD

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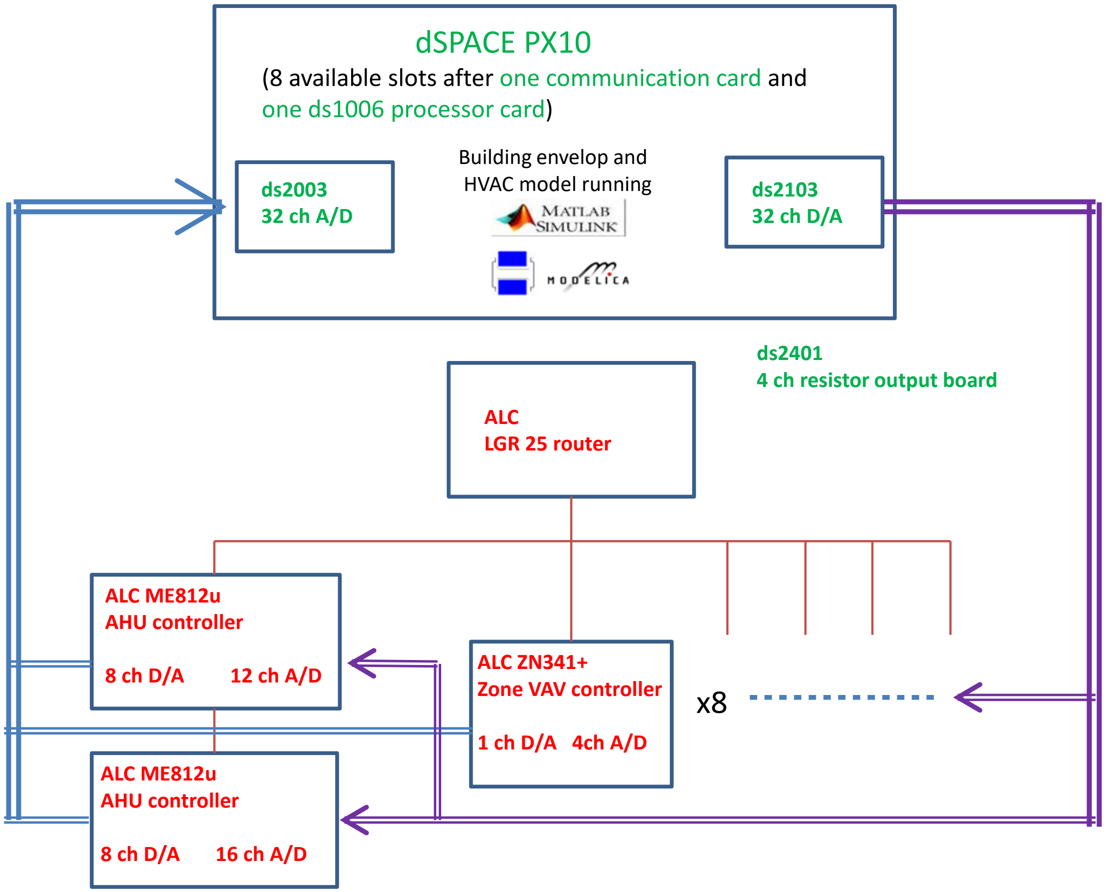
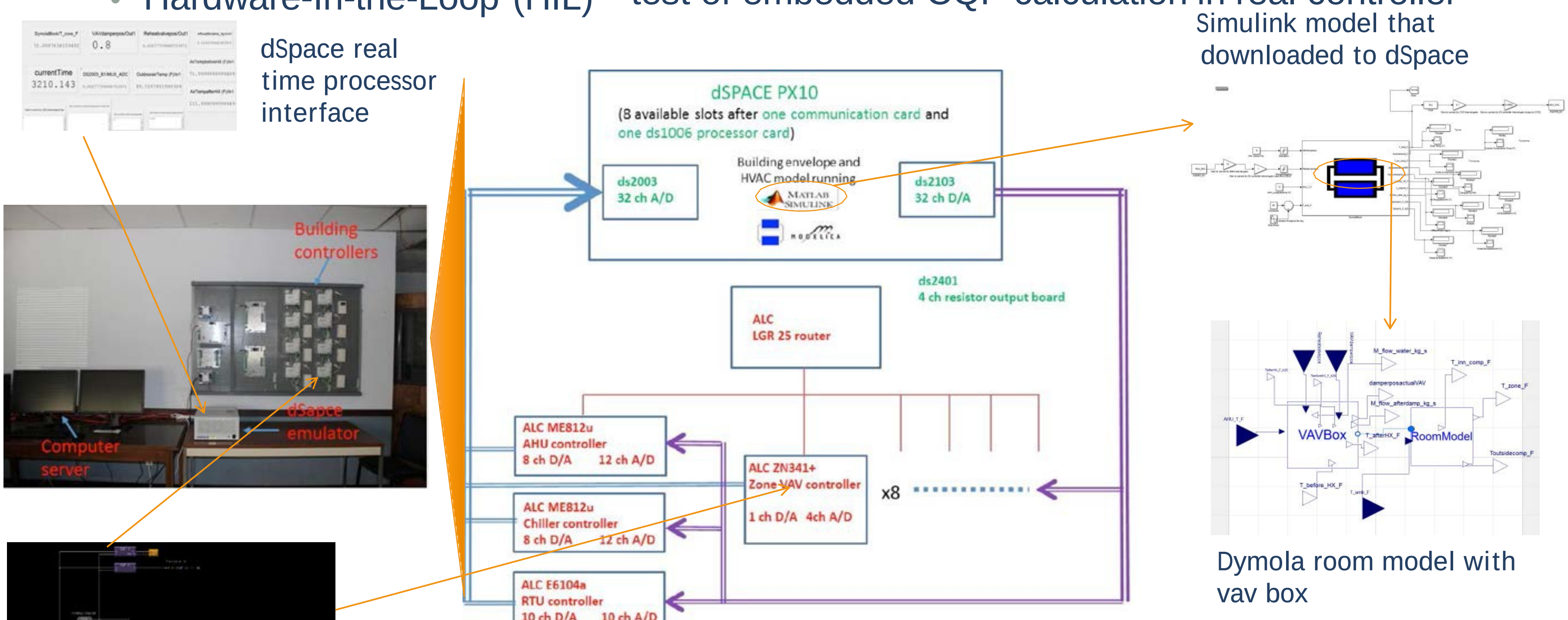
Hardware in the Loop - inline

- A room served by a VAV terminal
- Room and VAV modelled in Modelica
- Models downloaded to HiL machine connected to a real VAV box controller.
- The objective of this case study is to research different control algorithms including fault tolerant controls for VAV boxes.



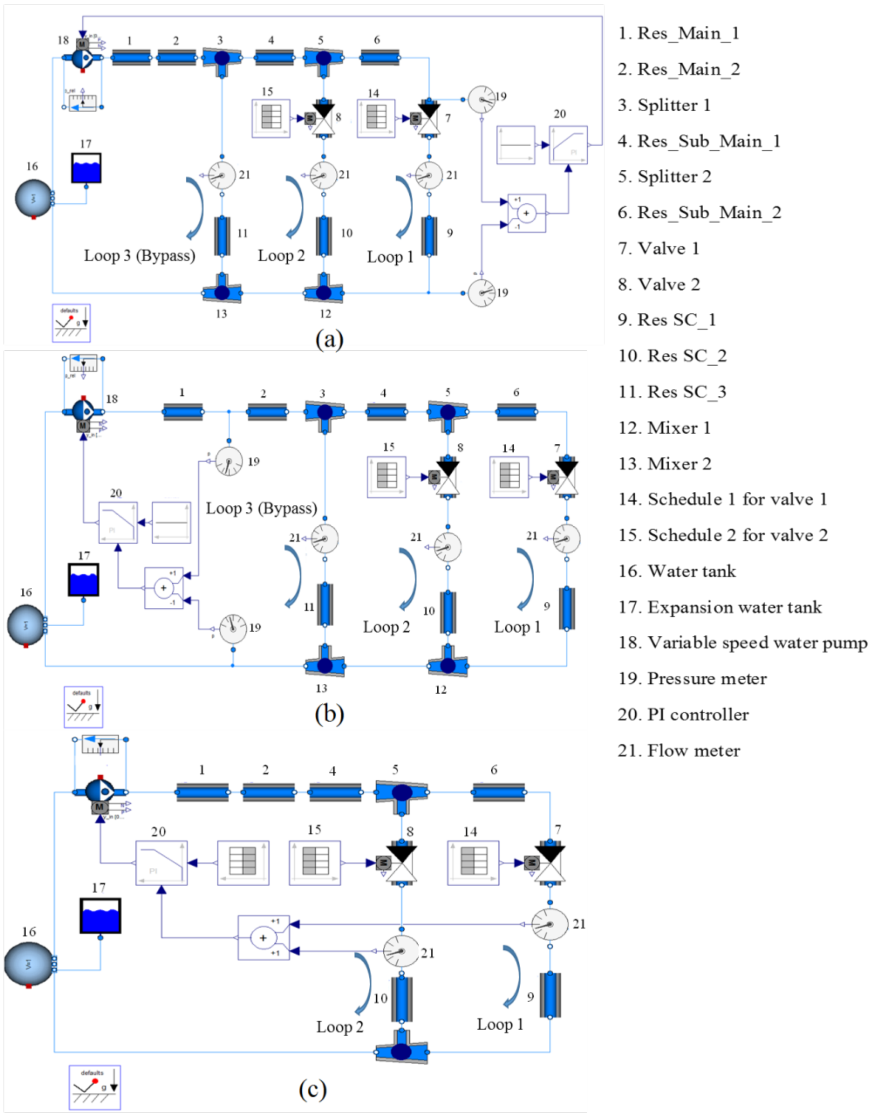
HiL Implementation

- **ASHRAE RP-1587 : Control Loop Performance Assessment - develop, evaluate and field test an objective and quantitative metric and method to monitor and evaluate HVAC closed loop control performance (Finished)**
  - Using Modelica to generate simulation data (normal and faulty operations) to evaluate the proposed Control Quality Factor (CQF)
  - Hardware-In-the-Loop (HIL) test of embedded CQF calculation in real controller



