



NUMERICAL SIMULATION OF HEAT- AND MOISTURE TRANSPORT IN CAPILLARY-POROUS BUILDING MATERIALS

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The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 260162



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Basics of simulation software DELPHIN



Basic of simulation



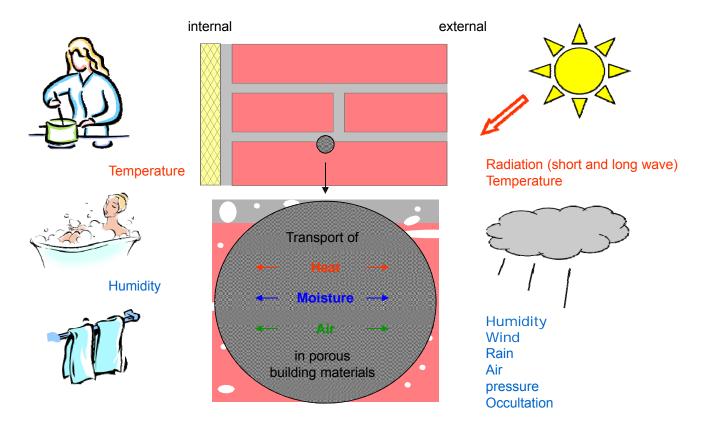
- Transient
 - Usage of dynamical boundary conditions (external und internal climate)
 - Thermal and hygric inertia of construction is considered
- Hygro-thermal
 - Heat conductivity and storage
 - Moisture transport (vapour and capillary conductivity) and moisture storage
- Building elements
 - Materials and systems/constructions
 - Constructional details
- Simulation
 - For analysis (expertises) and prediction (feasibility study/optimisation)



Basic of simulation



Transient transport processes in capillary-porous building materials





Basic of simulation



Basic knowledge for the use of simulation software

- Material properties
- Conserved quantity
- Transport processes
- Initial conditions
- Boundary conditions
- Mathematical method
- Space discretisation
- Time steps Precision

Physical state equations

Numerical solving method





Part 1

Physical basic equations and models



Mathematical basics and nomenclature

Einsteins' summation rule:

 $j_k = \sum_k j_k$ Usage of direction index implicates sigma sign

For cartesian coordinate systems:

Usage for partial derivative:

<u>k</u>	$= \underline{x}, \underline{y}$	', <u>Z</u>	
∂	$_\partial$	∂	∂
∂x_k	∂x	∂y	∂z

Example:

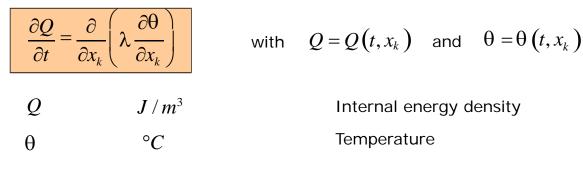
$$\frac{m = m(t, x_k)}{\frac{\partial m}{\partial x_k} = \frac{\partial m}{\partial x} + \frac{\partial m}{\partial y} + \frac{\partial m}{\partial z}}$$

Conserved quantity is defined in dependency of time and space

Partial derivatives are summed



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Change of internal energy in time (only heat storage):

$$\frac{\partial Q}{\partial t} = \rho_{dry} c_T \, \frac{\partial \theta}{\partial t}$$

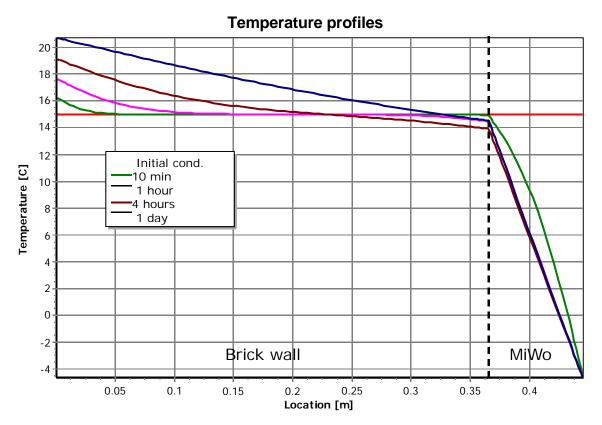
Important material parameter:

$ ho_{dry}$	kg / m^3	Density of dry materials
c_T	<i>J</i> /	Specific heat capacity
λ	kgK	Heat conductivity
	J / smK = W / mK	



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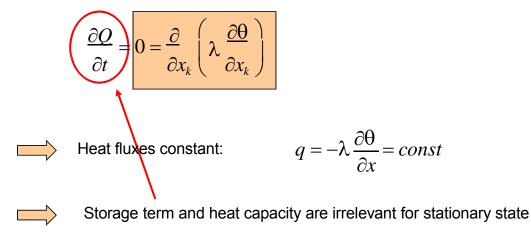






