Ground Source Heat Pump coupled with Aquifer Thermal Energy Storage System in Building

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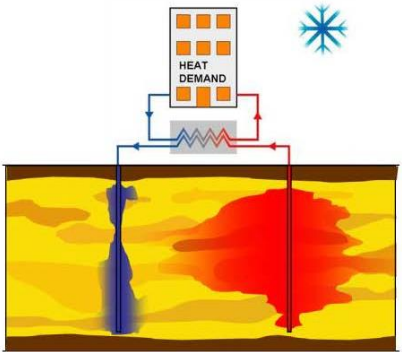
Aquifer Thermal Energy Storage (ATES)

- A large-scale natural subsurface storage for thermal energy
- An innovative method for thermal energy balance in smart grids

Cold season:

- The building requests thermal energy for the heating purpose
- Water is injected into cold well and is taken from warm well
- The stored water contains cold thermal energy for next season

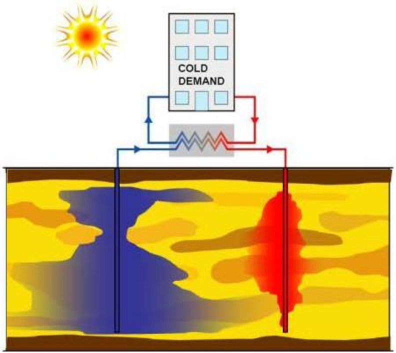


Aquifer Thermal Energy Storage (ATES)

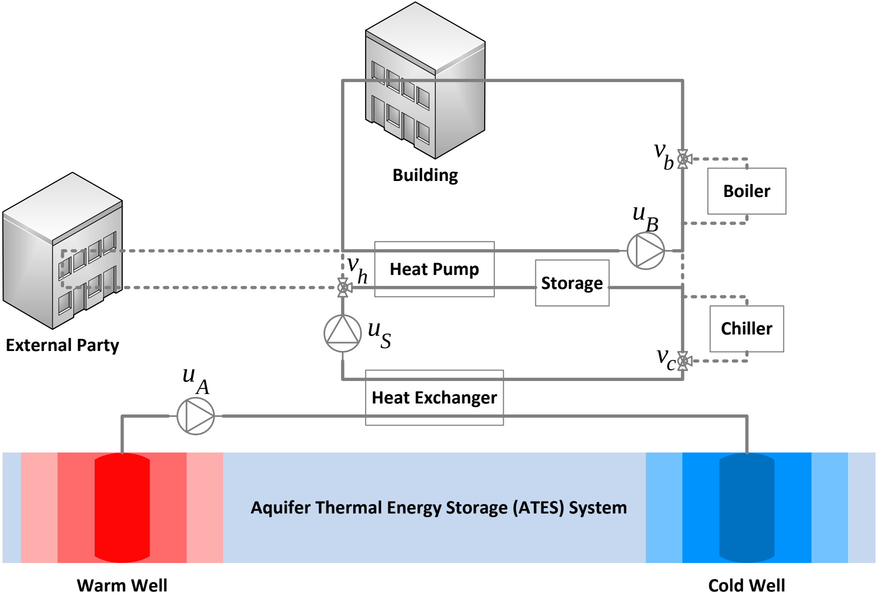
- A large-scale natural subsurface storage for thermal energy
- An innovative method for thermal energy balance in smart grids

Warm season:

- The building requests thermal energy for the cooling purpose
- Water is injected into warm well and is taken from cold well
- The stored water contains warm thermal energy for next season

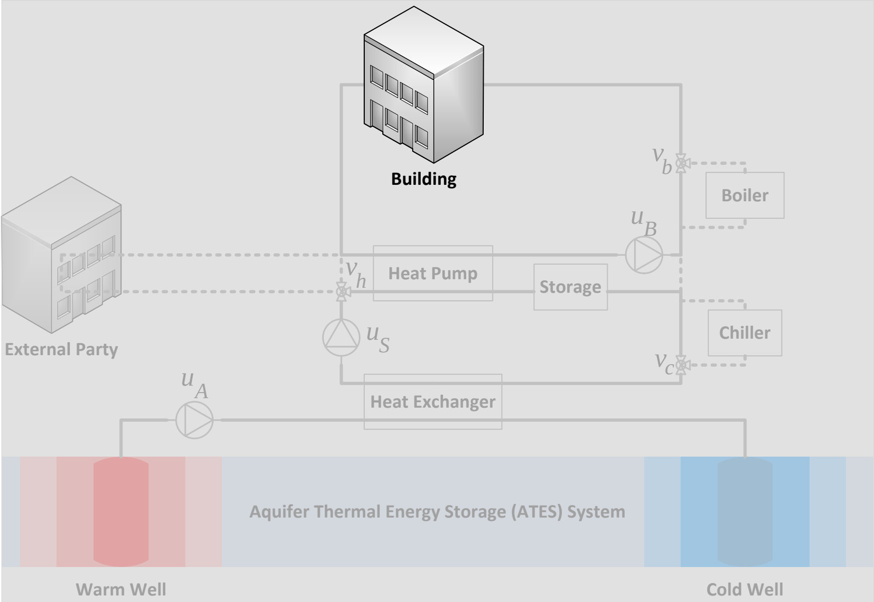


How to Develop a Predictive System Dynamics Model?

