Computational Building Physics

using COMSOL

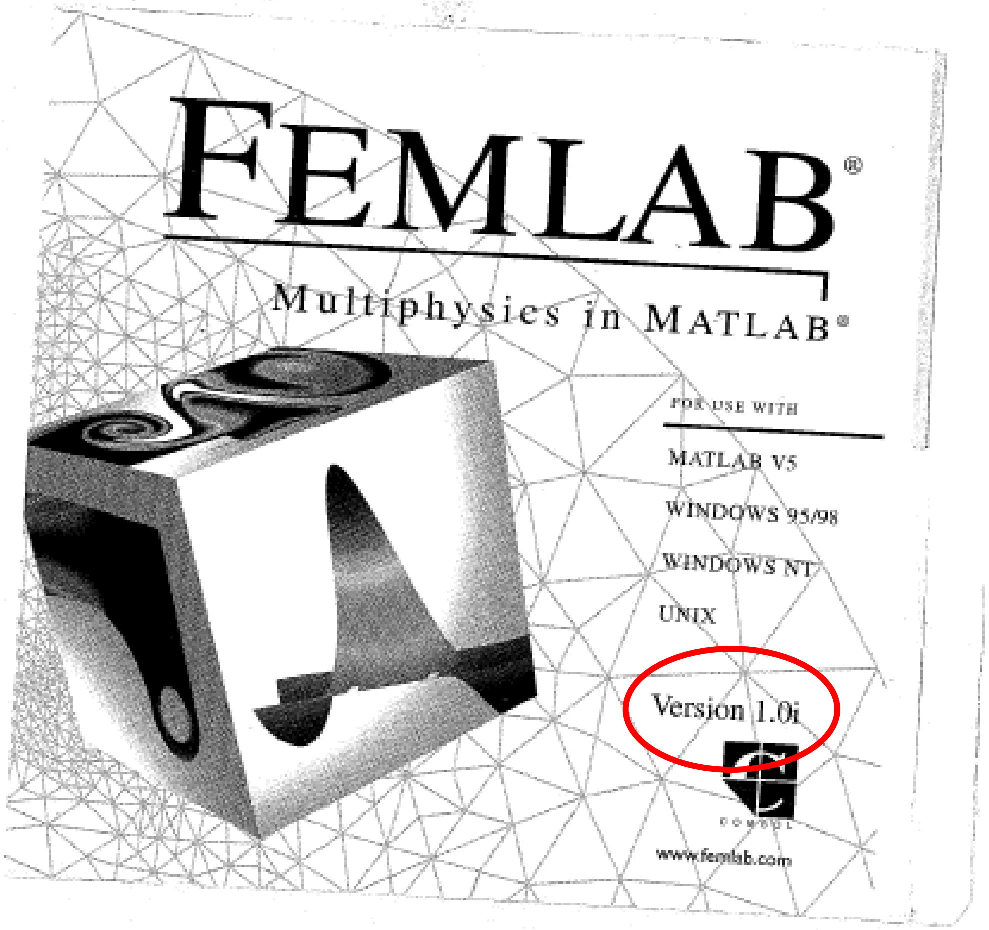
Research, Education & Practice

dr.ir. Jos van Schijndel

TU/e Technische Universiteit Eindhoven University of Technology

Where innovation starts

User since 1998(?)



Contents

- 1.Introduction
  - Complexity and scale levels
  - My computational laboratory
- 2.Combined heat, moisture, air, stress models for (building) constructions
- 3.From Material [~mm] to EU [~Mm] scale level
- 4.Conclusions

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1. Introduction
Complexity and Scale levels

- What is a 'Complex system'?

- Where are Complex systems in the built environment?

Introduction
Complexity and Scale levels

- **The whole is greater than the sum of the individual parts**

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Introduction
Complexity and Scale levels

- **Butterfly effect: Small parameter variations may produce large variations in the long term behavior of the system.**

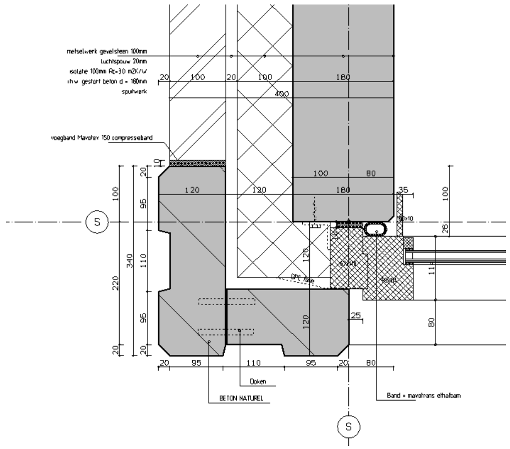
Introduction
Complexity and Scale levels

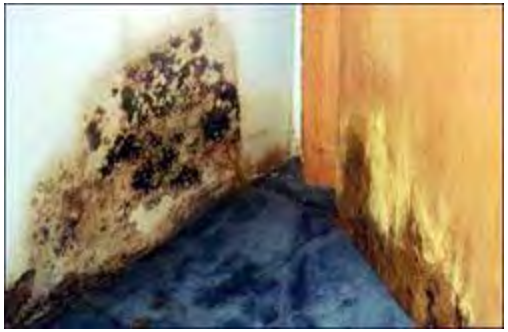
- **Where are the dynamic complex systems at the built environment ?**

Everywhere and on several scales

Scale levels, from left to right: EU; Urban area; Building; Material;

Introduction
Complexity and Scale levels

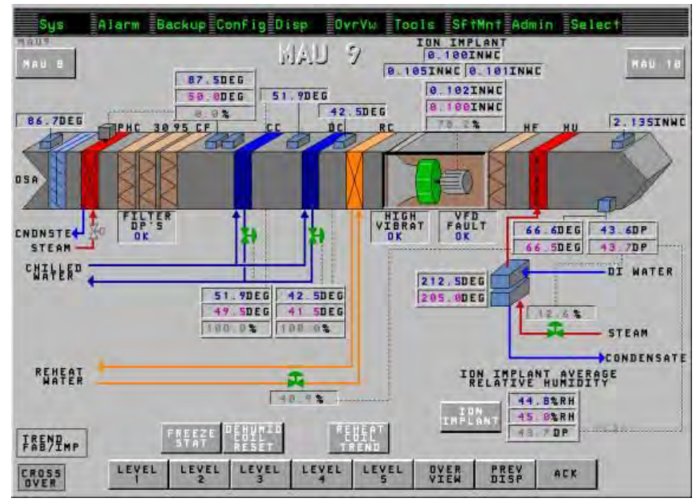




Material ~ mm

Present dynamic complex systems:
Material Physics
•Durability

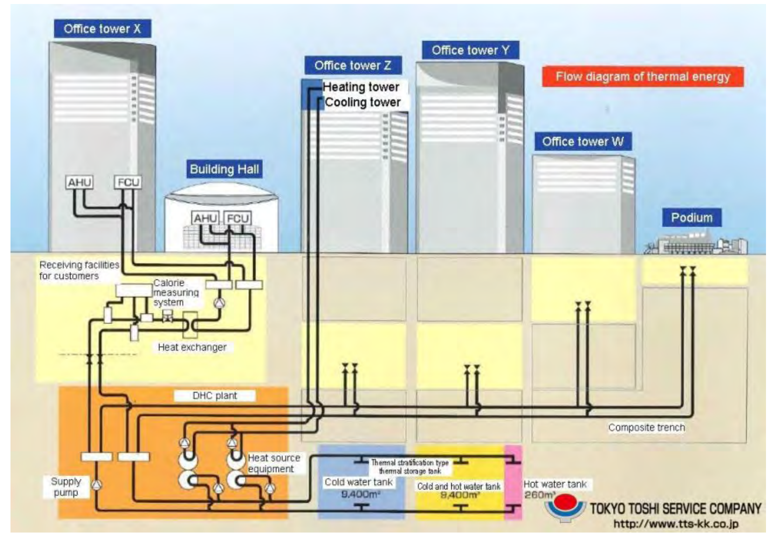
Introduction
Complexity and Scale levels



Building ~ 10 m

Present dynamic complex systems:
Building Physics
•Indoor climate
•Building systems

Introduction
Complexity and Scale levels



Urban Area ~ km

Present dynamic complex systems:
Urban Physics
•Urban Climate
•Urban district systems

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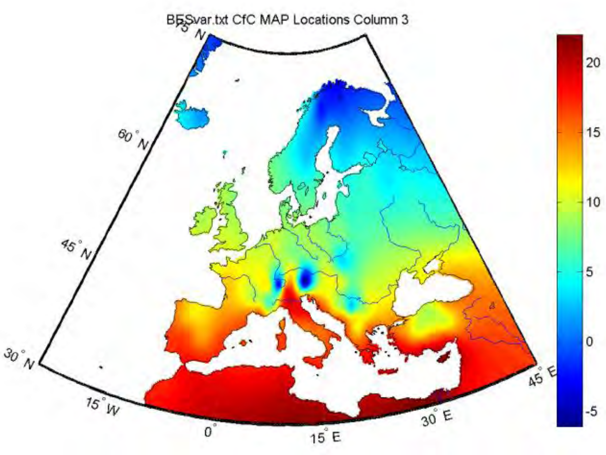
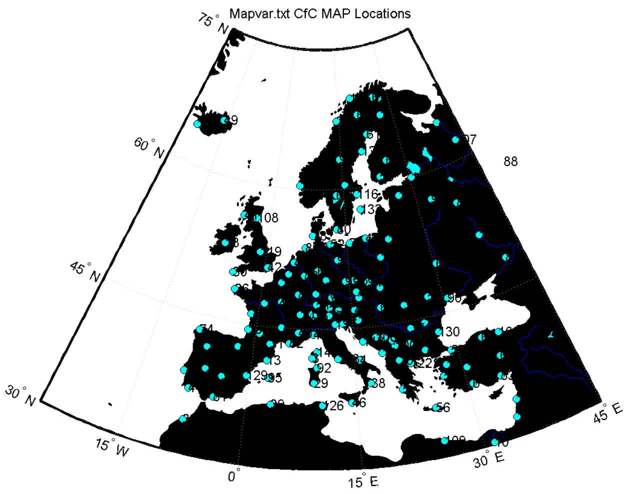
Introduction
Complexity and Scale levels