Transient heat conductivity - till achievement of steady-state conditions

Steady-state conditions = no change of conservation quantities in time anymore



At transient processes the storage term controls how quick the system responses to boundary conditions:

- high heat capacity slow achievement of stationary conditions
- low heat capacity

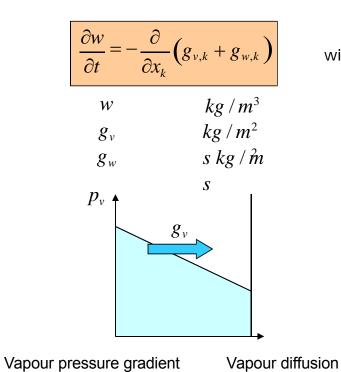
- quick response



Beficient energy for eu cultural heritage

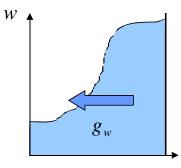
Physical basic equations and models

Water mass balance (transient conservation equation for moisture in building components):



with
$$w = w(t, x_k)$$

Water mass density Vapour flux density Capillary water flux density



Water content difference

capillary conductivity





$$\frac{\partial \rho_g}{\partial t} = -\frac{\partial}{\partial x_k} \left(g_{gc,k} + g_{gg,k} \right)$$
$$\frac{\rho_g}{g_{gc}} \frac{kg / m^3}{kg / m^2 s}$$
$$\frac{g_{gg}}{kg / m^2 s}$$

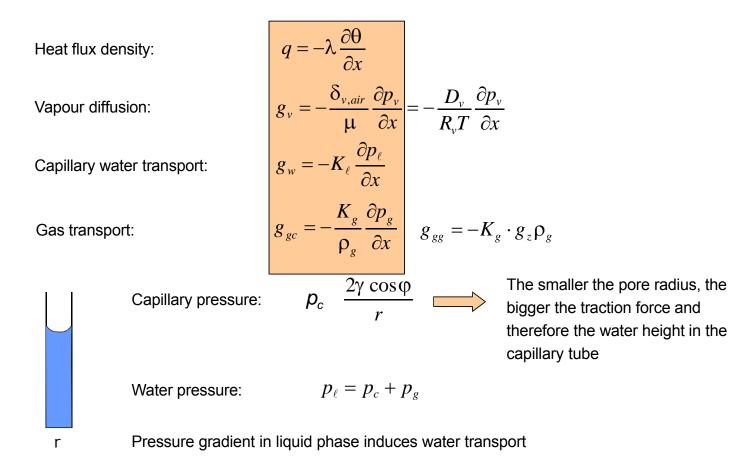
with
$$\rho_g = \rho_g(t, x_k)$$
 and $\rho_g = \rho_g(T, w, p_g)$

Gas density Convective gas flux density Gas flux density due to gravity



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Transport processes and models





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Transport processes and models Evaporative cooling and heat of condensation

Specific enthalpy of water vapour:

Specific enthalpy of water:

 h_{ν}

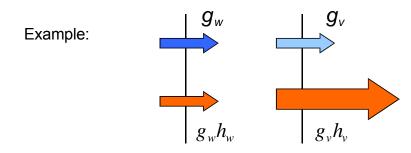
Evaporation enthalpy:

$$h_{v} = c_{T,v} \left(T - T_{Ref} \right) + H_{evap}$$
$$h_{w} = c_{T,w} \left(T - T_{Ref} \right)$$

 $H_{evap} = 3.08 \cdot 10^6 \text{ J/kg}$

 h_{w} Enthalpy transport of water vapour is much bigger than of liquid water!

although $c_{T,w} \square 2c_{T,v}$





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Summary

Conservation equations

Moisture mass balance:

$$\frac{\partial w}{\partial t} = -\frac{\partial}{\partial x_k} \left(g_{v,k} + g_{w,k} \right)$$
Energy balance:

$$\frac{\partial Q}{\partial t} = -\frac{\partial}{\partial x_k} \left(q_k + h_v g_{v,k} + h_w g_{w,k} \right)$$

En

Solution of equations

Initial conditions (one for each conservation equation), e.g.:

 T, ϕ or T, w

Boundary conditions (types):

Neumann (2 nd)	Describes fluxes from surroundings into construction, z.B. radiation heat flux, Vapour diffusion flux
Dirichlet (1 st)	Describes boundary values , e.g. surface temperature
Cauchy (3 rd)	Describes fluxes and boundary values



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Summary

Material parameters and material functions

 $\begin{array}{ccc} \text{General parameter:} & kg \ / \ m^3 \\ c_T & J \ / \\ & kgK \\ \text{Transport parameter:} \\ \lambda & W \ / \ mK \end{array}$