Control logic and CQF algorithms are programmed in Eikon Logic and downloaded on VAV box controller through WebCTRL

HiL Model

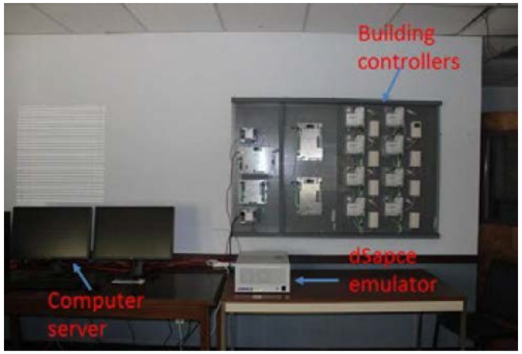


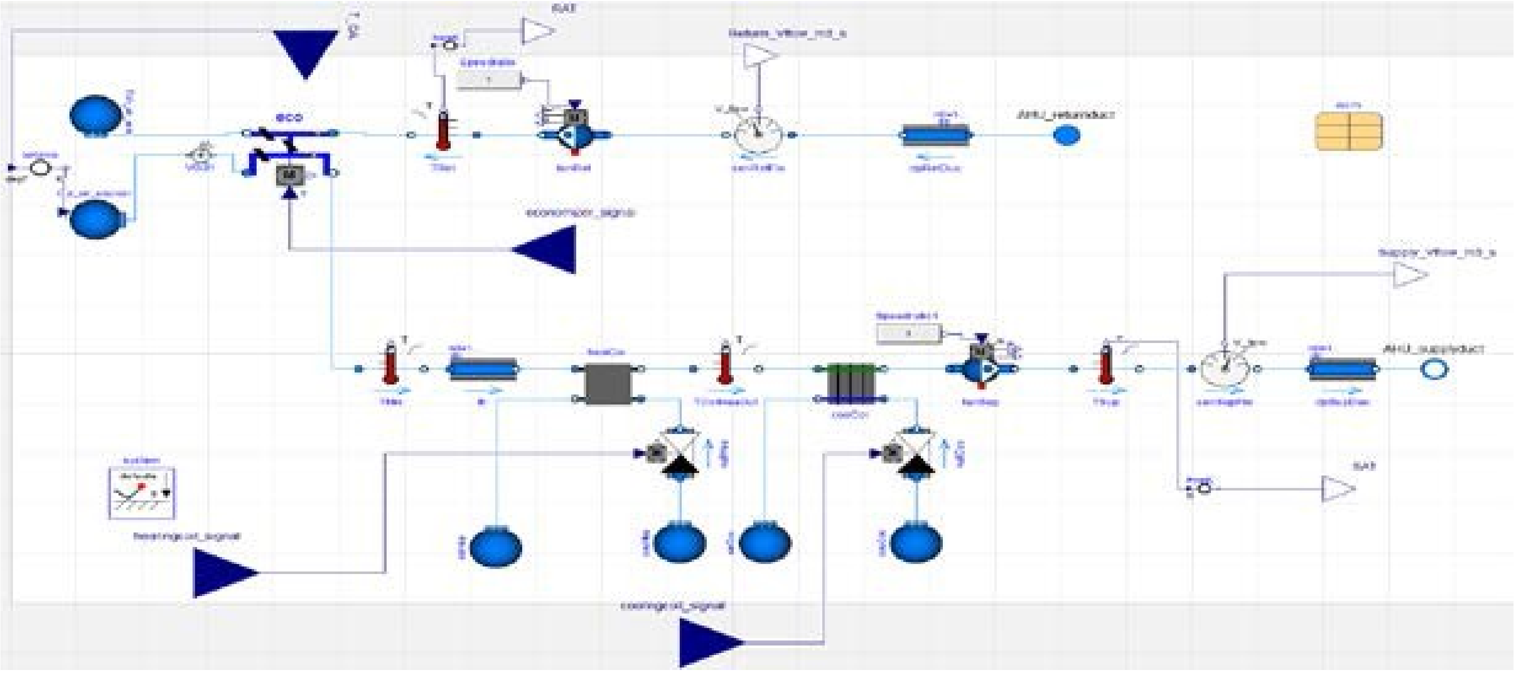
(a)Pumping system with fixed DP at the hydraulically furthest loop; (b)Pumping system with fixed DP between the main supply and return; (c) Pumping system with flow-demand -based control

- **A Modelica-Based Study on Different Control Strategies for Variable Speed Pump in Distributed Ground Source Heat Pump Systems**
- With Oak Ridge National Laboratory
- Simulation based study shows that the annual pumping energy consumption can be reduced by 62% using the flow-demand-based control
- The model validation is being conducted using experimental data from the tested at ORNL

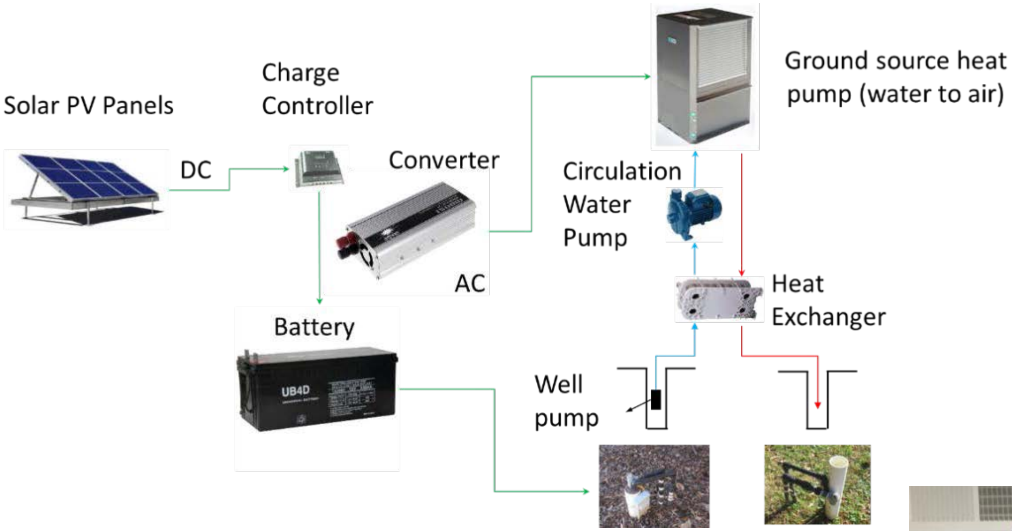
Project overview and current status

- Implementing Fault Tolerant Control using Hardware-in-the-loop with Modelica
- Focus on a single duct VAV system

