ETH zürich

Optimal Energy Management of Buildings and Districts

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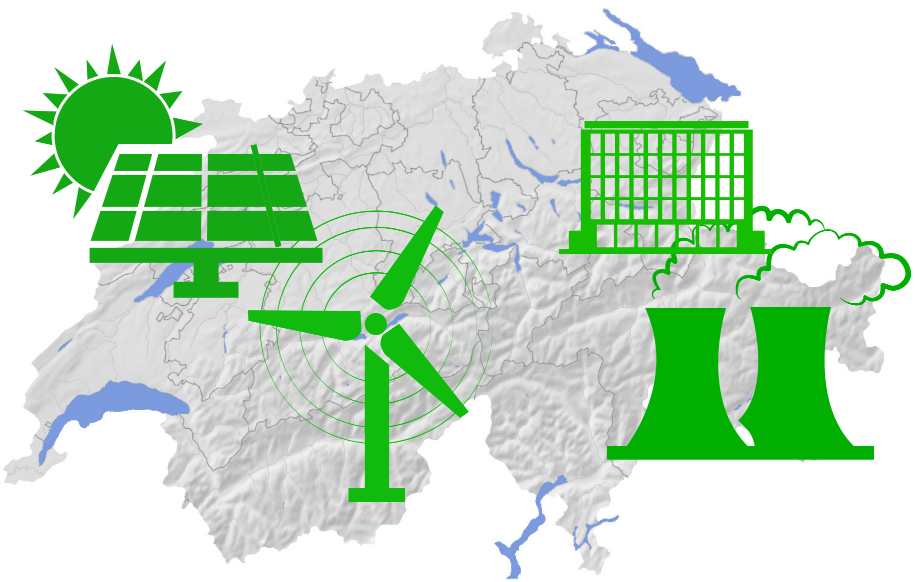
joint work with A. Georghiou, A. Eichler, R. S. Smith and J. Lygeros

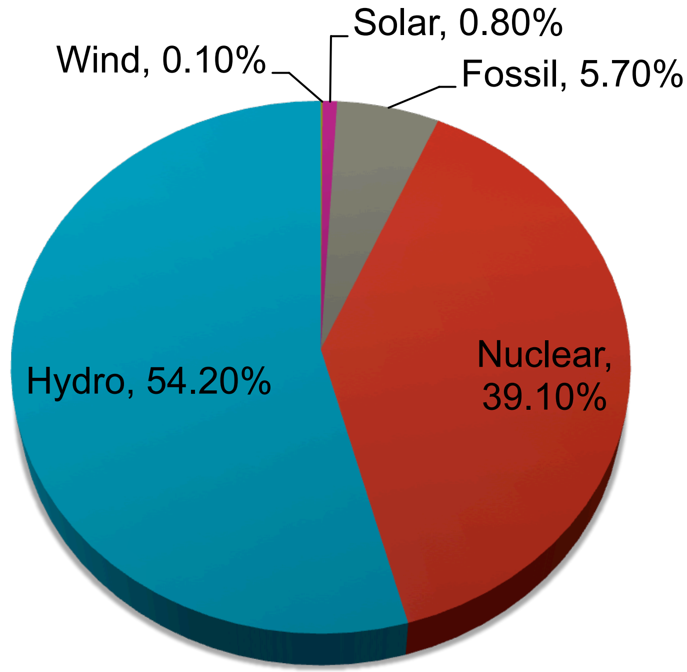
Automatic Control Laboratory (IfA)

Tuesday, 1st March, 2016

Background



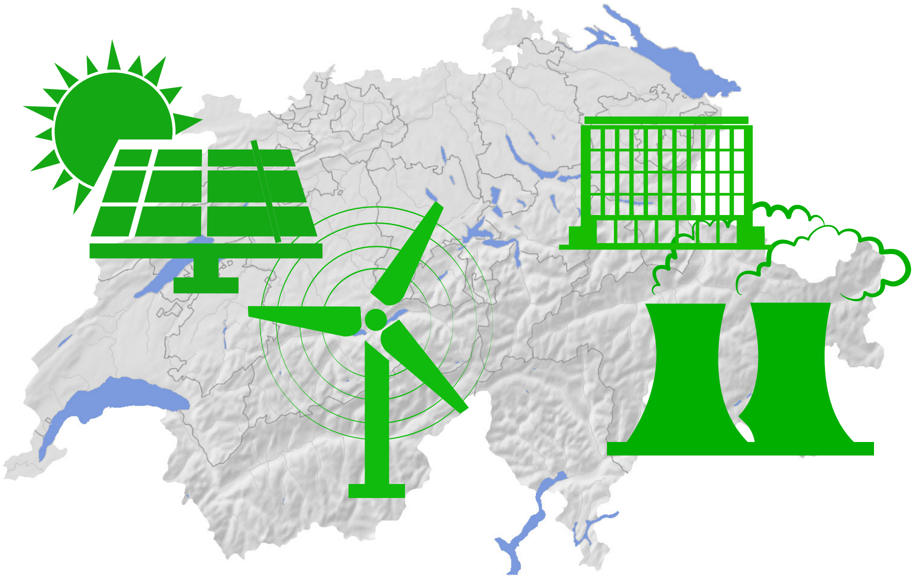
Electricity mix 2014



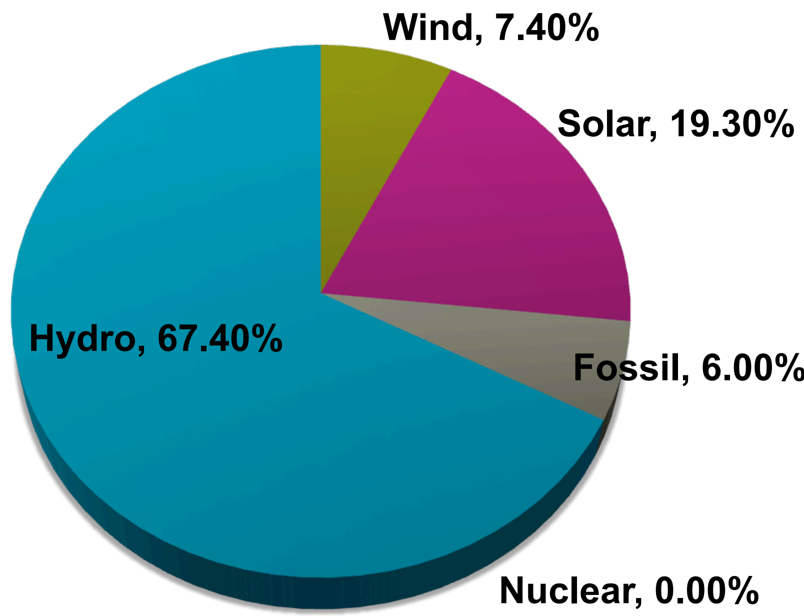
Schweizerische Eidgenoss
Confédération
Confederazion
Confederaziun

Energy Strategy 2050

Background



Electricity mix 2050



Schweizerische Eidgenoss...
Confédération
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Energy Strategy 2050

Motivation

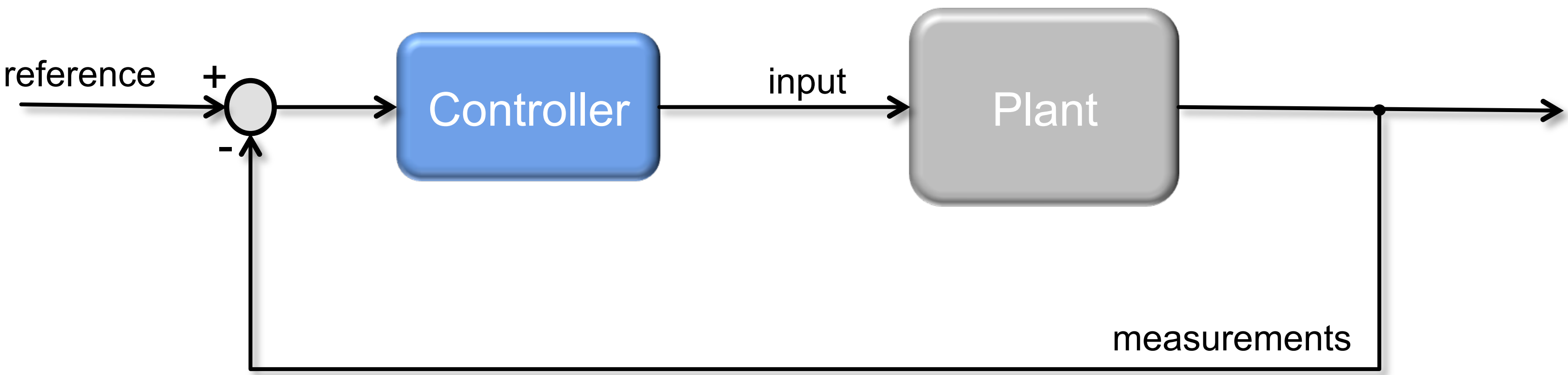
Opportunities

- Sharing energy efficient equipment (e.g. heat pumps, batteries)
- Shifting of energy between residential and commercial buildings