μ	_
\pmb{K}_ℓ	S

Moişture s	storage parameter: kg / m
$w(p_c)$	kg / m^3
$w(\phi)$	kg / m^3

Density of dry material Specific heat conductivity

Heat conductivity Water vapour diffusion resistance value Liquid water conductivity

Moisture retention curve (MRC) Sorption isotherm





Part 2 The numerical solving method





Control volume method

Used to transform partial differential equations into systems of ordinary differential equations

Analytic derivation using the example of heat conduction equation:

1. Transformed original equation:

- $\frac{\partial U}{\partial t} + \frac{\partial}{\partial x_k} (q_k) = 0$
- 2. Multiplied with function: $\omega \cdot \left[\frac{\partial U}{\partial t} + \frac{\partial}{\partial x_k} (q_k) \right] = 0$
- 3. Integrated over a volume:

$$\int_{V} \omega \cdot \left[\frac{\partial U}{\partial t} + \frac{\partial}{\partial x_{k}} (q_{k}) \right] = 0$$

$$\int_{V} \omega \cdot \left[\frac{\partial U}{\partial t} + \frac{\partial}{\partial x_{k}} (q_{k}) \right] dV = 0$$

Presumptions/preconditions:

$$w = const$$
 (= 0-order FEM)

and

$$\int_{V} \frac{\partial U}{\partial t} \, dV \, \Box \, \frac{\partial U}{\partial t} \, V$$





Control volume method

Analytic derivation using the example of heat conduction equation:

4. Equation transformed/simplified:

$$\frac{\partial U}{\partial t} = -\frac{1}{V} \int_{V} \frac{\partial}{\partial x_{k}} (q_{k}) dV$$

$$\frac{\partial U}{\partial t} = -\frac{1}{V} \prod_{A} \bar{n}_{k} A_{k} \bar{q}_{k} dA$$

5. Gauss-Green-Theorem:

6. Application for discrete areas:

$$\frac{\partial U}{\partial t} = -\frac{1}{V} \sum_{i} \vec{n}_{i} A_{i} \vec{q}_{k,i}$$

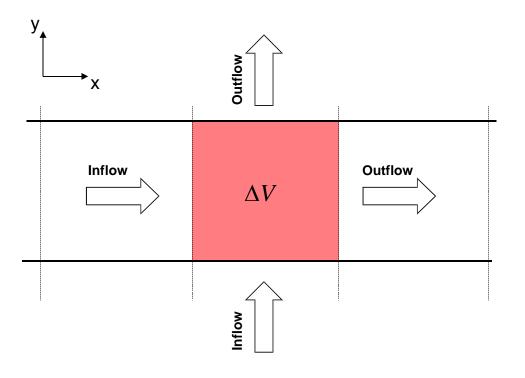
Example: 1D $\frac{\partial U}{\partial t} = \frac{1}{V} \left[A_l q_l - A_r q_r \right]$ $\frac{\partial U}{\partial t} = \frac{1}{\Delta x} \left[q_l - q_r \right] \quad \text{with the}$

with the borders of the volume
$$I = left$$
, $r = right$





Balancing of conserving quantities (mass + energy)



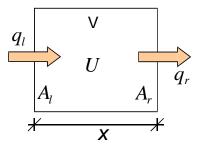
Change of density in the discrete volume = Difference between inflow and outflow





Control volume method

Derivation at concrete example:



Change of absolute conservation quantities per time = difference of fluxes

$$\Delta U \cdot V = \Delta t \left(A_l q_l - A_r q_r \right) \qquad \text{at which } A_l = A_r = A \quad \text{and} \quad V = \Delta x A$$

$$\text{ce} \qquad \frac{\Delta U}{\Delta t} = \frac{A}{V} \left(q_l - q_r \right) \qquad \text{and} \qquad \frac{\Delta U}{\Delta t} = \frac{1}{\Delta x} \left(q_l - q_r \right)$$

hence

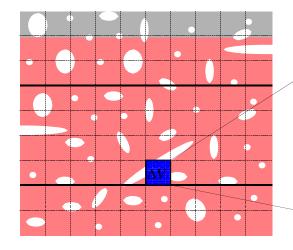
and for infinitesimal time steps:

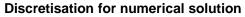
$$\frac{\partial U}{\partial t} = \frac{A}{V} \left(q_l - q_r \right)$$



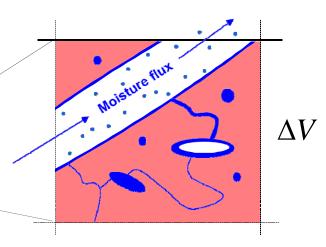


Discretisation





Material macroscopically homogenous Isotropic transport properties Properties of volume elements, representative for the material



