Energy savings in data centers: A framework for modelling and control of servers' cooling

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Definition: Data center

From Wikipedia[1]:

- [...] a **facility used to house computer systems** and associated components
- the main purpose [...] is **running the IT systems applications** [...] of the organization
- [...] large data centers are **industrial scale operations** using as much electricity as a small town

[1] wikipedia.org/wiki/Data_center


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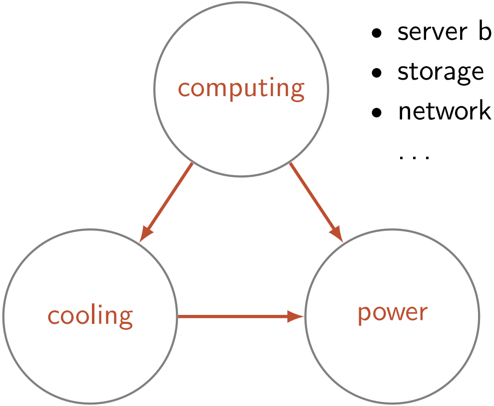
Structures within a data center and their logical connections



- server blades
- storage
- networking equipment

  ...

- CRACs
- Cooling towers

  ...

- UPSs
- PDUs

  ...

Footprint

EU-28: (year 2013)

- Industry market: 18.85 billion €
- Electrical power consumption: 103.4 GWh

  ($\sim 3\%$ of electrical power production)

- 38.6 metric tonnes of CO_2 emissions (347g/kWh)

Is there a problem to solve?

i) Electronics convert virtually all power into heat
ii) Cooling accounts for up to **40%** of power budget
iii) Computing's power consumption dependent on thermodynamical state
iv) DCs rarely operate at peak computing capacity[2]

Problem: Efficiency (static, nominal, cooling policies waste power)

[2] Often desired since it is paramount to maintain Quality of Service

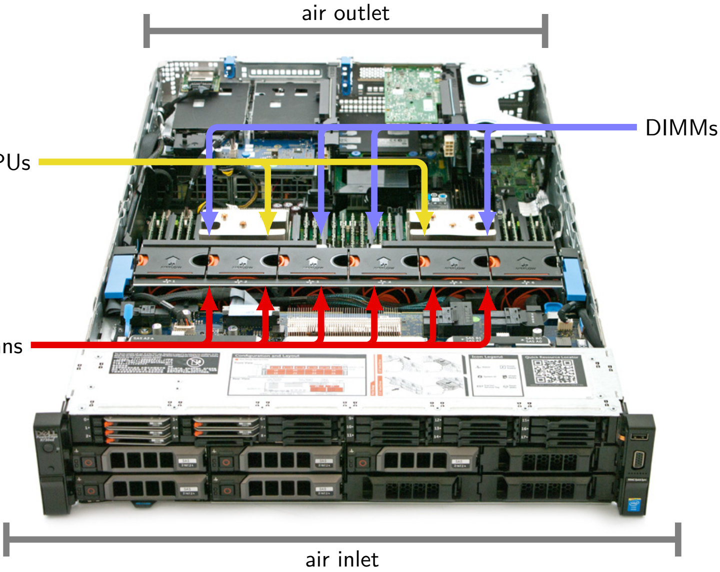
Control-oriented solution

Measure & predict the thermodynamical state
to reduce overprovision of the cooling resources

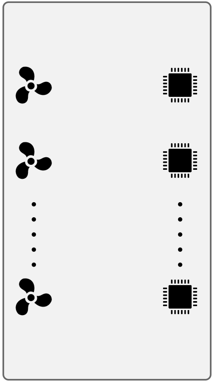
Potential control levels

i) single server level *(focus of this paper)*
ii) rack level
iii) room level

Example of "atomic unit": air-cooled blade



Modeling air-cooled blades, intuitions



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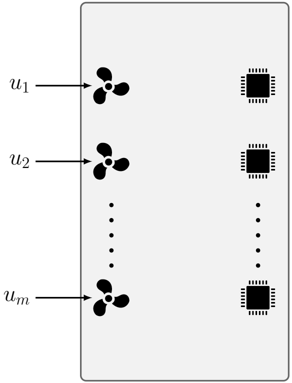

