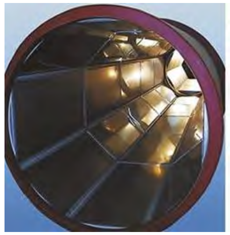
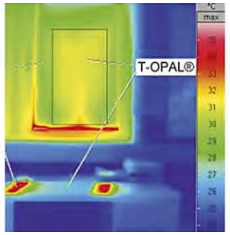
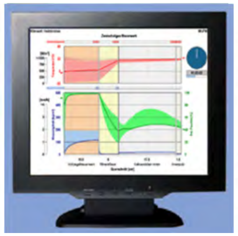
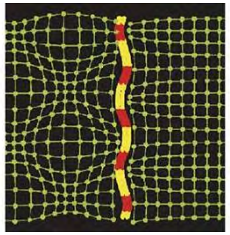



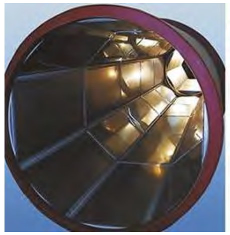
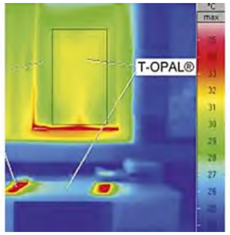




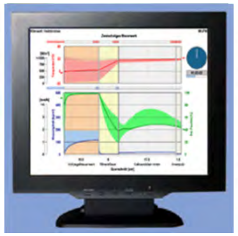
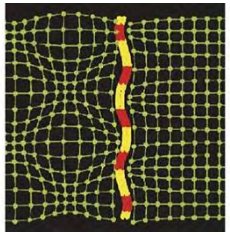

19th Annual Westford Symposium on Building Science

Bavarian Castles and all the know-how and the tools you need for that

Hartwig M. Künzel and Florian Antretter
(Fraunhofer Institute for Building Physics)

Fraunhofer IBP


19th Annual Westford Symposium on Building Science

Moisture control design by hygrothermal simulation

Hartwig M. Künzel
(Fraunhofer Institute for Building Physics)

Fraunhofer IBP

Moisture control design by hygrothermal simulation

Contents

Introduction

Moisture problems

Moisture loads

Standards and guidelines

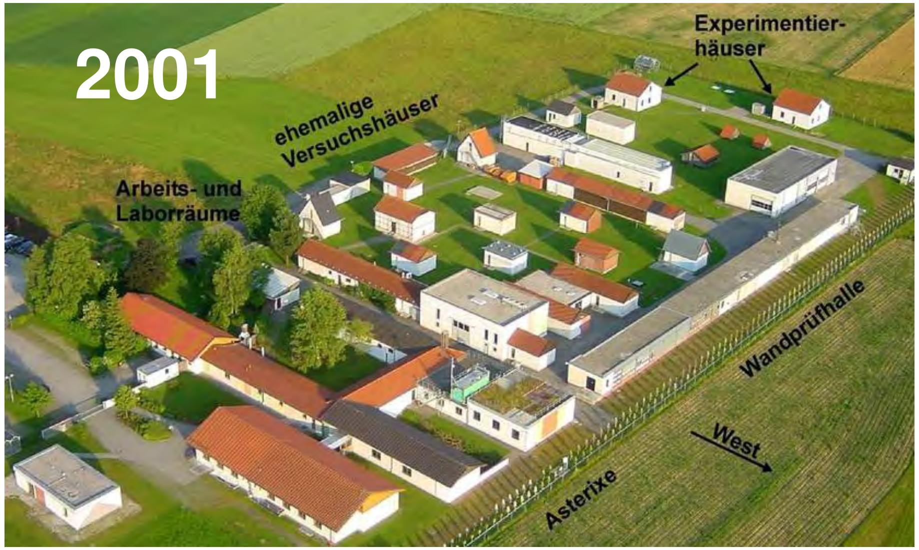
Hygrothermal simulation

Conclusions

Introduction

IBP field test site in Holzkirchen

60 years of field tests
= long-term durability observation



Fraunhofer IBP

Introduction

Measure-
ments help
to validate
calculations

Introduction

<u>Green roof investigation</u>

Water retention is good for the environment but not always for the building

Introduction

VERU test building to determine energy consumption required to meet comfort conditions

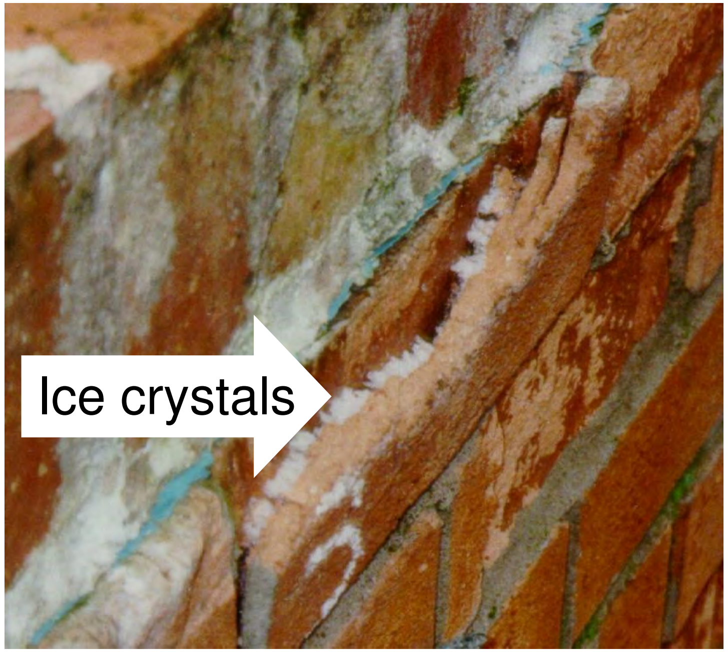
Moisture problems

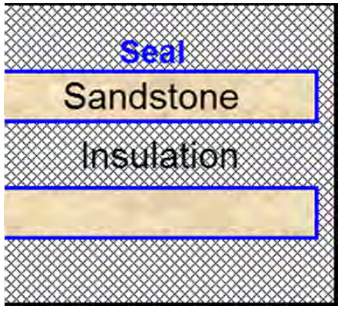
Degradation

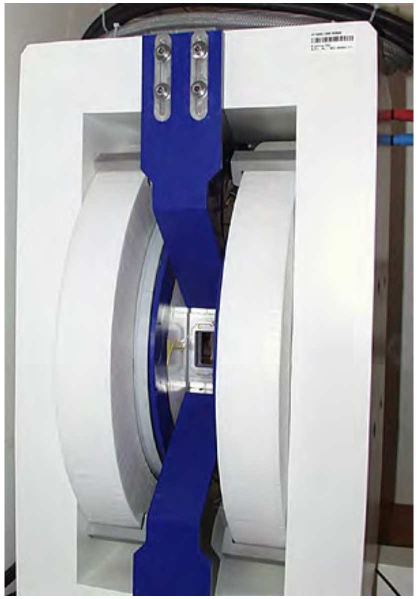
Moisture is the main cause for damage and degradation

Moisture problems

Damage

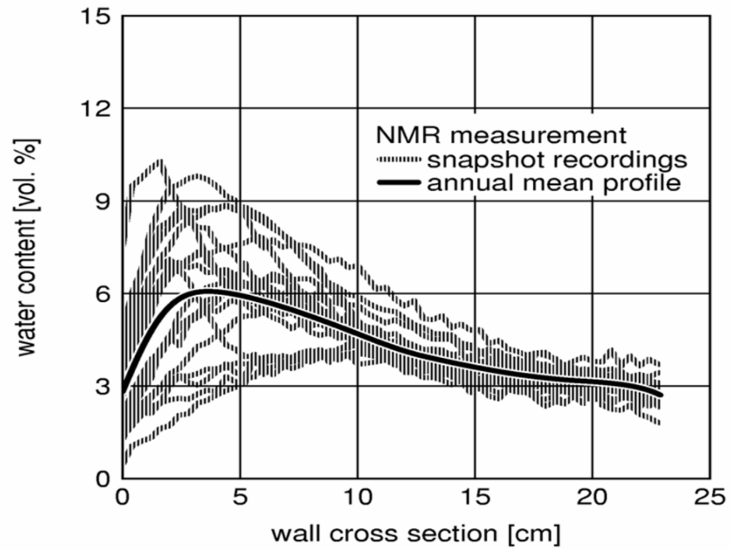


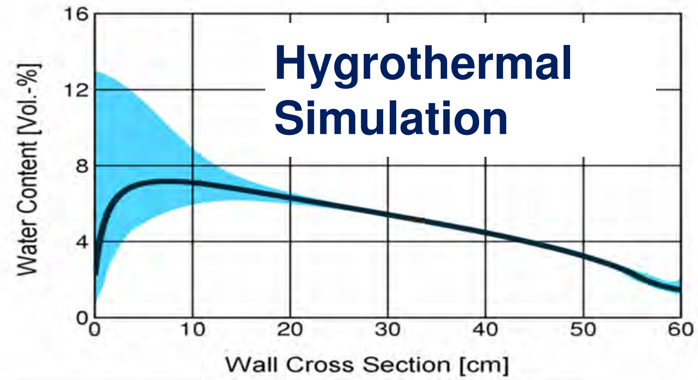




NMR-Scanner

Damage most likely at max. water content





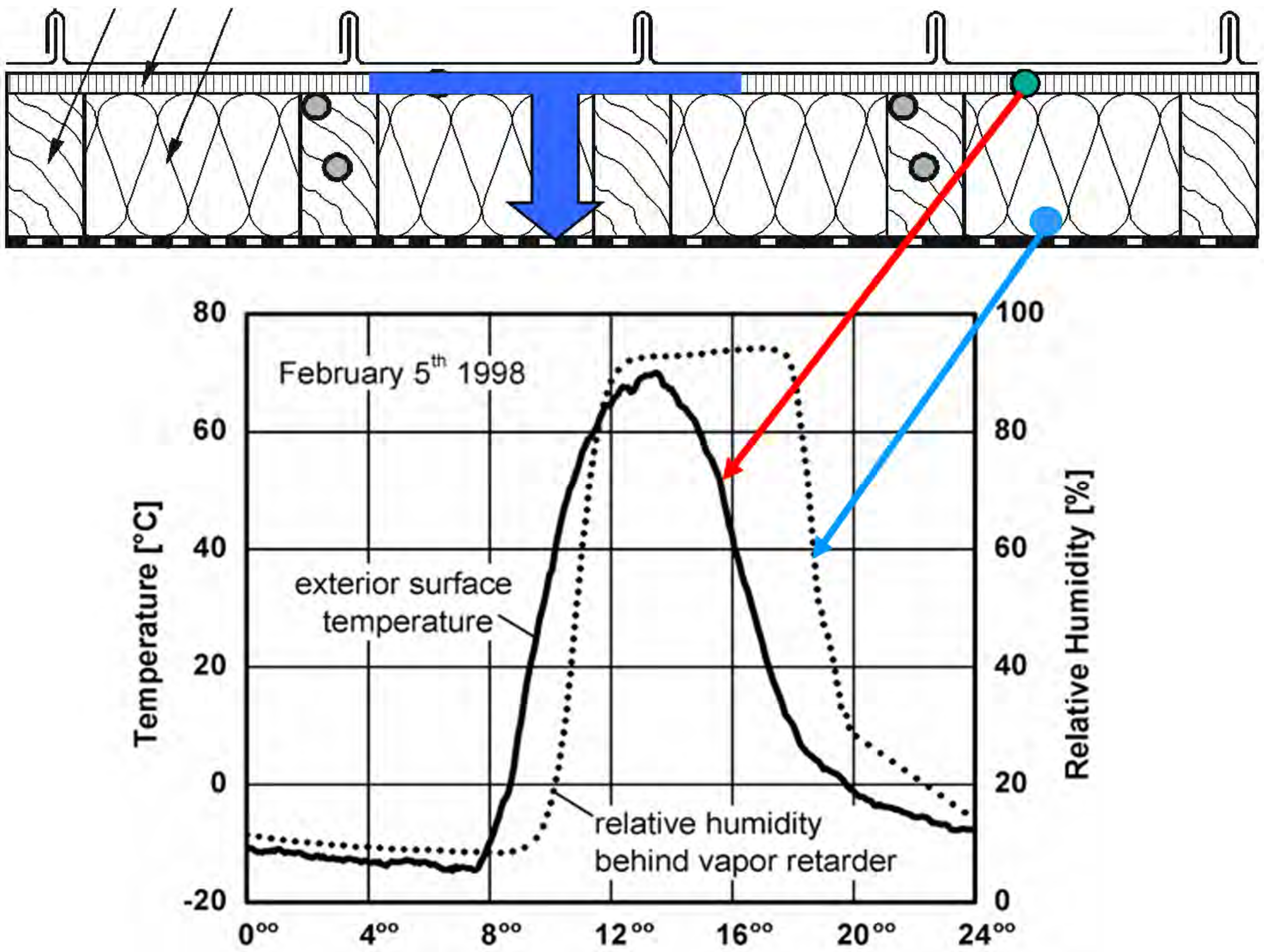
Moisture problems

Indoor air quality problem: visible mould

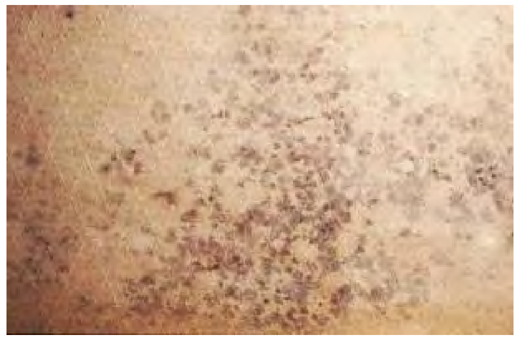
High indoor humidity provokes mould growth on thermal bridges in cold climates. In hot and humid climates unconditioned spaces are at risk

Moisture problems

Indoor air quality problem: invisible mould



Test house monitoring

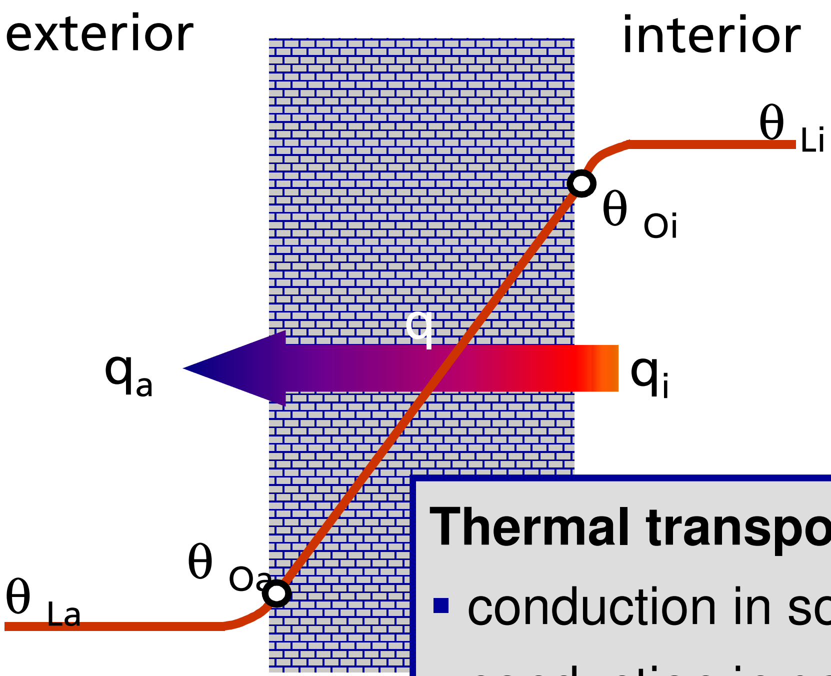


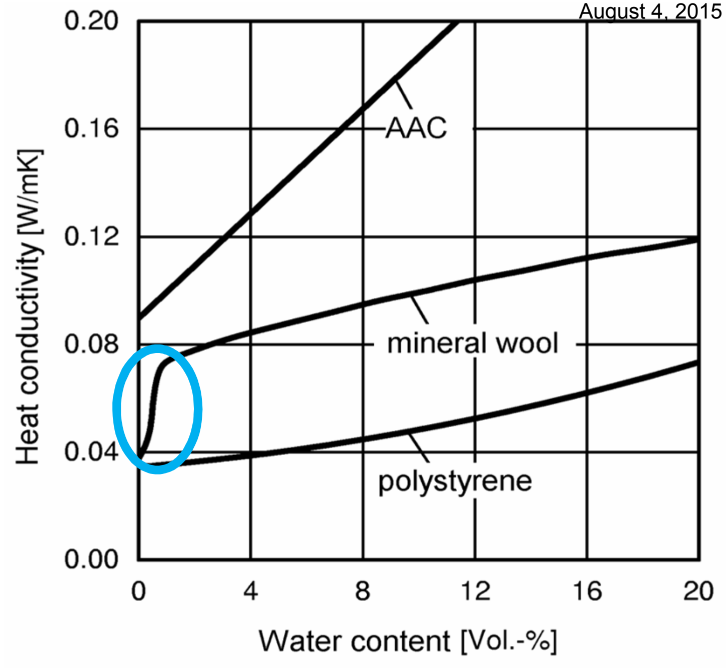
Mould stains

Mold due to moisture migration from hot to cold

Moisture problems

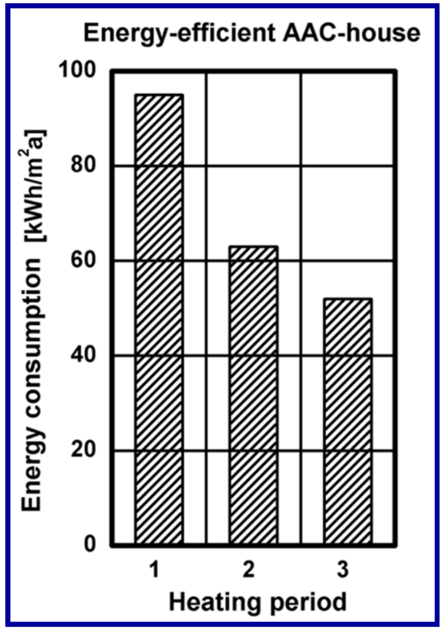
Moisture affects the thermal resistance





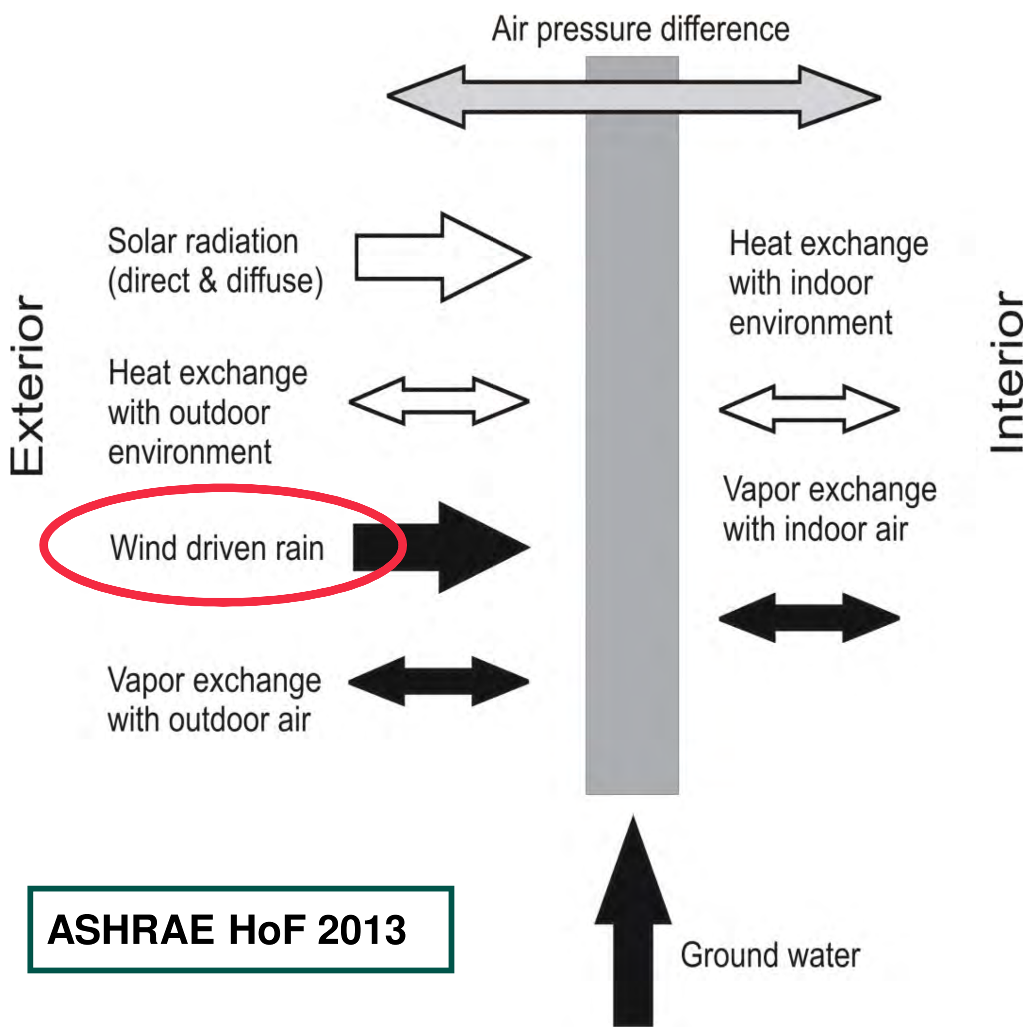
Thermal transport phenomena:

- conduction in solid matrix
- conduction in gas-filled pores
- **conduction in liquid phase**
- long-wave radiation (low-E degradation)
- **vapor diffusion with phase change**
- **air convection**

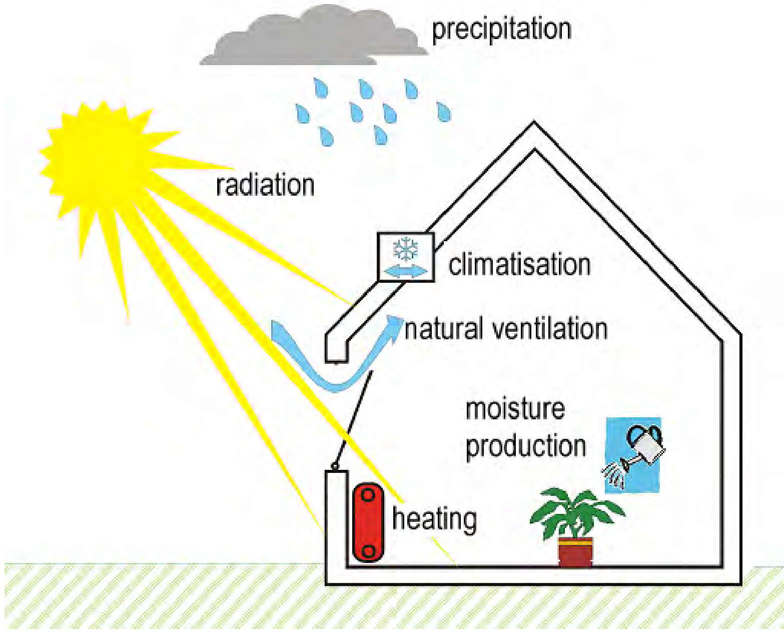


Moisture loads

Hygrothermal envelope loads



ASHRAE HoF 2013



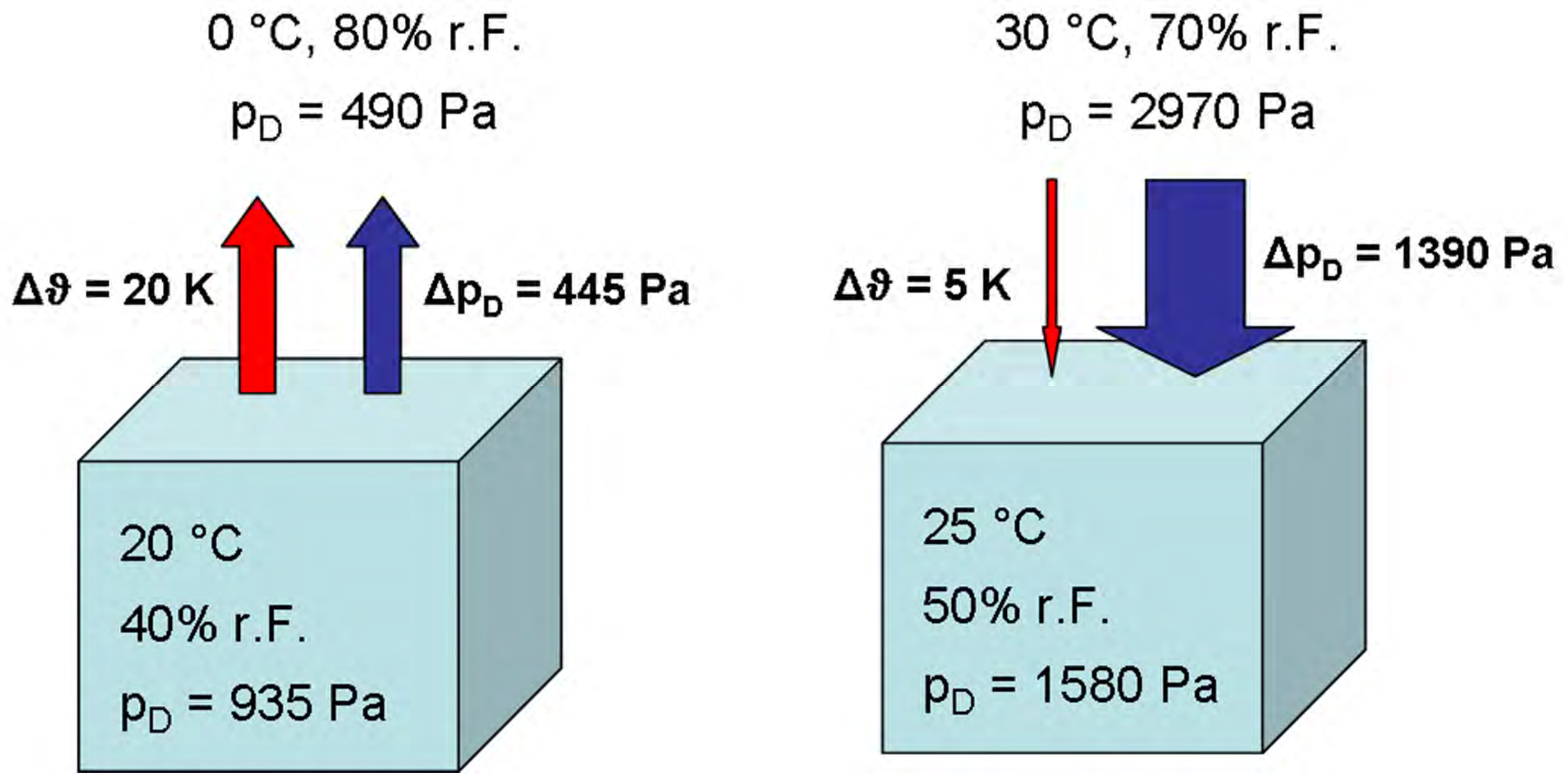
Moisture control:

Protecting buildings and building systems from exterior and interior moisture loads

Moisture loads

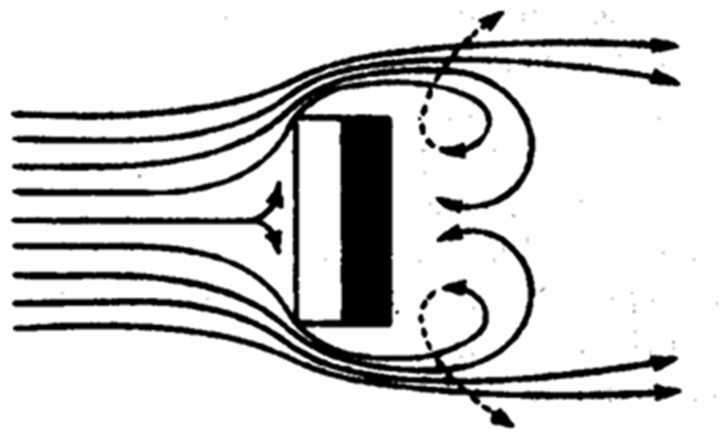
Temperature and vapor pressure gradients

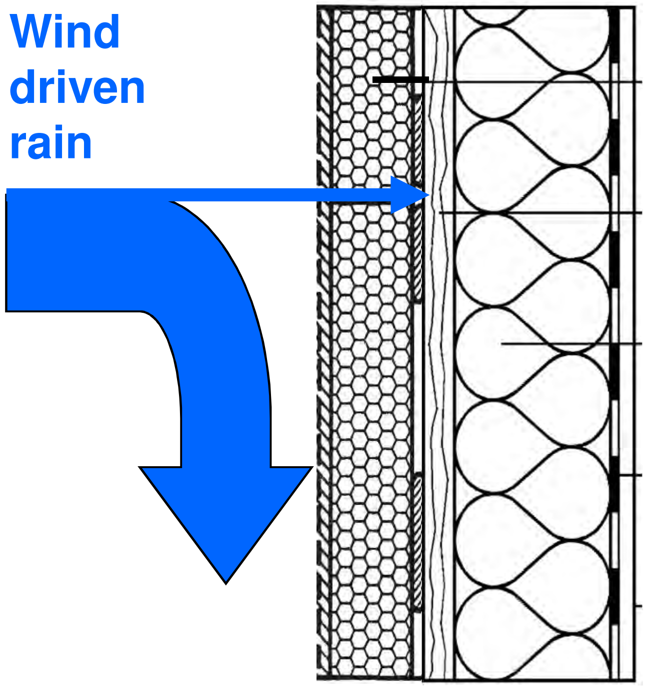
Heating period: outdoor temp. 0 °C **Cooling period: outdoor temp. 30 °C**



Moisture loads

Driving rain

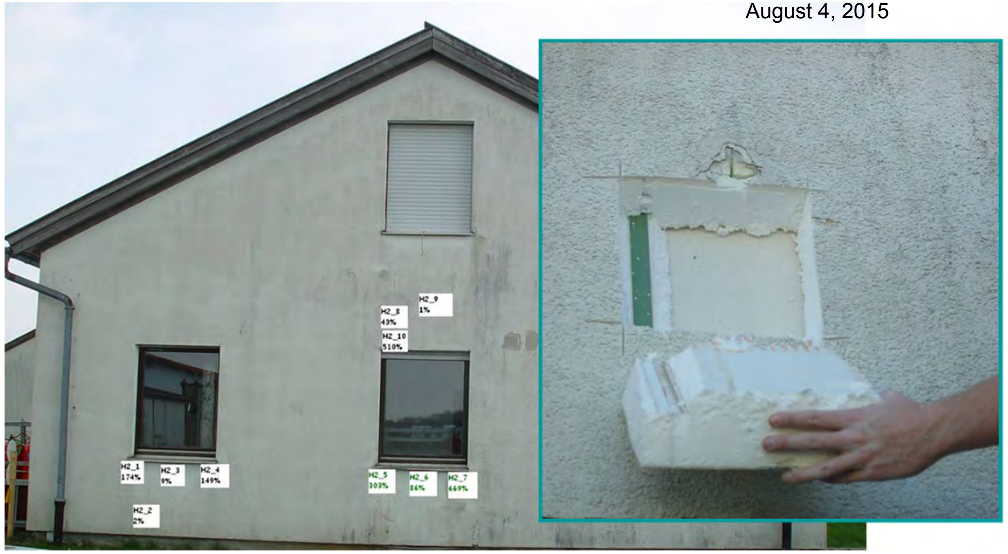




Driving rain is a major cause for building envelope failure

Moisture loads

Rainwater penetration



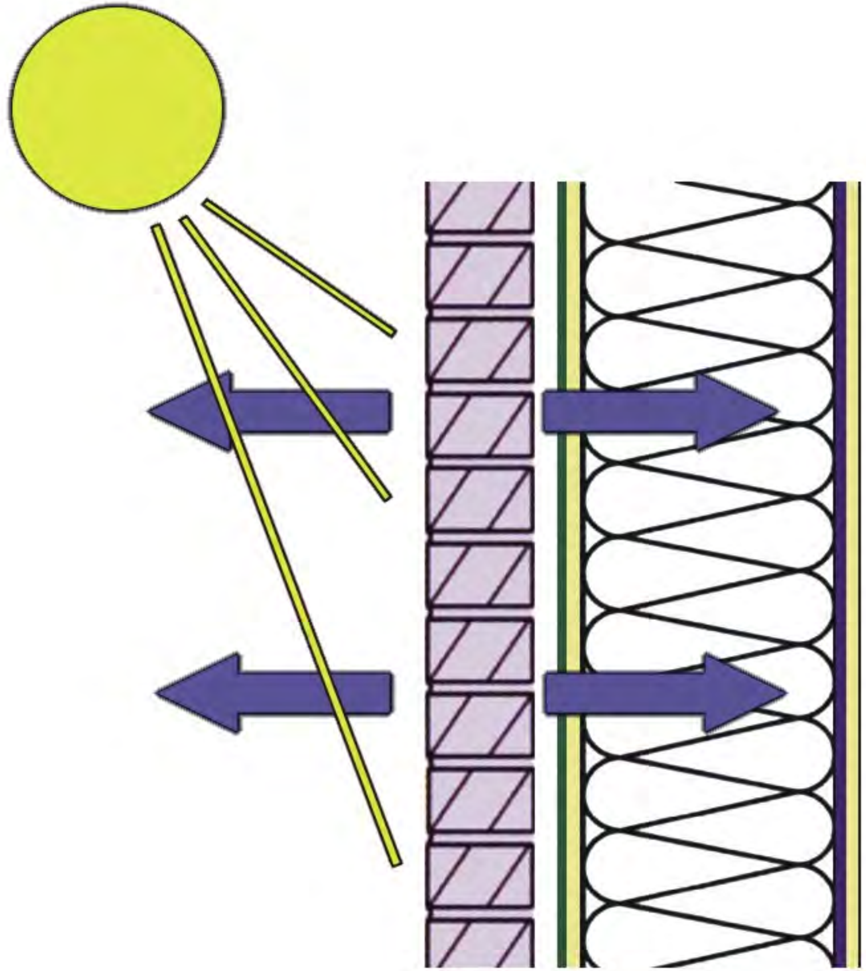
1990s: damaged EIFS walls in North America (wooden structures)

Reason: water penetration at window joints and wall connections

Rainwater penetration creates a habitat for ants behind EIFS, but no visible damage to the brick wall

Moisture loads

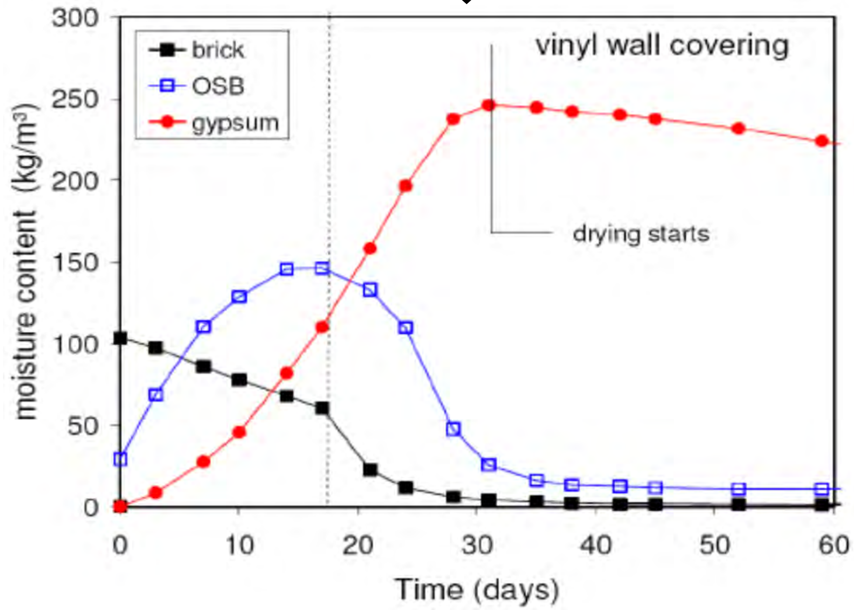
Solar vapor drive (walls)



ASHRAE report 1235-TRP (2010):

THE NATURE, SIGNIFICANCE AND CONTROL OF SOLAR-DRIVEN DIFFUSION IN WALL SYSTEMS

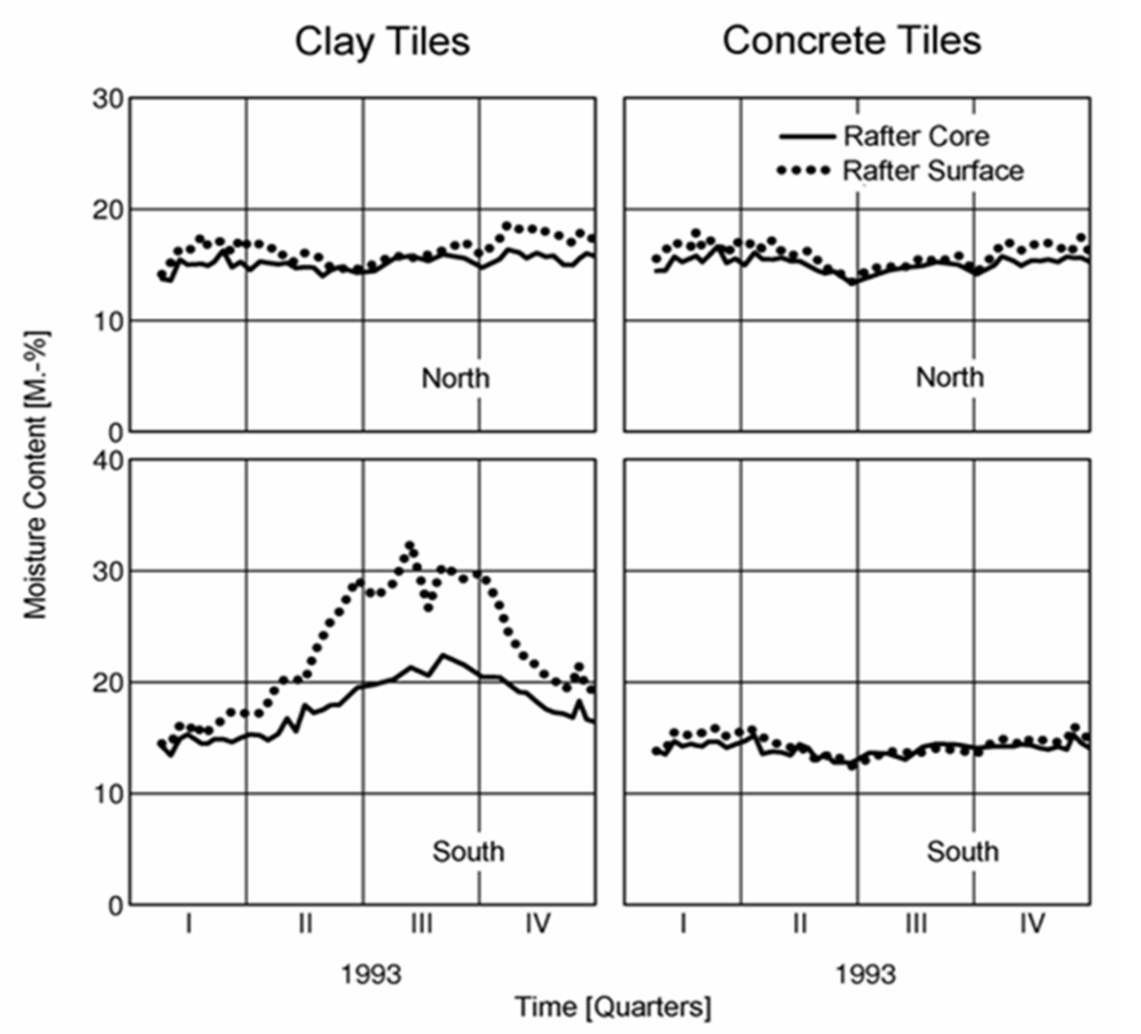
Lab test



Solar vapor drive occurs when sun heats up wet reservoir wall cladding

Moisture loads

Solar vapor drive (roofs)



Cathedral ceiling with blown-in cellulose fiber insulation

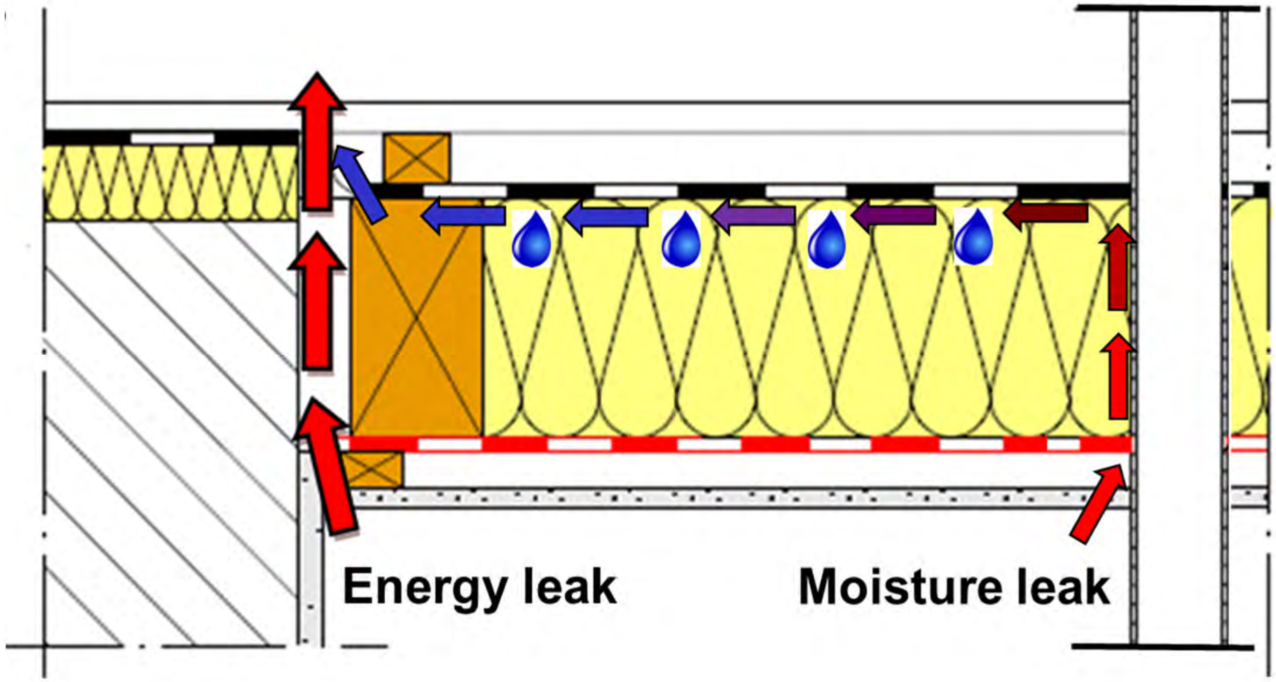
Solar vapor drive in roof assemblies may occur when the roofing tiles absorb moisture

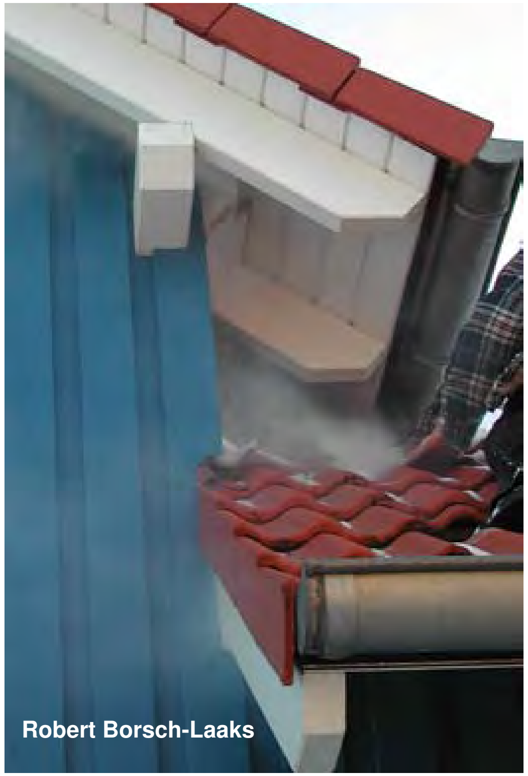
Moisture loads

Air flow through the envelope

German Std. DIN 68800-2 (2012) *Wood preservation – Preventive constructional measures in buildings*

Safety feature: moisture source 250 g/m² for roofs and 100 g/m² for walls to account for indoor air flow penetrating the building





Condensing moisture may be trapped

>> Double barrier components fail to meet the standard

Moisture loads

Construction moisture

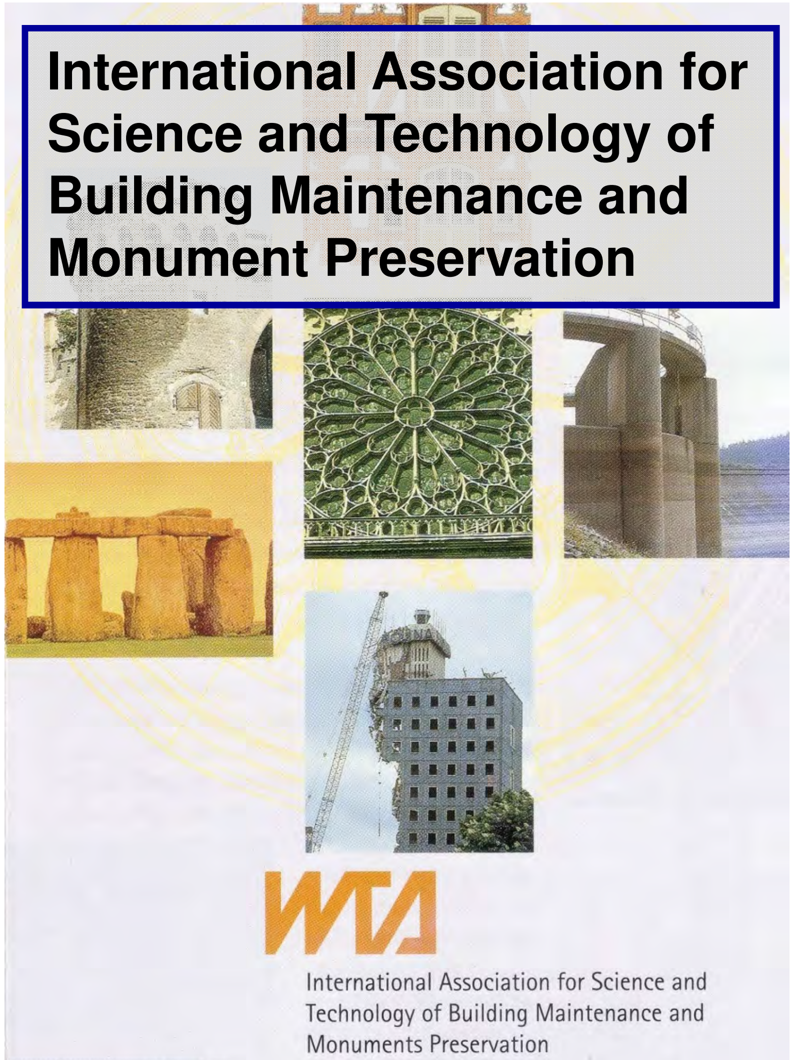
Foto: Mündl

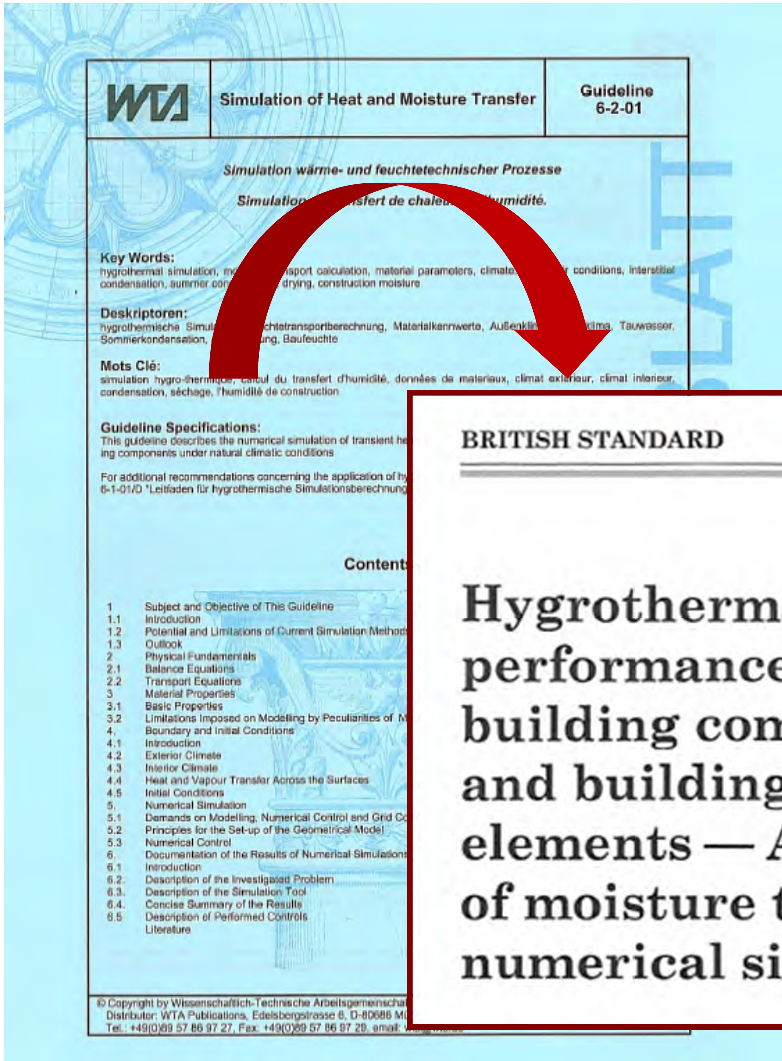
Foto: Mündl

Masonry moisture may move upwards into the roof

Standards and guidelines

WTA-Guideline 6-2: Simulation of Heat and Moisture Transfer (2001)





WTA | Simulation of Heat and Moisture Transfer | Guideline 6-2-01

Simulation wärme- und feuchtetechnischer Prozesse

Key Words: hygrothermal simulation, ... drying, construction moisture

Deskriptoren: hygrothermische Simul... Baufeuchte

Mots Clé: simulation hygro-thermique, calcul du transfert d'humidité, données de materiaux, climat extérieur, climat interieur, condensation, séchage, l'humidité de construction

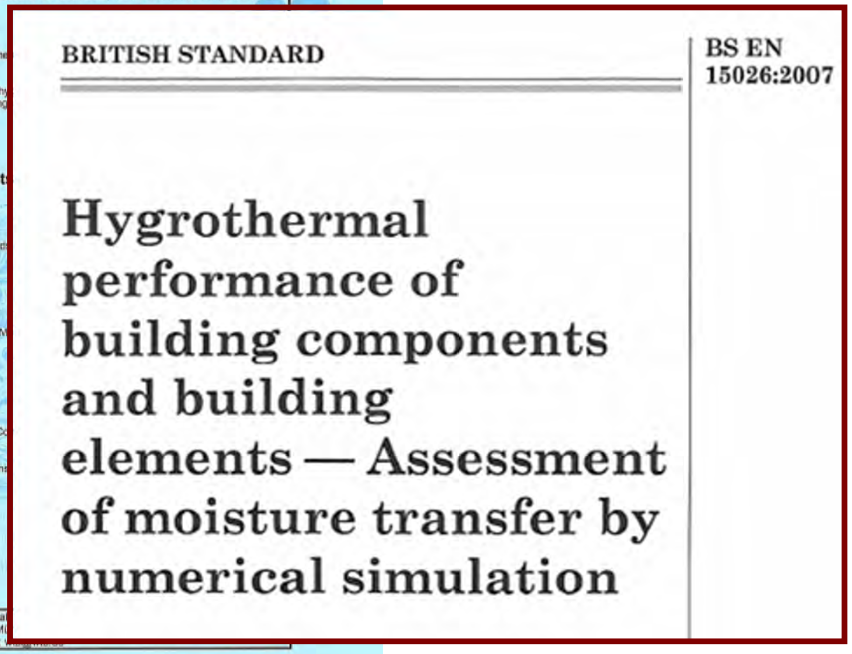
Guideline Specifications: This guideline describes the numerical simulation of transient he... ing components under natural climatic conditions

For additional recommendations concerning the application of hy... 6-1-01/D "Leitfaden für hygrothermische Simulationsberechnung..."

Contents

- 1 Subject and Objective of This Guideline
- 1.1 Introduction
- 1.2 Potential and Limitations of Current Simulation Methods
- 1.3 Outlook
- 2 Physical Fundamentals
- 2.1 Balance Equations
- 2.2 Transport Equations
- 3 Material Properties
- 3.1 Basic Properties
- 3.2 Limitations Imposed on Modelling by Peculiarities of ...
- 4 Boundary and Initial Conditions
- 4.1 Introduction
- 4.2 Exterior Climate
- 4.3 Interior Climate
- 4.4 Heat and Vapour Transfer Across the Surfaces
- 4.5 Initial Conditions
- 5 Numerical Simulation
- 5.1 Demands on Modelling, Numerical Control and Grid ...
- 5.2 Principles for the Set-up of the Geometrical Model
- 5.3 Numerical Control
- 6 Documentation of the Results of Numerical Simulations
- 6.1 Introduction
- 6.2 Description of the Investigated Problem
- 6.3 Description of the Simulation Tool
- 6.4 Concise Summary of the Results
- 6.5 Description of Performed Controls
- Literature

© Copyright by Wissenschaftlich-Technische Arbeitsgemeinschaft ...
Distributor: WTA Publications, Edelsbergstrasse 6, D-80686 M...



BRITISH STANDARD | BS EN 15026:2007

Hygrothermal performance of building components and building elements — Assessment of moisture transfer by numerical simulation

Standards and guidelines

European Standard BS EN 15026 (April 2007):

Hygrothermal performance of building components and building elements - Assessment of moisture transfer by numerical simulation

The hygrothermal equations described in this standard shall not be applied in cases where:

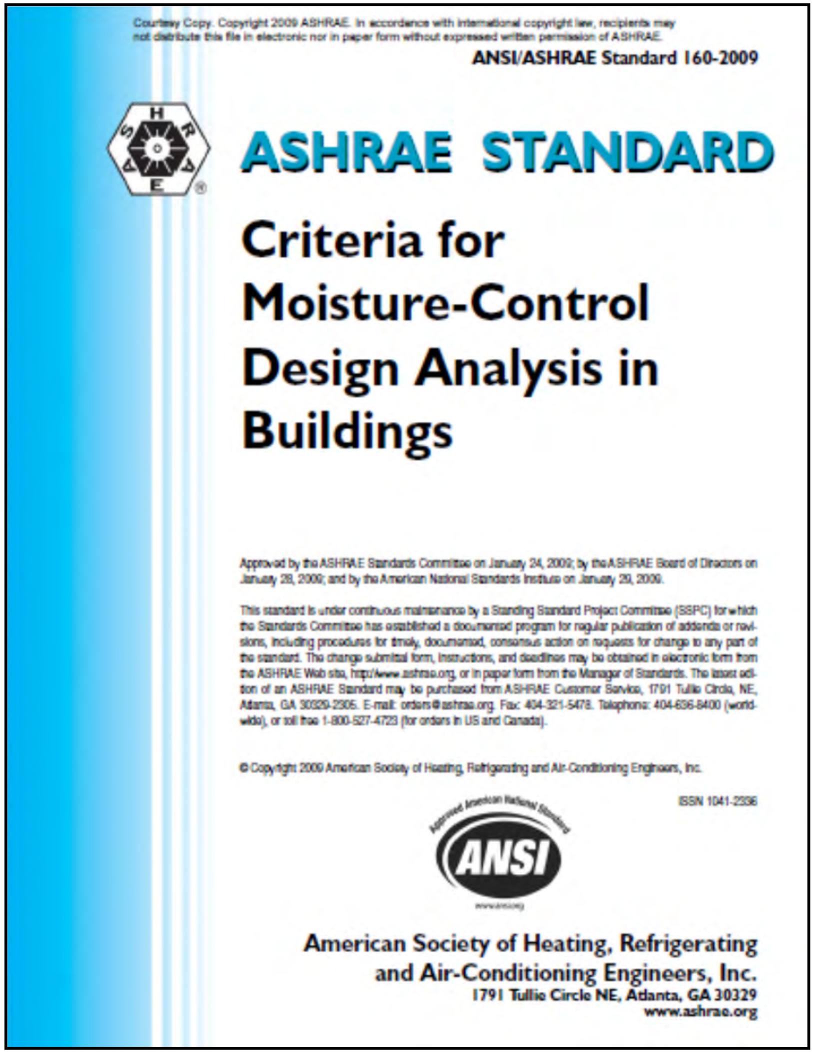
- convection takes place through holes and cracks;
- two-dimensional effects play an important part (e.g. rising damp, conditions around thermal bridges, effect of gravitational forces);
- hydraulic, osmotic, electrophoretic forces are present;
- daily mean temperatures in the component exceed 50 °C.

The standard deals only with perfectly assembled and installed components without defects

Fraunhofer IBP

Standards and guidelines

ANSI / ASHRAE Standard 160 (2009)



Courtesy Copy. Copyright 2009 ASHRAE. In accordance with international copyright law, recipients may not distribute this file in electronic nor in paper form without expressed written permission of ASHRAE.

ANSI/ASHRAE Standard 160-2009

ASHRAE STANDARD

Criteria for Moisture-Control Design Analysis in Buildings

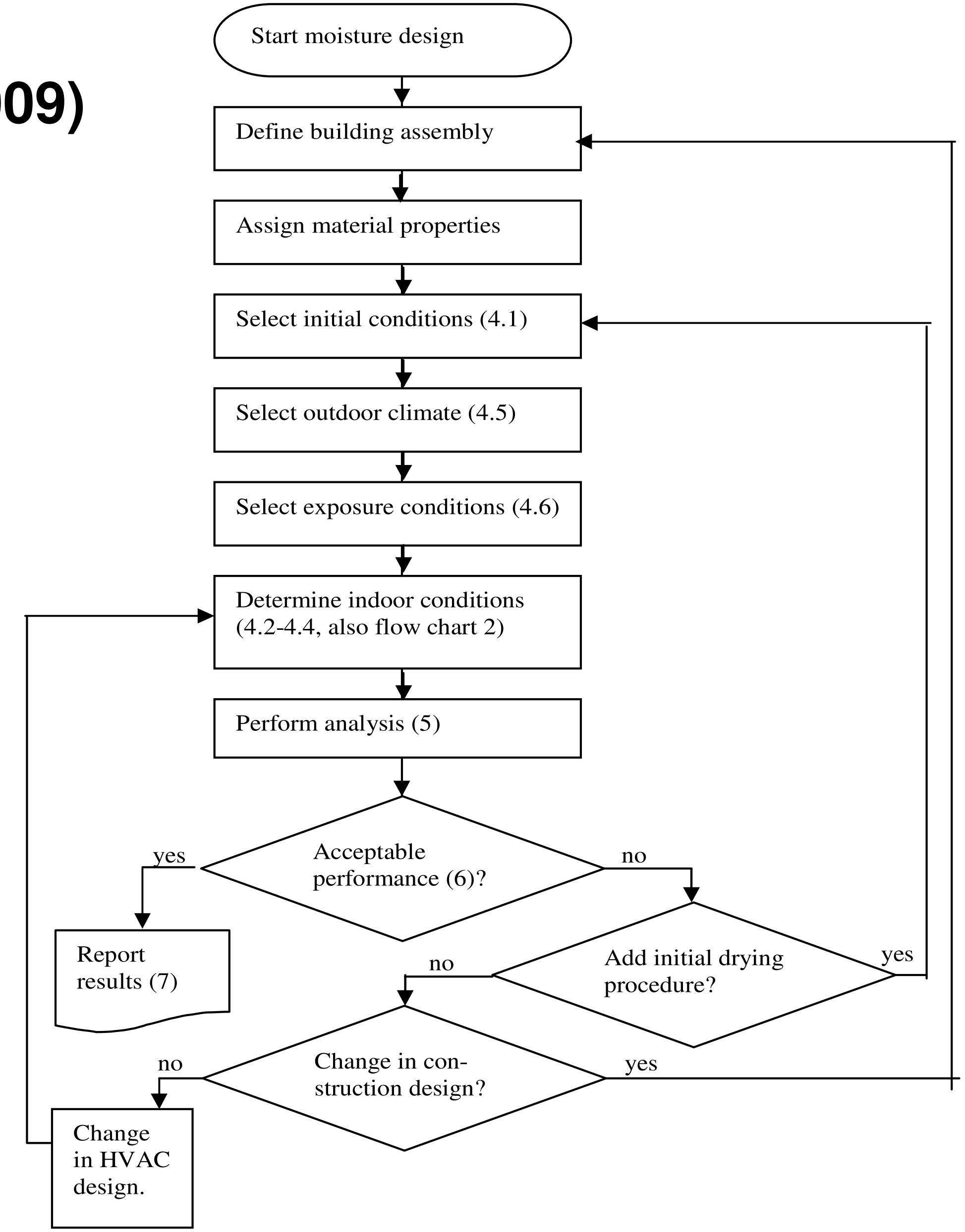
Approved by the ASHRAE Standards Committee on January 24, 2009; by the ASHRAE Board of Directors on January 28, 2009; and by the American National Standards Institute on January 29, 2009.