Definition of local state variables

- θ_{i} Water content
- T Temperature
- *φ Relative humidity*
- p_v Vapour pressure
- *p_c Capillary pressure*





Discretisation of partial derivation

Example: Heat fluxes between control volumes

$$f(x + \Delta x) = f(x) + \Delta x \frac{\partial f}{\partial x} + \frac{\Delta x^2}{2!} \frac{\partial^2 f}{\partial x^2} + \frac{\Delta x^3}{3!} \frac{\partial^3 f}{\partial x^3} + \dots$$

Estimation of 1. derivation of function (with fault 2nd order):

$$\frac{\partial f}{\partial x} = \frac{f(x + \Delta x) - f(x)}{\Delta x} + O(2)$$



Discrete formulation of heat flux Density between control volumes:

$$q_k = -\lambda \frac{\Delta \theta}{\Delta x_k}$$

 $q_k = -\lambda \frac{\partial \theta}{\partial x_k}$

Alexandra Troi - CNA Trasformare il costruito - Numerical simulation





Numerical solving methods at a glance

$$\frac{\partial U}{\partial t} = -\frac{\partial}{\partial x_k} \left(\lambda \frac{\partial \Theta}{\partial x_k} \right)$$

+ Control volume method + Discretisation of partial derivations = System of ordinary differential equation (one equation per control volume and conserving quantity)

e.g. 1D heat condductivity equation

$$\frac{\partial U_i}{\partial t} = \frac{1}{\Delta x_i} \left(\lambda_{i-1/2} \frac{\theta_{i-1} - \theta_i}{\Delta x_{i-1/2}} - \lambda_{i+1/2} \frac{\theta_i - \theta_{i+1}}{\Delta x_{i+1/2}} \right)$$

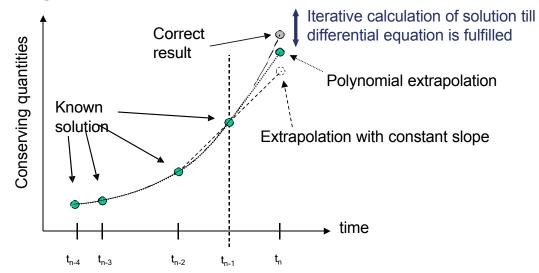




Numerical solution Discretised differential equation (example: moisture mass balance)

$$\frac{\partial w}{\partial t} = -\frac{1}{\Delta V} \left[\sum_{A} \left(g_{vapour} + g_{liquid} \right)_{A} \right]$$

Numerical Integration







Numerical solving methods at a glance

2 balance equations * n elements = number of equations & unknowns

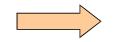
Vector with unknowns: $\mathbf{y} = \{Q_i, w_i\}$

System of differential equations:

$$\frac{\partial \mathbf{y}}{\partial t} = \mathbf{f}(t, \mathbf{y})$$

Solution of equation systems by time integration:

$$\mathbf{y}(t) = \mathbf{y}_0 + \int_t \mathbf{f}(t, \mathbf{y}) \, dt$$



Simulation software DELPHIN





Application of Delphin

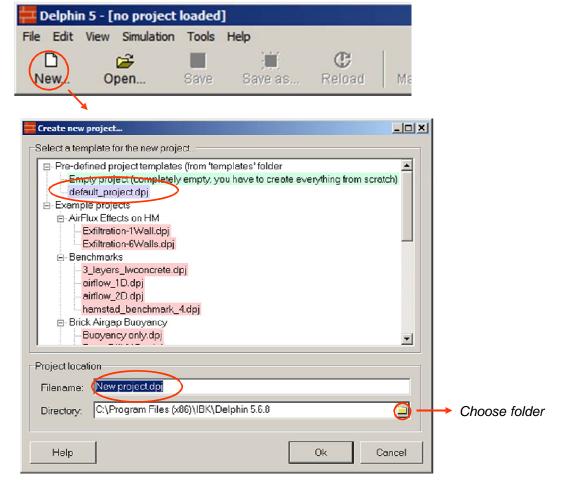




Steps - New Project

- Open new project template
- Choose memory location of the project
- Delphin project name

DELPHIN opens a standard template (*.dpj).