EU ~ 1 Mm

Present dynamic complex systems:
Global climate Physics
- (Future) Climate
- Mapping

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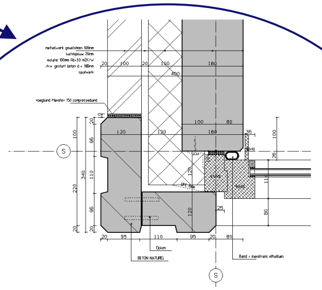
Introduction
My computational laboratory

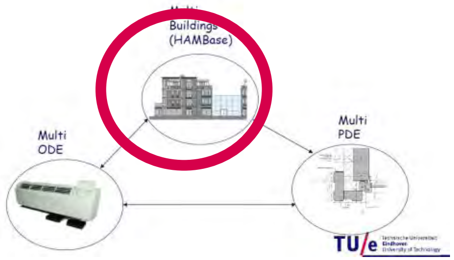
Multi Buildings
'HAMBase'
MatLab

Multi Systems & Control
ODE
SimuLink

Multi Details
PDE
Comsol

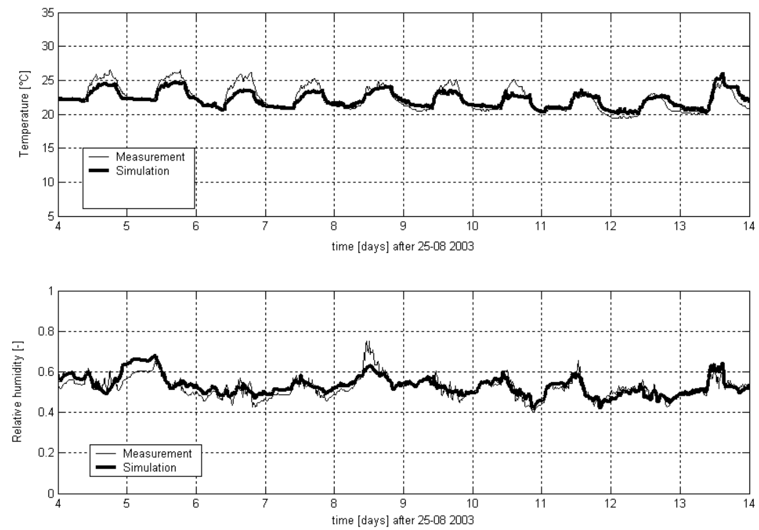


Tools Buildings modeling physics: HAMBase
scientific software: MatLab

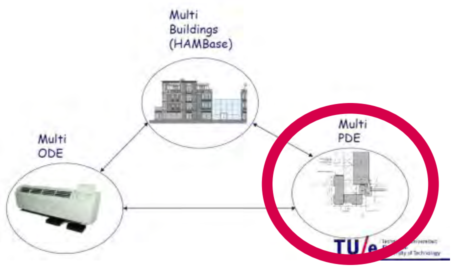


Anne Frank House

Simulation and validation

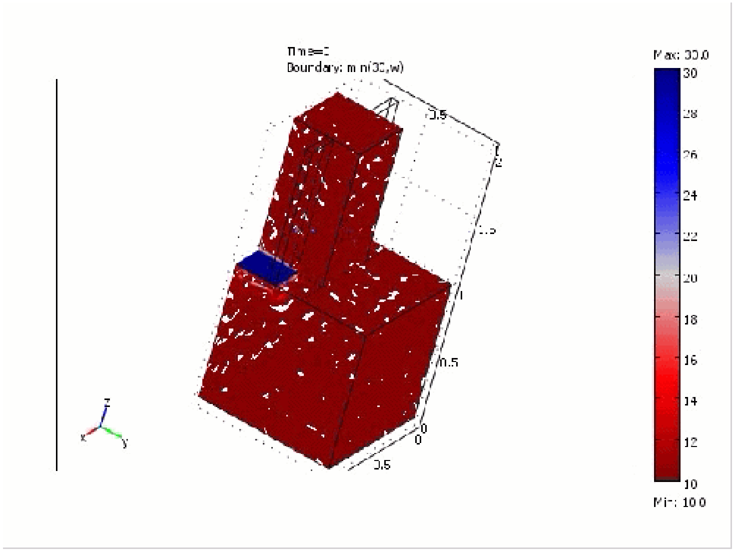


Tools Detail modeling physics: PDEs
scientific software: Comsol



Hunting Logde St. Hubertus

3D Moisture



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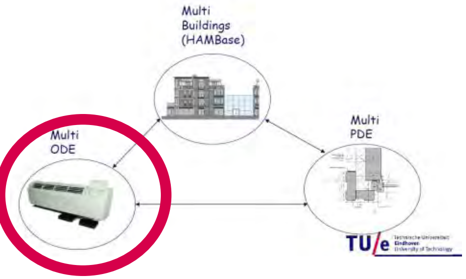
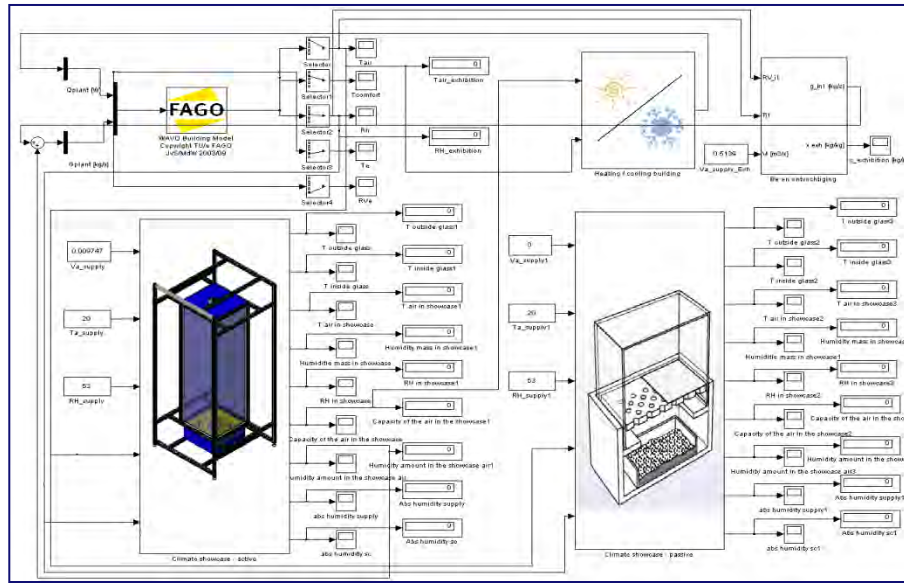
Tools Systems&Control modeling physics: ODEs
scientific software: SimuLink



Building systems failure modeling



Dutch Maritime Museum

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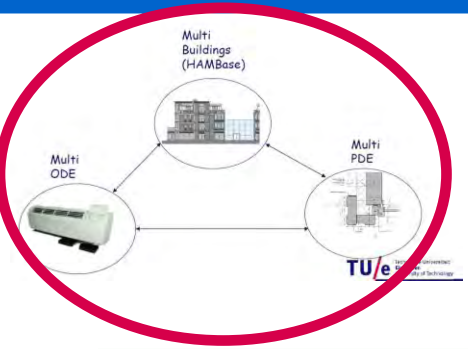
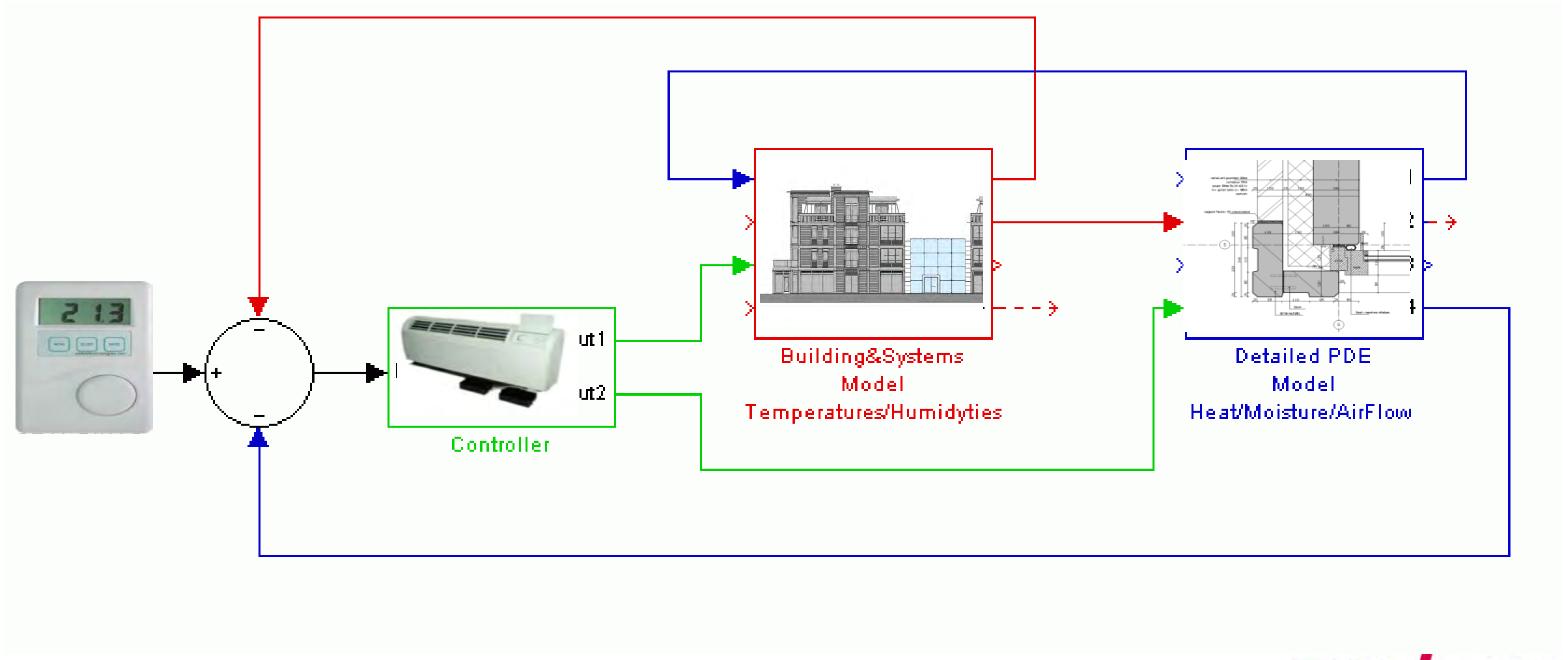
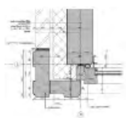
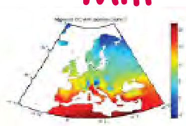
Introduction
My computational laboratory