This standard is under continuous maintenance by a Standing Standard Project Committee (SSPC) for which the Standards Committee has established a documented program for regular publication of addenda or revisions, including procedures for timely, documented, consensus action on requests for change to any part of the standard. The change submittal form, instructions, and deadlines may be obtained in electronic form from the ASHRAE Web site, http://www.ashrae.org, or in paper form from the Manager of Standards. The latest edition of an ASHRAE Standard may be purchased from ASHRAE Customer Service, 1791 Tullie Circle, NE, Atlanta, GA 30329-2305. E-mail: orders@ashrae.org. Fax: 404-321-5478. Telephone: 404-636-8400 (worldwide), or toll free 1-800-527-4723 (for orders in US and Canada).

© Copyright 2009 American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ISSN 1041-2336

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
1791 Tullie Circle NE, Atlanta, GA 30329
www.ashrae.org

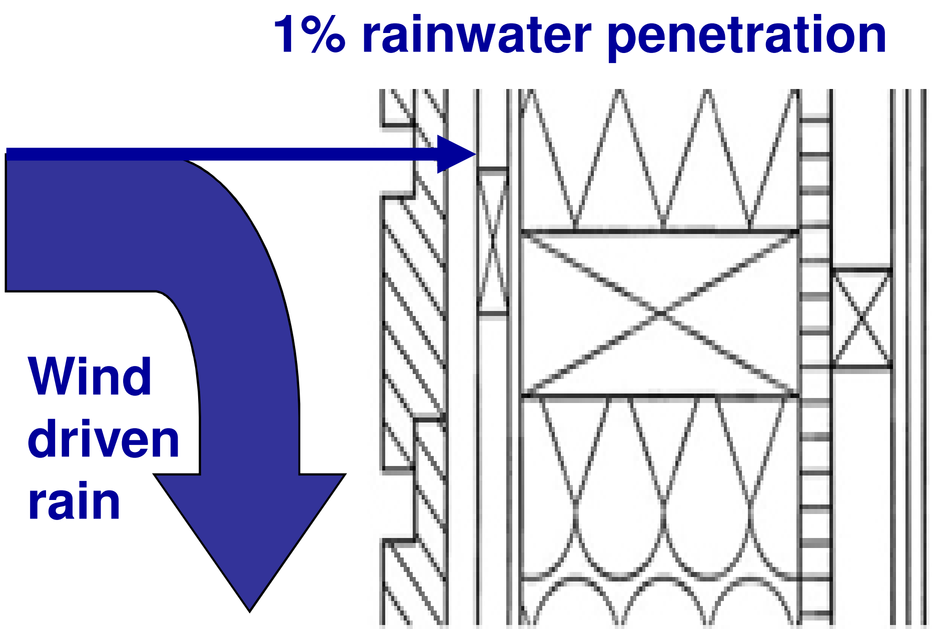


Fraunhofer IBP

Standards and guidelines

ANSI / ASHRAE Standard 160

Safety feature: consideration of imperfections at joints and connections of best practice façade constructions



Rainwater penetration:

In the absence of specific full scale test methods and data for the considered exterior wall system, **the default value for water penetration through the exterior surface is 1% of the water reaching that exterior surface.**

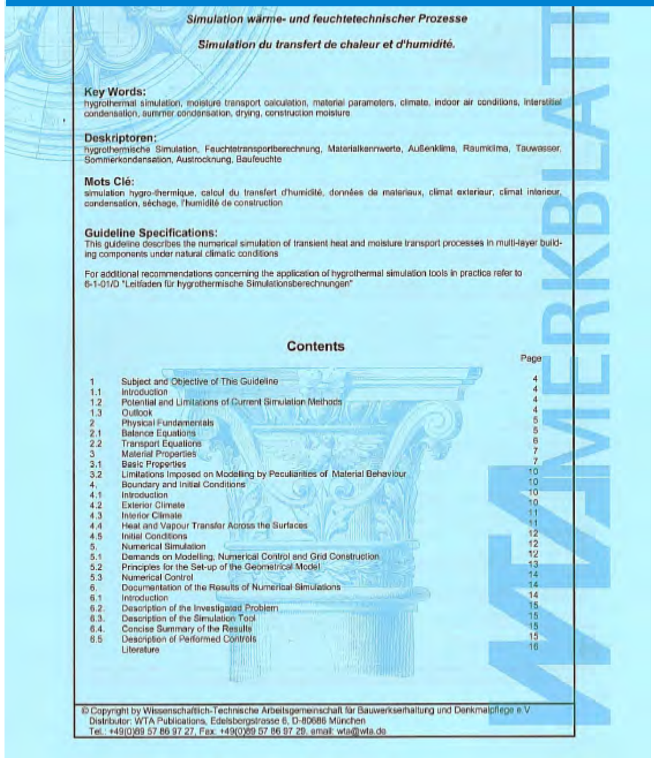
The deposit site for the water shall be the exterior surface of the WRB. If a WRB is not provided then the deposit site shall be described and a technical rationale shall be provided.

Standards and guidelines

WTA	Simulation of Heat and Moisture Transfer	Guideline 6-2 Edition: 12.2014/D

Simulation du transfert de chaleur et d'humidité

Simulation wärme- und feuchtetechnischer Prozesse



Simulation wärme- und feuchtetechnischer Prozesse

Simulation du transfert de chaleur et d'humidité.

Key Words:
hygrothermal simulation, moisture transport calculation, material parameters, climate, indoor air conditions, interstitial condensation, summer condensation, drying, construction moisture

Deskriptoren:
hygrothermische Simulation, Feuchtetransportberechnung, Materialkennwerte, Außenklima, Raumklima, Tauwasser, Sommerkondensation, Austrocknung, Baufeuchte

Mots Clé:
simulation hygro-thermique, calcul du transfert d'humidité, données de materiaux, climat exterieur, climat interieur, condensation, séchage, l'humidité de construction

Guideline Specifications:
This guideline describes the numerical simulation of transient heat and moisture transport processes in multi-layer building components under natural climatic conditions

For additional recommendations concerning the application of hygrothermal simulation tools in practice refer to 6-1-01/D "Leitfaden für hygrothermische Simulationsberechnungen"

Contents

		Page
1	Subject and Objective of This Guideline	4
1.1	Introduction	4
1.2	Potential and Limitations of Current Simulation Methods	4
1.3	Outlook	4
2	Physical Fundamentals	5
2.1	Balance Equations	5
2.2	Transport Equations	6
3	Material Properties	7
3.1	Basic Properties	7
3.2	Limitations Imposed on Modelling by Peculiarities of Material Behaviour	10
4.	Boundary and Initial Conditions	10
4.1	Introduction	10
4.2	Exterior Climate	10
4.3	Interior Climate	11
4.4	Heat and Vapour Transfer Across the Surfaces	11
4.5	Initial Conditions	12
5.	Numerical Simulation	12
5.1	Demands on Modelling, Numerical Control and Grid Construction	12
5.2	Principles for the Set-up of the Geometrical Model	13
5.3	Numerical Control	14
6.	Documentation of the Results of Numerical Simulations	14
6.1	Introduction	14
6.2.	Description of the Investigated Problem	15
6.3.	Description of the Simulation Tool	15
6.4.	Concise Summary of the Results	15
6.5	Description of Performed Controls	15
	Literature	16

5. Auxiliary models for a simplified consideration of special effects

5.1. Component ventilation

5.2. Condensation due to air convection through components

5.3. Driving rain penetration

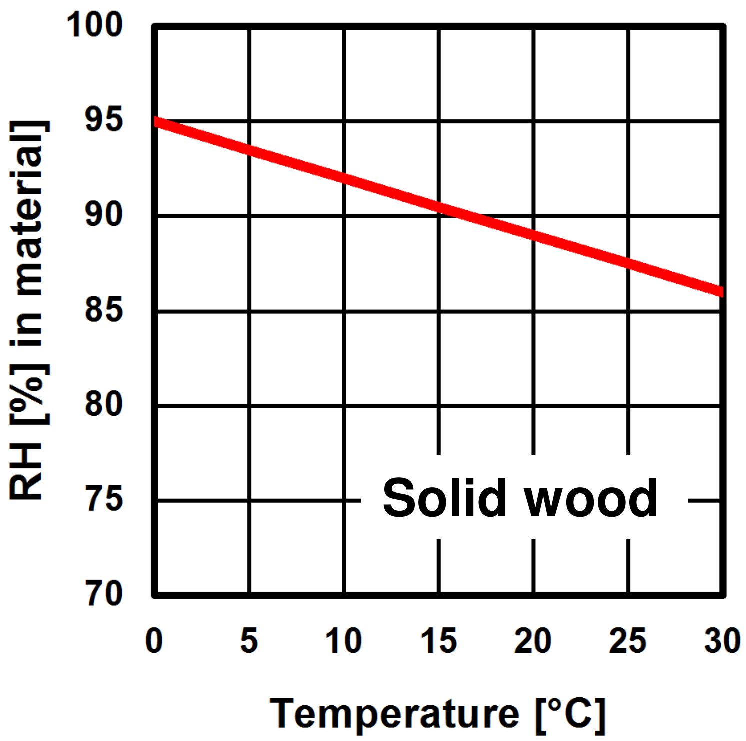
Imperfection models help to differentiate between poor design and poor installation

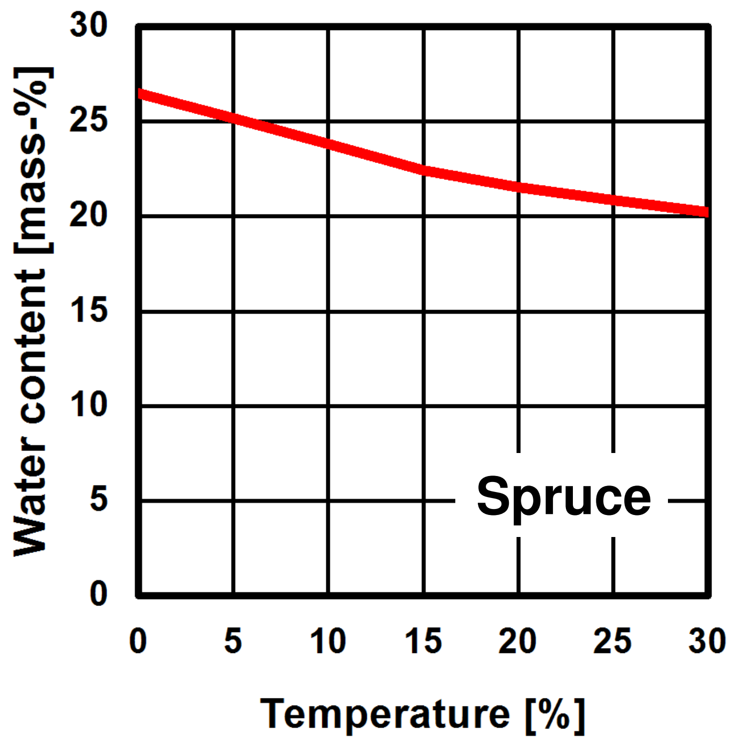
Standards and guidelines

Evaluation of transient hygrothermal simulation results for wood and wood based materials

WTA	Feuchtetechnische Bewertung von Holzbauteilen – Vereinfachte Nachweise und Simulation	Merkblatt 6-8-15-D **Draft**

Assessment of humidity in timber constructions – simplified verifications and simulation



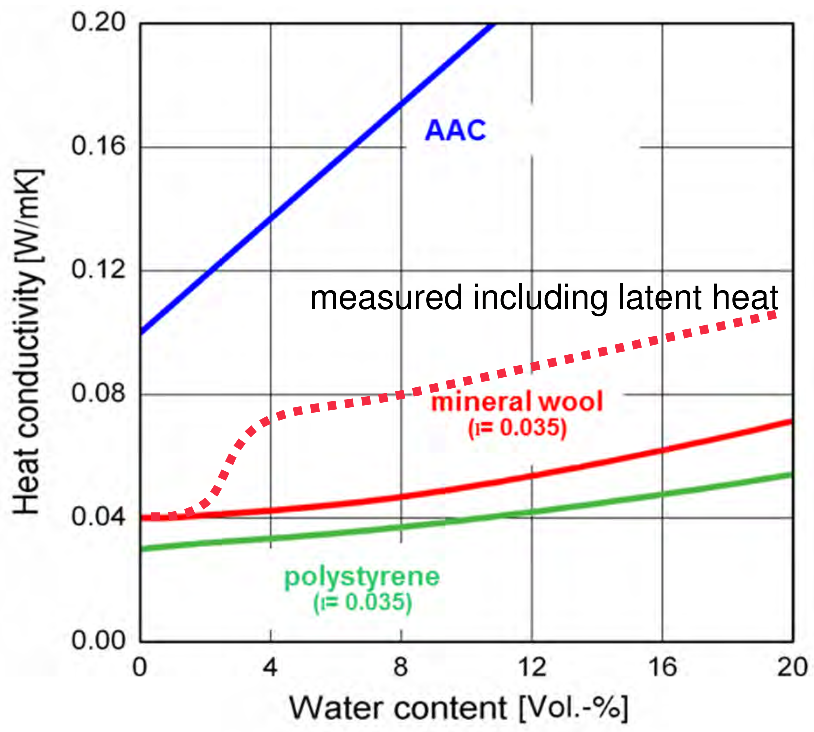


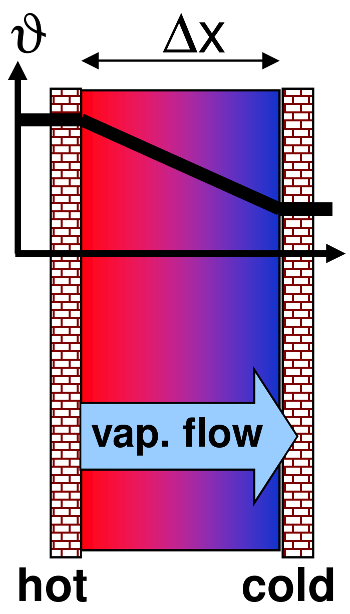
Safety limit to prevent rot

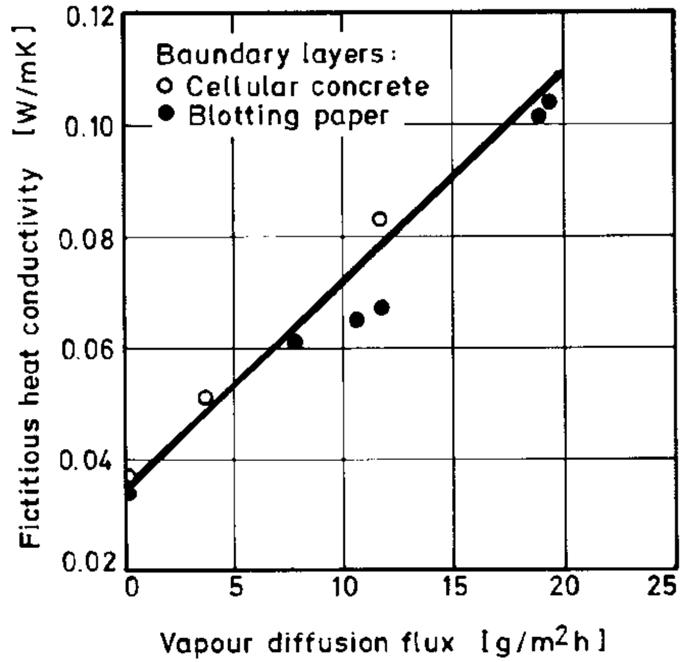
Standards and guidelines

EN 15026: transport phenomena to be considered – heat transfer

- heat storage of the dry building material and of the contained moisture
- heat transport by thermal conduction with moisture-dependent thermal conductivity
- latent heat transport by vapour diffusion with phase change (evaporation / cond.)



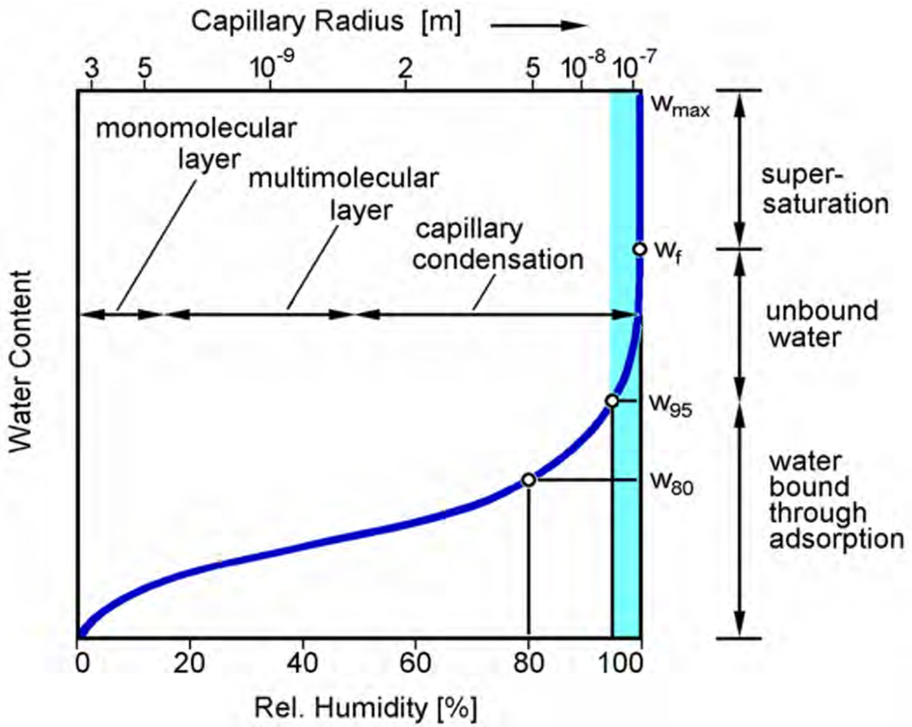


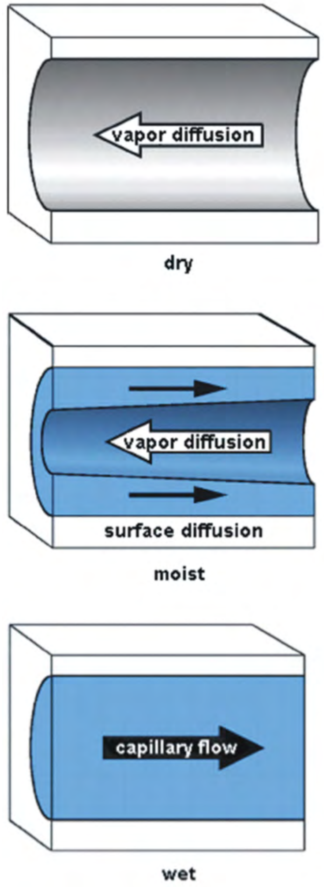


Standards and guidelines

EN 15026: transport phenomena to be considered – moisture transfer

- moisture storage by water vapour sorption and capillary forces
- water vapour transport by diffusion
- liquid transport by surface diffusion and capillary conduction





Hygrothermal simulation

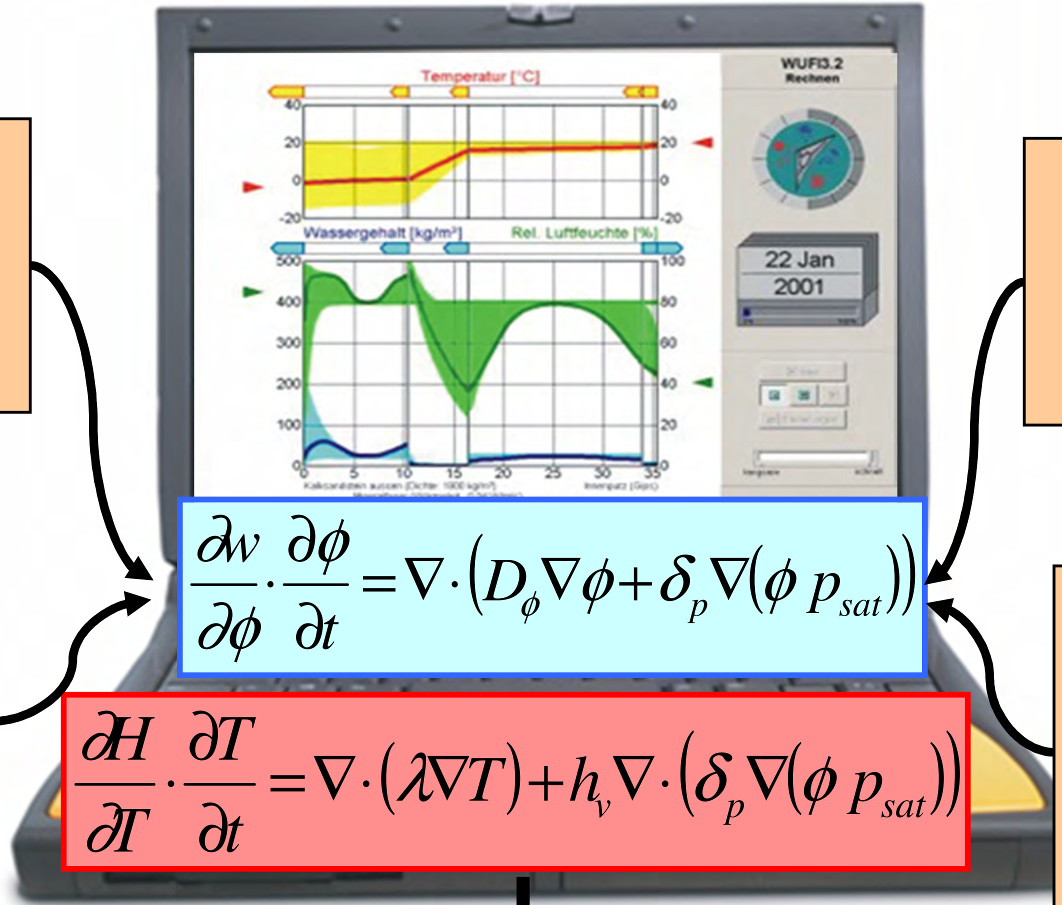
Input / output

Assembly composition

orientation
inclination

initial conditions

e.g. construction moisture



$$\frac{\partial w}{\partial \phi}\cdot\frac{\partial \phi}{\partial t} = \nabla\cdot\left(D_\phi \nabla\phi + \delta_p \nabla(\phi\, p_{sat})\right)$$

$$\frac{\partial H}{\partial T}\cdot\frac{\partial T}{\partial t} = \nabla\cdot(\lambda\nabla T) + h_v \nabla\cdot\left(\delta_p\nabla(\phi\, p_{sat})\right)$$

Material properties

ρ, c, **λ, μ**

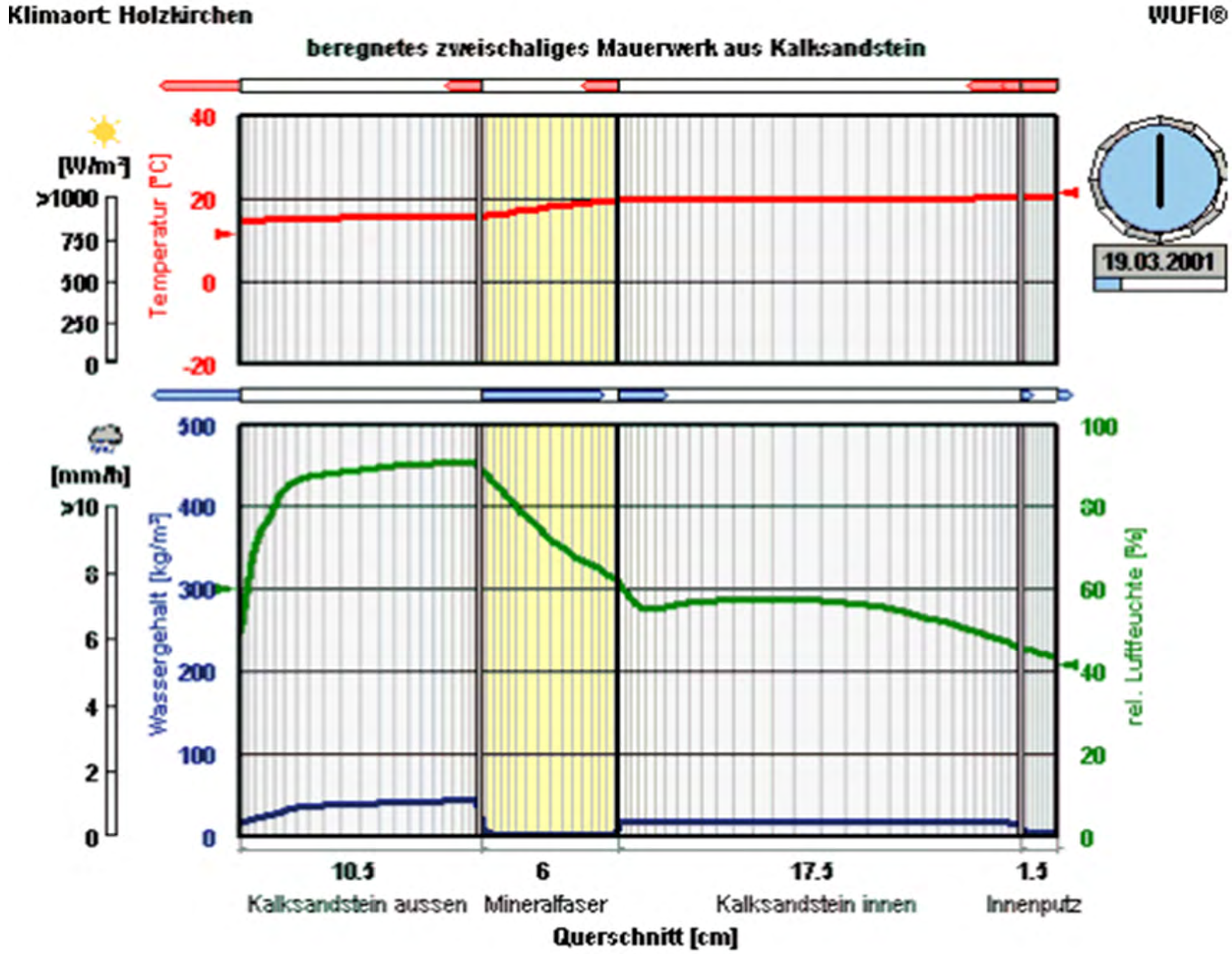
$w = f(\varphi)$, $D_w = f(w)$

Climate conditions

temperature, RH, radiation, precipitation, wind speed & direction

Dynamic temperature and moisture profiles
heat and moisture fluxes

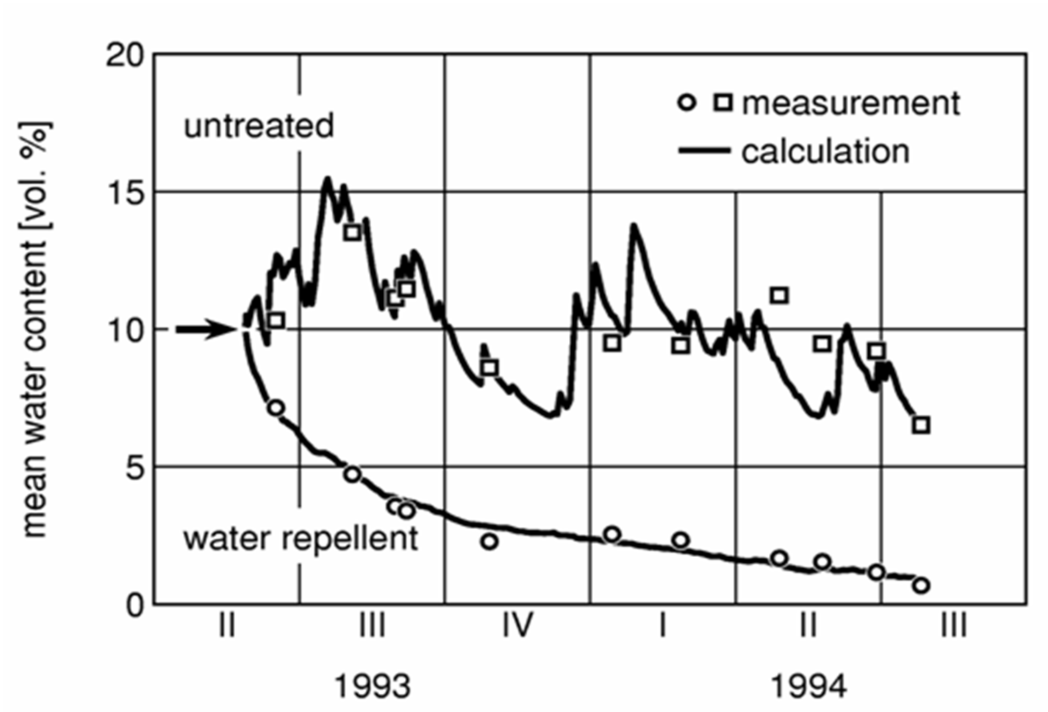
Hygrothermal simulation – walls

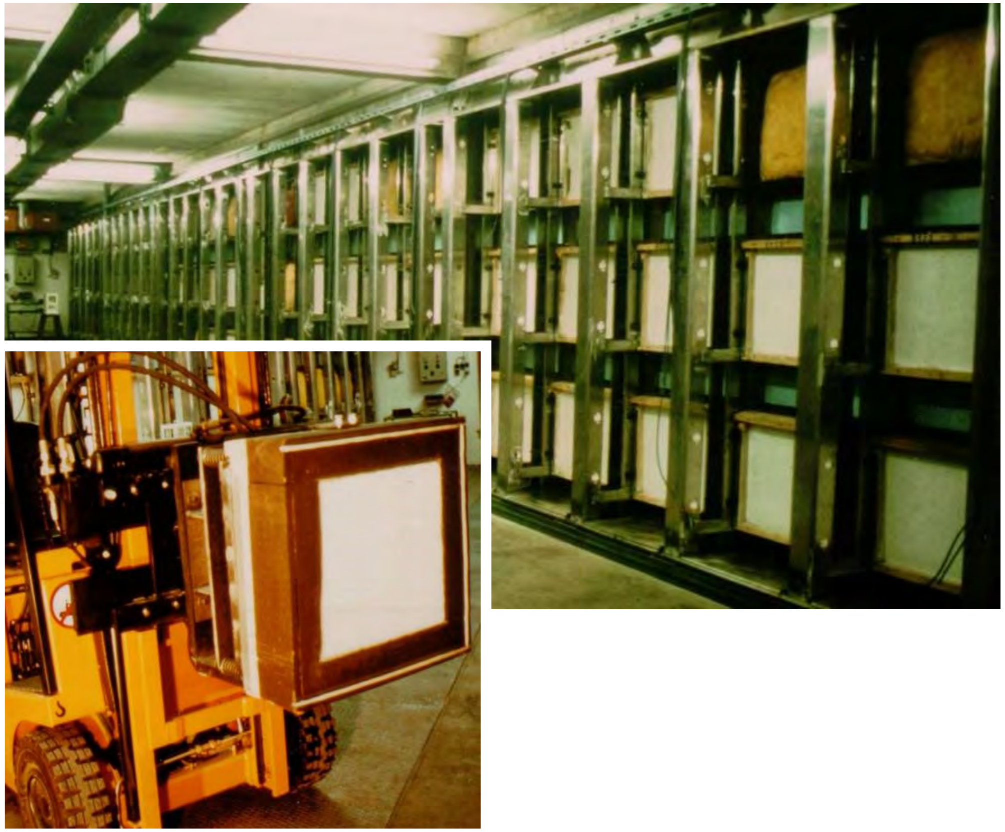


Hygrothermal simulation of dynamic temperature and moisture conditions in a cavity wall

Hygrothermal simulation

Validation example: brick masonry impregnated with water repellent siloxane



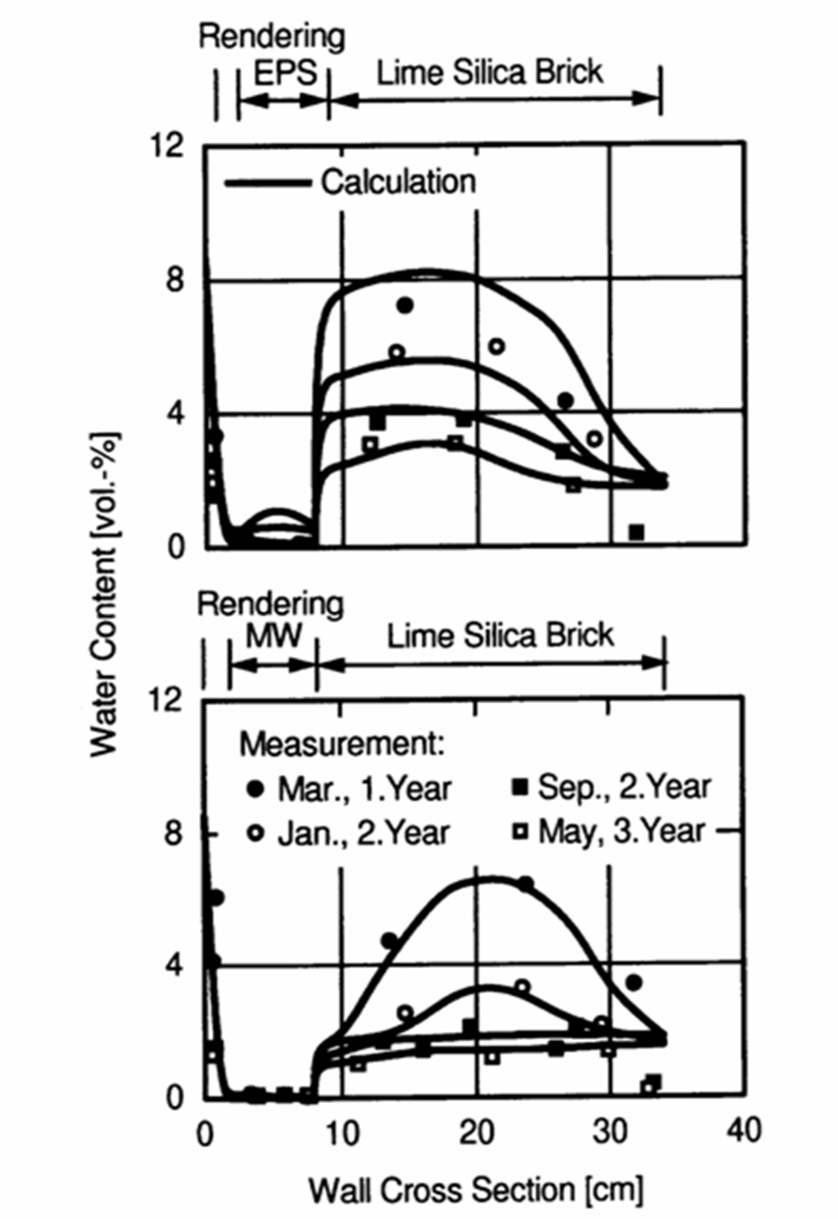


Fraunhofer IBP

Hygrothermal simulation

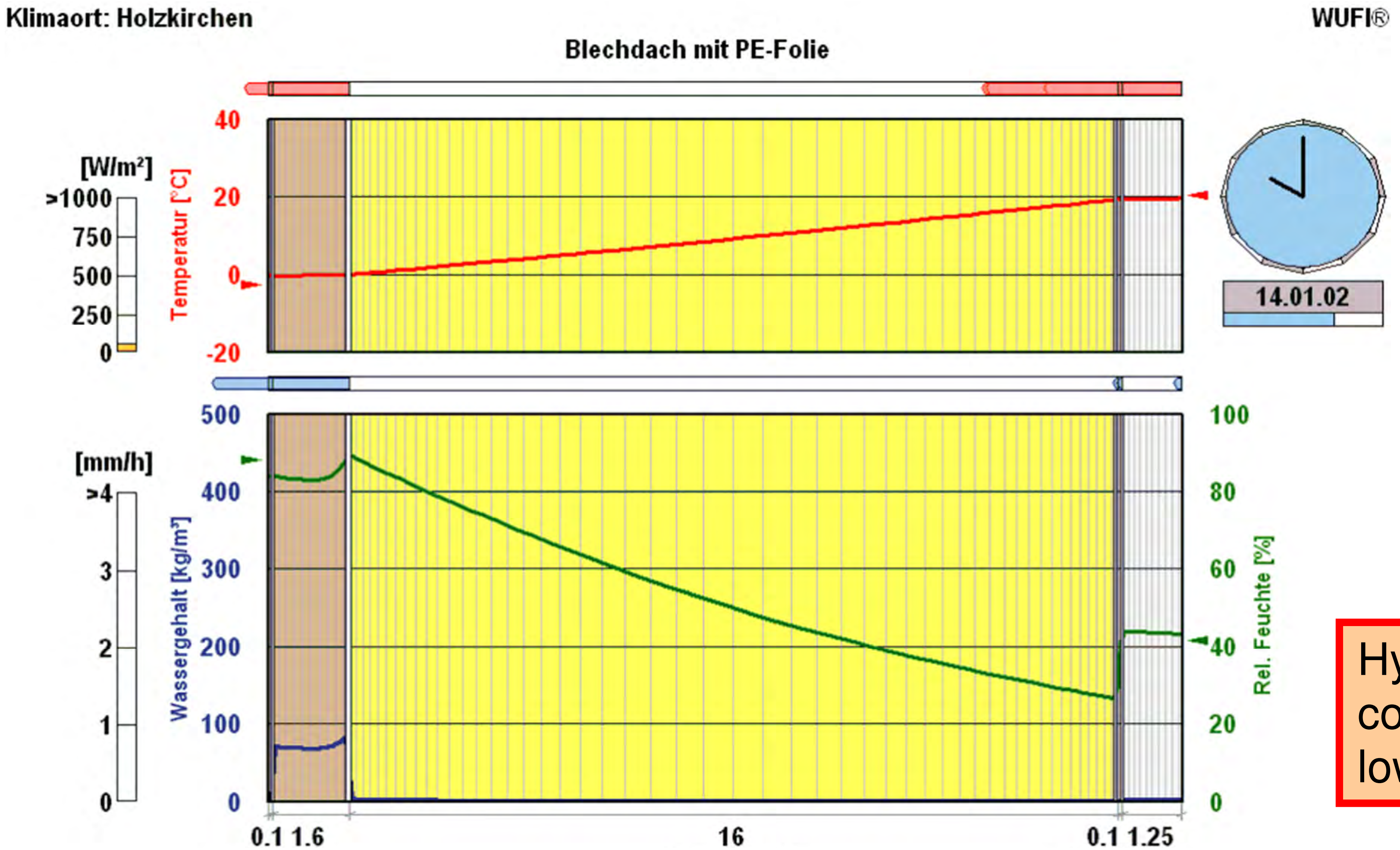
Validation example:
exterior insulation on masonry

Drill probing for moisture content determination



Fraunhofer IBP

Hygrothermal simulation – roofs



zinc, wooden sheathing / glass fiber insulation / poly, gyp. board

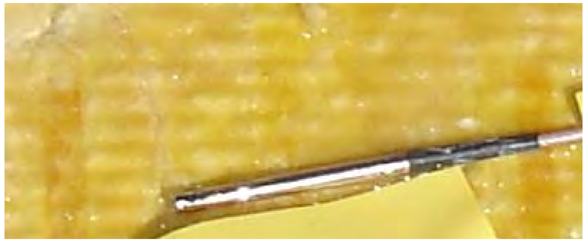
layer thickness [cm]

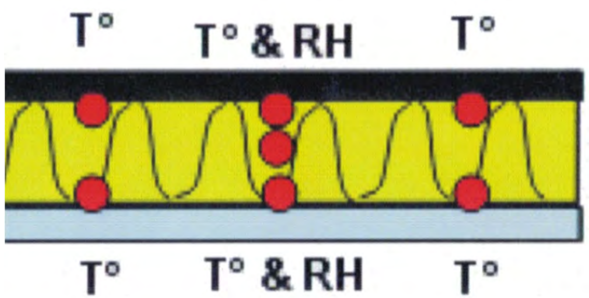
Hygrothermal conditions in a low-slope roof

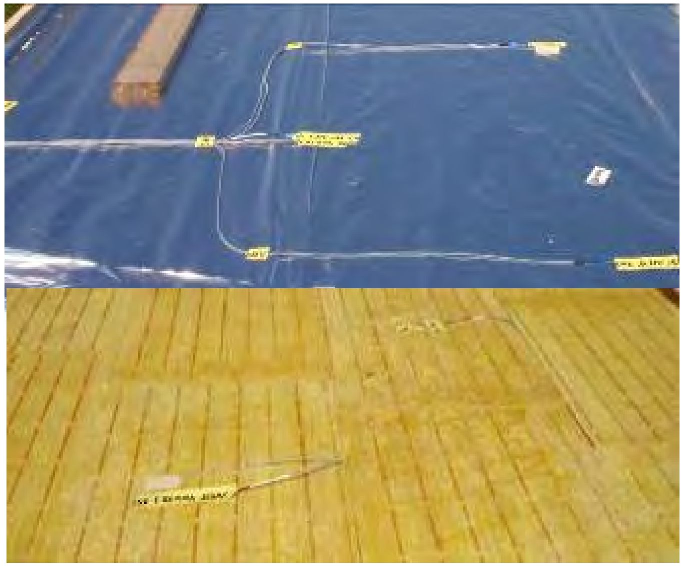
Fraunhofer IBP

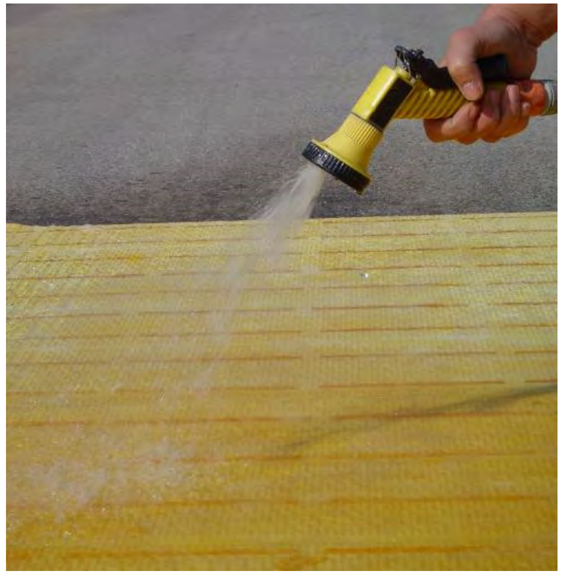
Hygrothermal simulation

Validation example: light-weight flat roofs with construction moisture



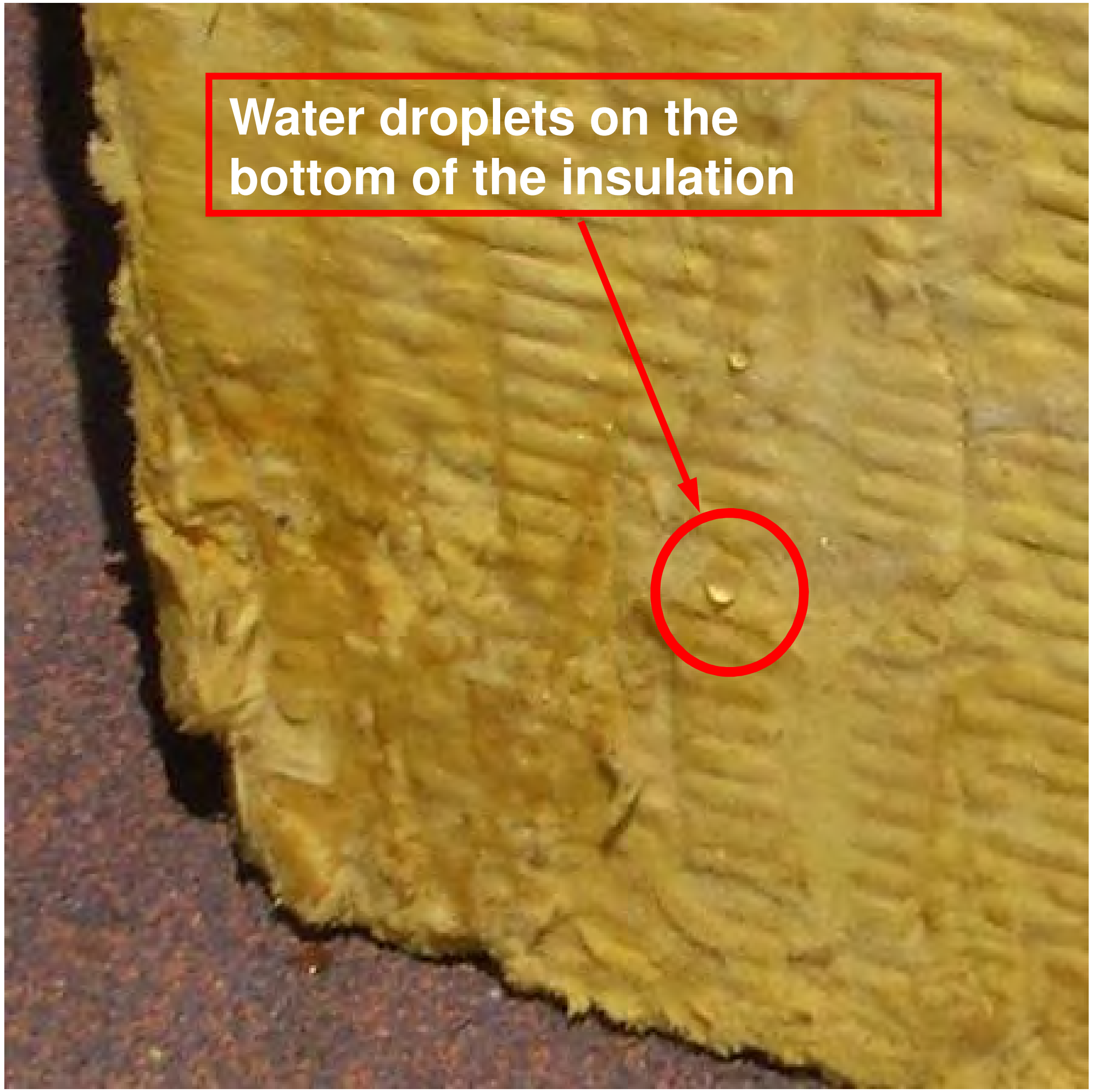






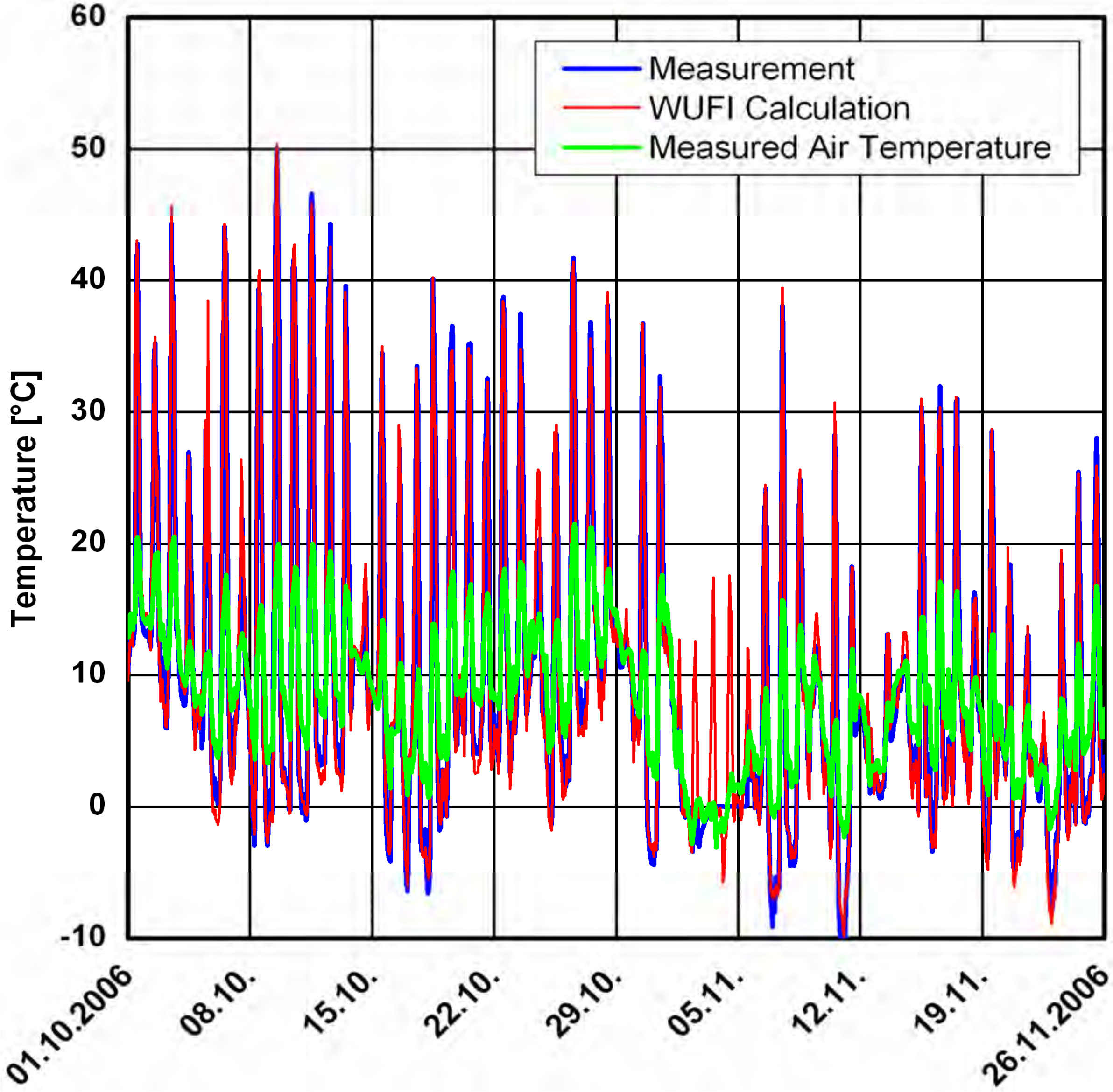
Hygrothermal simulation

Inspection of the roof after 3 years



Hygrothermal simulation

Surface temperature -
Comparison of calculation and measurement

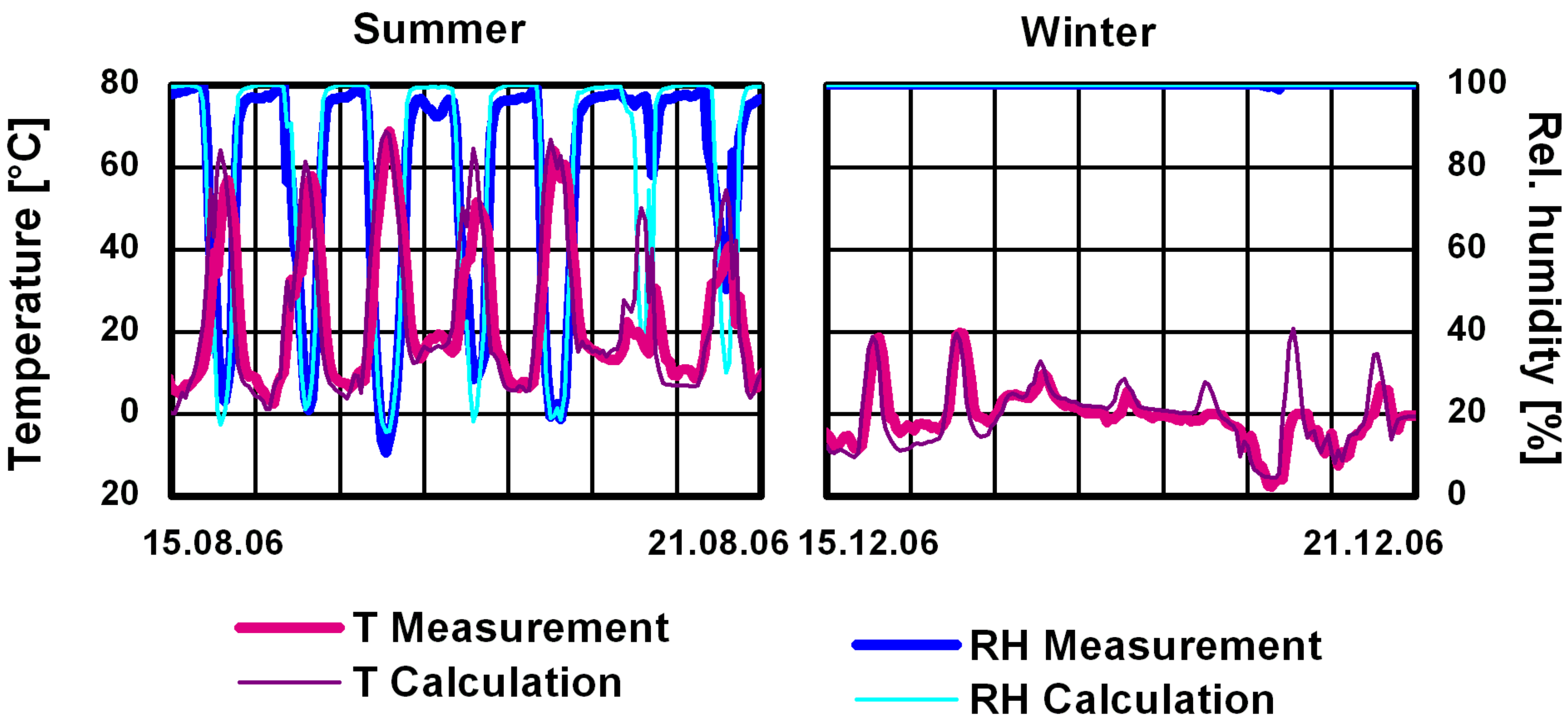


Exterior temp. sensor position (beneath the roofing membrane)

Hygrothermal simulation

Temperature and RH fluctuations within the roof assembly

Exterior sensor position (directly beneath the roofing membrane)

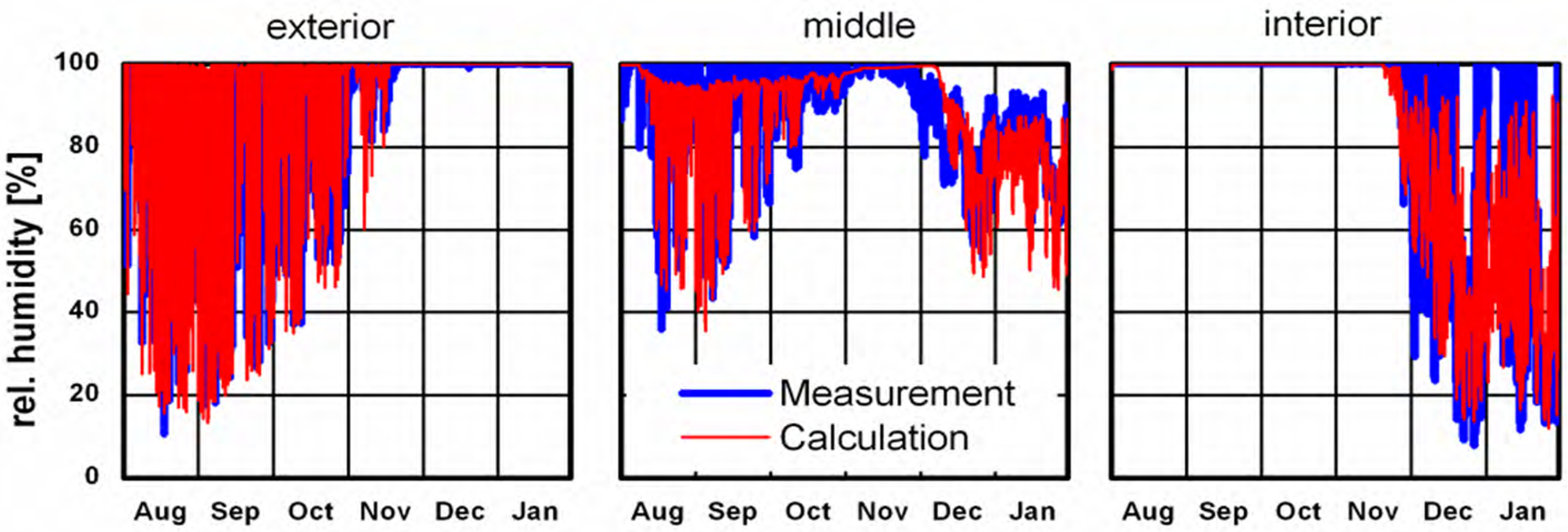


Fraunhofer IBP

Hygrothermal simulation

RH within the roof assembly (insulation thickness 90 mm)

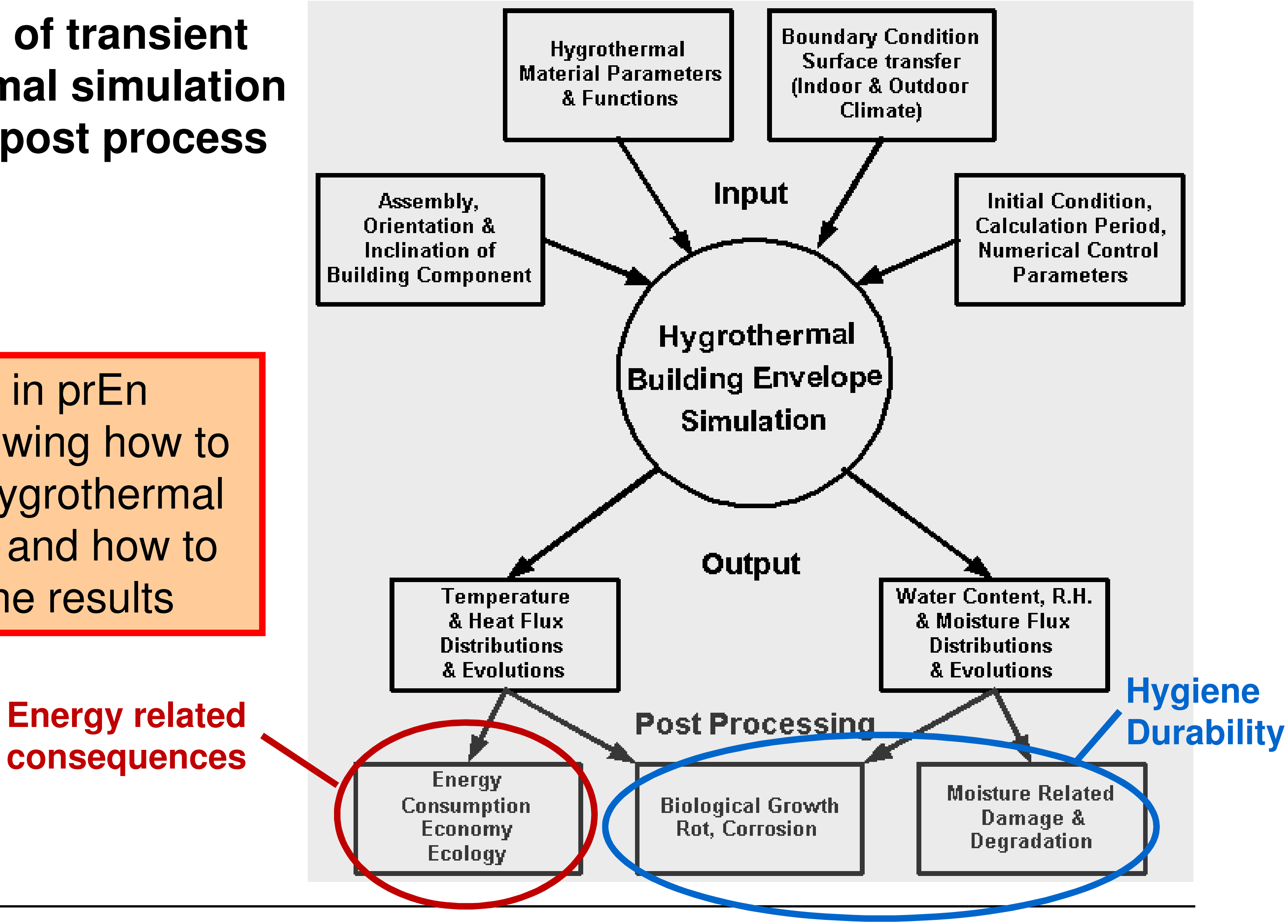
Humidity sensor positions



Hygrothermal simulation – result evaluation

Evaluation of transient hygrothermal simulation results by post process models

Flow chart in prEn 15026 showing how to perform hygrothermal simulation and how to evaluate the results



Hygrothermal simulation – result evaluation

Problem: effective R-value of “wet” insulation

Heat Transfer in a Wet Porous Thermal Insulation in a Flat Roof

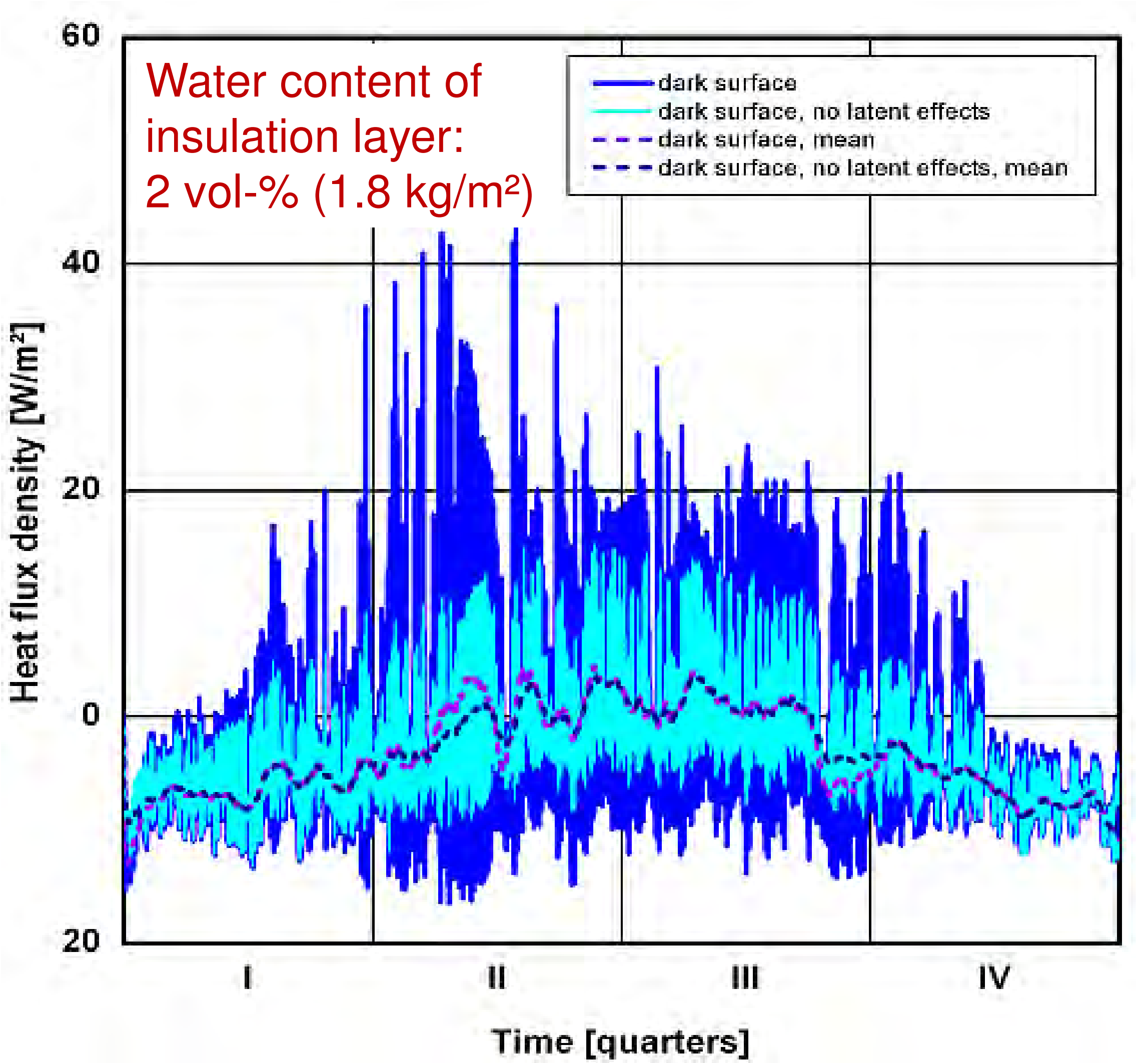
C. P. HEDLIN
Prairie Regional Station
Institute for Research in Construction
National Research Council of Canada
Saskatoon, Saskatchewan S7N 0W9

5. Latent heat conductances calculated in this way varied somewhat with moisture content of the specimen. Values for 1% moisture content specimens reached about 6.5 W/m²,kPa while those for a 9% moisture content specimen reached about 9.5 W/m²,kPa, for glass fiber 60 mm thick. The latter exceeds the value of 7.1 W/m²,kPa estimated for still air. It seems improbable that the rate of vapor movement in the glass fiber, which produces this heat flow, would exceed that in still air. Presumably the sensible heat component exceeds that for dry insulation, hence part of the heat flow attributed to vapor movement in this model is, in fact, due to sensible heat flow.