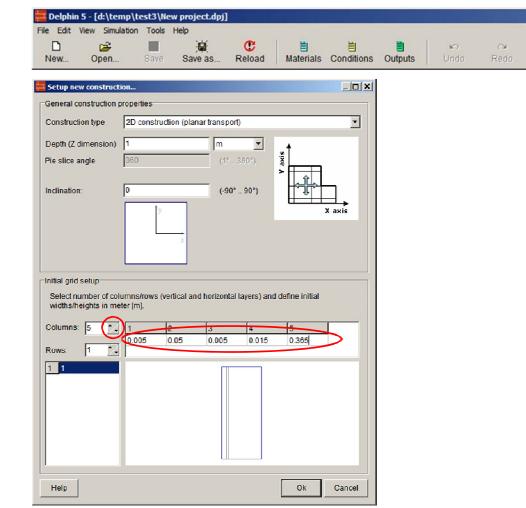
Steps - Construction

- Define type of construction, here: 1D horizontal
- Adjust number of material layers in x-direction
- Adjust thickness of different layer in [m]

Only transport in x-direction:

The height (y-direction) und depth (z-direction) should be 1 m to calculate a wall area of 1m².

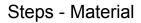
DELPHIN then opens the construction view and shows the succession of layers – initially without materials.



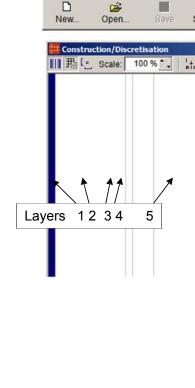




Sim...



- Import material
- Choose program or user data base
- Choose import modus
- Choose material and import it



File Edit View Simul

DELPHIN shows the imported materials in the material list.



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Edt Man Chudakan Taala



- Mark material and favoured layer
- Click on green assign button

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			No Material
			1 Historical Brick Cluster
			2 Calciumsilicate
			 Adhesive Covering Plaster Lime Cement Plaster (Transputz SG)
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			L.

DELPHIN generates a material assignment data set and colours layers with material assignment corresponding to the colour of the material.



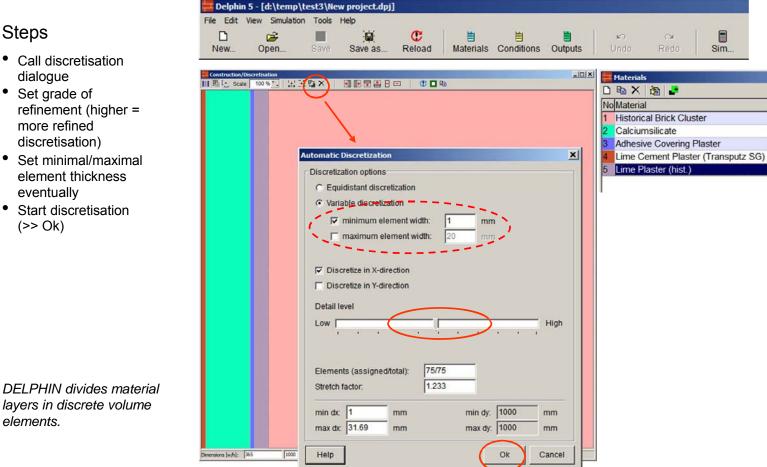
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EFFICIENT ENERGY FOR EU CULTURAL HERITAGE

Steps

- Call discretisation dialogue
- Set grade of refinement (higher = more refined discretisation)
- Set minimal/maximal element thickness eventually
- Start discretisation (>> Ok)

elements.





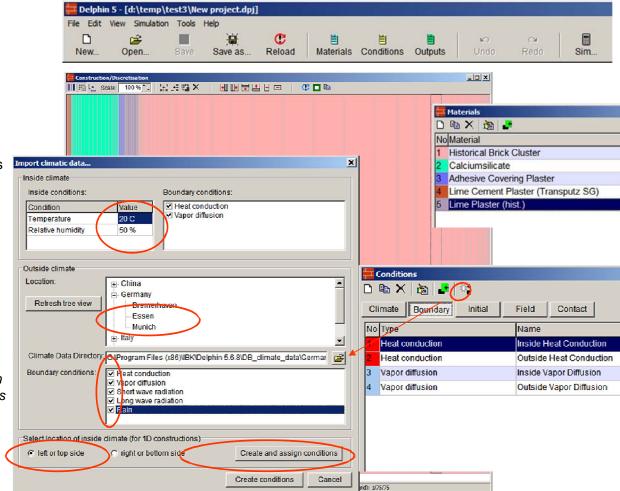
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EFFICIENT ENERGY FOR EU CULTURAL HERITAGE

Steps - Climate

- Import climate conditions
- Adjust internal and external climate data
- Import and assign boundary conditions data sets

DELPHIN shows the imported climate and boundary conditions in the conditions windows and enables the assignment to the construction.