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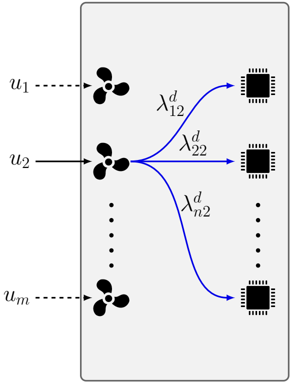
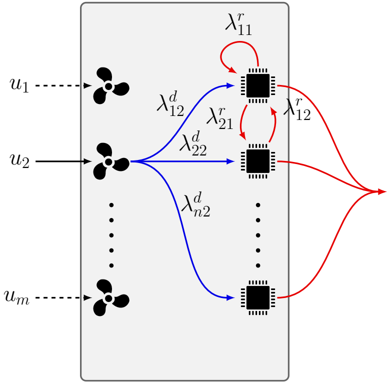


Modeling air-cooled blades, intuitions



Modeling air-cooled blades, in math

Notation

states:

- $\boldsymbol{x}^c = \begin{bmatrix} x_1^c & \dots & x_n^c \end{bmatrix}^T$ =: temperatures of IT components
- $\boldsymbol{x}^f = \begin{bmatrix} x_1^f & \dots & x_n^f \end{bmatrix}^T$ =: temperatures of air flows through IT components

exogenous inputs:

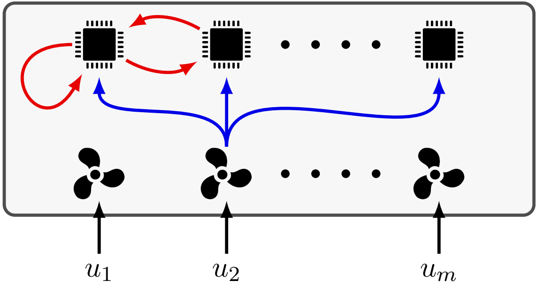
- $\boldsymbol{p} = \begin{bmatrix} p_1 & \dots & p_n \end{bmatrix}^T$ =: electrical power dissipated by IT components
- x^i =: temperature of air inlet

manipulable inputs:

- $\boldsymbol{u} = \begin{bmatrix} u_1 & \dots & u_m \end{bmatrix}^T$ =: air mass flows produced by fans

  (determining the air flows through the IT components $\boldsymbol{f} = \begin{bmatrix} f_1 & \dots f_n \end{bmatrix}^T$*)*

Ingredients to be modeled

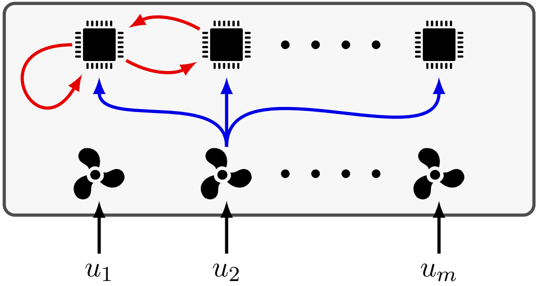


i) mass of the air flows $\boldsymbol{f}$

ii) temperature of the air flows $\boldsymbol{x}^f$

iii) temperature of the IT components $\boldsymbol{x}^c$

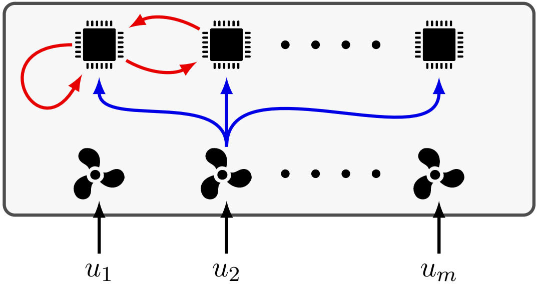
Model of the mass of the air flows



$$\boldsymbol{f} = \Lambda^d[\boldsymbol{u}] + \Lambda^r[\boldsymbol{f}] \qquad (1)$$

$$\Lambda[\boldsymbol{u}] = \sum_{i=1}^{\binom{m+d}{d}} a_i \boldsymbol{u}^{\boldsymbol{\alpha}_i} \qquad (2)$$