8. The results showed that glass fiber specimens containing 1, 9 and 15% moisture by volume produce daily average heat gains and losses about three times as great as dry insulation. The ratio did not appear to vary significantly with increased moisture content.

Hygrothermal simulation – result evaluation

Problem: effective R-value of “wet” insulation



Thermal performance:

Calculated heat flux density at the interior surface

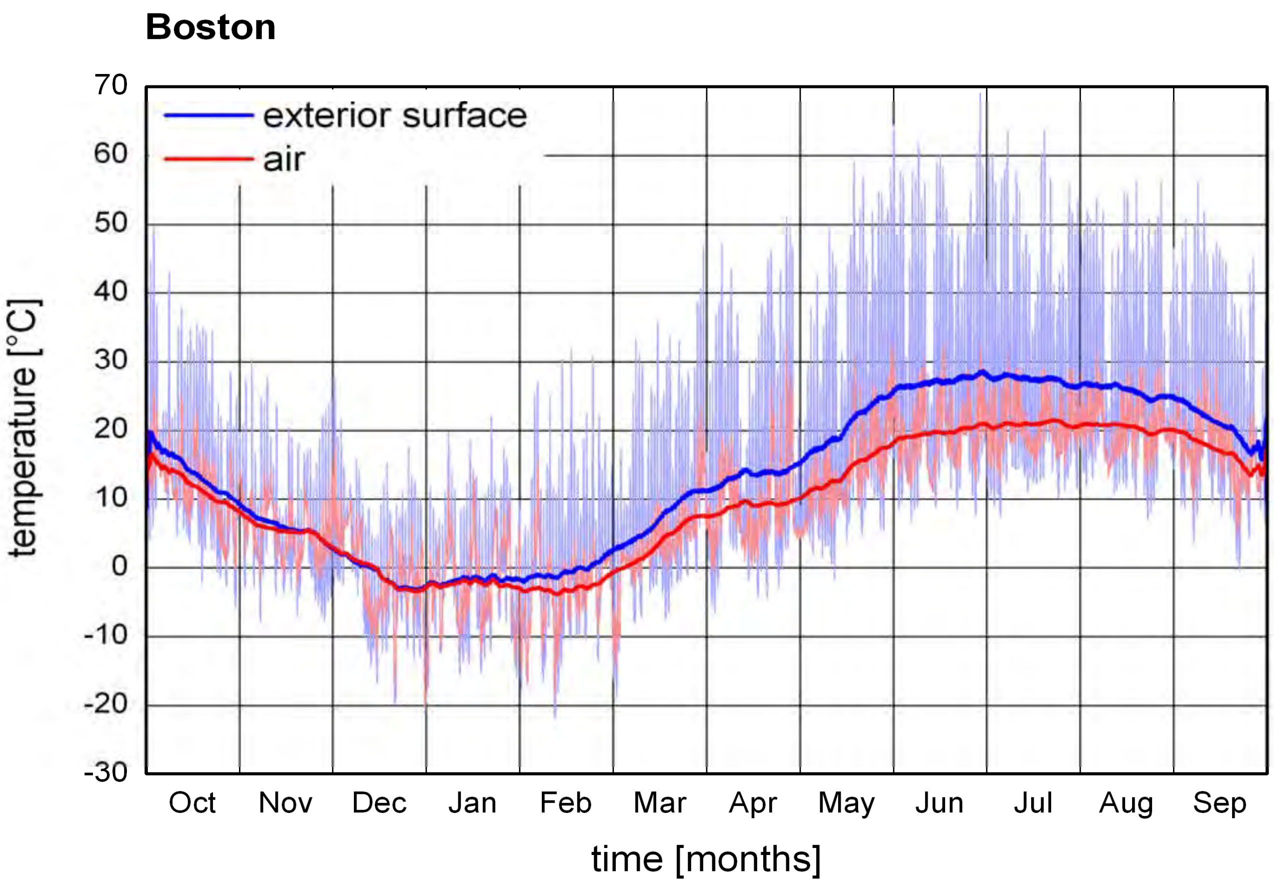
if > 0: inward flux
if < 0: outward flux

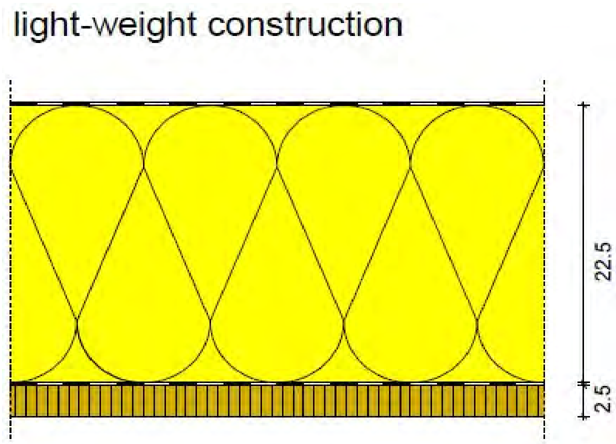
Short wave absorptivity of exterior surface: 0.9

Hygrothermal simulation – result evaluation

Example case: flat roof with fiber insulation in Boston

Temperatures

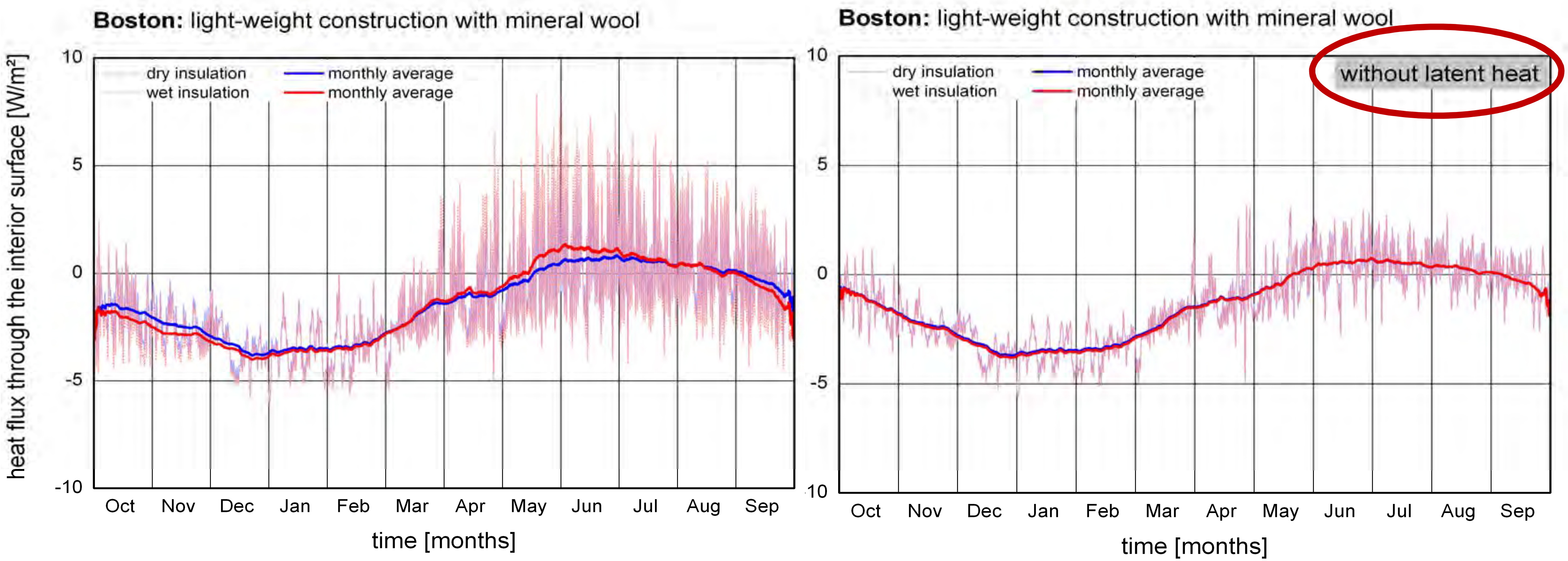




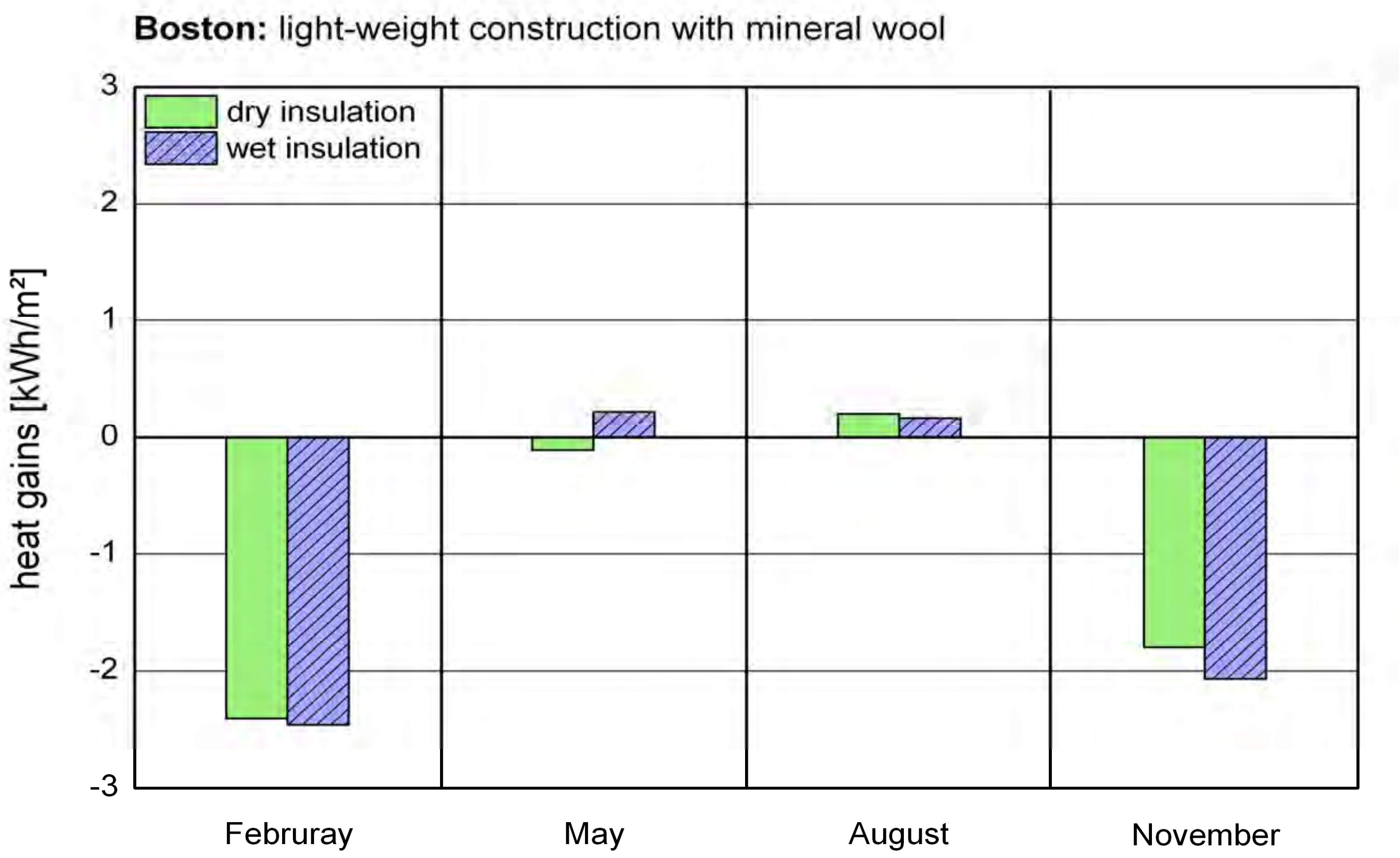
Hygrothermal simulation – result evaluation

Heat fluxes

Calculated hourly heat fluxes and their running monthly means at the interior surface of the flat roof with and without latent heat



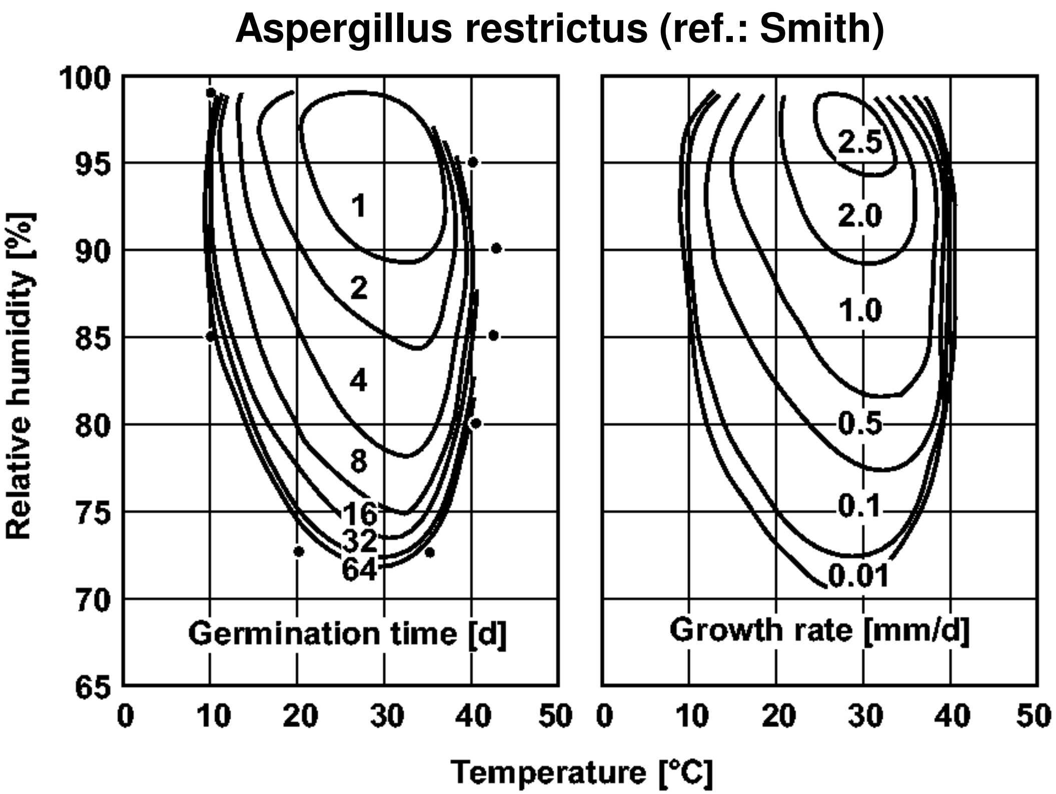
Hygrothermal simulation – result evaluation

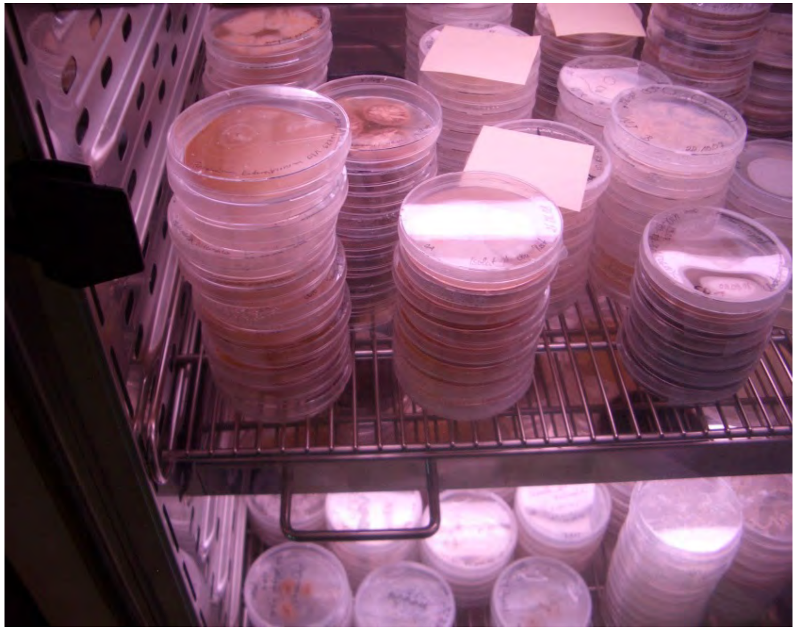


Impact of moisture in fiber glass insulation on effective thermal resistance during heating and cooling season is smaller than expected

Hygrothermal simulation – result evaluation

Problem: mold growth

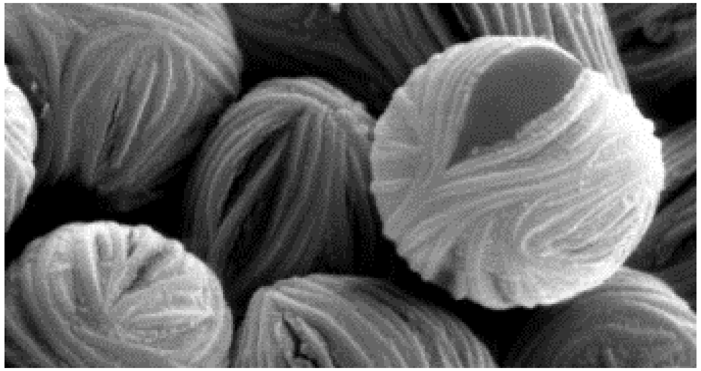


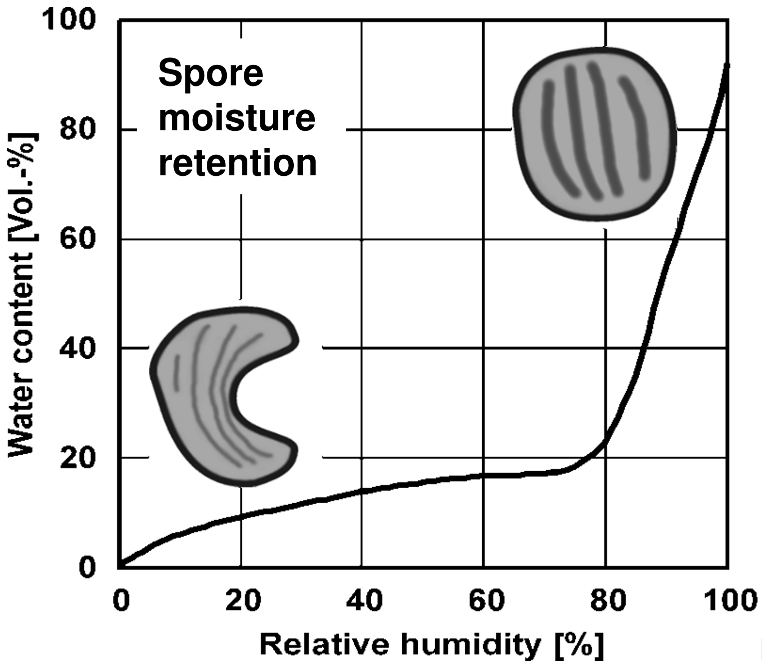


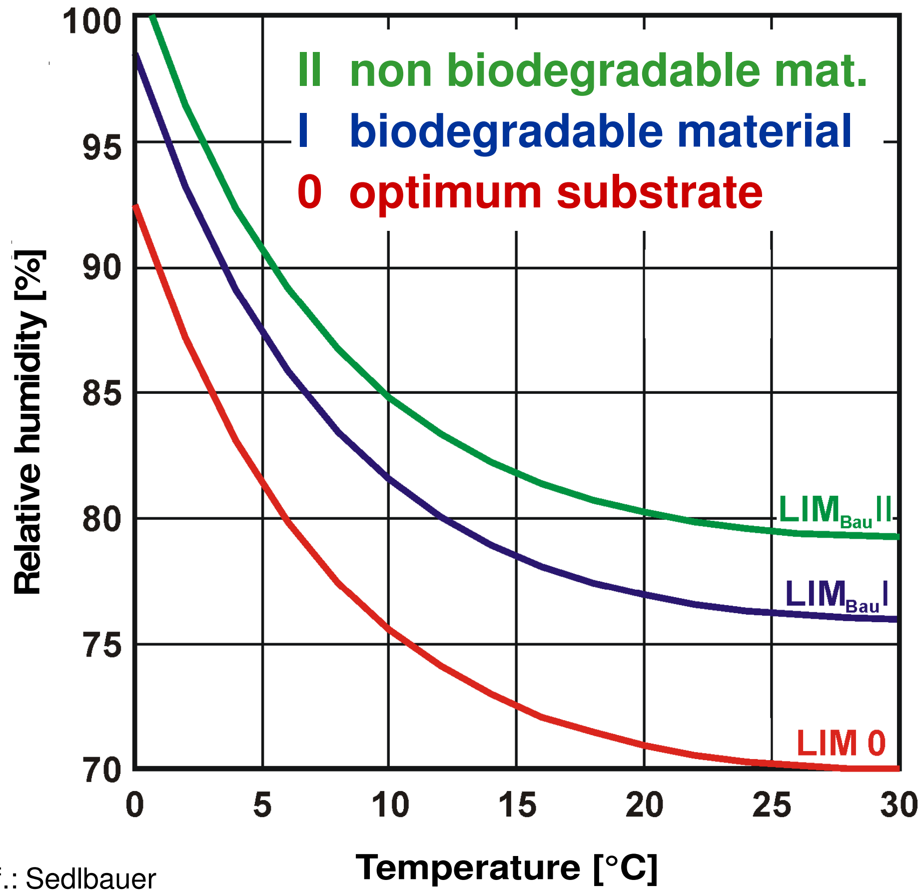
Mould germination time and growth depend mainly on RH, temperature and substrate quality

Hygrothermal simulation – result evaluation

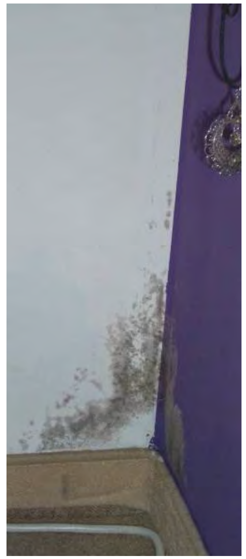
Modeling mold growth







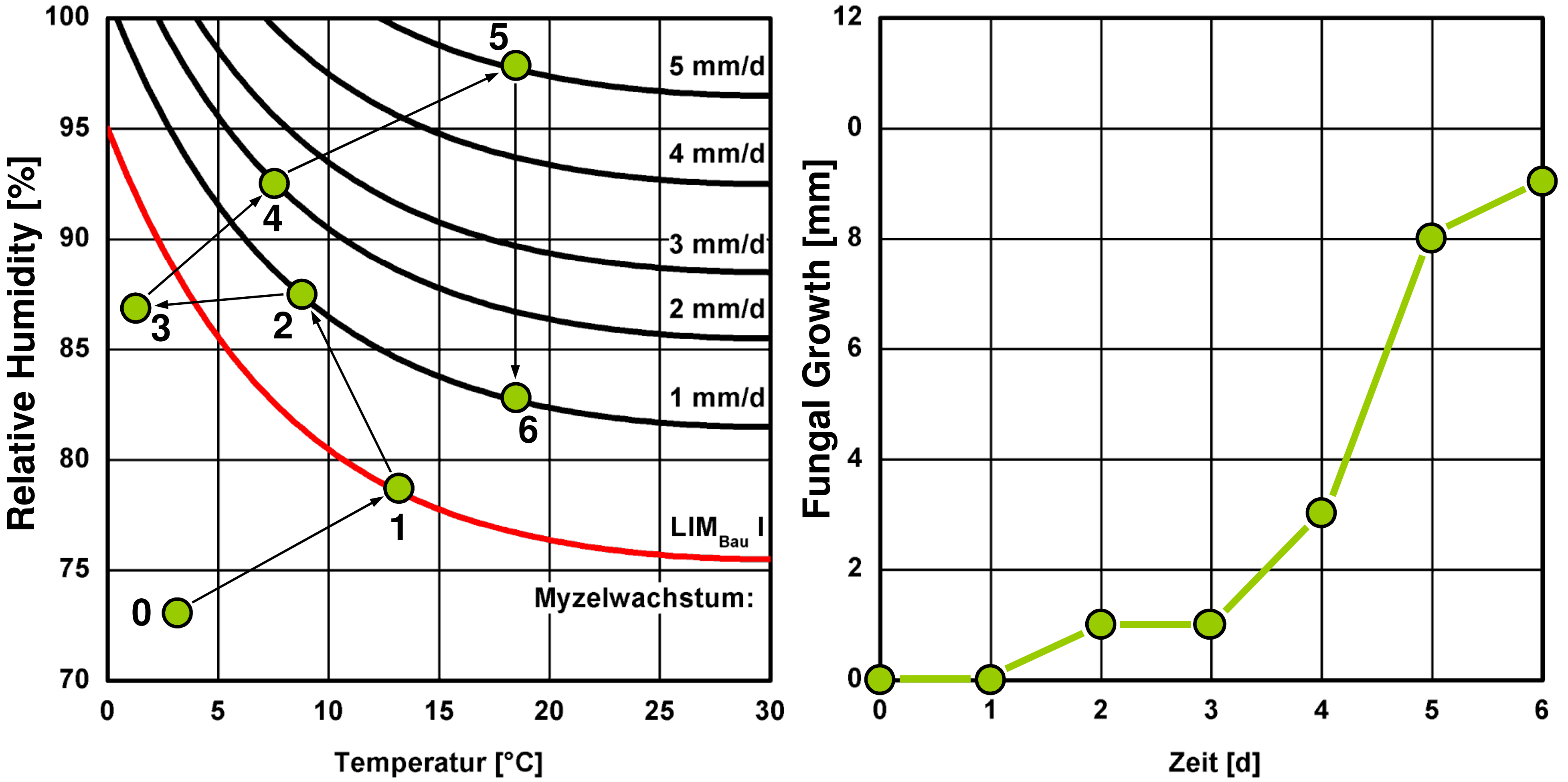
Ref.: Sedlbauer



Hygrothermal simulation – result evaluation

Modeling mold growth (Sedlbauer)

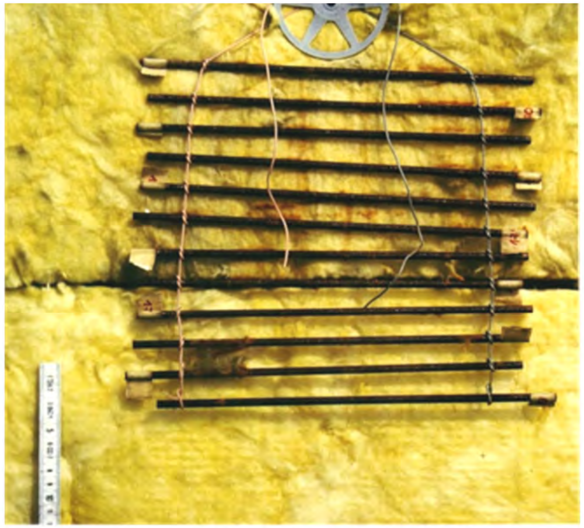
Viitanen from VTT has developed a model that accounts for mold decline under dry conditions

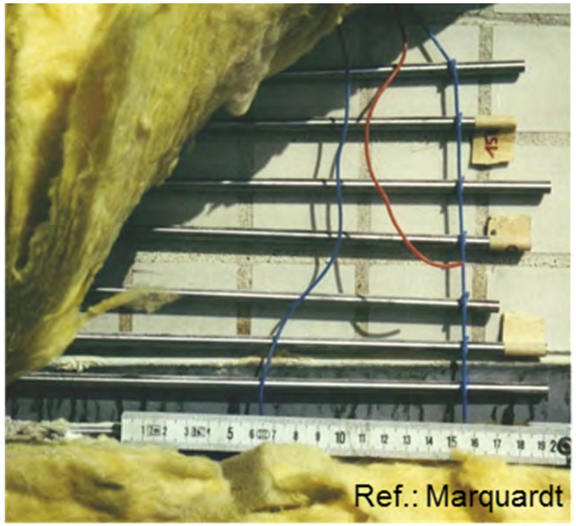


Hygrothermal simulation – result evaluation

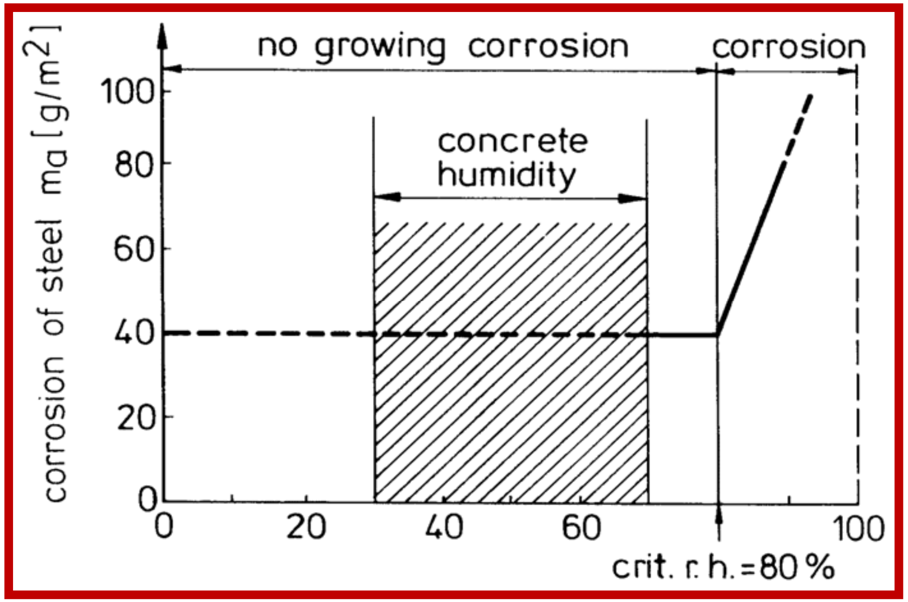
Problem: corrosion

Corrosion of concrete sandwich element after carbonation of exterior surface layer





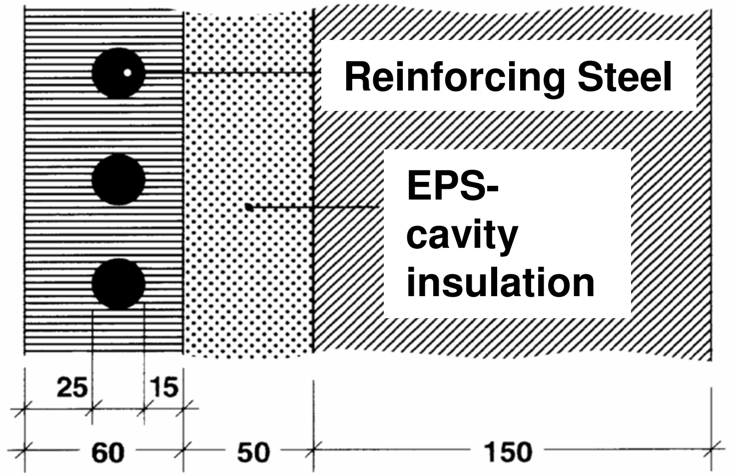
Steel bars behind cladding & behind insulation



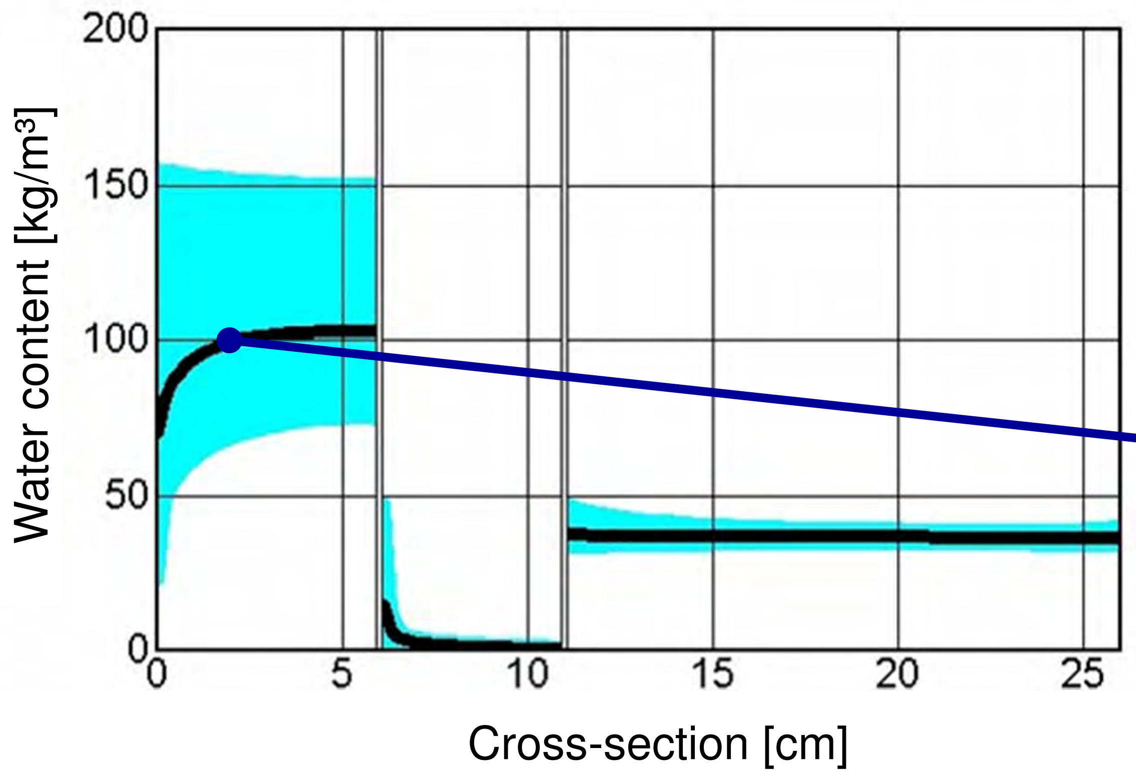
TU Berlin:
no corrosion in carbonated concrete < 80% RH

Hygrothermal simulation – result evaluation

Solving corrosion problems of sandwich panels by adding exterior insulation



WUFI® simulation over several years (Holzkirchen climate, exposed facade)

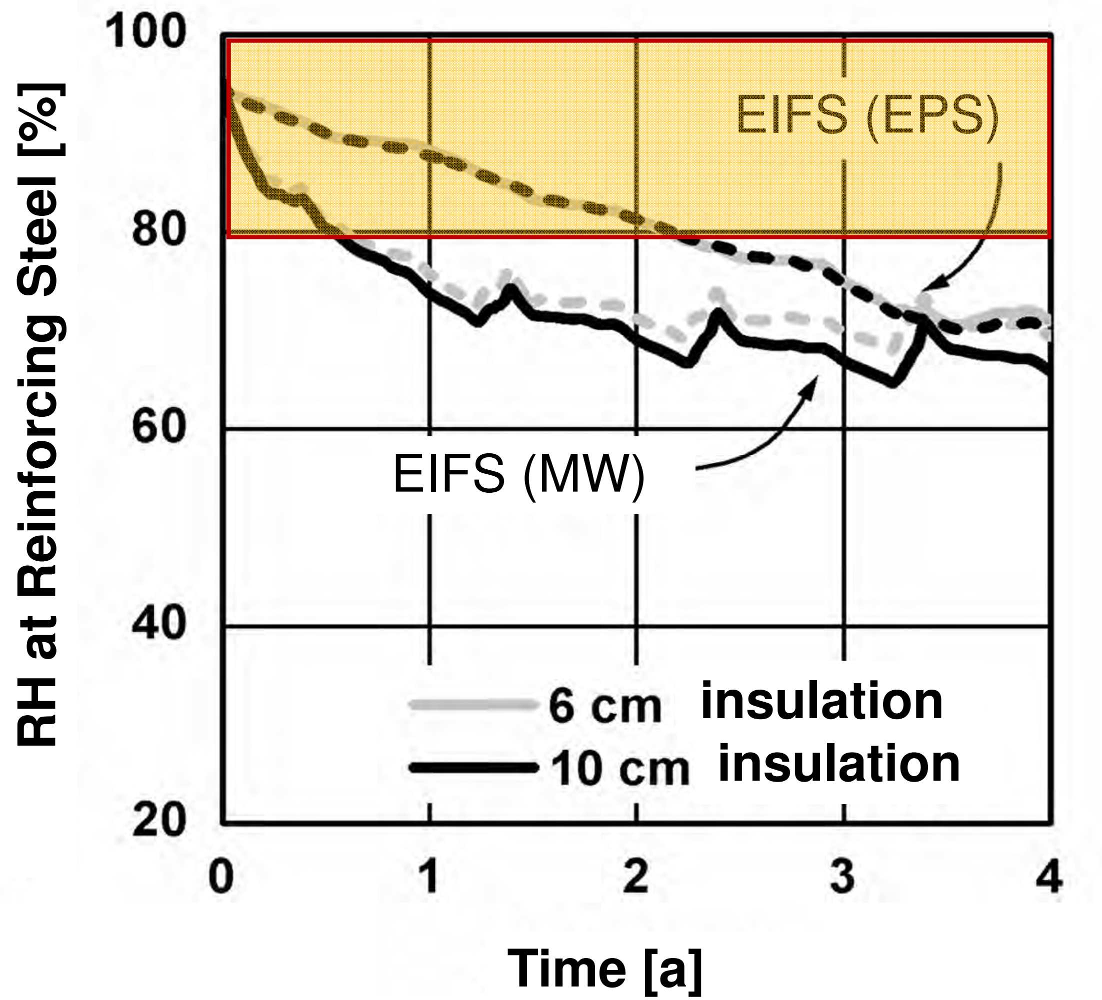


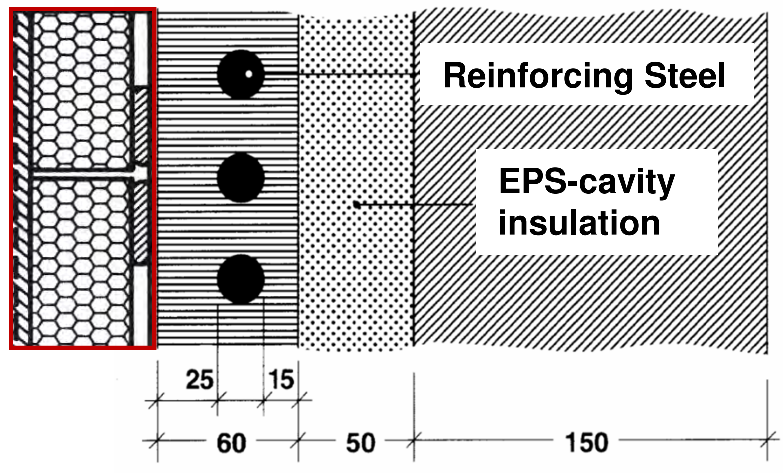
Concrete:
100 kg/m³ (10 vol.-%)
= EMC at 95% r.F.

Fraunhofer IBP

Hygrothermal simulation – result evaluation

Drying of exposed concrete sandwich element after thermal retrofit (WUFI sim.)

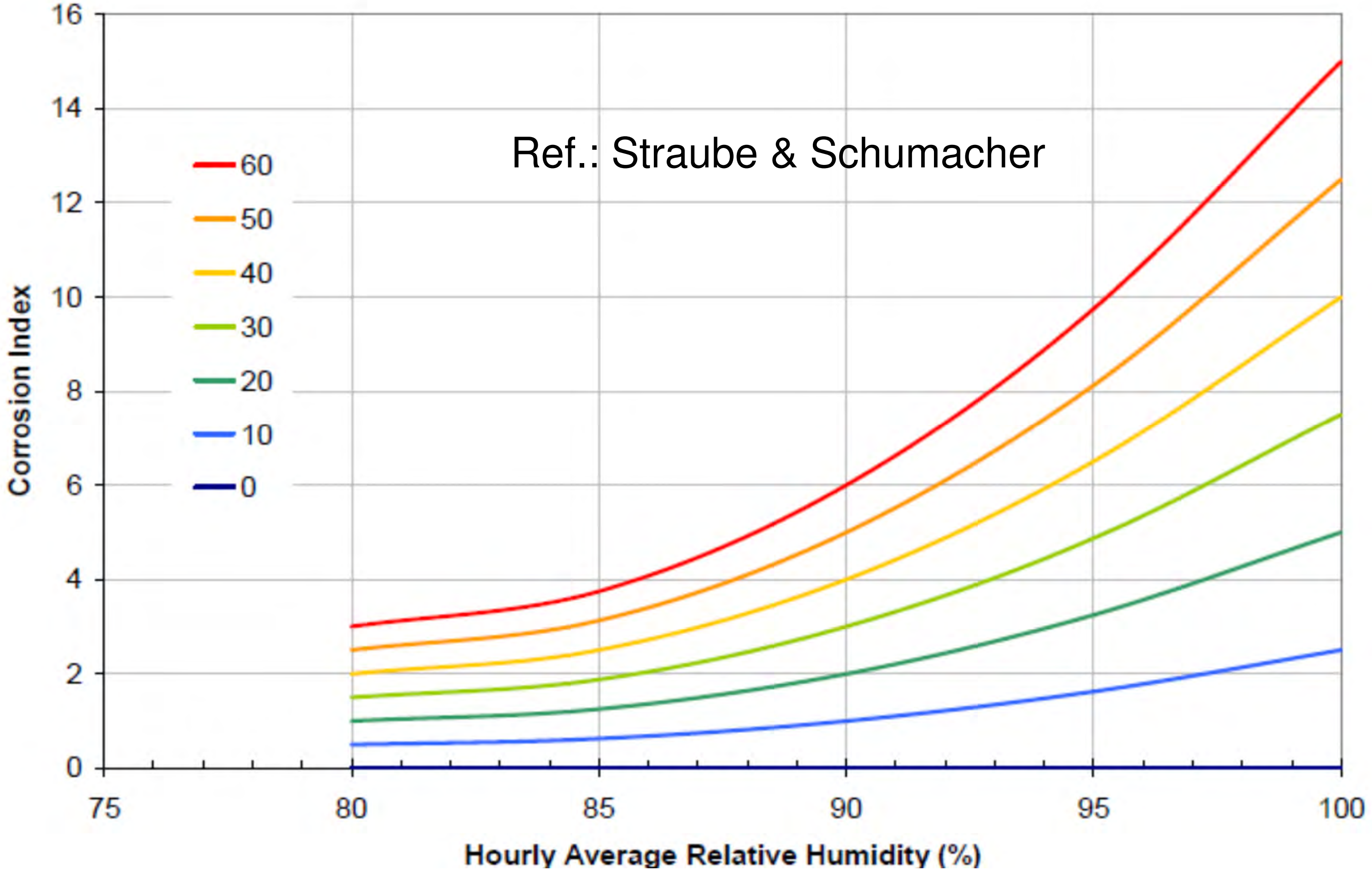




Corrosion discontinues between 6 months (MW) and 2 years (EPS) after application of EIFS

Hygrothermal simulation – result evaluation

Corrosion: from TOW (EMC 80%) to temperature and RH dependent corrosion rate

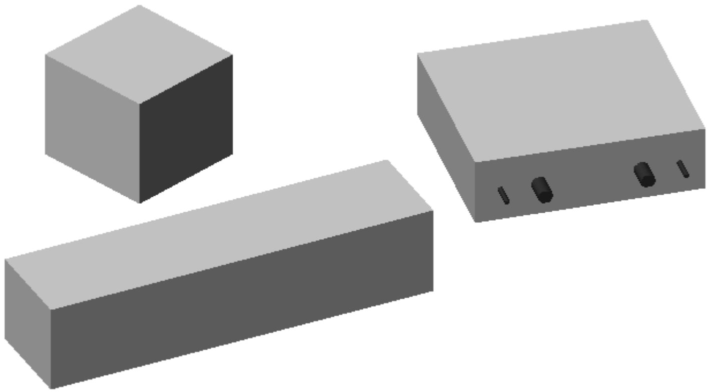


Predicting corrosion based on hygrothermal simulation results

Fraunhofer IBP

Hygrothermal simulation – result evaluation

Predicting corrosion of steel in historic mortars
(based on research results from Politecnico di Milano)



EXPOSURE CONDITIONS:

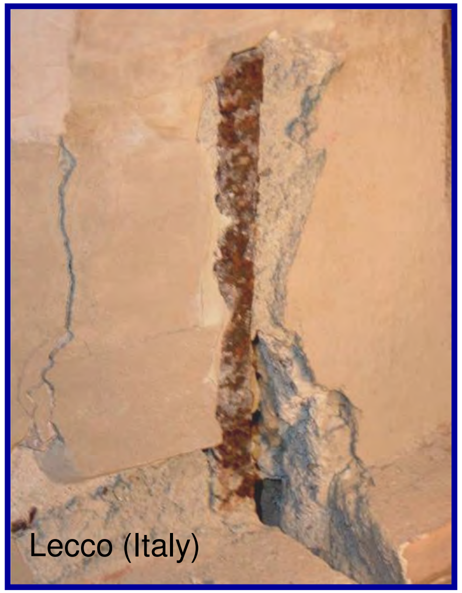
- **T ➔ 5-20-40°C**
- **RH ➔ 65-80-95% and in H_2O**
- **Time ➔ 50 and 7 days**

TYPE OF MORTAR:

- **Gypsum (*G*)**
- **Lime and Gypsum (*LG*)**
- **Lime and Pozzolana (*LP*)**
- **Lime and Cocciopesto (*LCP*)**
- **Lime and Cement (*LC*)**

CORROSION TESTS:

- **Electrical resistivity (ρ, Ωm)**
- **Corrosion potential (E_{corr}, mV)**
- **Corrosion rate (i_{corr}, mA/m²)**

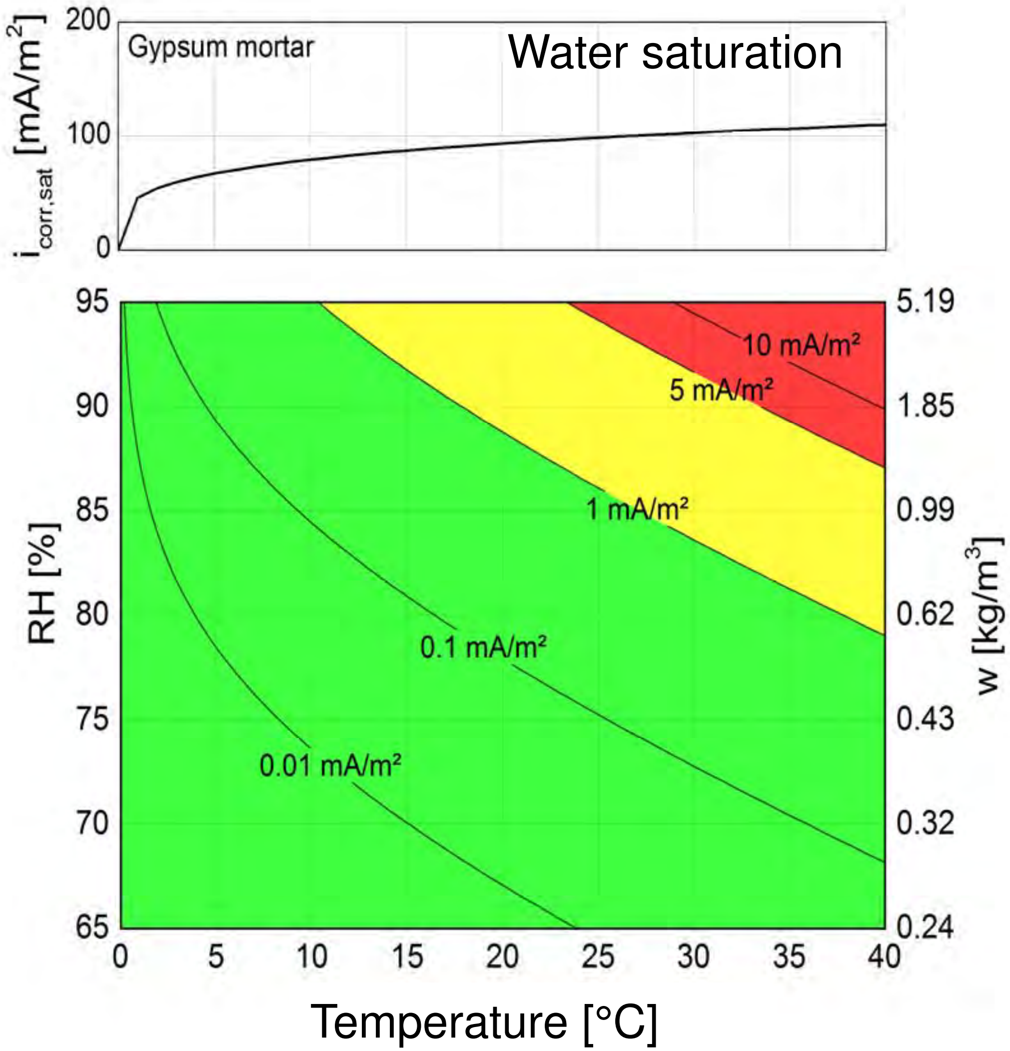


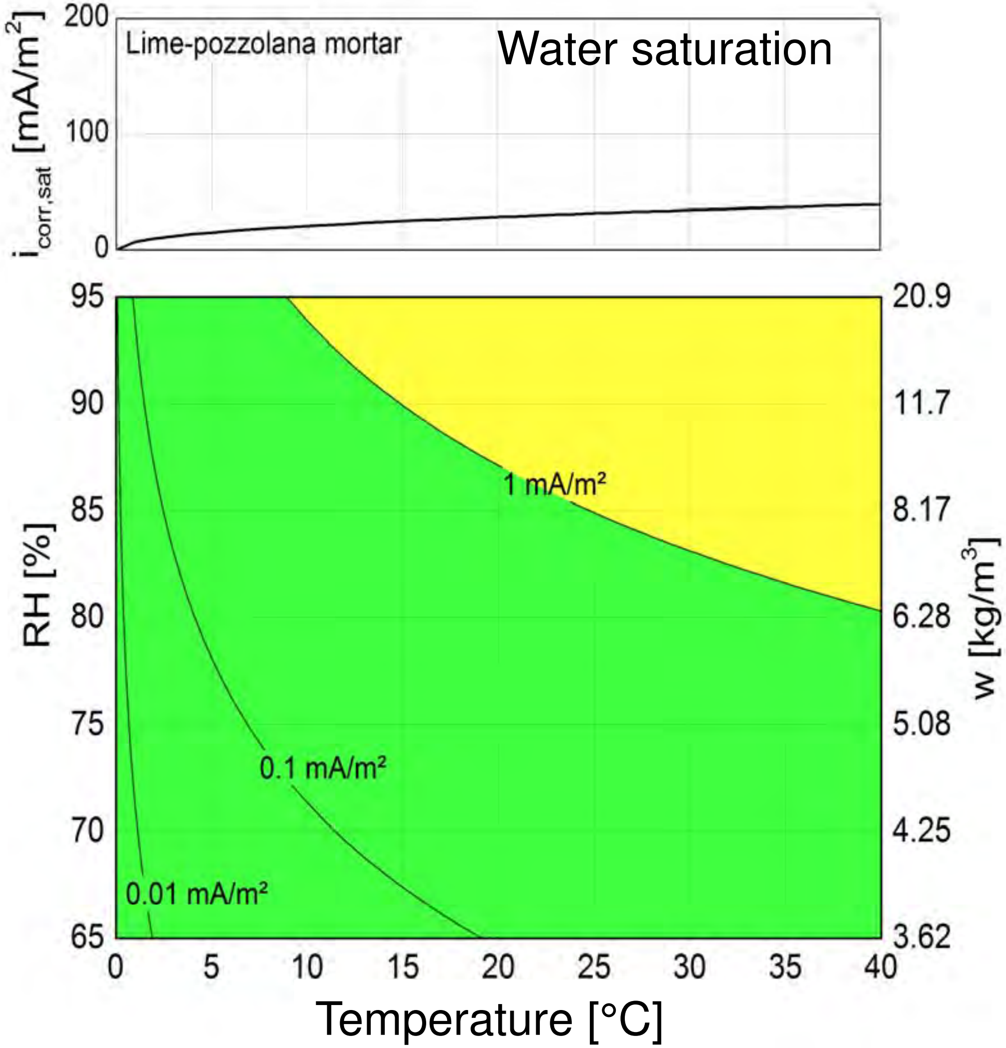
Lecco (Italy)

Determining temp. & RH dependent corrosion rate

Hygrothermal simulation – result evaluation

Corrosion progress of carbon steel in mortars: gypsum / lime-cement

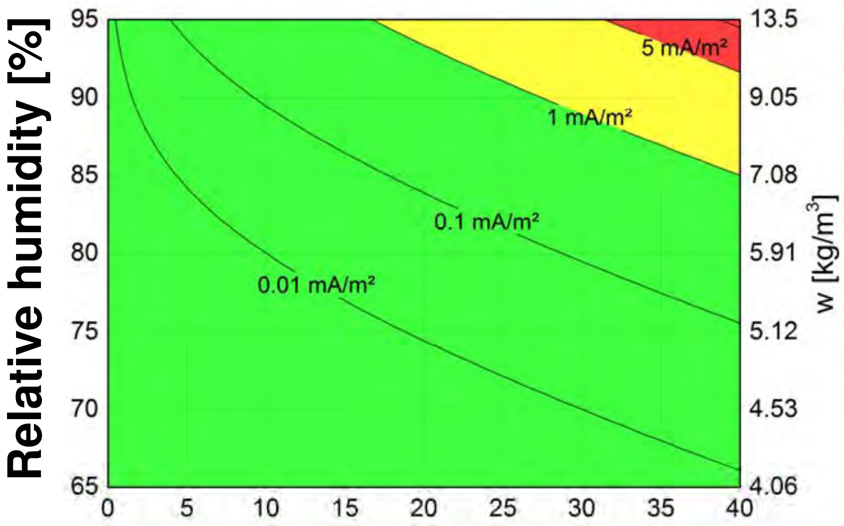


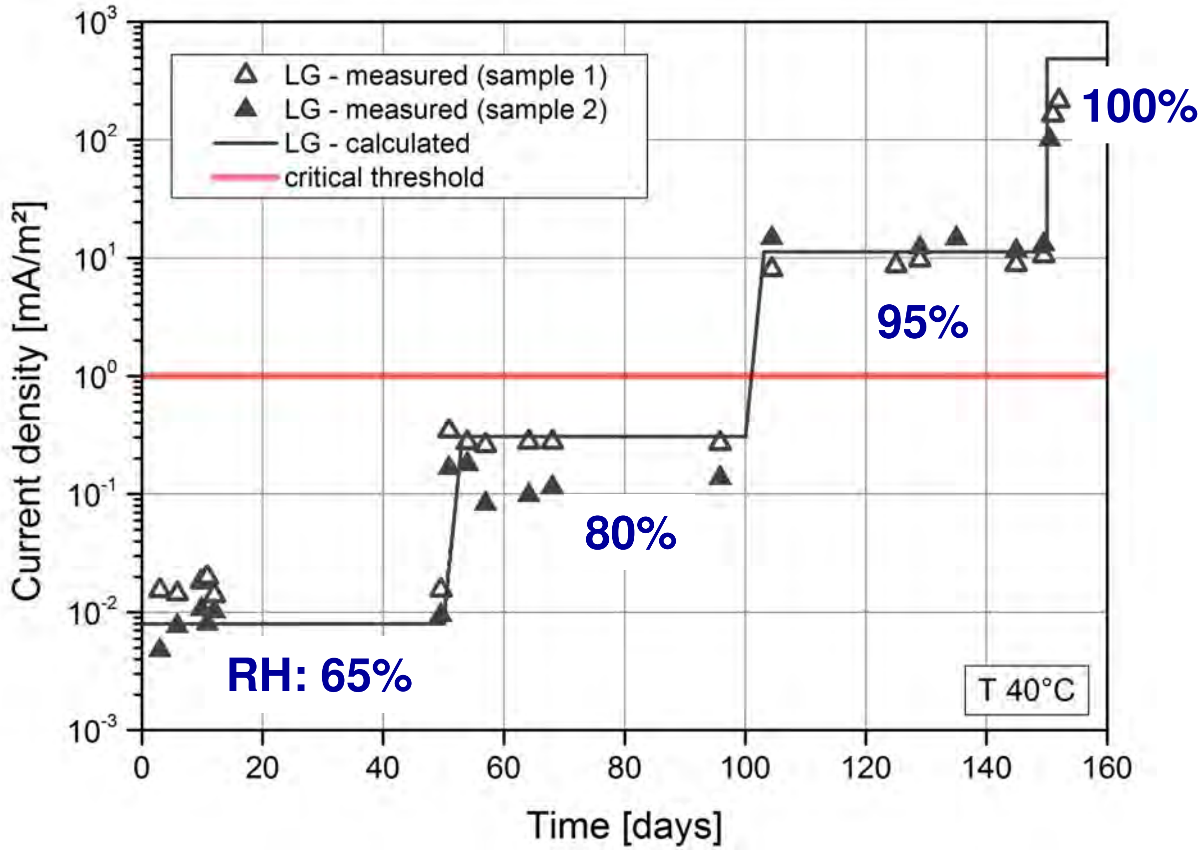


Hygrothermal simulation – result evaluation

Corrosion model validation

Lime and gypsum mortar (LG)
corrosion model vs. measured data



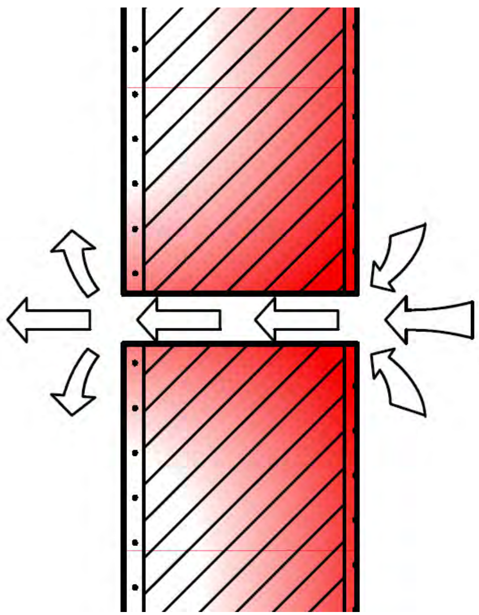


- Model results slightly overestimate corrosion rate (being on the safe side)
- Differences max. 1,5 µm/year
- Validation also at 5°C and 20°C and for other mortars

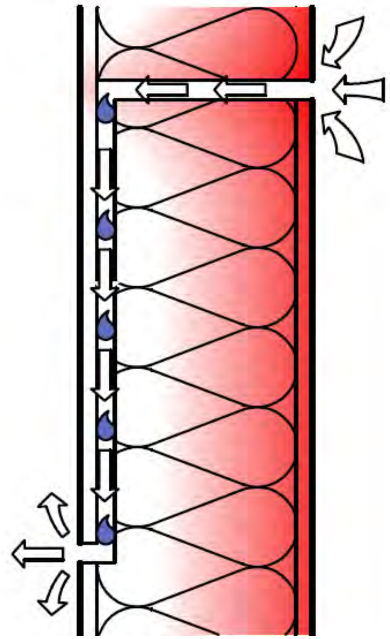
Hygrothermal simulation – air infiltration model

Condensation potential of different leak pattern

Energy leak



Moisture leak



Warming of the flow path in case of straight air flux ⇨

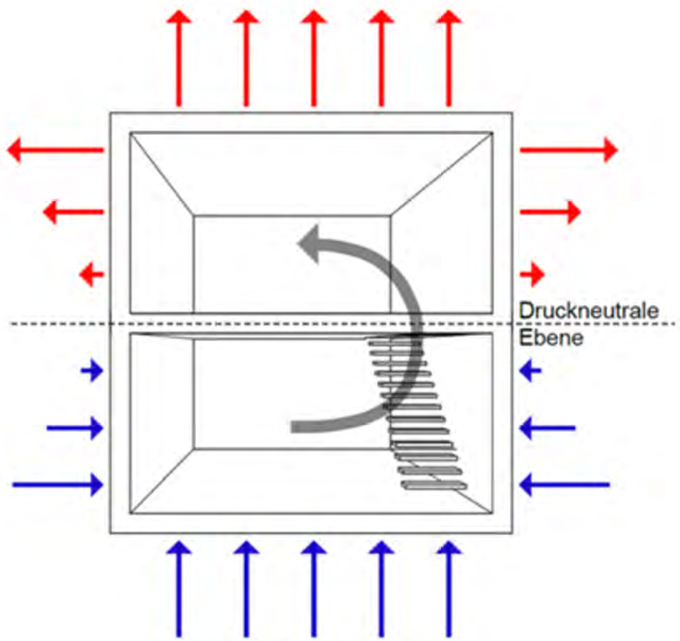
No or only little condensation

Cooling of the air in case of slow and indirect path ⇨

potential of serious condensation

Hygrothermal simulation – air infiltration model

Driving forces for air flow through building envelope systems



Wind

air pressure differentials depend on:
- wind speed and direction
- building height and geometry
- open windows, partition air-tightness

Stack

air pressure differentials due to buoyancy

$$\Delta P = \rho \cdot \frac{T_a - T_i}{T_i} \cdot g \cdot \frac{h}{2}$$

Fan pressurization

air pressure differentials due unbalanced ventilation (continuous / temporary)

Hygrothermal simulation – air infiltration model

Flow paths through building envelope components are 3D-phenomena of random nature

– they defy even sophisticated models

Only one guy thinks he can do it!