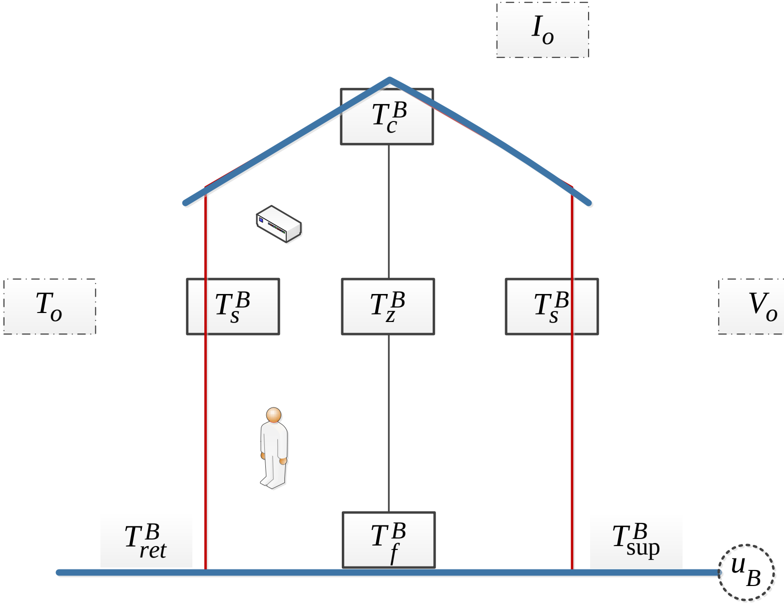


Outline

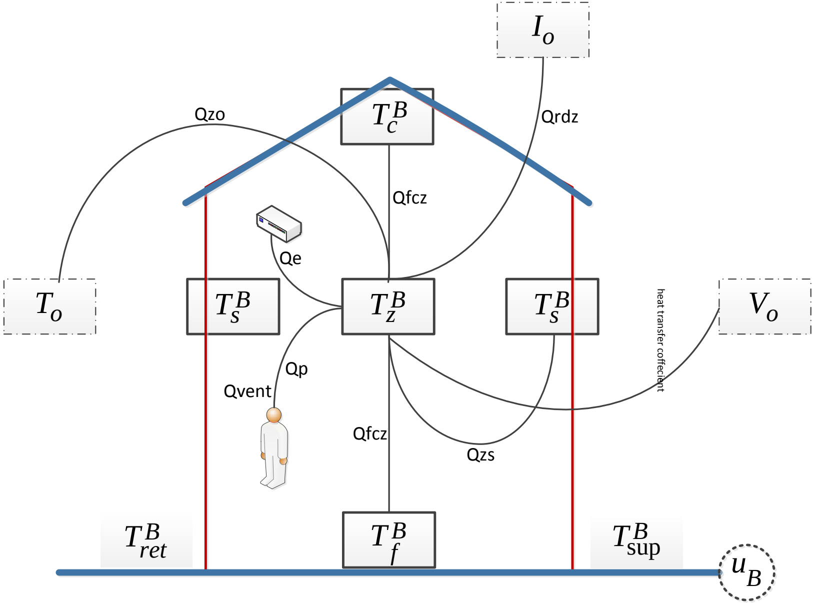
Single Agent System



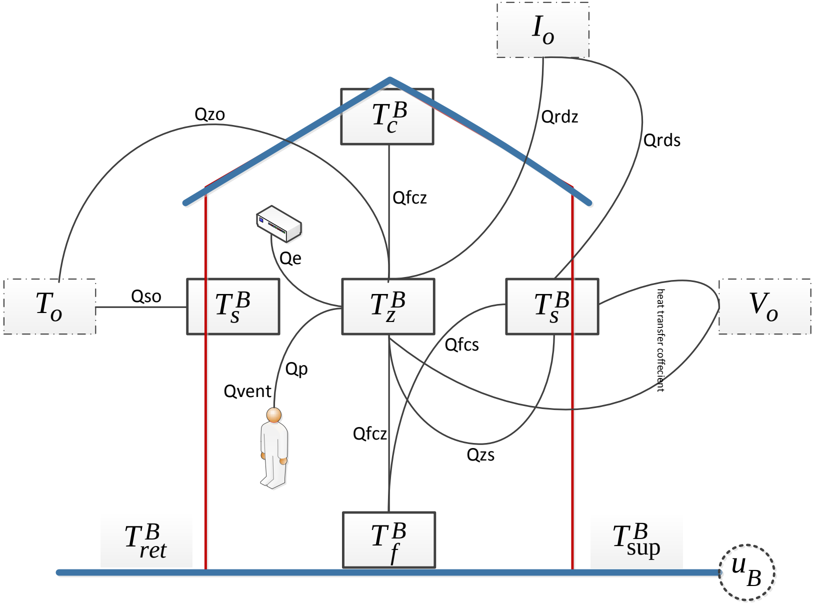
Building Thermal Comfort Relations



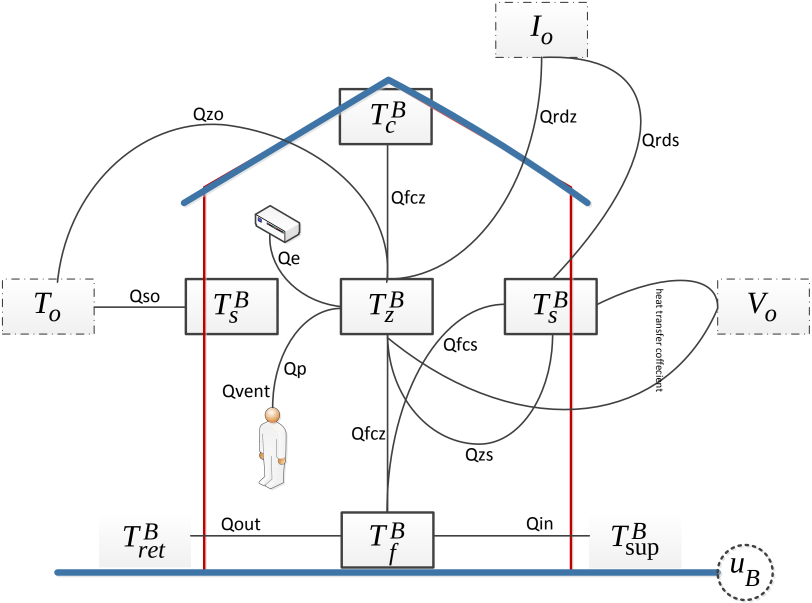
Building Thermal Comfort Relations



Building Thermal Comfort Relations



Building Thermal Comfort Relations



Building Thermal Comfort Model Formulation

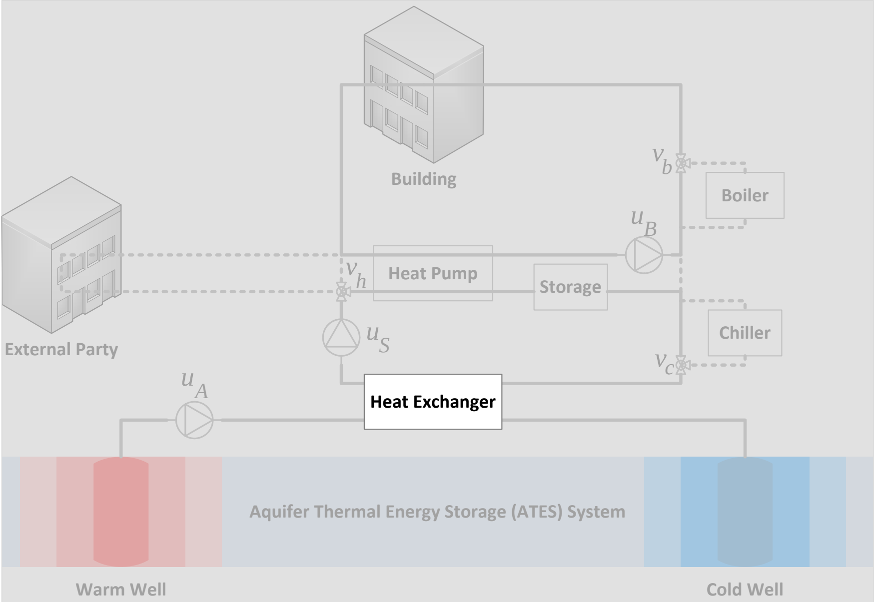
We define the following model:

Building Dynamical Model

$$\begin{aligned} \boldsymbol{x}_{\mathrm{B},\boldsymbol{k}+1} &= \boldsymbol{x}_{\mathrm{B},\boldsymbol{k}} + \boldsymbol{f}_{\mathrm{B}}(\boldsymbol{x}_{\mathrm{B},\boldsymbol{k}}, \boldsymbol{u}_{\mathrm{B},\boldsymbol{k}}, \boldsymbol{\nu}_{\mathrm{B},\boldsymbol{k}}, \boldsymbol{\nu}_{\mathrm{B}\boldsymbol{ext},\boldsymbol{k}})\boldsymbol{\tau} \\ \boldsymbol{y}_{\mathrm{B},\boldsymbol{k}} &= \boldsymbol{g}_{\mathrm{B}}(\boldsymbol{x}_{\mathrm{B},\boldsymbol{k}}, \boldsymbol{u}_{\mathrm{B},\boldsymbol{k}}) \end{aligned}$$

- Building inside variables (states): $\boldsymbol{x}_{\mathrm{B},\boldsymbol{k}} \in \mathbb{R}^{\mathbf{3}}$
