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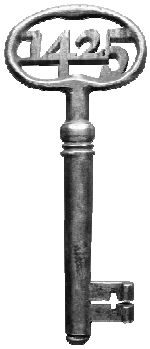

Dynamisch thermisch gedrag van gebouwen met BetonKernActivering

Publieke doctoraatsverdediging

Maarten Sourbron
10 September 2012
Promotor: Prof. dr. ir. L. Helsen
Co-promotor: Prof. dr. ir. M. Baelmans

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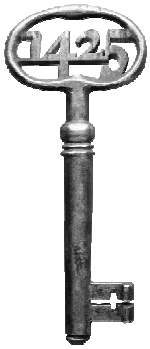

Dynamic thermal behaviour of buildings with Concrete Core Activation

Public Doctoral Defence

Maarten Sourbron
September 10, 2012
Supervisor-final responsible: Prof. dr. ir. L. Helsen
Supervisor: Prof. dr. ir. M. Baelmans

Content

- Introduction
  - Concrete Core Activation
  - Thermal comfort
- Problem and Goal
- Methodology
  - Measurements
  - CCA analysis
  - CCA + building analysis
- Results
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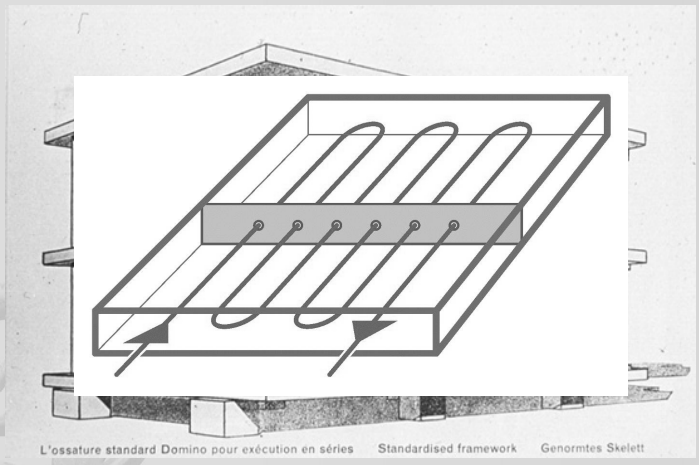
Concrete Core Activation

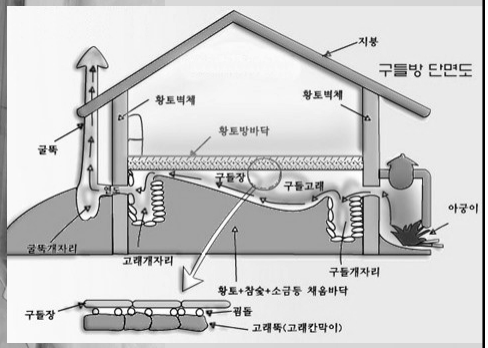


Le Corbusier, Domino-structuur

Not so new…

- Korean 'Ondol': warm stone (11th century B.C.)



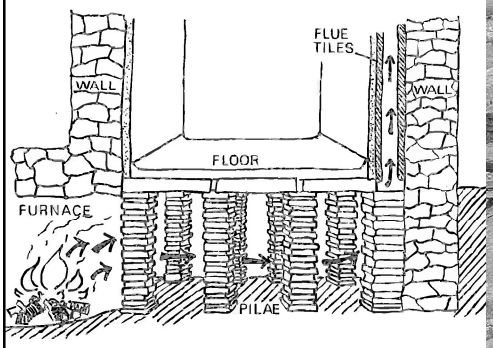


koreatechblog.com

www.skyscrapercity.com, Dr. Nick

Not so new…

- Roman ‘Hypocaust’: floor and wall heating

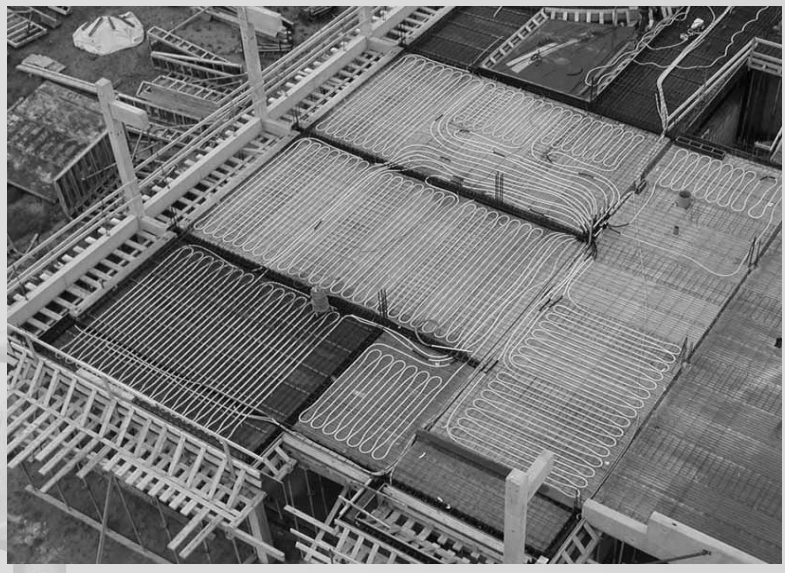


gallery.e2bn.org



Flickr, socorro66

Concrete Core Activation



Viessmann, Welkenraedt

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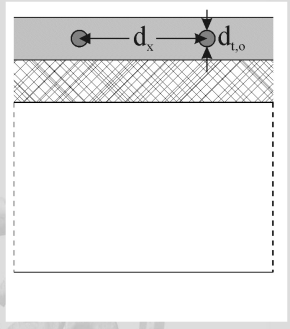
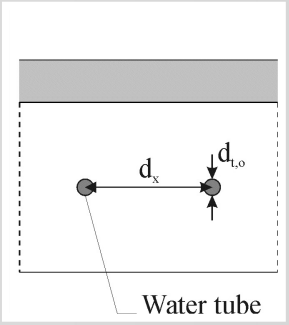
CCA: not just floor heating…