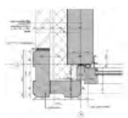
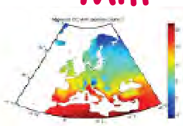
http://archbps1.campus.tue.nl/bpswiki/index.php/Hamlab



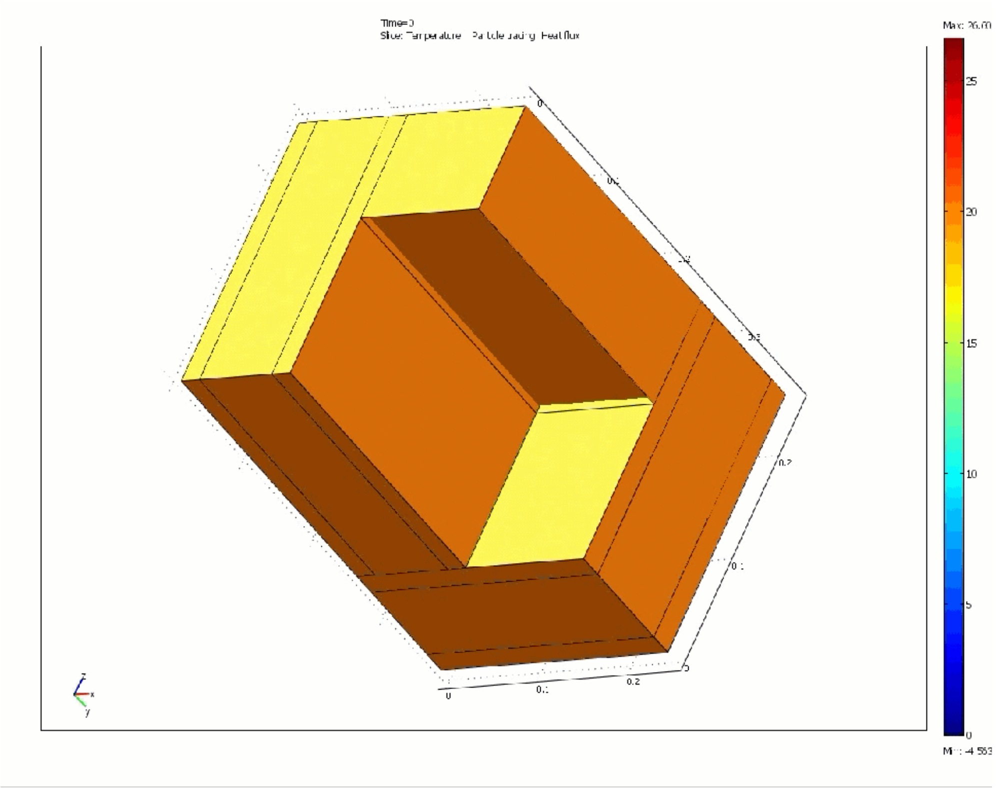
Computational Building Physics
Research Matrix

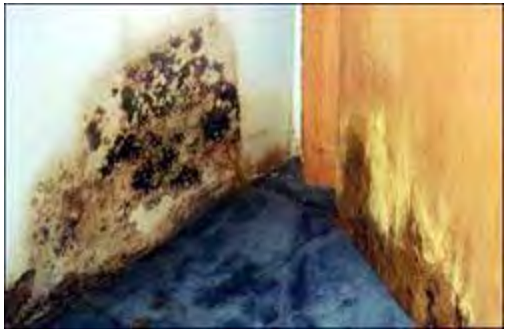
Topic / Scale	Heat	Moisture	Air	Stress
~ mm 				
~ m 				
~ km 				
~ Mm 				

Computational Building Physics
Heat

Topic / Scale	Heat	Moisture	Air	Stress
~ mm 				
~ m 				
~ km 				
~ Mm 				

Application 1: Heat 3D





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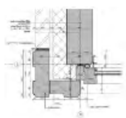
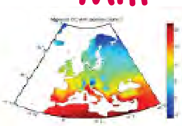
Computational Building Physics
Heat+Moisture

Topic / Scale	Heat	Moisture	Air	Stress
~ mm 				
~ m 				
~ km 				
~ Mm 				

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Application 2: Heat and moisture transport
PDEs

- **Potential T, LPc**
- **PDE coefficients formulation**
  - **Material properties**
  - **function of T, LPc**

$$C_T \frac{\partial T}{\partial t} = \nabla \cdot (K_{11} \nabla T + K_{12} \nabla LPc)$$

$$C_{LPc} \frac{\partial LPc}{\partial t} = \nabla \cdot (K_{21} \nabla T + K_{22} \nabla LPc)$$

$$LPc = {}^{10}\log(Pc)$$

$$C_T = \rho \cdot c$$

$$K_{11} = \lambda$$

$$K_{12} = -l_{lv} \cdot \delta_p \cdot \phi \cdot \frac{\partial Pc}{\partial LPc} \cdot Psat \cdot \frac{M_w}{\rho_a RT},$$

$$C_{LPc} = \frac{\partial w}{\partial Pc} \cdot \frac{\partial Pc}{\partial LPc}$$

$$K_{22} = -K \cdot \frac{\partial Pc}{\partial LPc} - \delta_p \cdot \phi \cdot \frac{\partial Pc}{\partial LPc} \cdot Psat \cdot \frac{M_w}{\rho_a RT},$$

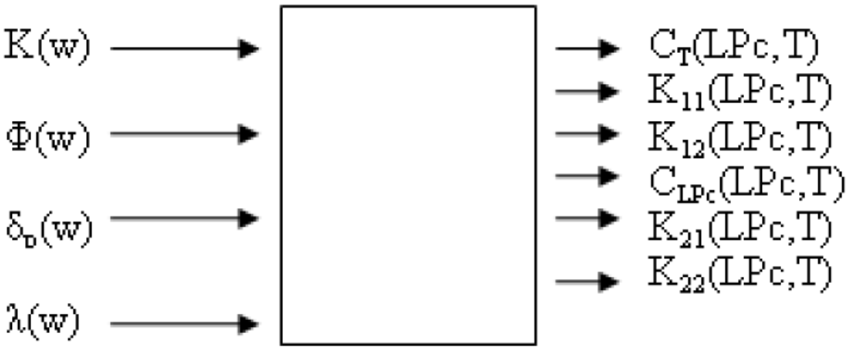
$$K_{21} = \delta_p \cdot \phi \cdot \frac{\partial Psat}{\partial T},$$

Calculating PDE coefficients using material properties, method 1/2

- **PDE coefficients lookup tables calculated in MatLab using:**
  - **heat conduction coefficients**
  - **specific heat**
  - **density**
  - **liquid permeability**
  - **moisture retention curve**
  - **vapour permeability**

$$C_T \frac{\partial T}{\partial t} = \nabla \cdot (K_{11} \nabla T + K_{12} \nabla LPc)$$

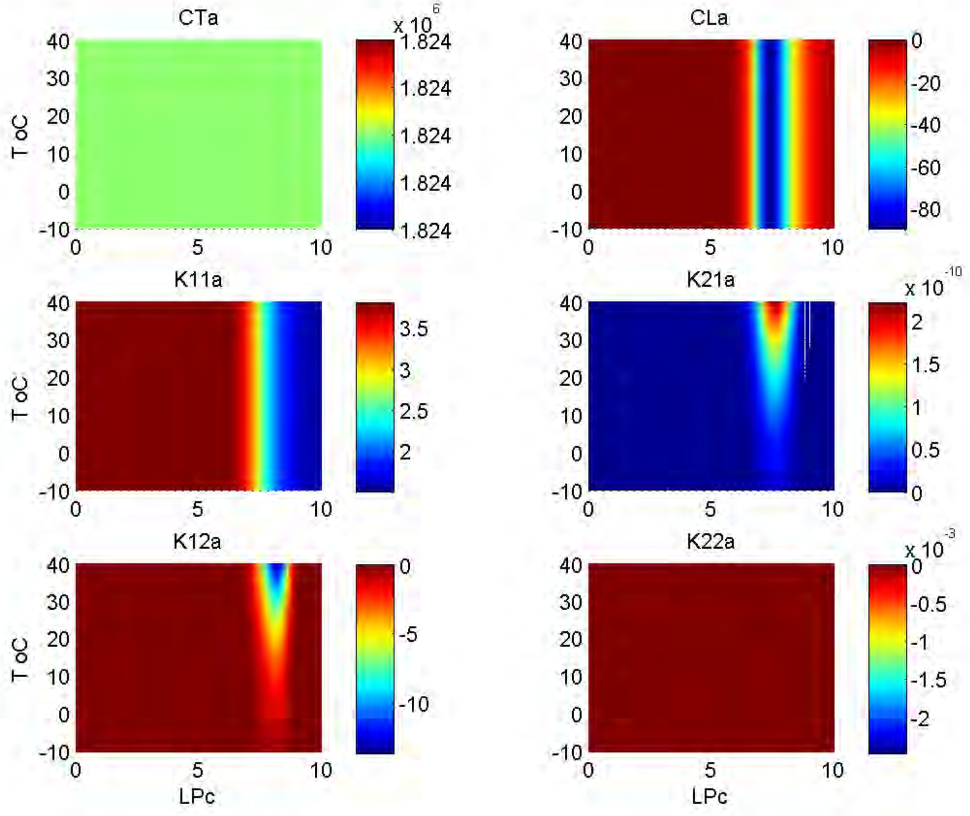
$$C_{LPc} \frac{\partial LPc}{\partial t} = \nabla \cdot (K_{21} \nabla T + K_{22} \nabla LPc)$$