- Building outside variables (uncertain): $\boldsymbol{\nu}_{\mathrm{B}\boldsymbol{ext},\boldsymbol{k}} \in \mathbb{R}^{\mathbf{3}}$
- Pump flow rate variable (control): $\boldsymbol{u}_{\mathrm{B},\boldsymbol{k}}$
- Supplied water temperature: $\boldsymbol{\nu}_{\mathrm{B},\boldsymbol{k}}$
- Returned water temperature: $\boldsymbol{y}_{\mathrm{B},\boldsymbol{k}}$
- Sampling period: $\boldsymbol{\tau}$

Single Agent System

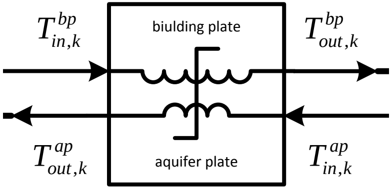


Heat Exchanger Model

A countercurrent heat exchanger is used and it presents via a static model.

Static Model Variables:

- Input water temperatures: $\boldsymbol{\nu}_{\mathrm{he},\boldsymbol{k}} \in \mathbb{R}^{\mathbf{2}}$
- Pump flow rates (control variables): $\boldsymbol{u}_{\mathrm{A},\boldsymbol{k}}, \boldsymbol{u}_{\mathrm{S},\boldsymbol{k}}$
- Output water temperatures: $\boldsymbol{y}_{\mathrm{he},\boldsymbol{k}} \in \mathbb{R}^{\mathbf{2}}$

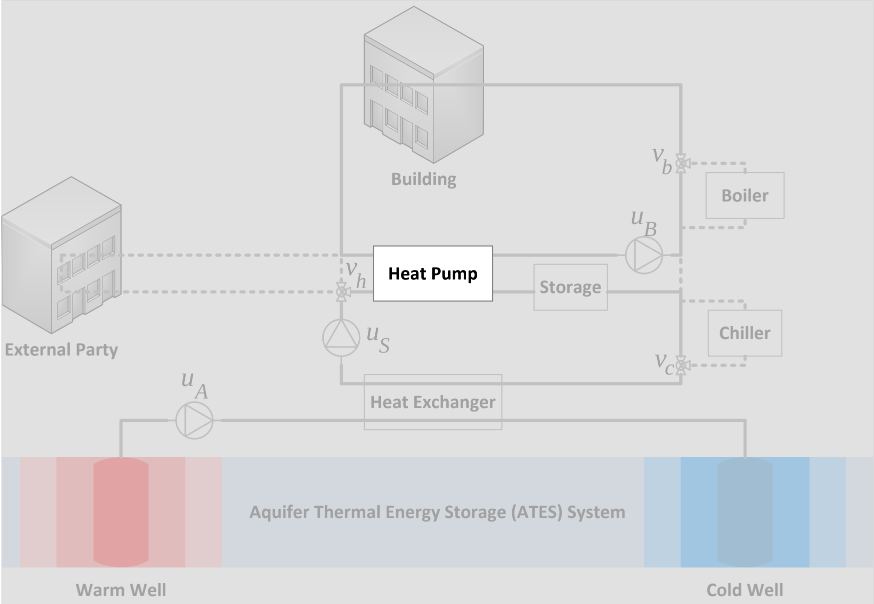


Heat Exchanger

Heat Exchanger Static Model

$$\boldsymbol{y}_{\mathrm{he},\boldsymbol{k}} = \mathrm{H}(\boldsymbol{\nu}_{\mathrm{he},\boldsymbol{k}}, \boldsymbol{u}_{\mathrm{A},\boldsymbol{k}}, \boldsymbol{u}_{\mathrm{S},\boldsymbol{k}})$$