Floor heating



Concrete Core Activation



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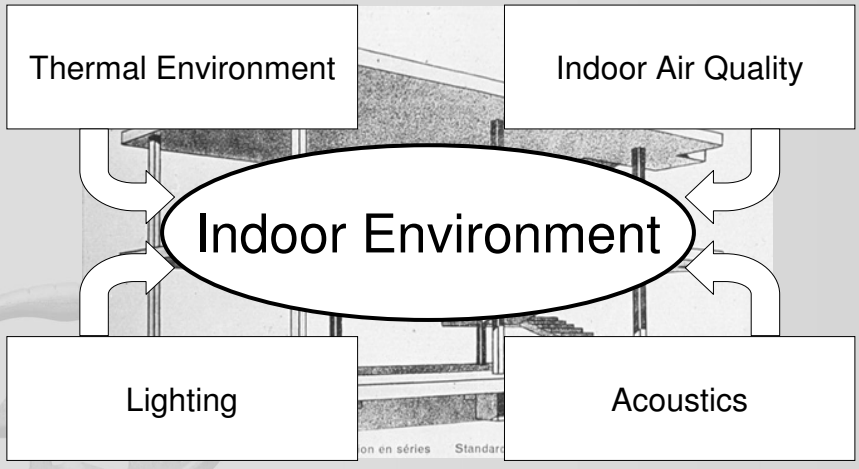
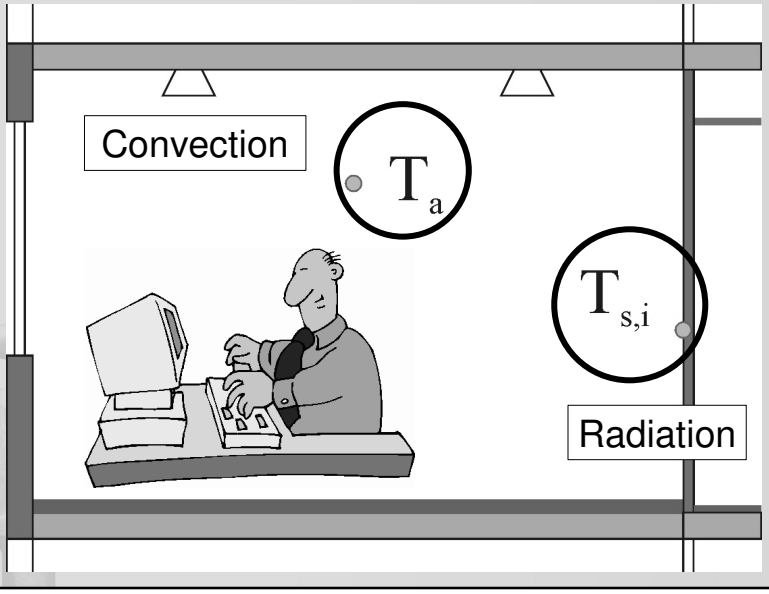
Comfort

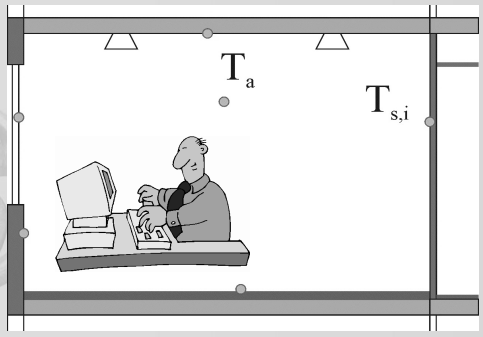


Thermal comfort ≈ Thermal balance



Thermal comfort: operative temperature

- $T_{operative}$ = uniform temperature that results in the same energy balance as in reality
- Simplified to: $$T_{op} = \frac{T_a + T_{s,mean}}{2}$$



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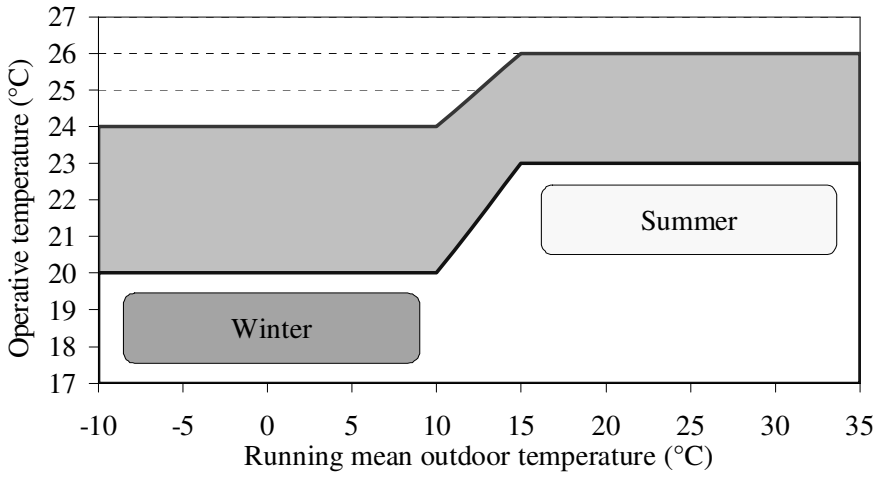
Thermal comfort: operative temperature