Calculating PDE coefficients using material properties, result 2/2

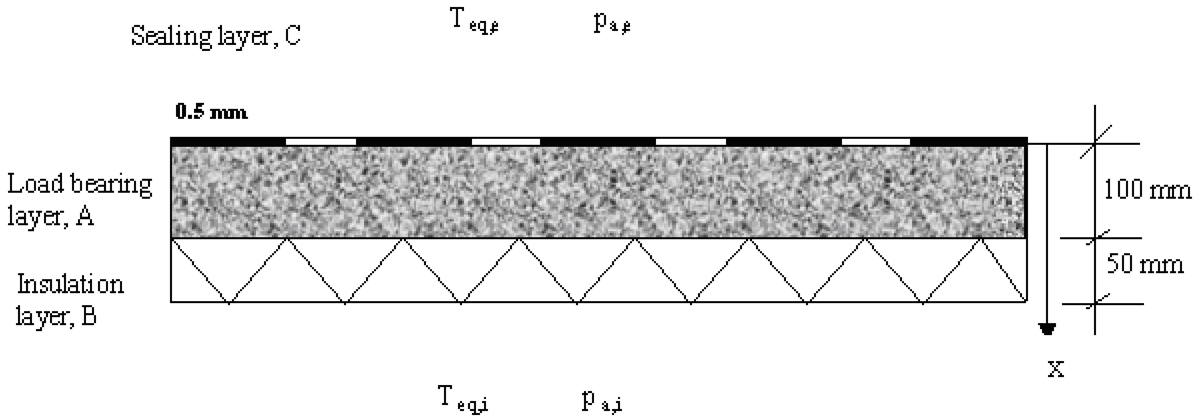
$$C_T \frac{\partial T}{\partial t} = \nabla \cdot (K_{11} \nabla T + K_{12} \nabla LPc)$$

$$C_{LPc} \frac{\partial LPc}{\partial t} = \nabla \cdot (K_{21} \nabla T + K_{22} \nabla LPc)$$



Verification
HAMSTAD Benchmark no 1

$$q = h_e \cdot (T_e - T)$$
$$g = 0$$



$$q = h_i \cdot (T_i - T) + l_{lv} \cdot \beta \cdot (p_i - p)$$
$$g = \beta \cdot (p_i - p)$$

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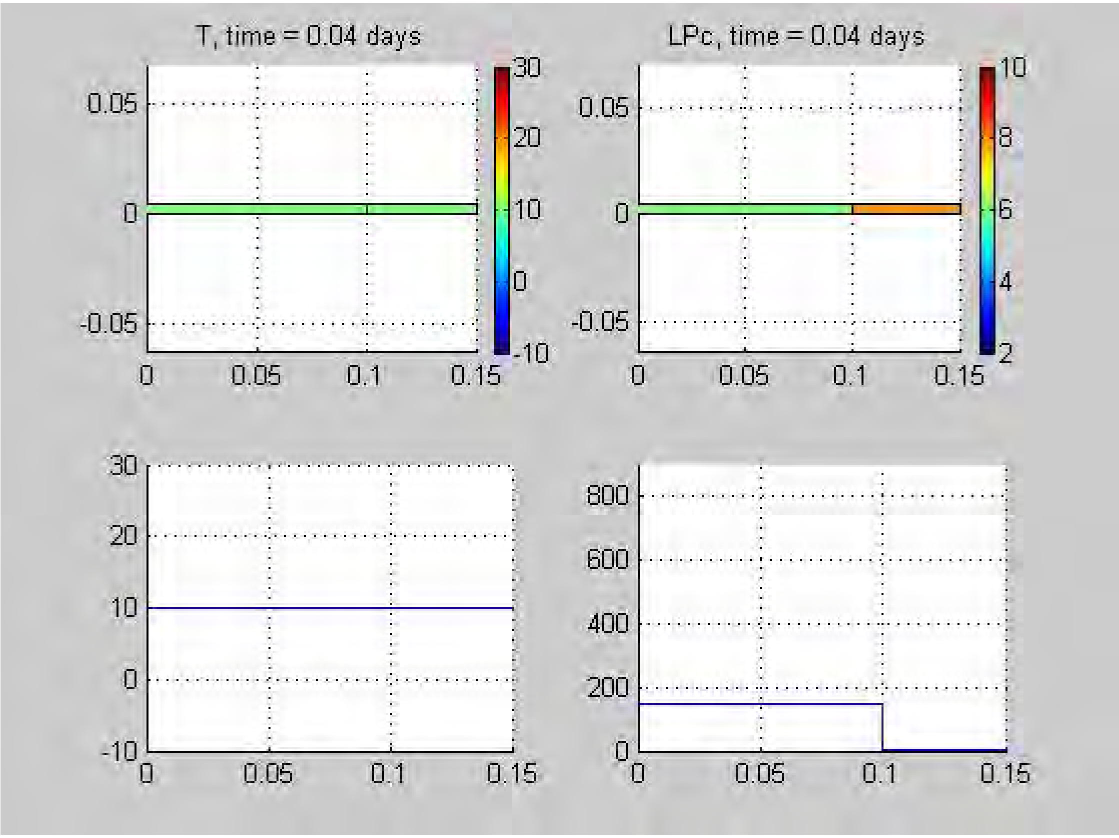
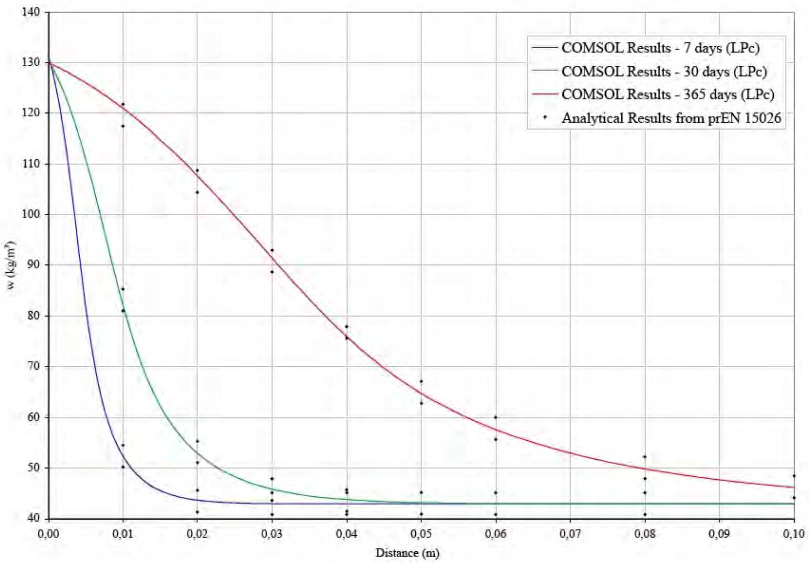
Verification
Heat & Moisture

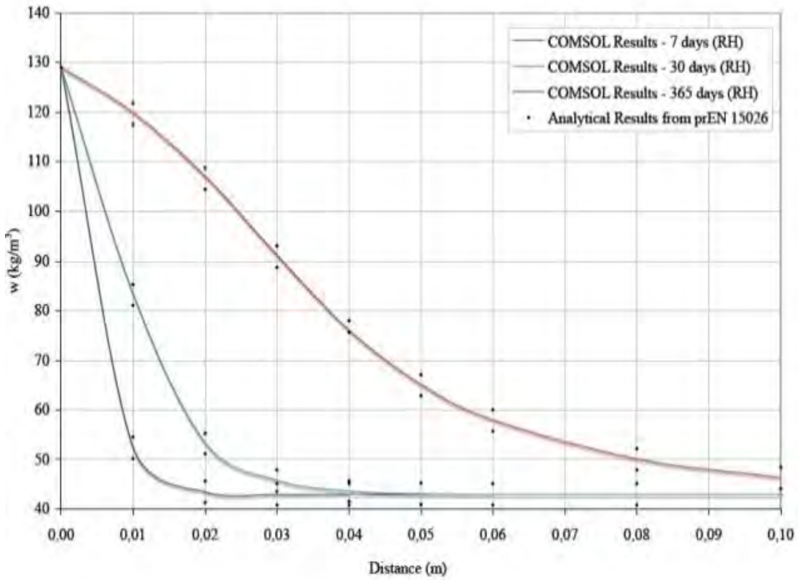


Verification
Moisture

LPc based model

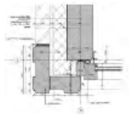
RH based model





Thanks to: Natalie Williams Portal (visit today, 4:00-5:30, Silchersaal)