Hygrothermal simulation – air infiltration model

Therefore a simple 1D approach is proposed

$$q_{CL} = k_{CL} \cdot (P_i - P_e)$$

q_{CL} [m³/m²h] air flow through moisture leaks

k_{CL} [m³/m²h·Pa] air permeability of …

CL = Component Leakage

Determination of k_{CL} is the challenge

Ask Anton!

TenWolde et al. (1998):

Moisture entry caused by infiltration corresponds to the amount of moisture which permeates by vapor diffusion through a retarder with 1 perm

Air permeability of moisture leaks k_{CL} = 0,007 m³/(m²h·Pa)

Hygrothermal simulation – air infiltration model

Transient moisture sources S_{CL} resulting from air penetration

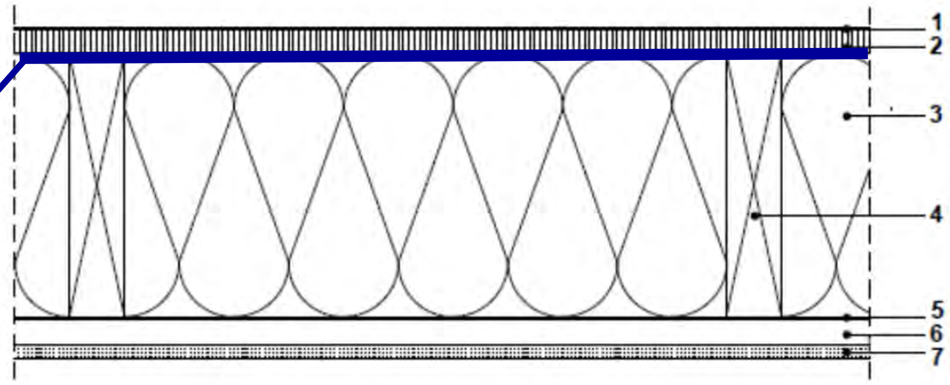
$$S_{CL} = q_{CL} \cdot \left(c_i - c_{sat,\,x_p}\right)$$

c_i [kg/m³] indoor vapor concentration

$c_{sat,xp}$ [kg/m³] sat. vap. con. at position x_p

Example flat roof:

condensation plane x_p

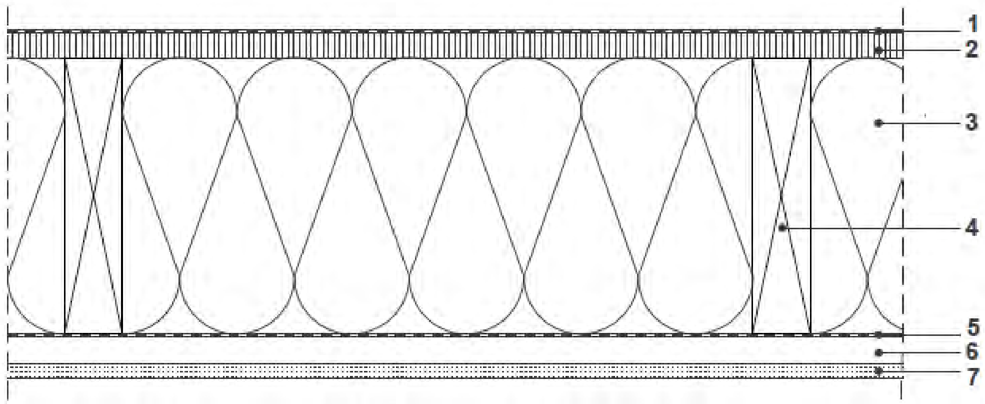


Model assumptions:

- Heat effects of penetrating air (sensible and latent) are neglected
- Only condensation at position x_p is considered – i.e. no sorption at high RH
- Convective drying is excluded (buoyancy model)

Hygrothermal simulation – air infiltration model

Application example: flat roof in Chicago



1	roofing membrane	
2	OSB	22 mm
3	mineral fiber insulation	240 mm
4	load bearing structure	240 mm
5	vapor barrier	
6	air layer	24 mm
7	gypsum board	12,5 mm

The moisture source due to air infiltration into the assembly is simulated as a function of the following parameters:

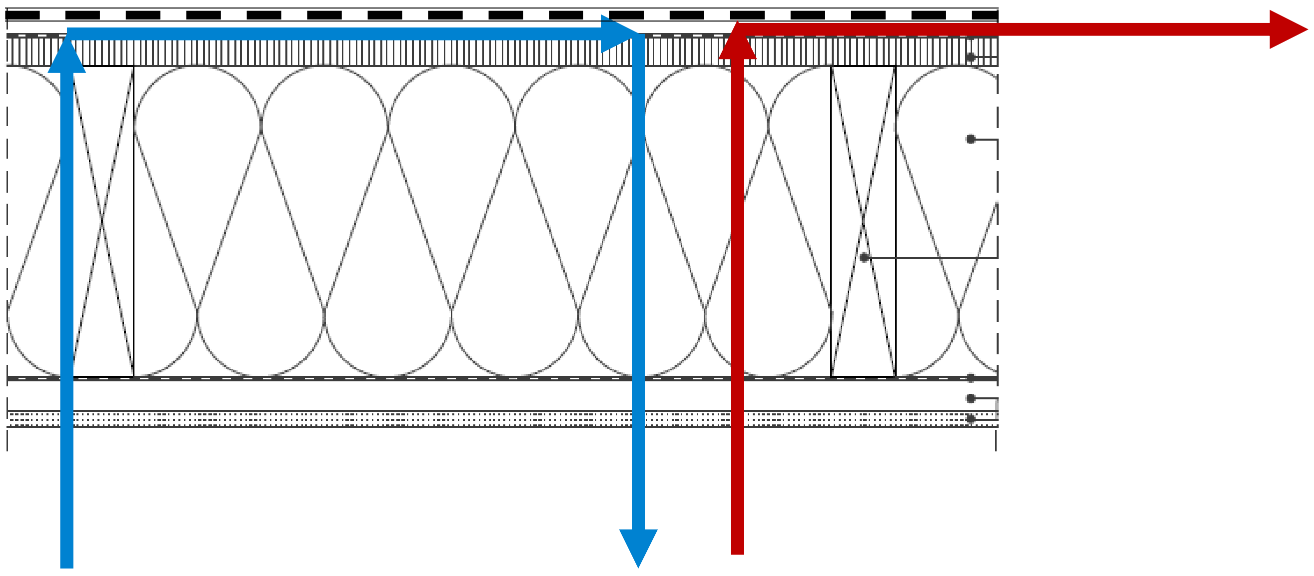
- air flow path (selection of condensation plane)
- stack height
- outdoor climate and indoor climate

Hygrothermal simulation – air infiltration model

Comparison: infiltration / convection of indoor air

Indoor air convection (looping, ventilation by indoor air)

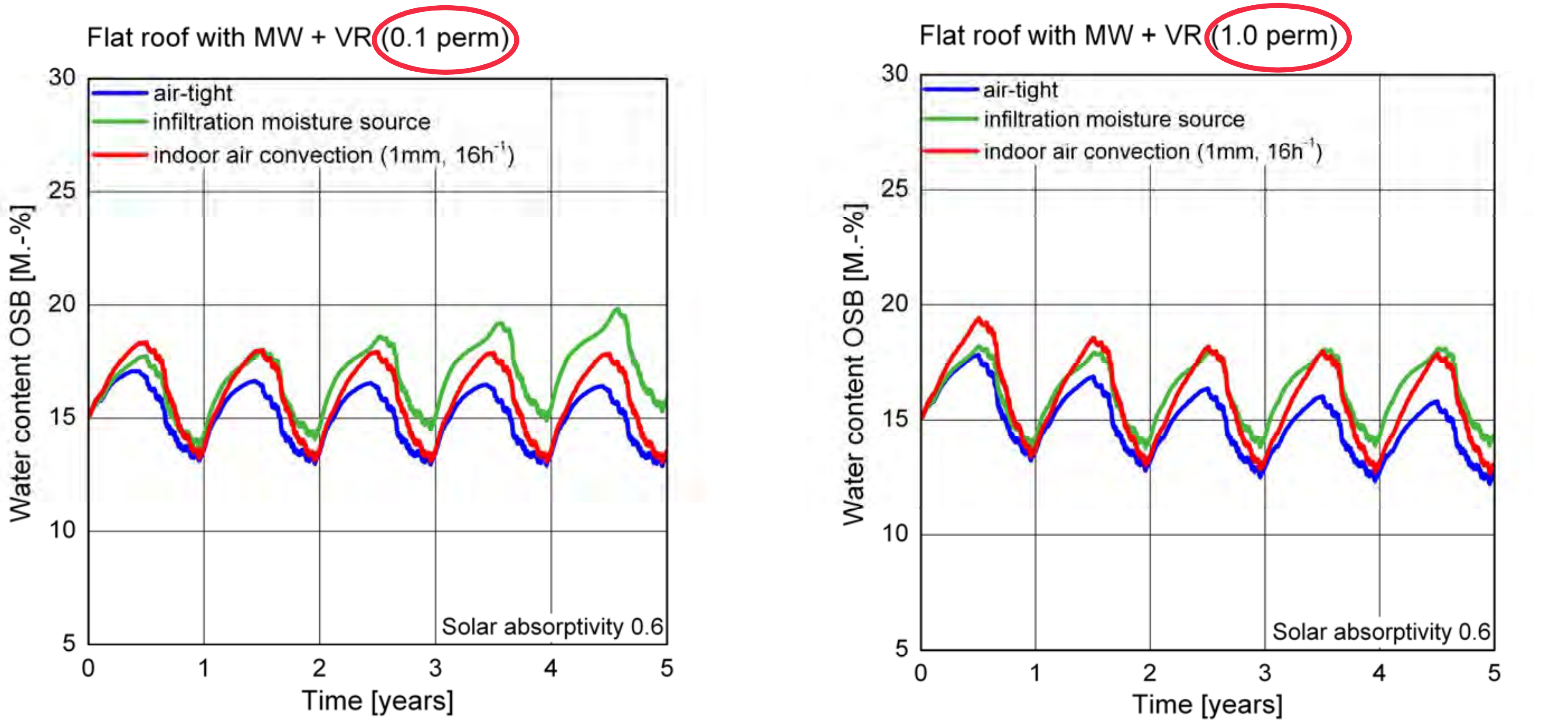
- Average width of air gap between sheathing an roofing membrane: 1 mm
- Air change rate corresponding to moisture source of infiltration model: 16 h^{-1}
- Constant ACH over whole year including all thermal effects



Hygrothermal simulation – air infiltration model

Evaluation of the OSB moisture content (MW & VR 0.1 / 1.0 perm)

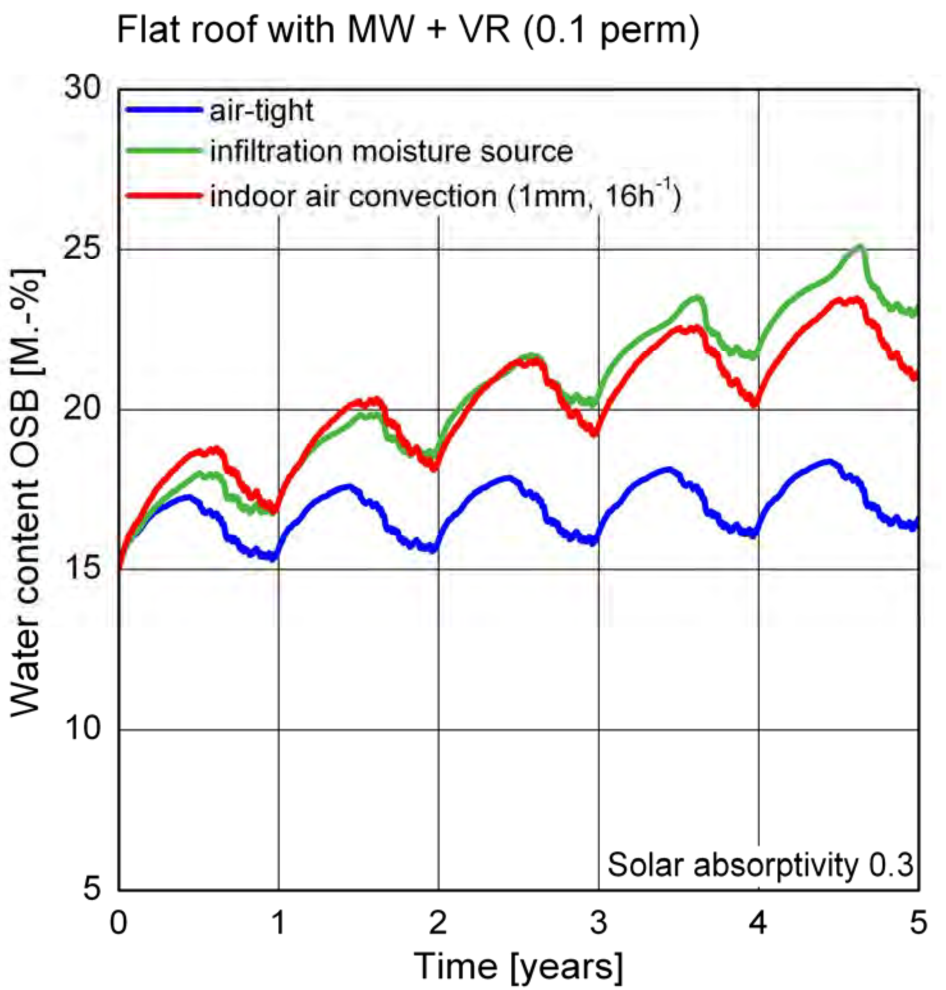
- different air flow models
- Chicago cold year, indoor climate acc. to Std. 160 (simpl. method)
- stack height of 5 m
- grey roofing membrane (a_s = 0.6)



Hygrothermal simulation – air infiltration model

Evaluation of the OSB moisture content (MW & EPS)

- **reflective roofing membrane (as = 0.3)**



Both airflow models give similar results in this case:

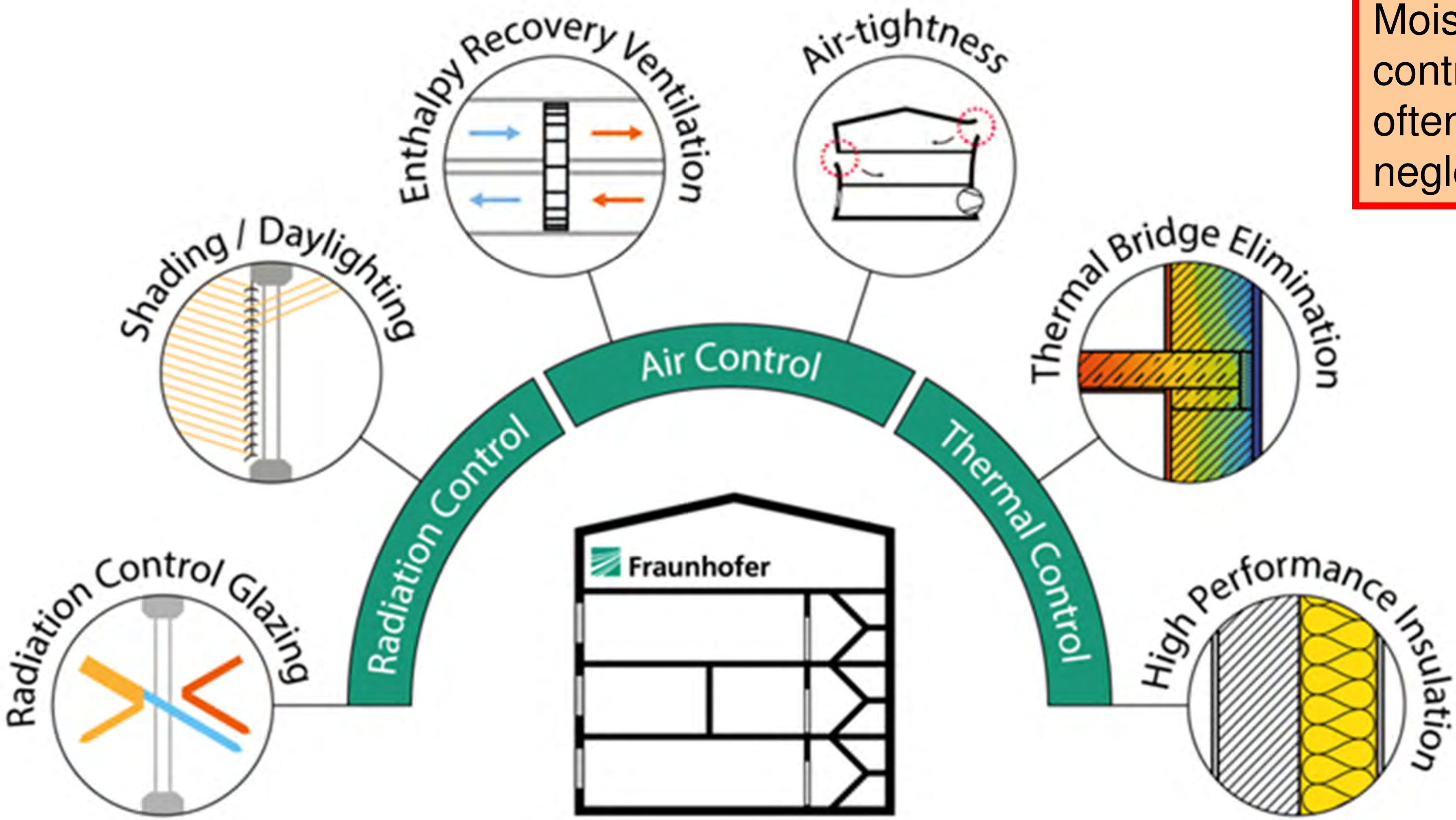
A cool roof in a cold climate may cause problems

I am afraid Andre hates me for this

Hygrothermal whole building analysis

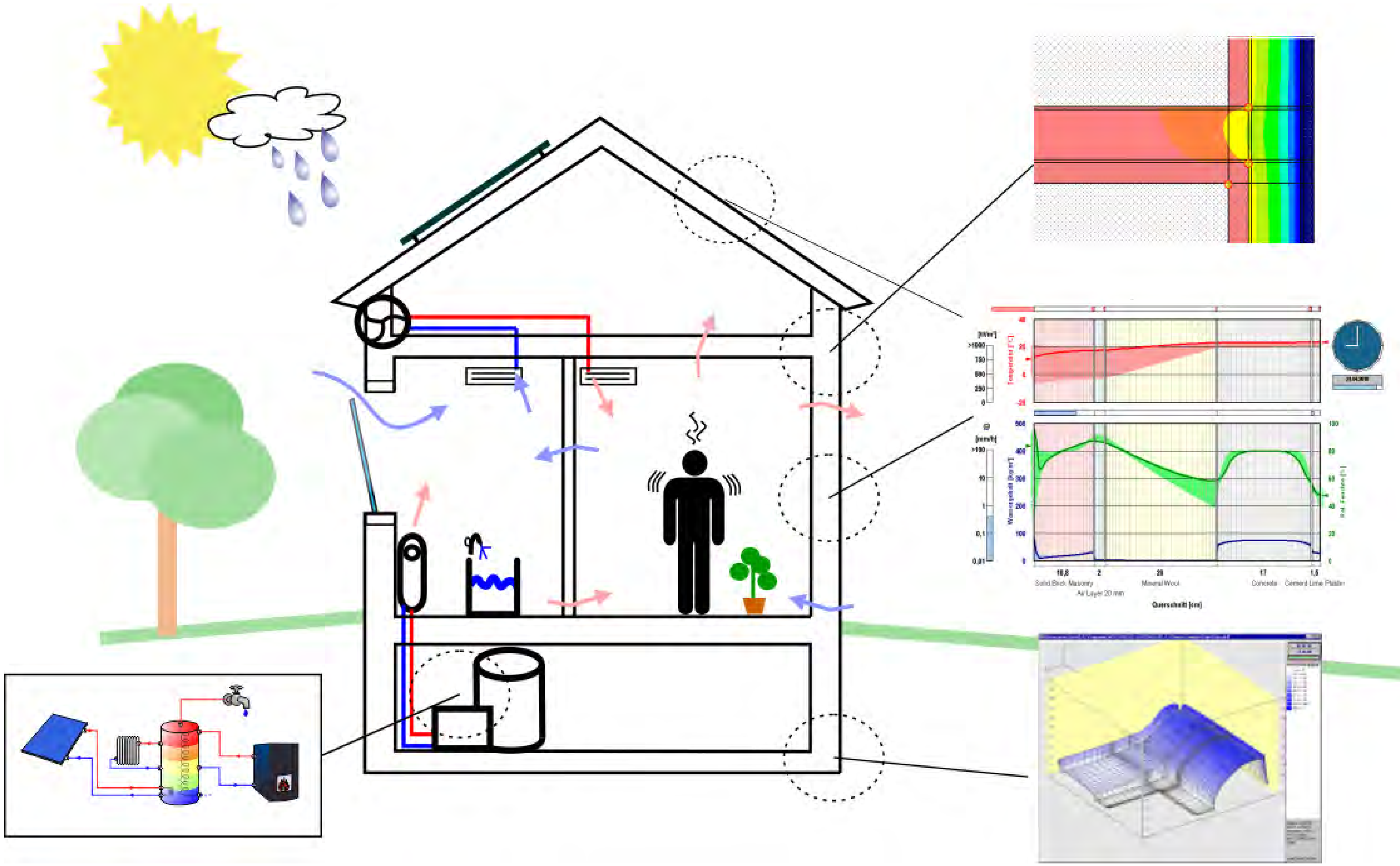
Passive design principles for energy efficient buildings

Moisture control is often neglected



Hygrothermal whole building simulation

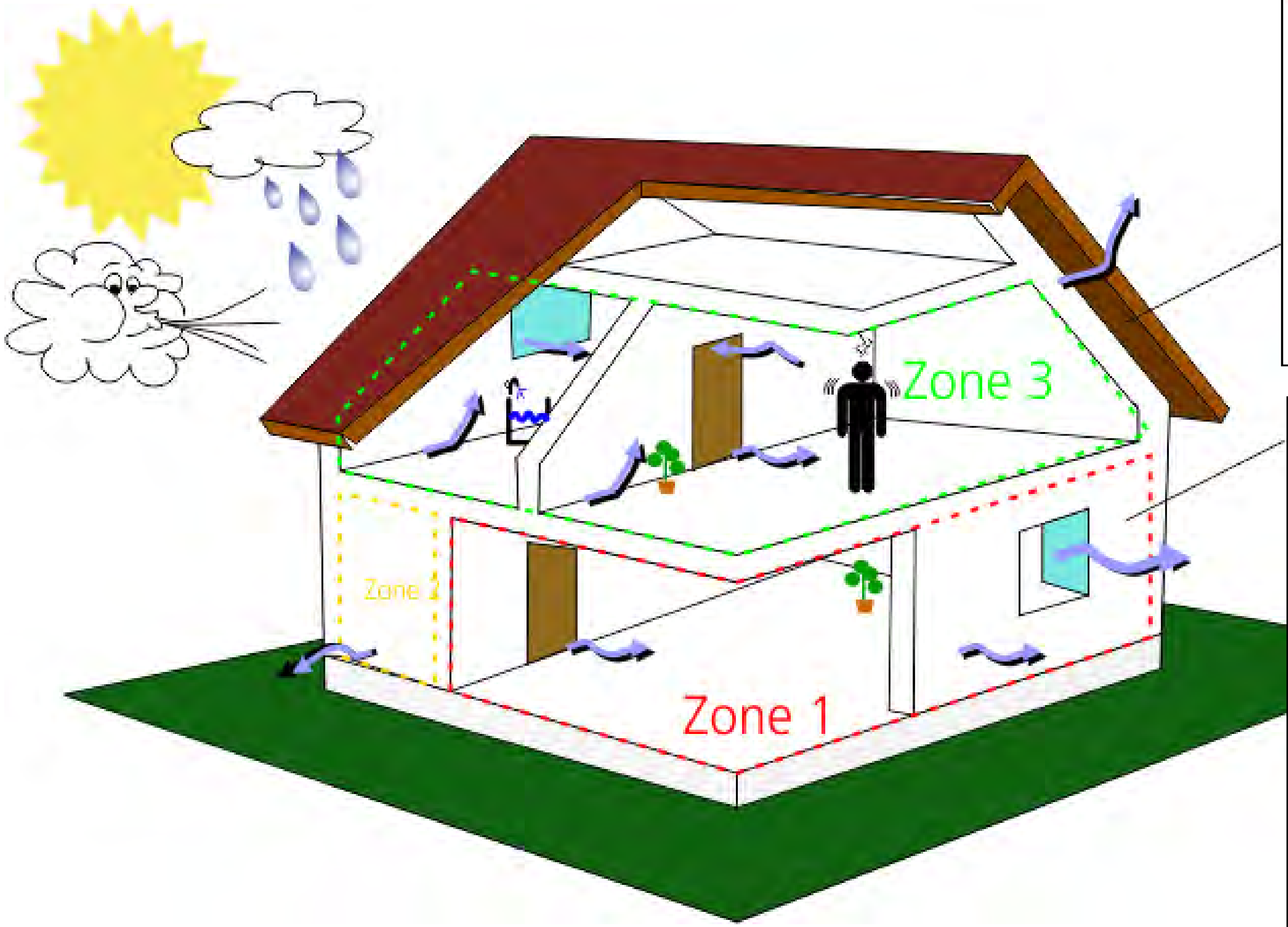
WUFI® Plus includes all heat and moisture exchange processes between the interior spaces and the building envelope

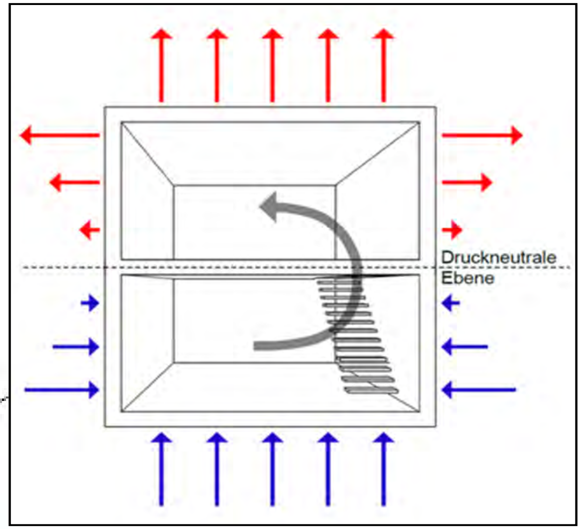


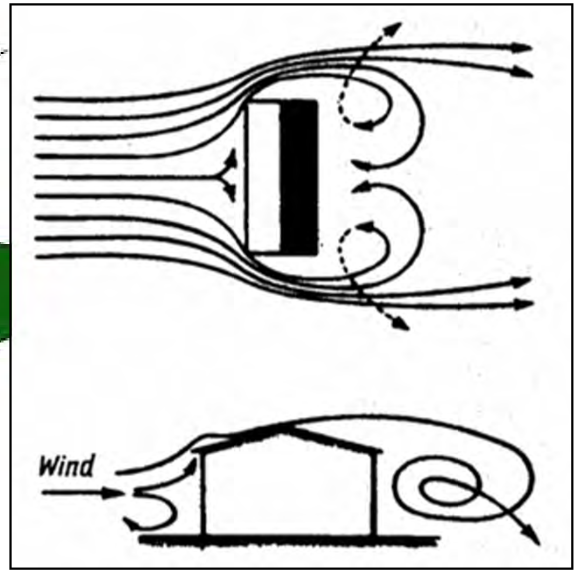
Thermal bridges bear the highest mould growth risk

Hygrothermal whole building simulation

WUFI® Plus includes interzonal air exchange







Warm & humid air entering a cold zone may cause mold problems

Conclusions

Envelope moisture control and indoor humidity control are essential for building durability and healthy indoor conditions

Transient hygrothermal conditions in buildings or building assemblies can be reliably obtained by numerical simulation

Degradation models based on HT simulation results exist for

- mold growth, rot (currently being developed)
- corrosion of steel in mortar (concrete)
- corrosion of metal fasteners in wood (FPL)

HT simulations help to

- predict climate and operation impacts on hygrothermal performance
- to identify the cause of damage or premature degradation
- to differentiate between design and installation failures

Challenge: designing buildings that are energy efficient, comfortable, healthy and durable (moisture tolerant)

75

Fraunhofer IBP

European and American awards for WUFI®


The Moisture Safety Prize 2011 from the Moisture Research Centre has been awarded to the research team behind the calculation tool

WUFI

For the development of a user friendly and widely spread tool with the ambition to improve the hygrothermal conditions in buildings.

Ingemar Samuelson
Director

FUKT CENTRUM
Moisture Research Centre

LUND UNIVERSITY


CERTIFICATE OF RECOGNITION

BuildingGreen

Publishers of Environmental Building News,™ GreenSpec® and LEEDuser

WUFI software from Fraunhofer IBP and Oak Ridge National Laboratory
has been selected as a

2013 TOP-10 GREEN BUILDING PRODUCT
from the *GreenSpec Database*

Alex Wilson, Executive Editor

BuildingGreen, Inc. ▪ Brattleboro, Vermont
Authoritative Information of Environmentally Responsible Building Design and Construction
www.BuildingGreen.com

www.wufi.com

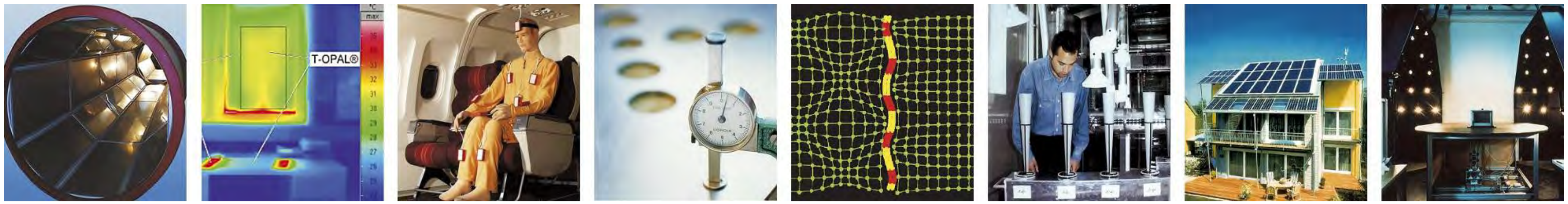
www.building-physics.com

Indoor climate surveys and analysis of occupant behavior

Florian Antretter – August 4th 2015

Nineteenth Annual Westford Symposium on Building Science

Auf Wissen bauen



Fraunhofer IBP

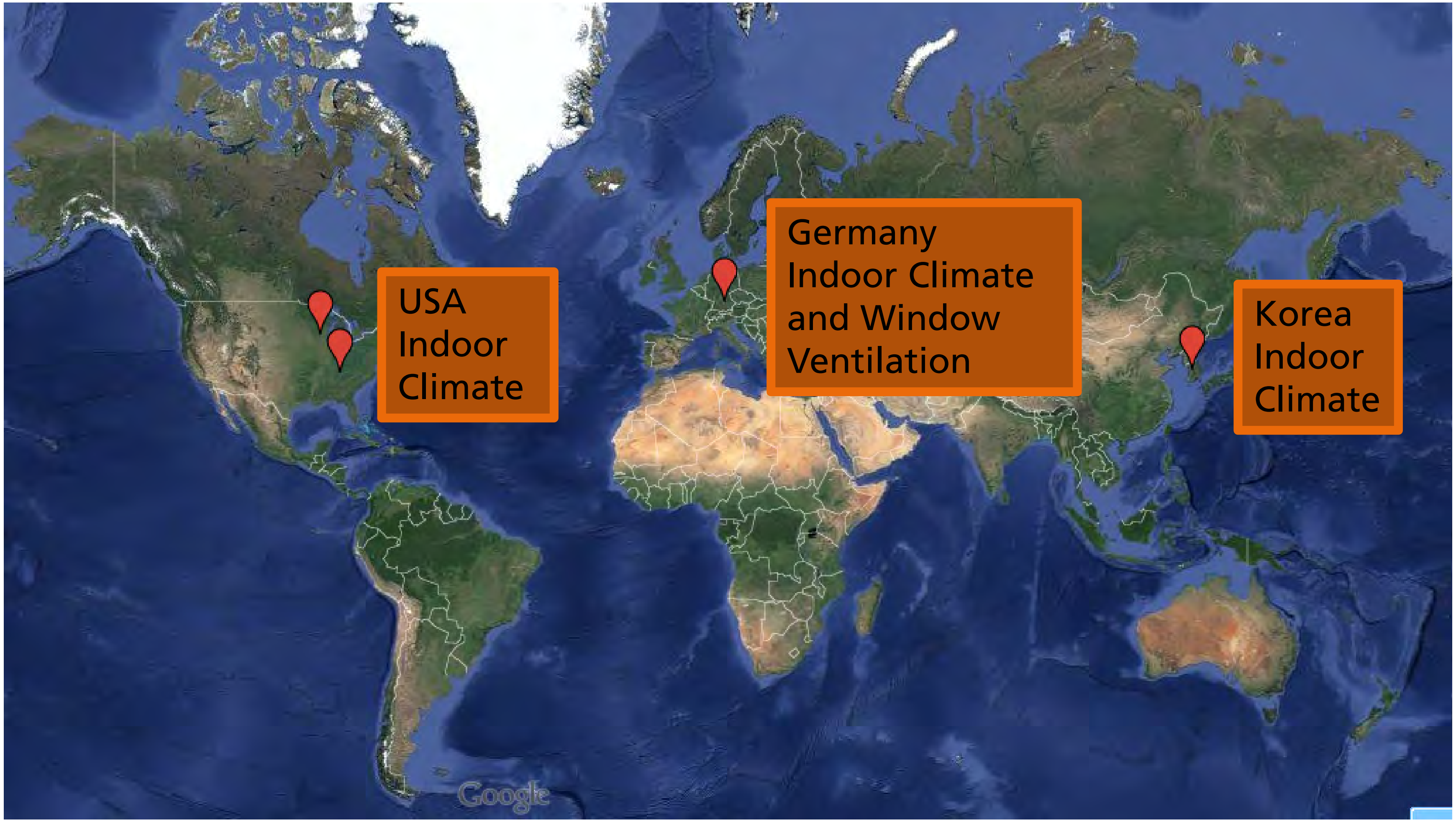
Outline

- Measurement of Indoor Climate and User Behavior
- Indoor Temperature and Relative Humidity Conditions
- Window Ventilation
- User Behavior Modeling

Fraunhofer IBP

Measurement of Indoor Climate and User Behavior

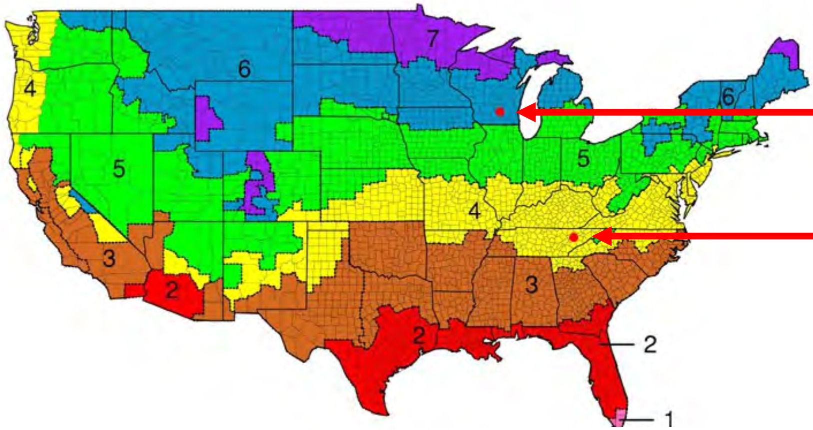
Measurement Locations



Fraunhofer IBP

Indoor Temperature and Relative Humidity Conditions

US Measurements - Location / Climatic Boundary Cond.



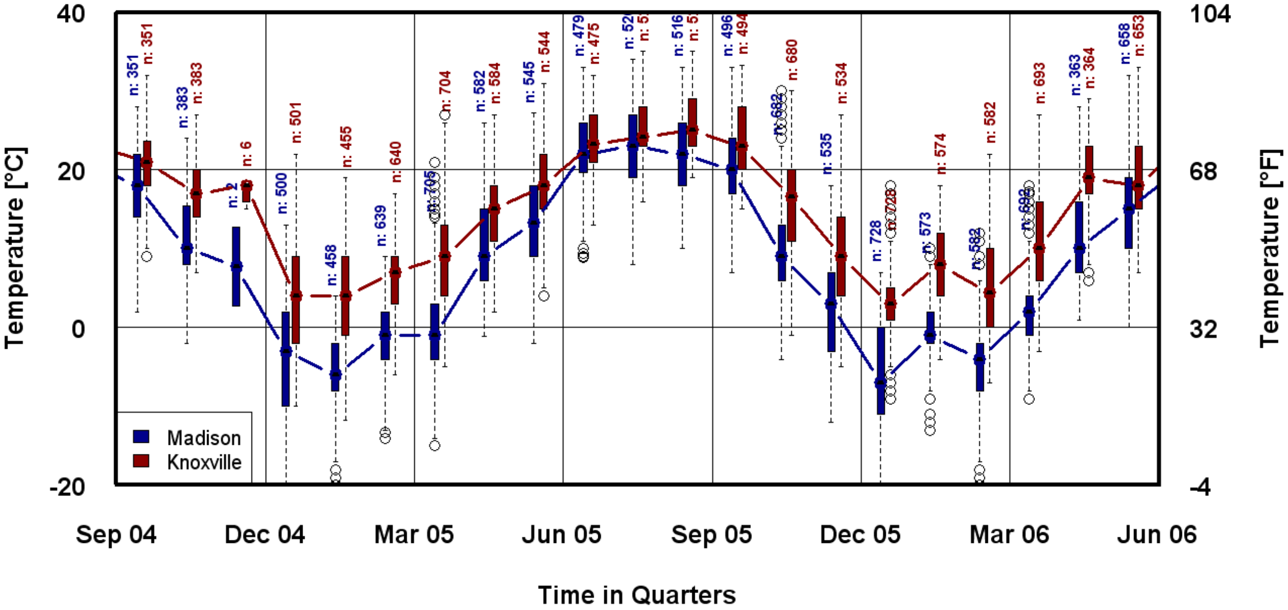
Madison, Wisconsin
Start: Feb. 2005

Knoxville, Tennessee
Start: Sep. 2004

Weather Data from EnergyPlus real-time weather database

Knoxville:	Max.	Min.
Temp. [°C]	25.2	2.9
Abs. Hum. [g/m3]	18.6	4.0

Madison:	Max.	Min.
Temp. [°C]	23.0	-6.4
Abs. Hum. [g/m3]	13.9	2.6



Fraunhofer IBP

US Measurements - Building Selection

- detached single family dwellings
- cross-section for one-family houses in respective area
- documentation of general building characteristics
- Total:
  - Knoxville: 10
  - Madison: 11





Fraunhofer IBP

Temperature/Relative Humidity Measurement

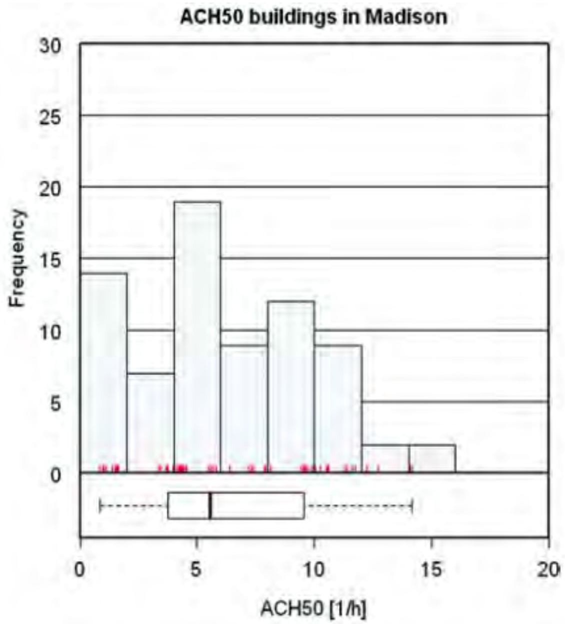
- calibrated temperature/RH data loggers
- 15 minute measurement interval
- logger location:
  - living room
  - kitchen
  - sleeping room
  - bathroom
  - crawlspace/basement
- installation height approx. 5 ft
- away from external walls/inner heat sources

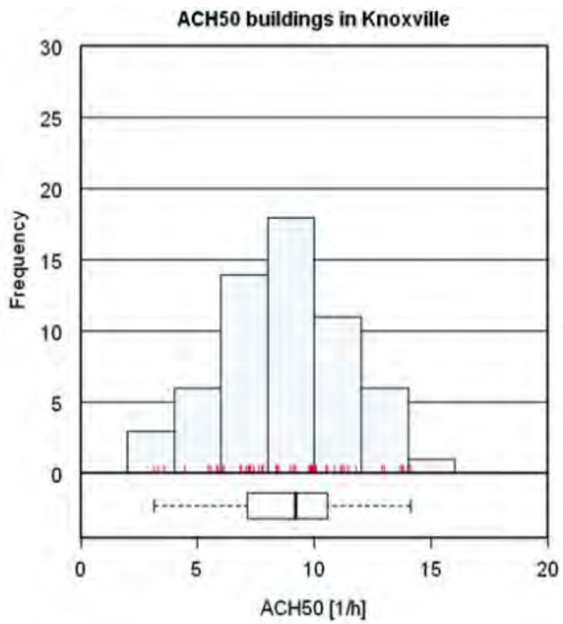
Fraunhofer IBP

Blower Door Tests

Madison: 0.9 – 12.2 ACH@50Pa

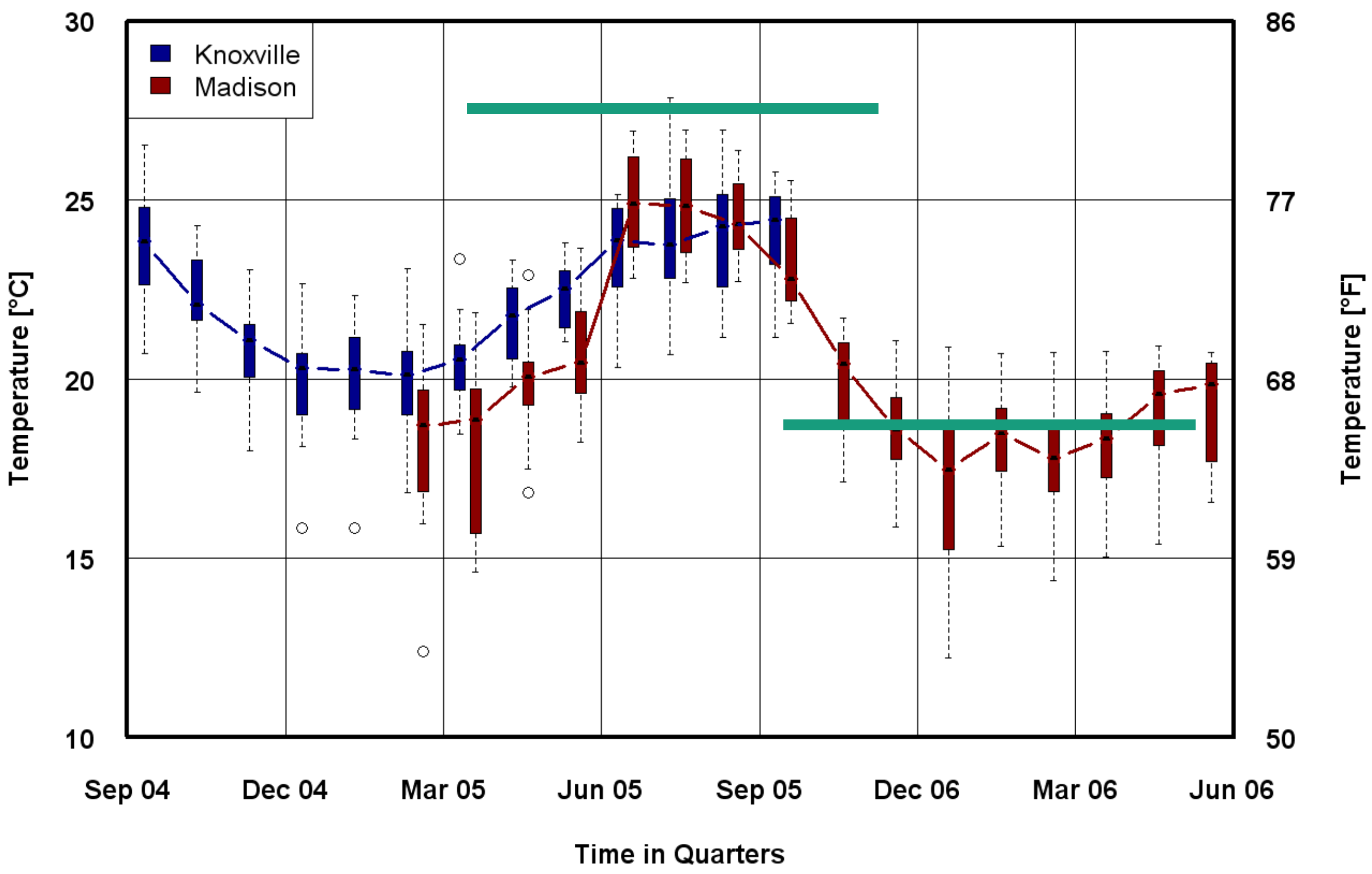
Knoxville: 3.3 – 14.0 ACH@50Pa





Fraunhofer IBP

Inner temperature – living rooms monthly mean



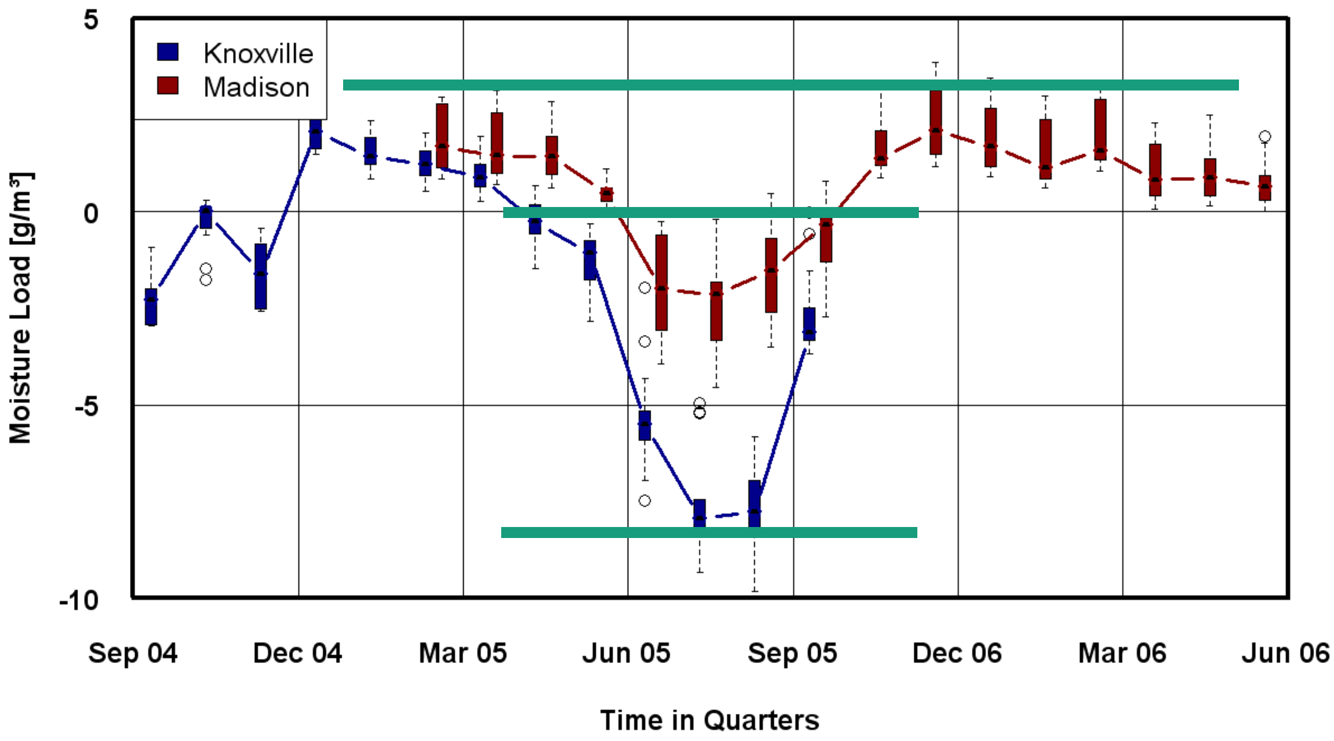
- no mean temperatures above 28 °C

- very low mean temperatures in Madison

  (50 % below 18 °C)

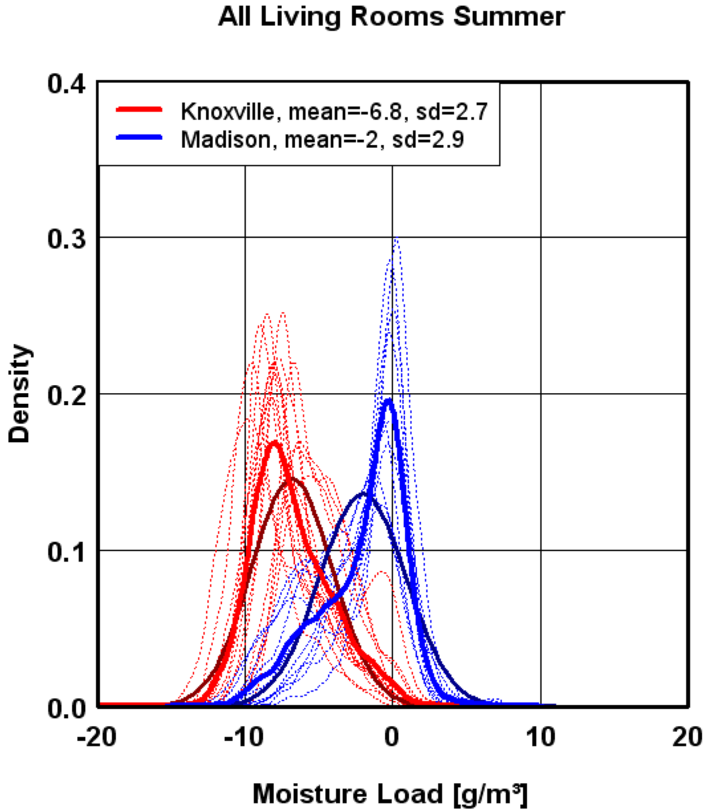
Fraunhofer IBP

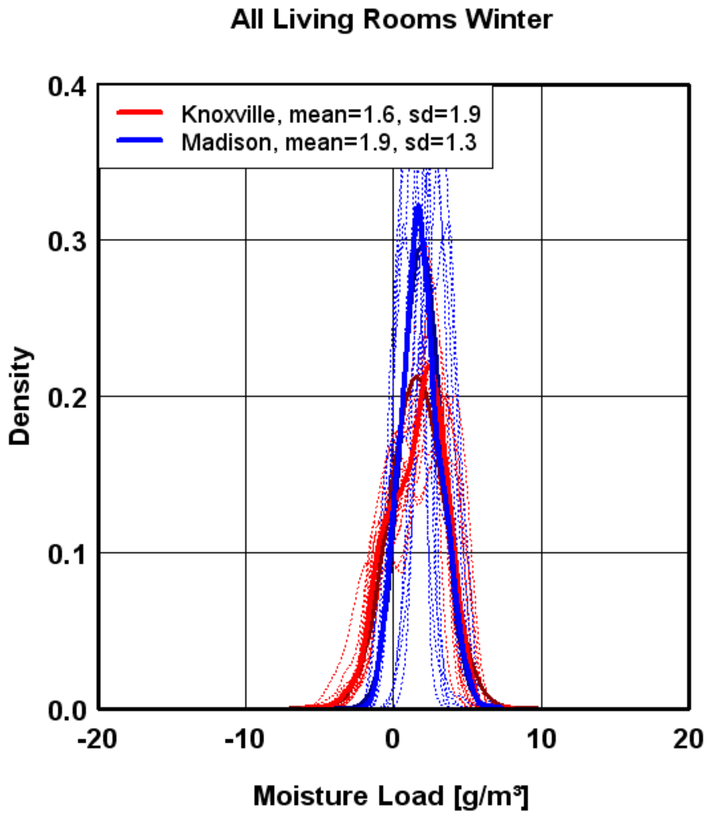
Moisture load – living rooms monthly mean



- no very high moisture loads in all month
- dehumidification for all buildings in both locations
- High negative moisture loads in cooling period