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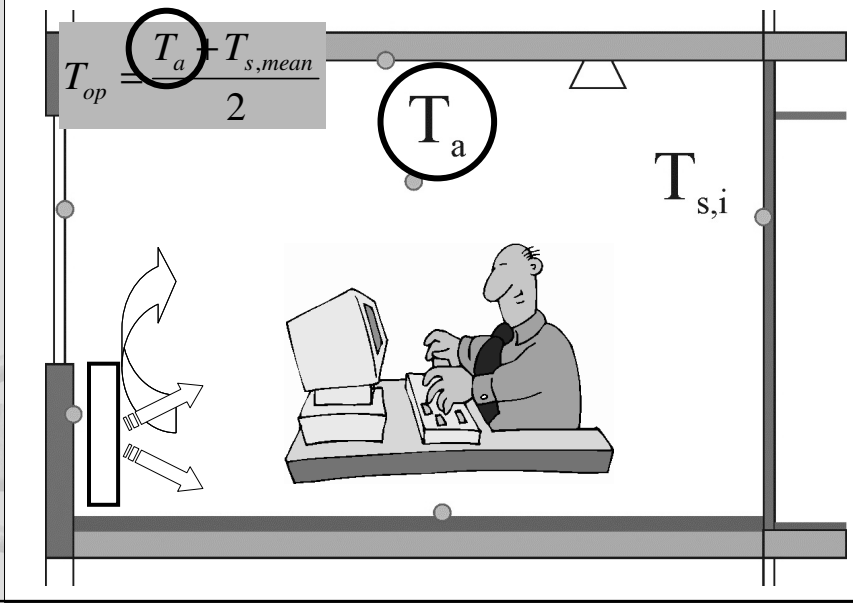
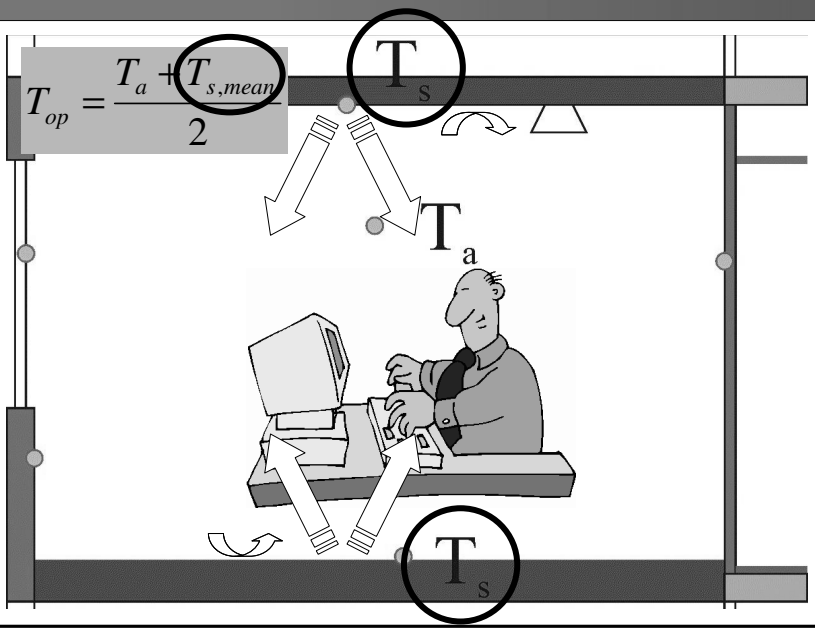
Creating thermal comfort



Creating thermal comfort

$$T_{op} = \frac{T_a + T_{s,mean}}{2}$$



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Why Concrete Core Activation?

- Radiative heating/cooling more comfortable
- Low temperature heating/high temperature cooling
  - Heat pumps, ground cooling, night cooling
- Large thermal mass
  - Heat/cold storage
  - CCA uncouples heat/cold production from heat/cold emission

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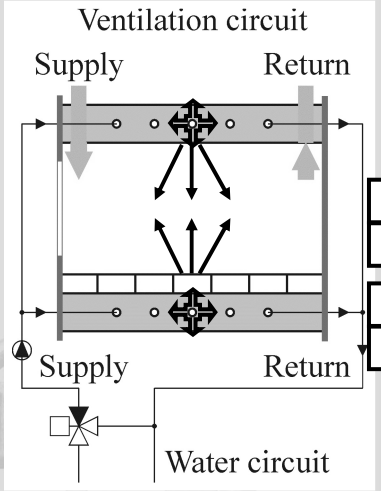
Uncoupled production/emission



~ $(T_{ceiling} - T_{zone})$

~ $(T_{floor} - T_{zone})$

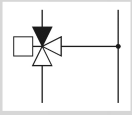
Heat transfer CCA-zone

Not controllable

Heat transfer water-CCA

Controllable

Temperature control



Flow rate control



Goal

- Analysis of CCA dynamic thermal behaviour IN A BUILDING
  - Controller design guidelines
- Simplified dynamic model of CCA and CCA-building
  - Usable in a building controller

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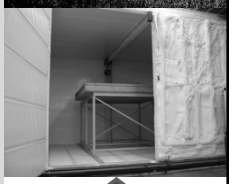
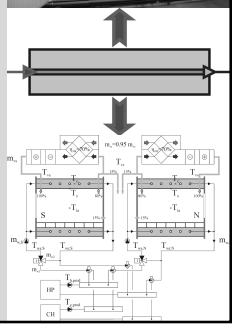
Methodology

- Measurements in a building
- Analysis of CCA
  - Measurements in test room
  - Steady state analysis
  - Analytical solution for transient analysis
- Analysis of CCA + building
  - Simulation model
  - Conventional control
  - Model based Predictive Control







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An example: Nathan building

- Nathan Import/Export, Duiven (The Netherlands)