Single Agent System

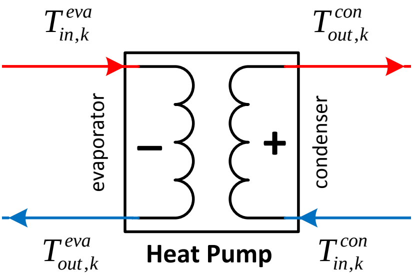


Heat Pump Model

An electrical water to water heat pump is used with static model.

Static Model Variables:

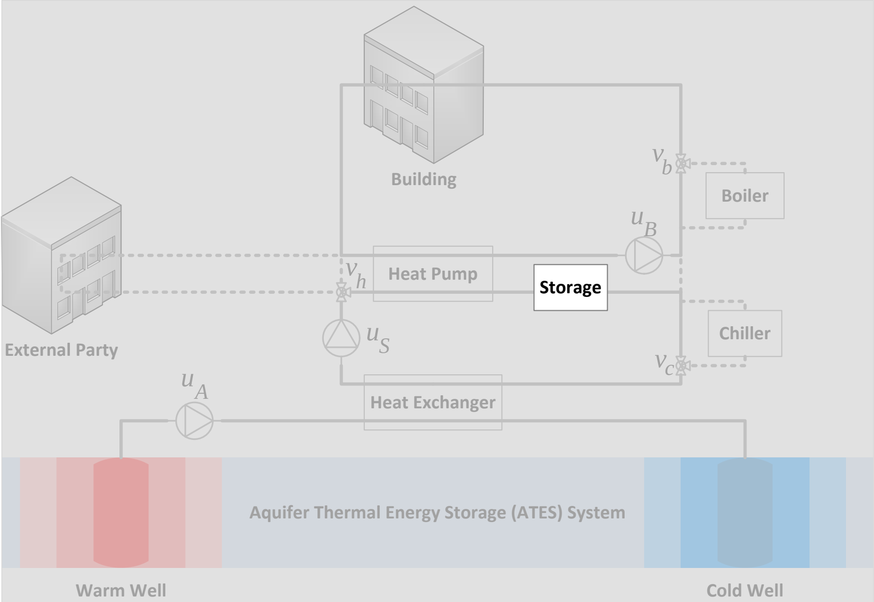
- Input water temperatures: $\boldsymbol{\nu}_{\mathrm{hp},\boldsymbol{k}} \in \mathbb{R}^{\mathbf{2}}$
- Pump flow rates (control variables): $\boldsymbol{u}_{\mathrm{B},\boldsymbol{k}}, \boldsymbol{u}_{\mathrm{S},\boldsymbol{k}}$
- Output water temperatures: $\boldsymbol{y}_{\mathrm{hp},\boldsymbol{k}} \in \mathbb{R}^{\mathbf{2}}$



Heat Pump Static Model

$$\boldsymbol{y}_{\mathrm{hp},\boldsymbol{k}} = \mathrm{P}(\boldsymbol{\nu}_{\mathrm{hp},\boldsymbol{k}}, \boldsymbol{u}_{\mathrm{B},\boldsymbol{k}}, \boldsymbol{u}_{\mathrm{S},\boldsymbol{k}})$$

Single Agent System



Storage Tank Model

We define an storage tank model with the following first order difference equations:

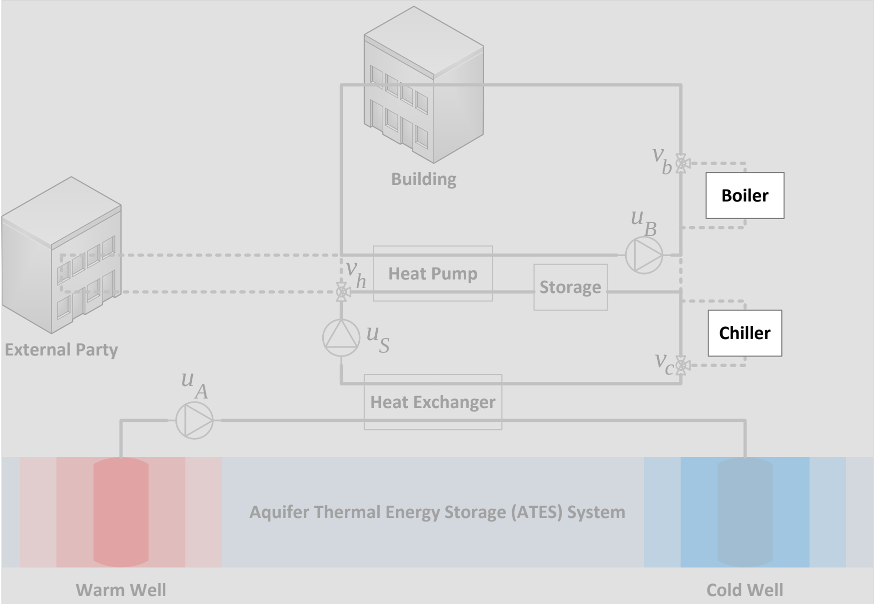
$$V_{s,k+1} = V_{s,k} + V_{in,k} - V_{out,k}$$
$$T_{s,k+1} = \frac{V_{s,k}}{V_{s,k} + V_{in,k}} T_{s,k} + \frac{V_{in,k}}{V_{s,k} + V_{in,k}} T_{in,k}$$