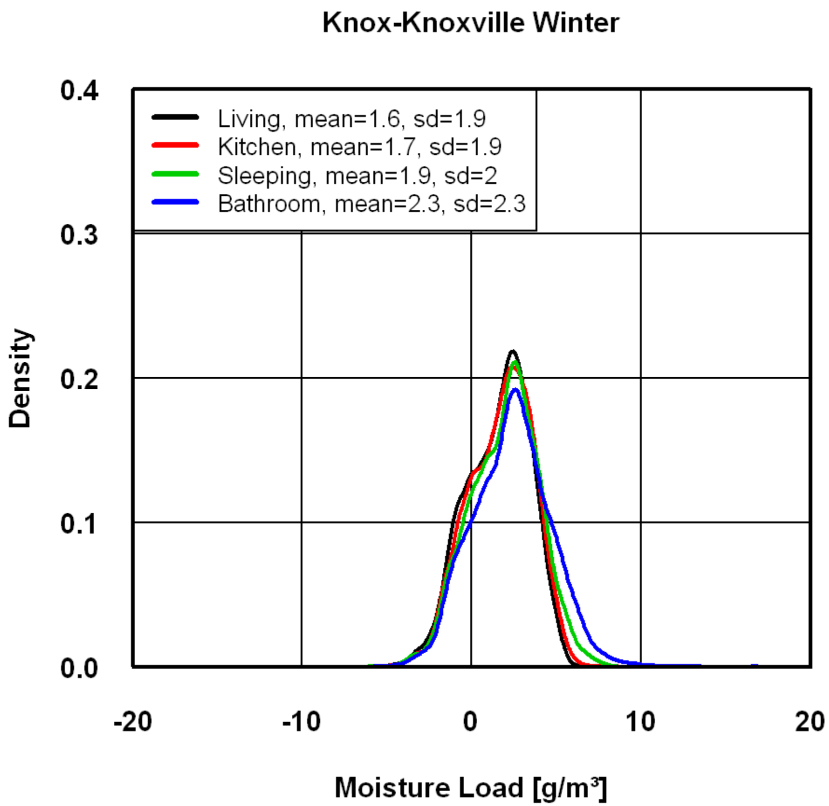
Distribution Representation

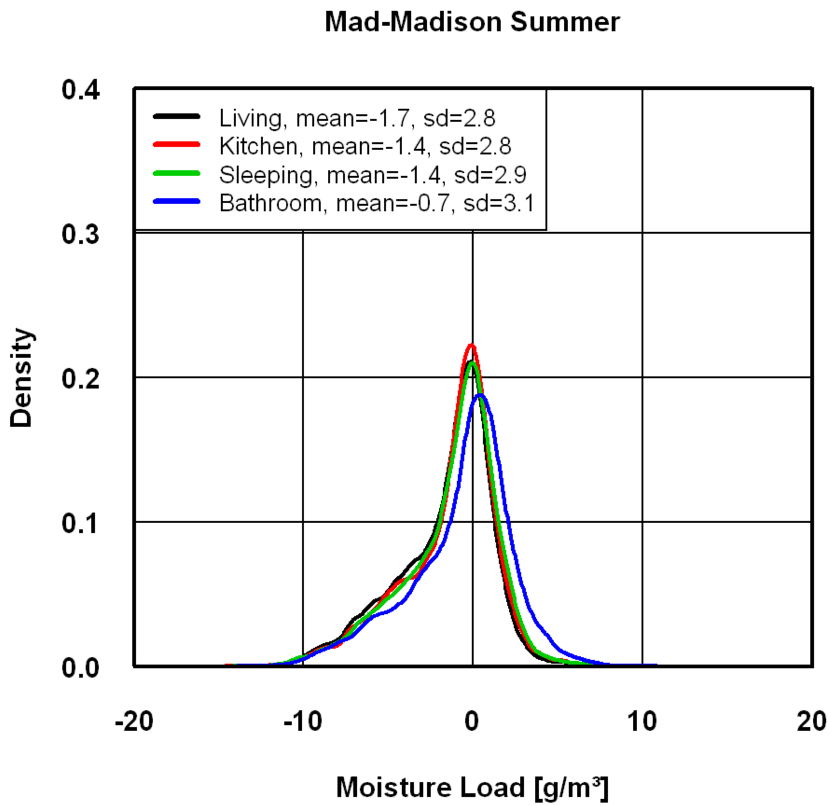




- bi-modal distribution
- no simple distribution representation possible

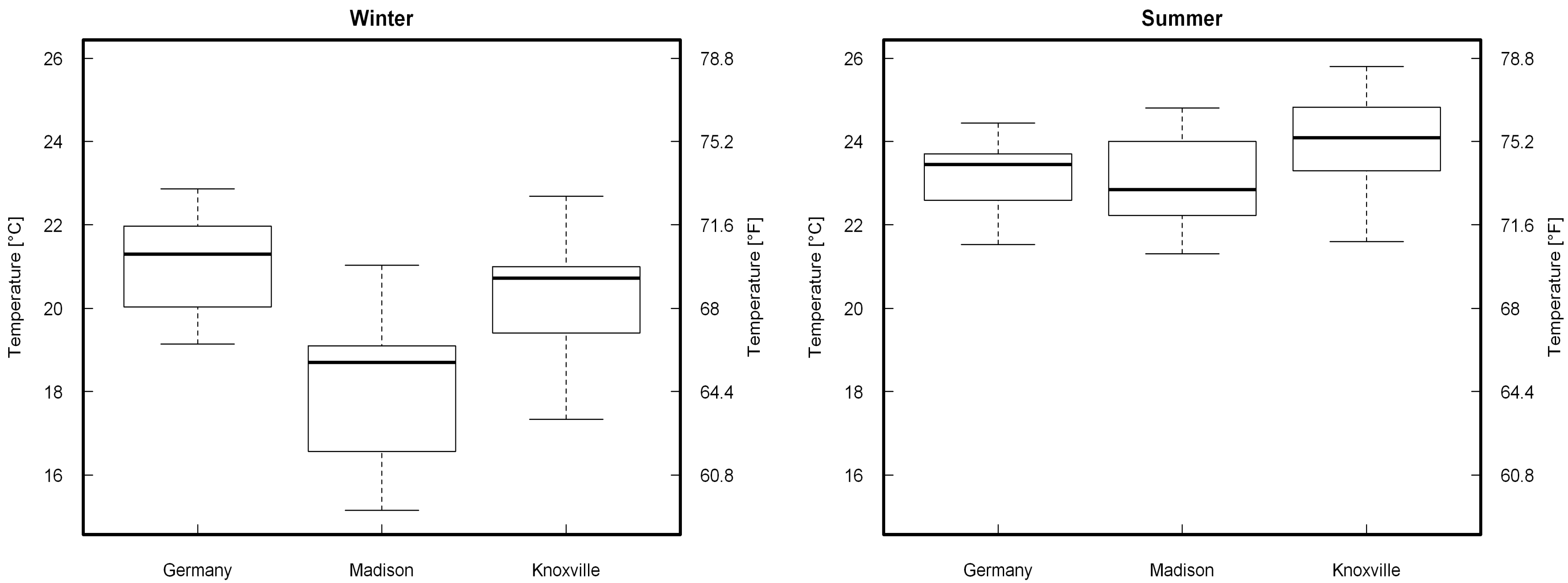
Moisture Load depending on Type of Room





- very similar distributions in all rooms
- slightly higher loads in bathrooms

Measurements in Residential Buildings – Set-Point



Distribution of mean temperatures in 10 living rooms in North America and Germany (in winter and summer)

Comparison with Standards

- minimum temperatures only partially match mean measured values
- maximum temperature threshold is not exceeded in most of the times

- monthly mean moisture loads are below class 2 (Knoxville) and class 3 (Madison) from DIN EN ISO 13788
- density distributions allow short time excess estimation

- calculating RH from temperature with standard moisture loads would lead to too high relative humidity's
- measured RH fit well in DIN EN ISO 15026 and ASHRAE 160 simple method range

Relative Humidity Means and Standard Deviations

Room	Knoxville		Madison	
	Living Mean/SD, %	Bath Mean/SD, %	Living Mean/SD, %	Bath Mean/SD, %
Winter	40.1/8.3	44.3/8.3	32.0/8.5	36.6/10.6
Spring	43.0/7.9	46.4/7.3	39.7/9.9	46.5/13.6
Summer	50.5/7.5	52.4/6.6	51.1/8.5	55.0/8.8
Fall	53.9/7.6	56.9/7.2	48.9/9.2	54.9/10.3

Fraunhofer IBP

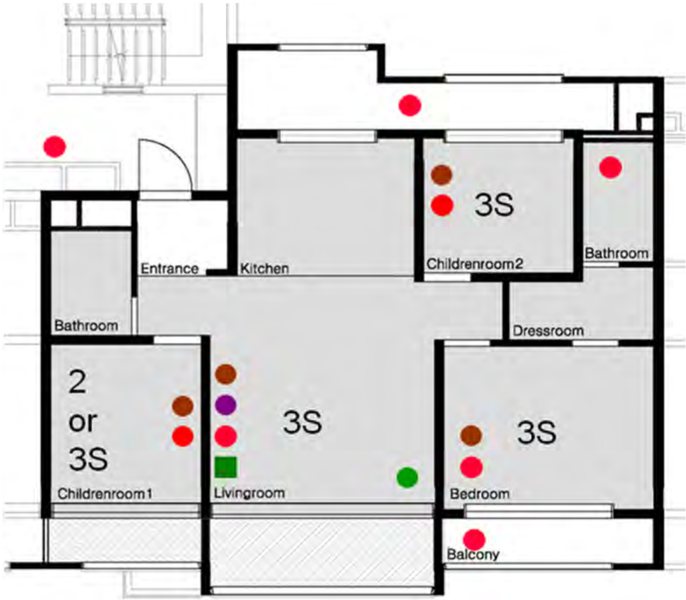
Measurements in Korea

Project: Optimization of Comfort and Energy Efficiency in Korean high rise residential building




Comprehensive Measurements (6 apartments)

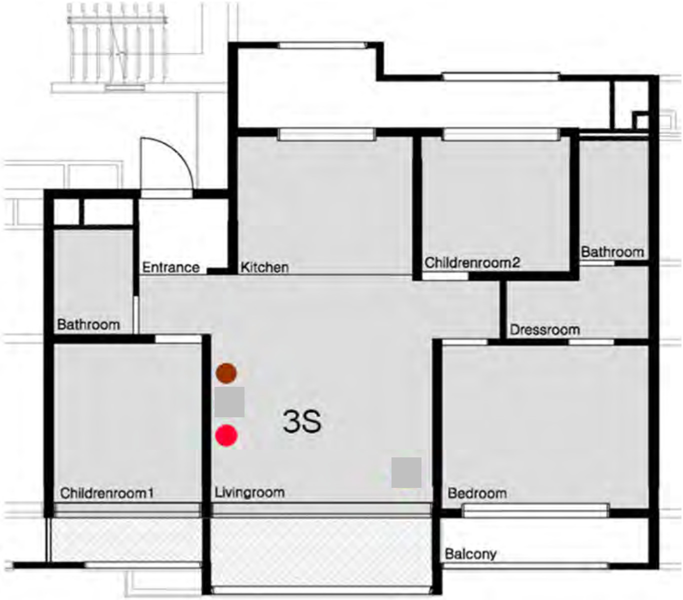
From May 2009 to July 2010



- Air temperature + Humidity
- Globe temperature
- CO_2
- Energy consumption of air conditioner

Simple Measurements (18 apartments)

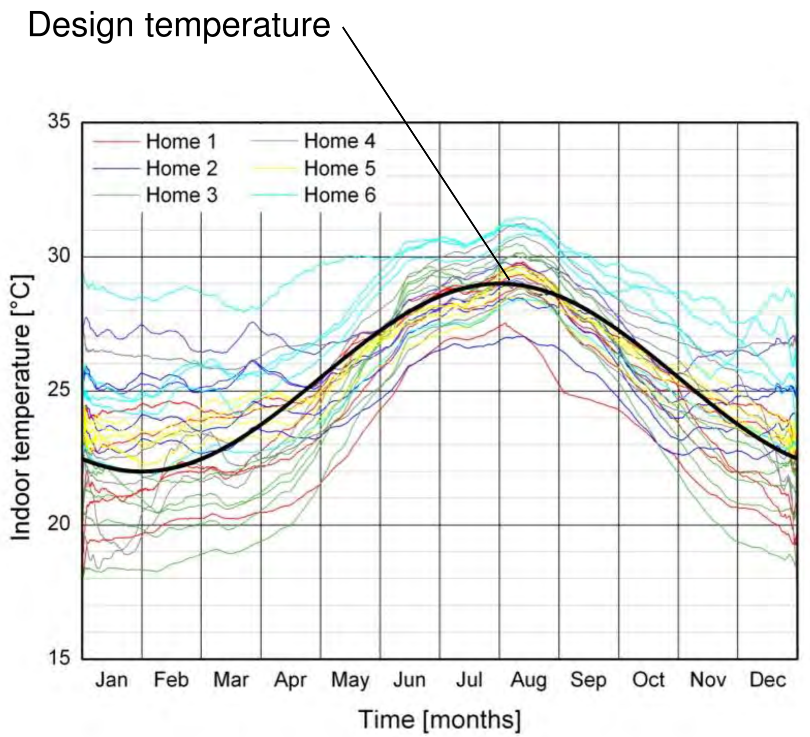
From May 2009 to July 2010



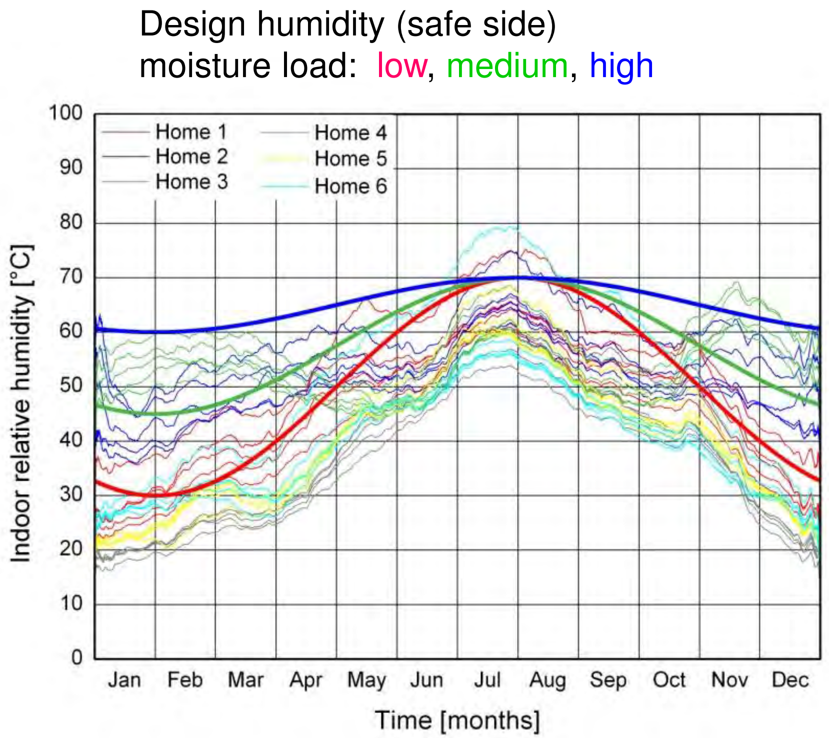
- Air temperature + Humidity
- CO_2

Proposed Design Conditions for Asia

Annual course of room temperature in different rooms of the monitored dwellings



Annual course of relative humidity in different rooms of the monitored dwellings

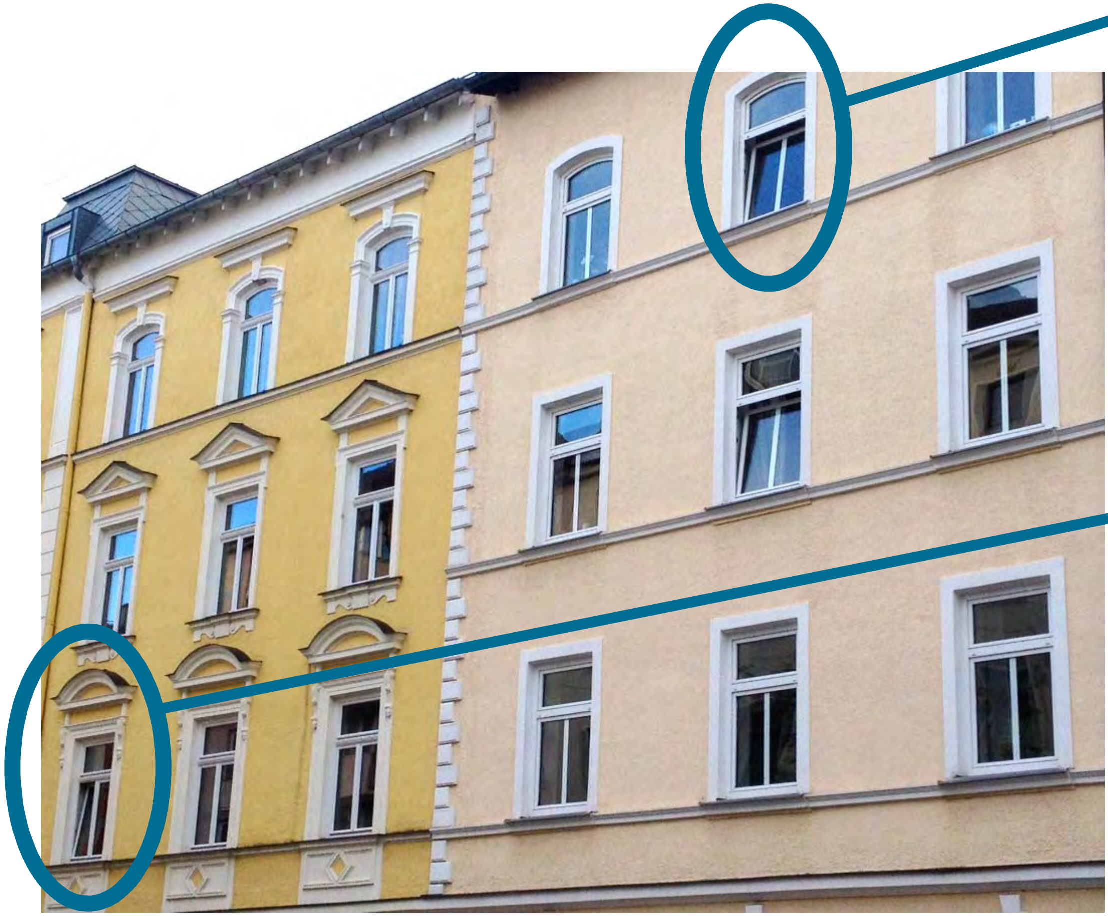


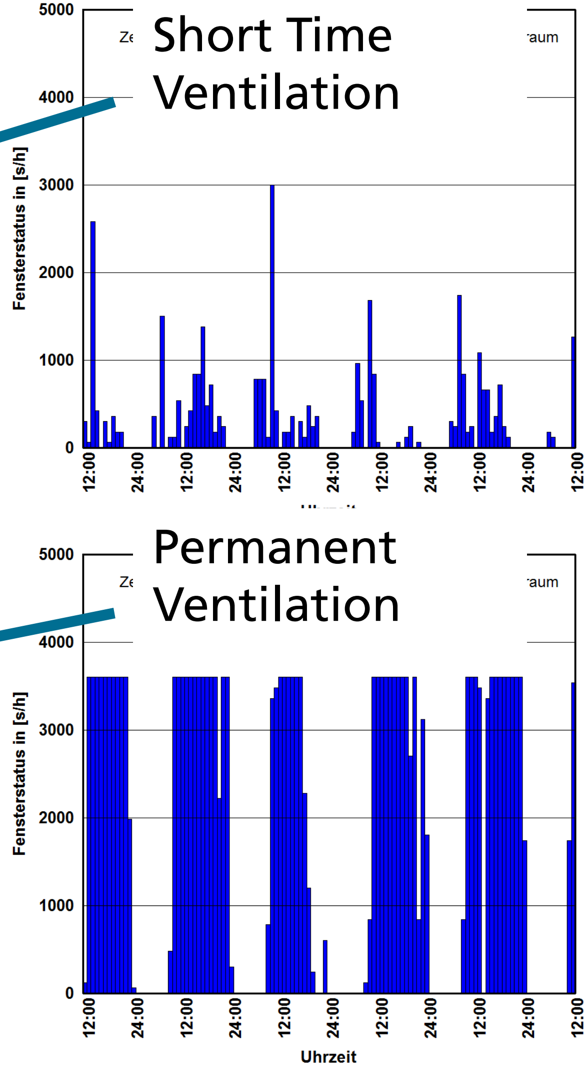
Fraunhofer IBP

Window Ventilation

Fraunhofer IBP

User dependent ventilation?

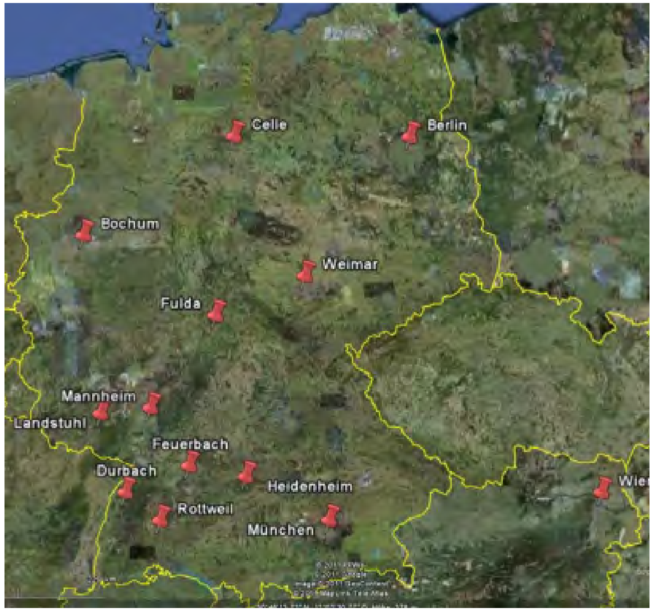




Measurement Projects in German Residential Buildings

- Only residential buildings
- Measurement period 2 – 3.5 years
- Hourly measurements of
  - Exterior climate
    (Temperature, RH, Radiation, ...)
  - Indoor climate (Temperatur, RH, ...)
  - Window status
- General Information about
  - Room type
  - Ventilation system
  - Building airtightness

→ Number of open windows (opening probability) and mean opening duration



Fraunhofer IBP

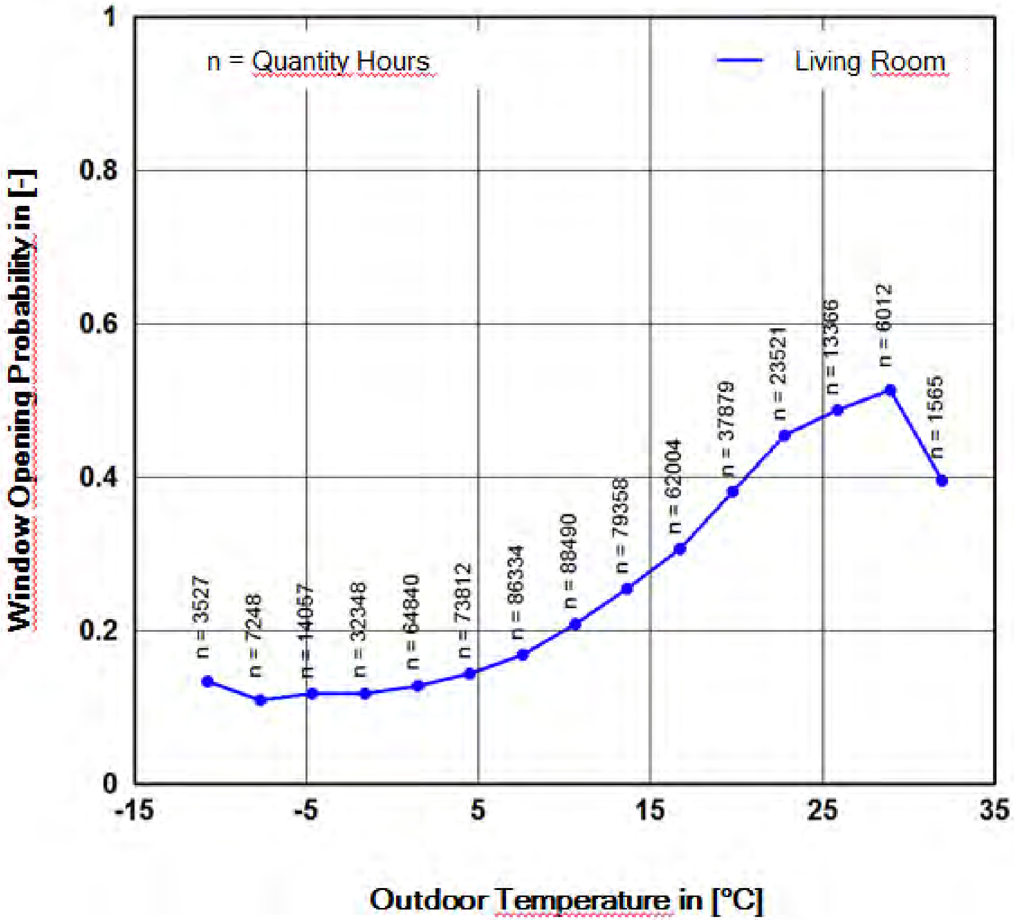
Conclusions from Literature Search

- Main Exterior Influences are exterior temperature, high wind and rain
- Main Internal Influences are interior temperature, CO_2 concentration and room type
- Time dependent and correlated effects are often not taken into account
- Cultural and ethnical habits are not taken into account
- Models base mainly on measurements in office buildings
- Categorization of user types is rarely found
- Main modeling methods are Logistic Regression, Markov-Chains, Survival Analysis

Impact of exterior climate

- Increase in opening probability with increasing exterior temperature
- Above 27 °C (80 F) exterior temperature decreasing opening probability

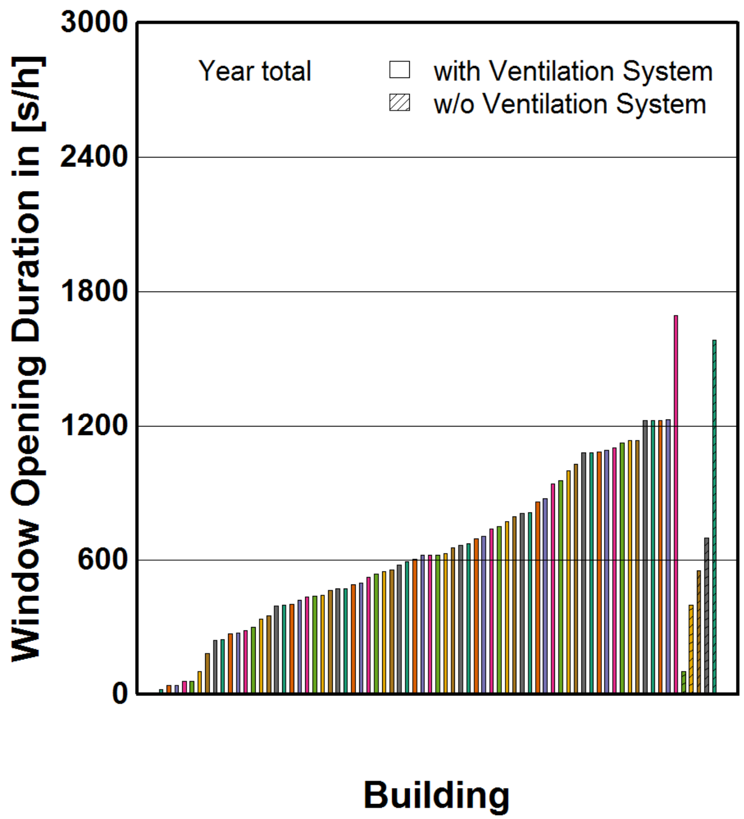
→ High dependence on exterior temperature



Impact of ventilation system

- Only very few buildings with very little manual ventilation activity
- Same bandwith in apartments with and without ventilation system

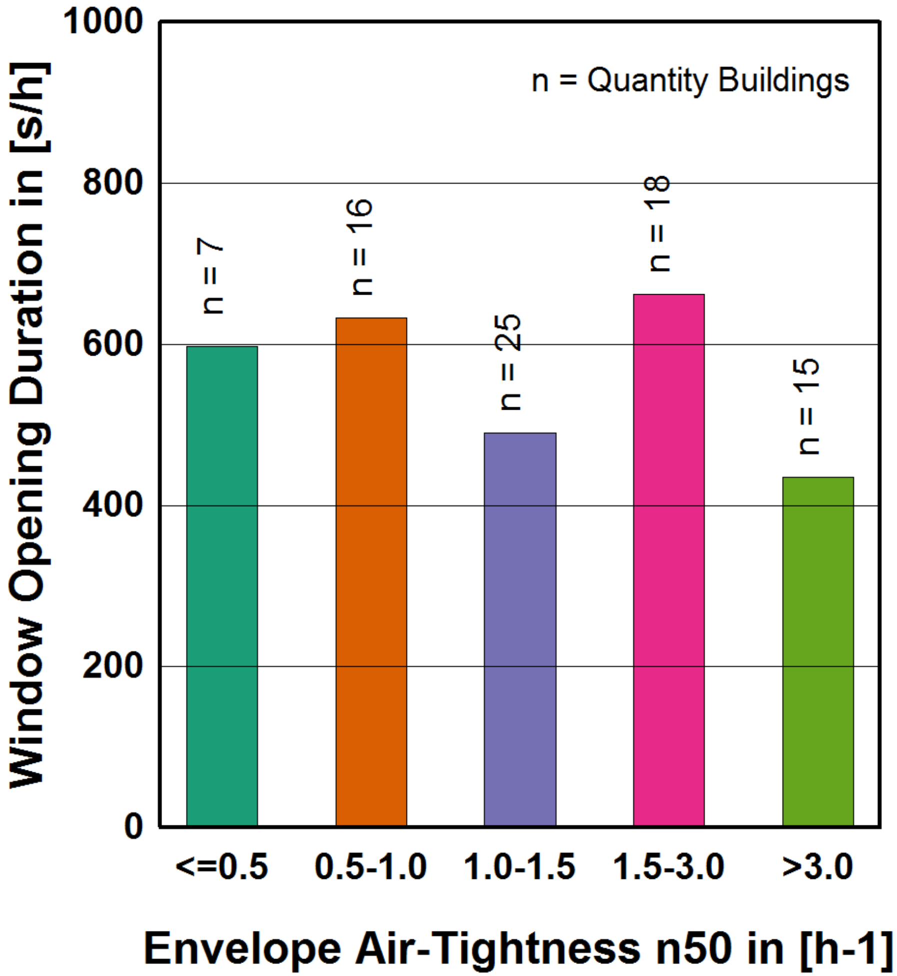
→ The existence of a ventilation system has only little influence on the window opening behaviour (but limited data source!)



Impact of building air tightness

- No differences between buildings with different airtightness levels

→ Building air tightness with little influence

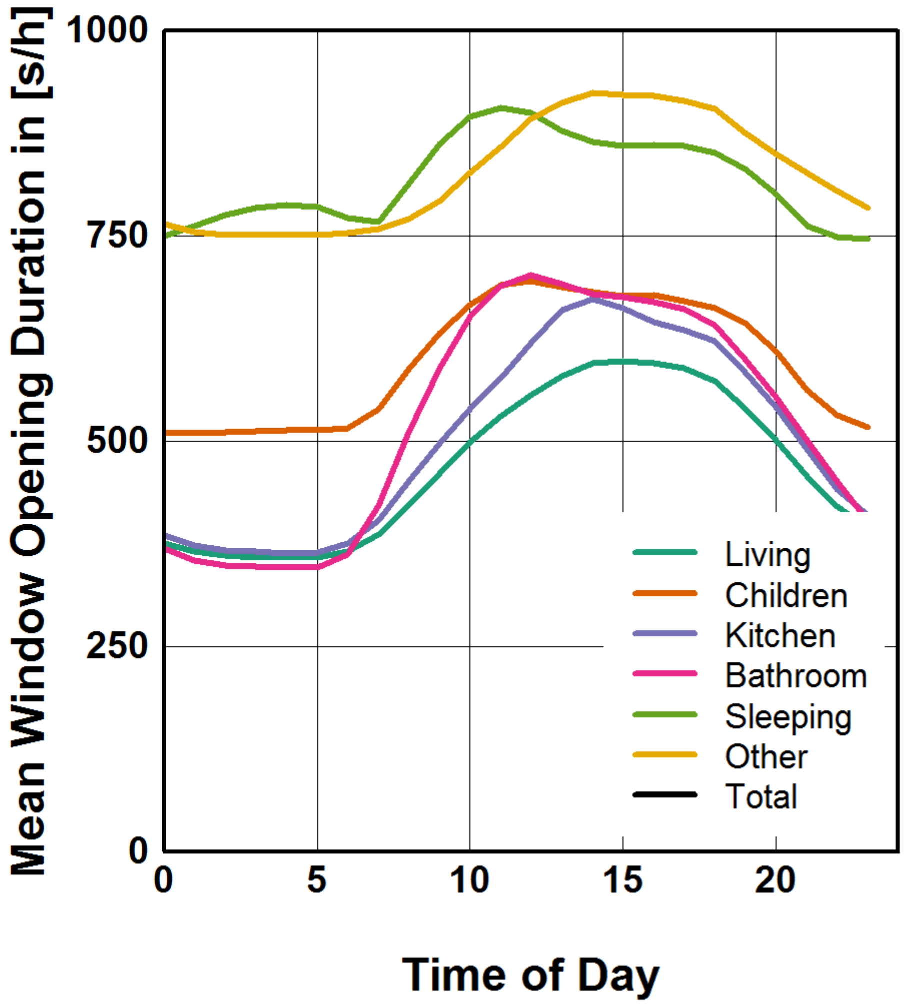


Fraunhofer IBP

Impact of time of the day per room type

- Sleeping rooms are opened continously
- Living rooms with a clear day profile

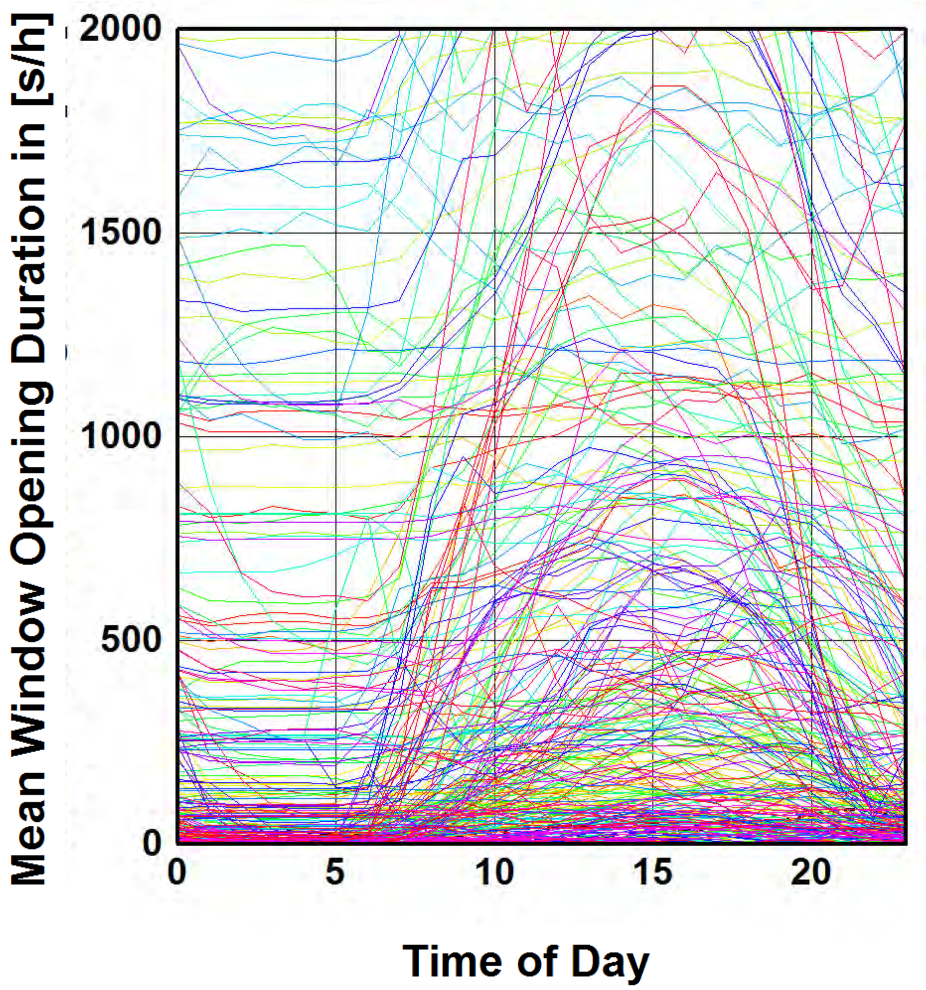
→ Type of room and temporal resolution is important



Individual user behavior

- Very irregular manual window opening in all measured living rooms
- High bandwith of opening durations

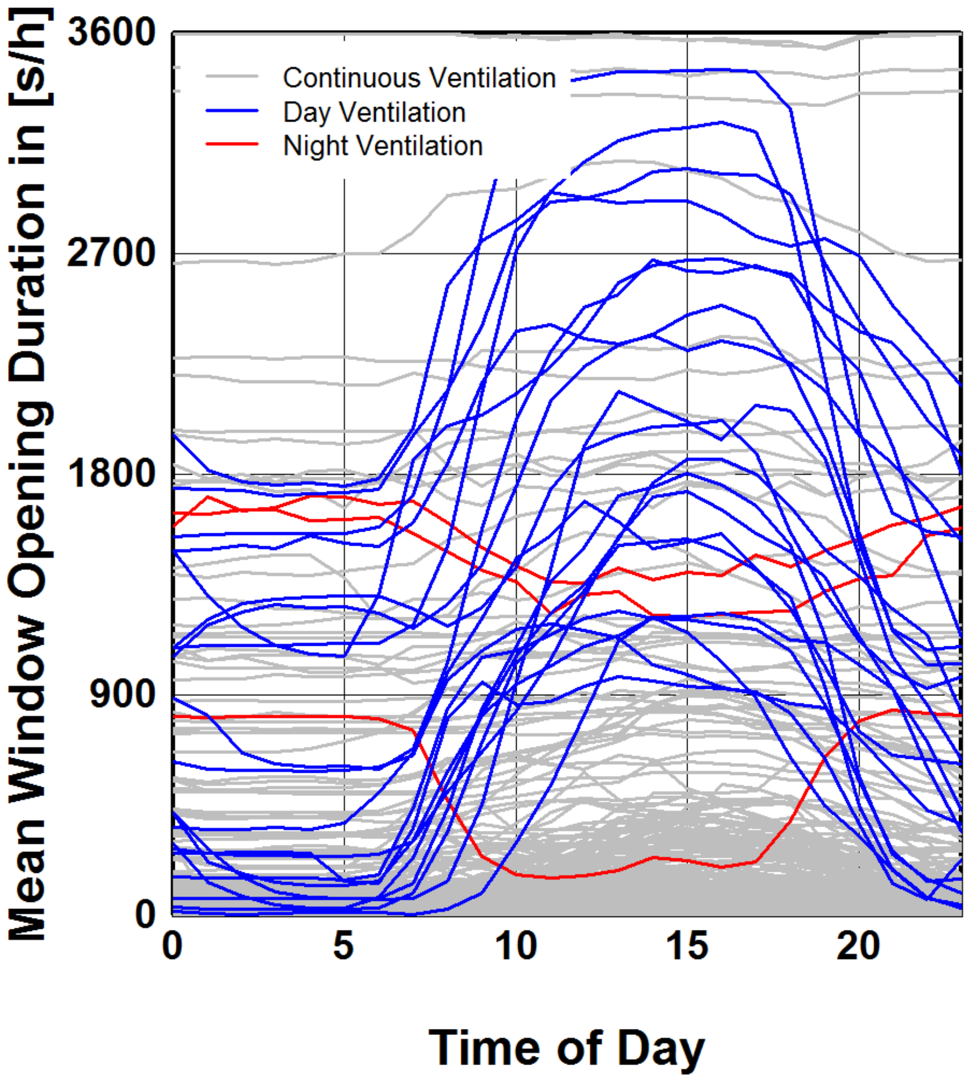
→ Categorization of users is important



Derivation of user profiles

- Differentiation in day, night and continuous ventilation types
- Differentiation between high and low frequency ventilation types

→ Categorization of users is possible and useful

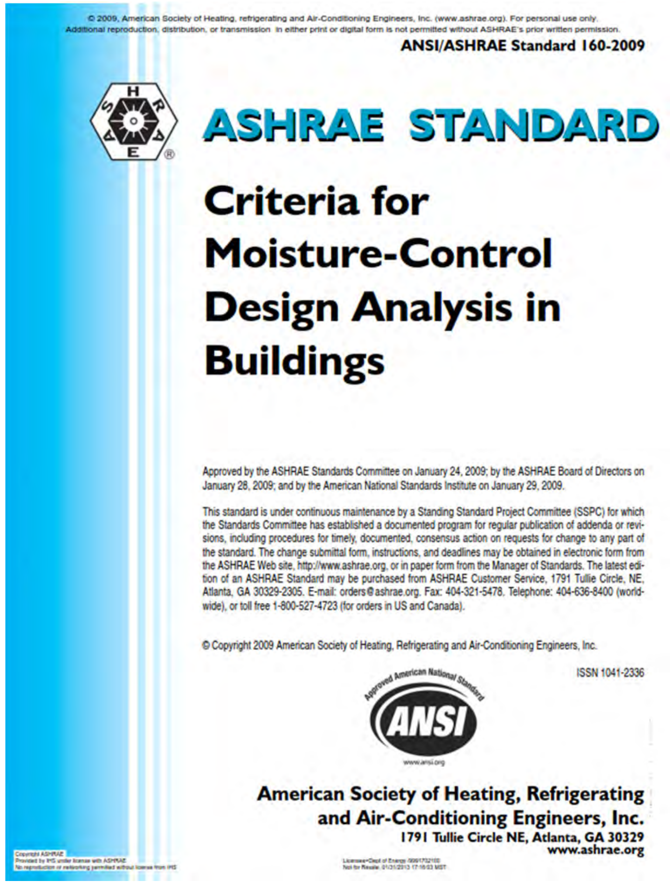


Fraunhofer IBP

Why do we do it?

Provide information for standards and simulations

- Moisture and temperature conditions for hygrothermal component simulations
- Moisture loads and ventilation conditions for hygrothermal building simulations
- Real life set-point information for energetic simulations


© 2009, American Society of Heating, refrigerating and Air-Conditioning Engineers, Inc. (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

ANSI/ASHRAE Standard 160-2009

ASHRAE STANDARD

Criteria for Moisture-Control Design Analysis in Buildings

Approved by the ASHRAE Standards Committee on January 24, 2009; by the ASHRAE Board of Directors on January 28, 2009; and by the American National Standards Institute on January 29, 2009.

This standard is under continuous maintenance by a Standing Standard Project Committee (SSPC) for which the Standards Committee has established a documented program for regular publication of addenda or revisions, including procedures for timely, documented, consensus action on requests for change to any part of the standard. The change submittal form, instructions, and deadlines may be obtained in electronic form from the ASHRAE Web site, http://www.ashrae.org, or in paper form from the Manager of Standards. The latest edition of an ASHRAE Standard may be purchased from ASHRAE Customer Service, 1791 Tullie Circle, NE, Atlanta, GA 30329-2305. E-mail: orders@ashrae.org. Fax: 404-321-5478. Telephone: 404-636-8400 (worldwide), or toll free 1-800-527-4723 (for orders in US and Canada).

© Copyright 2009 American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ISSN 1041-2336

Approved American National Standard ANSI

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
1791 Tullie Circle NE, Atlanta, GA 30329
www.ashrae.org

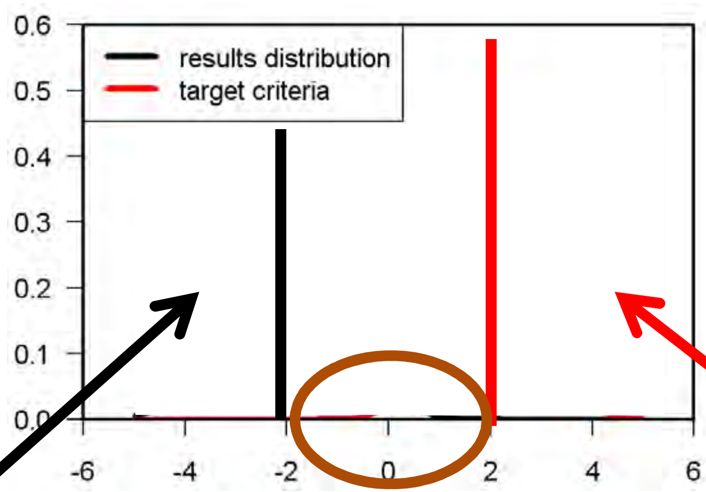
Design Optimization with Probabilistic Modeling

Building Use and Occupant Behavior

Probability Distribution

Optimized Design

e.g. Moisture content of wood based board



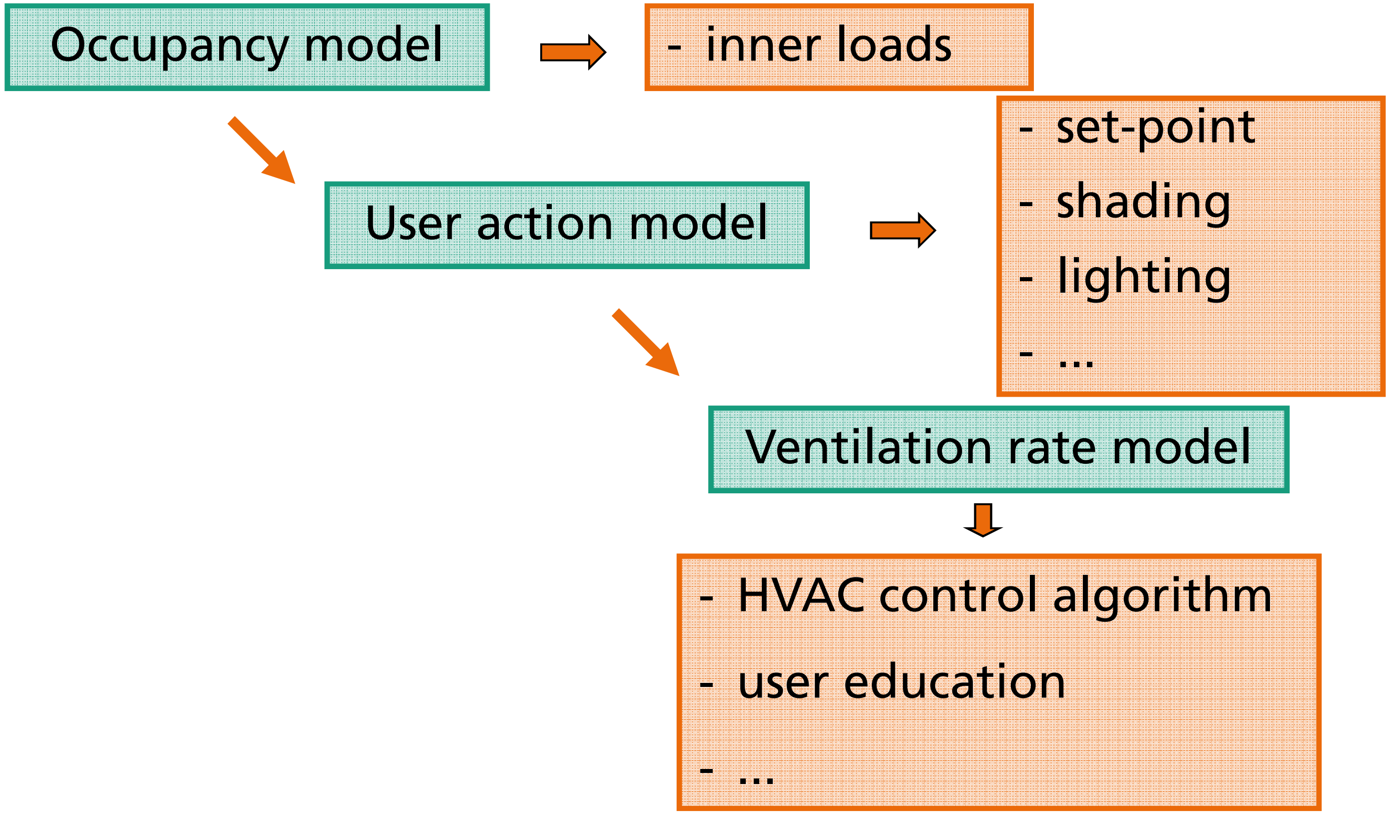
12 M-% 18 M-%

Results Distribution, e.g. moisture content of board

Target Criteria, e.g. critical moisture content

Fraunhofer IBP

Improved Control and Self Learning Systems



Conclusions and Outlook

What did we learn?

- The US is not Europe is not Asia.
- Some like to cook.
- I want to open my windows. Oh – and is there a ventilation system?
- My wife is different. Yours too.

→ We can understand how users operate their buildings (and model it)

→ We can integrate this knowledge in the design phase

  → More robust design

  → Less „negative"user interaction with the intended building operation

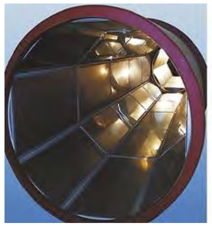
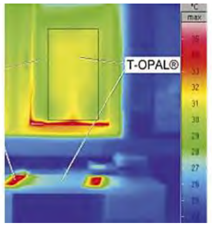
→ We can use this knowledge for online building operation optimization (e.g. self learning ventilation/thermostat/… control, IoT)

Indoor climate surveys and analysis of occupant behavior

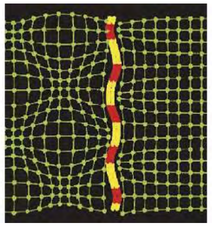
Florian Antretter – August 4th 2015

Nineteenth Annual Westford Symposium on Building Science

Auf Wissen bauen





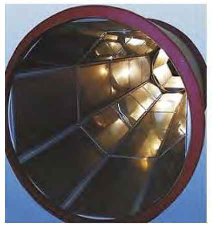
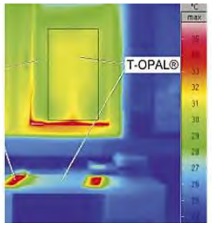

Fraunhofer IBP

Static versus dynamic passive building design

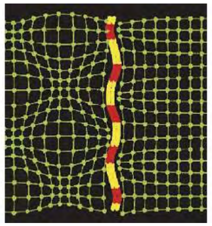
Florian Antretter – August 4th 2015

Nineteenth Annual Westford Symposium on Building Science

Auf Wissen bauen





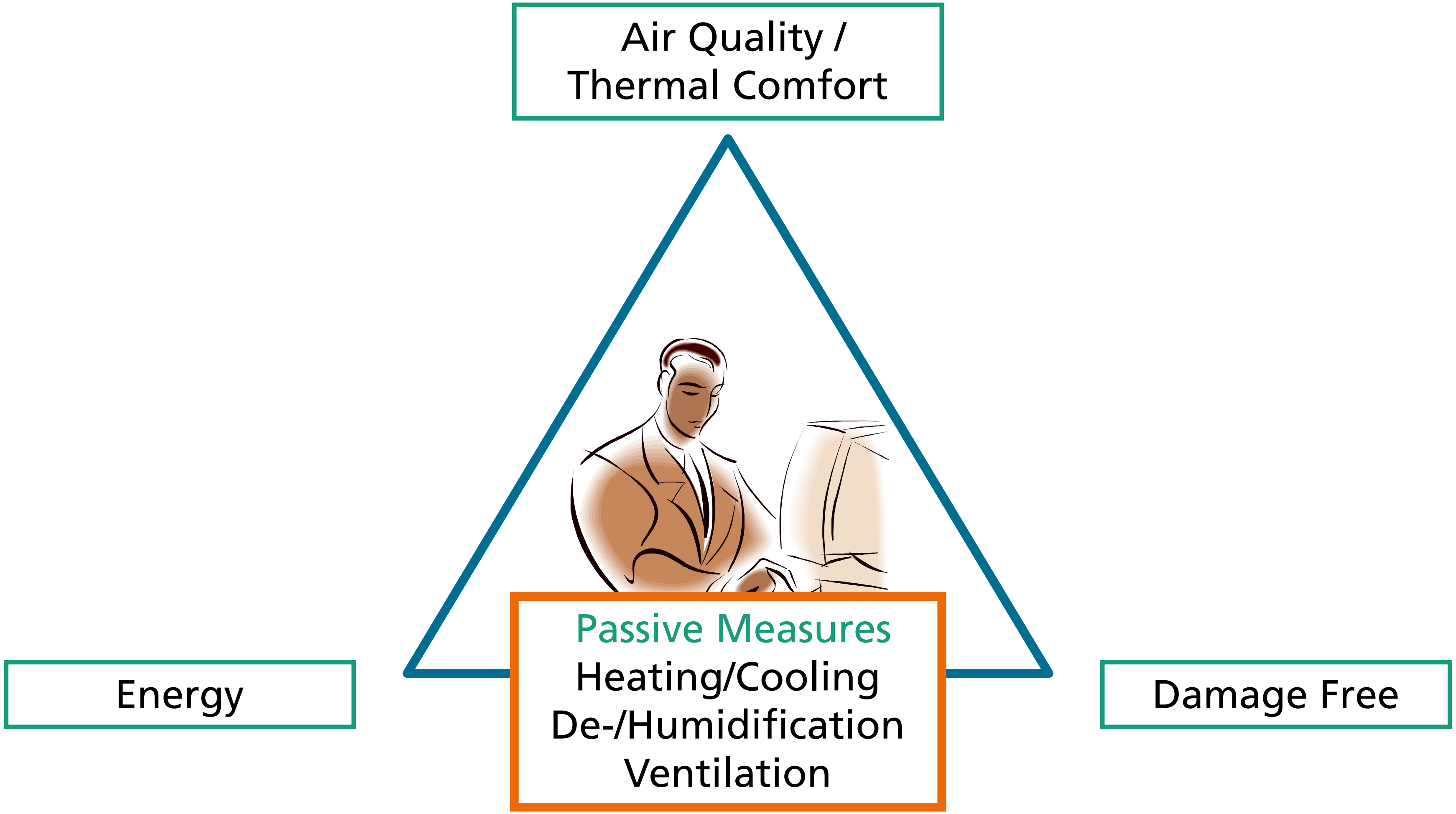

Fraunhofer IBP

Outline

- Passive Building Principles
- Current practice in passive building modeling
- New holistic design tool
- Examples
- Conclusions and Outlook

Passive Building Principles

Requirements on Buildings



Fraunhofer IBP

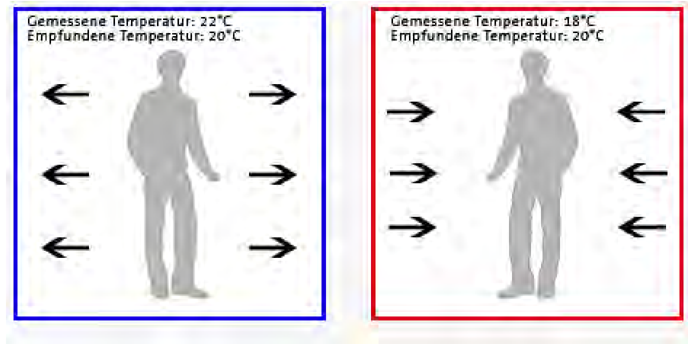
Passive Building Principles in one term: Passive House

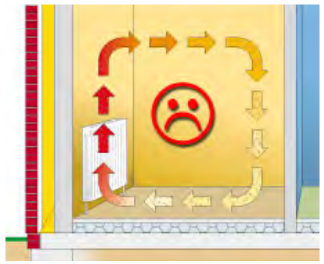
- The term Passive House („Passivhaus“) relates to a certain building standard
- „Passive“ refers to the heat demand of the building - the major energy sources are „passive“ (Solar Energy, Persons, Devices etc.)

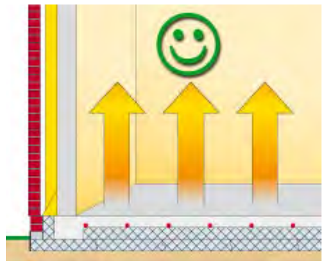
- It‘s main aspectes are:
  - High standard thermal insulation / optimized window layout
  - Airtightness
  - Ventilation system with energy recovery
  - Efficient heating system

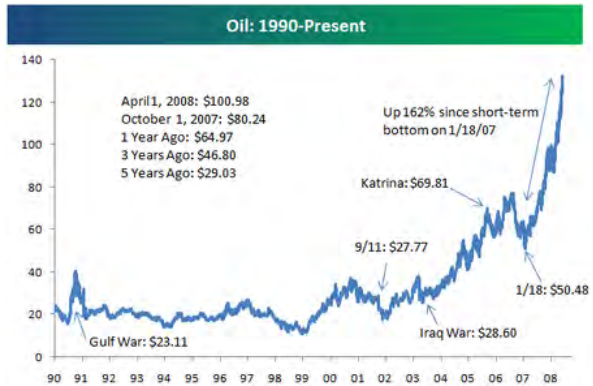
Why Passive House?