Computational Building Physics
Heat+Moisture+Air

Topic / Scale	Heat	Moisture	Air	Stress
~ mm 				
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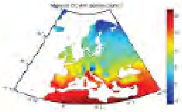
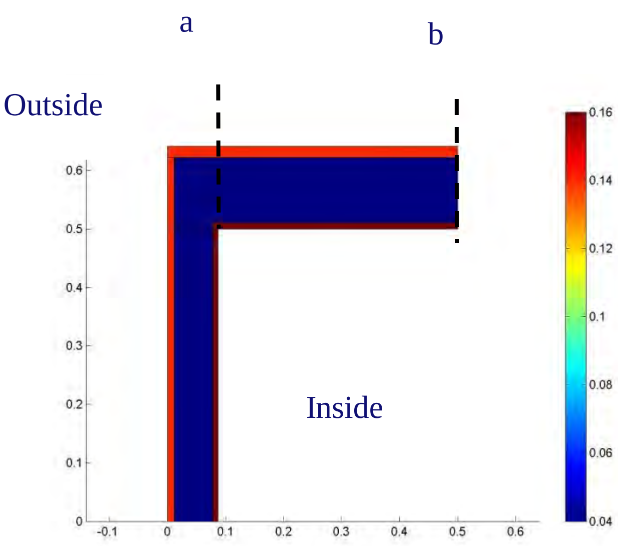
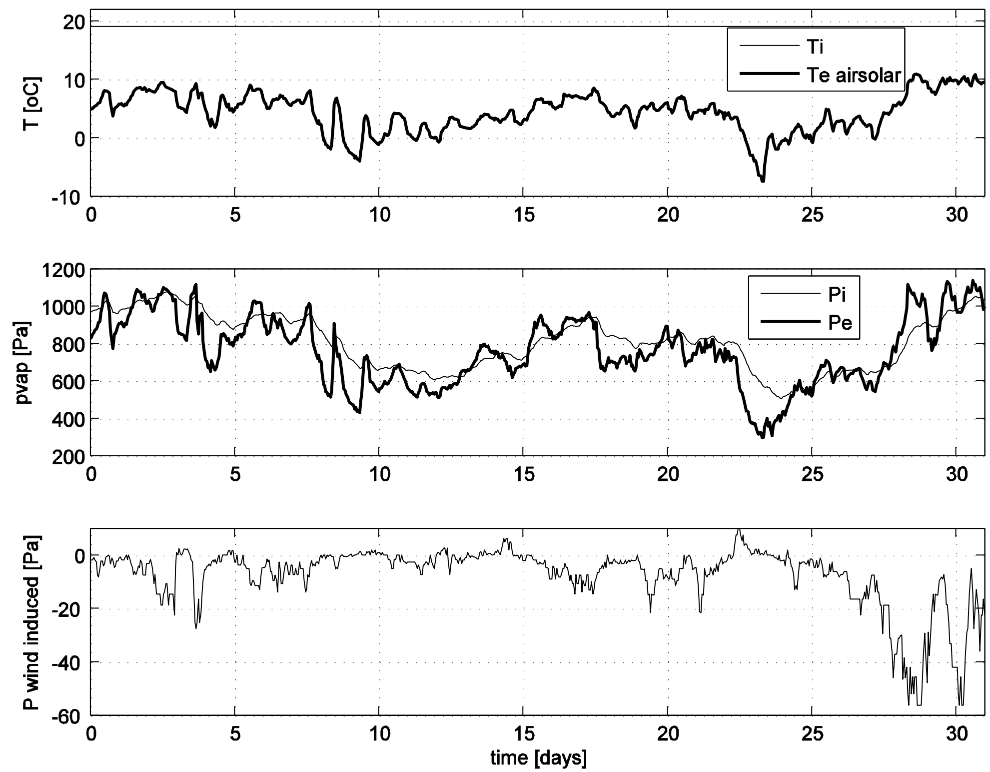
~ Mm 				

Application 3 HAM modeling
Influence of micro air movement





HAM modeling
Physics

PDEs

$$Heat: \rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-\lambda \nabla T) + \rho C_p \mathbf{u} \cdot \nabla T = 0$$

$$Air: \frac{\partial P}{\partial t} + \nabla \cdot (-K \nabla P) = 0; \mathbf{u} = K \nabla P$$

$$Moisture: \frac{\partial p_v}{\partial t} + \nabla \cdot (-D \nabla p_v) + \mathbf{u} \cdot \nabla p_v = 0$$

Boundary values

$$\textbf{Heat}: \; Flux: \mathbf{n} \cdot (\lambda \nabla T) = h(T_{\text{inf}} - T); Insulation: \mathbf{n} \cdot (\lambda \nabla T) = 0$$

$$\textbf{Air}: \; Pressure: P = P_0; Insulation: \mathbf{n} \cdot K \nabla P = 0$$

$$\textbf{Moisture}: \; Flux: \mathbf{n} \cdot (D \nabla p_v) = \beta(p_{v\text{inf}} - p_v); Insulation: \mathbf{n} \cdot (D \nabla p_v) = 0$$

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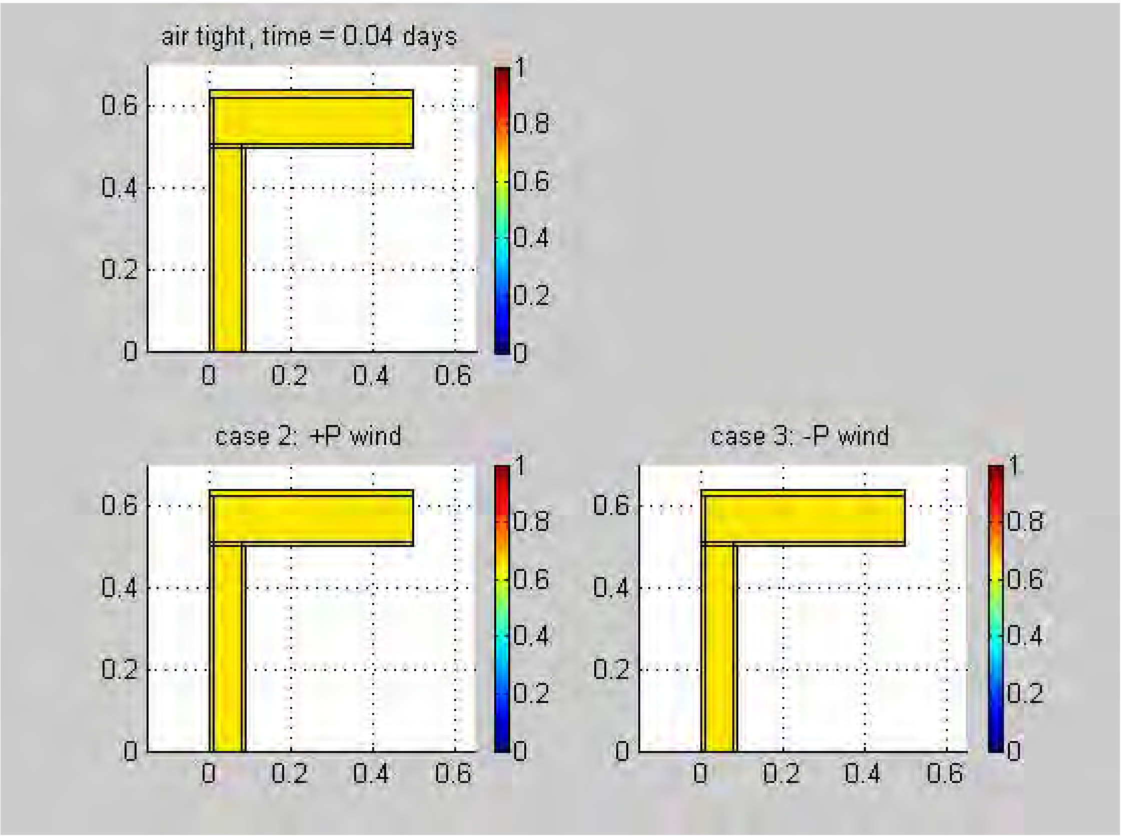
HAM modeling
Simulation of Relative Humidity

Air velocity

= 0



Air velocity

+10 µm /s

Air velocity

-10 µm /s

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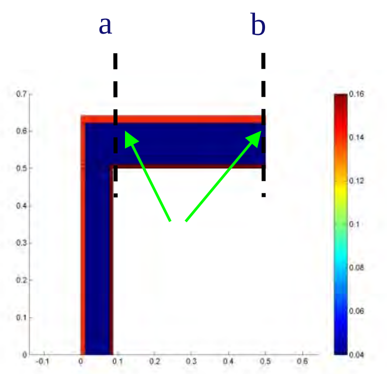
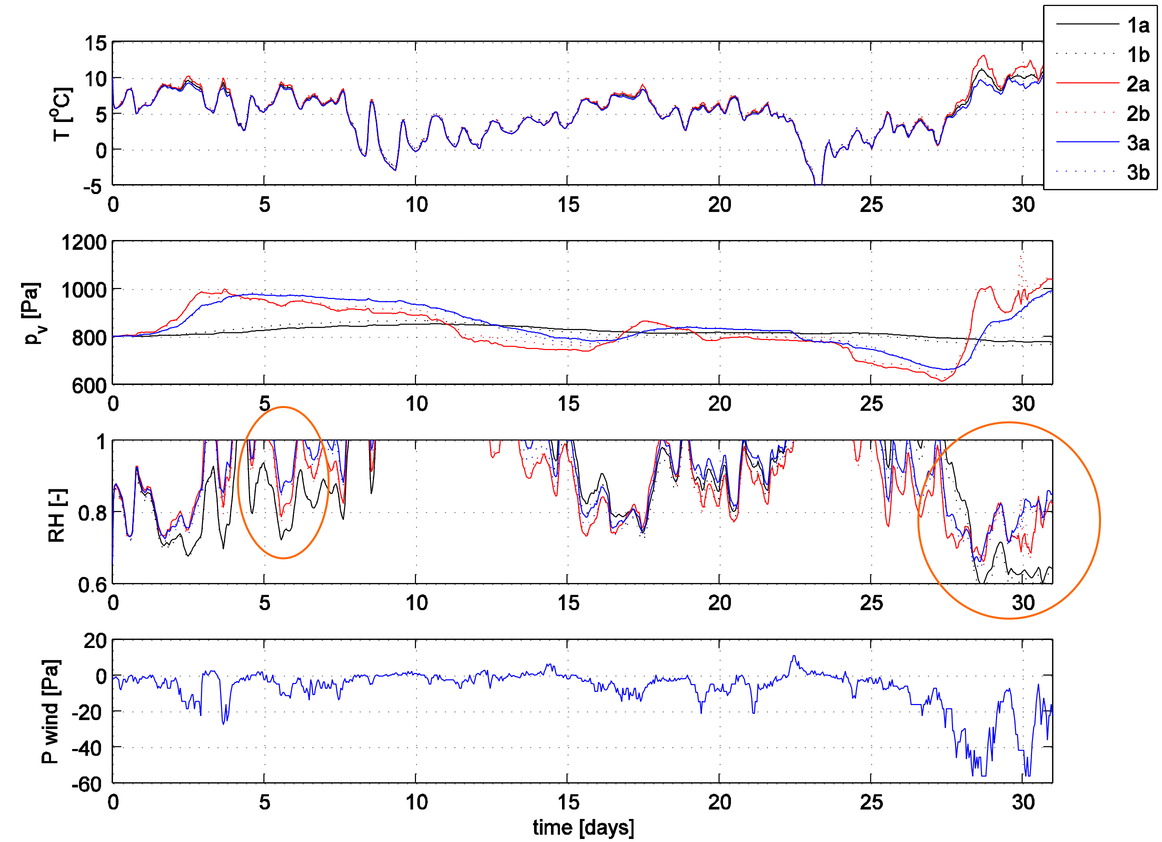
HAM modeling
Influence of micro air movement