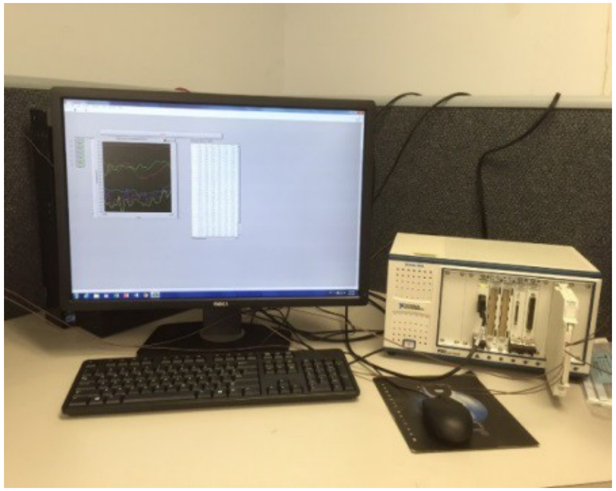


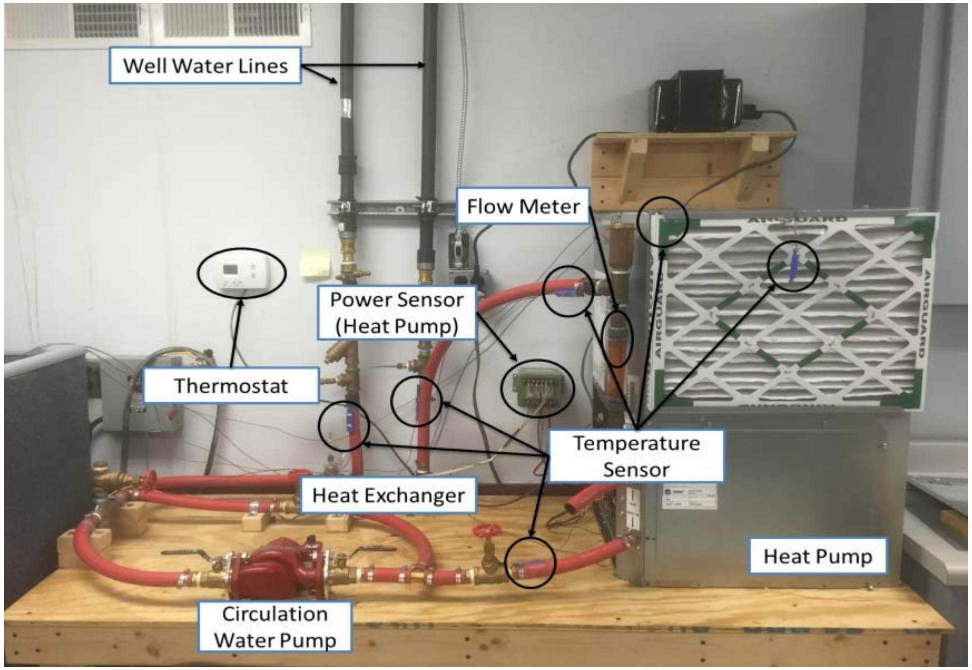


Project overview and current status



- **Modeling of a Solar Powered Ground Source Heat Pump System using Modelica**
- Data is being collected from an experimental testbed in the lab
- Working on the Modelica model





LBL (USA)

MPC

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- Heat Pumps

HIL

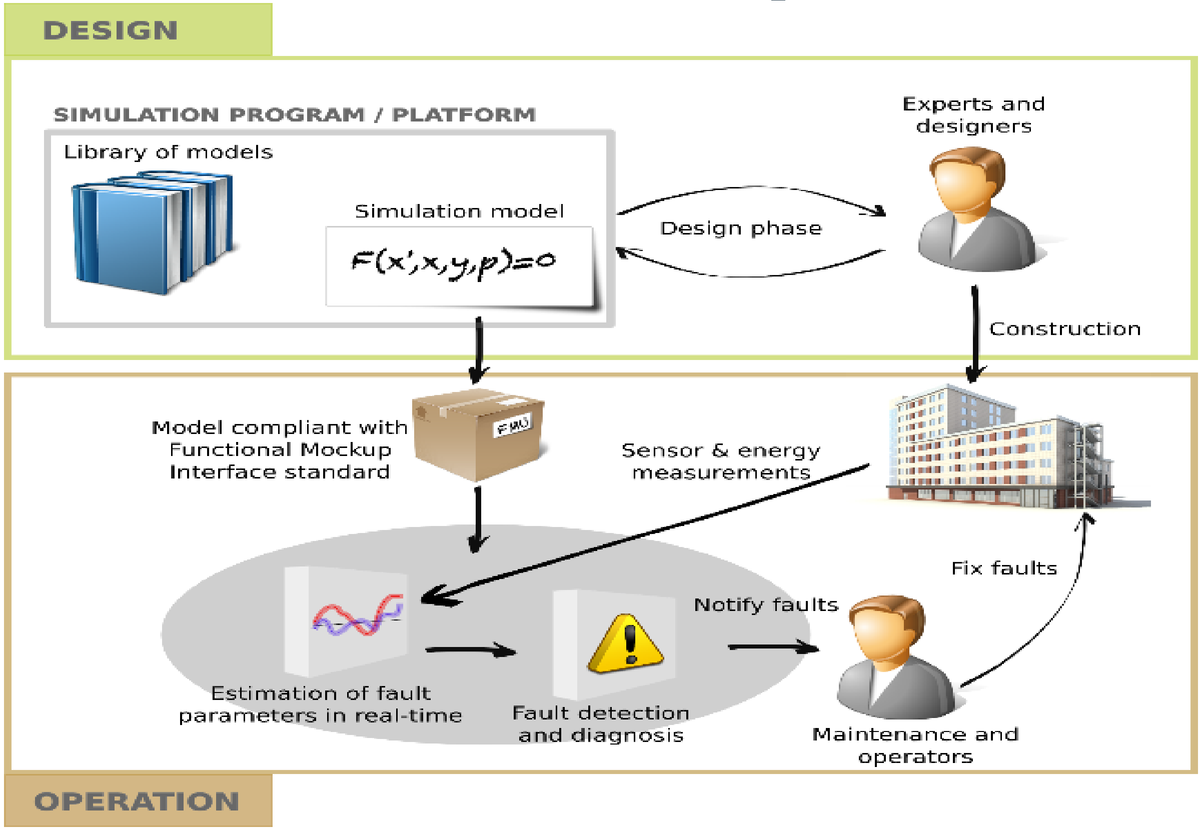
- HVAC close-loop control

FDD

- AHU FD
- **Chillers in District Cooling**
- AHU FDD Automated Reasoning
- AHU FDD Grey Box

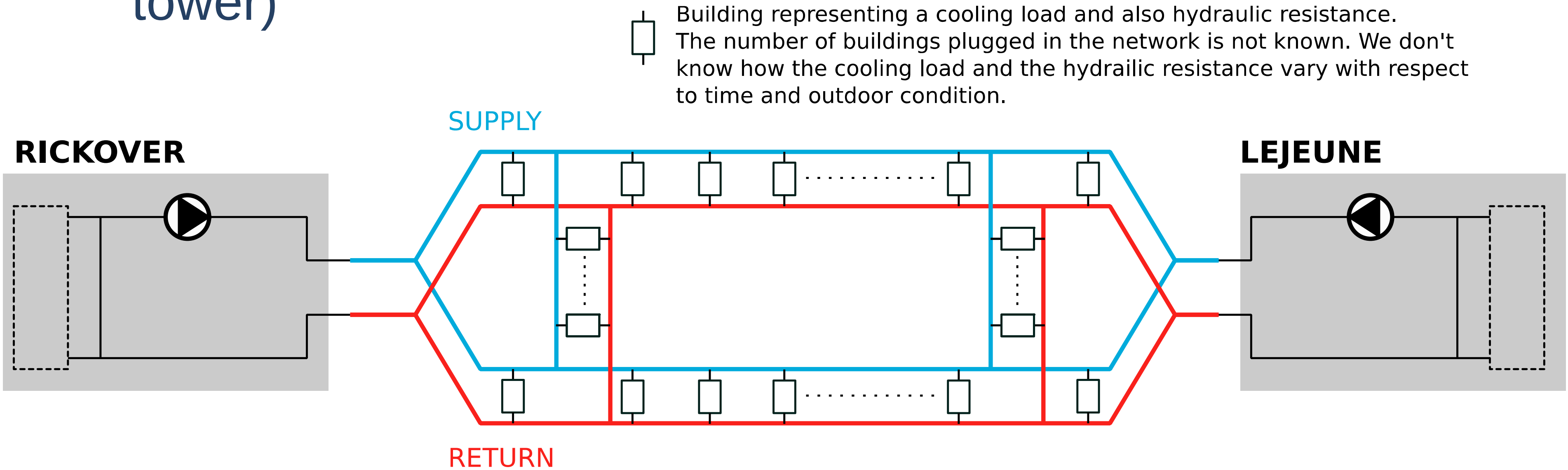
Model-based FDD for District Cooling Systems

- 20 buildings utilize the chilled water (CHW) for air conditioning.
- CHW provided to the central loop by two separate plants located in different zones of the campus.



FDD case study - online

- Six chillers
  - 2 x 1250 Ton 734 kW (single compressor, fixed speed)
  - 4 x 2500 Ton 1512 kW (two stage compressor, fixed speed)
- Eight cooling towers
  - 2 x 37.3 kW (two fan per tower)



FDD results

Details of fault identification algorithm, comparison between expected and estimated COP. The red rectangles have been identified as faulty periods where the performance of the chiller were lower than expected.