- Comfort and Indoor Climate
  - Less temperature stratification, warm surfaces
  - Constant fresh air supply
- Very low energy demand
  - High quality insulation and windows
  - Prevention of thermal bridges
- Economical and ecological reasons
  - Reduced CO_2 output
  - Higher resilience
  - More independence from energy market prices







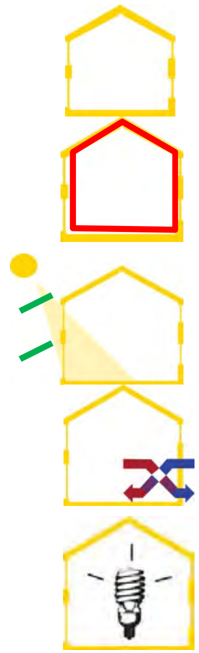


Fraunhofer IBP

Passive Building Principles

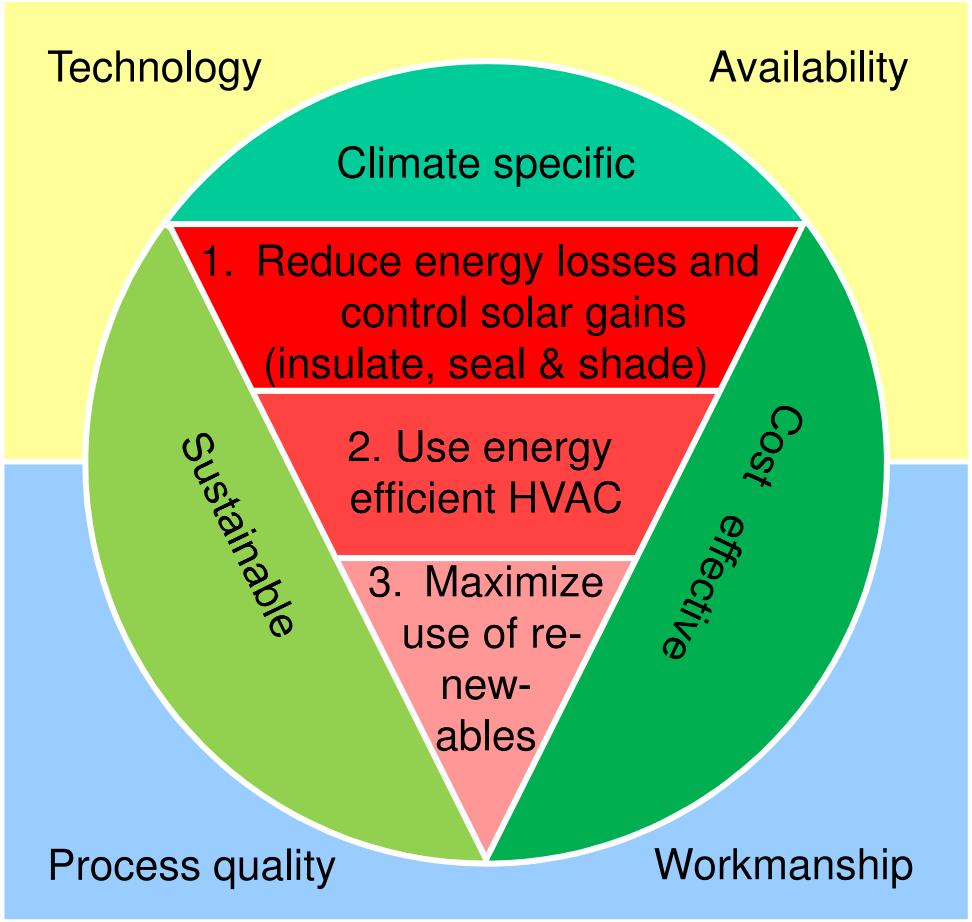
General Principles for Low Energy Buildings

- Building site selection and orientation
- Building geometry (size, shape, spacing)
- Window placement, selection of glazing properties and solar protection (Daylighting design, shading, passive solar gains)
- Continuous insulation, connection details free of thermal bridges
- Air-sealing, air-tight construction
- Thermal and hygric mass (as appropriate)
- Ventilation (natural or mechanical, with heat-and-moisture recovery as appropriate)



Designing Energy Efficient Buildings – A Holistic Task

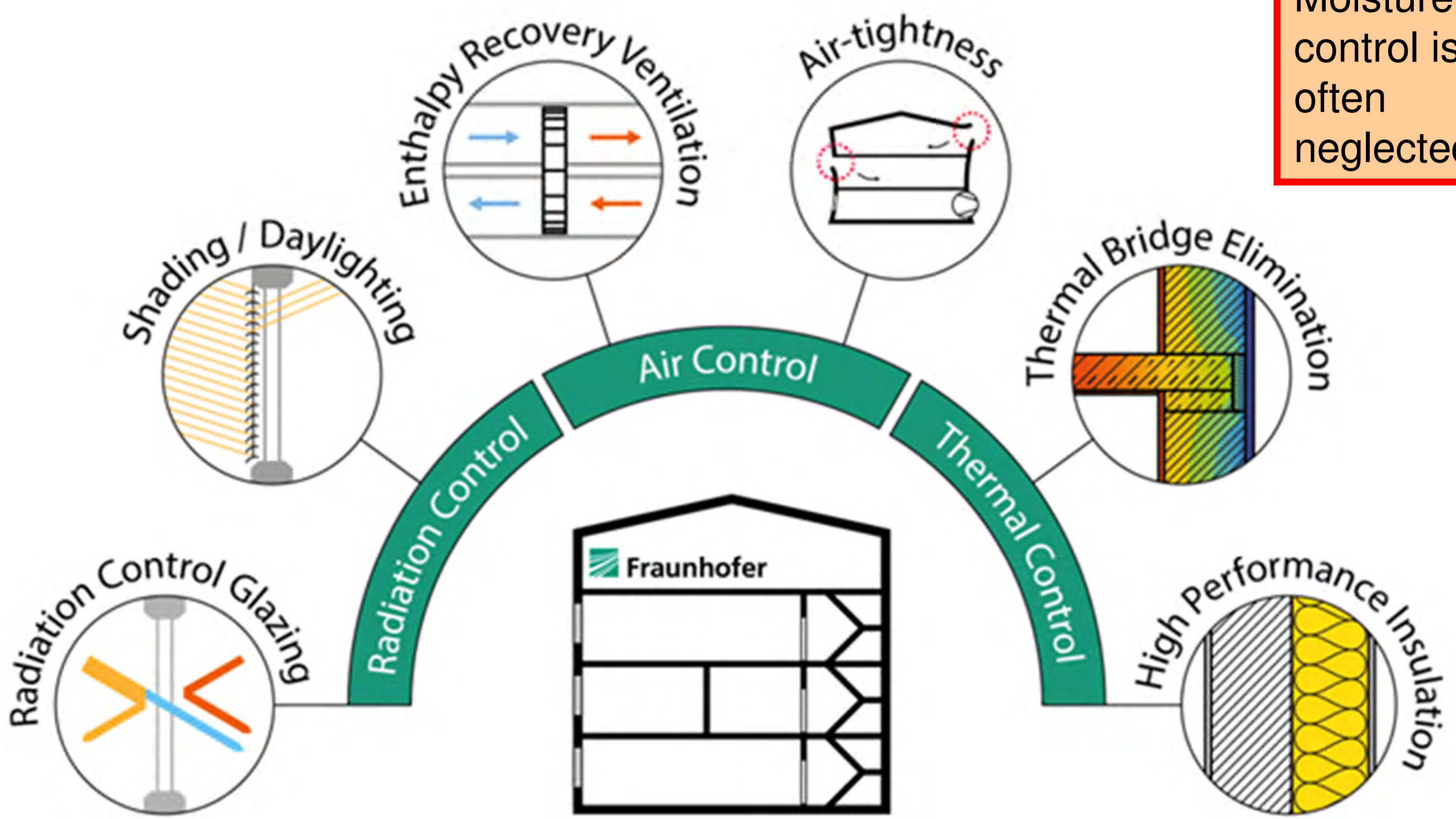
- A holistic building energy concept addresses comfort, hygiene, and durability
- Passive measures are indispensable and may be supported by efficient HVAC system and renewable energies
- Climate-specific and economical solutions require individual design
- Availability of technology to be considered
- Workmanship quality to be carefully planned and supervised



Source: Fraunhofer IBP

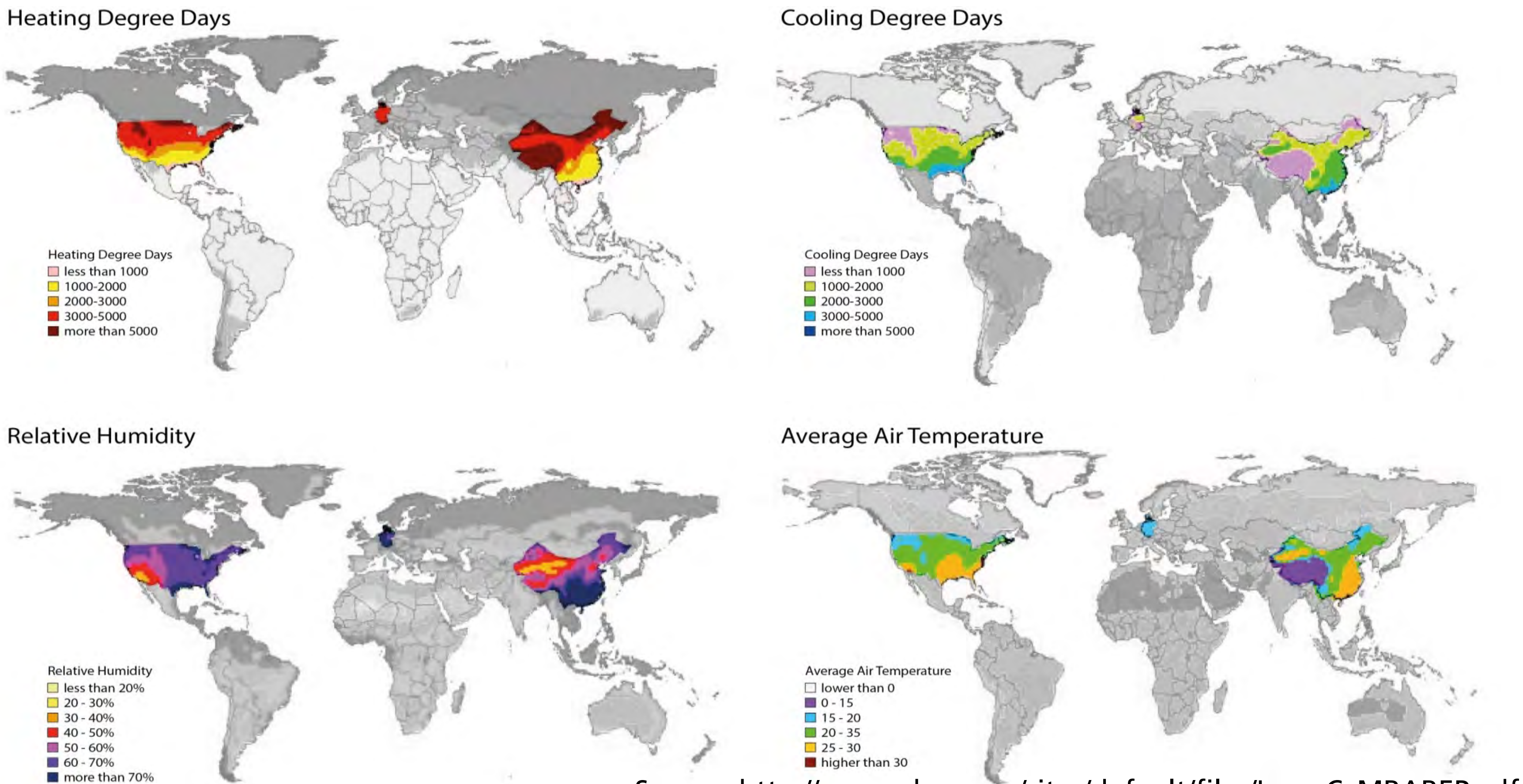
Passive Design Principles for Energy Efficient Buildings

Moisture control is often neglected



Fraunhofer IBP

World wide application of the standard requires deep analysis of hygrothermal building performance



Source: http://www.gbpn.org/sites/default/files/Low_C_MBABEP.pdf

Fraunhofer IBP

Current practice in building modeling/hygrothermal design

Fraunhofer IBP

Limitations of previous Passive House assessment

General

- Static calculation (Only annual / monthly method)
- No realistic inclusion of thermal inertia

Analysis

- No real comfort analysis
- No damage analysis (e.g. mold growth)

Limited Validation

- Only verified for European climates
- No broad scale North American verification

© nelsoncleancare.com

Usability

- No user-friendly input
- No assistance for missing / incorrect Data

Fraunhofer IBP

State of the art - building energy assessment

Thermal Conditions in Zones and Building Energy Use (Examples)

- Balance based: PHPP, …
- Dynamic: Energy Plus, TRNSYS, WUFI Plus, IDA-ICE, ESP-r, …

Used for

- design of buildings with low energy use
- assessment of the integral interaction of building, HVAC and use

→ expected indoor thermal conditions and energy use

but…

- no hygrothermal interaction with the envelope

Fraunhofer IBP

State of the art - hygrothermal component simulation

Hygrothermal Conditions on and in Building Components

- Steady-state (e.g. Glaser (Dew Point) method)
- Dynamic (e.g. WUFI, Delphin, HygricIRC, …)

Used for

- ensuring damage-free constructions
- computation of the coupled heat and moisture transfer in building components with predefined boundary conditions

→ expected temperature and moisture distribution in building components and energy and mass fluxes on surfaces

but…

- no interaction with the room
- predefined inner boundary conditions

Fraunhofer IBP

The ideal world…

Building energy design / certification:

- Passive house design / certification (monthly or annual balances)
- Dynamic building energy simulation

Comfort analysis on a room by room basis

- e.g. ASHRAE 55

Building component analysis

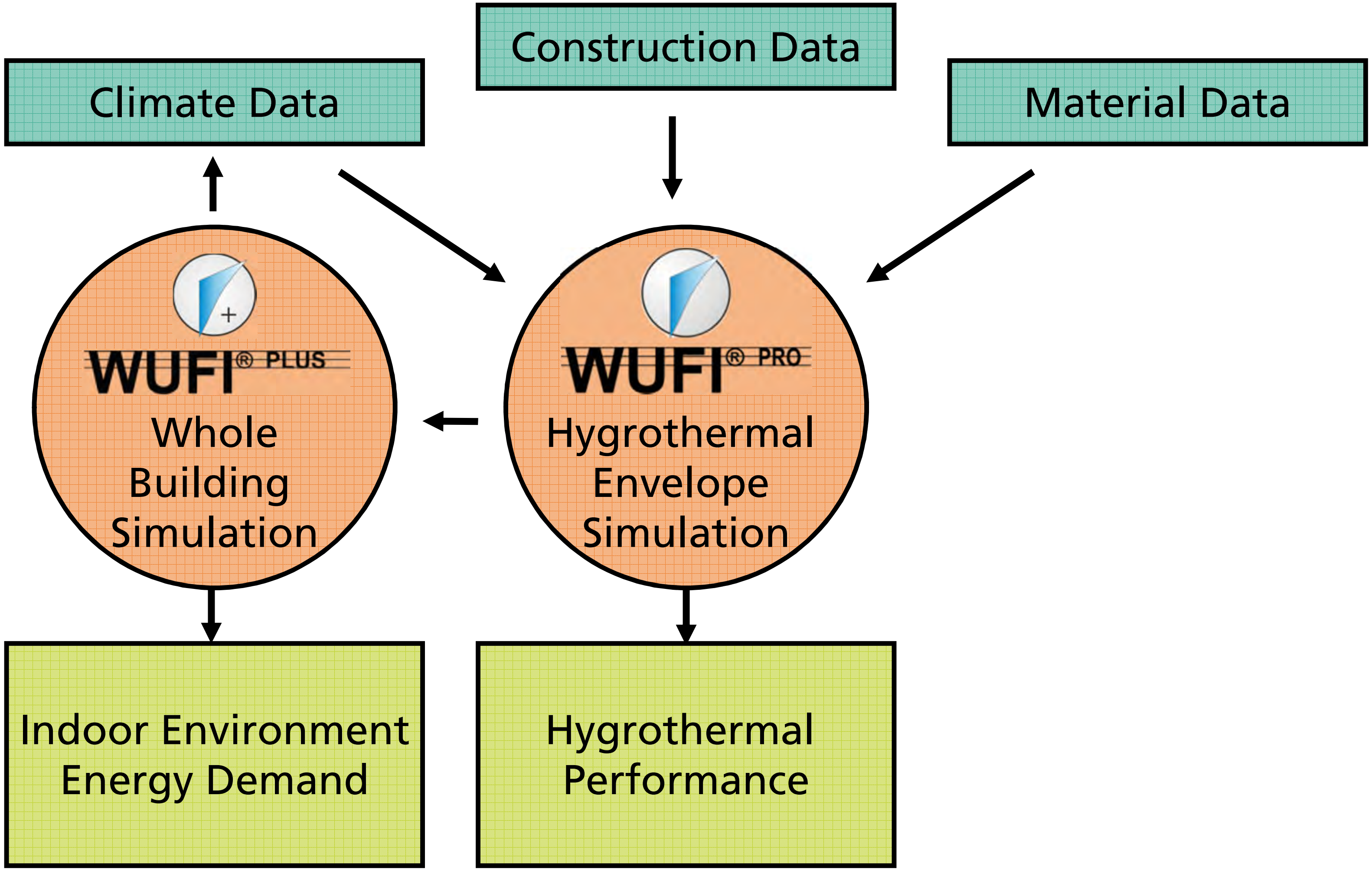
- Hygrothermal component simulation
- Interaction with the room

All based on "one" building model!

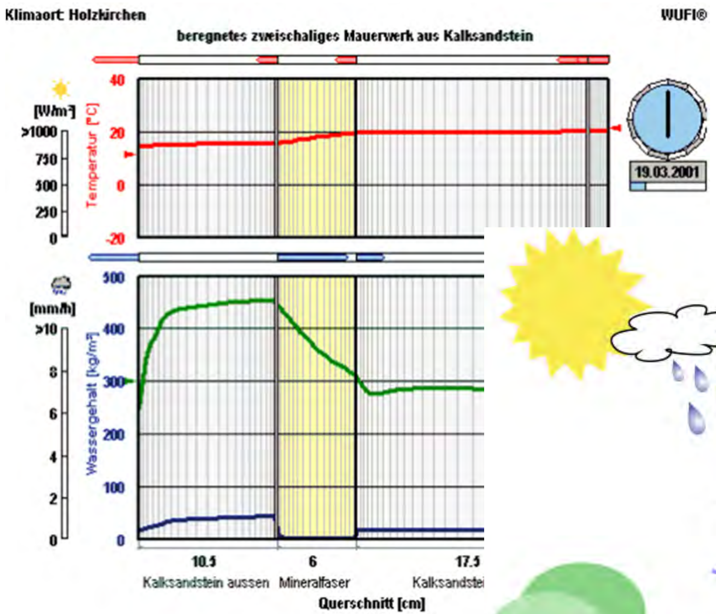
Building simulation with WUFI Plus/Passive

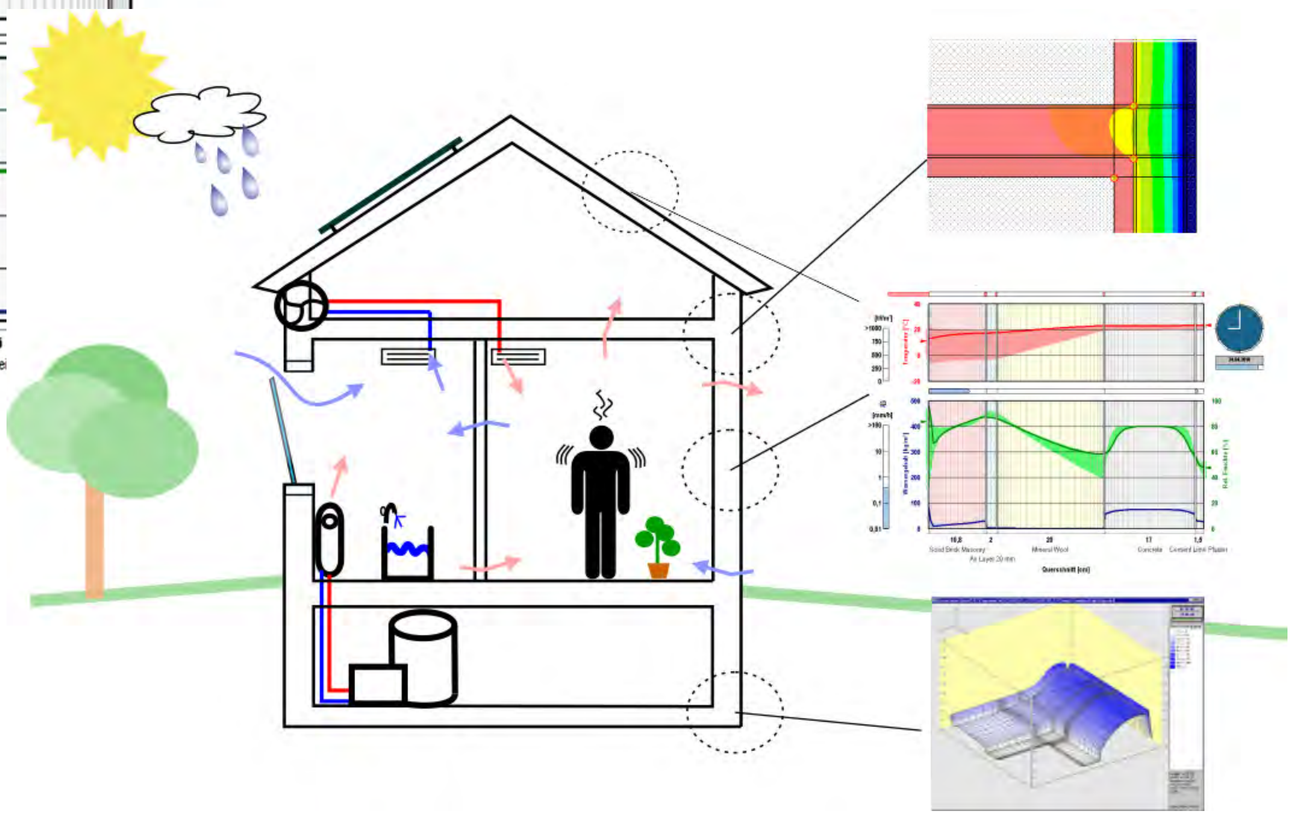
Fraunhofer IBP

Hygrothermal Whole Building Simulation



Balances – from Component to Whole Building

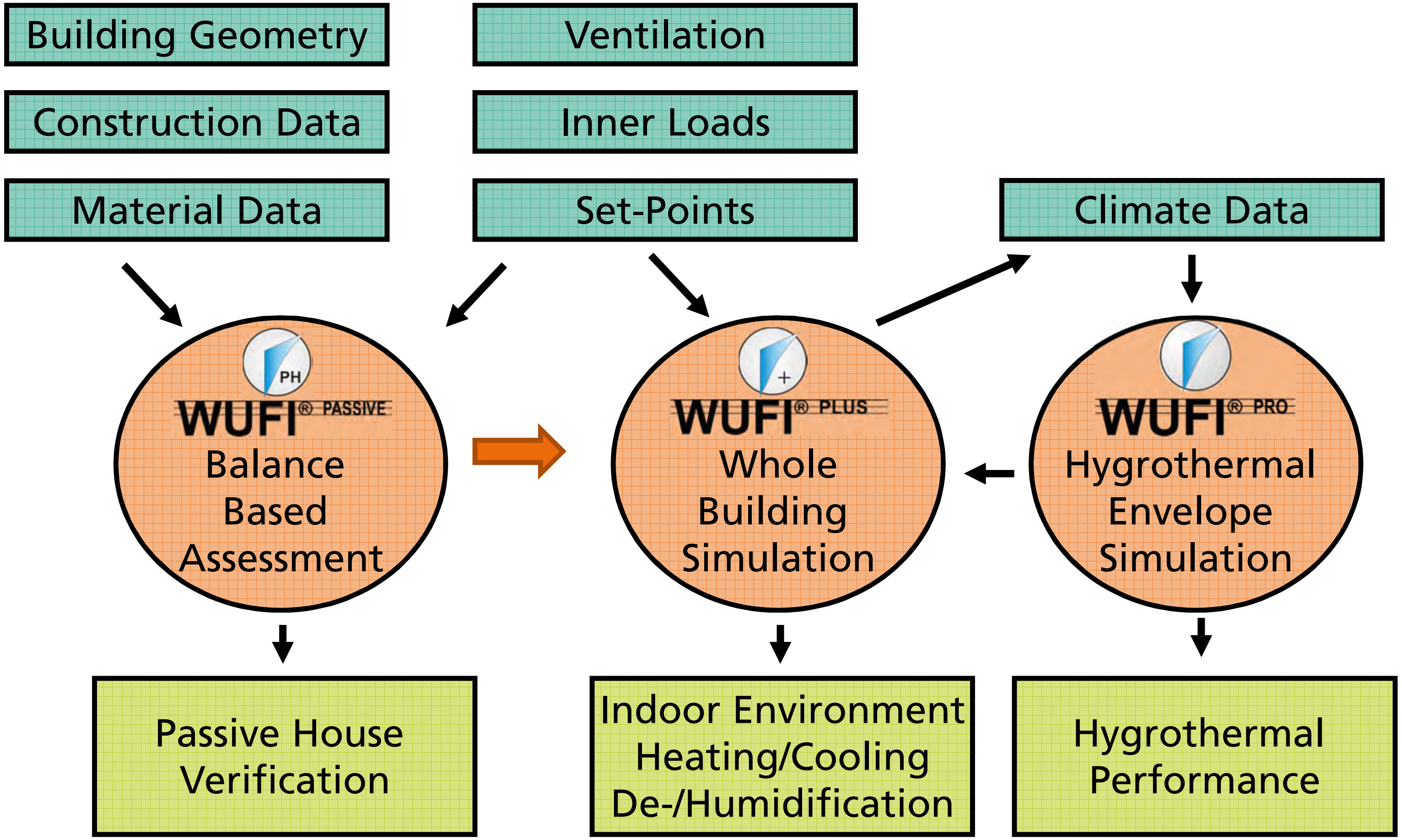




- Weather
- Ventilation
- Inner Loads
- Set-Points
- HVAC

Fraunhofer IBP

Combination for a new tool – WUFI Passive



Fraunhofer IBP

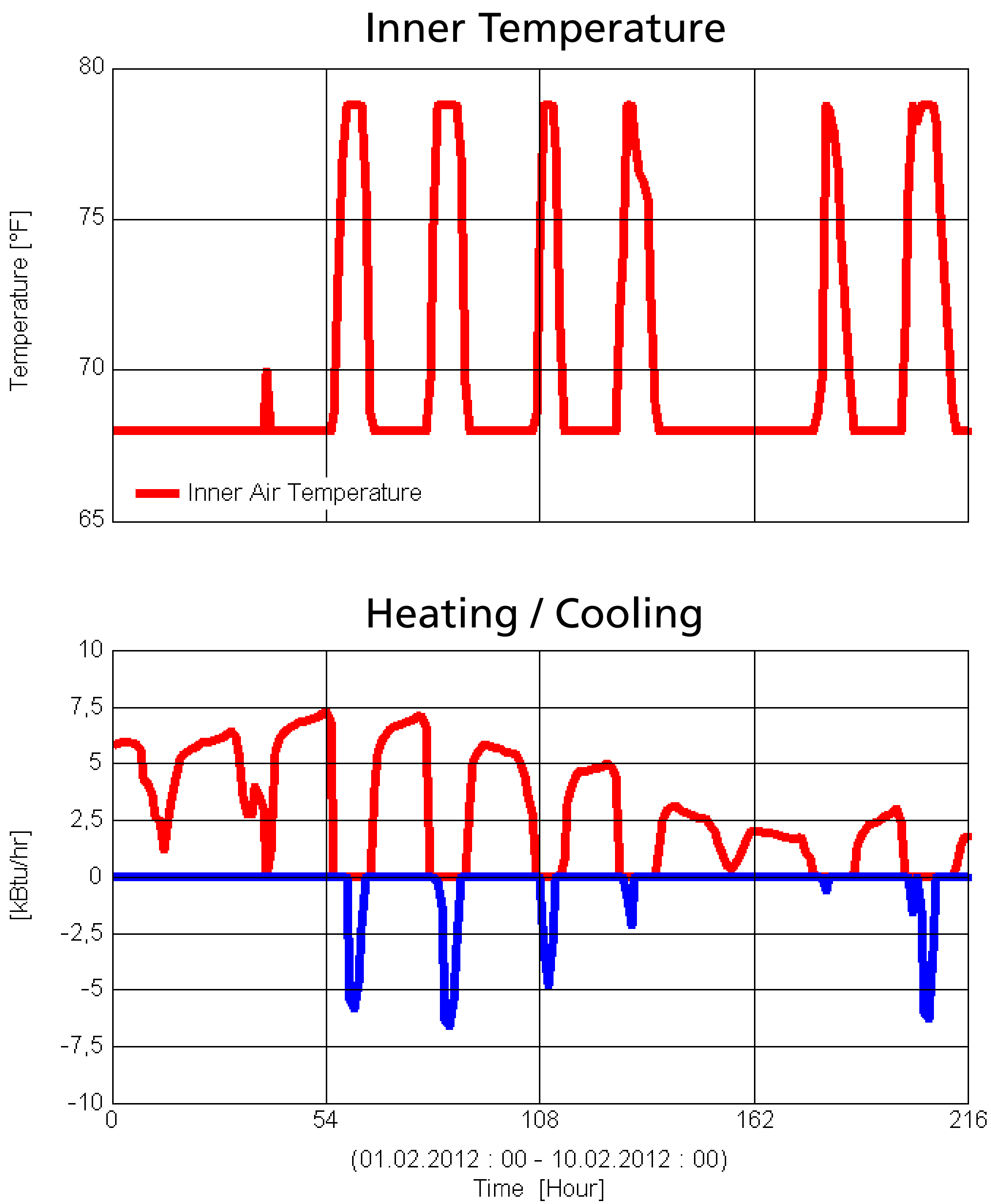
Results Examples

Fraunhofer IBP

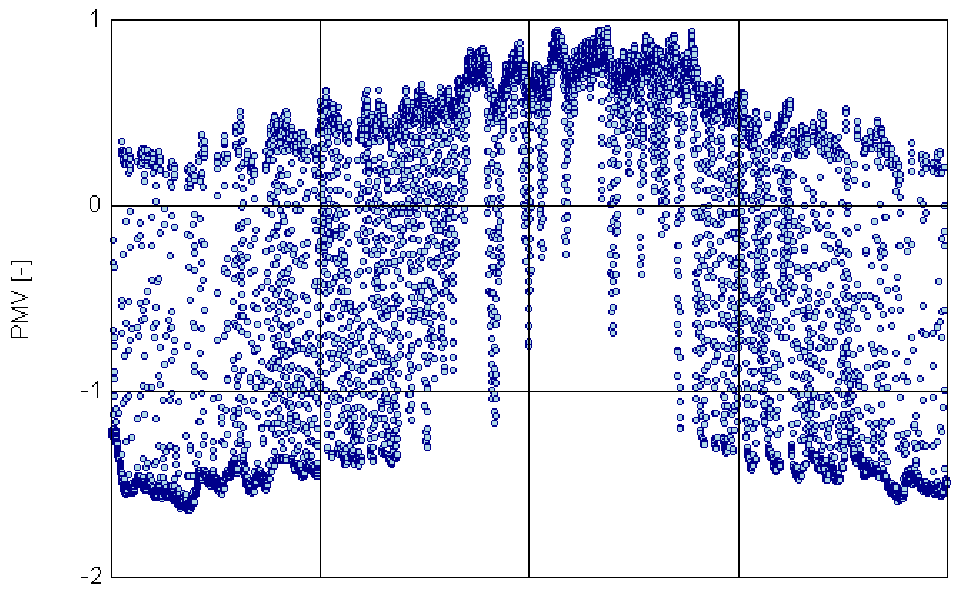
Dynamic output
Inner climate

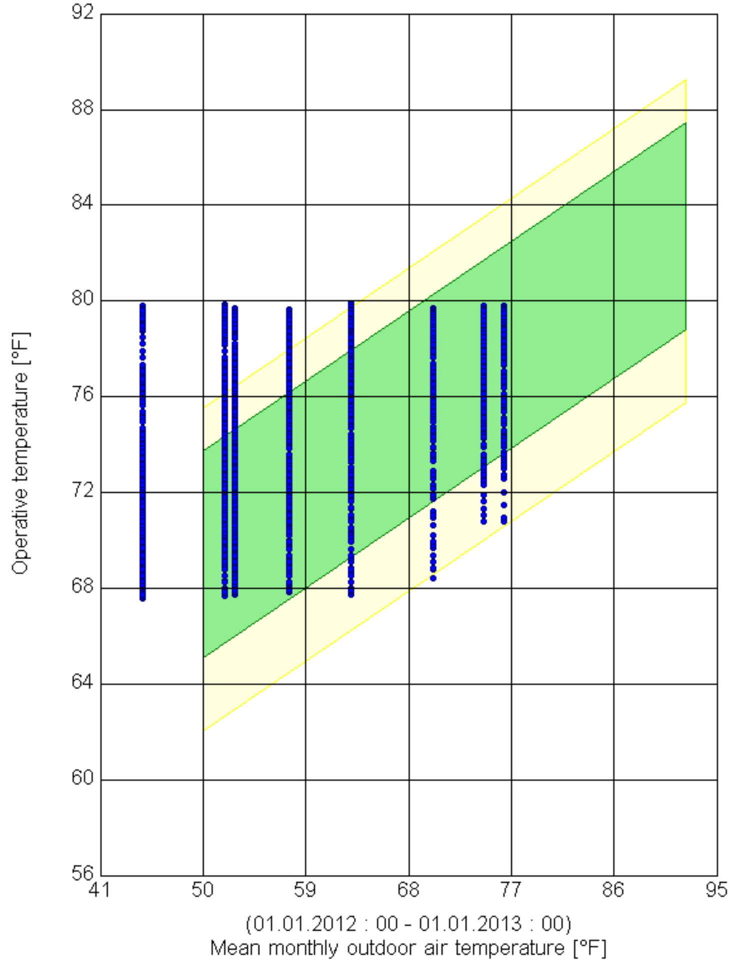
Dynamic conditions indoor

- Hourly values for inner temperature and RH
- Easy assessment of improvement strategies
- Assessment of effect of thermal and hygric inertia



Dynamic output – Comfort conditions





Comfort assessment (ASHRAE 55)

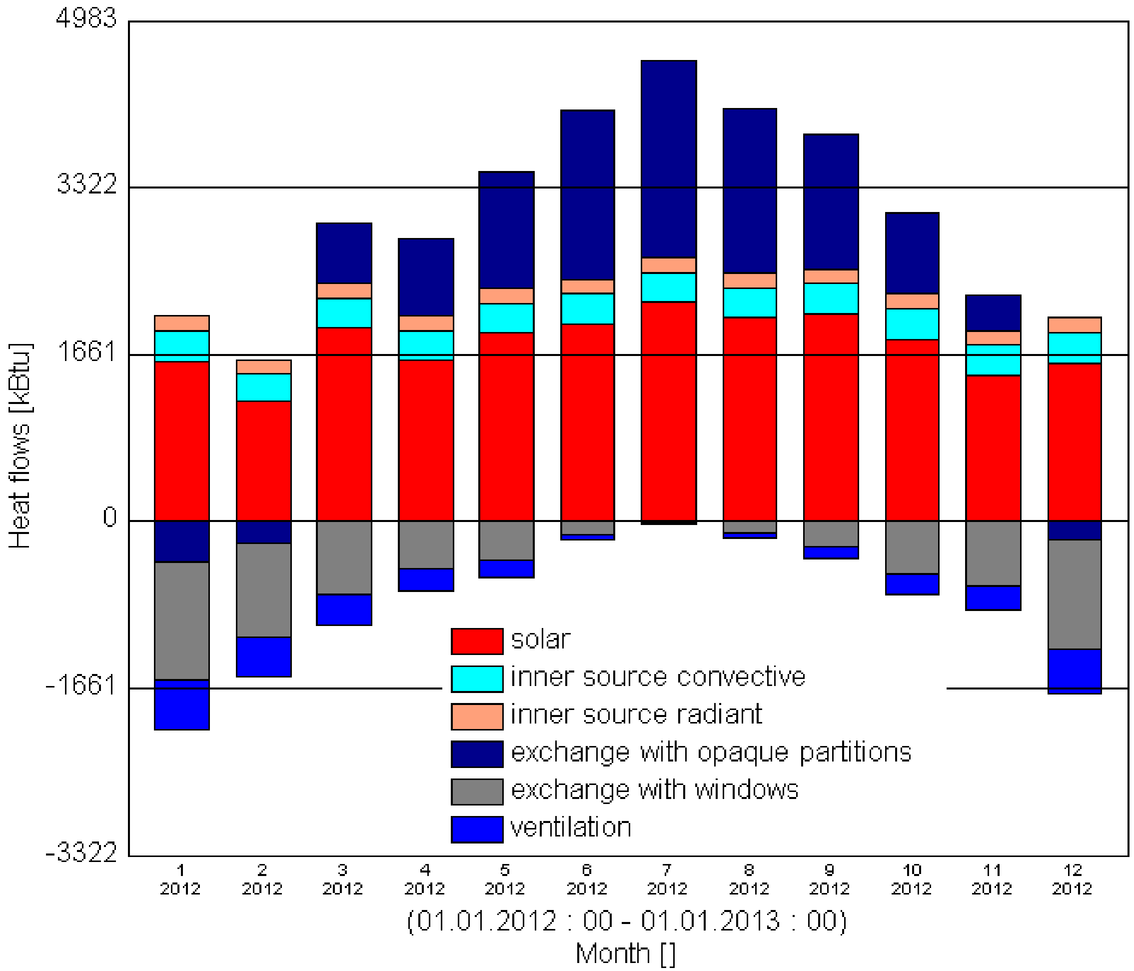
- Predicted mean vote
- Adaptive method
- Overheating hours

Fraunhofer IBP

Dynamic output – Heat flows

Heat / moisture flows

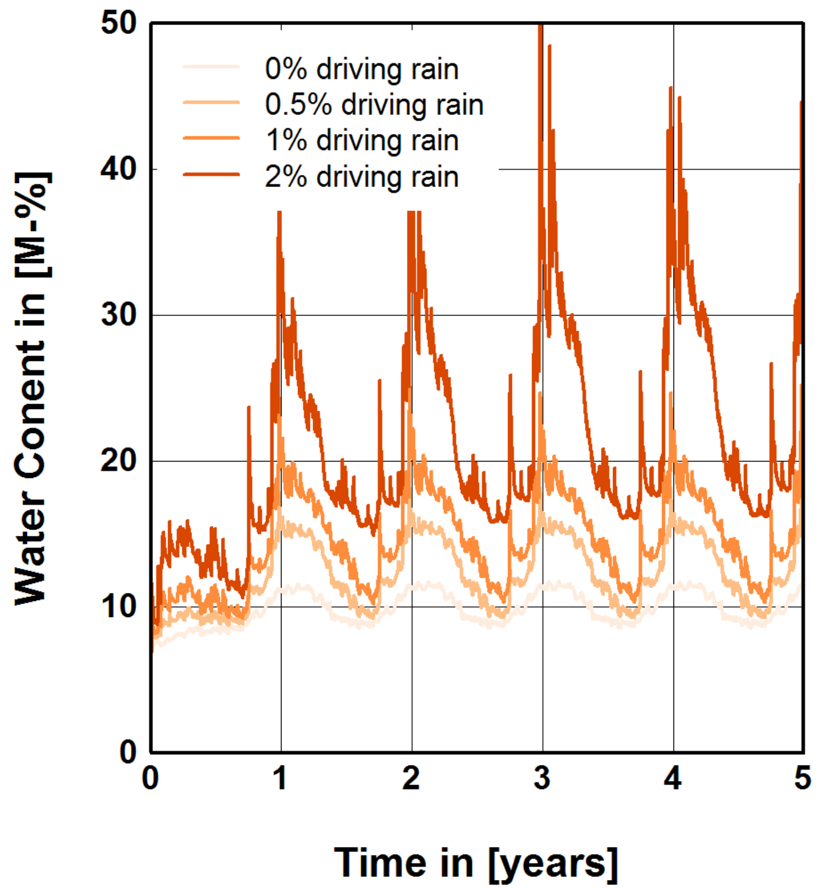
- Hourly values for all heat and moisture flows
- Monthly sums of heat and moisture flows
- Assessment of impact of different measures



Dynamic output – Component performance

Hygrothermal component performance

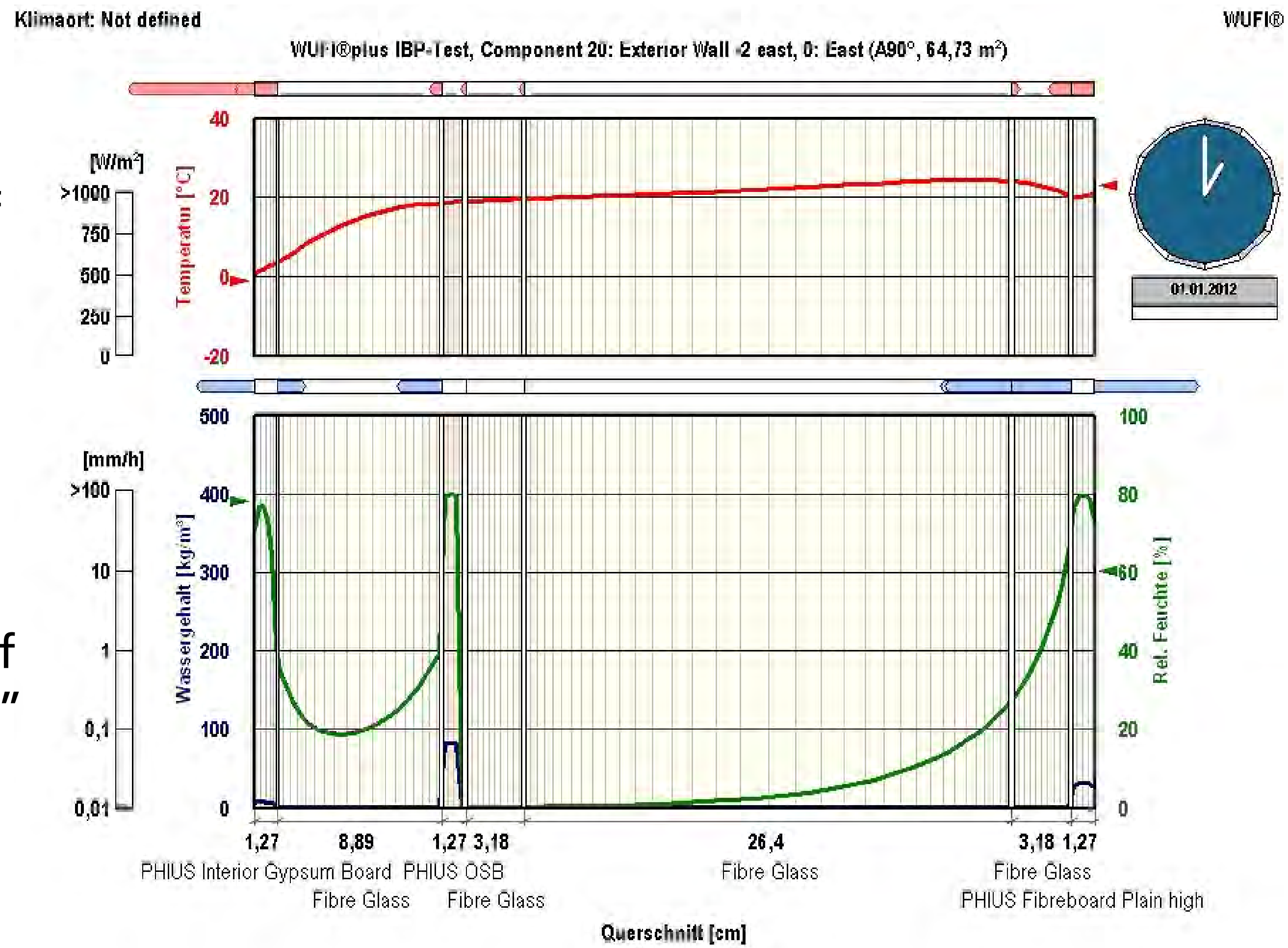
- Hourly values for layer temperatures, RH and water content
- Easy moisture safety assessment



Dynamic output – Movie

Movie

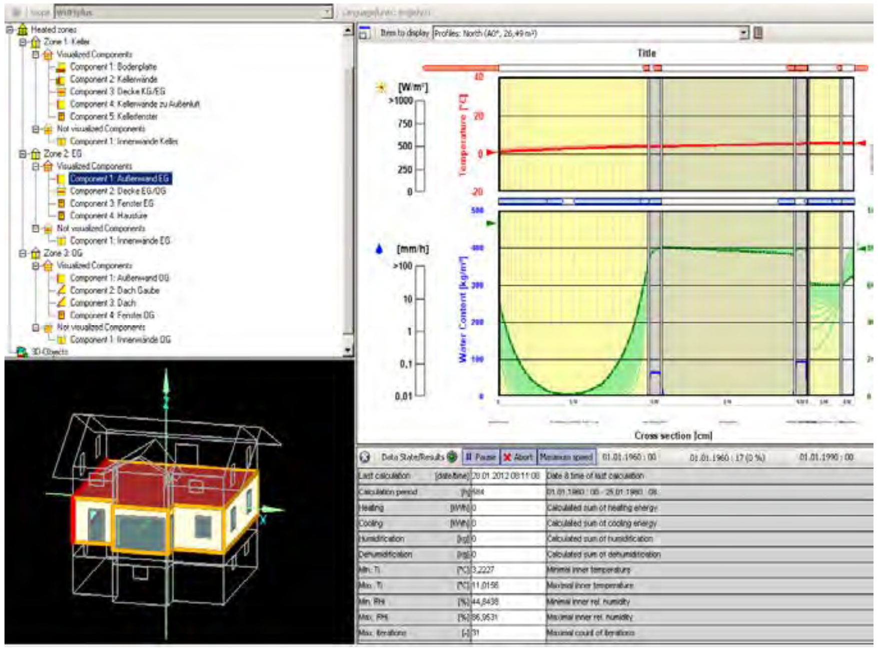
- Visualization of temperature and moisture distribution
- Heat and moisture fluxes on surfaces
- Identification of "problem spots" in the assembly



Sophisticated building performance assessment

Examples for additional modeling options

- Shading strategies
- Ventilation strategies
- Use of thermal and hygric inertia
- Different usage profiles
- Insulated shutters
- Envelope optimization
- Change in size and orientation
- Window properties and size optimization



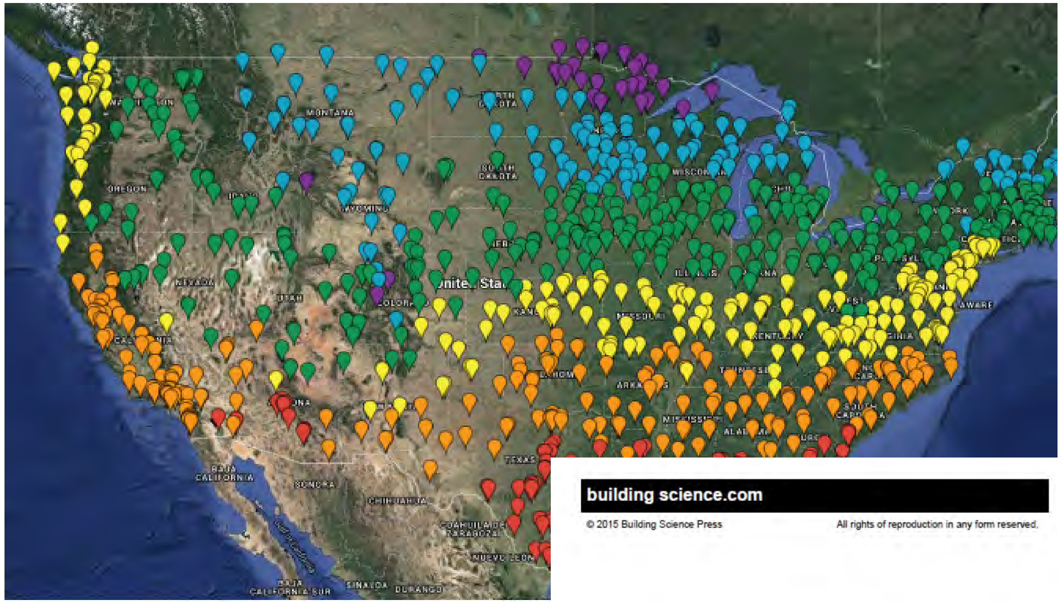
Conclusions and Outlook

Fraunhofer IBP

PHIUS building certification program

- Climate specific adoption of passive building standard
- Ensuring cost effectiveness while providing resilient high performance buildings
- Global network of experts to collect and spread passive building experience

→ Best solutions for healthy and comfortable passive houses in all climate zones



GPBC
GLOBAL PASSIVE BUILDING COUNCIL

www.globalpassive.net

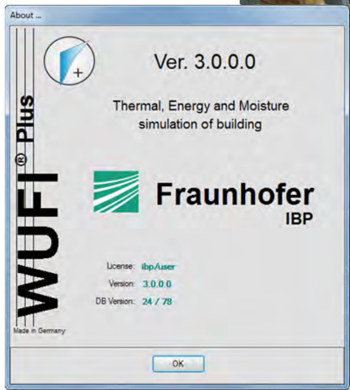
Climate-Specific Passive Building Standards

Building America Report - 1405
March 2015
G. Wright (PHIUS), K. Klingenberg (PHIUS), Betsy Pettit, FAIA

Fraunhofer IBP

Conclusions

- Buildings are designed for their occupants
- Cost effective passive measures first!
- Design tools are available for combined analysis of energy, comfort and hygrothermal component performance
- Design of net-zero and positive energy buildings require detailed HVAC and photovoltaic simulation to match production and demand



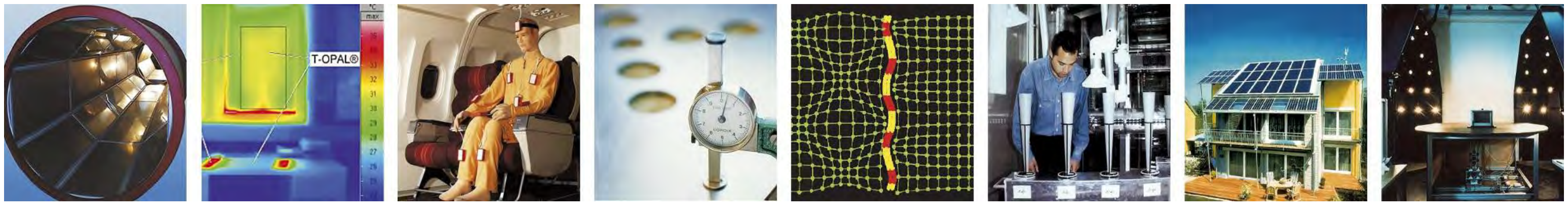
Fraunhofer IBP

Static versus dynamic passive building design

Florian Antretter – August 4th 2015

Nineteenth Annual Westford Symposium on Building Science

Auf Wissen bauen



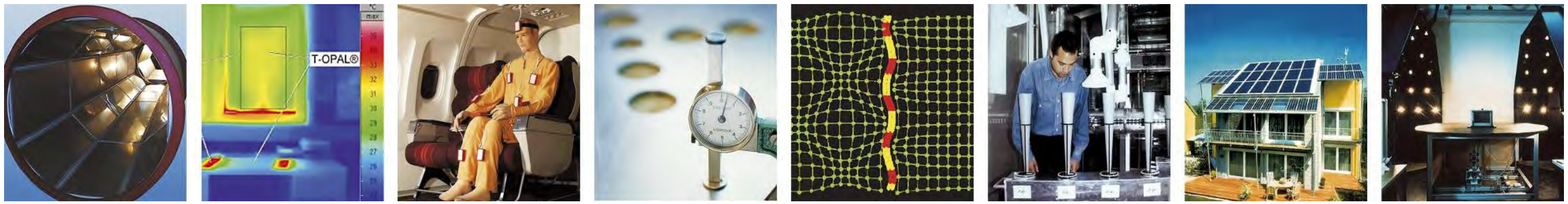
Fraunhofer IBP

Is hygric inertia (moisture buffering) comparable to thermal inertia?

Florian Antretter – August 4th 2015

Nineteenth Annual Westford Symposium on Building Science

Auf Wissen bauen



Fraunhofer IBP

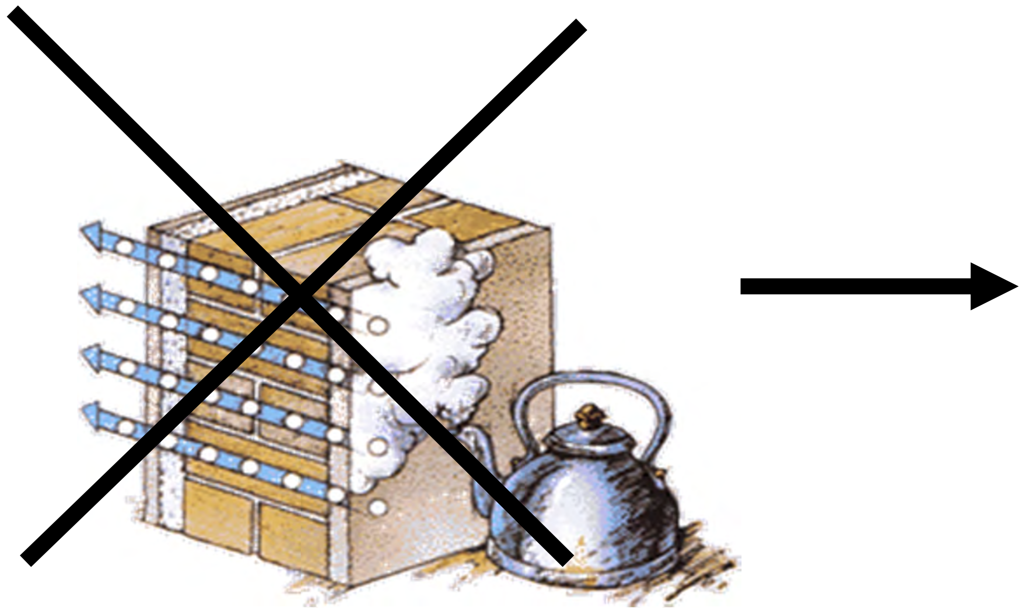
Outline

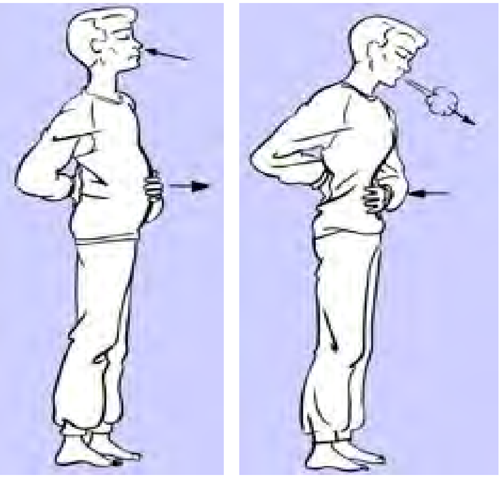
- What is moisture buffering?
- Field test with wood based linings
- Experimental test with a special tile and energetic impact
- And the German castles?

Fraunhofer IBP

What is moisture buffering?

Principle of moisture buffering



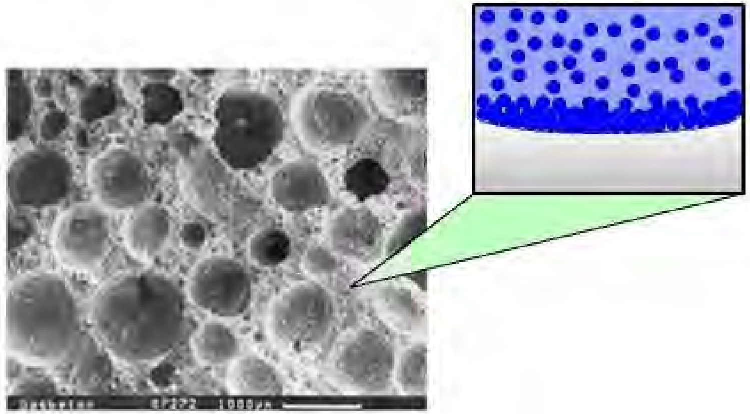


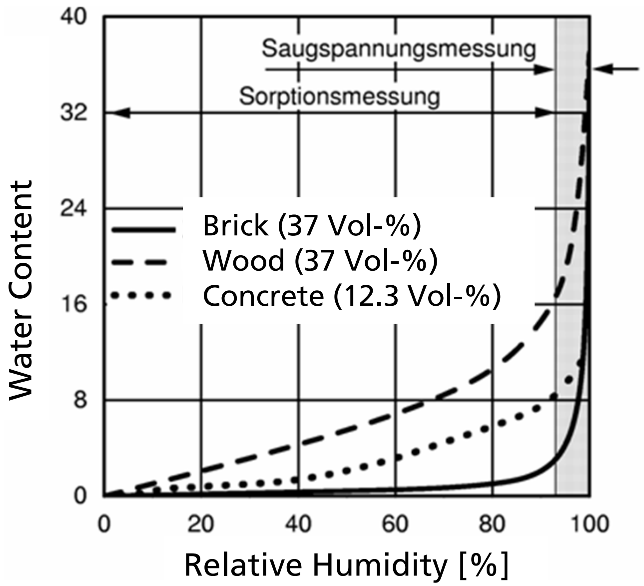
Buffer = Cache

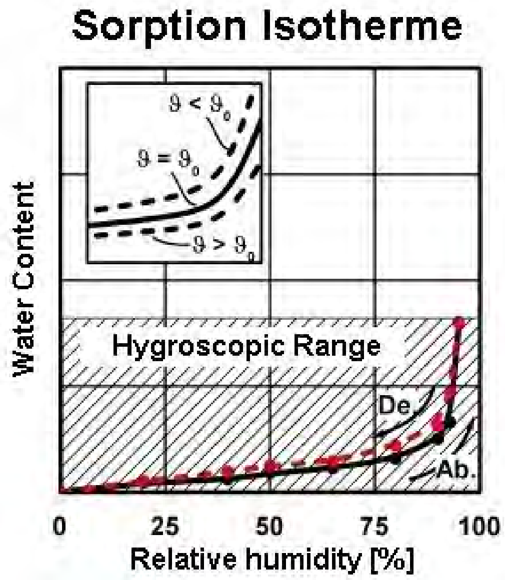
Moisture buffering of the building enclosure is a transient process which depends on the moisture storage as well as on the moisture transport properties of the interior surface layers

Principle of moisture buffering

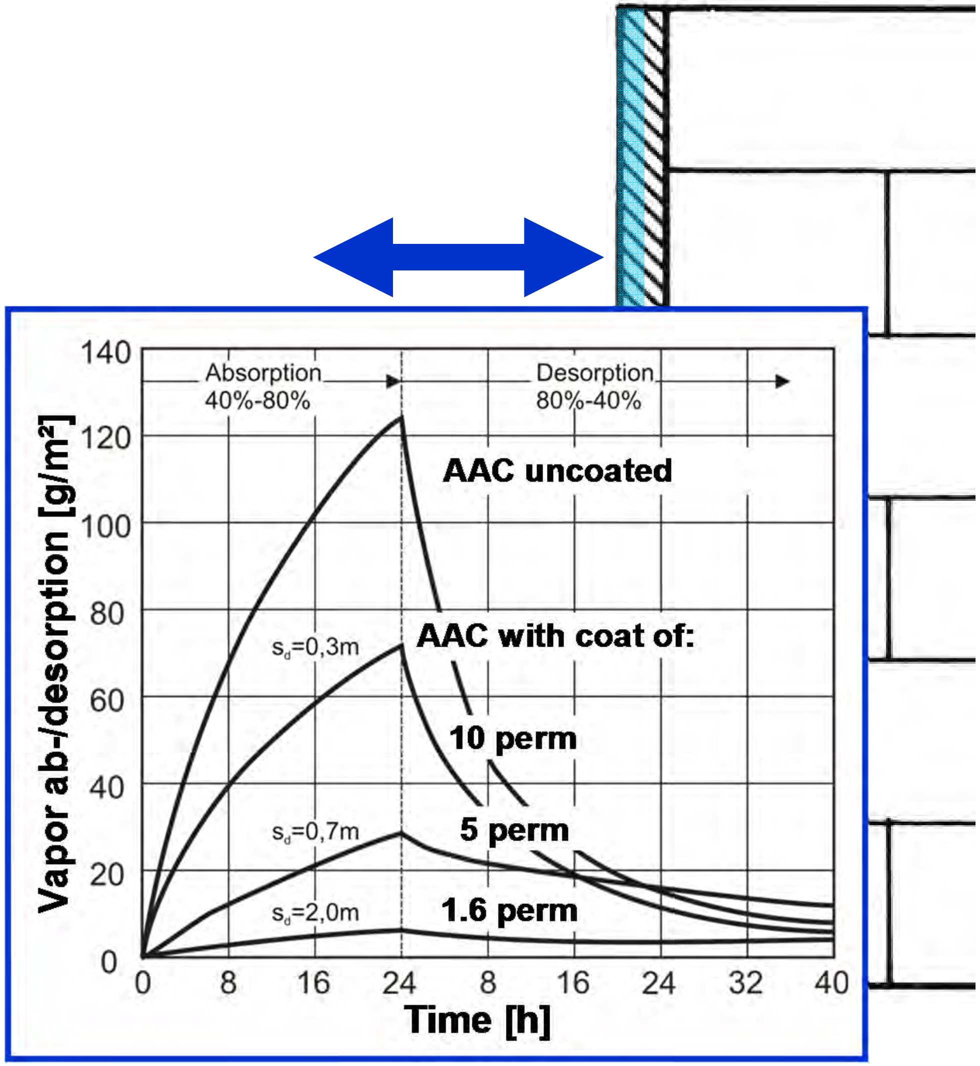
- Water molecules attach to the inner surfaces of porous materials
- The higher the humidity, the thicker the molecule layer
- With decreasing surrounding humidity the water molecules are desorbed again







Principle of moisture buffering



Main influence factors:

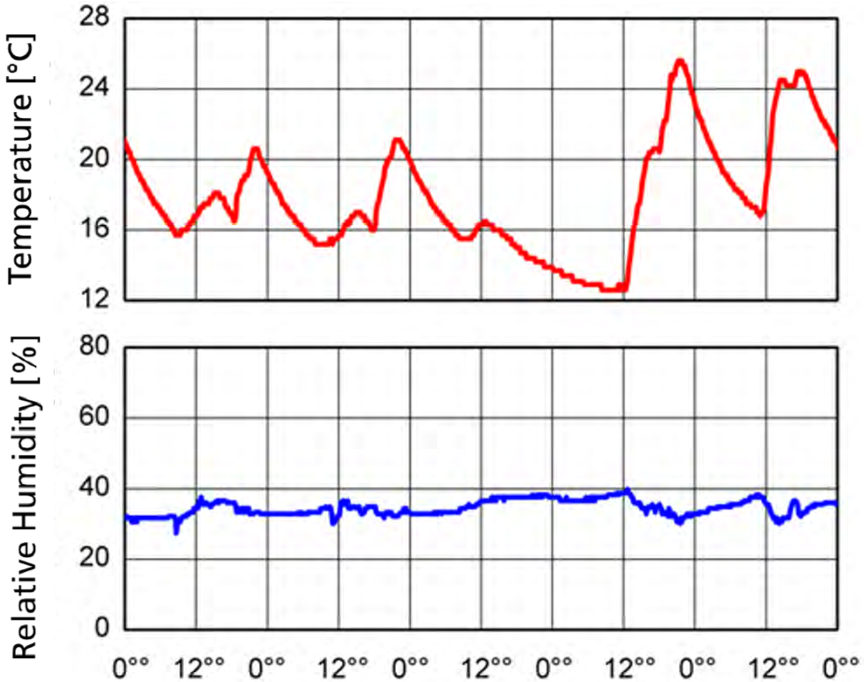
- Humidity range (Diffusion/Sorption)
- Area in contact with indoor air
- Surface transfer conditions
- Surface coatings

Determination of moisture buffer potential of building material in practice require:

- Realistic field test
- Hygrothermal building sim.