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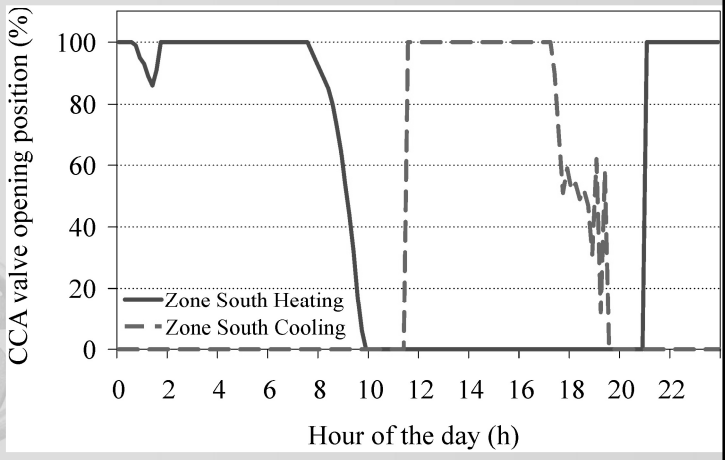
An example: Nathan building

- Well designed system, but **unadapted control strategy**

Heating:
$T_z < 21$°C

Cooling:
$T_z > 22.5$°C

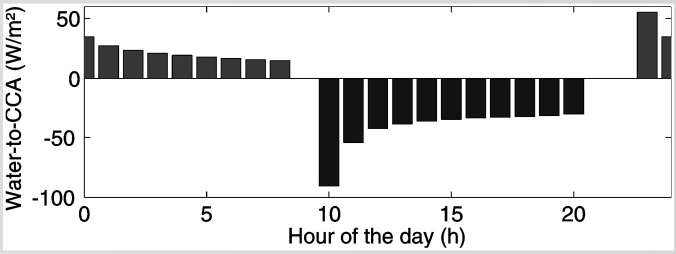


An example: Nathan building

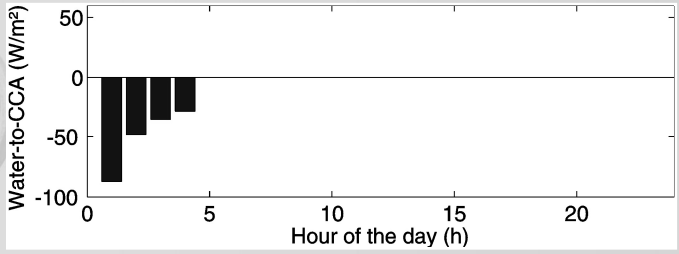
- Compared to 'Only Cooling control strategy'

Heating:
$T_z < 21$°C

Cooling:
$T_z > 22.5$°C

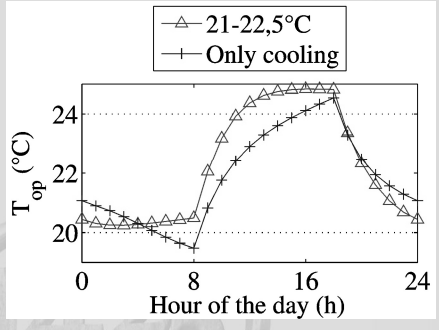


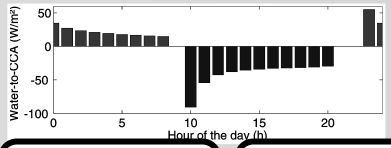
Cooling:
0h – 4h



An example: Nathan building

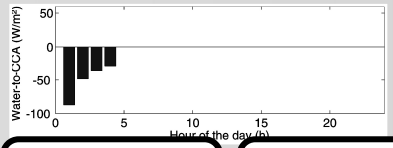
- Compared to 'Only Cooling control strategy'