Fraunhofer ISE (Germany)

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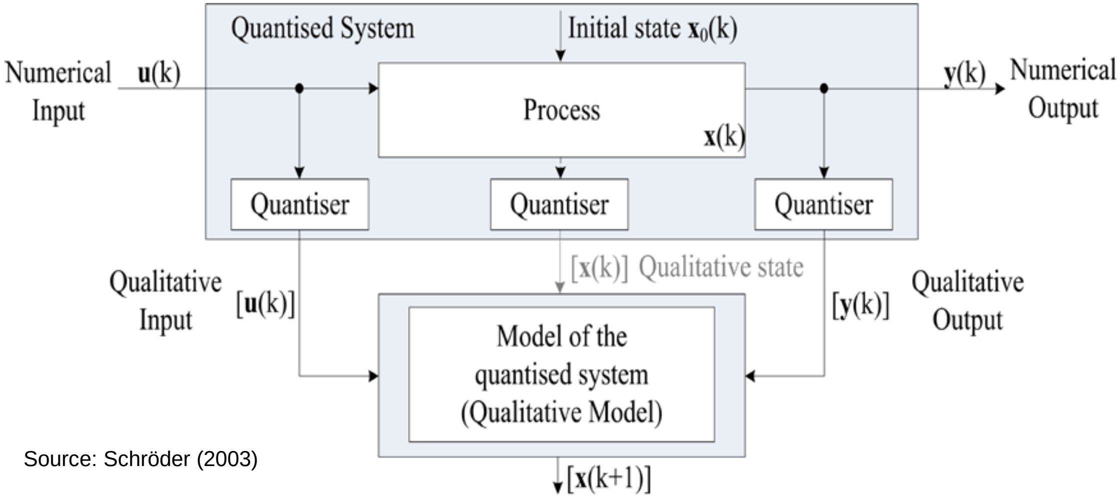
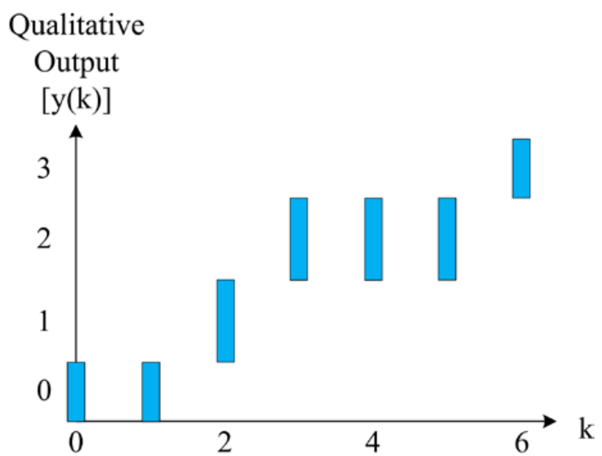
MB-Qualitative FD of AHU components

- The basis for using a qualitative model for fault detection is a quantised system



Source: Schröder (2003)



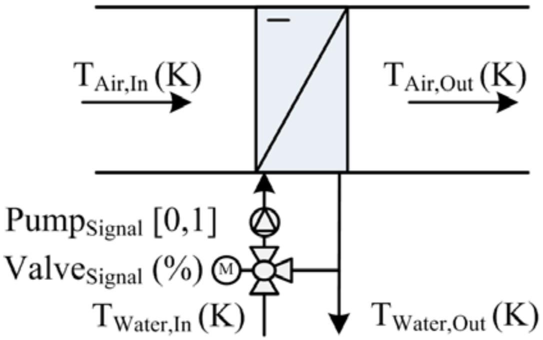
- The quantised system shows the qualitative behaviour of the process

Fault Detection - offline

- Different faults have been simulated with the Modelica fault triggering library, developed by the German Aerospace Center (DLR)
- The basis for Fault Detection is a qualitative observation algorithm
- The algorithm yields for each time step the probability vector $\boldsymbol{p}_{\mathrm{z}}$ which describes the possible behaviour of the system states depending on the measured qualitative input-output combination
- If the probability vector contains only zeros, the measured input-output combination is inconsistent with the qualitative model and a fault can be structurally detected

Application example

- Cooler of an HVAC&R System:
  - 8 physical signals,
  - Measured nominal and faulty condition



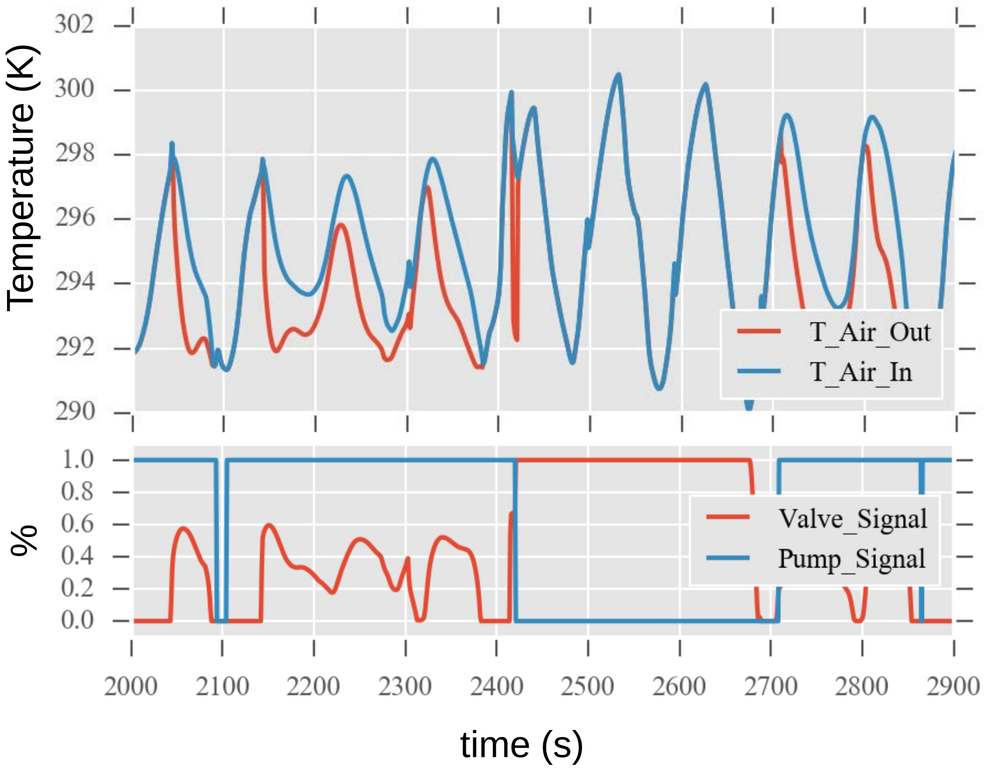
- Signals and partitioning of the spaces
  - 5 qualitative intervals for the temp inputs

    2 qualitative intervals for valve inputs
  - 5 qualitative intervals the outputs
- Sampling Time $T_s = 900s$
- **The behaviour relation of the automaton is a 10-dimensional tensor**
- **The behaviour relation includes more than $3.9 \cdot 10^6$ values**

- Higher number of inputs, outputs and states → combinatorial explosion of the behavior relation of the stochastic automaton
- Behavior relation can be reduced by a non-negative CP-tensor decomposition