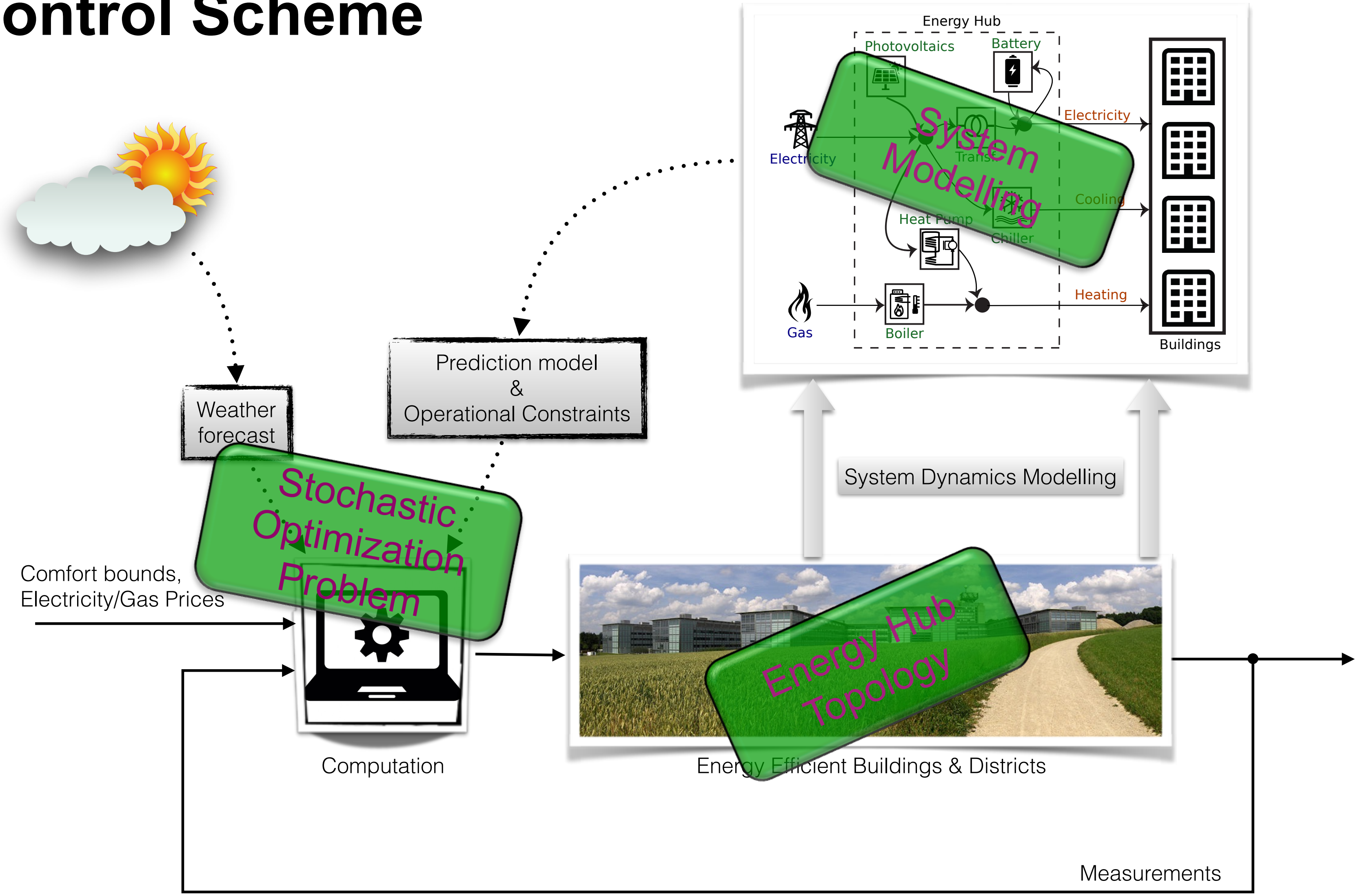
Challenges

- Regulation of energy exchange between hub devices and buildings
- Operation under uncertain conditions (e.g. weather, occupancy)

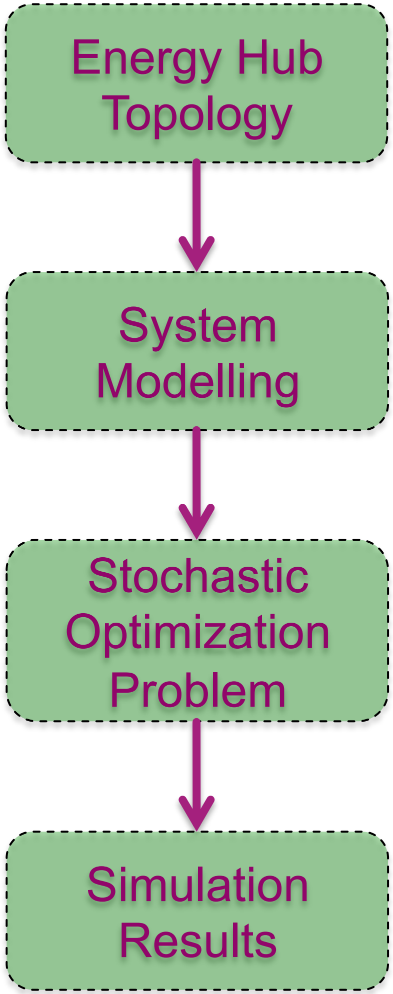
Control scheme



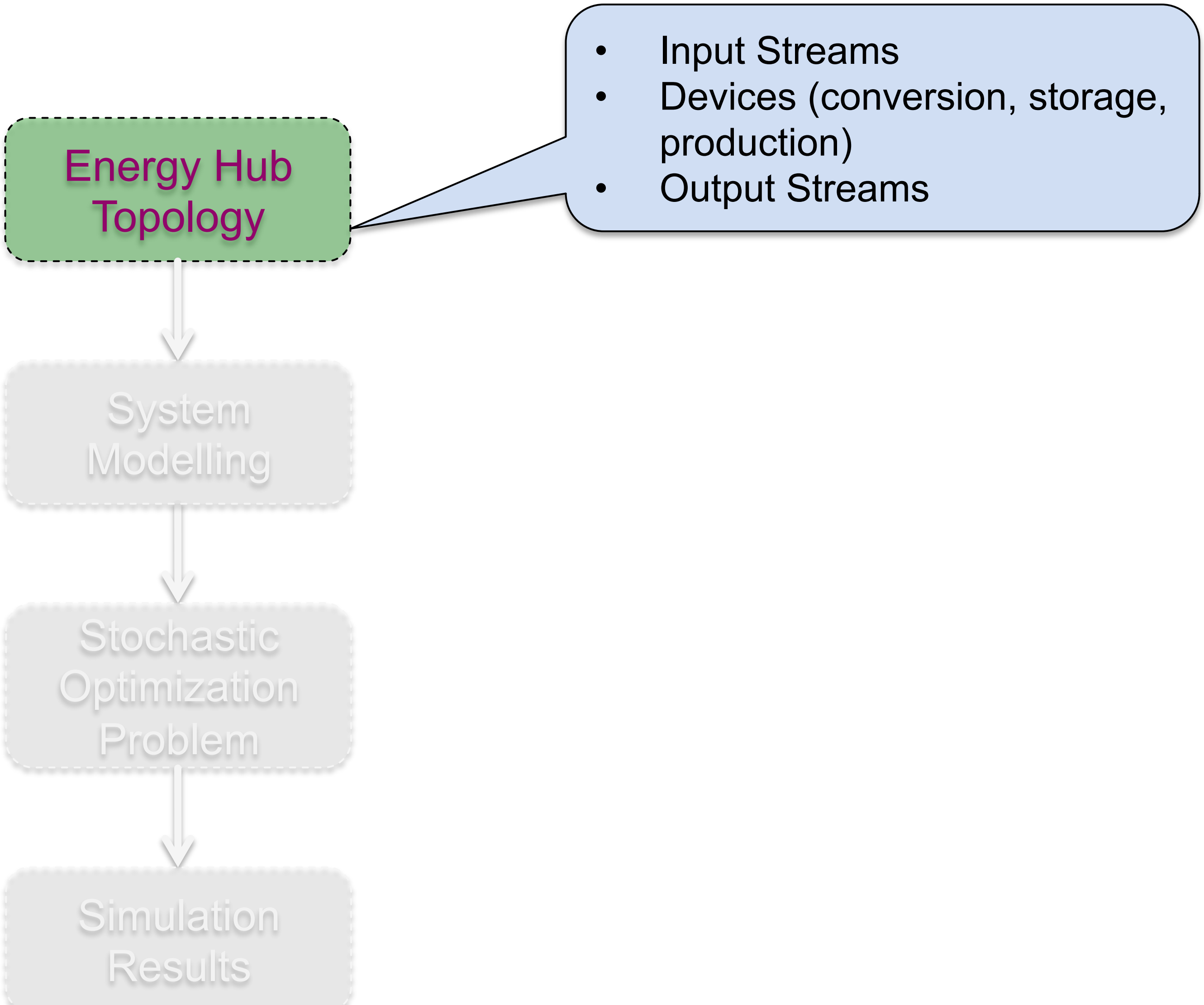
Control Scheme



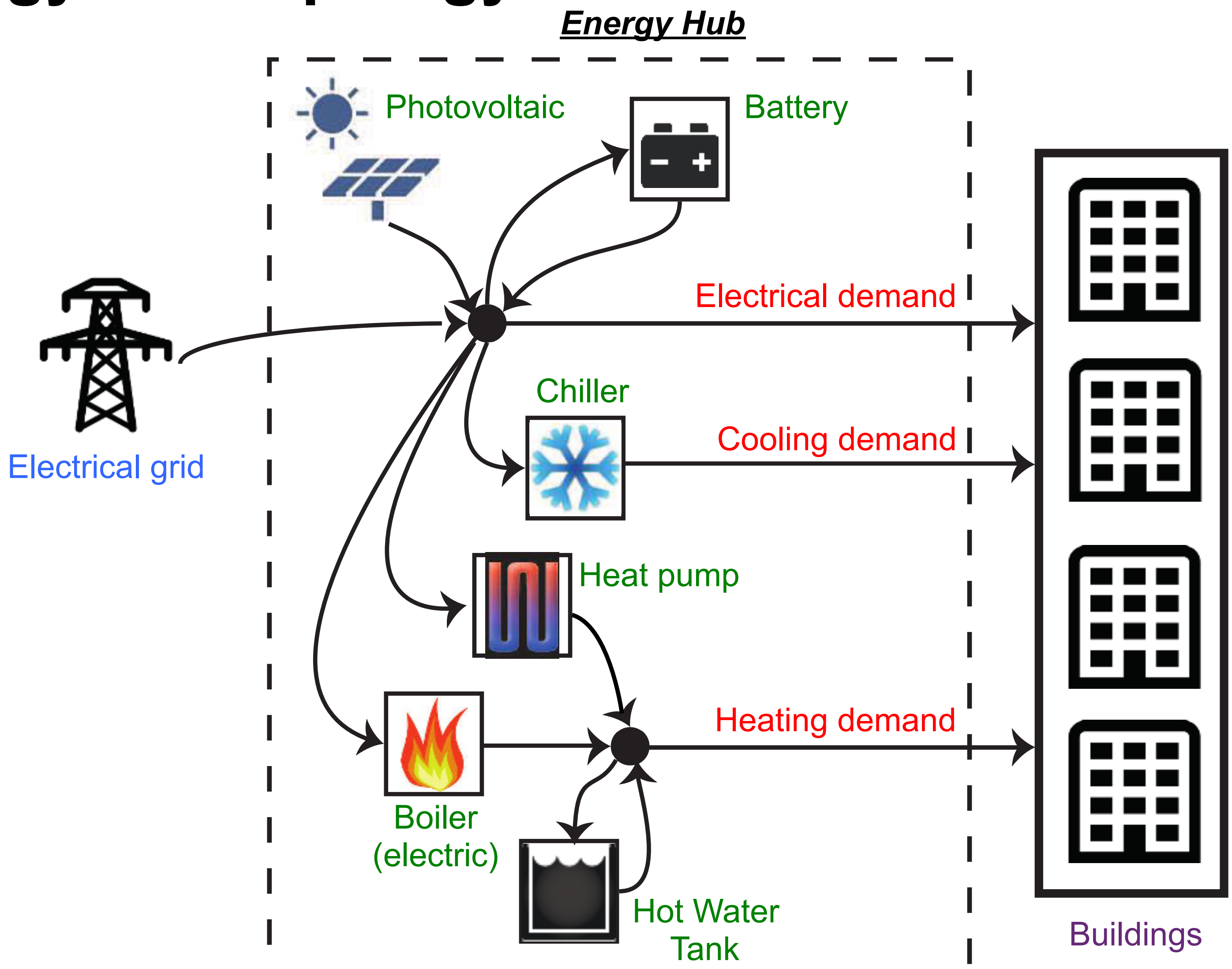
Outline


Energy Hub Topology
System Modelling
Stochastic Optimization Problem
Simulation Results