Storage Dynamical Model

$$\boldsymbol{x}_{\mathrm{S},k+1} = f_{\mathrm{S}}(\boldsymbol{x}_{\mathrm{S},k}, \boldsymbol{u}_{\mathrm{S},k}, \boldsymbol{\nu}_{\mathrm{S},k})$$
$$\boldsymbol{y}_{\mathrm{S},k} = g_{\mathrm{S}}(\boldsymbol{x}_{\mathrm{S},k})$$

- Tank temperature and volume variables (state): $\boldsymbol{x}_{\mathrm{S},k} \in \mathbb{R}^2$
- Pump flow rate variable (control): $\boldsymbol{u}_{\mathrm{S},k}$
- Input water temperature: $\boldsymbol{\nu}_{\mathrm{S},k}$
- Output water temperature: $\boldsymbol{y}_{\mathrm{S},k}$

Single Agent System



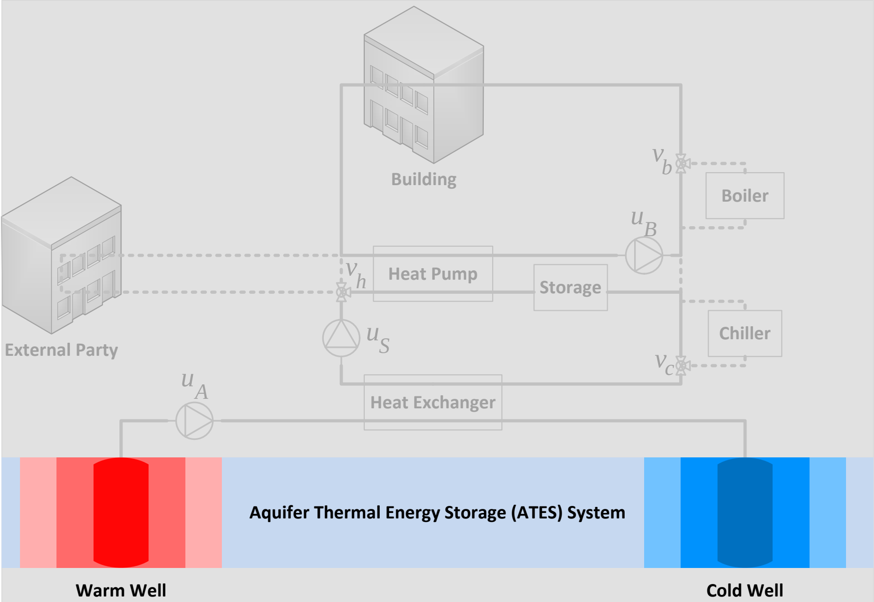
Boiler and Chiller Model

We define the boiler and chiller water temperatures with the following relations:

$$\text{Boiler: } \begin{cases} \mathsf{T}^{\text{boi}}_{\boldsymbol{out},\boldsymbol{k}} = \mathbf{90}^{\circ}\mathrm{C} \\ \mathsf{T}^{\text{boi}}_{\boldsymbol{in},\boldsymbol{k}} = \mathsf{T}_{\text{bypass},\boldsymbol{k}} \\ \boldsymbol{u}_{\boldsymbol{b},\boldsymbol{k}} = \boldsymbol{v}_{\boldsymbol{b},\boldsymbol{k}} \boldsymbol{u}_{\mathrm{B},\boldsymbol{k}} \end{cases} \qquad \text{Chiller: } \begin{cases} \mathsf{T}^{\text{chi}}_{\boldsymbol{out},\boldsymbol{k}} = \mathbf{5}^{\circ}\mathrm{C} \\ \mathsf{T}^{\text{chi}}_{\boldsymbol{in},\boldsymbol{k}} = \mathsf{T}_{\text{bypass},\boldsymbol{k}} \\ \boldsymbol{u}_{\boldsymbol{c},\boldsymbol{k}} = \boldsymbol{v}_{\boldsymbol{c},\boldsymbol{k}} \boldsymbol{u}_{\mathrm{S},\boldsymbol{k}} \end{cases}$$

- Boiler valve position (control): $\boldsymbol{v}_{\boldsymbol{b},\boldsymbol{k}} \in \mathbf{[0, 1]}$
- Chiller valve position (control): $\boldsymbol{v}_{\boldsymbol{c},\boldsymbol{k}} \in \mathbf{[0, 1]}$

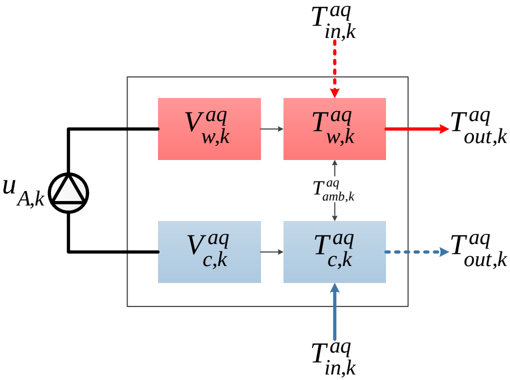
Single Agent System



Aquifer Thermal Energy Storage System Principle

Similar modeling as the storage model by introducing different modes:

- Water is taken from one of the wells and is injected into the counterpart well.
- Taken water has constant temperature until the aquifer water temperature dominates.
- Injected water has gained thermal energy and it is stored for the next upcoming season.