Fraunhofer IBP

Moisture buffering under real use conditions



Relevance for intermittent heating

Very small relative humidity fluctuations despite huge temperature fluctuations

Fraunhofer IBP

Advantages and disadvantages of moisture buffering

Advantages of moisture buffering materials

- More uniform indoor climate especially in the case of intermittent heating or high changes in moisture load
- Effect on surface temperature due to latent heat effects
- Energy saving potential by combining moisture buffering with adapted ventilation

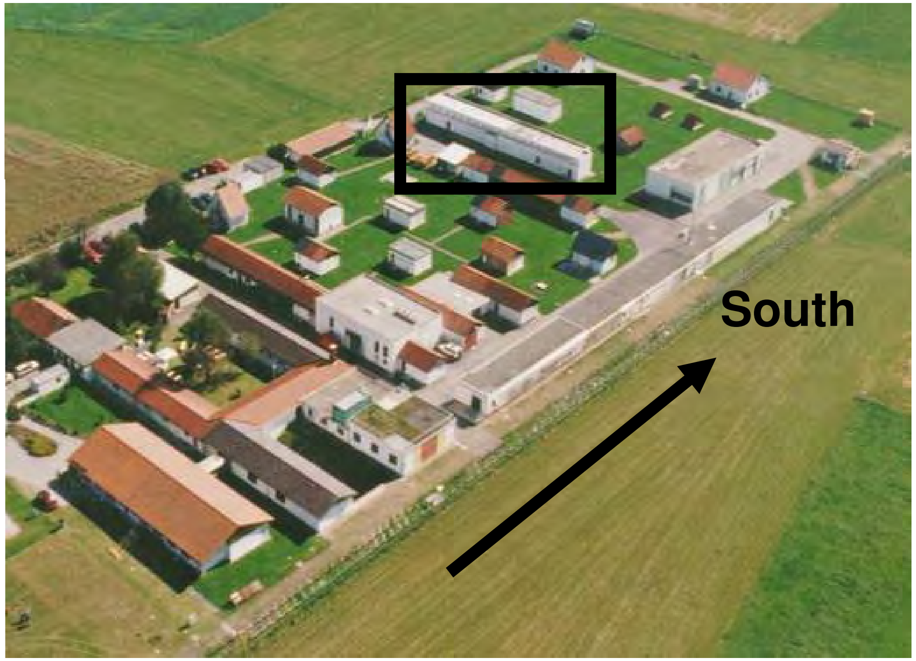
Disadvantages of moisture buffering materials

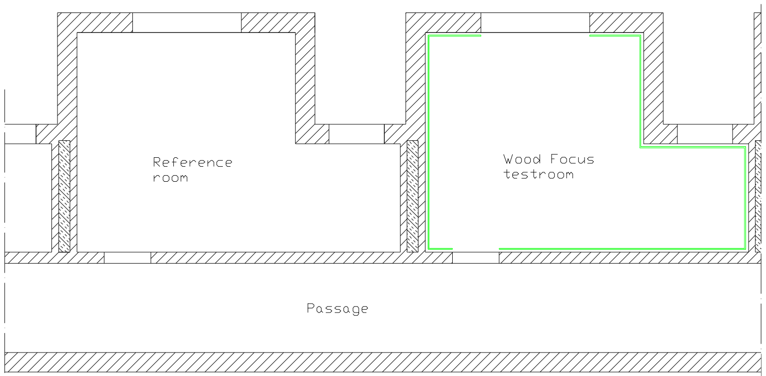
- Reduced effectiveness of shock ventilation

Fraunhofer IBP

Field Test

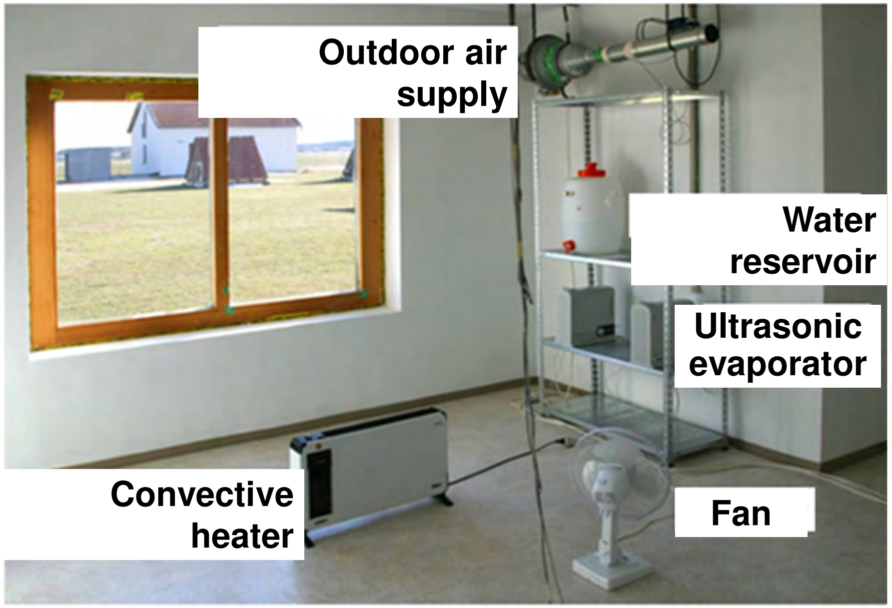
Test facility at IBP test site





- Two identical test rooms
- well insulated
- with external wall section including window facing south
- surrounded by heated spaces above and north

Test facility

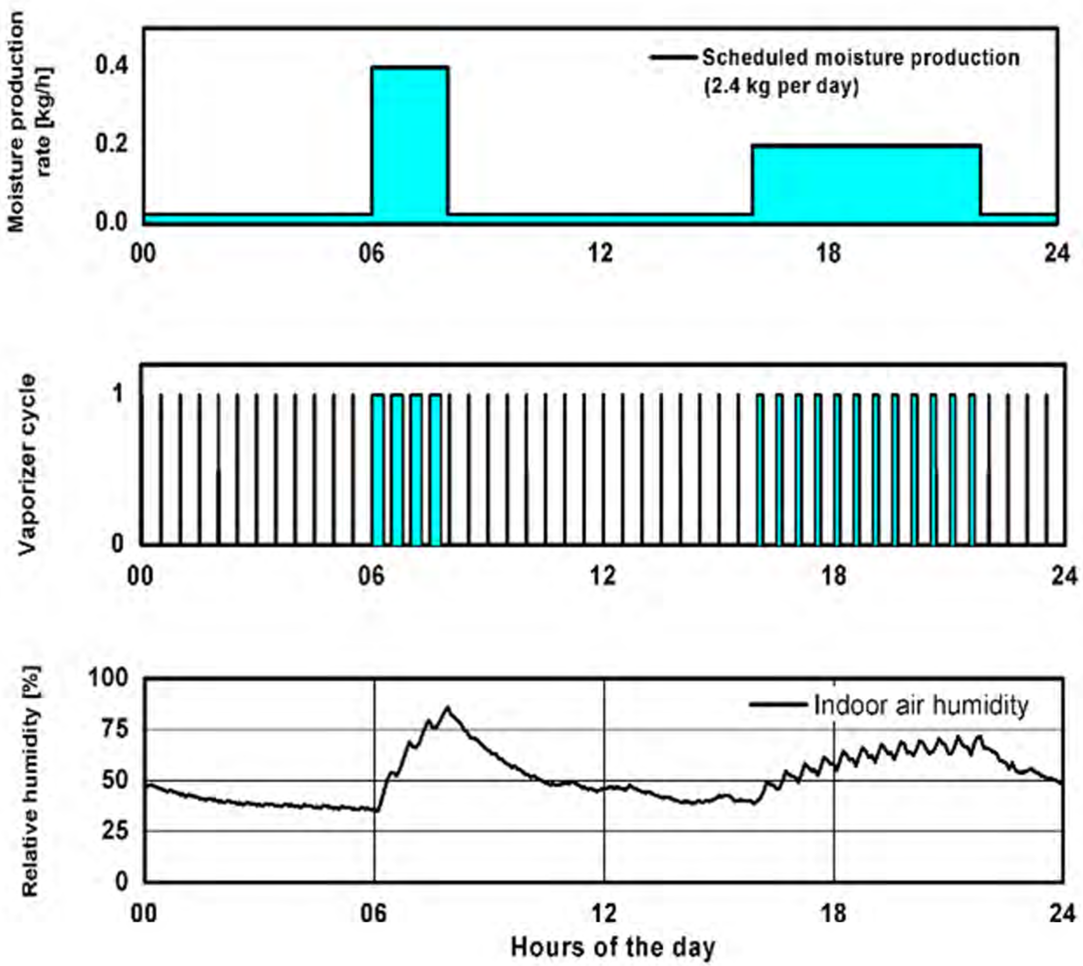


Reference room with interior plaster and paint coat

Interior lining test room with aluminum wall paper

Both rooms have a non absorbent vinyl floor cover

Daily profile of vapor generation



Vapor generation control of by time switch

Daily mean generation rate: 2 g/m³h (12 Ltr/d in 100 m² flat)

Fraunhofer IBP

Installed interior linings



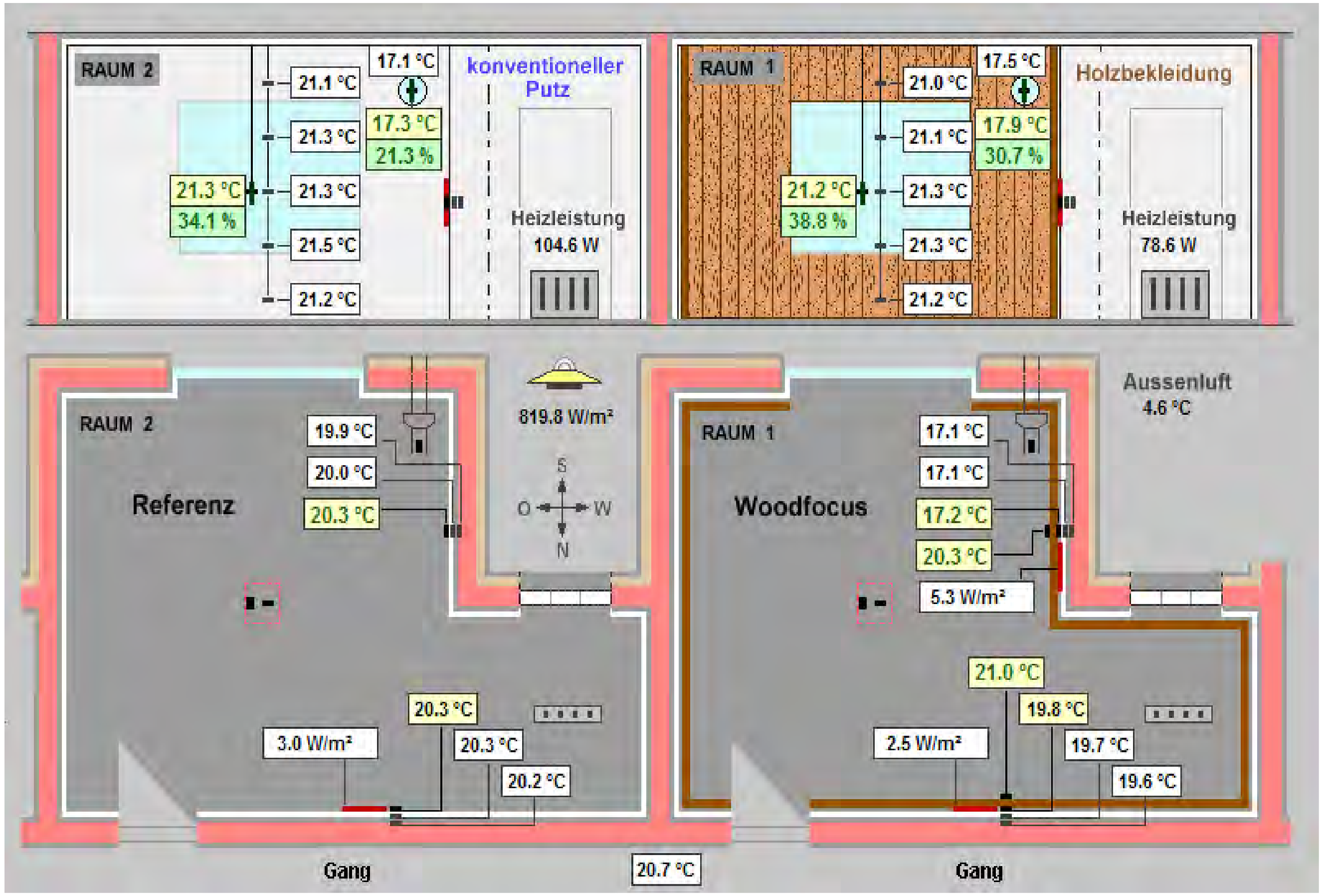


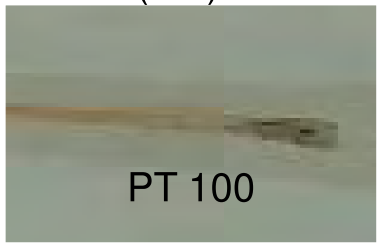

Test preparation

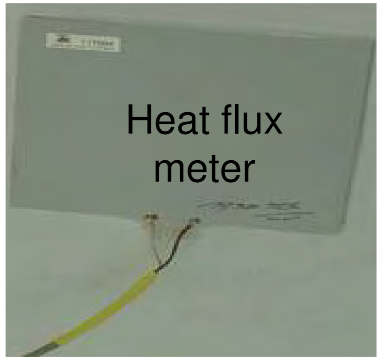
Storage of lining materials at 20° C und 50% RH prior to installation in test room

Fraunhofer IBP

Sensor positions and data logging

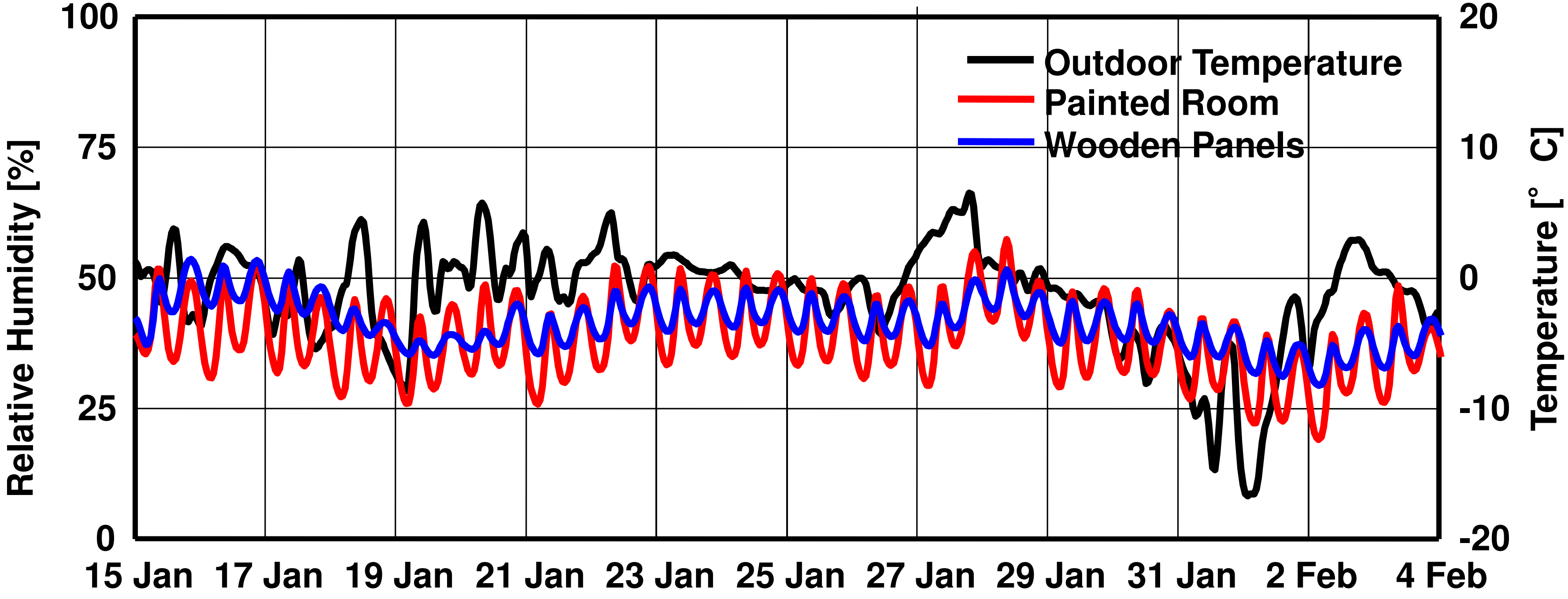




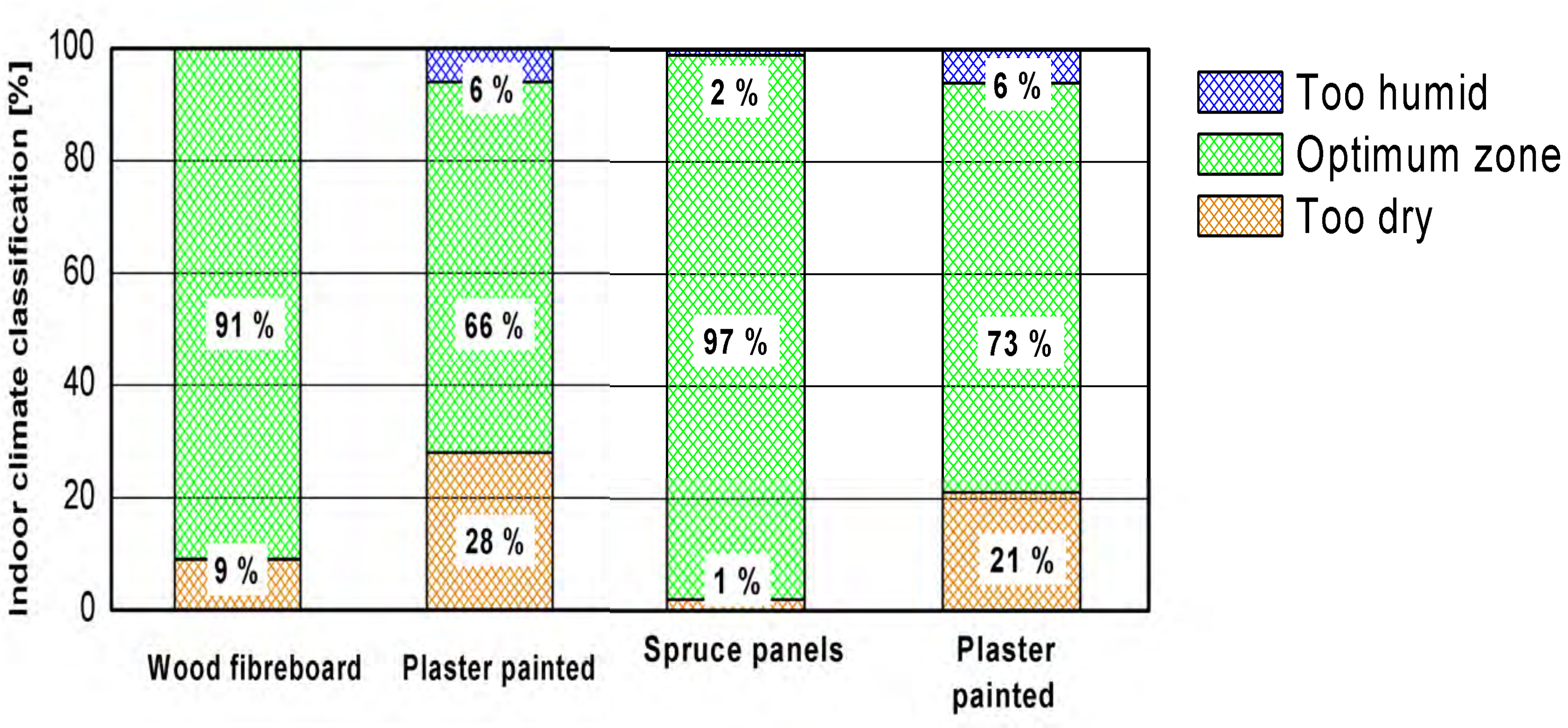


Fraunhofer IBP

Experimental results



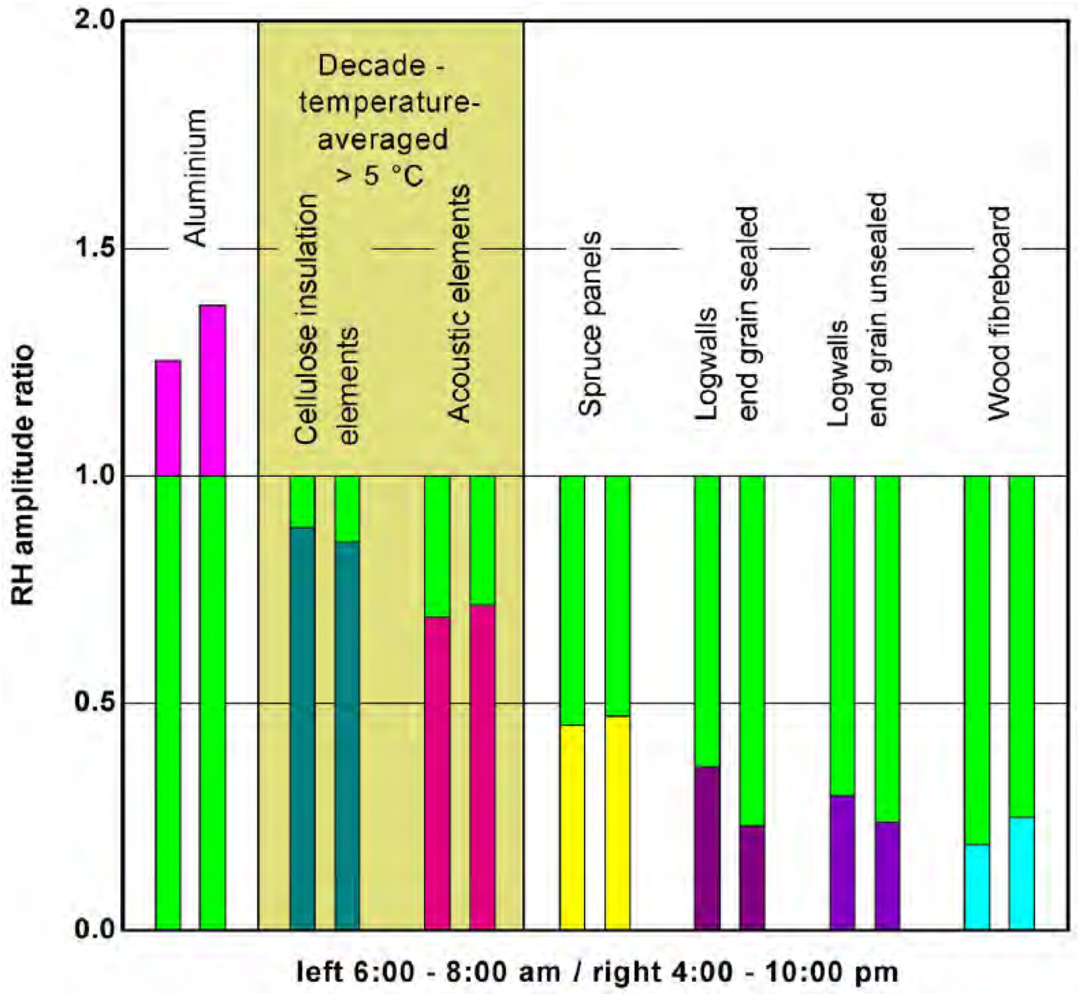
Moisture buffering effect of wood based interior linings

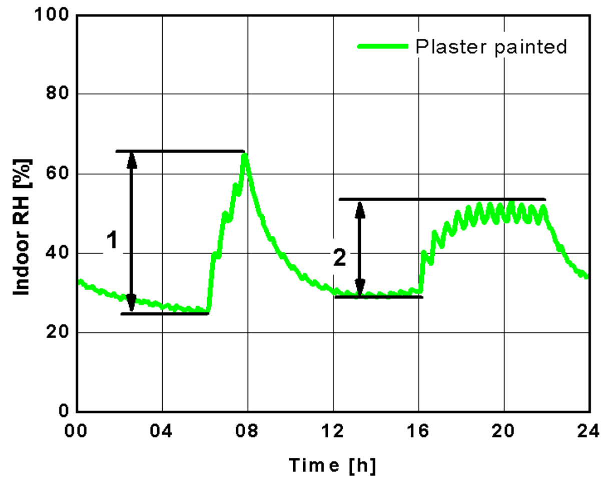


Optimum zone: RH between 40% and 60%

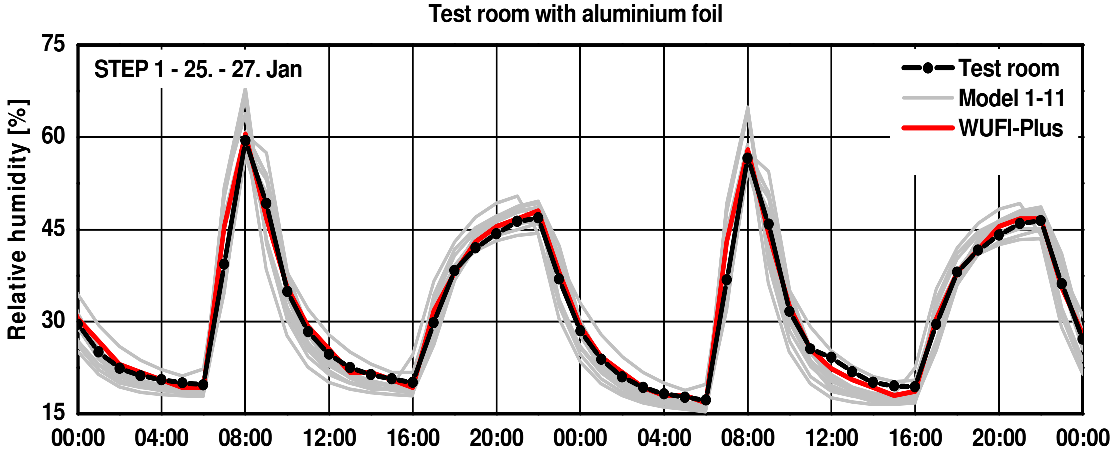
Fraunhofer IBP

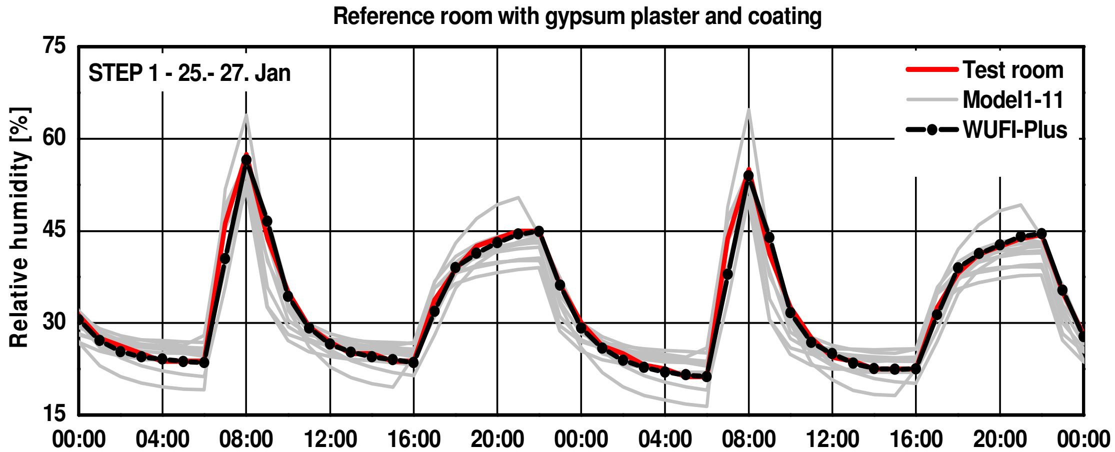
RH Amplitude Ratio for All Materials





Hygrothermal Whole Building Simulation - Validation



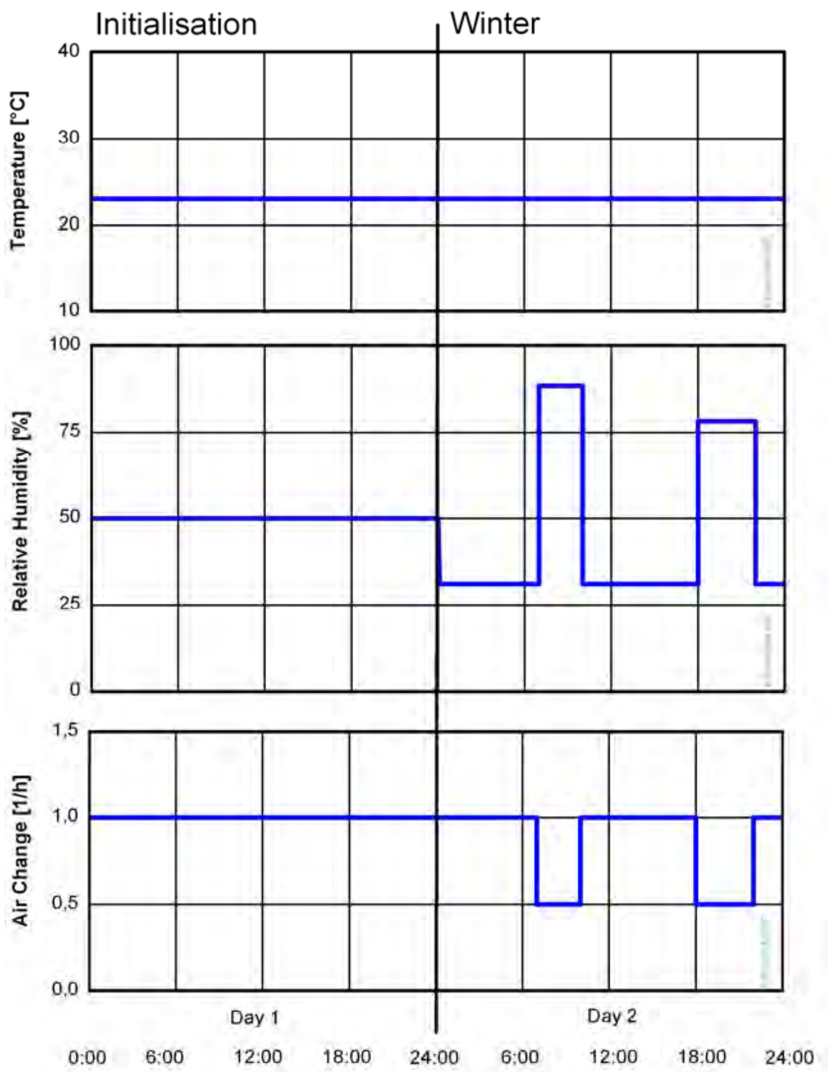


Fraunhofer IBP

Laboratory Experiment and Upscaling via Simulation

Fraunhofer IBP

Laboratory Experiment to Assess Moisture Buffering



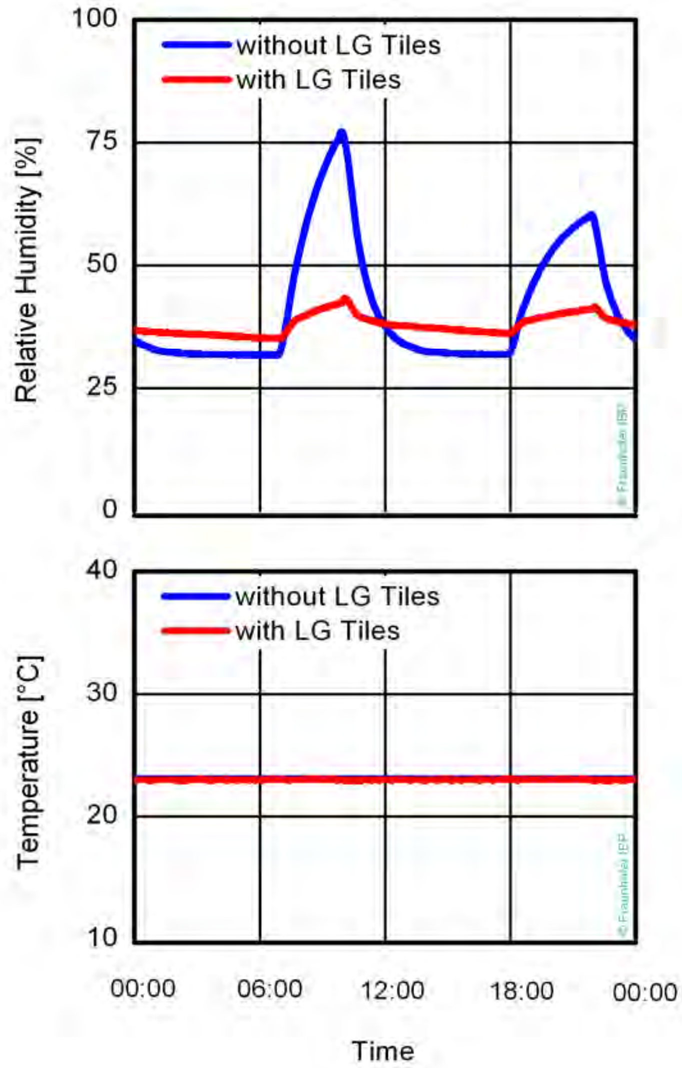
Moisture buffering tiles in controlable climate chamber

Fraunhofer IBP

Results comparison and effect of the interior tile - winter

Test results „Winter“ case

- constant temperature 23 °C
- RH fluctuations
  - without LG tiles: 45 %
  - with LG tiles: 7 %
- duration of moisture production does not influence the moisture buffering



Fraunhofer IBP

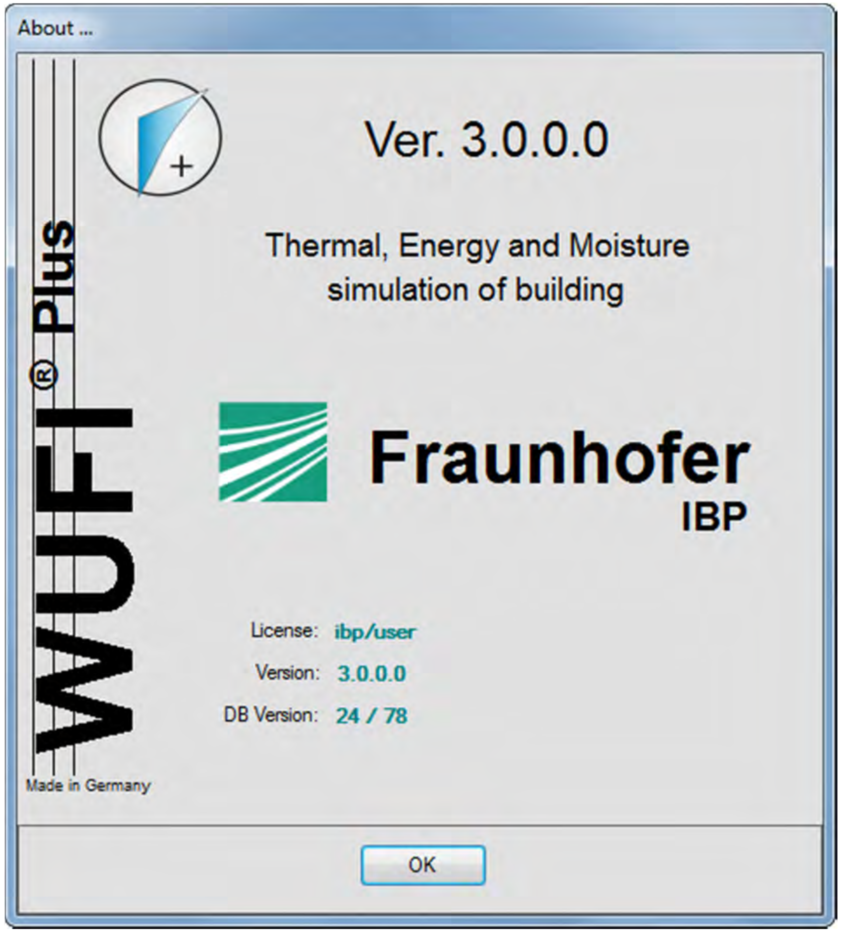
Validation Simulation – Used Tool

Use of hygrothermal whole building simulation tool:

WUFI Plus

because of:

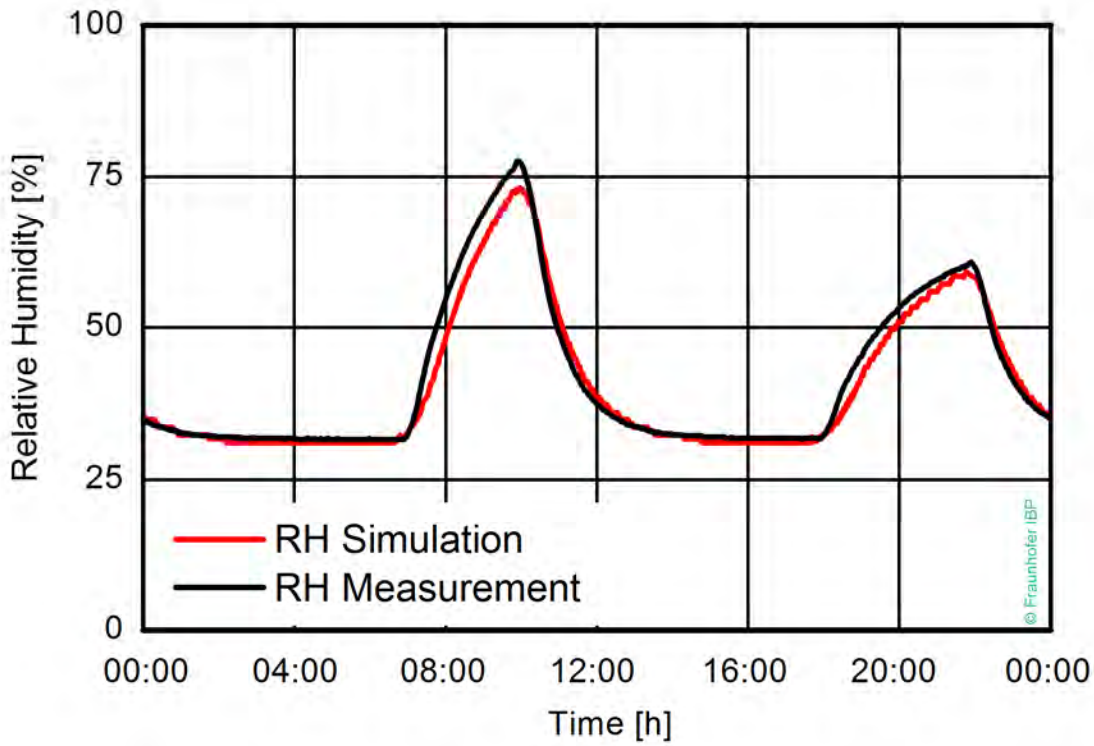
- Connection of hygrothermal component calculation and energetic building simulation
- Transient coupled heat and moisture transport calculations
- Arbitrary time steps



Fraunhofer IBP

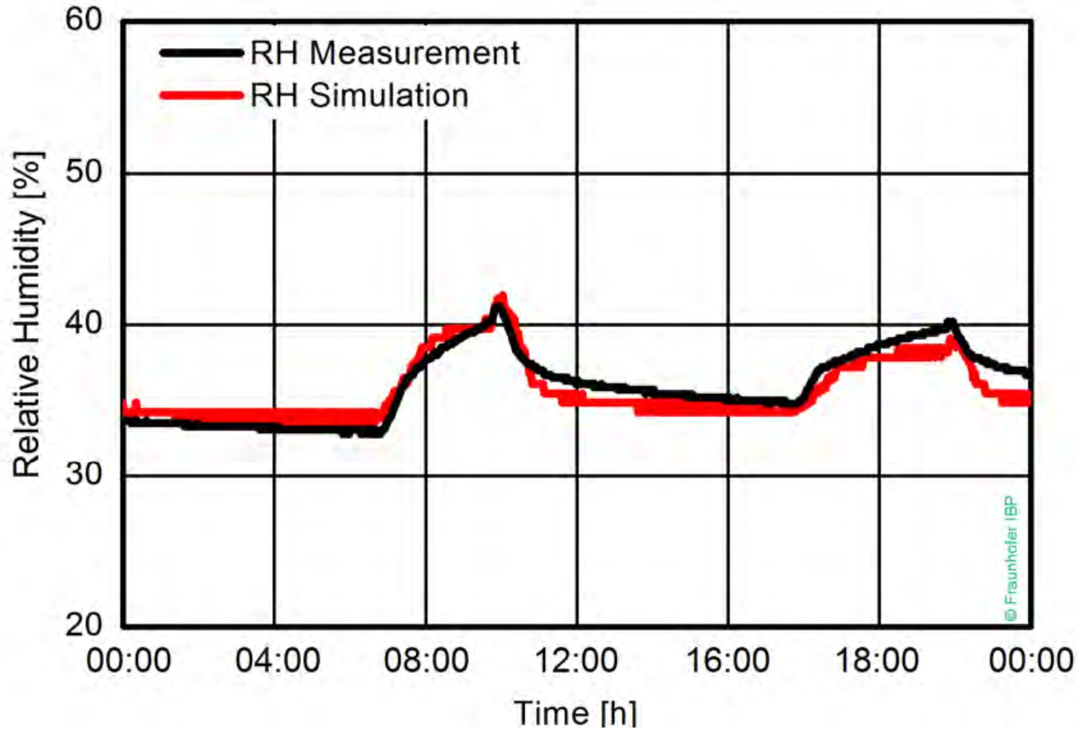
Results for one day in winter - without tiles

- very good agreement between measurement and simulation
- highest peak slightly under predicted with WUFIplus



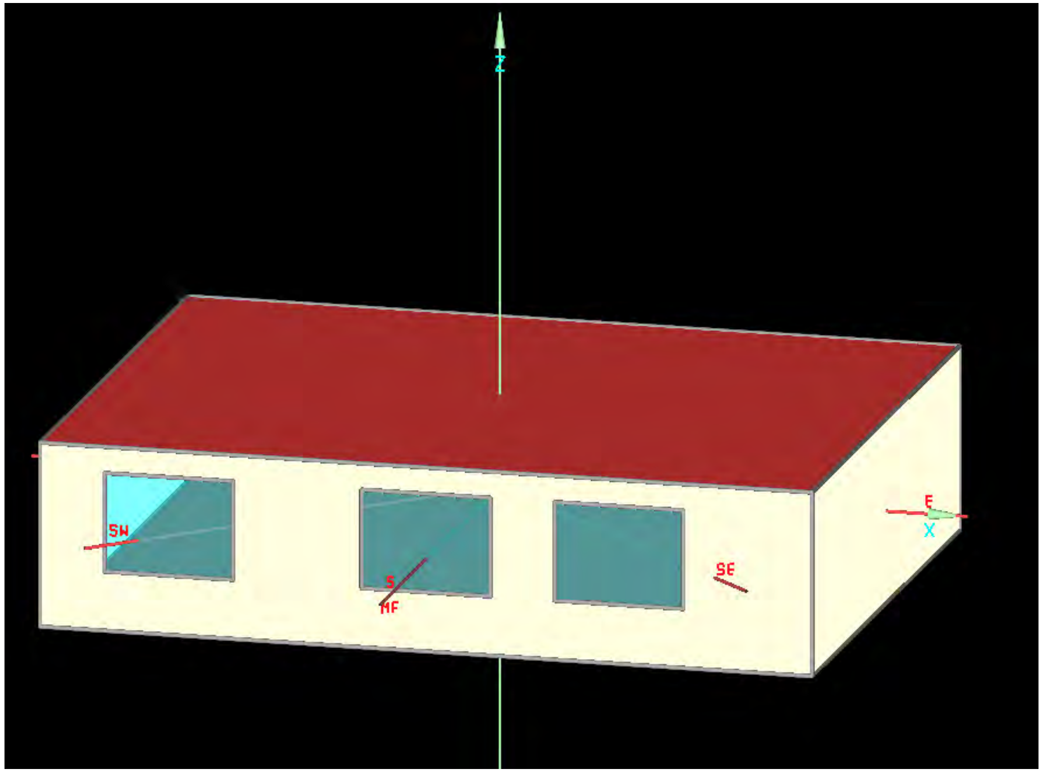
Results for one day in winter - with tiles

- details show excellent agreement for the increase in RH during moisture production cycle
- simulation predicts a slightly faster decline after reaching the peak level



Fraunhofer IBP

Base case for real room parameter study



Area: 96,7m²

Volume: 229,8m³

3 small North windows (5.4 m²)

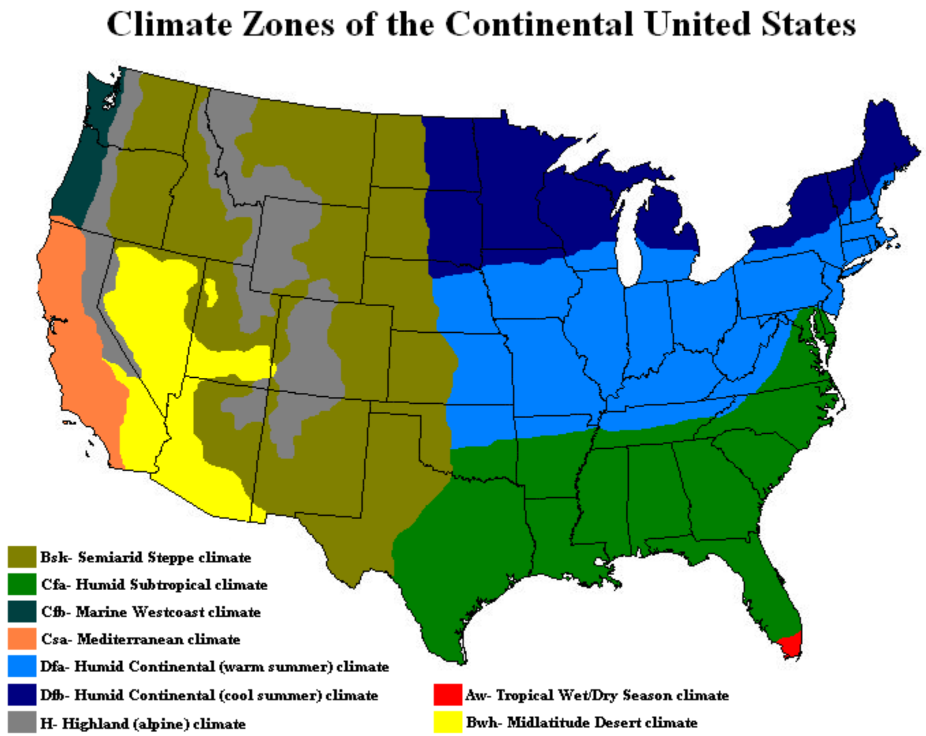
3 bigger South windows (9.0 m²)

Inner walls and ceiling to room with the same climate

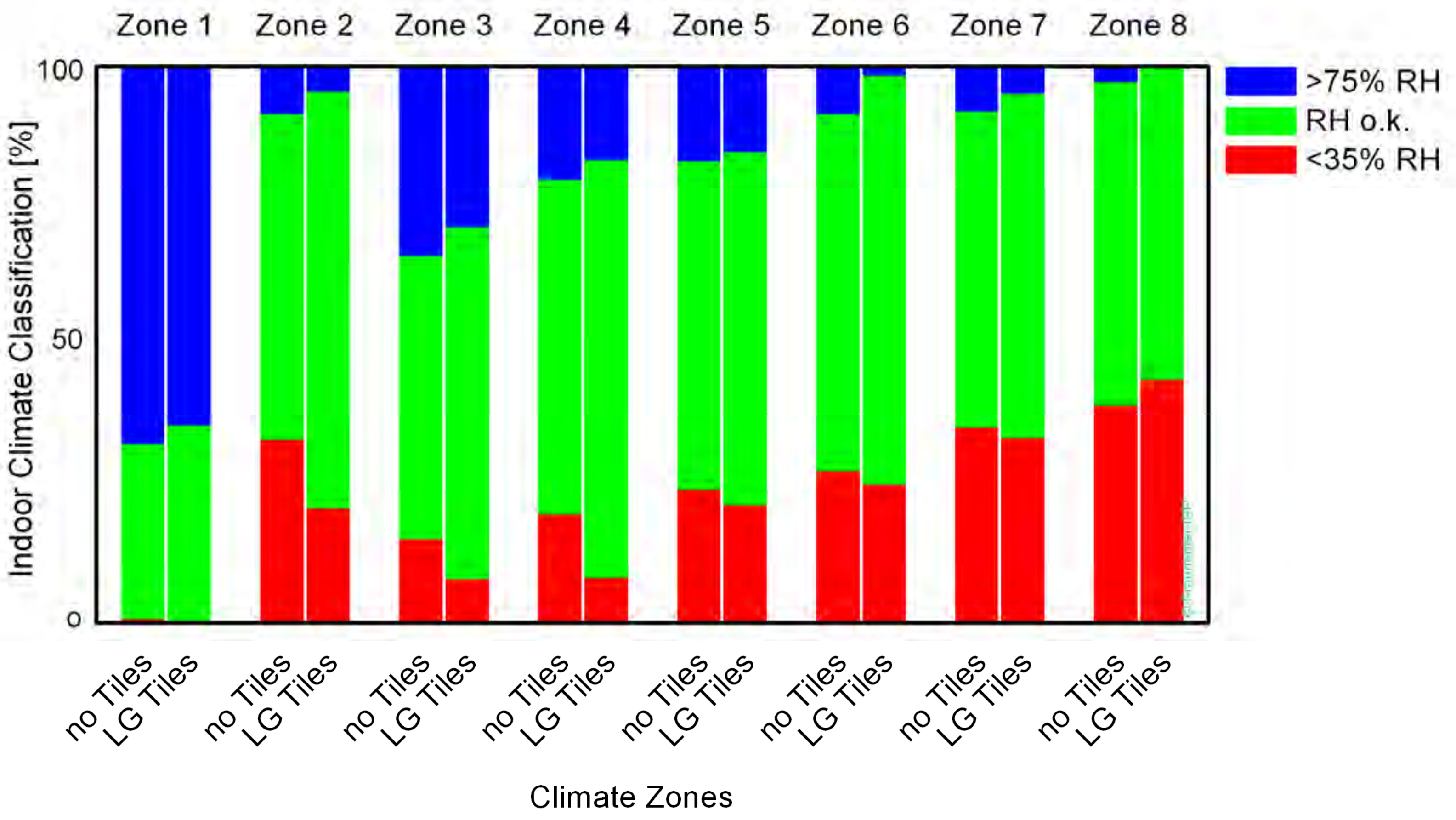
Fraunhofer IBP

Boundary conditions for real room study

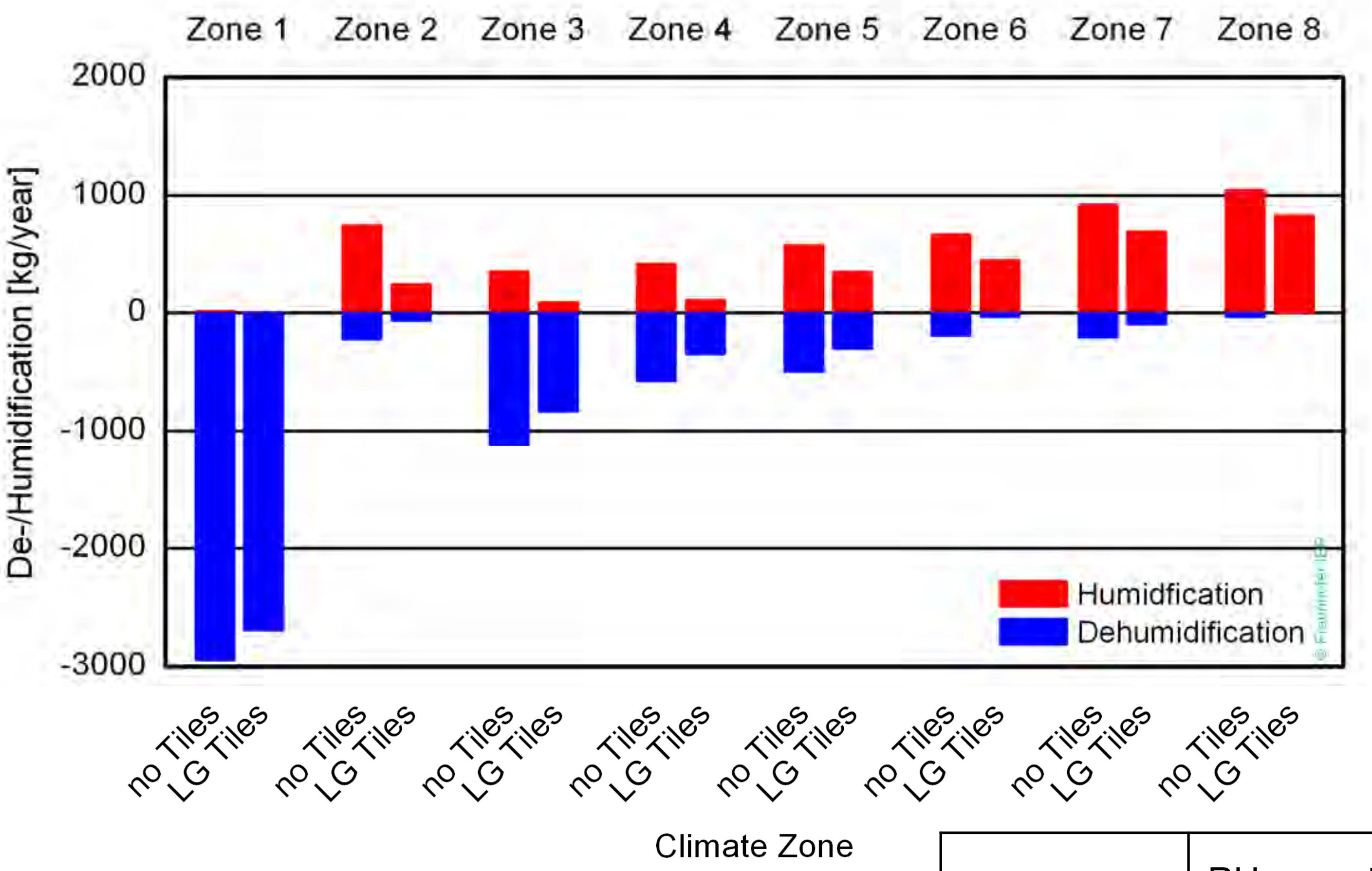
Climate	Anchorage, Atlanta, Baltimore, Chicago, Fargo, Miami, Minneapolis, Phoenix
Interior Surface	ceiling and one wall covered with LG tiles; no LG tiles
HVAC	Heating and cooling plus de-/humidification
Design Conditions	Temp: max: 25° Temp: min: 20° Natural Ventilation: 0,5 /h
Inner Loads (with daily production cycles)	Heat conv. = 4589W Heat rad. = 1926W Moisture = 7845g CO_2 = 2151,9g



Use of the tile in different climatic zones



Humidification and dehumidification climate zone dependent



Additional Conditions	RH: max: 75% RH: min : 35%

Fraunhofer IBP

And the Bavarian Castles?

The Kings House on the Schachen

Conclusions and Outlook

Fraunhofer
IBP

Conclusions and Outlook

- Hygric and thermal inertia are comparable – it's just storage of humidity/energy
- Hygric inertia can provide
  - Passive indoor climate stabilization
  - Reduction of extreme RH conditions
  - Improvement of comfort conditions
  - Reduction of humidification / dehumidification demand

→ As energy use for heating/cooling and de-/humidification is significantly influenced in rooms with moisture buffering surfaces, the use of modeling tools capable of modeling the hygrothermal interaction between room and surrounding surfaces must be highly recommended!

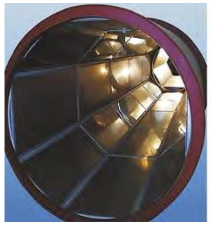
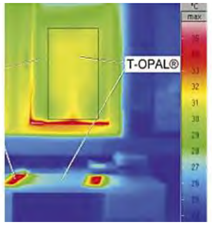
Fraunhofer IBP

Is hygric inertia (moisture buffering) comparable to thermal inertia?