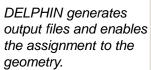
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Delphin 5 - [d:\temp\test3\New project.dpj]

Steps - Outputs

- Start Outputs-Wizard
- Deactivate VOCoutputs, activate water content
- Generate and assign output files

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EFFICIENT ENERGY FOR EU CULTURAL HERITAGE

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Steps - Simulation

- Open modelling and simulation properties
- Define starting point and total duration of simulation

Modeling/Simulat Solver settings. Solver settings. Pallutant/VOC sin Output related o m Run Simulation Run batch file ling and Simulation Settings del features Defaults alance equations	nulation opti ptions	-	Mate		Dendition
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DELPHIN: Program operation



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Steps – Simulation-	2	Lime Plaster (hist.) Historical Brick Cluster
	art simulation X Solver settings Solver: External Solver (standard) Solver parameters	
	Start options Verbose Level: 1 - Normal output (detailed init + output time) Run options: Test init Close console window after finishing simulation Wait after each output Command line:	Assignment Info
DELPHIN starts the numeric solver in a	*\$(INSTALL_DIR)/delphin_solver.exe* -v1 *d:\temp\test3\New project.dpj* Add to batch file Run simulation from start ntinue simulation Check simulation log files Help	Name Historical Birck Cluster Selection type Material Condition type Selected range 40,1 – 75,1 Location ELEMENT Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Computer Compute
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DELPHIN: Program operation

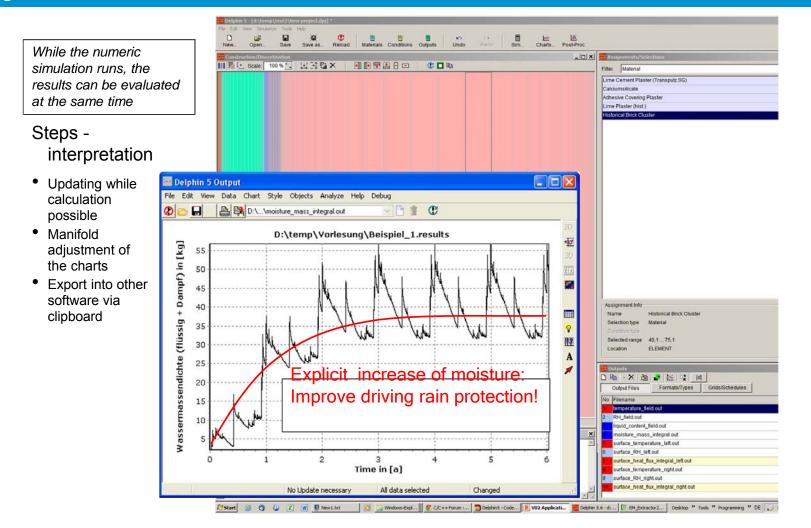


While the numeric simulation runs, the results can be evaluated at the same time	IS-[dt]temp[tist3]Menu penject.dp] * Vern Snuktion: Tools felo OpenSave Save xaReload Materials Conditions Or pcben/(Depochestion Coate: 100 % ↓↓	tiputs Undo Redb Sim. Charts Post-Proc C ■ Ra	
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DELPHIN: Program operation