Heating:
430 Wh

Cooling:
270 Wh

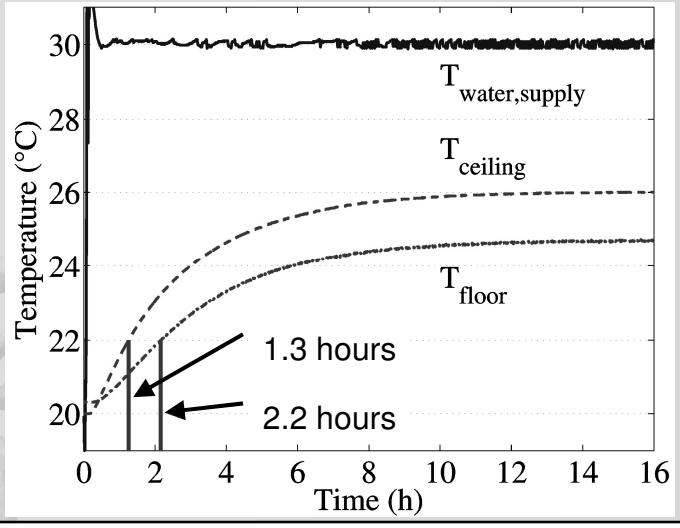


Heating:
0 Wh

Cooling:
170 Wh

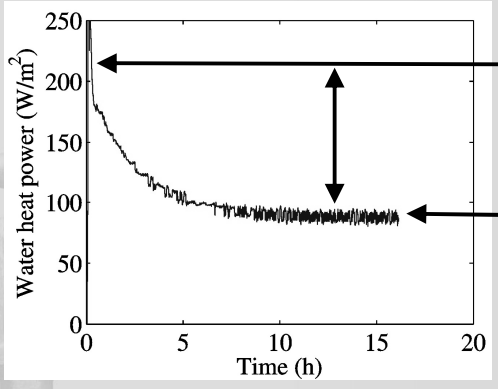
CCA measurements

- Measurement on 20 cm CCA-slab with hollow cores



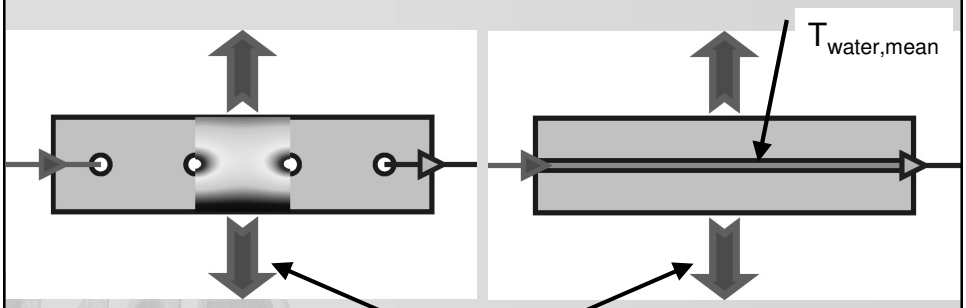
CCA measurements

- Limited thermal power
- Another important transient effect: large initial thermal power



CCA thermal model

- Reality
- EMPA-model (Koschenz and Lehmann):

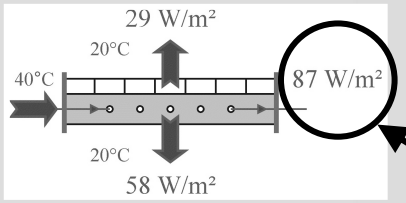


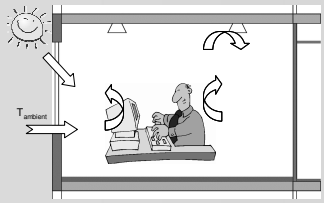
Equal thermal output

EMPA
Materials Science & Technology

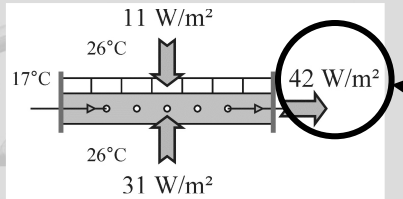
CCA thermal power - building thermal loads

- CCA with raised floor and heat pump / direct cooling





- Heat loss
  20 to 40 W/m²



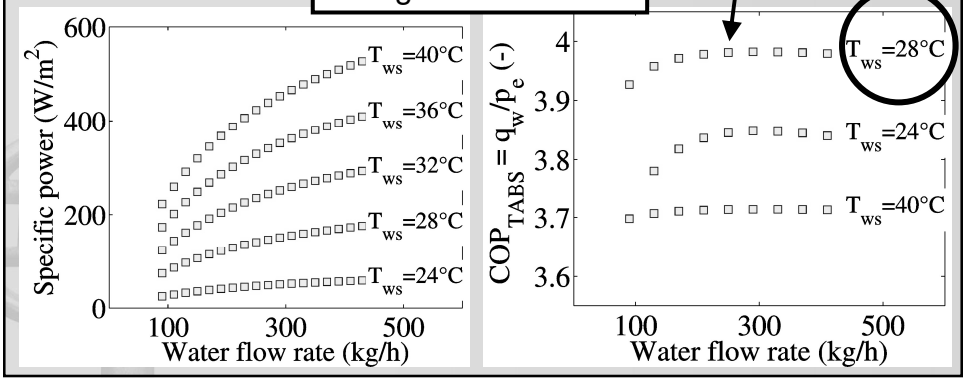
- Heat load
  20 to >100 W/m²

CCA steady state analysis

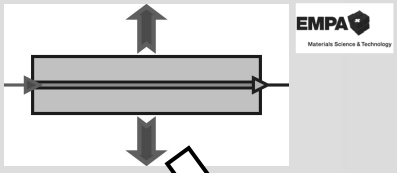
- Controlling T_{ws} *or* $\dot{m}$?
- $T_{ws}+1$ → Electricity$_{heat\text{-}pump}$: +0.7%
- $\dot{m}+1$ → Electricity$_{circulation\text{-}pump}$: +2%

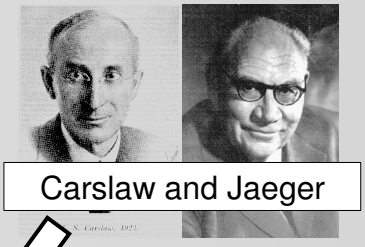
250 kg/h
= 21 kg/h.m²

No general results!



CCA transient analysis: analytical solution





Carslaw and Jaeger

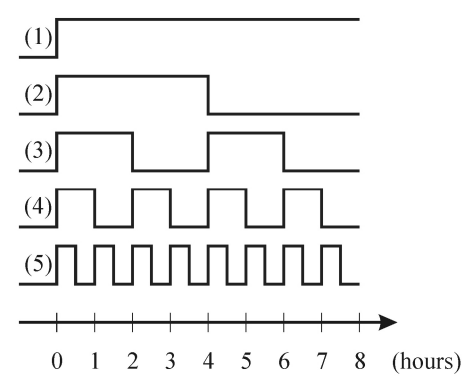
$$T(\xi,\mathrm{Fo}) = C\xi + D + \sum_{n=1}^{\infty} A_n Z_n(\xi) e^{\left(-\beta_n^2\,\mathrm{Fo}\right)} Z_{n,init}$$