Outline


Energy Hub Topology
• Input Streams
• Devices (conversion, storage, production)
• Output Streams
System Modelling
Stochastic Optimization Problem
Simulation Results

Energy hub topology



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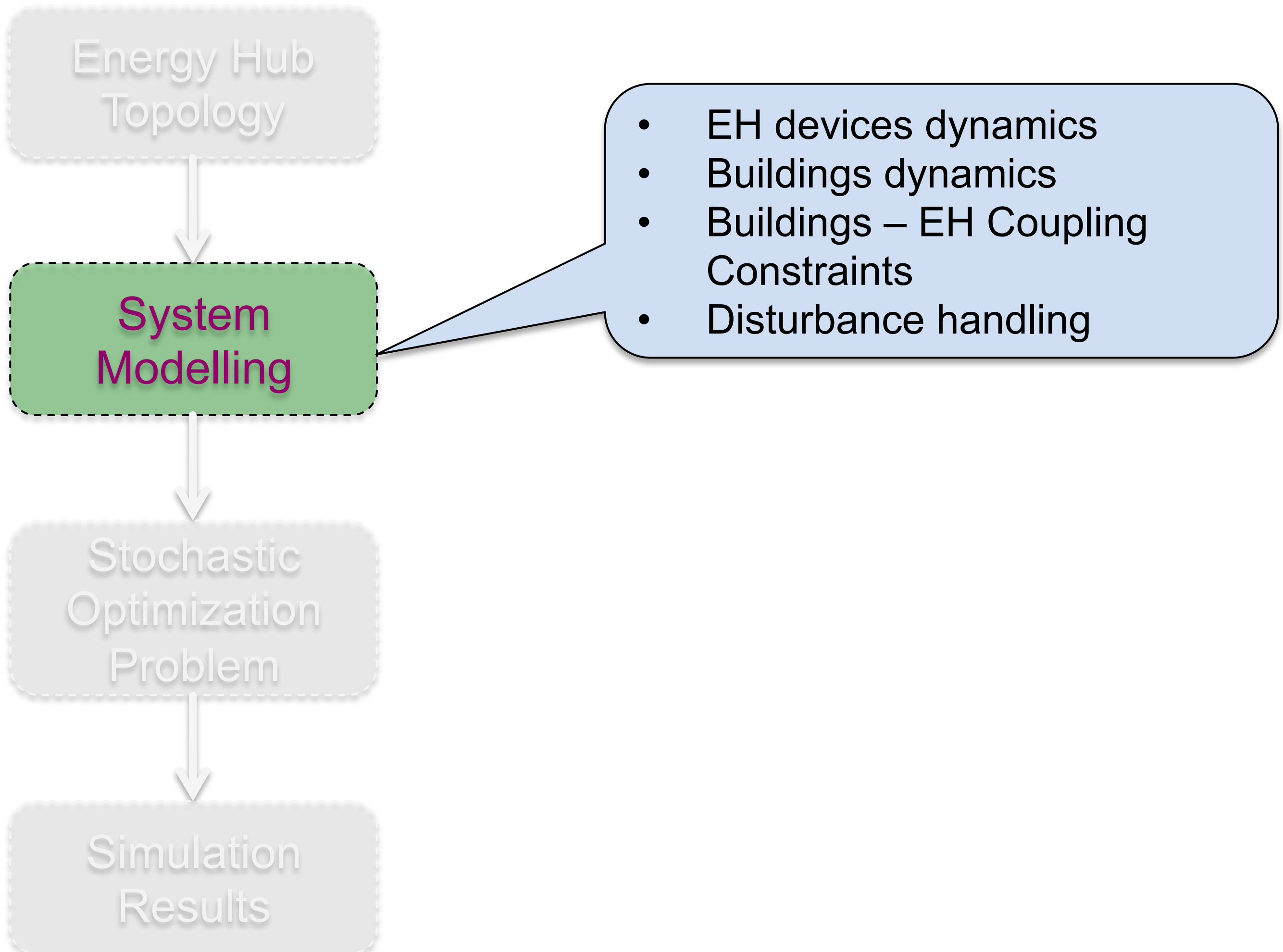
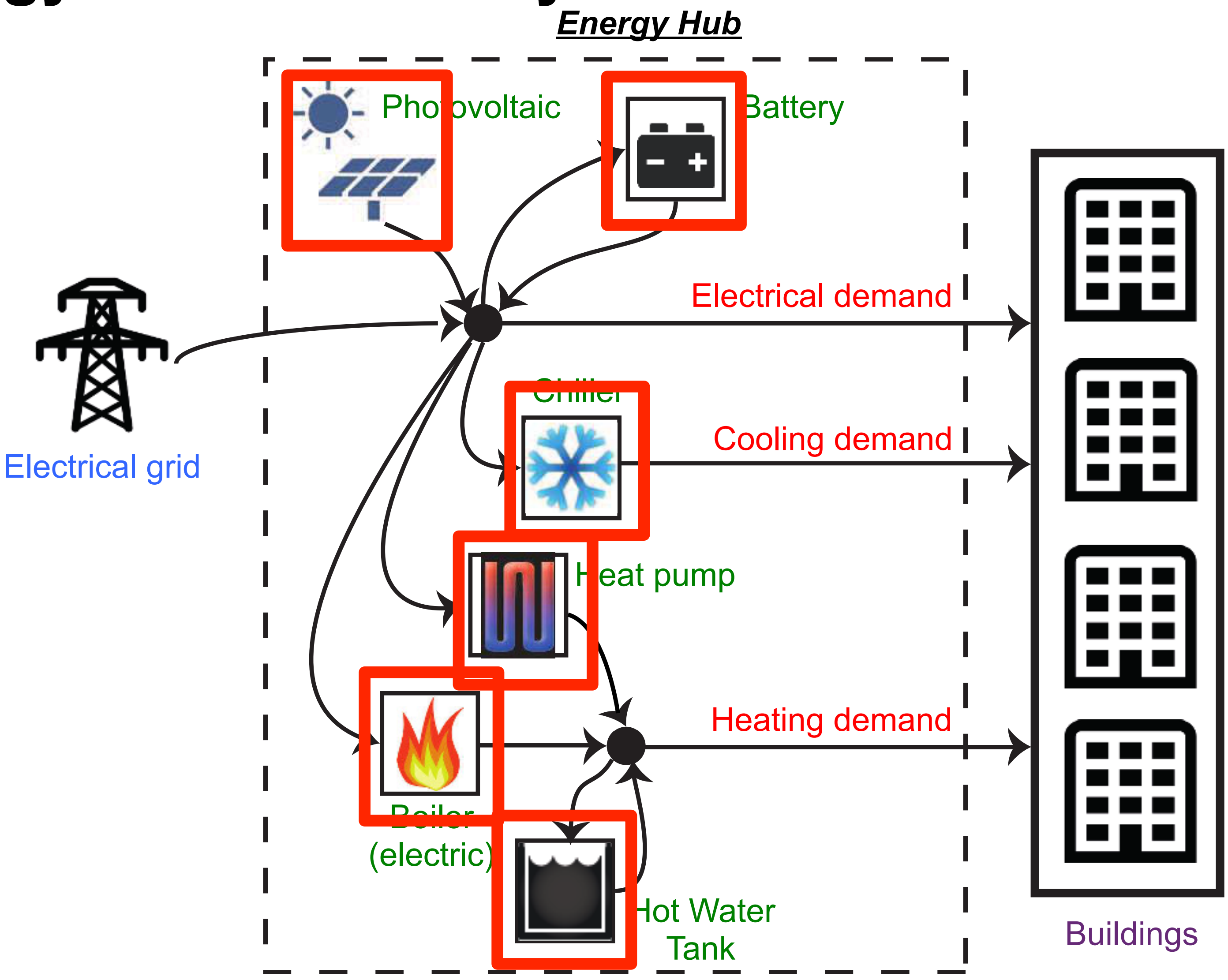
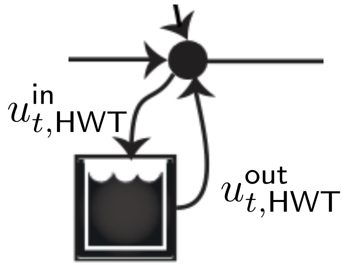

Energy Hub Topology
System Modelling
Stochastic Optimization Problem
Simulation Results
• EH devices dynamics
• Buildings dynamics
• Buildings – EH Coupling Constraints
• Disturbance handling