Summary

A (so far immeasurable) low air movement of order 10^{-5} m/s seems to have significant impact on the RH

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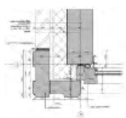
Computational Building Physics
Heat+Moisture+Air+Stress

Topic / Scale	Heat	Moisture	Air	Stress
~ mm 				
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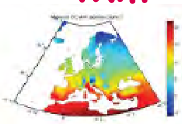
~ Mm 				

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Application 4 HAMS modeling
Including stress and strain

$$\rho c_p \frac{\partial T}{\partial t} = \nabla(k \nabla T) \qquad [1]$$

$$\frac{\partial Pv}{\partial t} = \nabla(D(Pv)\nabla Pv) \qquad [2]$$

$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{pmatrix} = \begin{pmatrix} \frac{1}{E_x} & -\frac{\nu_{xy}}{E_Y} & 0 \\ -\frac{\nu_{yx}}{E_x} & \frac{1}{E_y} & 0 \\ 0 & 0 & \frac{1}{G_{xy}} \end{pmatrix} \begin{pmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{pmatrix} + \begin{pmatrix} \alpha_x \\ \alpha_y \\ 0 \end{pmatrix} \Delta\theta + \begin{pmatrix} \kappa_x \\ \kappa_y \\ 0 \end{pmatrix} \Delta w \qquad [5]$$

where:
$\varepsilon_x \varepsilon_y$ = normal strain components [-]
γ_{xy} = shear strain component associated with two axis [-]
ν_{xy}, ν_{yx} = Poisson's ratio [-]
E_x, E_y = Young's moduli [N/m²]
G_{xy} = shear modulus [N/m²]
α_x, α_y = linear thermal expansivity [m/mK]
θ = temperature [°C]
κ_x, κ_y = linear deformation due to changes in moisture content [m/m(kg/m³)]
w = moisture content [kg/m³]

Thanks to: Zara Huijbregts (visit today, 4:00-5:30, Silchersaal)

Application 4 HAMS modeling
Including stress and strain

Figure 2. Cracks in a door of one of the cabinets

Figure 1. Exploded view of the construction of one cabinet door (Source: Rijksmuseum, Amsterdam)

Thanks to: Zara Huijbregts (visit today, 4:00-5:30, Silchersaal)

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Application 4 HAMS modeling
Including stress and strain

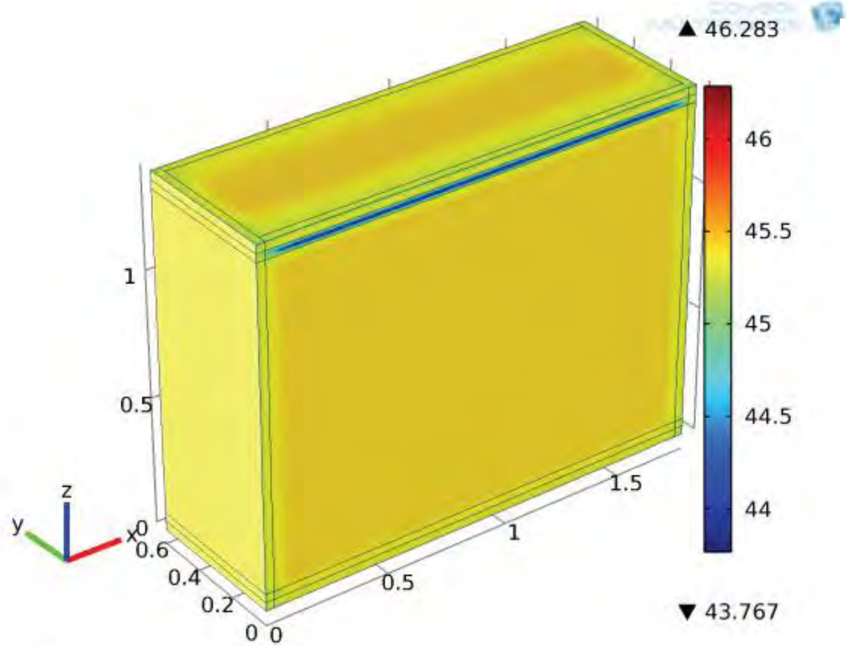


Figure 5. RH distribution over cabinet at t = 1000

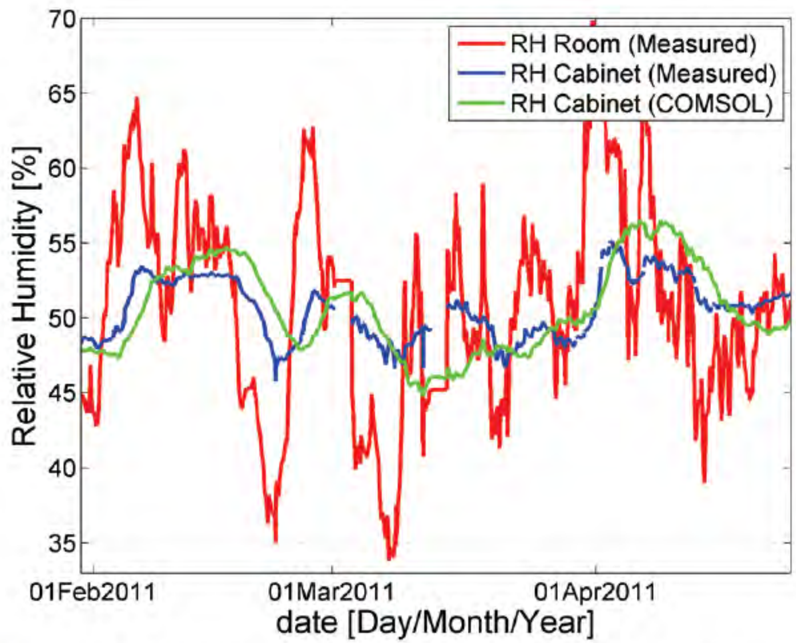


Figure 7. Comparison between measured relative humidity in castle and cabinet and simulated relative humidity in COMSOL

Thanks to: Zara Huijbregts (visit today, 4:00-5:30, Silchersaal)

Application 4 HAMS modeling
Including stress and strain

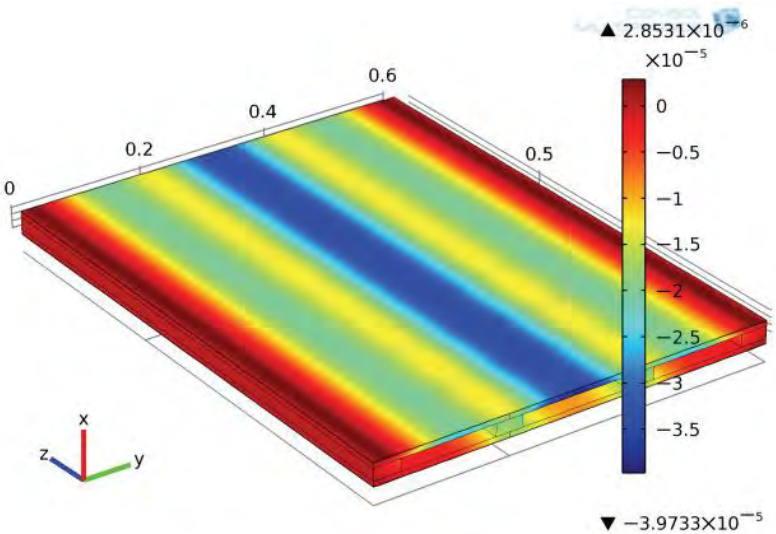


Figure 8. Predicted deformation at the external side of the cabinet door at t = 1000

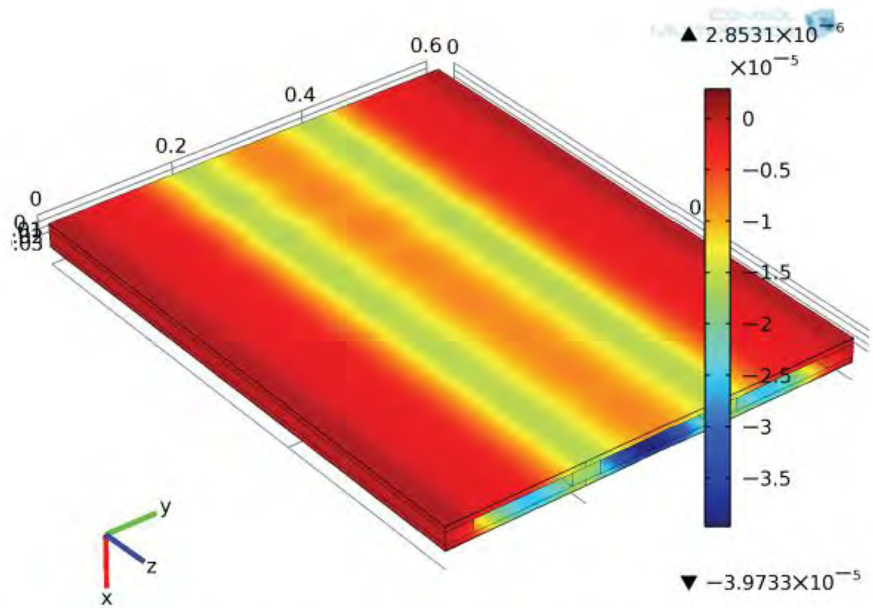
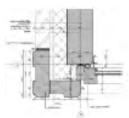


Figure 9. Predicted deformation at the internal side of the cabinet door at t = 1000

Thanks to: Zara Huijbregts (visit today, 4:00-5:30, Silchersaal)