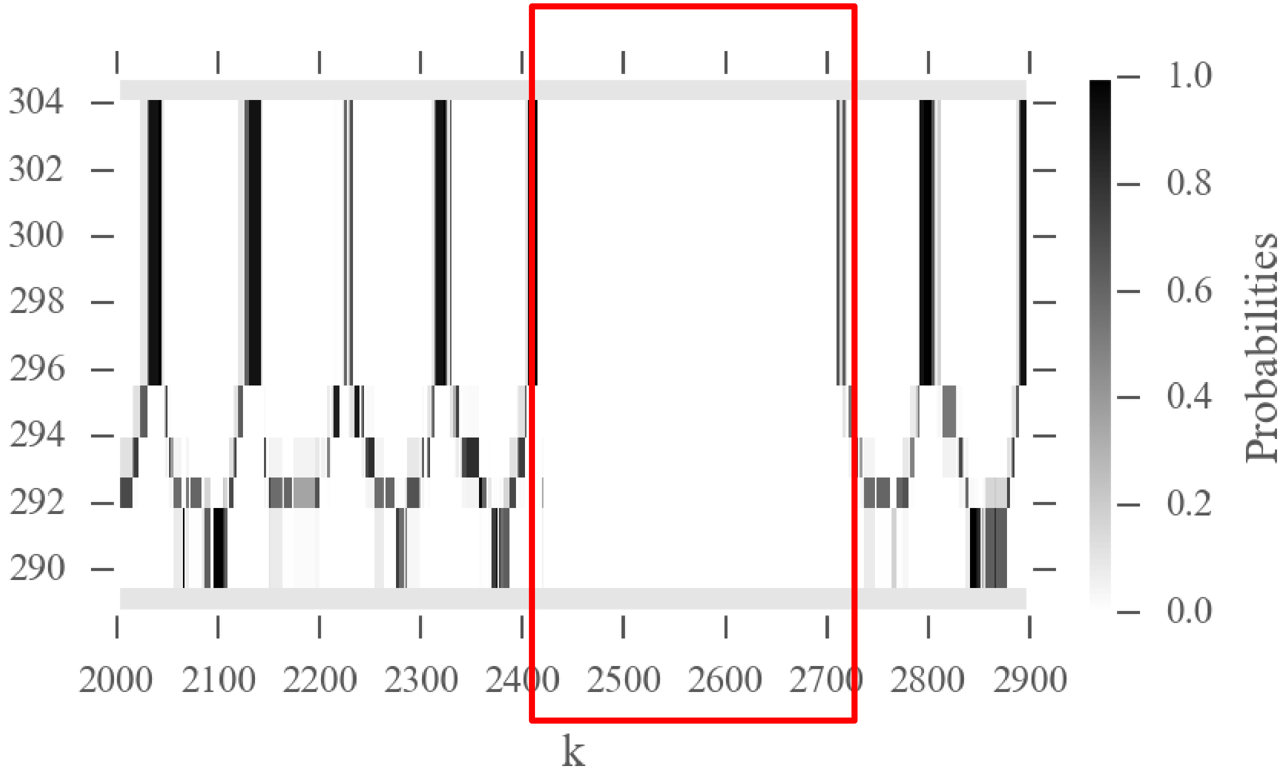
Application example

- Fault simulation with Modelica Fault Triggering Library
- The simulated fault describes a malfunction of the pump leading to a fully opened valve, because the controller tries to reach the regarded set point of the air outlet temperature



Application example

- Qualitative state trajectory for a faulty condition



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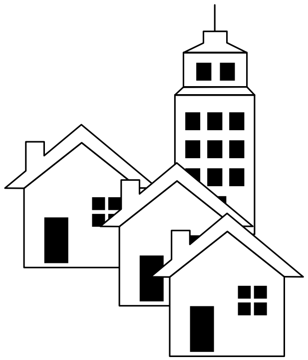
- Chillers in District Cooling
- AHU FDD Automated Reasoning
- **AHU FDD Grey Box**

Quantitative MB-FDD of AHUs - offline



Suboptimal HVAC

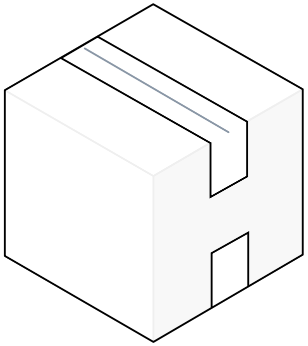
- Lack of standardization
- Lack of awareness
- Expensive system

Increase of energy use during operational phase

Easy to implement

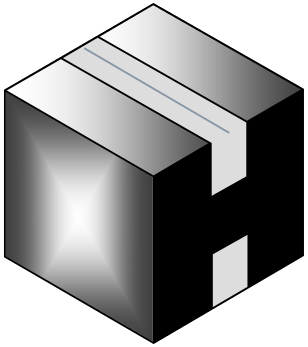
Open concepts, tools and languages

Fault detection



White box model (detailed Modelica Model)

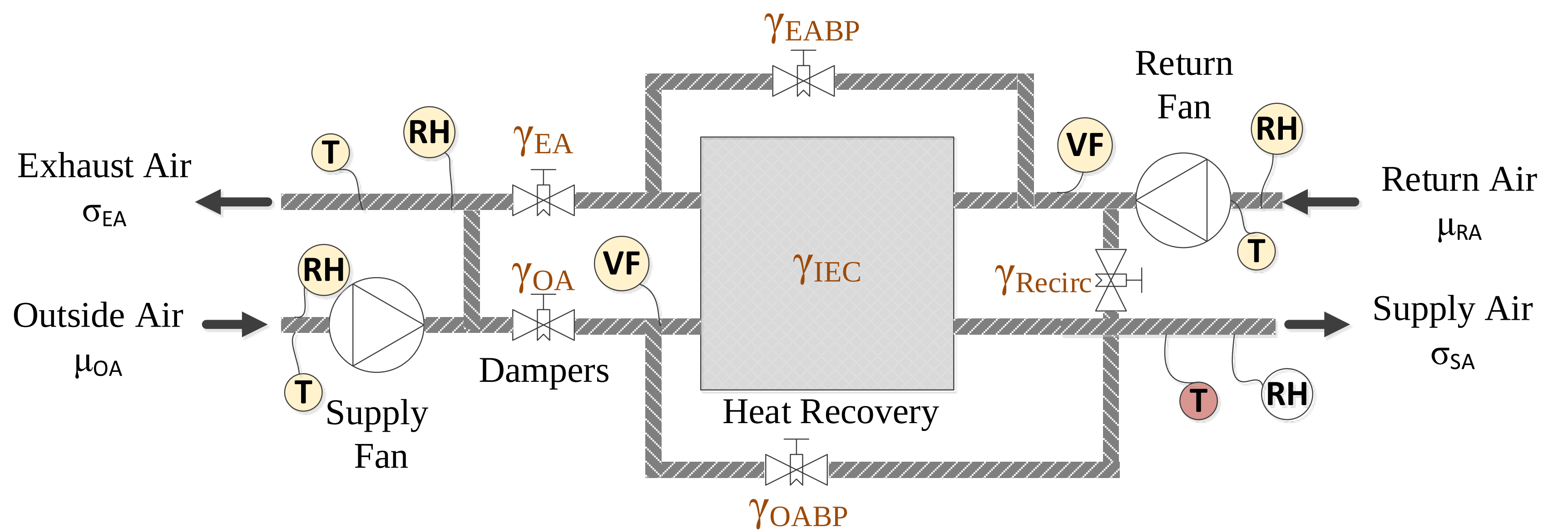
Fault diagnosis



Black box model (Classifiers)

HVAC system: Mixing box

Control system: γ_{EA}, γ_{EABP}, γ_{OA}, γ_{IEC}, γ_{Recirc}, γ_{OABP}

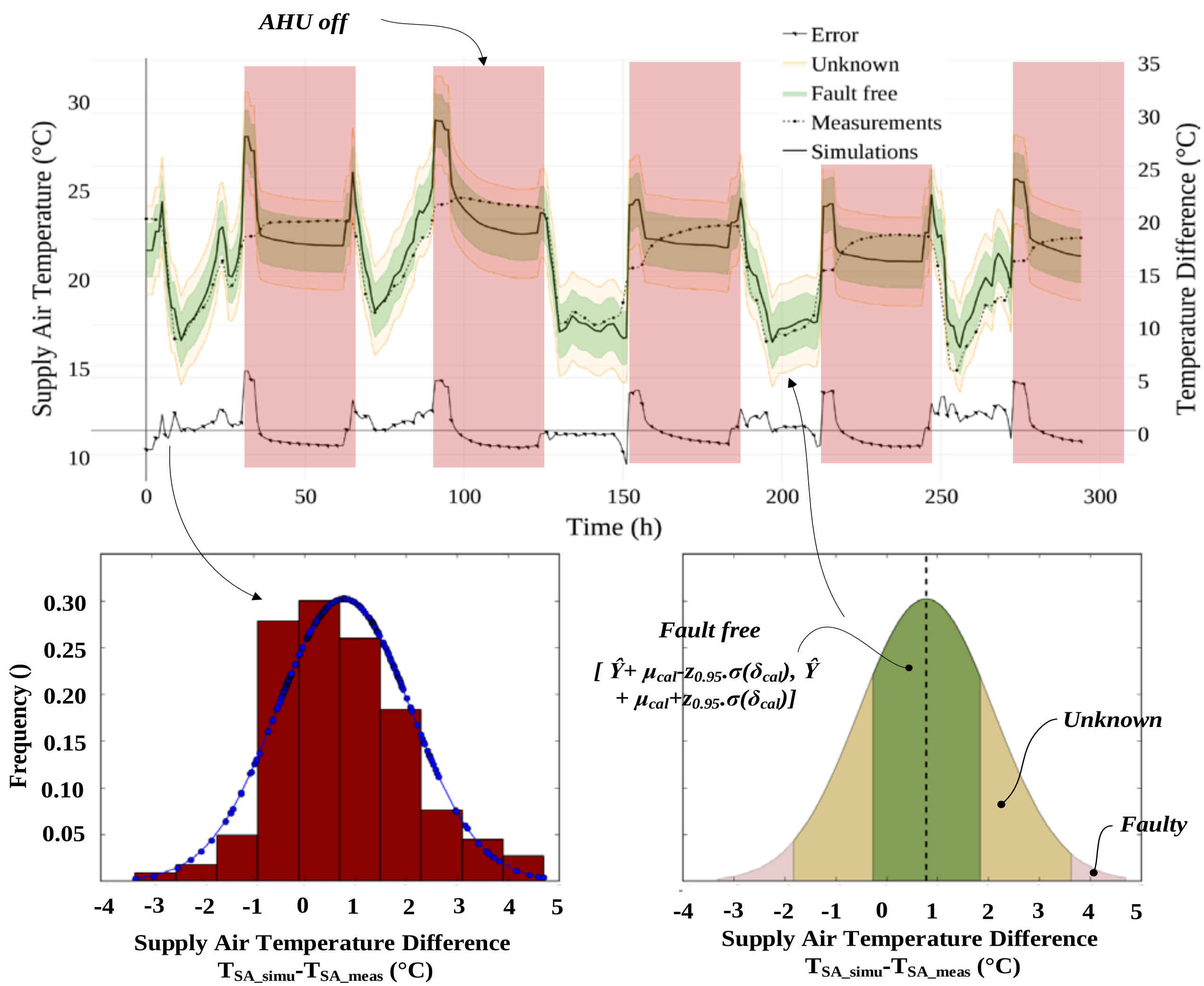


OA: Outside Air
EA: Exhaust Air
EABP: Exhaust Air By Pass
OABP: Outside Air By-Pass
IEC: Indirect Evaporative Cooling