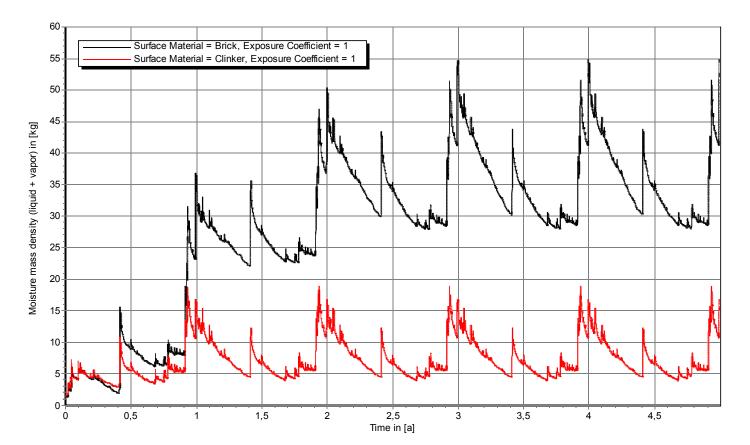




DELPHIN: results



Different materials



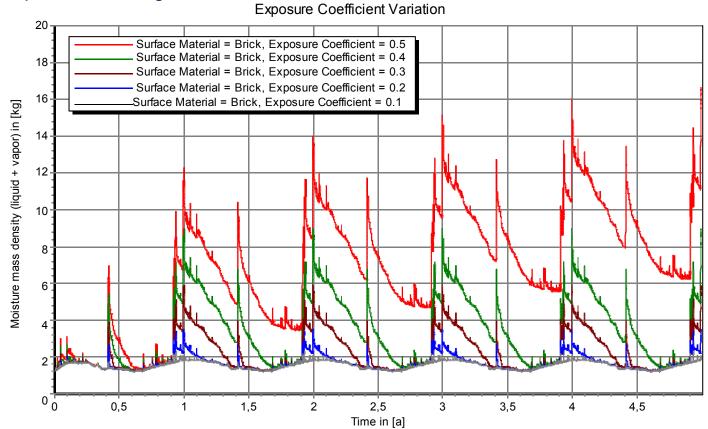
Surface Material Variation



DELPHIN: results



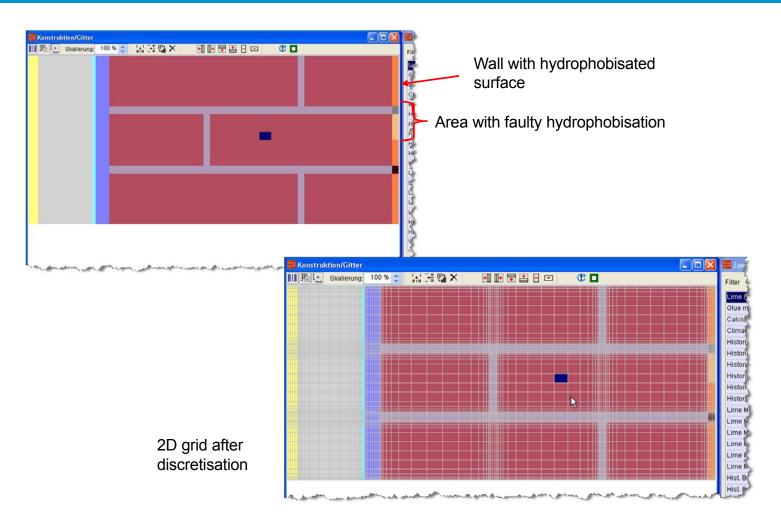
Rain protection/roofing:





DELPHIN – Analysis of 2D problems

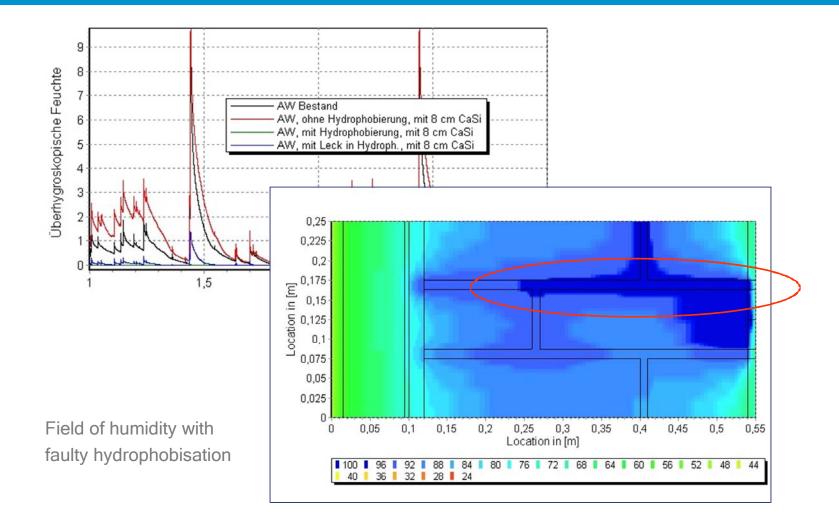






DELPHIN – Analysis of 2D problems

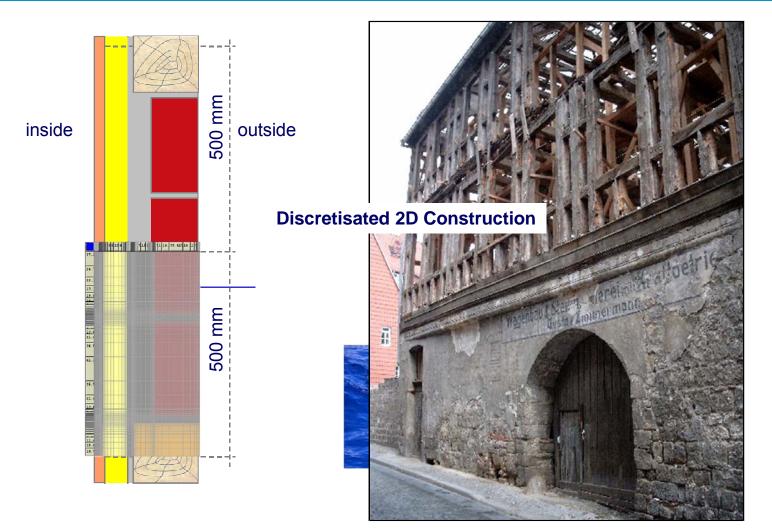






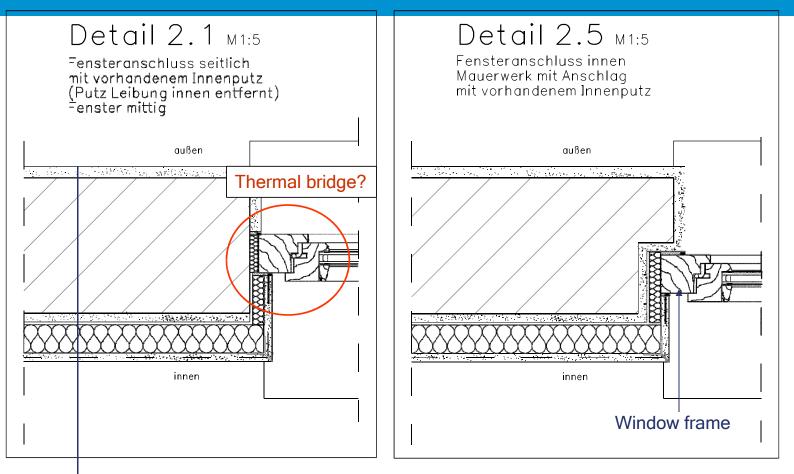
Rehabilitation and Building in older housing stock







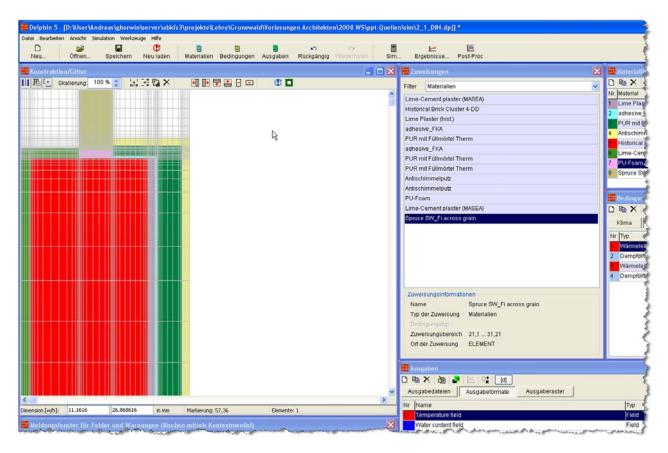




- Plaster, Brick, Plaster, Glue mortar, Insulation, Plaster





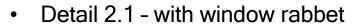


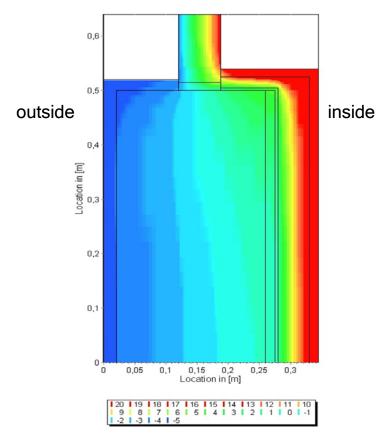


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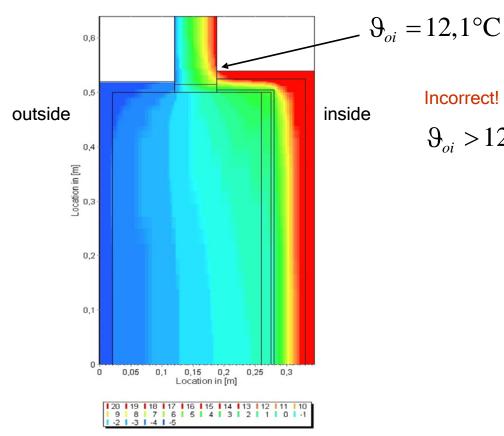








Detail 2.1 - without window rabbet •



Incorrect! DIN 4108-2 demands:

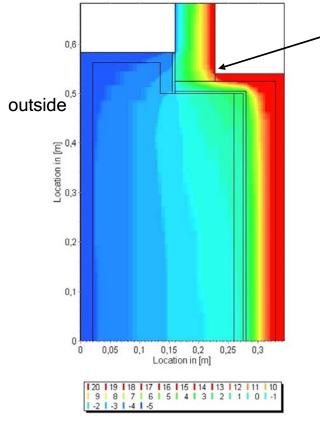
$$\vartheta_{oi} > 12, 6^{\circ}C$$



• Detail 2.5 - with window rabbet

Sencult EFFICIENT ENERGY FOR EU CULTURAL HERITAGE

 $\vartheta_{oi} = 13,8^{\circ}C$ Ok, thermal protection fulfilled.



inside

Minimum thermal protection of the guideline ensures, that the dew point temperature resp. minimum pretensions for mould are not reached or exceeded (e.g. on wallpaper).

What about the internal condensate?





· Critical moisture content: Condensation and drying behaviour