Energy hub devices dynamics



Energy hub devices dynamics



We model the i-th energy hub device with the following linear dynamical system,

$$\boldsymbol{x}_{t+1,i} = A_i \boldsymbol{x}_{t,i} + B_i^{\text{in}} \boldsymbol{u}_{t,i}^{\text{in}} + B_i^{\text{out}} \boldsymbol{u}_{t,i}^{\text{out}} + C_i \boldsymbol{\xi}_t,$$
$$(\boldsymbol{x}_{t,i}, \boldsymbol{u}_{t,i}^{\text{in}}, \boldsymbol{u}_{t,i}^{\text{out}}, \boldsymbol{\xi}_t) \in \mathcal{H}_{t,i},$$

where

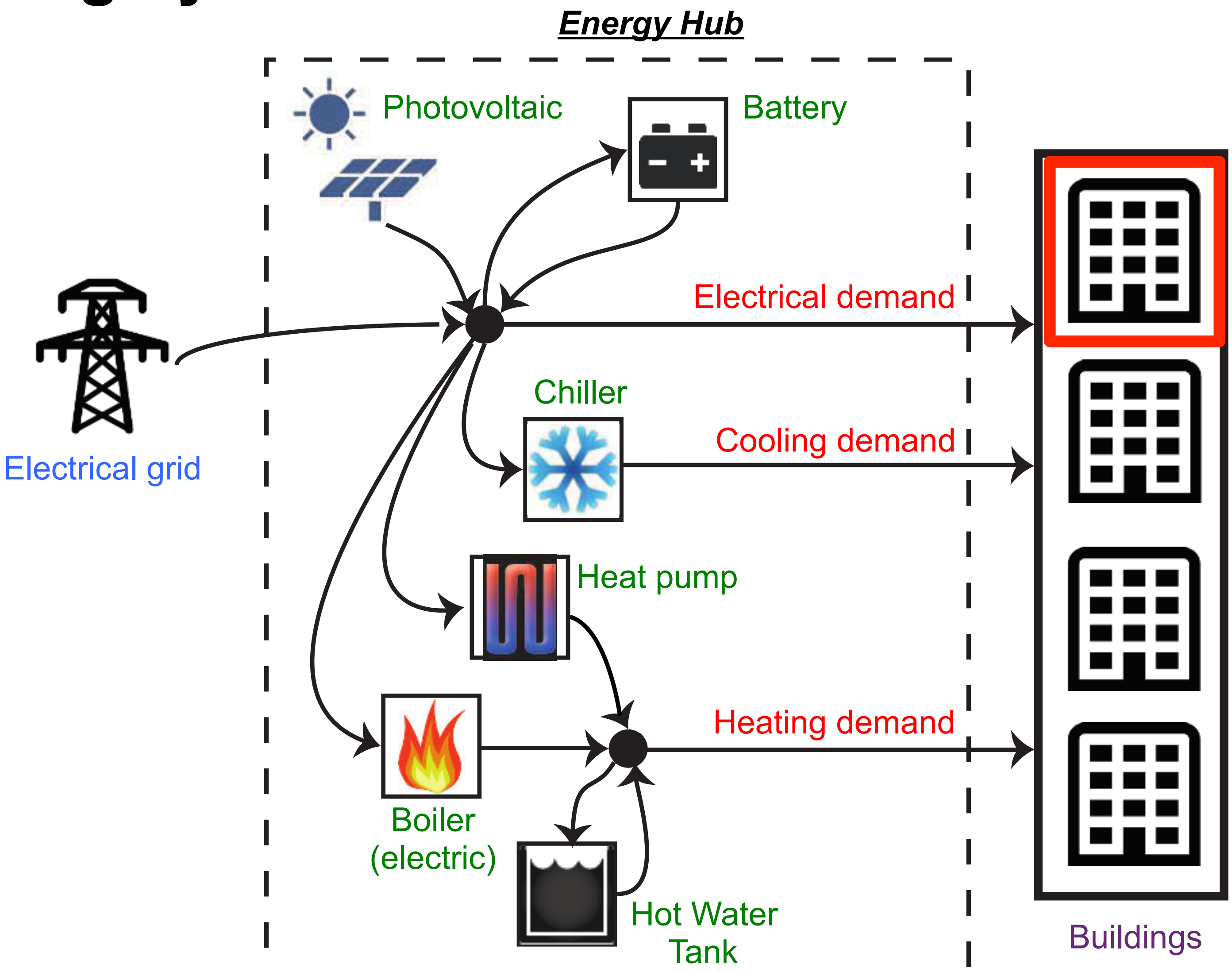
$\boldsymbol{x}_{t,i}$: states (e.g. water's temperature)

$\boldsymbol{u}_{t,i}^{\text{in}}, \boldsymbol{u}_{t,i}^{\text{out}}$: control variables (e.g. power flows)

$\boldsymbol{\xi}_t$: disturbances (e.g. ambient temperature)

$\mathcal{H}_{t,i}$: operational constraints (e.g. operation limits)

Building dynamics

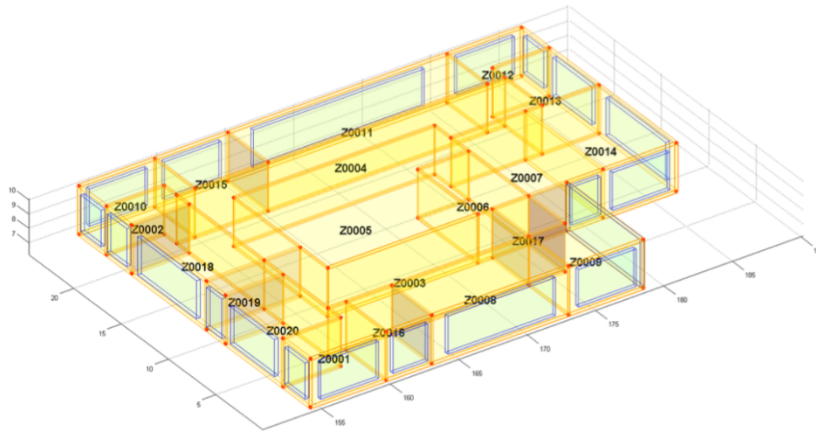


Building dynamics

Type: Swiss office building
Floor area: 600 m^2
Location: Allschwill, Basel

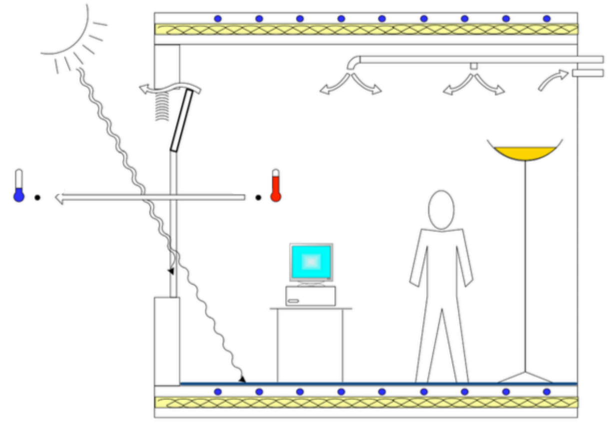
```
ThermalModelData with properties:

                 zones : [1x20 Zone]
     building_elements : [1x124 BuildingElement]
         constructions : [1x10 Construction]
             materials : [1x18 Material]
               windows : [1x20 Window]
            parameters : [1x12 Parameter]
nomass_constructions : [1x1 NoMassConstruction]
          source_files : [1x1 struct]
              is_dirty : 1
```



[1] Sturzenegger, D., Gyalistras, D., Semeraro, V., Morari, M., Smith, R. S., "*BRCM Matlab Toolbox: Model Generation for Model Predictive Building Control*", American Control Conference, 2014.

Building dynamics



- Bi-linear model

$$x_{t+1,i} = A_i x_{t,i} + B_i u_{t,i} + C_i \xi_t + \sum_{j \in \mathcal{D}_i^{\mathrm{b}}} \left(D_{i,j} \xi_t + E_{i,j} x_{t,i} \right) u_{t,i,j},$$

where

$x_{t,i}$: states (e.g. room and wall temperatures)

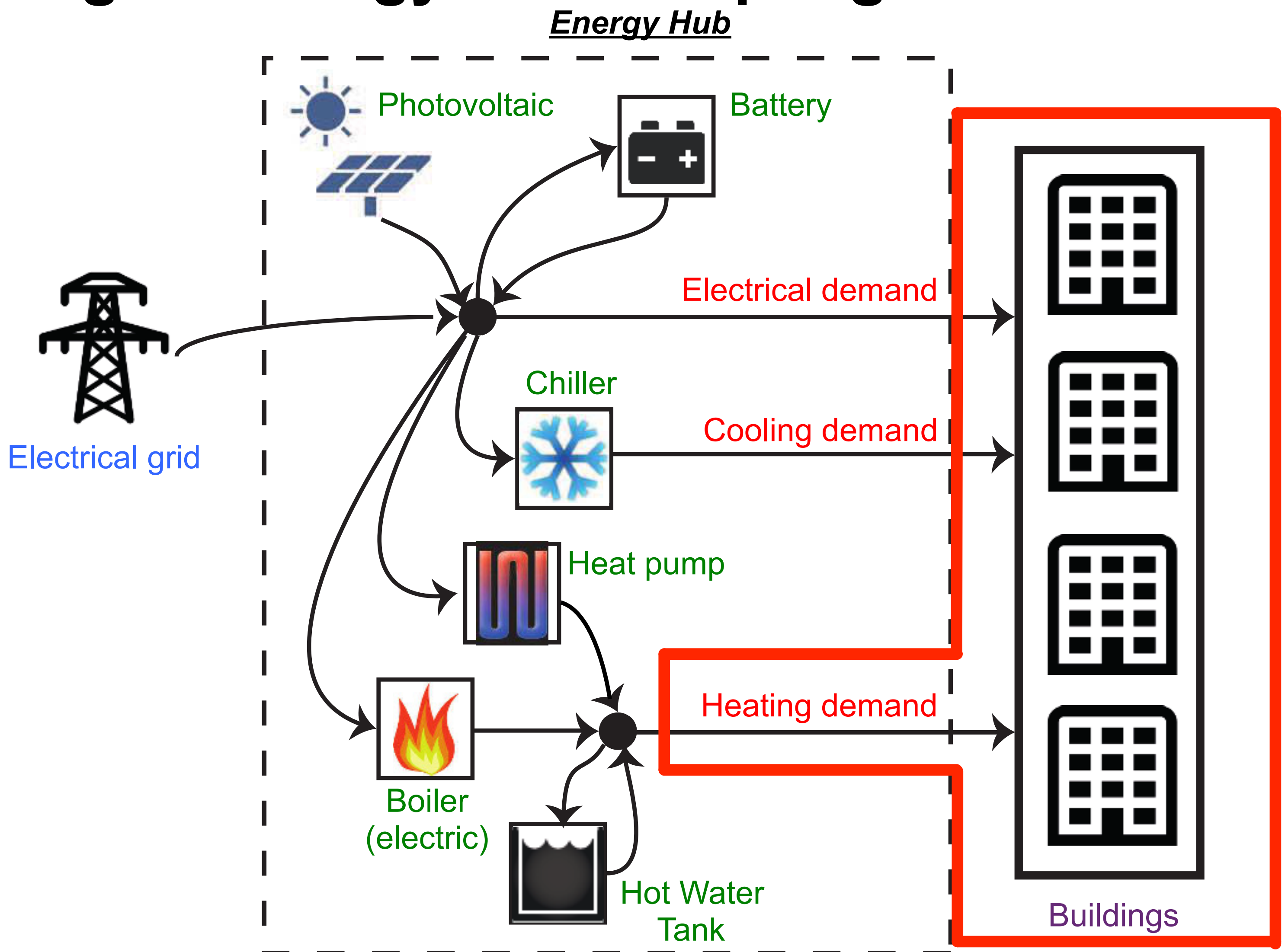
$u_{t,i}$: inputs in the set $\mathcal{D}_i^b$ (e.g. radiators, AHU, TABS)

$\xi_{t,i}$: disturbances (e.g. solar radiation, ambient temperature)