Aquifer Thermal Energy Storage System Model

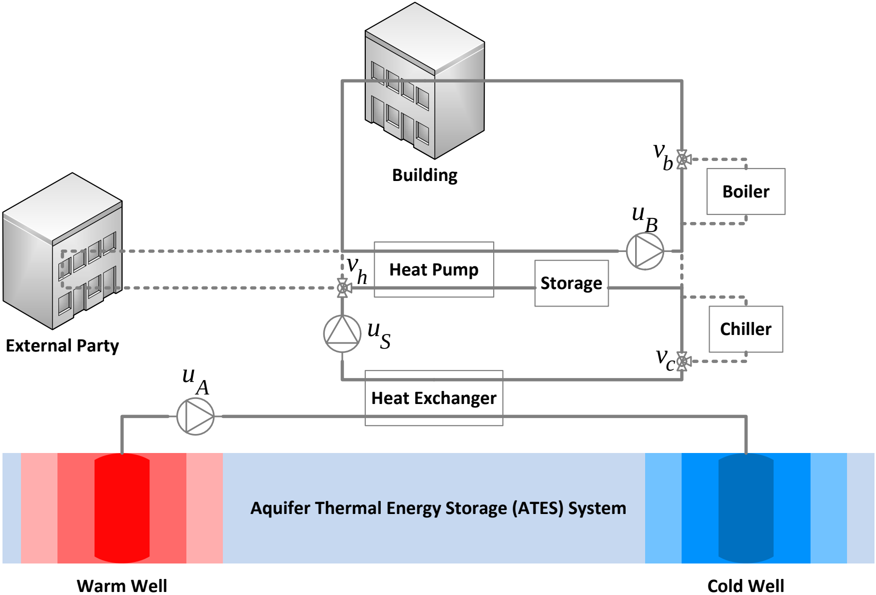
We define the following Model:

ATES system Dynamical Model

$$\begin{aligned} \boldsymbol{x}_{\mathrm{A},\boldsymbol{k}+1} &= \boldsymbol{f}_{\mathrm{A}}(\boldsymbol{x}_{\mathrm{A},\boldsymbol{k}}, \boldsymbol{u}_{\mathrm{A},\boldsymbol{k}}, \boldsymbol{\nu}_{\mathrm{A},\boldsymbol{k}}, \boldsymbol{s}_{\boldsymbol{w},\boldsymbol{k}}, \boldsymbol{s}_{\boldsymbol{c},\boldsymbol{k}}) \\ \boldsymbol{y}_{\mathrm{A},\boldsymbol{k}} &= \boldsymbol{g}_{\mathrm{A}}(\boldsymbol{x}_{\mathrm{A},\boldsymbol{k}}, \boldsymbol{s}_{\boldsymbol{w},\boldsymbol{k}}, \boldsymbol{s}_{\boldsymbol{c},\boldsymbol{k}}) \end{aligned}$$

- Wells temperature and volume variables (state): $\boldsymbol{x}_{\mathrm{A},\boldsymbol{k}} \in \mathbb{R}^{4}$
- Pump flow rate variable (control): $\boldsymbol{u}_{\mathrm{A},\boldsymbol{k}}$
- Output water temperature: $\boldsymbol{y}_{\mathrm{A},\boldsymbol{k}}$
- Input water temperature: $\boldsymbol{\nu}_{\mathrm{A},\boldsymbol{k}}$

Interconnections Between Each Subsystem



Interconnections Between Each Subsystem

1. **ATES system:** $\nu_{A,k} := T^{aq}_{in,k}$, $y_{A,k} := T^{aq}_{out,k}$
   - $T^{aq}_{in,k} = T^{ap}_{out,k}$
2. **Heat exchanger:** $\nu_{he,k} := [T^{ap}_{in,k}, T^{bp}_{in,k}]$, $y_{he,k} := [T^{ap}_{out,k}, T^{bp}_{out,k}]$
   - $T^{ap}_{in,k} = T^{aq}_{out,k}$ and $T^{bp}_{in,k} = (1 - v_{c,k})T_{s,k} + v_{c,k}T^{chi}_{out,k}$
3. **Heat pump:** $\nu_{hp,k} := [T^{con}_{in,k}, T^{eva}_{in,k}]$, $y_{hp,k} := [T^{con}_{out,k}, T^{eva}_{out,k}]$
   - $T^{con}_{in,k} = s_{n,k}(s_{w,k}T^{bp}_{out,k} + s_{c,k}T^{B}_{ret,k}) + (1 - s_{n,k})(s_{w,k}T^{ext}_{out,k} + s_{c,k}T^{B}_{ret,k})$
   - $T^{eva}_{in,k} = s_{n,k}(s_{c,k}T^{bp}_{out,k} + s_{w,k}T^{B}_{ret,k}) + (1 - s_{n,k})(s_{w,k}T^{ext}_{out,k} + s_{c,k}T^{B}_{ret,k})$
4. **Storage model:** $\nu_{S,k} := T_{in,k}$, $y_{S,k} := T^{s}_{out,k}$
   - $T^{s}_{in,k} = v_{h,k}(s_{w,k}T^{con}_{out,k} + s_{c,k}T^{eva}_{out,k}) + (1 - v_{h,k})T^{B}_{ret,k}$
5. **Building model:** $\nu_{B,k} := T^{B}_{sup,k}$, $y_{B,k} := T^{B}_{ret,k}$

$$T^{B}_{sup,k} = v_{h,k}(s_{w,k}T^{eva}_{out,k} + s_{c,k}((1 - v_{b,k})T^{con}_{out,k} + v_{b,k}T^{boi}_{out,k})) + (1 - v_{h,k})T^{bp}_{out,k}$$

Single Agent Representation

Consider compact formulation of dynamical agent system:

Single Agent Model

$$\boldsymbol{x_{k+1}} = \boldsymbol{f(x_k, u_k, v_k, s_k, w_k)}$$

- State variables: $\boldsymbol{x_k} := [\boldsymbol{x}_{\mathrm{B},\boldsymbol{k}}, \boldsymbol{x}_{\mathrm{S},\boldsymbol{k}}, \boldsymbol{x}_{\mathrm{A},\boldsymbol{k}}] \in \mathbb{R}^{\mathbf{9}}$
- Pump flow rate variables: $\boldsymbol{u_k} := [\boldsymbol{u}_{\mathrm{B},\boldsymbol{k}}, \boldsymbol{u}_{\mathrm{S},\boldsymbol{k}}, \boldsymbol{u}_{\mathrm{A},\boldsymbol{k}}] \in \mathbb{R}^{\mathbf{3}}$
- Valve position variables: $\boldsymbol{v_k} := [\boldsymbol{v_{b,k}}, \boldsymbol{v_{c,k}}, \boldsymbol{v_{h,k}}] \in [\mathbf{0}, \mathbf{1}]^{\mathbf{3}}$
- Operating mode variables: $\boldsymbol{s_k} := [\boldsymbol{s_{w,k}}, \boldsymbol{s_{c,k}}, \boldsymbol{s_{n,k}}] \in \{\mathbf{0}, \mathbf{1}\}^{\mathbf{3}}$
- Uncertain variables: $\boldsymbol{w_k} := [\mathrm{T}_{\boldsymbol{o,k}}, \mathrm{I}_{\boldsymbol{o,k}}, \mathrm{V}_{\boldsymbol{o,k}}] \subseteq \boldsymbol{\Delta} \in \mathbb{R}^{\mathbf{3}}$
- State variables are available at each sampling time $\boldsymbol{k}$.

Outline

Control Problem Formulation

We formulate an optimization problem as follows:

$$\begin{array}{ll} \min\limits_{\{u_k, v_k\}_{k=1}^{N}} & \text{Objective Function: Reference Tracking} \\ \text{subject to:} & \text{Nonlinear System Dynamics} \\ & \text{State and Control Bounds} \\ & \text{Valves, Modes and Uncertainty Sets} \\ & \text{Heat Exchanger Capacity Constraints} \\ & \text{Heat Pump Capacity Constraints} \end{array}$$

Proposed Formulation

Stochastic Mixed-Integer Nonlinear Optimization Problem

Control Problem Formulation

We formulate an optimization problem as follows:

$$\min_{\{u_k, v_k\}_{k=1}^{N}} \quad \mathbb{E}\left[\sum_{k=1}^{N} \gamma(\mathrm{T}_{z,k}^{\mathrm{B}} - \mathrm{T}_{\mathrm{set}})^2\right]$$

subject to: Nonlinear System Dynamics

State and Control Bounds

Valves, Modes and Uncertainty Sets

Heat Exchanger Capacity Constraints

Heat Pump Capacity Constraints

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subject to: $\quad x_{k+1} = f(x_k, u_k, v_k, s_k, w_k)$

State and Control Bounds

Valves, Modes and Uncertainty Sets

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subject to:

$$x_{k+1} = f(x_k, u_k, v_k, s_k, w_k)$$

$$x_{\min} \leq x_k \leq x_{\max} \;,\; u_{\min} \leq u_k \leq u_{\max}$$

Valves, Modes and Uncertainty Sets

Heat Exchanger Capacity Constraints

Heat Pump Capacity Constraints

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subject to:

$$x_{k+1} = f(x_k, u_k, v_k, s_k, w_k)$$

$$x_{\min} \le x_k \le x_{\max}\ ,\ u_{\min} \le u_k \le u_{\max}$$

$$0 \le v_k \le 1\ ,\ s_k \in \{0, 1\}\ ,\ w_k \in \Delta$$

Heat Exchanger Capacity Constraints

Heat Pump Capacity Constraints

Proposed Formulation

Stochastic Mixed-Integer Nonlinear Optimization Problem

Control Problem Formulation

We formulate an optimization problem as follows:

$$\min_{\{u_k, v_k\}_{k=1}^{N}} \quad \mathbb{E}\left[\sum_{k=1}^{N} \gamma(\mathrm{T}^{\mathrm{B}}_{z,k} - \mathrm{T}_{\mathrm{set}})^2\right]$$

subject to:

$$x_{k+1} = f(x_k, u_k, v_k, s_k, w_k)$$

$$x_{\min} \le x_k \le x_{\max} \ , \ u_{\min} \le u_k \le u_{\max}$$

$$0 \le v_k \le 1 \ , \ s_k \in \{0, 1\} \ , \ w_k \in \Delta$$

$$\nu_{\mathrm{he}}^{\min} \le \nu_{\mathrm{he},k} \le \nu_{\mathrm{he}}^{\max} \ , \ y_{\mathrm{he}}^{\min} \le y_{\mathrm{he},k} \le y_{\mathrm{he}}^{\max}$$

Heat Pump Capacity Constraints

Proposed Formulation

Stochastic Mixed-Integer Nonlinear Optimization Problem

Control Problem Formulation

We formulate an optimization problem as follows:

$$\min_{\{u_k, v_k\}_{k=1}^{N}} \quad \mathbb{E}\left[\sum_{k=1}^{N} \gamma(\mathrm{T}^{\mathrm{B}}_{z,k} - \mathrm{T}_{\mathrm{set}})^2\right]$$

subject to:

$$x_{k+1} = f(x_k, u_k, v_k, s_k, w_k)$$

$$x_{\min} \leq x_k \leq x_{\max} \ , \ u_{\min} \leq u_k \leq u_{\max}$$

$$0 \leq v_k \leq 1 \ , \ s_k \in \{0, 1\} \ , \ w_k \in \Delta$$

$$\nu_{\mathrm{he}}^{\min} \leq \nu_{\mathrm{he},k} \leq \nu_{\mathrm{he}}^{\max} \ , \ y_{\mathrm{he}}^{\min} \leq y_{\mathrm{he},k} \leq y_{\mathrm{he}}^{\max}$$

$$\nu_{\mathrm{hp}}^{\min} \leq \nu_{\mathrm{hp},k} \leq \nu_{\mathrm{hp}}^{\max} \ , \ y_{\mathrm{hp}}^{\min} \leq y_{\mathrm{hp},k} \leq y_{\mathrm{hp}}^{\max}$$