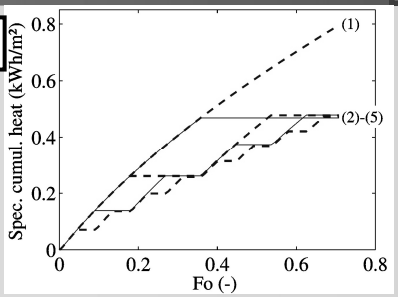
$$\dot{q}(\xi,\mathrm{Fo}) = -\frac{\lambda_c}{L}\left[C + \sum_{n=1}^{\infty} A_n\beta_n\left(\cos(\beta_n\xi) - \frac{\beta_n}{\mathrm{Bi}_1}\sin(\beta_n\xi)\right) e^{\left(-\beta_n^2\,\mathrm{Fo}\right)} Z_{n,init}\right]$$

$$q(\xi,\mathrm{Fo}) = -L\rho c\left[C\,\mathrm{Fo} + \sum_{n=1}^{\infty} A_n\beta_n\left(\cos(\beta_n\xi) - \frac{\beta_n}{\mathrm{Bi}_1}\sin(\beta_n\xi)\right)\frac{1-e^{\left(-\beta_n^2\,\mathrm{Fo}\right)}}{\beta_n^2} Z_{n,init}\right]$$

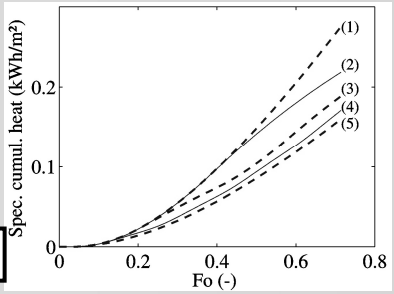
CCA transient analysis: pump run-time

Heat from water to CCA





Heat from CCA to zone



CCA transient analysis

- Simplified expression for transferred heat *q*: using the solution for *n=1*

Analytical solution for *q* with n=1

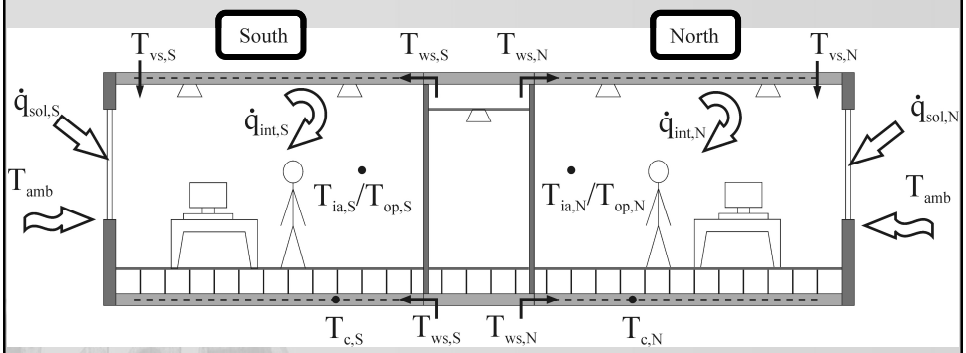
$$\mathrm{Fo} = \frac{W\left(e^{\left[\beta_1^2 \frac{1}{C}\left(\frac{q_{room}}{L\rho c}+K_1\right)\right]\frac{K_1}{C}\beta_1^2}\right) - \beta_1^2 \frac{1}{C}\left(\frac{q_{room}}{L\rho c}+K_1\right)}{\beta_1^2}$$

$$\mathrm{Fo} = \frac{W\left(e^{\left[\beta_1^2 \frac{1}{C}\left(\frac{q_{water}}{L\rho c}+K_2\right)\right]\frac{K_2}{C}\beta_1^2}\right) - \beta_1^2 \frac{1}{C}\left(\frac{q_{water}}{L\rho c}+K_2\right)}{\beta_1^2}$$

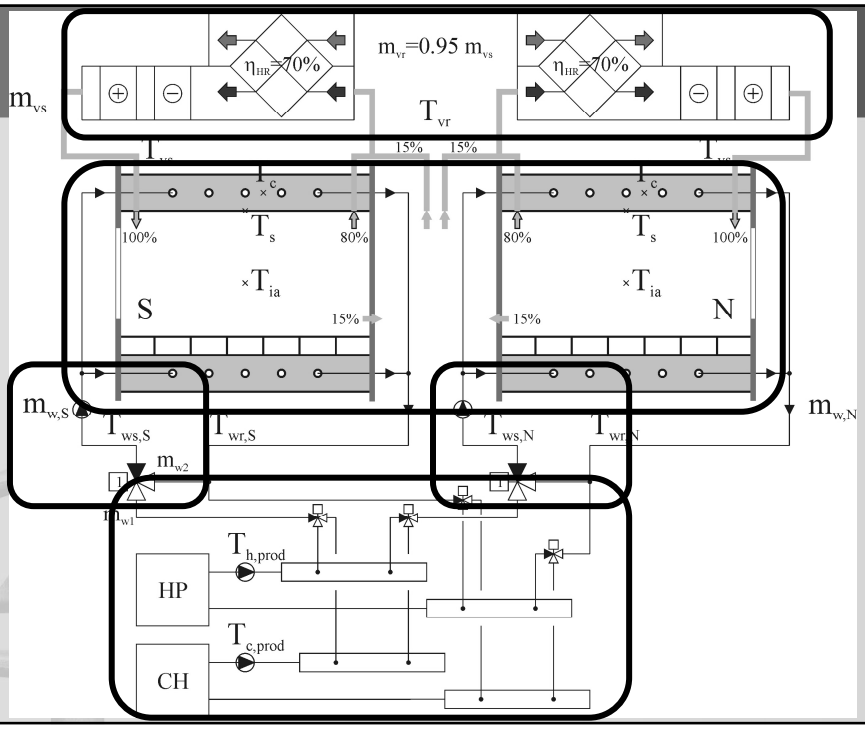
$$\mathrm{Fo} = -\frac{1}{\beta_1^2}\ln\left(1+\frac{q_{sto}}{L\rho c\,(K_2-K_1)}\right)$$