Model of the mass of the air flows



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$$\Lambda[\boldsymbol{u}] = \sum_{i=1}^{\binom{m+d}{d}} a_i \boldsymbol{u}^{\boldsymbol{\alpha}_i} \qquad (2)$$

Generalizes:

i) models without *warm* recirculation flows ($\Lambda^r = 0$)

ii) models preserving total mass-flows (Λ^d and Λ^r row-stochastic matrices)

Model of the temperature of the air flows

Assumptions:

i) perfect flow mixing

ii) heat energy conservation

$$x_j^f = \frac{\Lambda^d_{(j)}[\boldsymbol{u}] \cdot x^i + \sum_{h=1}^{n} \Lambda^r_{(j,h)}[\boldsymbol{f}] \cdot x_h^c}{f_j} \tag{3}$$

Model of the temperature of the air flows

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corresponds to averaging

Model of the temperature of the IT components

$$\begin{aligned}\dot{x}_j^c &= \underbrace{-h_j f_j(\boldsymbol{u})\left(x_j^c - x_j^f(\boldsymbol{u}, \boldsymbol{x}^c, x^i)\right)}_{\text{convection}} \\ &+ \underbrace{\begin{bmatrix} R_{(j)} & \rho_j \end{bmatrix} \begin{bmatrix} \boldsymbol{x}^c \\ x^i \end{bmatrix}}_{\text{conduction}} \\ &+ \underbrace{b_j p_j}_{\text{electrical power}}\end{aligned} \tag{4}$$

Model of the temperature of the IT components

$$\dot{x}_j^c = \underbrace{-h_j f_j(\boldsymbol{u})\left(x_j^c - x_j^f(\boldsymbol{u}, \boldsymbol{x}^c, x^i)\right)}_{\text{convection}} + \underbrace{\begin{bmatrix} R_{(j)} & \rho_j \end{bmatrix} \begin{bmatrix} \boldsymbol{x}^c \\ x^i \end{bmatrix}}_{\text{conduction}} + \underbrace{b_j p_j}_{\text{electrical power}} \tag{4}$$

Euler forward discretization:

$$x_j^c(k+1) = \Psi_j^{\Delta}(x_j^c(k), \boldsymbol{u}, \boldsymbol{p}, x^i) \tag{5}$$

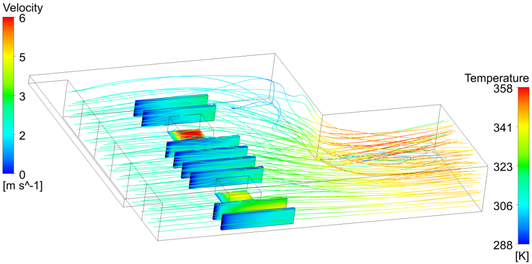
Minimum cost fan control

$$
\begin{aligned}
&\min_{\boldsymbol{u}(0),\ldots,\boldsymbol{u}(H-1)} \sum_{t=0}^{H-1} \sum_{h=1}^{m} \left(u_h(t)\right)^3 \\
&\text{subject to (for } 0 \le t \le H-1, 1 \le j \le n\text{):} \\
&\quad \boldsymbol{x}^c(0) = \boldsymbol{x}_0^c \\
&\quad \boldsymbol{u}_{\min} \preceq \boldsymbol{u}(t) \preceq \boldsymbol{u}_{\max} \\
&\quad \boldsymbol{x}^c(t+1) \preceq \boldsymbol{x}_{\max}^c \\
&\quad x_j^c(t+1) = \Psi_j^{\Delta}\left(x_j^c(t), \boldsymbol{u}(t), \boldsymbol{p}(t), x^i\right)
\end{aligned}
\tag{6}
$$

numerical simulations

i) how accurate is the polynomial flows model?
ii) how conservative is the control strategy?