T Temperature Sensor
RH Relative Humidity Sensor
VF Volume Flow Sensor

γ_i: Control signals
σ_i : Outputs
μ_i : Inputs

Fault Detection



Fault Diagnosis and Categorization

Initial commissioning training set:

T_{OA}, T_{EA}, T_{RA}, T_{SA}, RH, V_F, γ_{EA}, γ_{EABP},

γ_{OA}, γ_{IEC}, γ_{Recirc}, γ_{OABP}

T_{OA}

T_{EA}

T_{RA}

T_{SA}

RH

V_F

K Nearest Neighbors Classifiers

$\gamma^*_{\mathbf{EA}}$

$\gamma^*_{\mathbf{EABP}}$

$\gamma^*_{\mathbf{OA}}$

$\gamma^*_{\mathbf{IEC}}$

$\gamma^*_{\mathbf{Recirc}}$

$\gamma^*_{\mathbf{OABP}}$

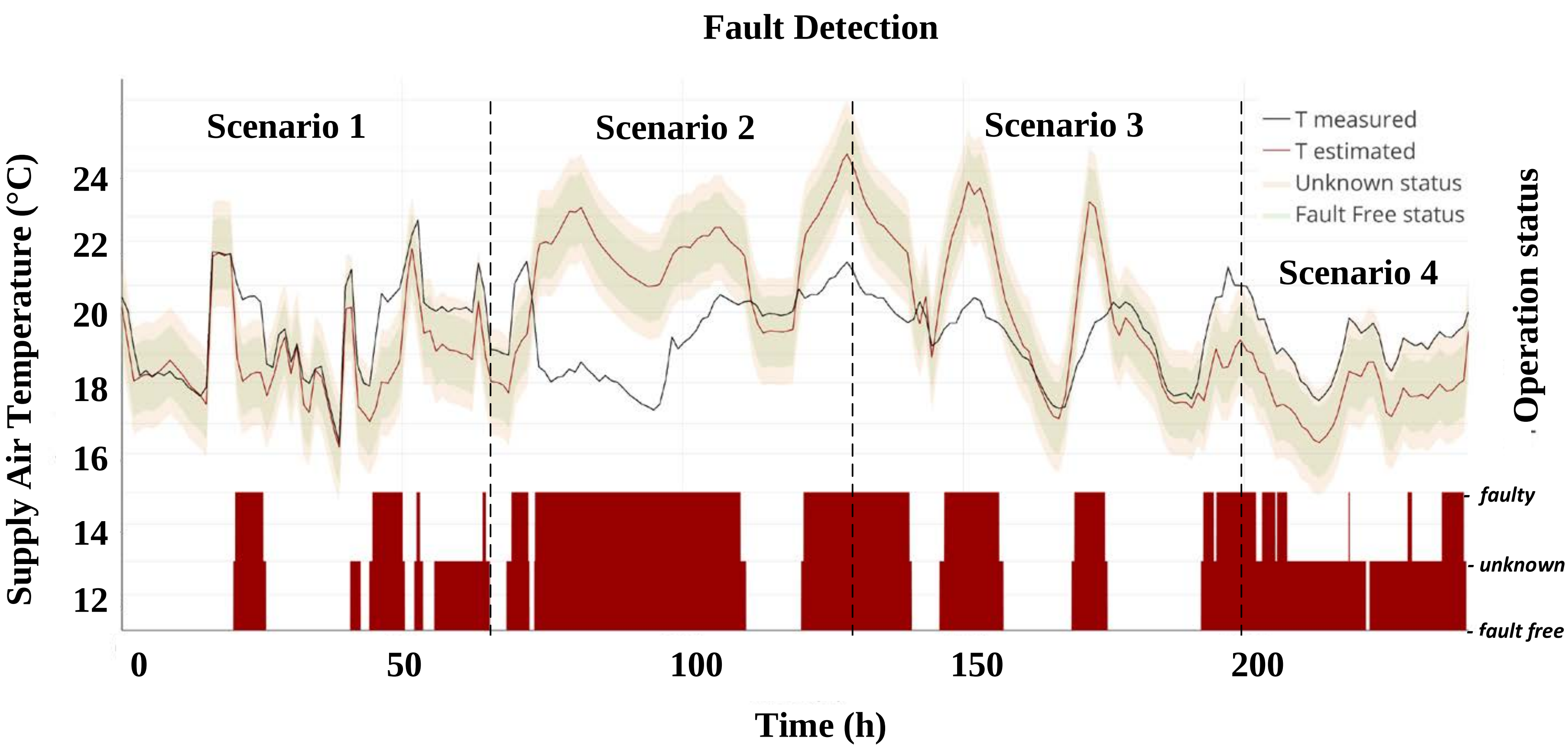
If γ^* AND $\gamma \in$ *Same Class* $p(\gamma^*) > 0.75 \rightarrow$ fault free

If γ^* AND $\gamma \in$ *Same Class* $p(\gamma^*) < 0.75 \rightarrow$ unknown

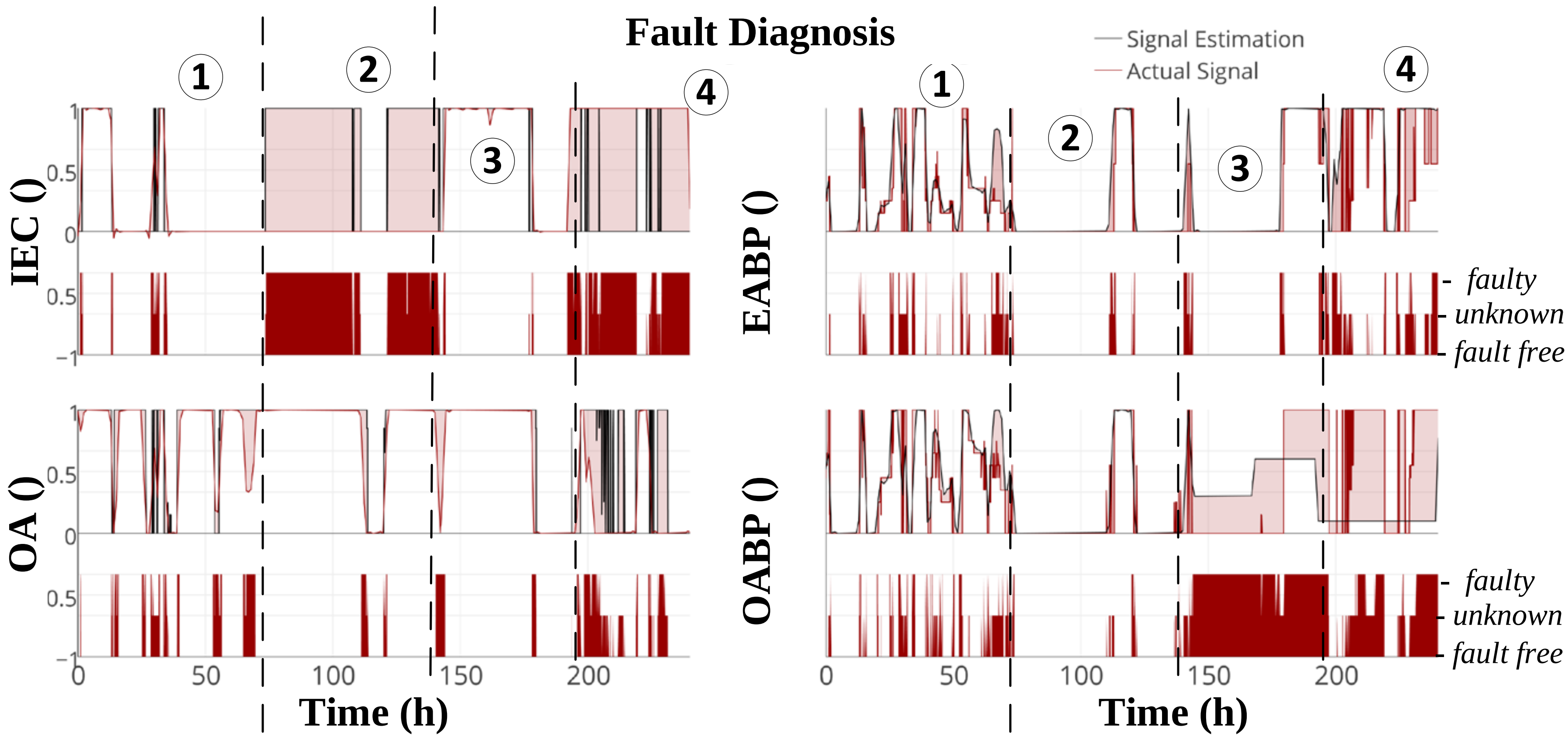
If γ^* AND $\gamma \in$ *Different Class* $p(\gamma^*) > 0.75 \rightarrow$ faulty

Application: virtual scenario

1) No error introduced.
2) The Indirect Evaporative Cooling (IEC) keeps running despite a stop signal.
3) The Outside Air damper bypass (OA BP) is stuck on closed status.
4) Multiple errors introduced (faulty OA BP and IEC).