CCA + building

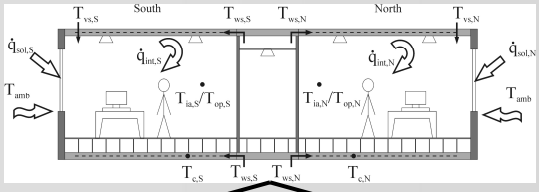
- Building that fits CCA



- Heating load: **26 W/m²**
- Cooling load: **25 W/m²** (office hours average)



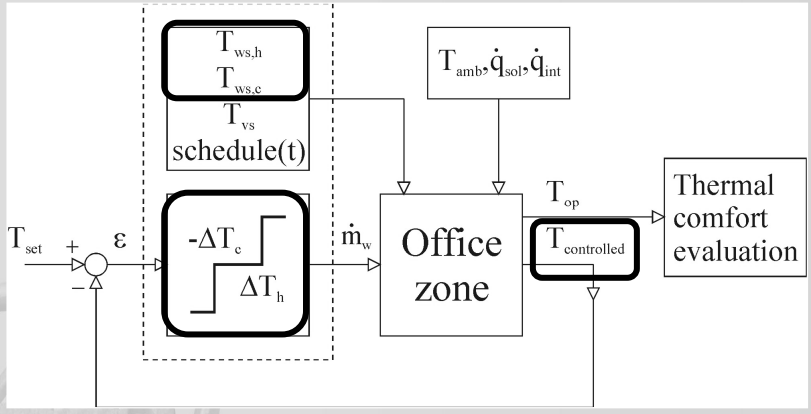
CCA + building



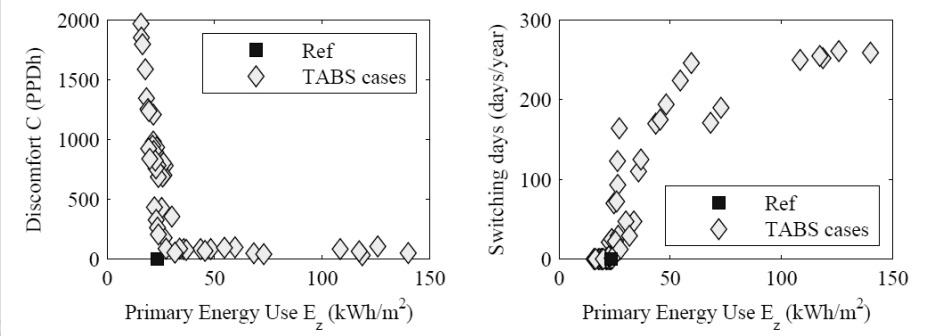
'Conventional' feedback control

Model based Predictive Control (MPC)

CCA + building: Conventional control



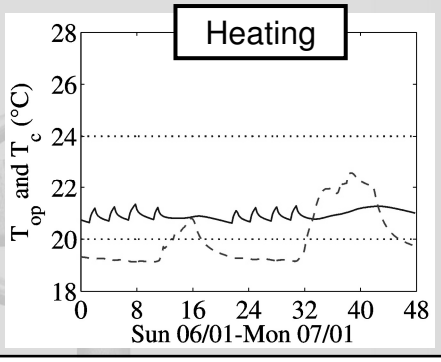
CCA + building: Conventional control

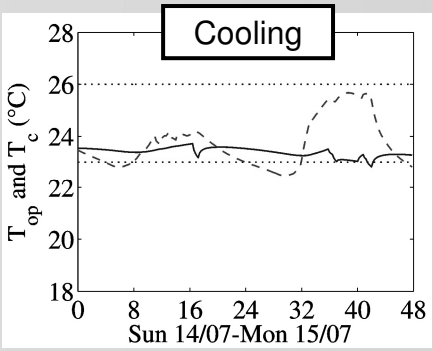


No heating and cooling of CCA during 1 day

CCA + building: Conventional control

- Best results: keep CCA at temperature
  - $T_{controlled} = T_{ceiling}$
  - Heating on: $T_{comfort,min}$
  - Cooling on: $T_{comfort,max} - 2$°C
  - Heating/cooling curve: +3°C/-3°C

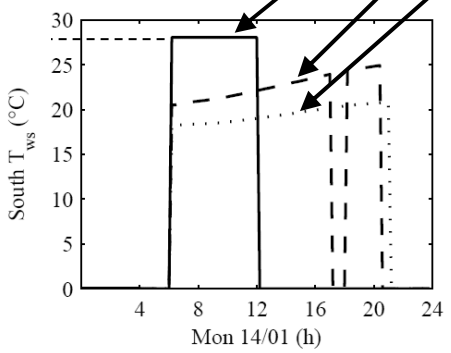


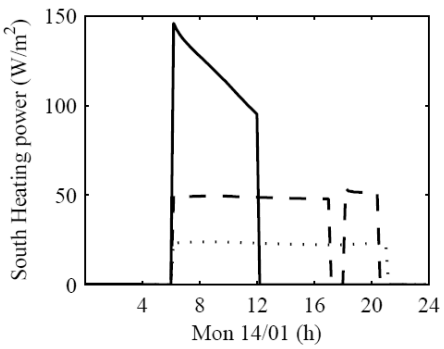


CCA + building: Conventional control

- Limited production power

Unlimited
50 W/m²
25 W/m²

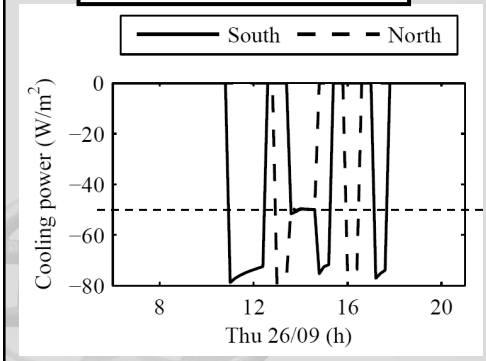




CCA + building: Conventional control

- Alternating zone operation

Designed at 50 W/m²



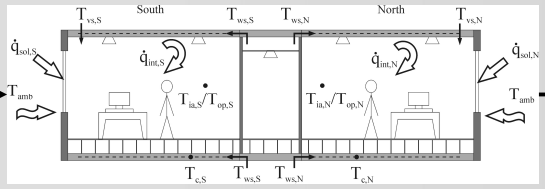
South: x W
North: y W
Production: x+y W

South: x W
North: y W
Production: x+y W

CCA + building: MPC

- Optimal use of thermal inertia
- Combination of CCA and fast reacting system:
  - Air Handling Unit
- Possible solution with
  MPC (Model based Predictive Control)