Validation of the model using CFD

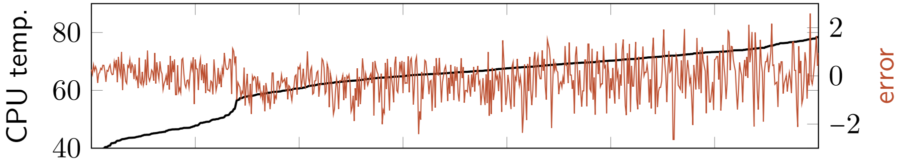


Algorithm:

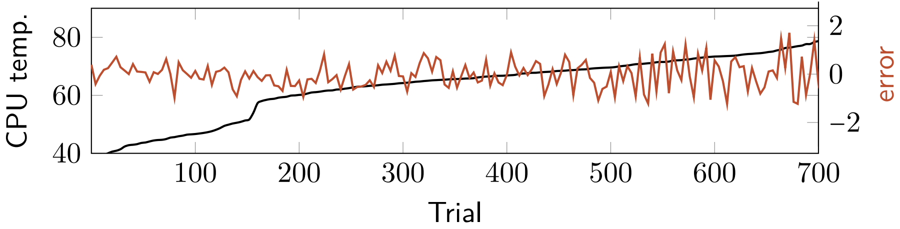
1. set boundary conditions (i.e., $\boldsymbol{p}, \boldsymbol{u}, x^i$)
2. use CFD model as a virtual plant
3. estimate the parameters using RLS

Validation of the model using CFD

deg(Λ^d) = 2, deg(Λ^r) = 1



deg(Λ^d) = 2, deg(Λ^r) = 2

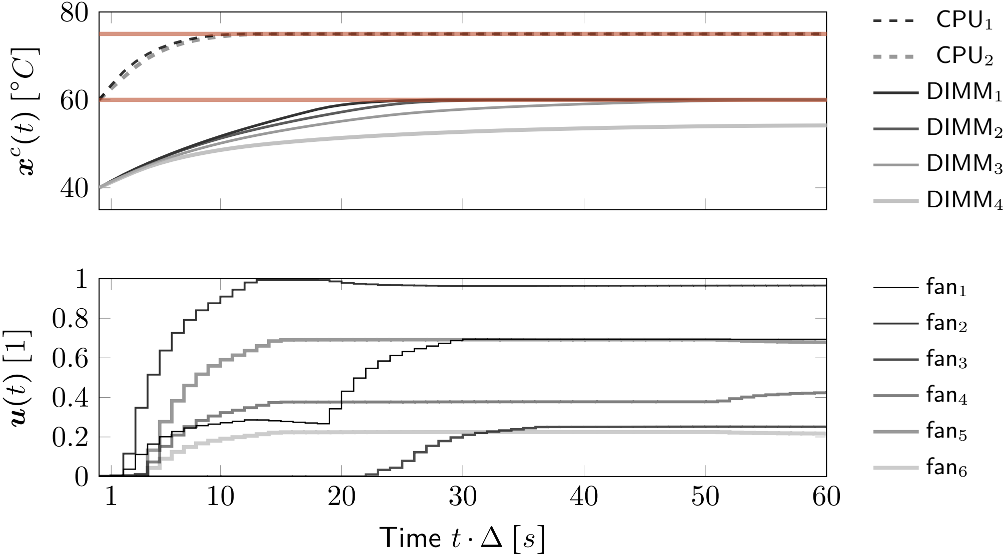


Validation of the control strategy

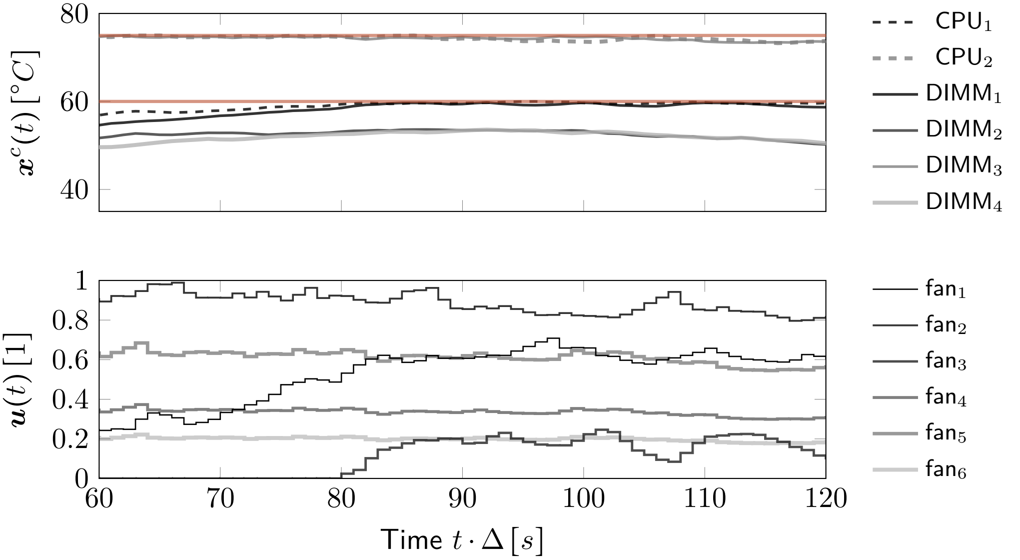
Experiment 1: $\boldsymbol{p}(t) = \boldsymbol{p}_{\max}$