Application: virtual scenario



NUI Galway (Ireland)

MPC

- Energy Control Underground Public Spaces
- Chiller Plant
- Heat Pumps

HIL

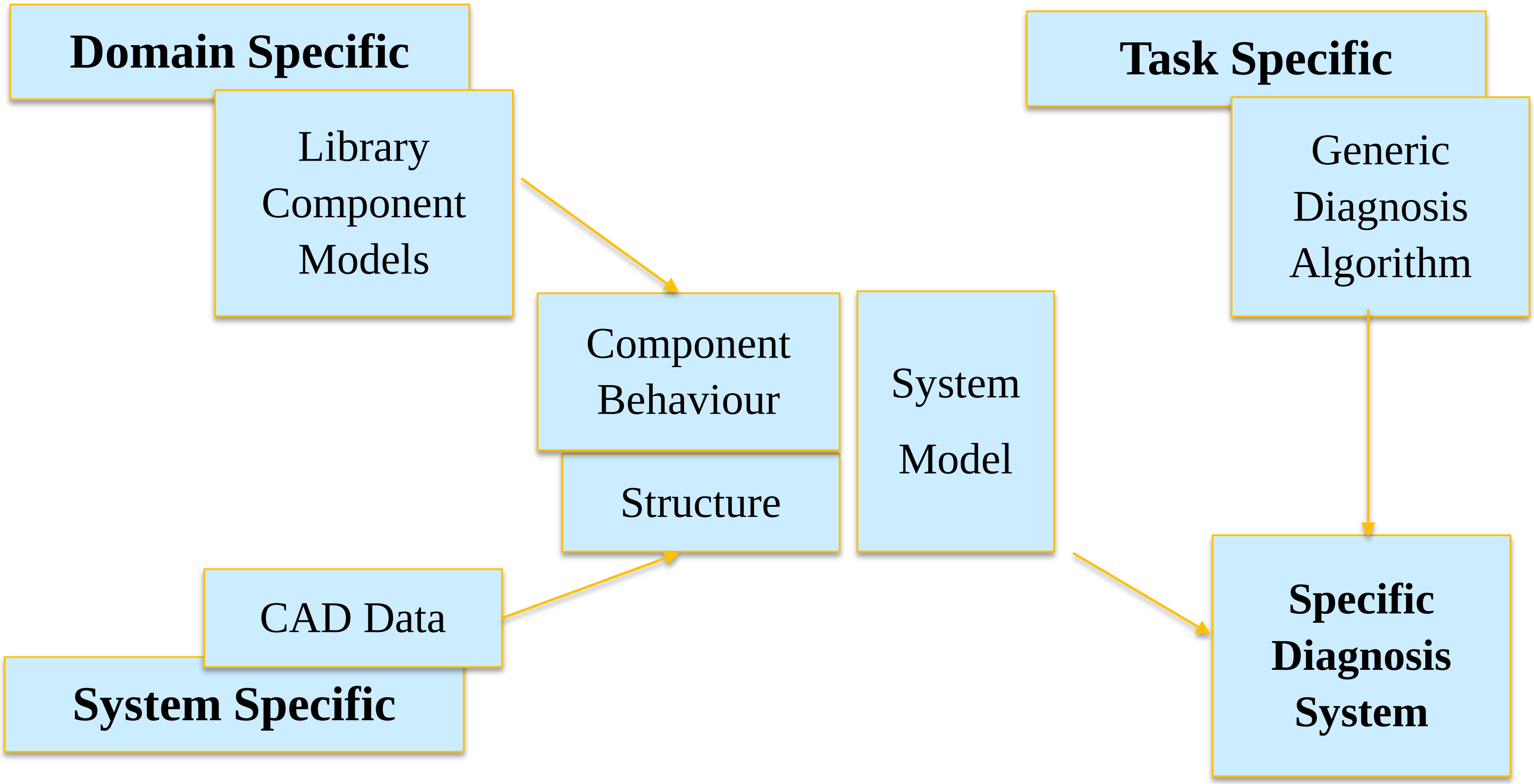
- HVAC close-loop control

FDD

- AHU FD
- Chillers in District Cooling
- **AHU FDD Automated Reasoning**
- AHU FDD Grey Box

An intuitive introduction

- Generate diagnostics systems instead of programming them

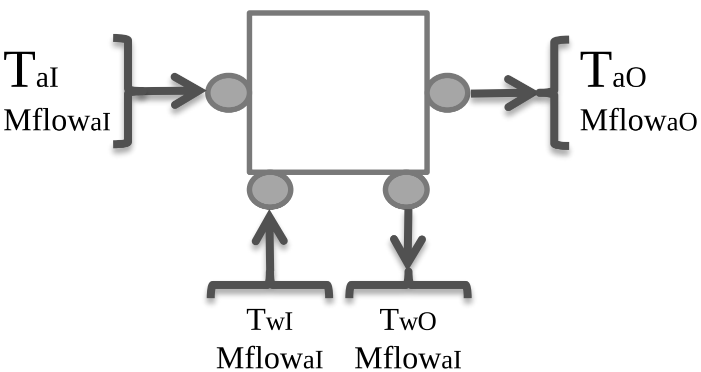


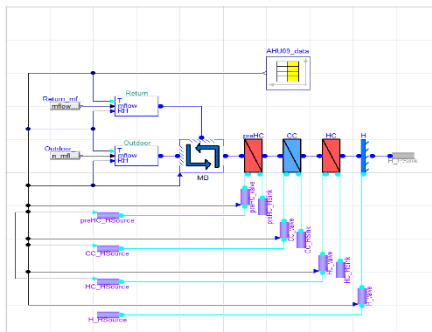
QMBD: Domain Specific

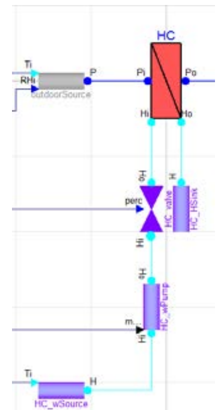
Modelica Component Library → Modelica Model Composition → Modelica Model Calibration → Modelica OK Model

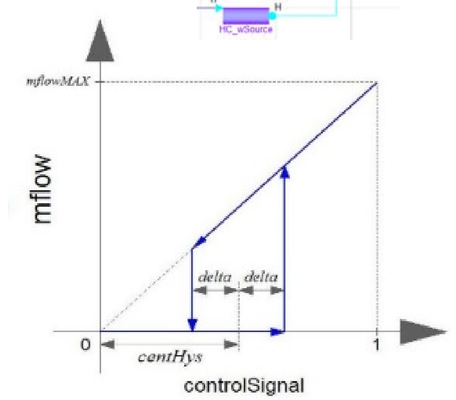
$$Q = c_a * Mflow_{aI} * (T_{aO} - T_{aI})$$

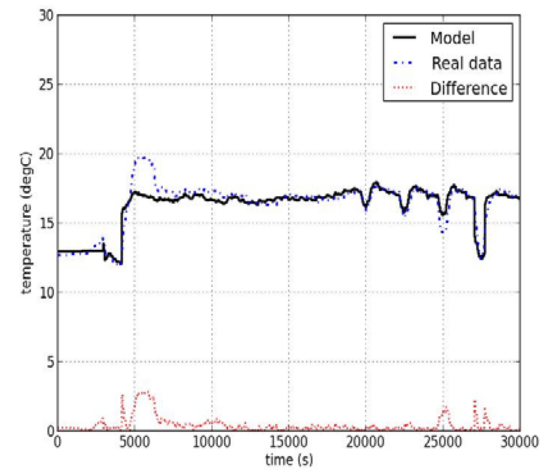
$$Q = c_w * Mflow_{wI} * (T_{wI} - T_{wO})$$











QMBD: Task Specific

Modelica Component Library → Model Transformation (Discretization) → Qualitative Component Library