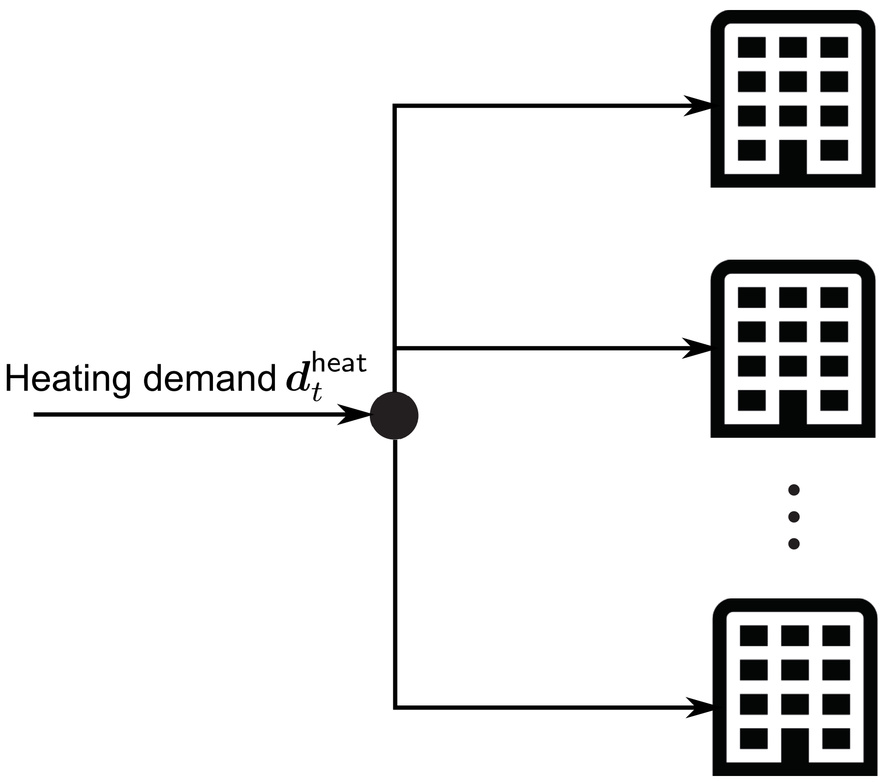
- Comfort and input constraints

$21^o\mathrm{C} \leq x_{t,i}^{\text{room}} \leq 25^o\mathrm{C}$ and $u_{t,i} \in \mathcal{U}_i$

Buildings – Energy Hub Coupling



Buildings – Energy Hub Coupling

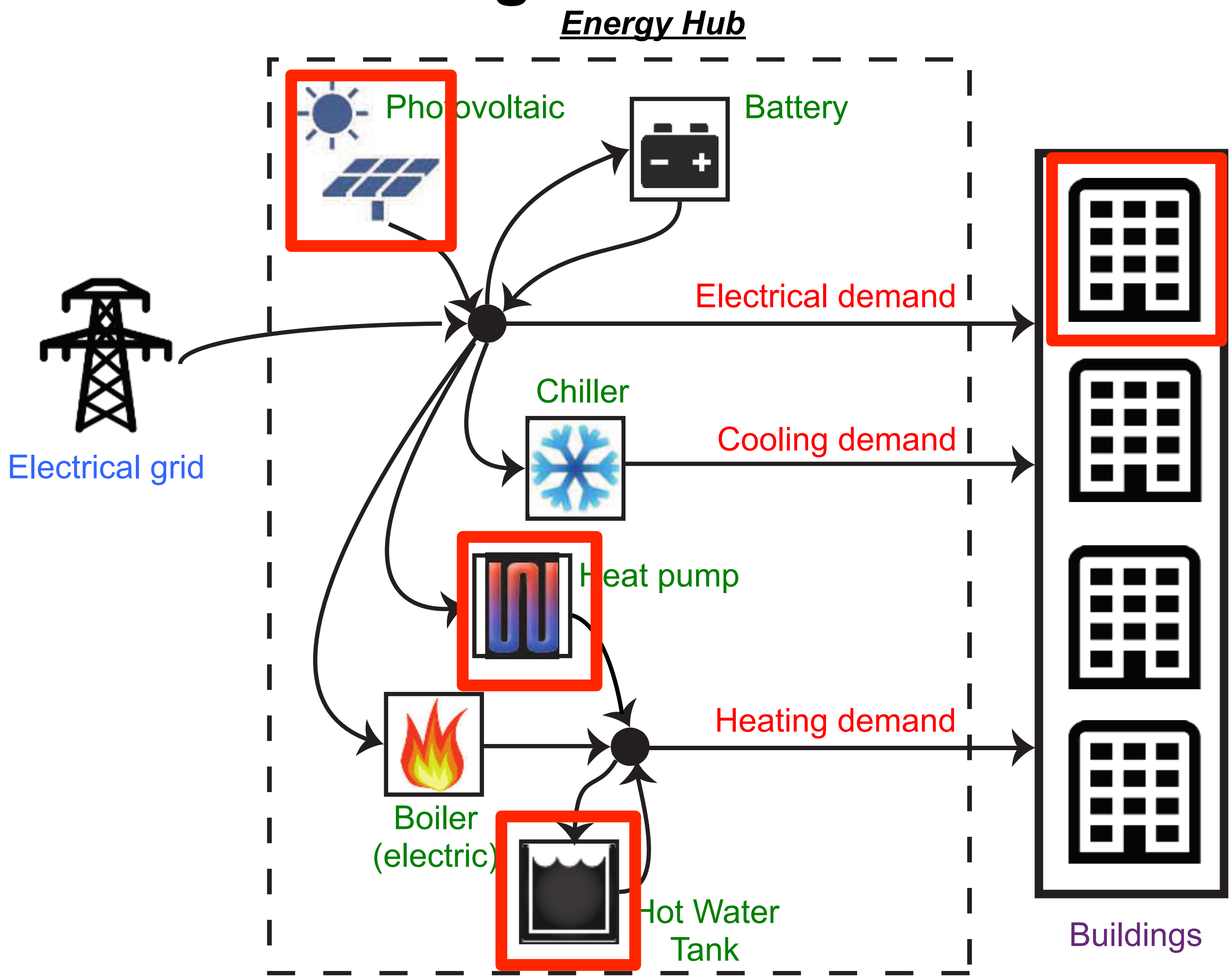


Heating energy balancing:

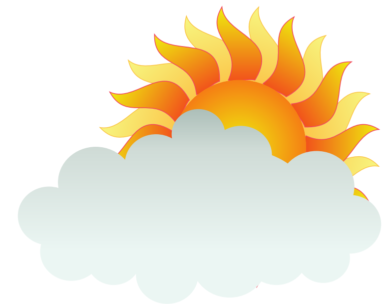
$$\boldsymbol{d}_t^{\text{heat}} = \sum_{i \in \mathcal{B}} \boldsymbol{u}_{t,i,\text{radiator}} + \sum_{i \in \mathcal{B}} \boldsymbol{u}_{t,i,\text{TABS}}$$

Similarly for other sources:
electricity, cooling, etc.

Disturbance handling



Disturbance handling



The uncertainty set for the stochastic process ξ_t is defined as,

$$\Xi = \left\{ \begin{array}{lll} \boldsymbol{\xi} \in \mathbb{R}^k \text{ s.t } & \boldsymbol{\xi}_t = f_t + \boldsymbol{\epsilon}_t, & t = 1, \ldots, T, \\ & \boldsymbol{\epsilon}_t \in [\underline{\text{eb}}_t, \overline{\text{eb}}_t], & t = 1, \ldots, T, \\ & \boldsymbol{\epsilon}_{t+1} - \boldsymbol{\epsilon}_t \in [\underline{\text{db}}_t, \overline{\text{db}}_t], & t = 1, \ldots, T-1, \end{array} \right\}.$$