Experiment 2: $\boldsymbol{p}(t)$ = stochastic process with seasonal trends *(medium-high loads)*

Validation of the control strategy - Experiment 1



Validation of the control strategy - Experiment 2



Conclusions

i) promising ability at capturing complex convective cooling effects
ii) functional structure open to other cooling applications
iii) can be identified starting from CFD models

Conclusions and future works

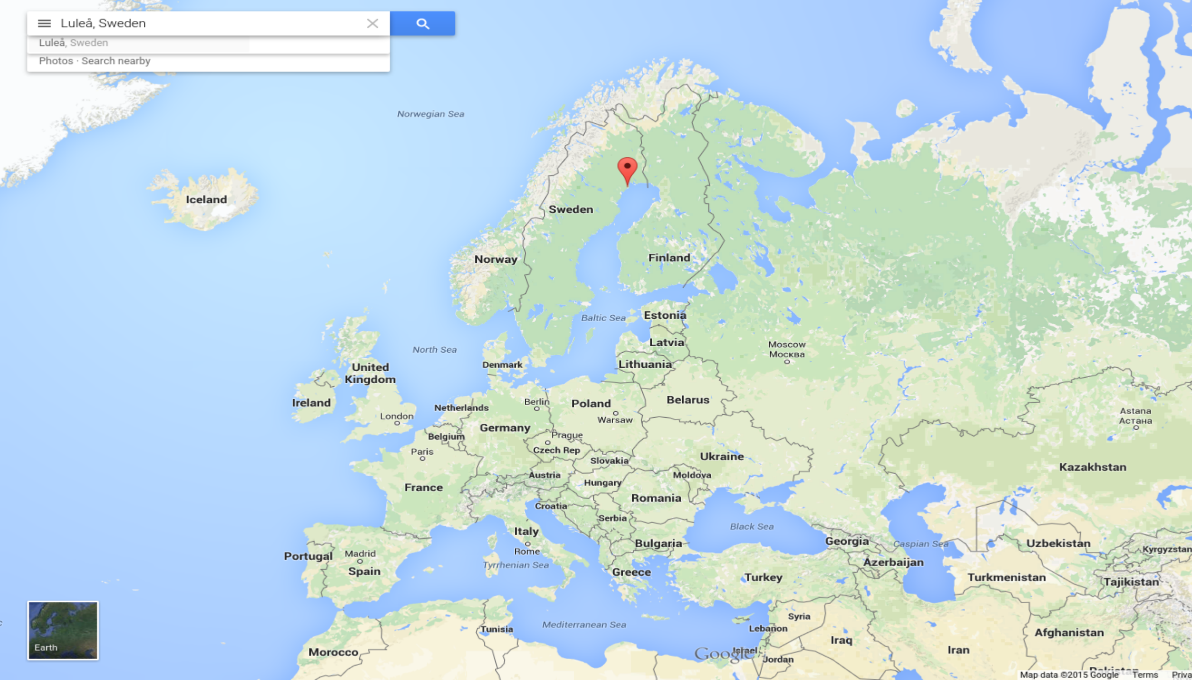
i) promising ability at capturing complex convective cooling effects
ii) functional structure open to other cooling applications
iii) can be identified starting from CFD models

i) validate on real plants
ii) generalize to “datacenter room control”
iii) generalize to generic thermal networks

RISE SICS North ICE

- 3000 - 4000 servers (2MW)
- 160 m^2 lab
- biogas back up generators
- connections with the urban district heating network
- Generality, Flexibility and Expandability

Experiment-as-a-Service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RISE SICS North ICE

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