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Optimal HVAC control for state-of-the-art office building: methodology and open questions

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Model predictive control

$$\min \quad J(x, u)$$ → Cost

$$\text{s.t.} \quad \dot{x} = f(x, u)$$ → System

$$0 = h(x, u)$$
$$0 \leq g(x, u)$$ → Constraints

System

System

- Building envelope
  - Zones
  - Glazing
  - Walls

- Occupants and internal gains

- Controls

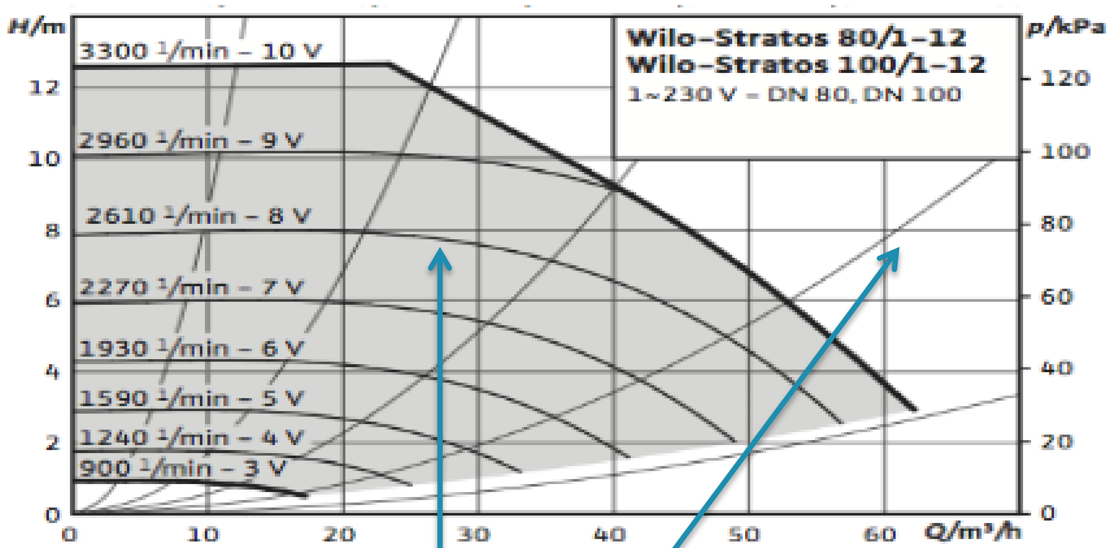
System

- HVAC
  - Ventilation
    - Heat exchangers
    - Fans
    - Ducts
    - Chiller
    - VAV
    - Humidifier

- HVAC
  - Hydronics
    - Heat exchangers
    - Pump
    - Pipes
    - Heat pump
    - Valve
    - Heater
    - Solar collector
    - Thermal storage
    - Bore field
    - Concrete core activation

System (non-)linearities

- Building envelope: l
  - Thermal conducti
  - Thermal convecti
  - Thermal radiatior
- Heat exchangers: r
  - NTU method:



- Speed controlled fans/pumps:
  - Similarity laws
  - Pump curve
  - Load curve

$$\frac{\dot{m}_1}{\dot{m}_2} = \frac{n_1}{n_2}$$

$$\frac{dp_1}{dp_2} = \left(\frac{n_1}{n_2}\right)^2$$

$$\frac{P_1}{P_2} = \left(\frac{n_1}{n_2}\right)^3$$

$$\dot{m}_1 = f(dp_1)$$

$$\dot{m}_2 = f(dp_2)$$

System (non-)linearities

- Ducts / pipes
  - Load curve for fan / pump!
  - Conservation of mass
  - Perfect mixing of energy: $$\frac{\mathrm{d}T}{\mathrm{d}t} = -\frac{(T - T_{in})\dot{m}}{m_{pipe}}$$
  - Discontinuous mixing in splitter around zero flow
- Chiller / heat pump, heater similar

$$Q = f(T_1, T_2, ...)$$

$$COP = f(T_1, T_2, ...)$$

$$Pel = \frac{Q}{COP}$$

$$T_{out} = T_{in} + \frac{Q}{\dot{m}c_p}$$

System (non-)linearities

- Thermal storage
  - Bi-directional flows
  - Mixing or stratified temperature?