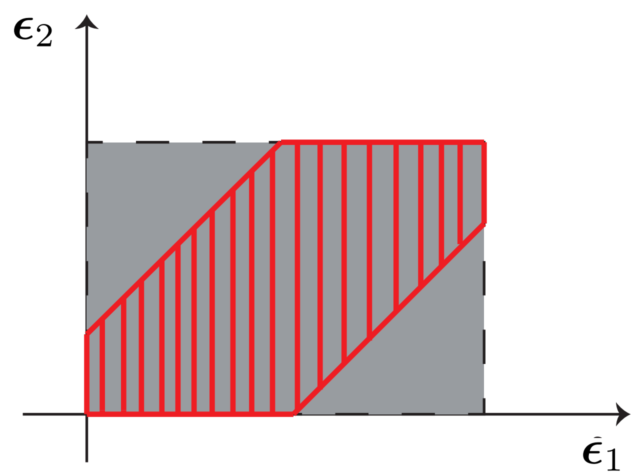
where

T : prediction horizon

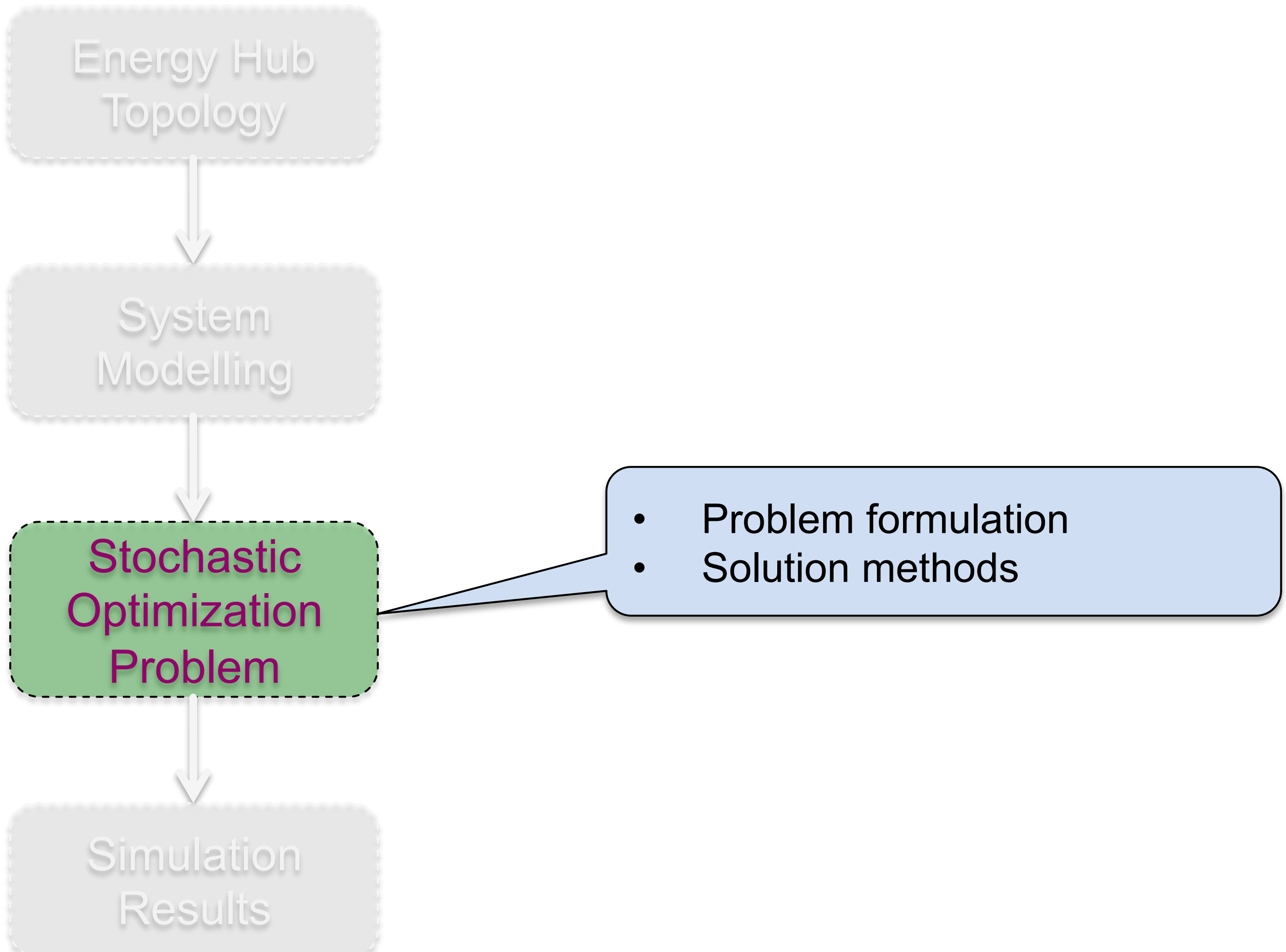
f_t : forecast

$\underline{\text{eb}}_t$, $\overline{\text{eb}}_t$: bounds on error

$\underline{\text{db}}_t$, $\overline{\text{db}}_t$: bounds on error correlation



Outline


Energy Hub Topology
System Modelling
Stochastic Optimization Problem
Simulation Results
• Problem formulation
• Solution methods

Optimization problem

$$\begin{aligned}\text{minimize } & \mathbb{E}\left(\sum_{t\in\mathcal{T}} c_t \boldsymbol{p}_t\right)\\ \text{such that } & \left.\begin{array}{l}\text{Energy Hub Constraints},\\ i\text{-th Building System}, \ i\in\mathcal{B},\\ \text{Coupling Constraints}.\end{array}\right\} \forall \boldsymbol{\xi}_t \in \Xi\end{aligned}$$

Cost of energy purchased from grid

Disturbances (e.g solar rad., temp.)

where c_t : time-varying prices
$\boldsymbol{p}_t$: (decision variable) Energy purchased from the grid
$\mathcal{T}$: time horizon
$\mathcal{B}$: set of buildings

Solution method

$$\begin{aligned} \text{minimize } & \mathbb{E}\left(\sum_{t\in\mathcal{T}} c_t \boldsymbol{p}_t\right) \\ \text{such that } & \left.\begin{array}{l} \text{Energy Hub Constraints}, \\ i\text{-th Building System}, \; i \in \mathcal{B}, \\ \text{Coupling Constraints}. \end{array}\right\} \forall \boldsymbol{\xi}_t \in \Xi \end{aligned}$$

Issues		Methodologies

Solution method

$$\boldsymbol{x}_{t+1,i} = A_i \boldsymbol{x}_{t,i} + B_i \boldsymbol{u}_{t,i} + C_i \boldsymbol{\xi}_t + \sum_{j \in \mathcal{D}_i^{\mathrm{b}}} \left(D_{i,j} \boldsymbol{\xi}_t + E_{i,j} \boldsymbol{x}_{t,i} \right) \boldsymbol{u}_{t,i,j},$$

Issues

- Nonlinear Building Dynamics

Methodologies

- Linearization around current operating point and forecasts

Solution method

$$21^o\text{C} \leq \boldsymbol{x}_{t,i}^{\text{room}} \leq 25^o\text{C}$$

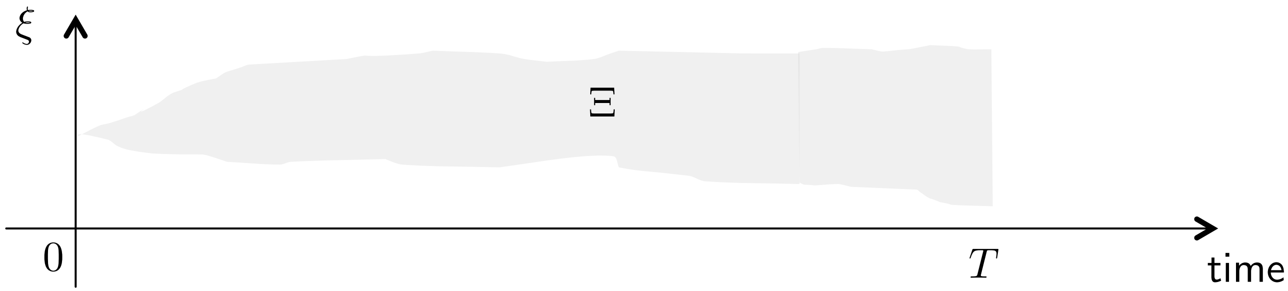
Issues	Methodologies
• Nonlinear Building Dynamics • Infeasibility for some initial conditions	• Linearization around current operating point • Constraint relaxation using slack variables

Solution method

$$\begin{aligned} \text{minimize } & \mathbb{E}\left(\sum_{t\in\mathcal{T}} c_t \boldsymbol{p}_t\right) \\ \text{such that } & \left.\begin{aligned} & \text{Energy Hub Constraints}, \\ & i\text{-th Building System}, \ i \in \mathcal{B}, \\ & \text{Coupling Constraints}. \end{aligned}\right\} \forall \boldsymbol{\xi}_t \in \Xi \end{aligned}$$

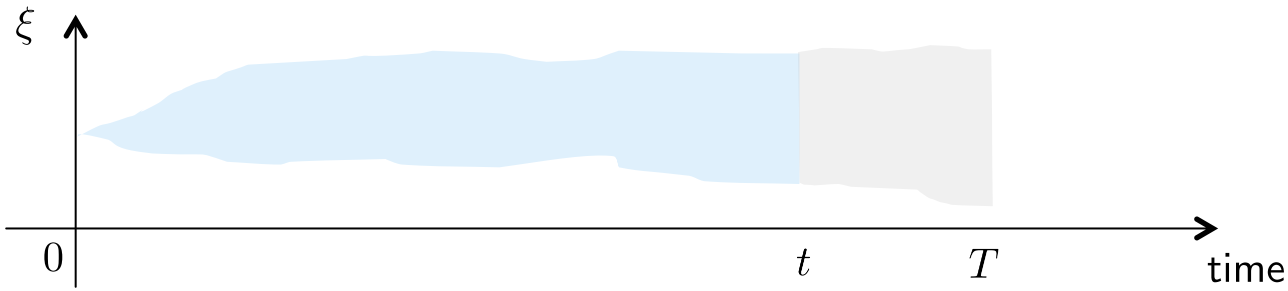
Issues	Methodologies
• Nonlinear Building Dynamics • Infeasibility for some initial conditions • Constraint satisfaction for every disturbance realization	• Linearization around current operating point • Constraint relaxation using slack variables • Robust Optimization methods

Control methodology



Method	Information Structure	Decision variables Structure	Disturbances
Affine Decision Rules			
Open Loop Policies			
Certainty Equivalent Problem			

Control methodology



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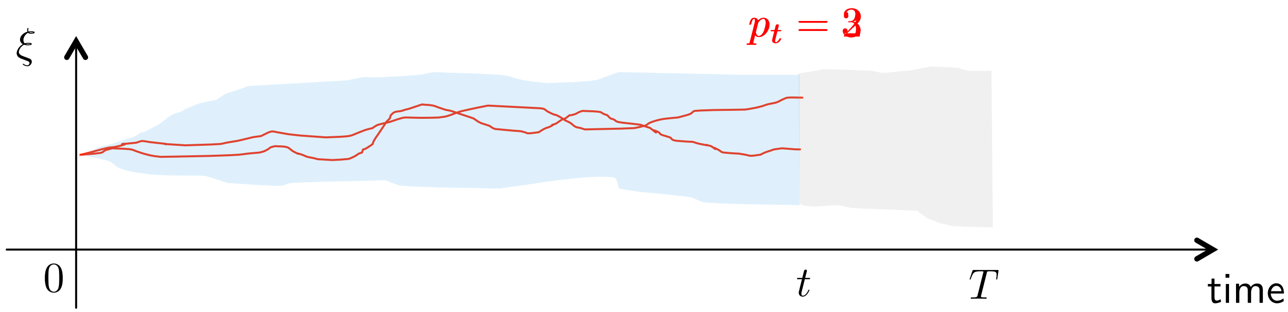
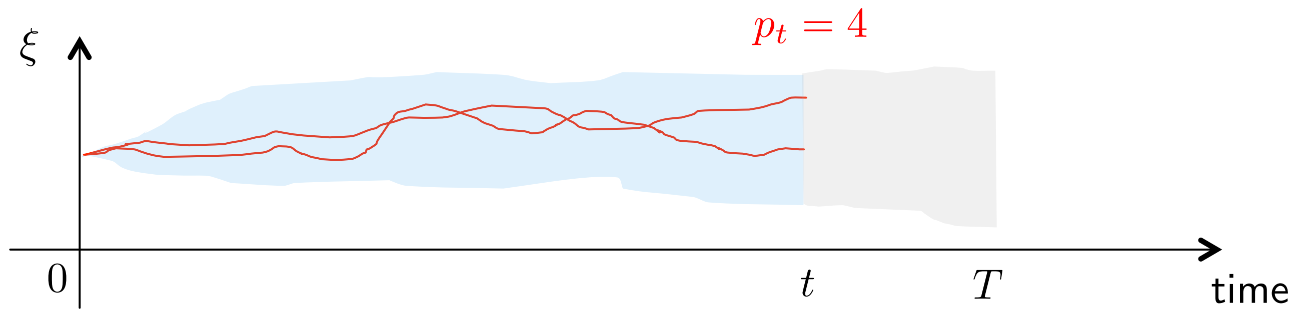
Control methodology