Computational Building Physics
Heat, including Building Scale

Topic / Scale	Heat	Moisture	Air	Stress
~ mm 				
~ m 				
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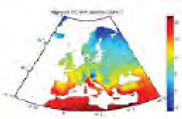
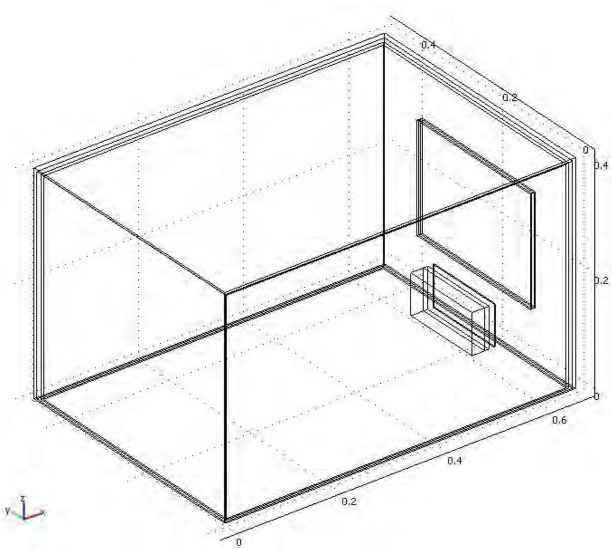
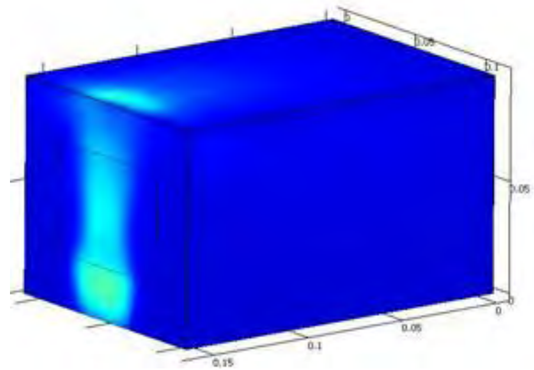
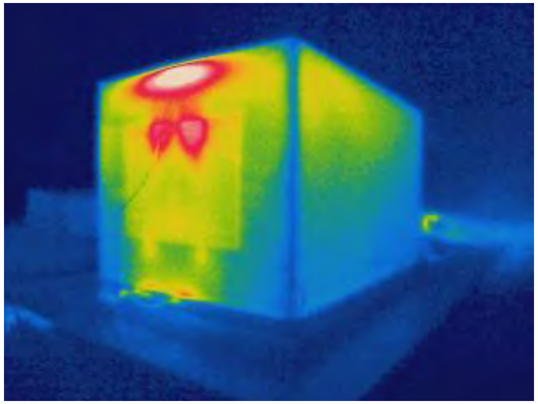
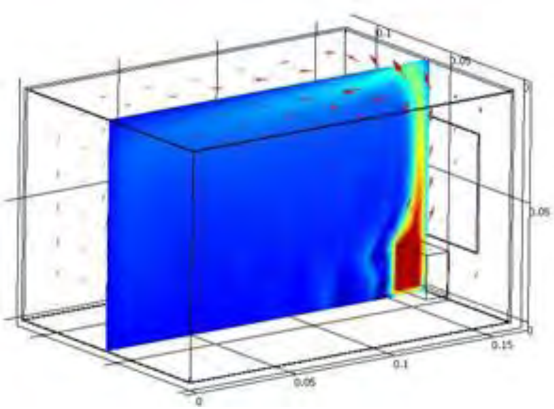
~ Mm 				

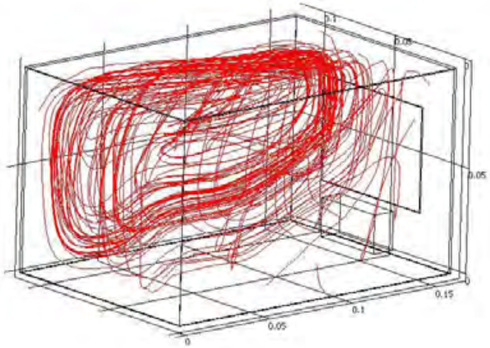
Application 5
Heat, including Building Scale











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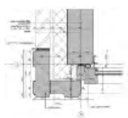
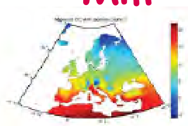
Computational Building Physics
Heat, including Urban Scale

Scale \ Topic	Heat	Moisture	Air	Stress
~ mm 				
~ m 				
~ km 				
~ Mm 				

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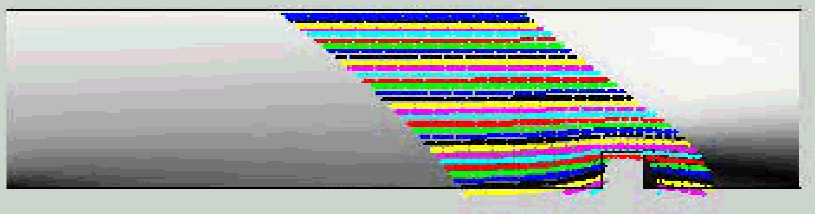
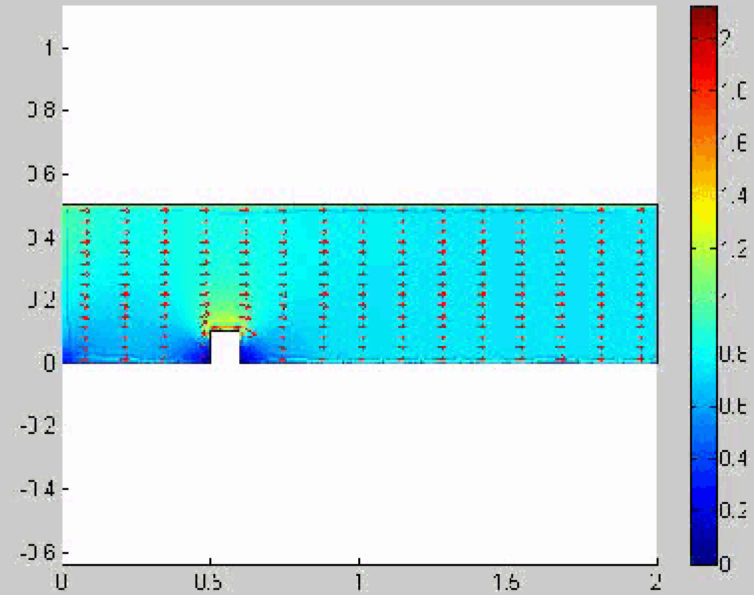
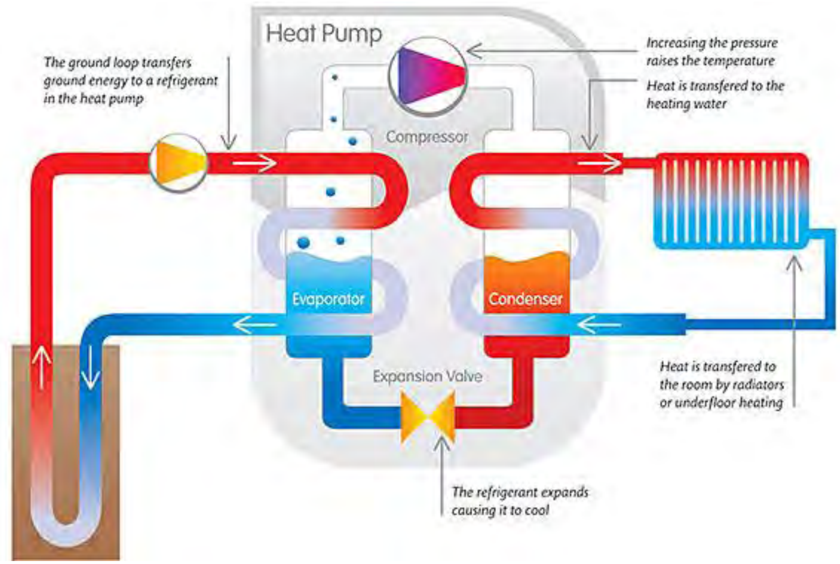
Application 6
Wind & driving rain at Urban Scale





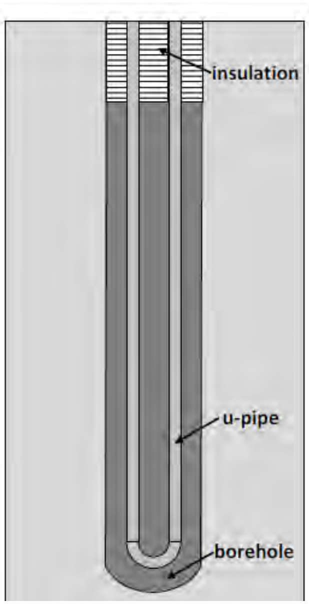
Application 7
Ground energy at Urban Scale

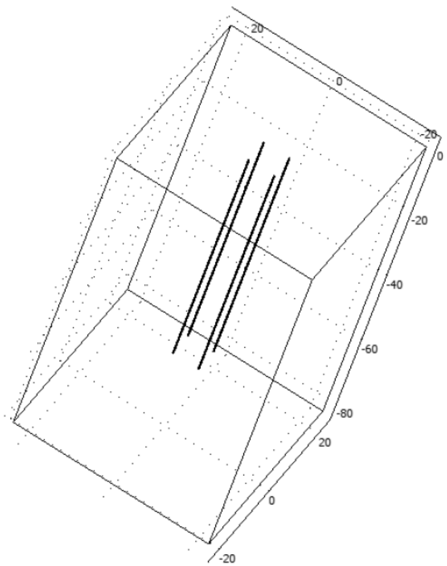
Figure 7.3 *Image and location of the Anatomy House in Göteborg (Microsoft, 2010).*