$$m_{tot} = m_{hot} + m_{cold}$$

$$E_{hot} = c_p \cdot T_{hot} \cdot m_{hot}$$

$$\frac{\mathrm{d}E_{hot}}{c_p\,\mathrm{d}t} = \dot{m}_{in} \cdot T_{in} - \dot{m}_{out} \cdot T_{hot}$$

- Internal/external gains: non-linear functions of time

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System dynamics

- Fast dynamics:
  - Sensors
  - Pipes
  - Air temperature
  - Heat production devices
- Slow dynamics
  - Building envelope

Approach for MPC

- Fast dynamics -> small time steps -> slow
  - Neglect fast dynamics
- Building envelope
  - Large state space
  - -> Model order reduction
  - *But which techniques to use?*
    - Asymptotic waveform evaluation
    - Arnoldi method
    - Laguerre method
    - Truncation method
    - Hankel norm reduction
    - Proper orthogonal decomposition, etc

Approach for MPC

- Simplify pipe hydronics: $Q = \dot{m} c_p \Delta T$
  - Into: Q

$$Q < \dot{m}_{nom} \cdot c_p \cdot \Delta T$$

$$Q < \Delta T_{nom} \cdot c_p \cdot \dot{m}$$

- Heat exchanger

$$Q < a \cdot (T_1 - T_2) = Q_{max}$$

  - Post-processing using mass flow rate required
  - *Problem if bi-directional heat flow or fixed mass flow rate*
  - *How to obtain feasible solution?*

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Approach for MPC

- Pumps/fans
  - Ignore pressure drops, control mass flow rate directly
  - Fit cost curve based on expected working points:

$$P_{el,pump} = c_1 + c_2 \cdot \dot{m} + c_3 \cdot \dot{m}^2$$

$$\dot{m} \leq \dot{m}_{max}$$

  - Post-processing required for finding pump speed
  - *Sub-optimal -> better approach?*

Approach for MPC

- Heat pump

$$Q$$

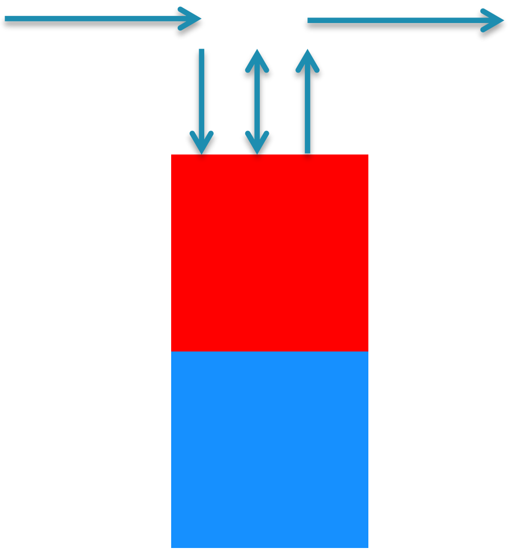
$$Q < Q_{max} = f(T)$$

$$P_{el} = \frac{Q}{COP_{nom}} \neq f(T) \ldots$$

  - *Time modulation for Q?*

Approach for MPC

- Thermal storage



$$m_{tot} = m_{hot} + m_{cold}$$
$$E_{hot} = c_p \cdot T_{hot} \cdot m_{hot}$$
$$\frac{\mathrm{d}E_{hot}}{c_p\,\mathrm{d}t} = \dot{m}_{in} \cdot T_{in} - \dot{m}_{out} \cdot T_{hot}$$

  - *Calculation using Q? But then no way to find T*
  - *Force T = T_{high} to be constant, but then suboptimal*
- Internal gains: inputs

Conclusion

- Building: linear
  - Model order reduction, but which technique to use?

- HVAC:
  - Can use heat flows Q -> linear
  - But how to reformulate constraints and cost function?
  - Generic way for performing post-processing?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