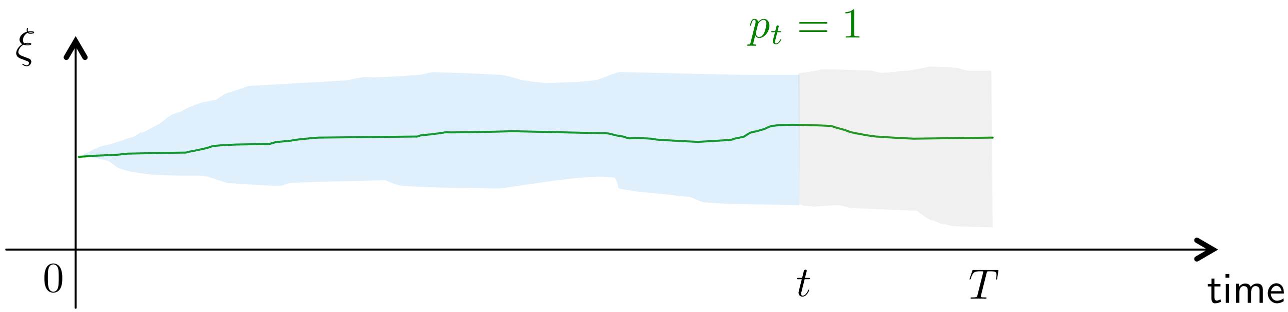
Method	Information Structure	Decision variables Structure	Disturbances
Affine Decision Rules	$I_t = (\mathbf{1}, \boldsymbol{\xi}_1, \ldots, \boldsymbol{\xi}_t)$	$\boldsymbol{p}_t = p_{t,0} + \sum_{s=0}^{t} p_{t,s}\, \boldsymbol{\xi}_s$	$\boldsymbol{\xi}_t \in \Xi$
Open Loop Policies			
Certainty Equivalent Problem			

Control methodology



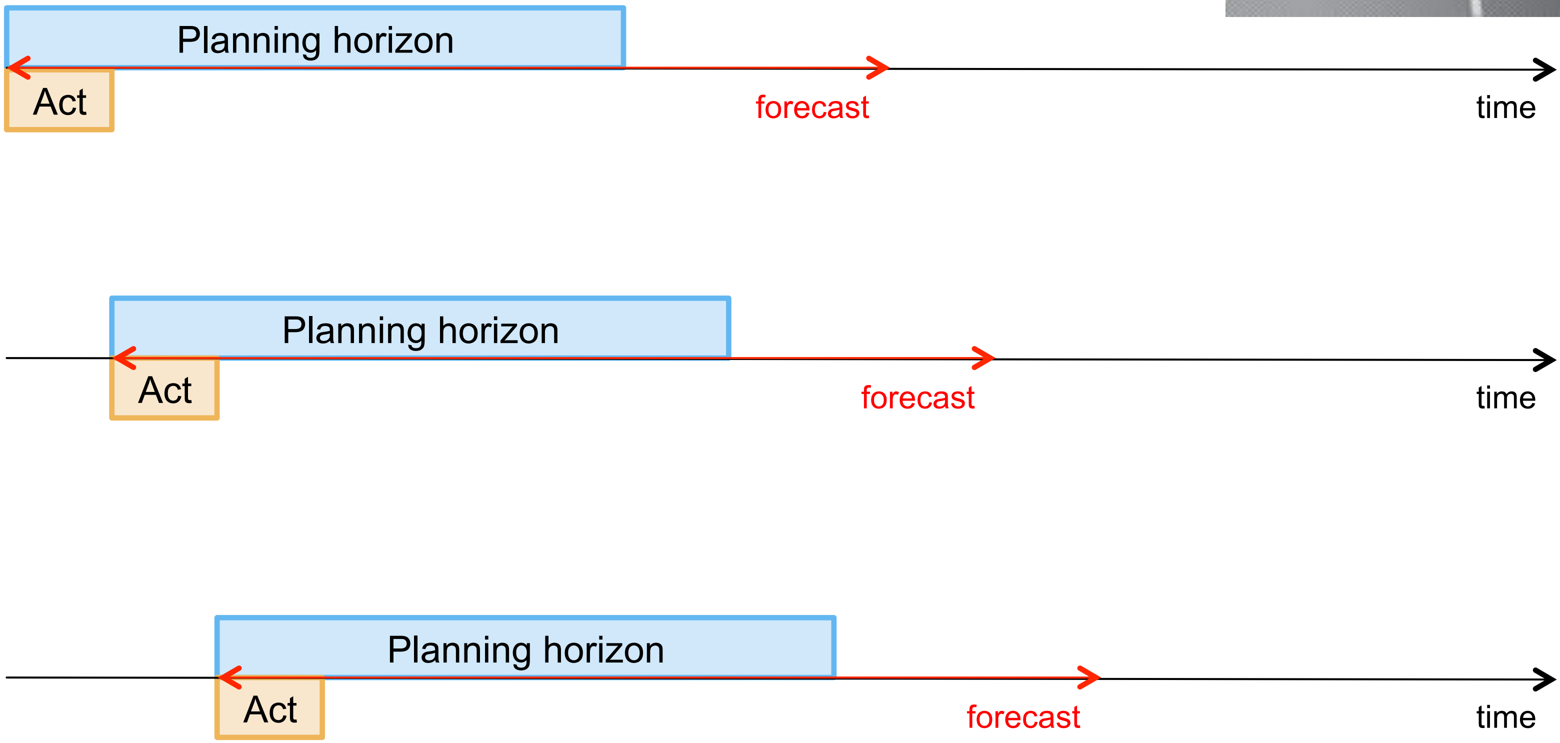
Method	Information Structure	Decision variables Structure	Disturbances
Affine Decision Rules	$I_t = (\mathbf{1}, \boldsymbol{\xi}_1, \ldots, \boldsymbol{\xi}_t)$	$\boldsymbol{p}_t = p_{t,0} + \sum_{s=0}^{t} p_{t,s}\, \boldsymbol{\xi}_s$	$\boldsymbol{\xi}_t \in \Xi$
Open Loop Policies	$I_t = (\mathbf{1})$	$\boldsymbol{p}_t = p_{t,0}$	$\boldsymbol{\xi}_t \in \Xi$
Certainty Equivalent Problem			

Control methodology

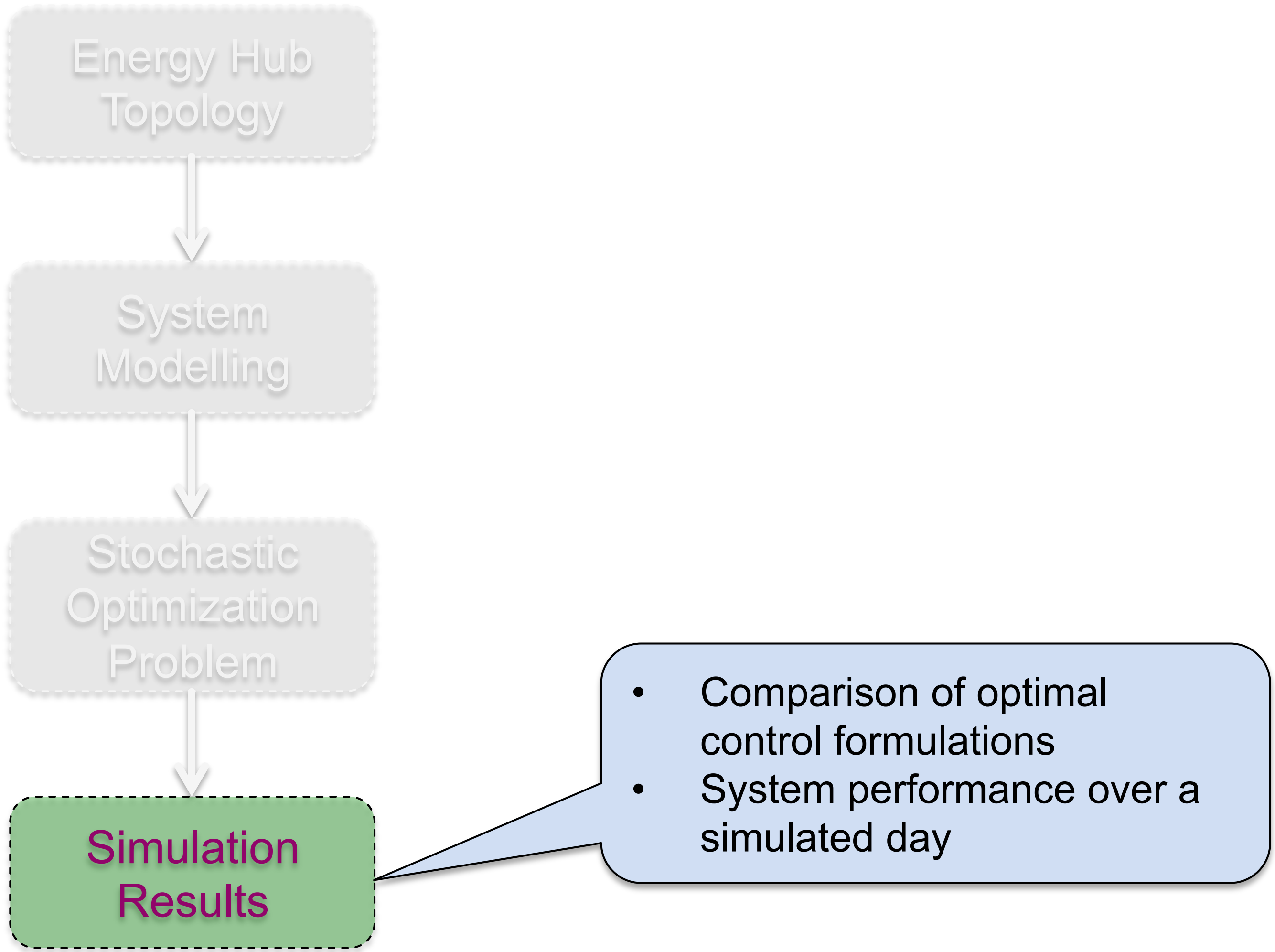


Method	Information Structure	Decision variables Structure	Disturbances
Affine Decision Rules	$I_t = (\mathbf{1}, \boldsymbol{\xi}_1, \ldots, \boldsymbol{\xi}_t)$	$\boldsymbol{p}_t = p_{t,0} + \sum_{s=0}^{t} p_{t,s}\, \boldsymbol{\xi}_s$	$\boldsymbol{\xi}_t \in \Xi$
Open Loop Policies	$I_t = (\mathbf{1})$	$\boldsymbol{p}_t = p_{t,0}$	$\boldsymbol{\xi}_t \in \Xi$
Certainty Equivalent Problem	$I_t = (\mathbf{1})$	$\boldsymbol{p}_t = p_{t,0}$	$\boldsymbol{\xi}_t = \mathbb{E}\{\boldsymbol{\xi}_t\}$