Proposed Formulation

Stochastic Mixed-Integer Nonlinear Optimization Problem

Control Problem Formulation

We formulate an optimization problem as follows:

$$\begin{aligned}
\min_{\{u_k, v_k\}_{k=1}^{N}} \quad & \mathbb{E}\left[\sum_{k=1}^{N} \gamma(\mathrm{T}_{z,k}^{\mathrm{B}} - \mathrm{T}_{\mathrm{set}})^2\right] \\
\text{subject to:} \quad & x_{k+1} = f(x_k, u_k, v_k, s_k, w_k) \\
& x_{\min} \le x_k \le x_{\max} \ , \ u_{\min} \le u_k \le u_{\max} \\
& 0 \le v_k \le 1 \ , \ s_k \in \{0, 1\} \ , \ w_k \in \Delta \\
& \nu_{\mathrm{he}}^{\min} \le \nu_{\mathrm{he},k} \le \nu_{\mathrm{he}}^{\max} \ , \ y_{\mathrm{he}}^{\min} \le y_{\mathrm{he},k} \le y_{\mathrm{he}}^{\max} \\
& \nu_{\mathrm{hp}}^{\min} \le \nu_{\mathrm{hp},k} \le \nu_{\mathrm{hp}}^{\max} \ , \ y_{\mathrm{hp}}^{\min} \le y_{\mathrm{hp},k} \le y_{\mathrm{hp}}^{\max}
\end{aligned}$$

Proposed Formulation

Stochastic Mixed-Integer Nonlinear Optimization Problem

Outline

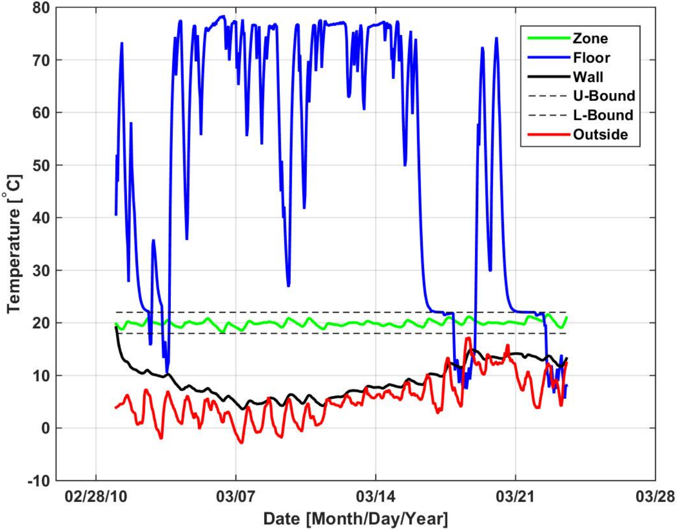
Simulation Study

A single agent model control problem formulation:

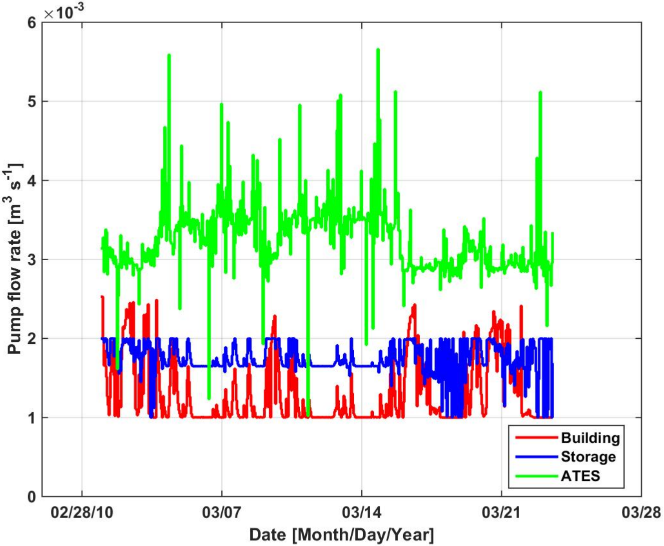
- Sampling period: **1**h
- Prediction horizon: **24**h
- No integer variables (fixed)
- No stochastic terms (deterministic controller)
- Linear approximation of HP & HE complex subsystems
- Remove complex constraints of HP & HE:

$$\boldsymbol{\nu}_{\text{he}}^{\mathbf{min}} \leq \boldsymbol{\nu}_{\text{he},\boldsymbol{k}} \leq \boldsymbol{\nu}_{\text{he}}^{\mathbf{max}} \ , \ \boldsymbol{y}_{\text{he}}^{\mathbf{min}} \leq \boldsymbol{y}_{\text{he},\boldsymbol{k}} \leq \boldsymbol{y}_{\text{he}}^{\mathbf{max}}$$
$$\boldsymbol{\nu}_{\text{hp}}^{\mathbf{min}} \leq \boldsymbol{\nu}_{\text{hp},\boldsymbol{k}} \leq \boldsymbol{\nu}_{\text{hp}}^{\mathbf{max}} \ , \ \boldsymbol{y}_{\text{hp}}^{\mathbf{min}} \leq \boldsymbol{y}_{\text{hp},\boldsymbol{k}} \leq \boldsymbol{y}_{\text{hp}}^{\mathbf{max}}$$

Simulation Results



Simulation Results



Outline

1. Single Agent System Dynamics
2. Control Problem Formulation
3. Simulation Study
4. Conclusions

Concluding Remarks

- ATES System Dynamics Model
- Building Climate Comfort System Dynamics Model
- Integrated ATES System into Building Climate Comfort System

- Important Features:
  - Complete mathematical models of building thermal equipment
  - Developed model is highly complex and nonlinear; it can be considered as a thermal energy demand of a building

Achievements & Developments

- Complete Predictive Model of the ATES System
  [Rostampour et al., EGU, 2017]
- ATES in Smart Thermal Grids + Preventing Mutual Interactions
  [Rostampour et al., IFAC, 2017]
- Distributed Stochastic MPC for ATES in Smart Thermal Grids
  [Rostampour et al., Submitted, 2017]

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