CCA + building: MPC



Measurements

MPC:
optimal profile of T_{ws}, T_{vs}, pump, fan, ... for
min(energy cost, thermal discomfort cost)

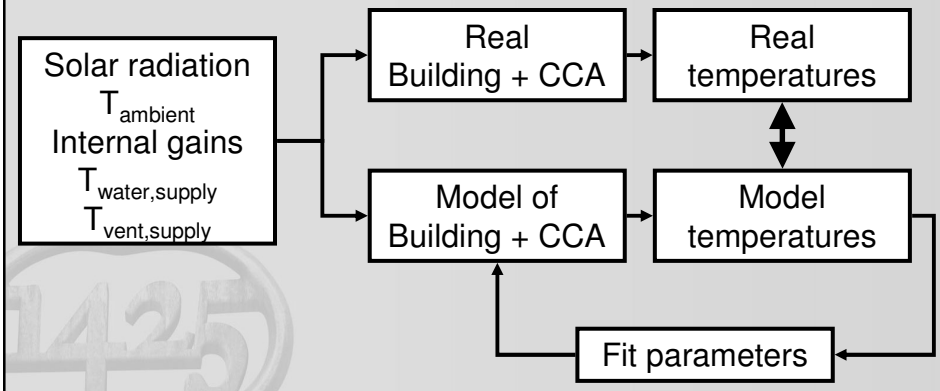
Model of
Building + CCA

Model of energy and
thermal discomfort cost

Predictions of
weather, occupation, …

CCA + building: MPC

- Model of building + CCA
  - Parameter identification



CCA + building: MPC

- Model of building + CCA
  - Parameter identification
- Only **theoretical inputs** yield good models
- Impact of **solar radiation** needs to be correct!

CCA + building: MPC

- MPC defines optimal T_{ws}, T_{vs}
  - minimal CCA heating energy cost
  - minimal CCA cooling energy cost
  - minimal ventilation air heating energy cost
  - minimal ventilation air cooling energy cost
  - minimal hours 'too cold'
  - minimal hours 'too hot'
- For
  - Specific building
  - Initial state of the building
  - Minimal and maximal T_{ws} and T_{vs}
  - Operation hours
  - Maximal heating/cooling power production

Optimal inputs

Energy cost

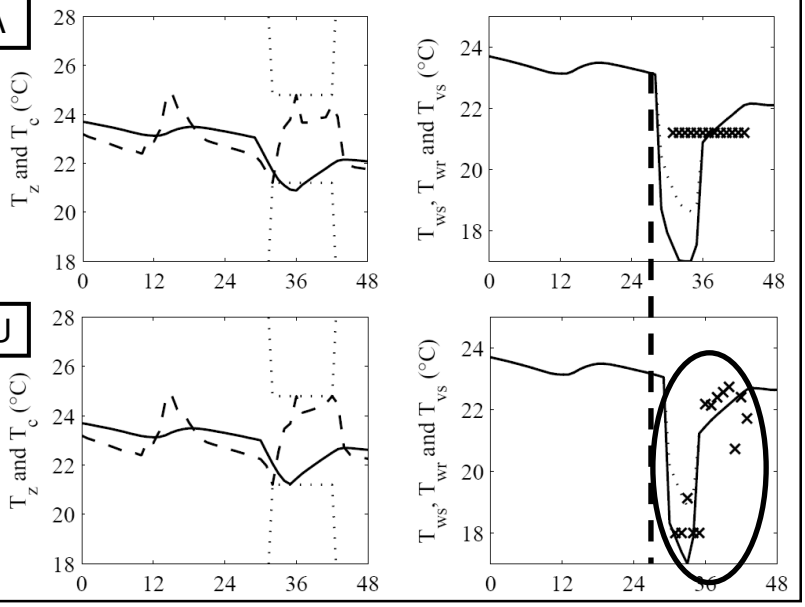
Discomfort cost

Constraints

CCA+AHU MPC: cooling

Only CCA

CCA+AHU



Content

- Introduction
  - Concrete Core Activation
  - Thermal comfort
- Problem and Goal
- Methodology
  - Measurements
  - CCA analysis
  - CCA + building analysis
- Results
- Conclusions

Conclusions: CCA important features

- Limited thermal power
- Slow reacting system
- High start-up thermal power
- (CCA requires) a high quality building

Conclusions: conventional control

- Control strategy determines size of production system
- No heating/cooling switching in 1 day
- Conventional control: keep CCA-temp. at level
- 'High' T_{ws} to load CCA quickly (not too high: overload)
- Alternating zone operation to reduce production power

Conclusions: MPC

- Good candidate for integrated control
- Controlling CCA + fast system (AHU)
- Sensitive to errors
  - Model
  - Predictions
  - Measurements
  - Cost function

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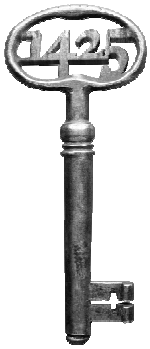

Thank you