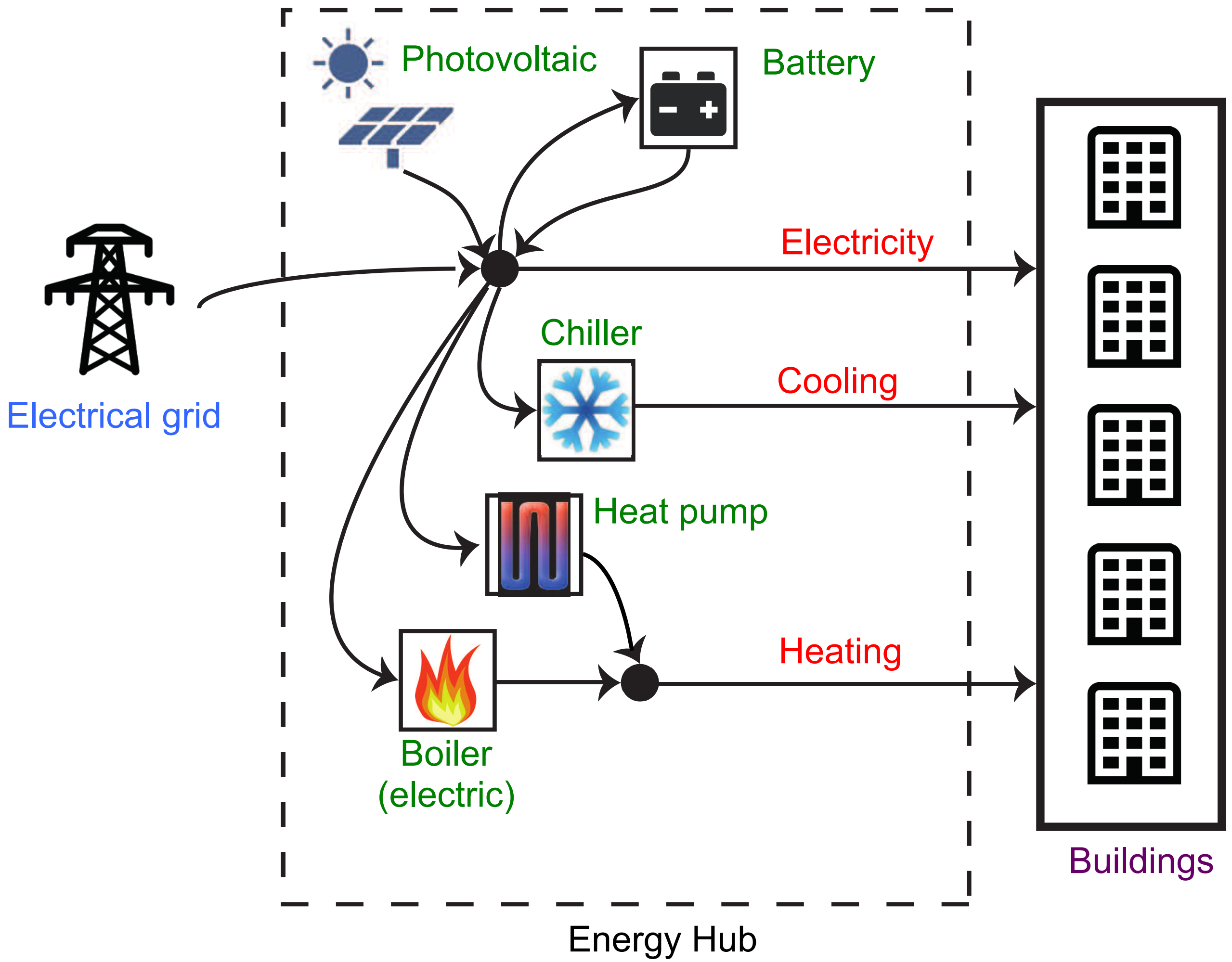
Receding horizon



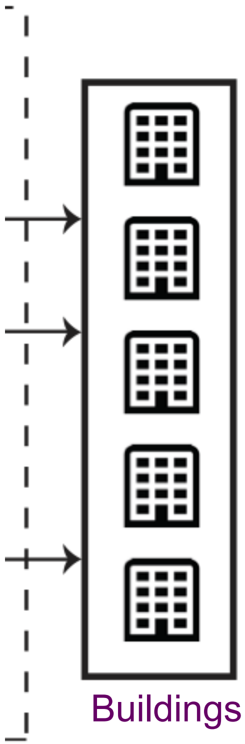
Outline


Energy Hub Topology
System Modelling
Stochastic Optimization Problem
Simulation Results
• Comparison of optimal control formulations
• System performance over a simulated day

Problem set up



Problem set up

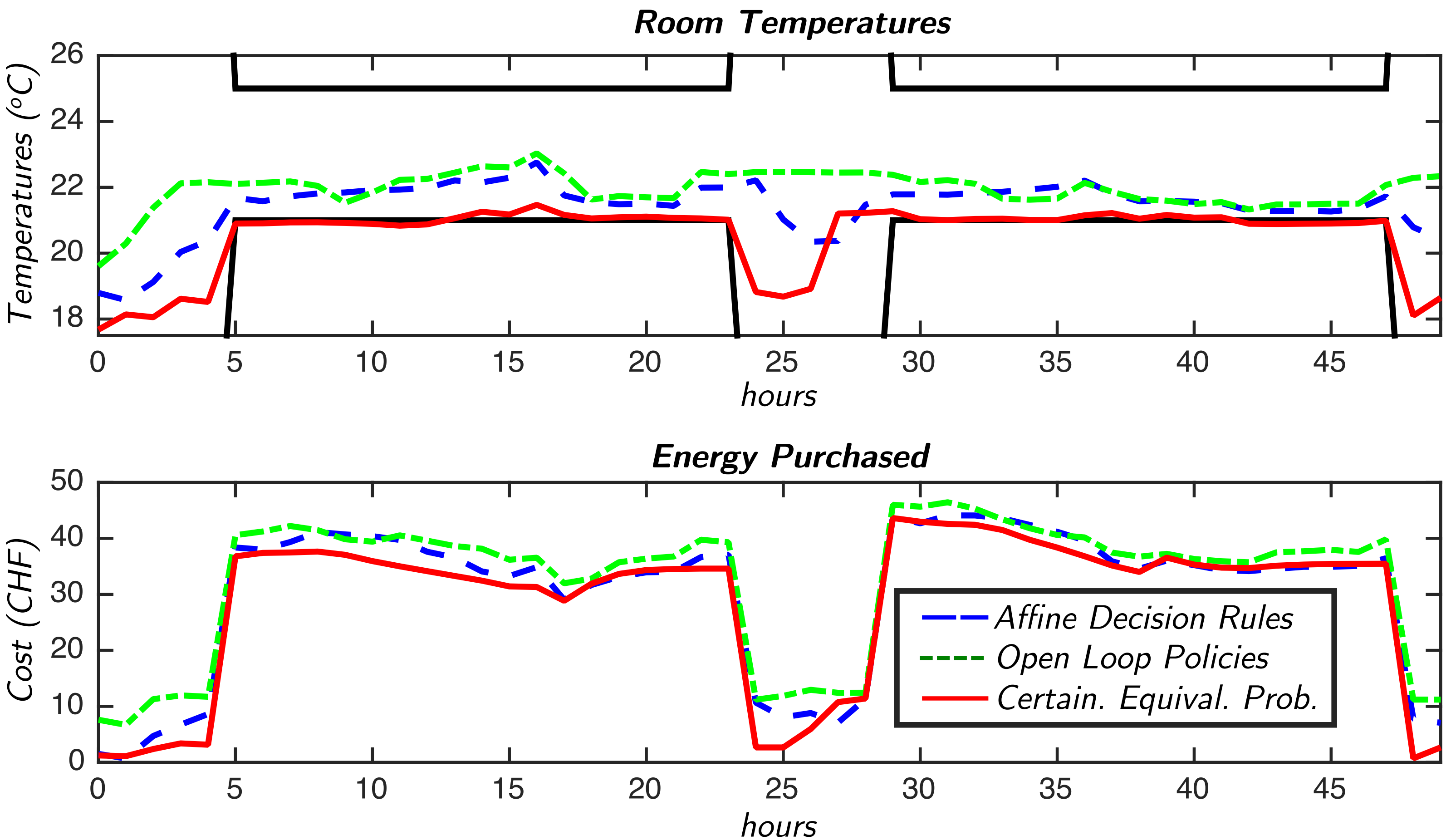


Building specifications

No.	Area(m^2)	WFA	BT	CT	Input Devices
1	420	30%	SP	heavy	AHU, blinds, radiator
2	228	50%	SP	light	AHU, blinds, TABS
3	276	80%	SA	light	AHU, blinds, TABS
4	516	50%	SA	heavy	AHU, blinds, radiator
5	324	50%	SP	heavy	AHU, blinds, radiator

WFA: Window Fraction Area
BT: Building Type
CT: Construction Type

Control of building temperatures



- Winter period, with the ambient temperature ranging around 5 °C.

Comparison of Optimal Control Formulations

Winter (mean, std.)

Method	Energy Purchased per Building (CHF)	Comfort Constraints Violations per Room (Kh)
Certainty Equivalent Problem	(393, 6.7)	(3.2, 0.2)
Open Loop Policies	(453, 4.8)	(0.6, 0.1)
Affine Decision Rules	(426, 6.2)	(0.5, 0.1)

Summer

Method	Energy Purchased per Building (CHF)	Comfort Constraints Violations per Room (Kh)
Certainty Equivalent Problem	(30, 2.1)	(1.2, 0.1)
Open Loop Policies	(54, 2.9)	(0.4, 0.05)
Affine Decision Rules	(49, 3.1)	(0.2, 0.05)

- 8 consecutive weeks (January 1st and June 29th)

References

[1] Darivianakis G., Georghiou A., Smith R. S. and Lygeros J. "***A Stochastic Optimization Approach to Cooperative Energy Management via an Energy Hub***", IEEE Conference on Decision and Control, 2015.

[2] Sturzenegger, D., Gyalistras, D., Semeraro, V., Morari, M. and Smith, R. S., "*Model Predictive Climate Control of a Swiss Office Building: Implementation, Results and Cost-Benefit Analysis*", IEEE Transactions on Control Systems Technology, 2015.

[3] Sturzenegger, D., Gyalistras, D., Semeraro, V., Morari, M. and Smith, R. S., "*BRCM Mat-lab Toolbox: Model Generation for Model Predictive Building Control*", American Control Conference, 2014.