$Q = c_a * Mflow_{aI} * (T_{aO} - T_{aI})$
$Q = c_w * Mflow_{wI} * (T_{wI} - T_{wO})$

Deviations

$\Delta x := x_{act} - x_{ref}$

$0 = c_a * Mflow_{aI} * (T_{aO} - T_{aI}) - c_w * Mflow_{wI} * (T_{wI} - T_{wO})$
$0 = \Delta (c_a * Mflow_{aI} * (T_{aI} - T_{aO})) \oplus \Delta (c_w * Mflow_{wI} * (T_{wI} - T_{wO}))$
$0 = \Delta T_{aI} \ominus \Delta T_{aO} \oplus \Delta mflow_w$

Table 1. Relation on temperature deviations and water flow deviation

$\Delta mflow_w$	ΔT_{aI}	ΔT_{aO}
0	-	-
0	0	0
0	+	+
-	-	-
-	0	-
-	+	*
+	-	*
+	0	+
+	+	+

Table 2 Qualitative representation of the OK mode

Cmd	$\Delta mflow_w$
0	0
+	0

Table 3 Qualitative representation of the stuck closed valve mode

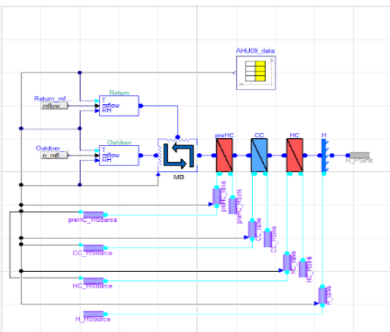
Cmd	$\Delta mflow_w$
0	0
+	-

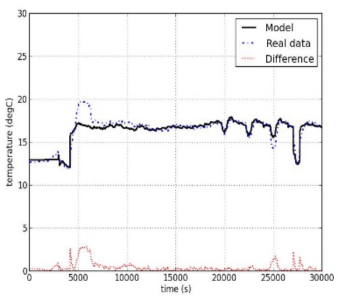
Table 4 Qualitative representation of the passing valve mode

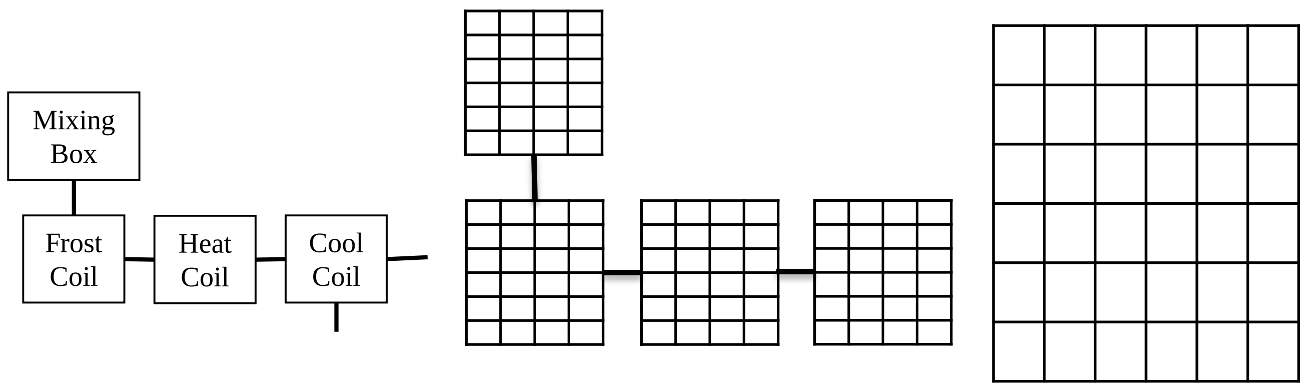
Cmd	$\Delta mflow_w$
0	+
+	0
+	+

QMBD: System Specific

Modelica OK Model → Plant Topology Extraction → Automated Model Composition → Qualitative Diagnosis Model

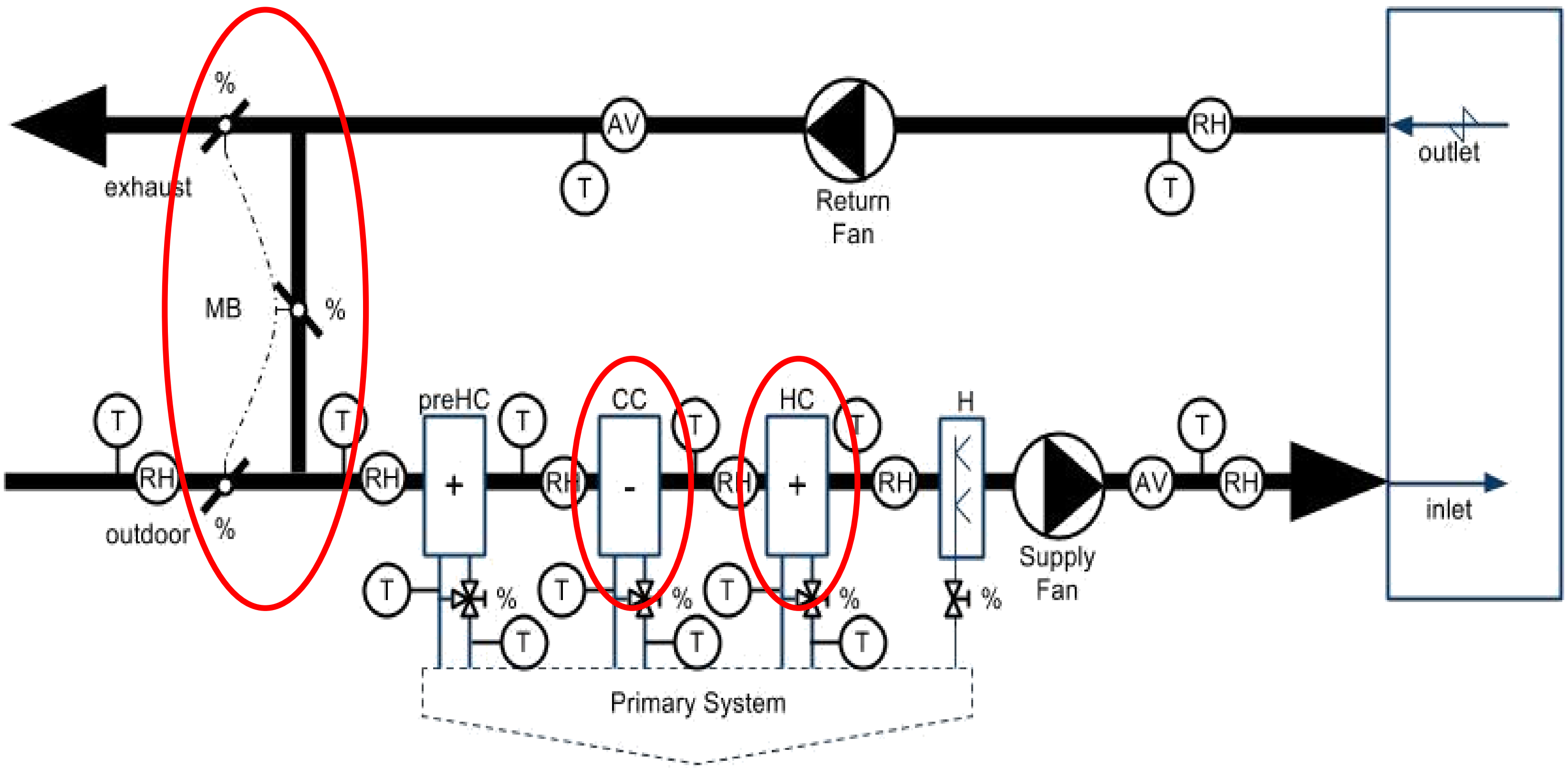






Results - offline

- Air handling unit



Results comparison against APAR

Component	MB		CC		HC	
Scenario	APAR	QMBD	APAR	QMBD	APAR	QMBD
Nominal	-	-	-	-	-	-
Passing Cooling Coil Valve	-	-	-	X	-	-
Passing Heating Coil Valve	-	X	-	-	X	X
Stuck Mixing Damper	X	X	-	-	-	-

Concluding remarks

- The Modelica component oriented language integrates in hybrid modelling processes
- The Modelica object-oriented approach allows for the development and the management of large and complex models. In such large-scale applications, the translators, the modelling language and environment are significantly stressed, and their robustness proved an enabling factor of the overall modelling process

Concluding remarks

- Modelica allows for a seamless use of the models developed in the design phase during the operational phase, for example, by exporting models as FMUs.
- It is important to note that the advantages of Modelica can turn against the unexperienced developer. For example, because of the object-orientation employed in many libraries, it can be difficult to predict the depth to which a change in one component can have an effect in other components in the library. Annex60 library is working on regression tests to avoid these side effects

Thank you for your attention

(any more) Questions?

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