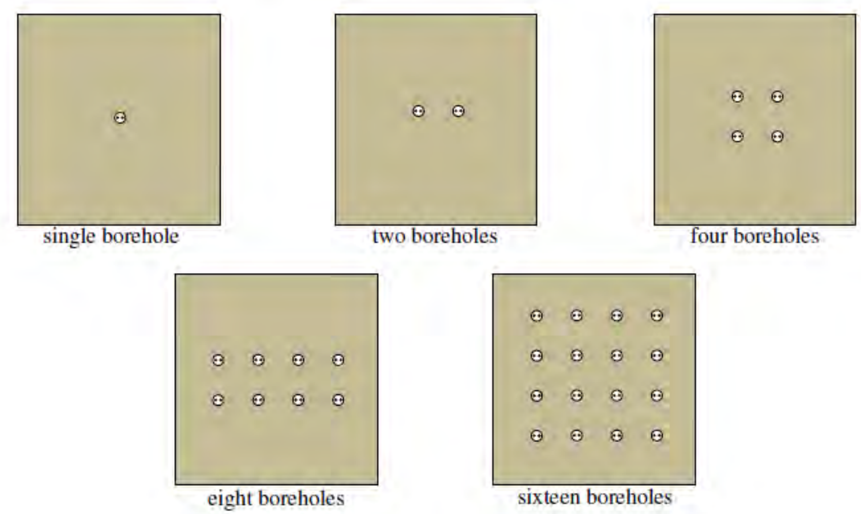


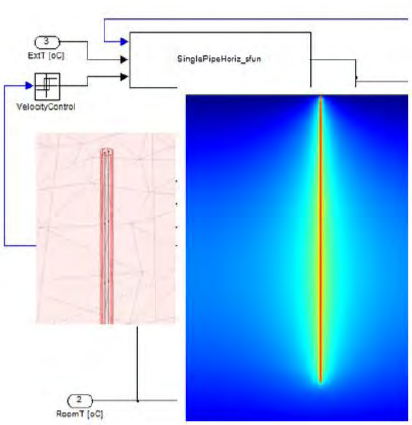
Thanks to: David van Reenen

Application 7
Ground energy at Urban Scale









Thanks to: David van Reenen

Application 7
Ground energy at Urban Scale

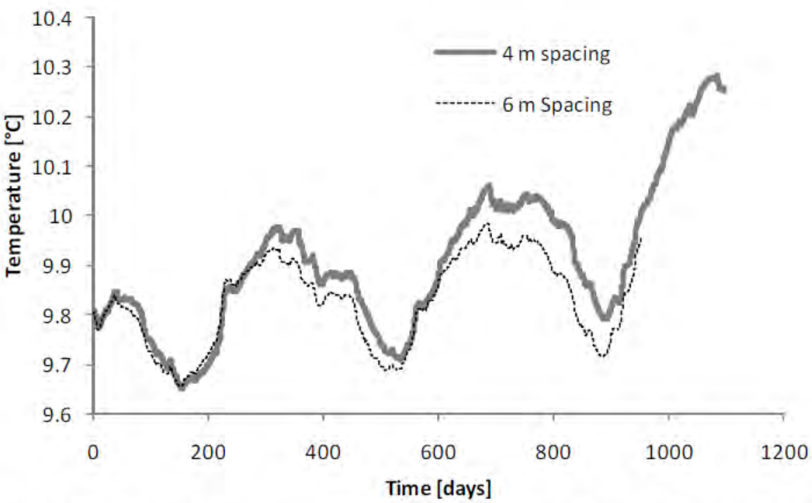


Figure 6.13 *Ground temperature at a distance of 2 m from the borehole for the Gothenburg simulations.*

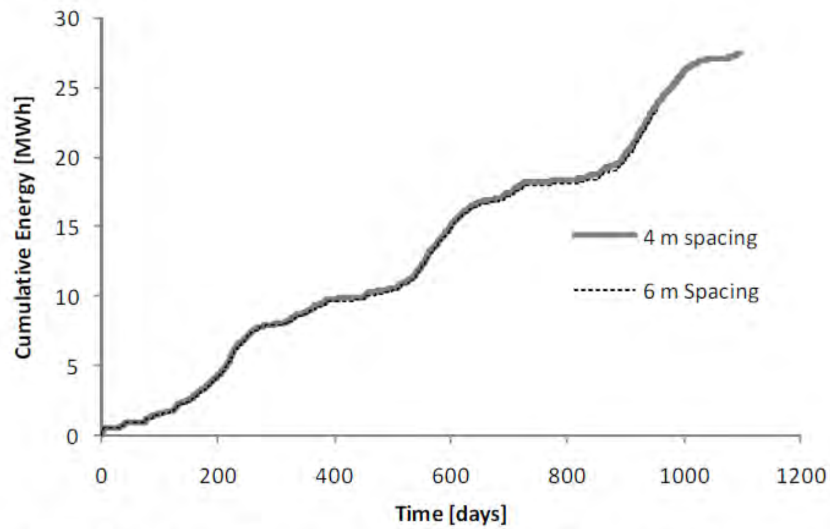
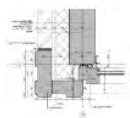
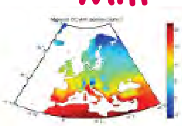


Figure 6.11 *Cumulative absolute energy supplied to the building zone for the Gothenburg simulations.*

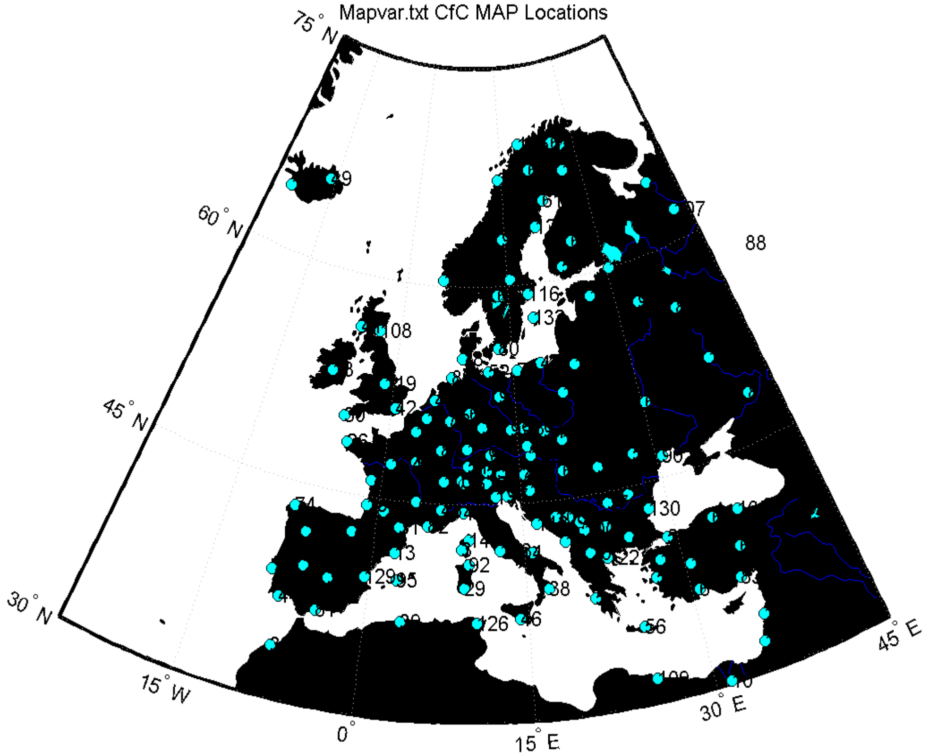
Thanks to: David van Reenen

Computational Building Physics
Heat, including EU Scale

Scale \ Topic	Heat	Moisture	Air	Stress
~ mm 				
~ m 				
~ km 				
~ Mm 				

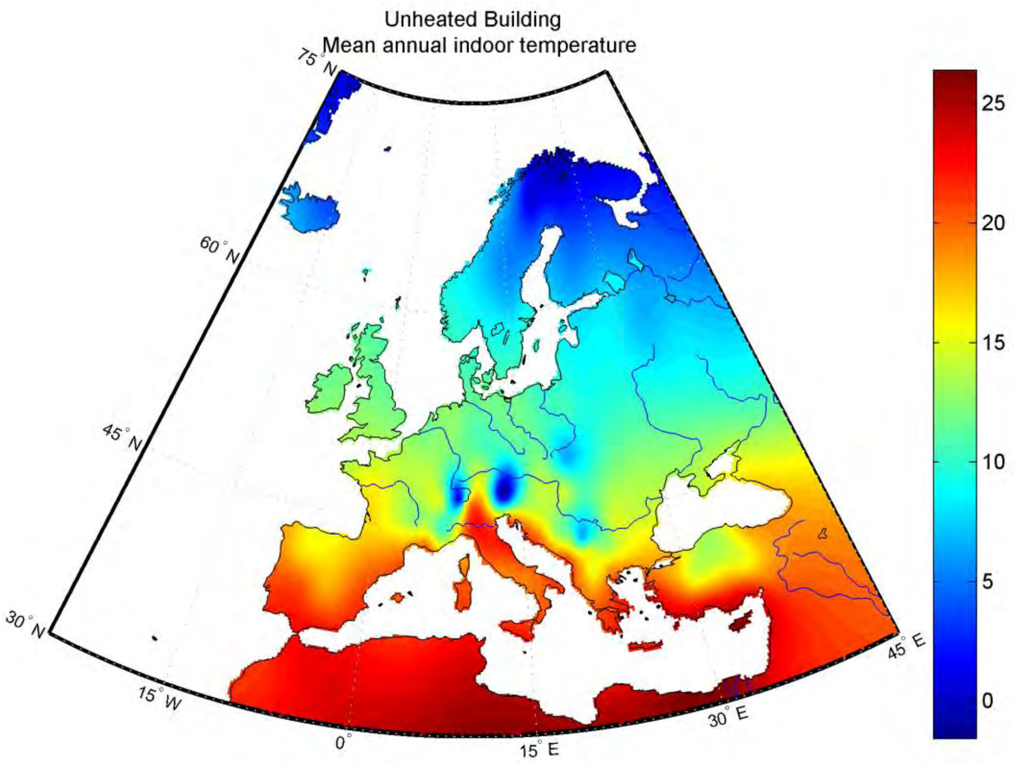
Application 8
Incorporate EU Scale

- **Weather Stations**
- **Used as boundary values for the external climate**



Application 8
Incorporate EU Scale

- Subject building constructions to external climates
- Map performances



Conclusion

- COMSOL is a state-of-art Multiphysics modeling tool for doing research in the area of building physics
- High performance on
  - 1,2 & 3D capabilities
  - Grid & solvers techniques
  - Visualization
  - Flexibility due to PDE abstraction level
- Also an excellent tool for education
- Our models are available at http://sts.bwk.tue.nl/hamlab/

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- **Thank you**

- **Questions?**