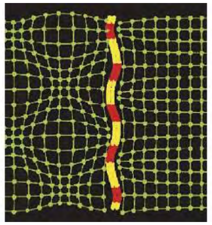
Florian Antretter – August 4th 2015

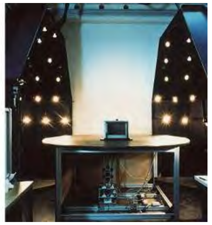
Nineteenth Annual Westford Symposium on Building Science

Auf Wissen bauen



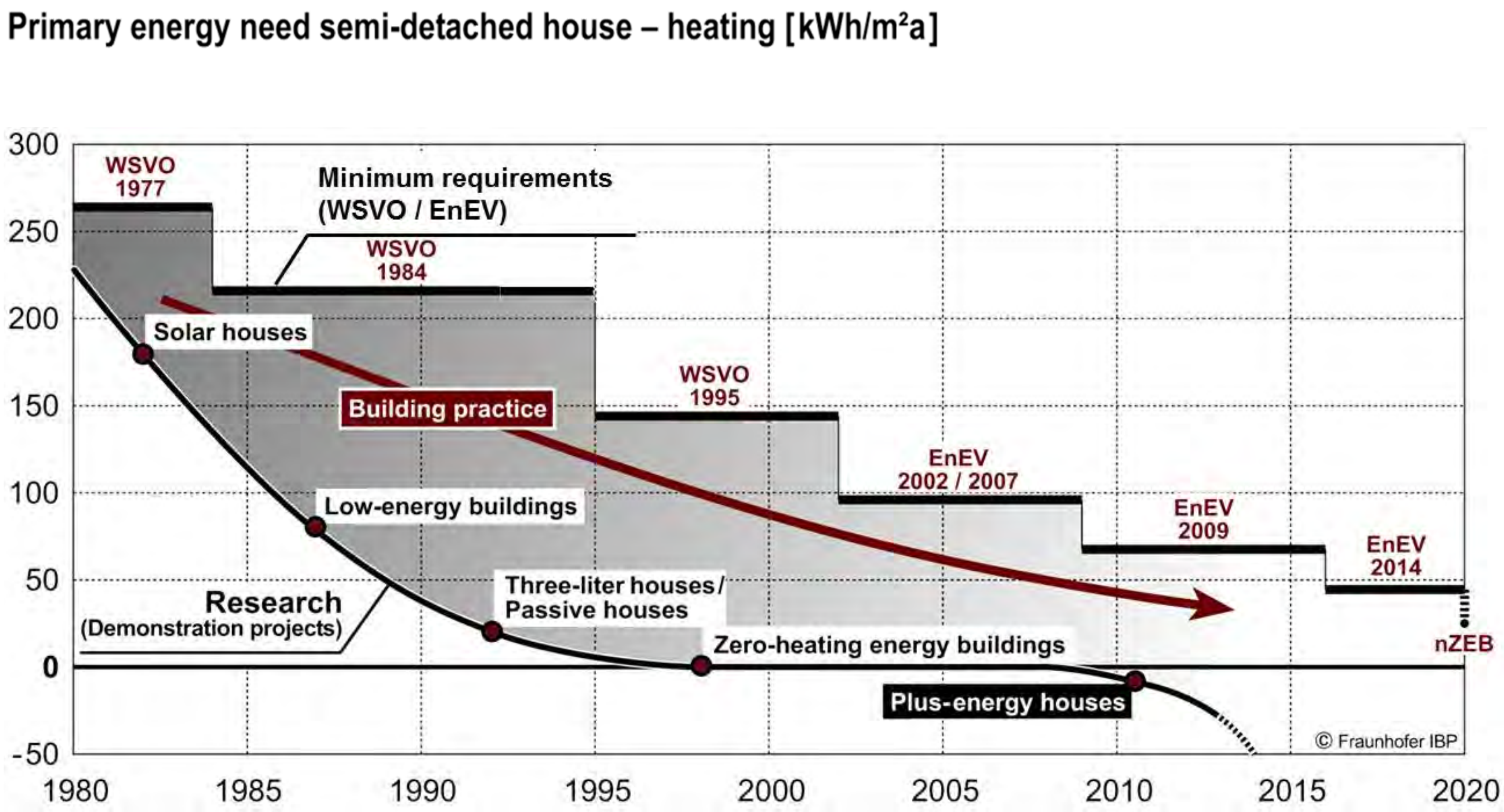


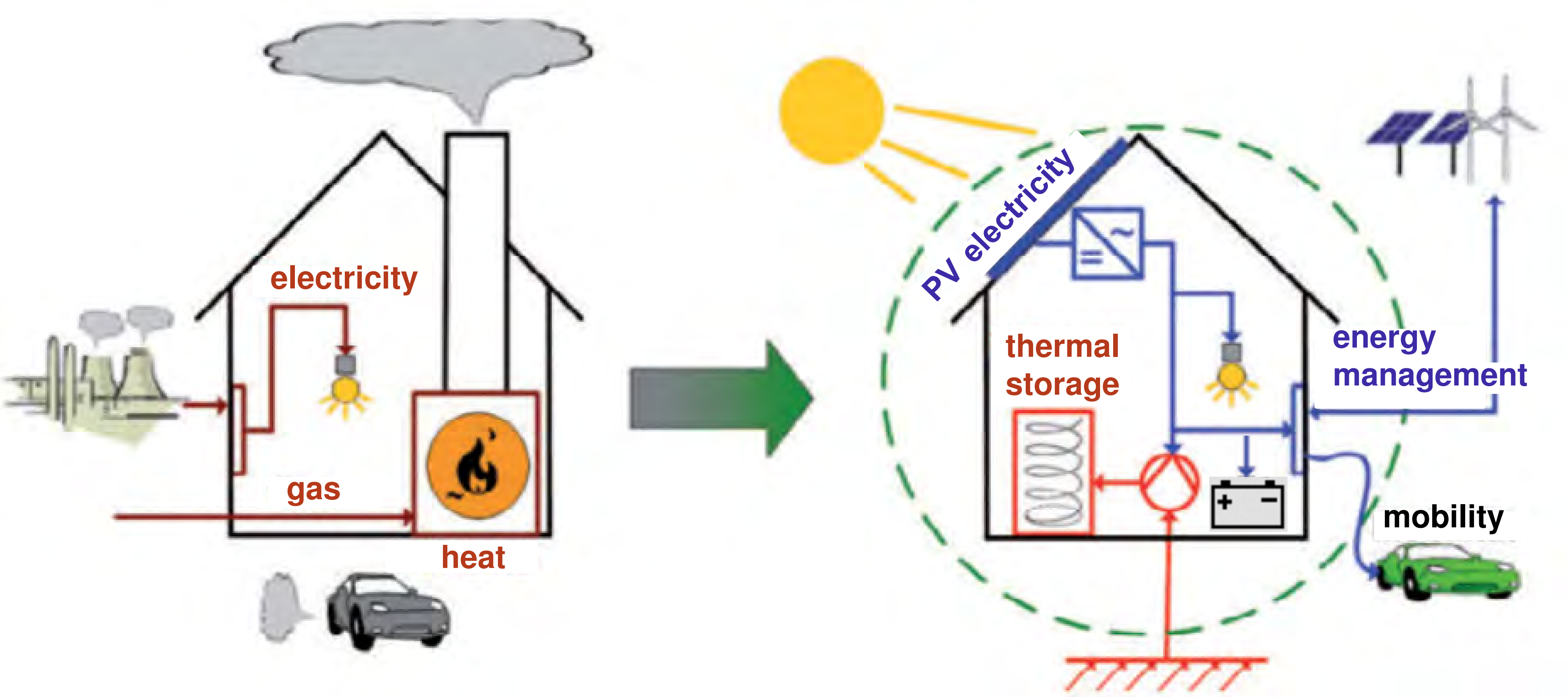
Fraunhofer
IBP

Today's challenges –
Renewable energy supply and intermittent operation

Impact of technology progress on buildings
Development of energy efficiency requirements



Impact of technology progress on buildings
From energy consumer to energy producer

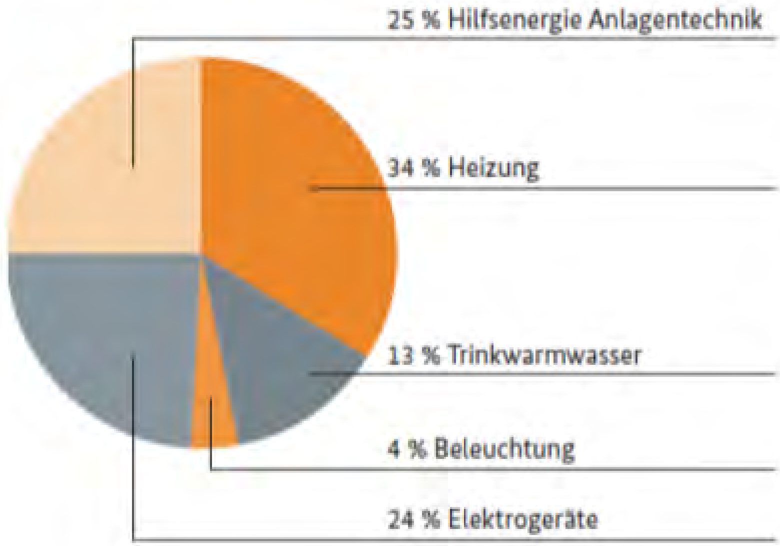


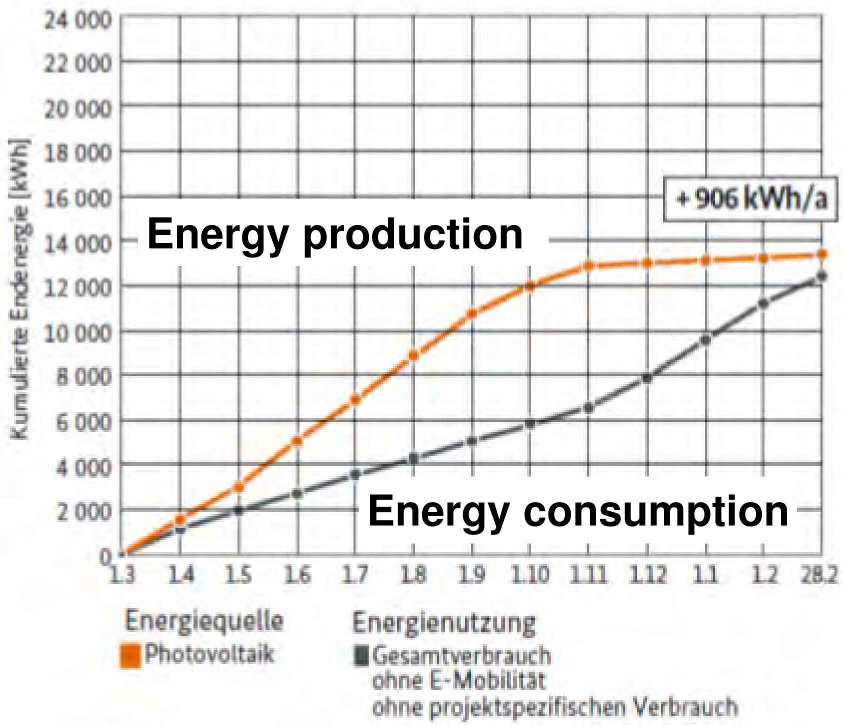
From energy consumer to energy producer ?

Example for German Plus Energy House Projects
Effizienzhaus Plus

Example for German Plus Energy House Projects

Effizienzhaus Plus – Results of first year of operation



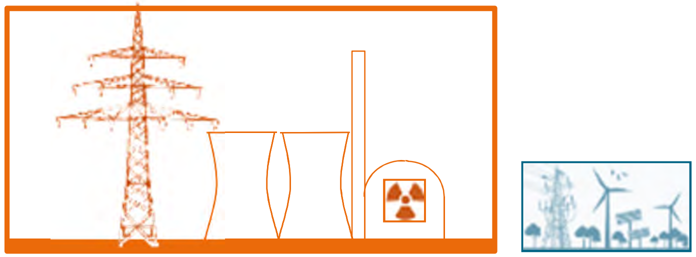


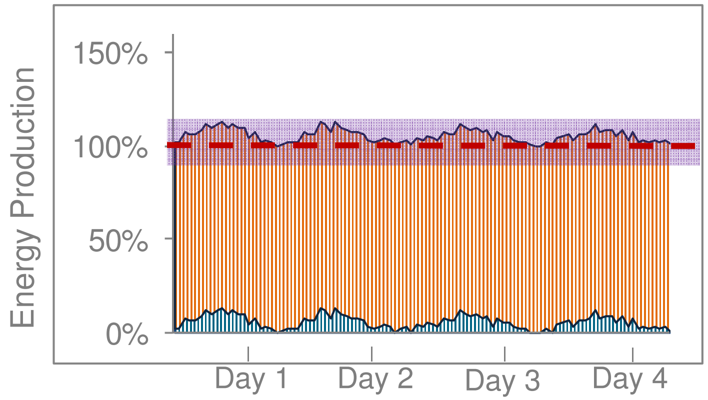
Challenge: Time-shift between energy production an consumption

Energy supply of tomorrow

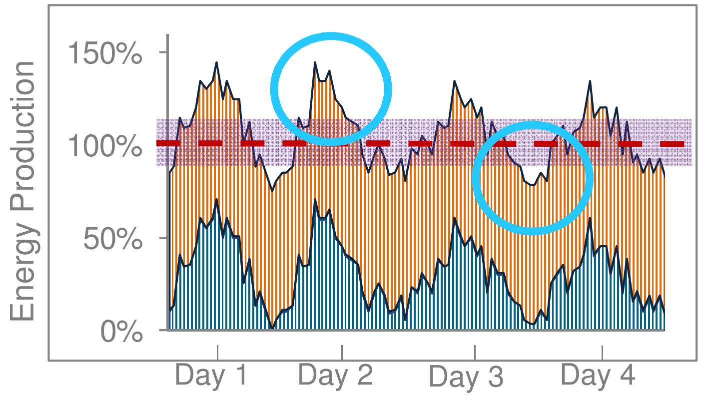
Increasing amount of renewables leads to fluctuating supply

Year 2000
Renewables: 6 %





Year 2020
Renewables: 35 %

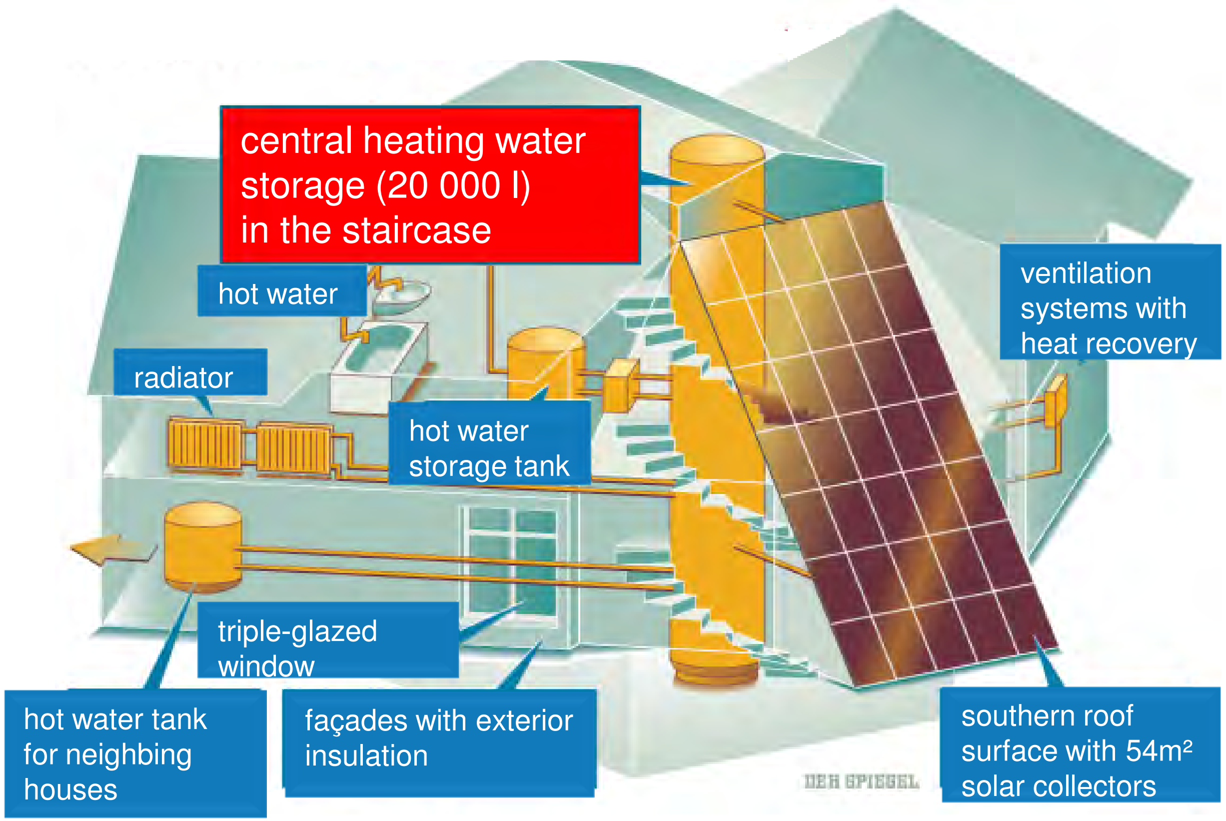


Conventional Energy
Energy Demand
Renewable Energy
Grid flexibility

Energy Management for buildings:
Save energy in times of low energy supply – consume and store when supply is high

Fraunhofer IBP

Energy storage in buildings
Thermal energy storage – seasonal storage capacity



Location Berlin

Zero heat energy house with large water tank
Works, but is too expensive for wide-spread application

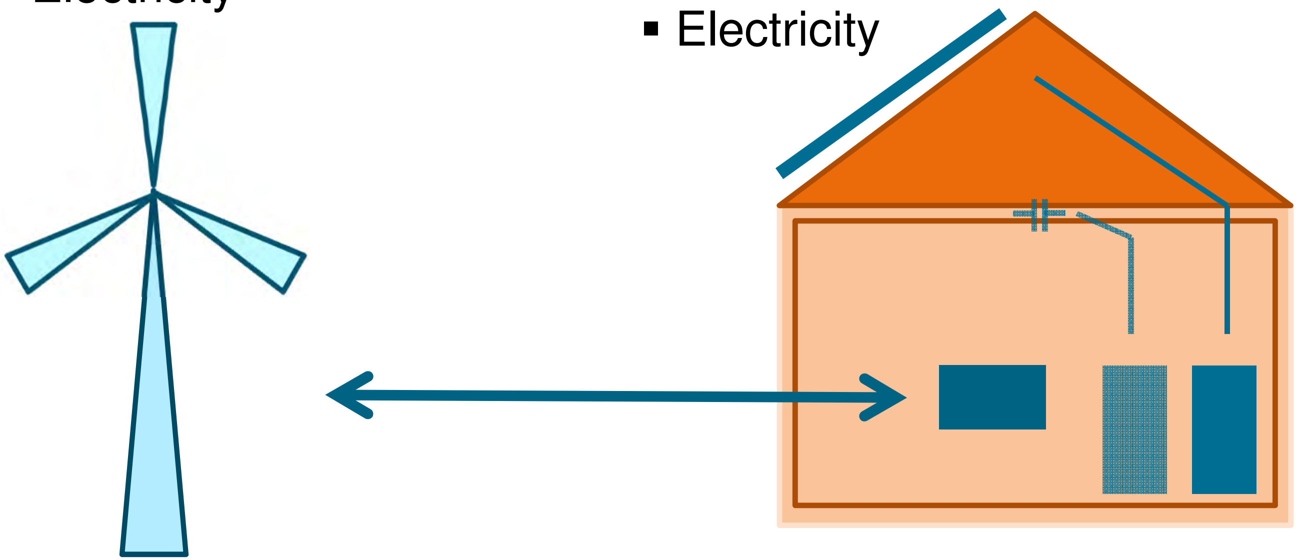
Energy storage in buildings

Short term energy storage

Grid
- Electricity

Production
- Heat
- Electricity

Demand
- Heat
- Electricity

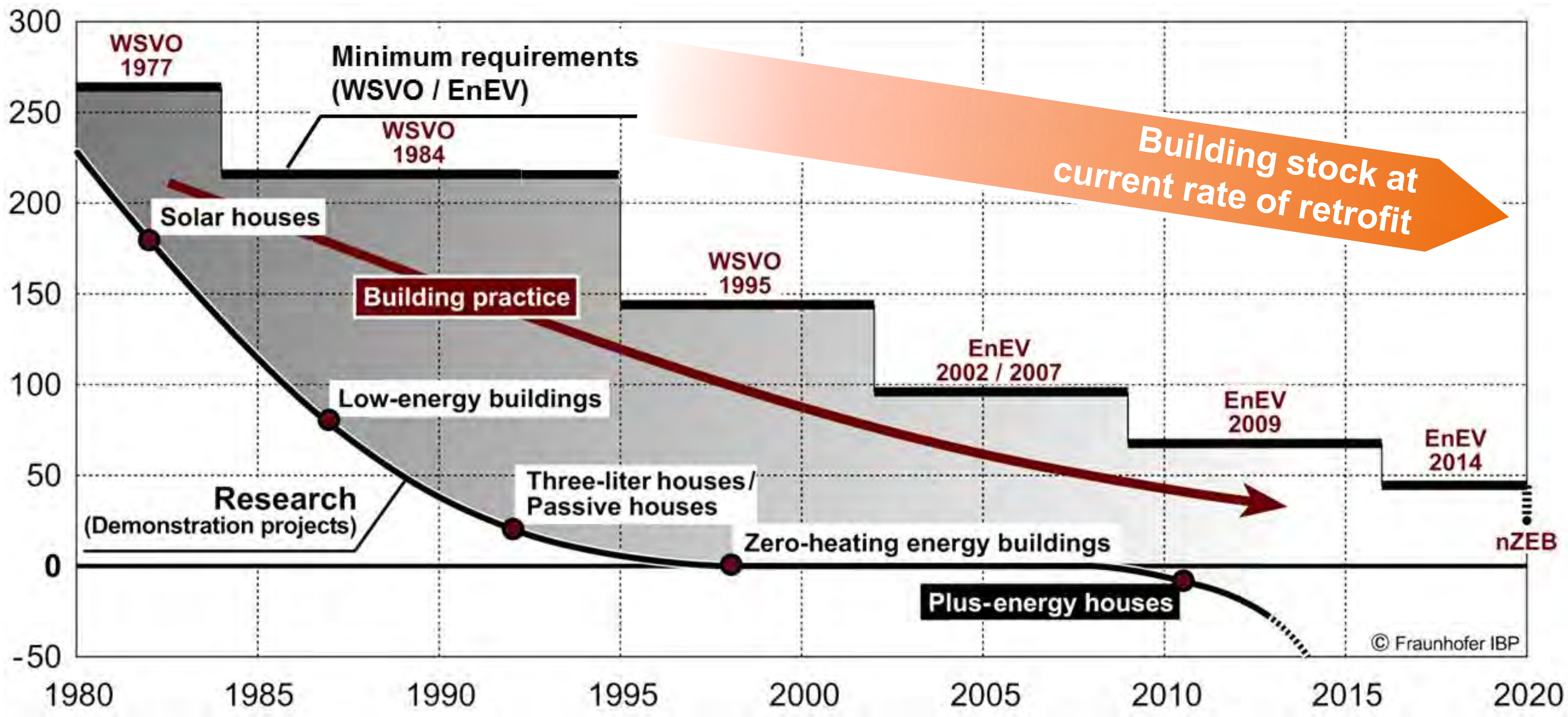


Storage
- Heat
- Electricity

Storage capacity must respond to typical weather cycles that effect renewable electricity production (e.g. ≈ 10 days in Central Europe)

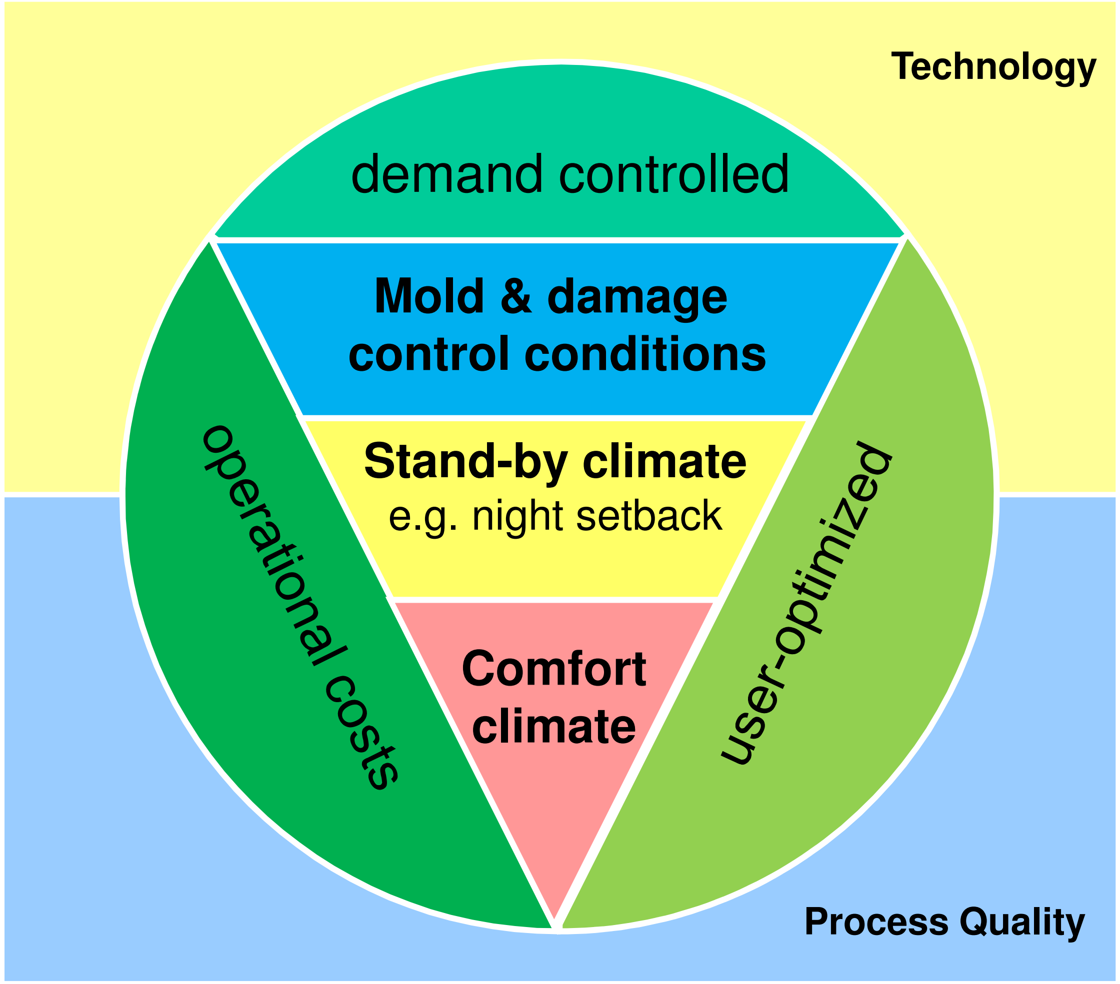
Existing building stock in the city of tomorrow
Low efficiency requires large storage capacities

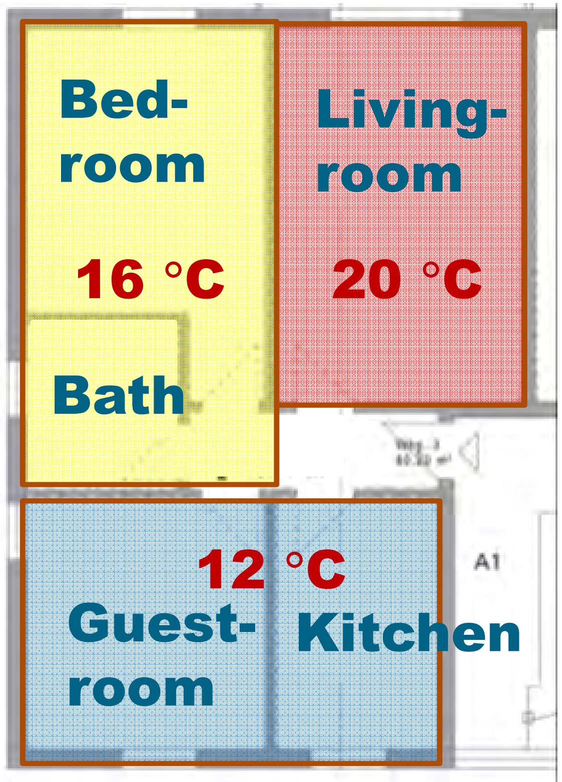
Primary energy need semi-detached house – heating [kWh/m²a]



Existing building stock in the city of tomorrow

Solution: Adapted building operation





Fraunhofer IBP

Adapted building operation

First challenge (idle-mode):
Damage prevention in intermittently operated spaces

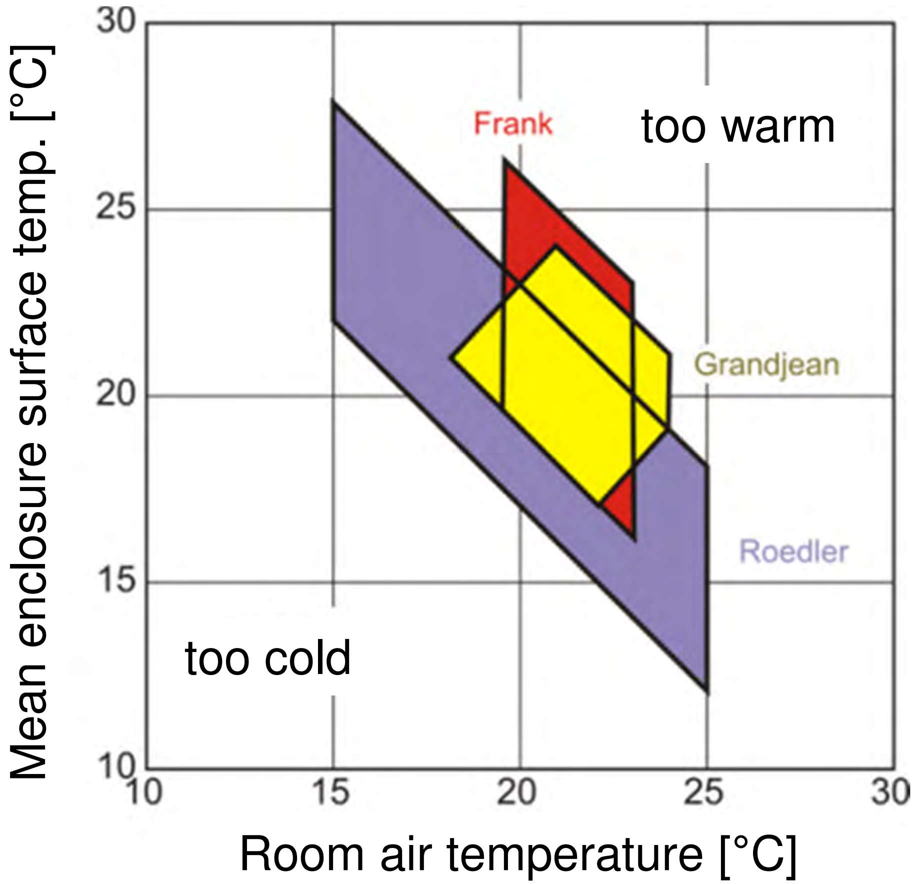
cold
climate

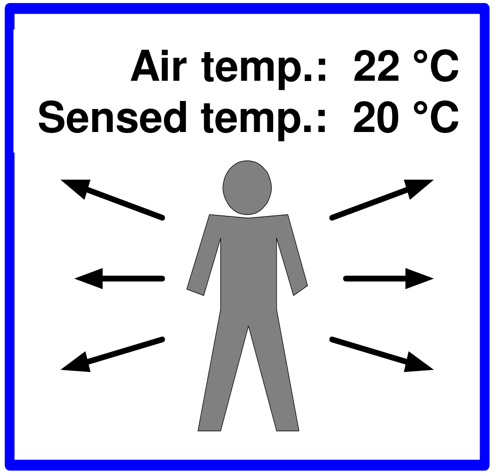
hot & humid
climate

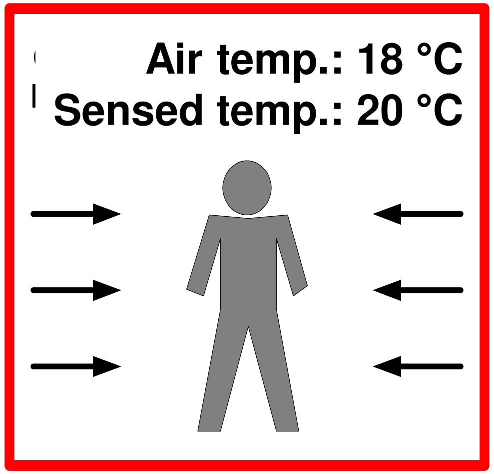
Adapted building operation

Second challenge (Stand-by mode): Reaching comfort conditions as fast as possible

Thermal comfort depends on air & enclosure temperatures

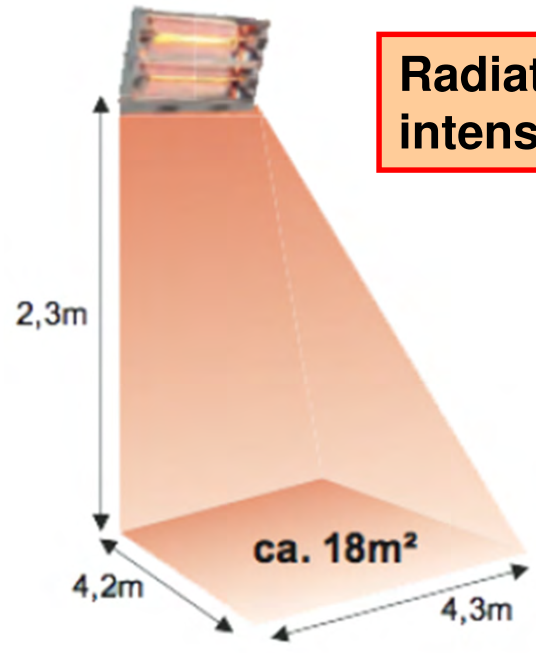




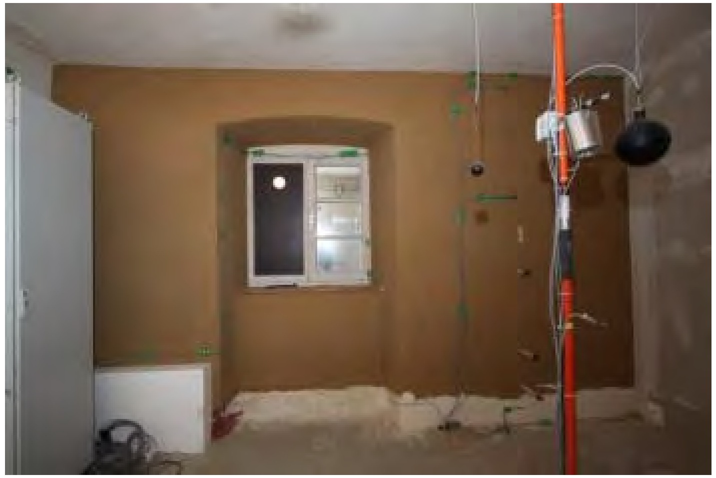


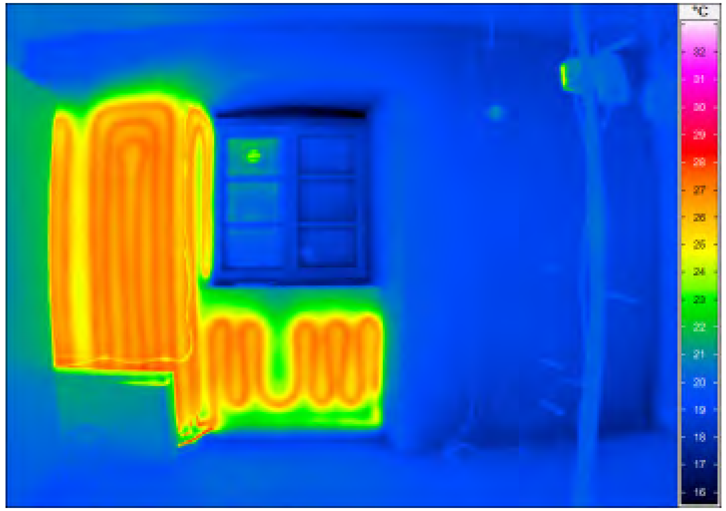
HVAC systems for adapted building operation

Radiation heat provides comfort conditions quickly



Radiation heat with high intensity or large surface

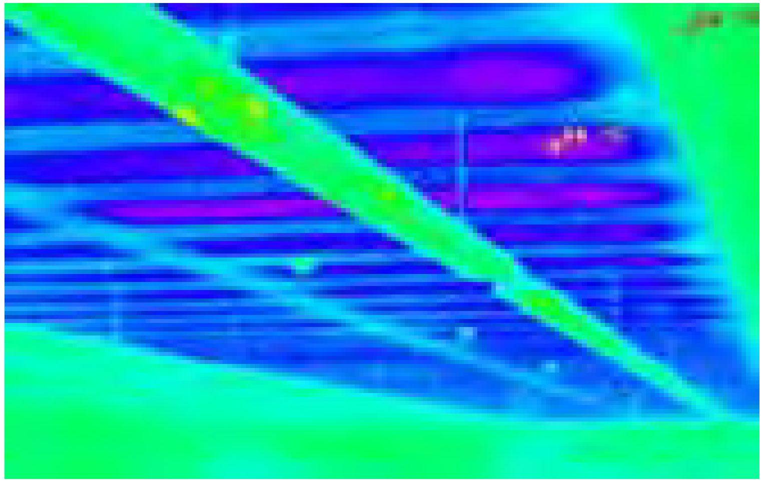




Fraunhofer IBP

HVAC systems for adapted building operation

Challenge: Fast and intensive radiative cooling



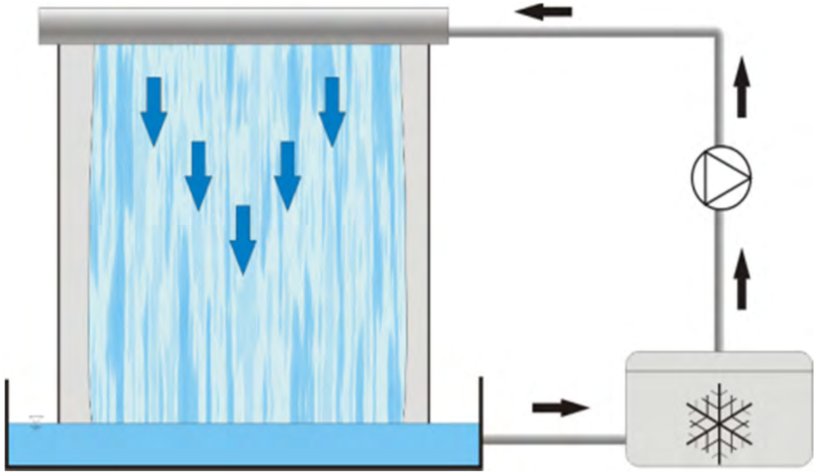
Thermograph of chilled ceiling

Performance limits: Water droplets due to overcooling !!

Fraunhofer IBP

HVAC systems for adapted building operation

Solution example: chilled water fall – cools and dehumidifies!



HVAC systems for adapted building operation

Example: chilled water fall – cools and dehumidifies!

Source: c+p monotop wall

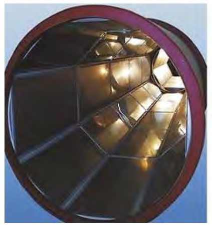
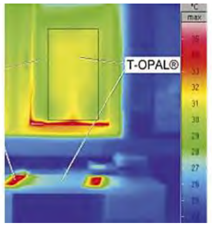
Freshness of chilled water fall provides comfortable conditions in hot and humid environments – Comfort Oasis

Targeting future challenges – Fluctuating building operation

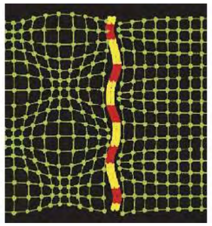
Florian Antretter – August 4th 2015

Nineteenth Annual Westford Symposium on Building Science

Auf Wissen bauen






Fraunhofer IBP

Outline

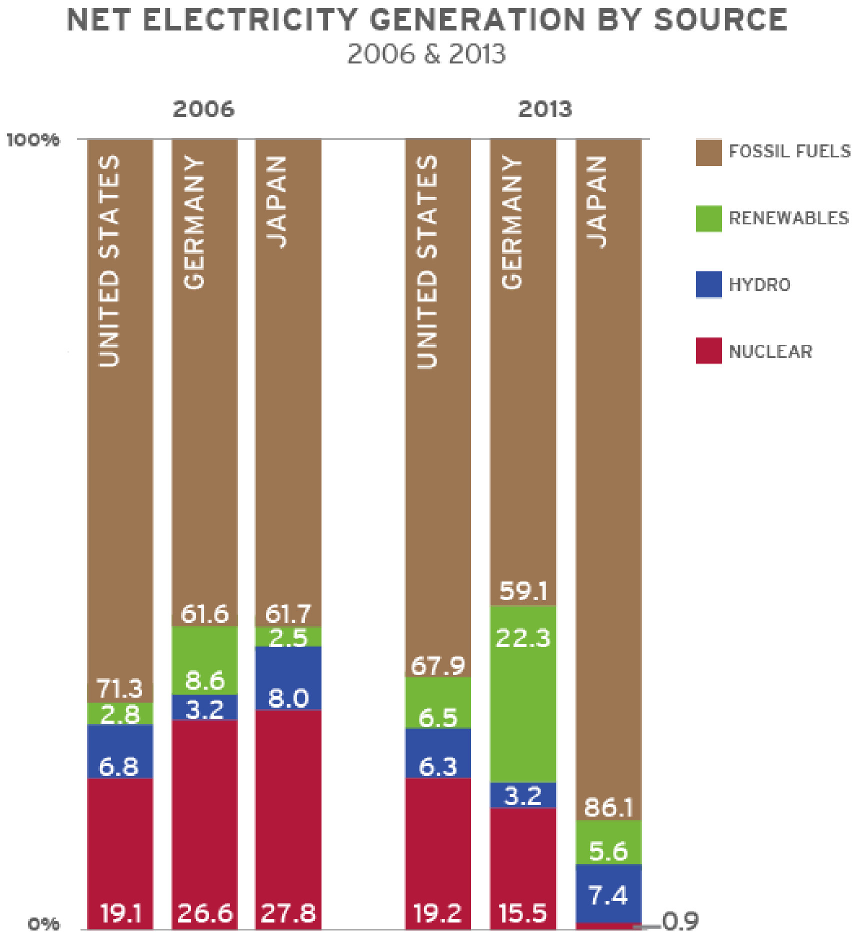
- Challenges due to renewable energy production
- Long term shift – using buildings as thermal storage
- Short term shift – Intermittent operation
- HVAC impacts

Renewable Energy Production Challenges

Fraunhofer IBP

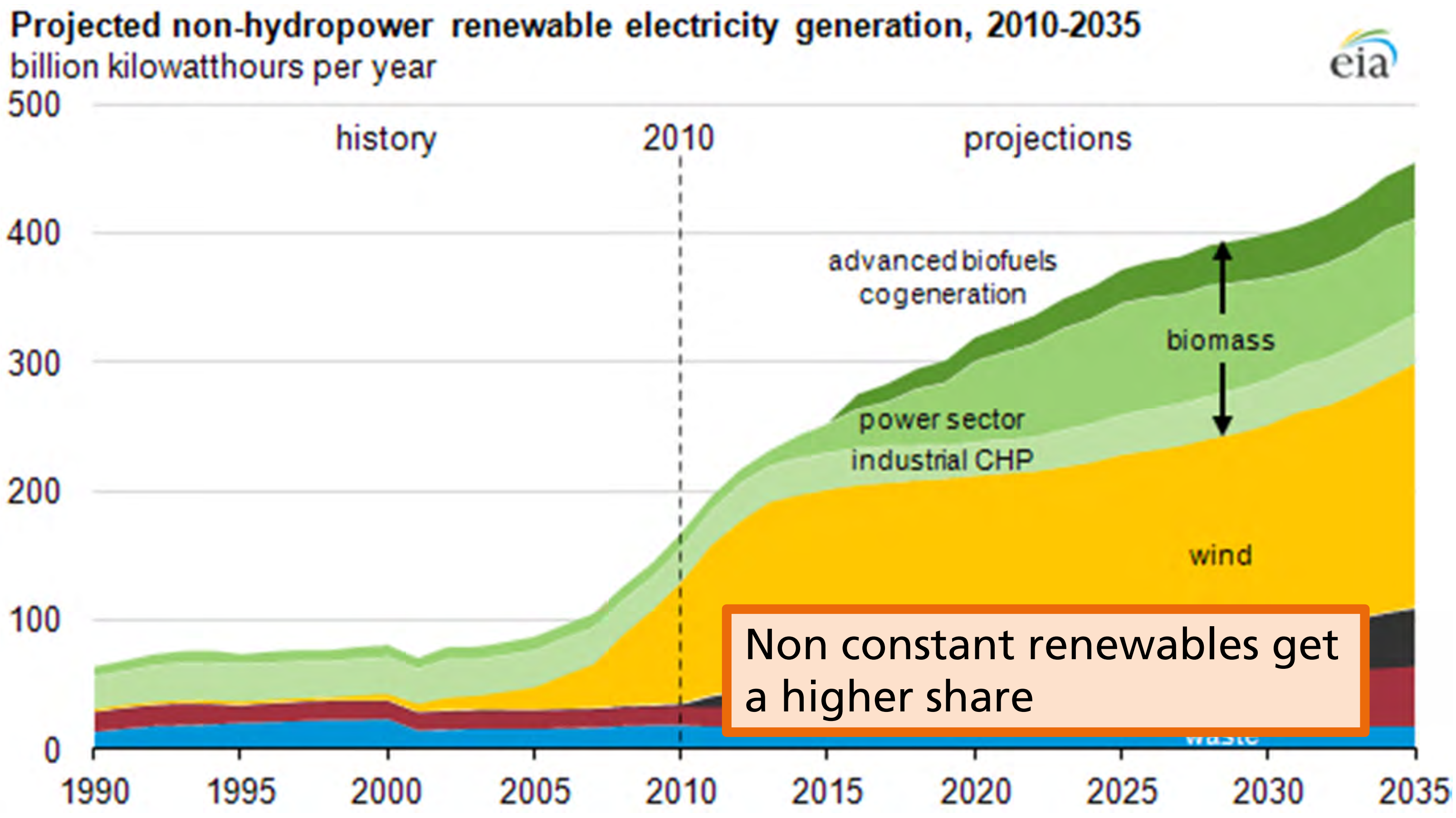
Renewable Energy Production

- Increasing renewable energy production
- Renewables are often not constant and harder to plan



Source: Data for Japan, Germany, and United States compiled from IEA, Energy Balances of OECD Countries. Figures for 2013 are preliminary estimates.

Prediction of Renewable Energy Production US

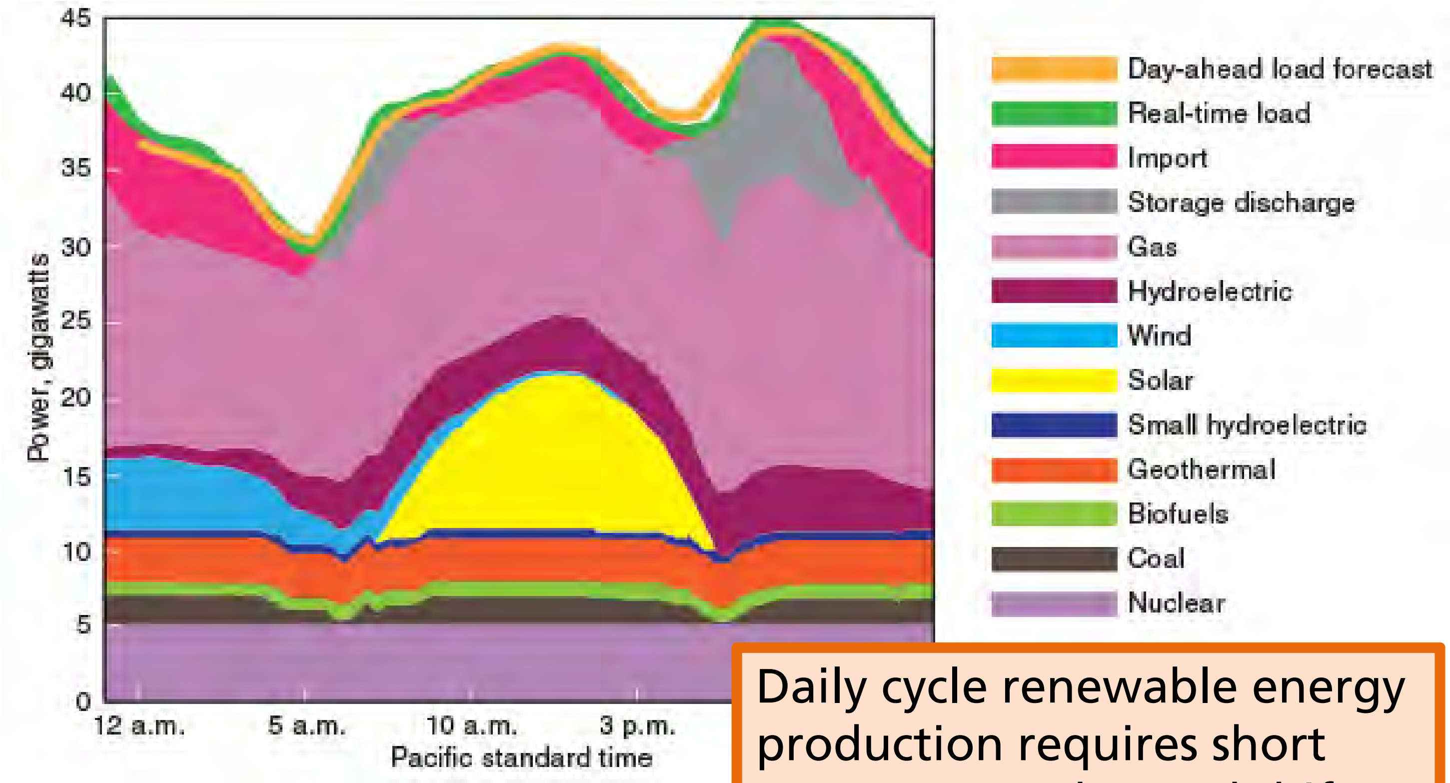


Source: EIA

Fraunhofer IBP

Day Profile of Electrical Energy Demand vs. Production

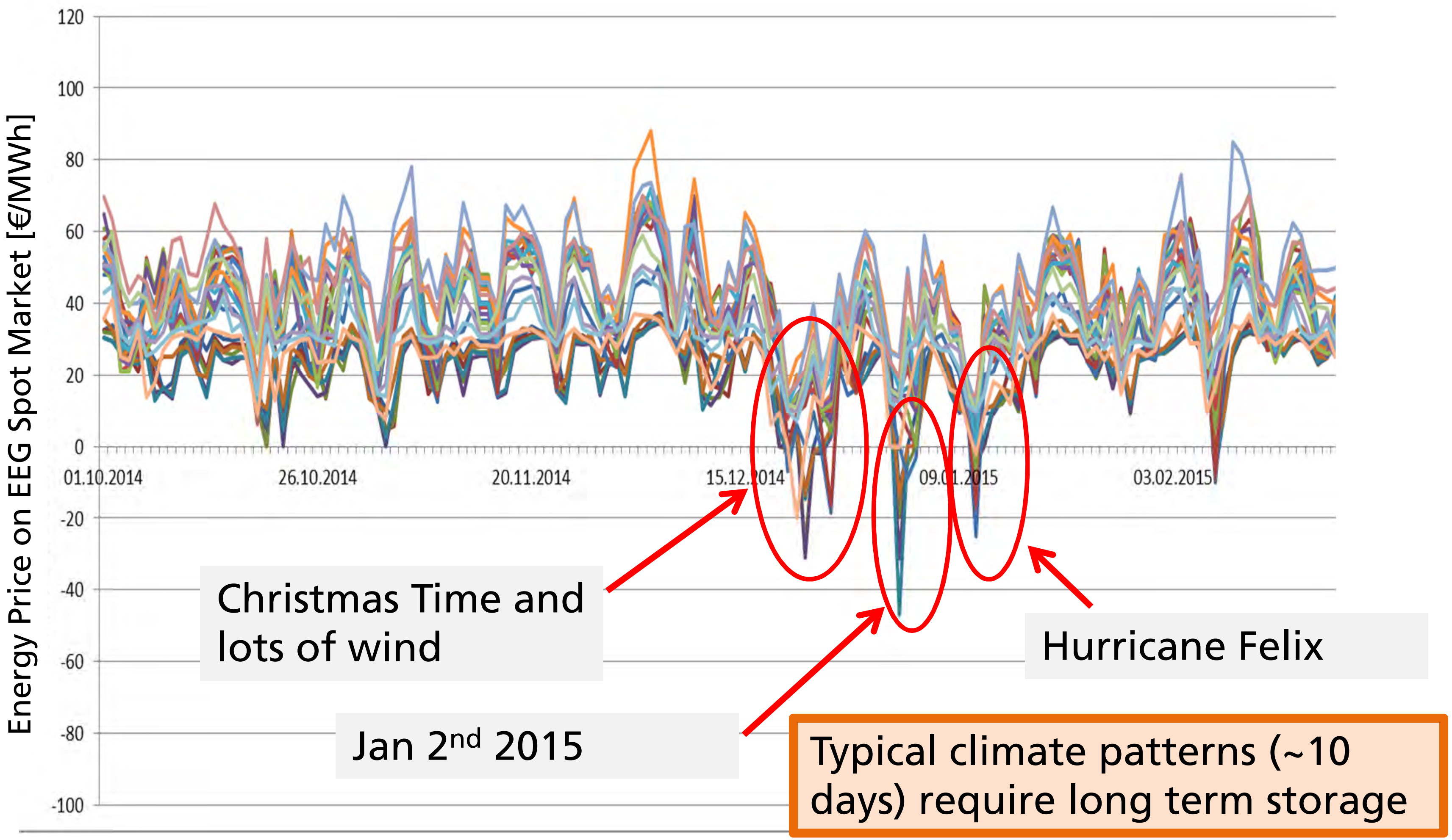
Simulated day profile of a 2020 California winter day



Source: https://str.llnl.gov

Daily cycle renewable energy production requires short term storage/demand shift

2014/2015 Winter European Energy Exchange Prices



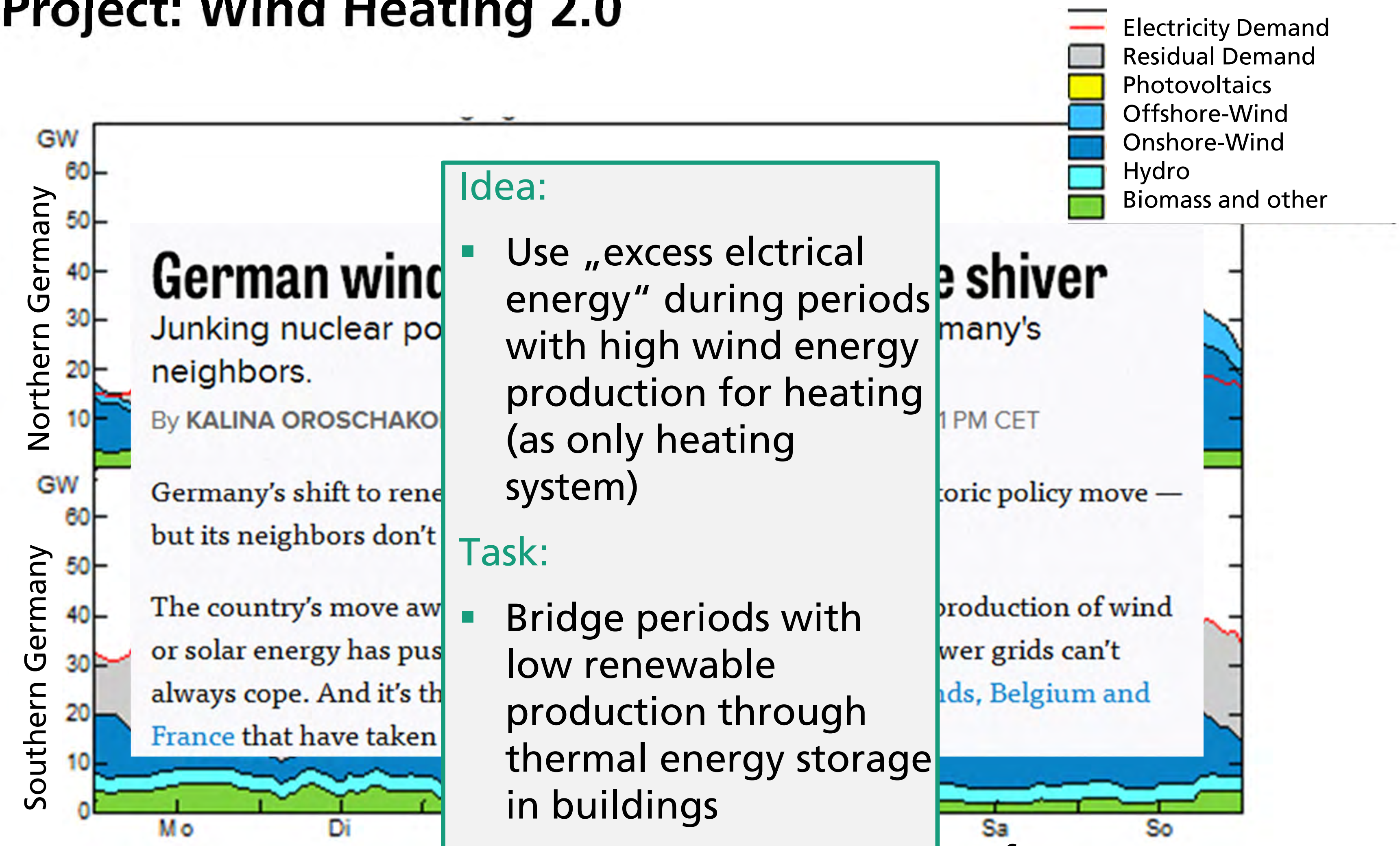
Typical climate patterns (~10 days) require long term storage

Fraunhofer IBP

Storing Excess Wind Energy in Buildings

Fraunhofer IBP

Project: Wind Heating 2.0



Idea:

- Use „excess elctrical energy“ during periods with high wind energy production for heating (as only heating system)

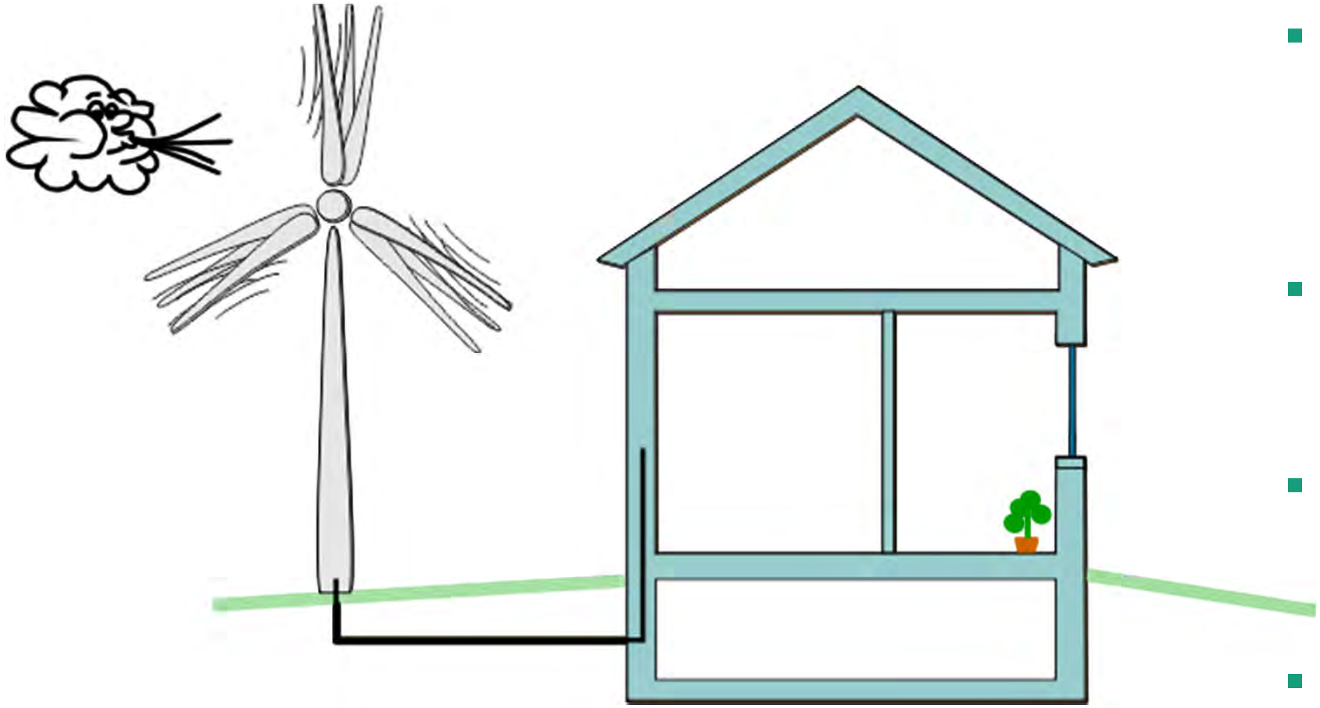
Task:

- Bridge periods with low renewable production through thermal energy storage in buildings

Source:
Fraunhofer IWES im Auftrag von Agora Energiewende

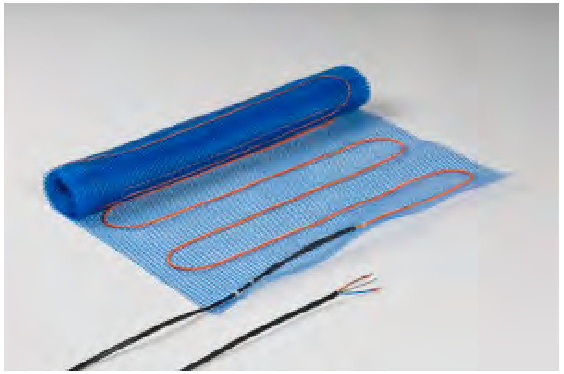
Fraunhofer IBP

Idea of Using the Building Structure



- Amount and distribution of thermal mass in building
- Insulation of interior components
- Additional water (or even PCM) storage
- Suitable systems (electrical direct, heat pumps, …)

Modeling of Loaded Component



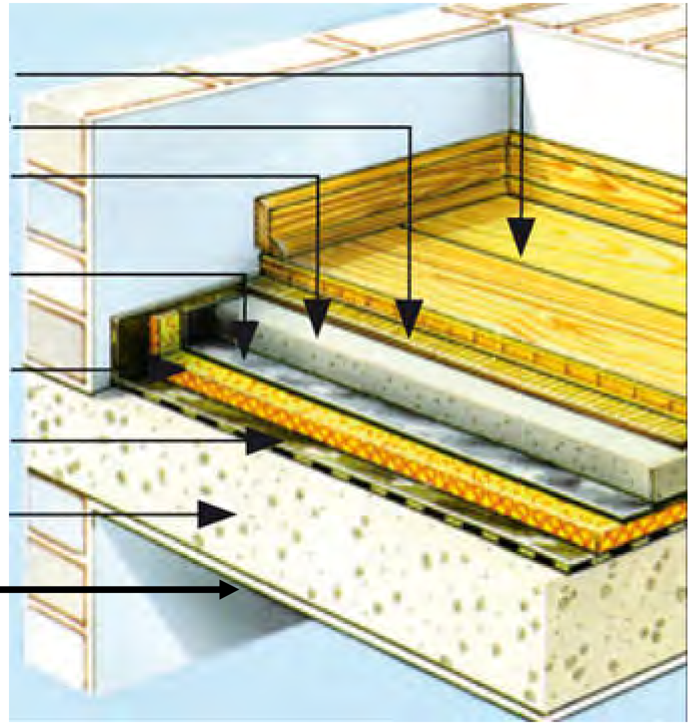
Electrical Panel Heating

Flooring

Concrete screed

Sound insulation

Reinforced concrete

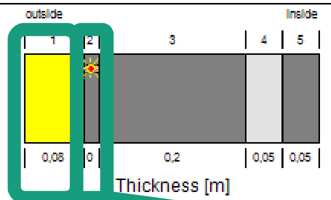


Homogenous layers

Thermal resistance: 3,332 m²K/W

Heat transfer coefficient (U-value): 0,28 W/m²K

Thickness: 0,4 m



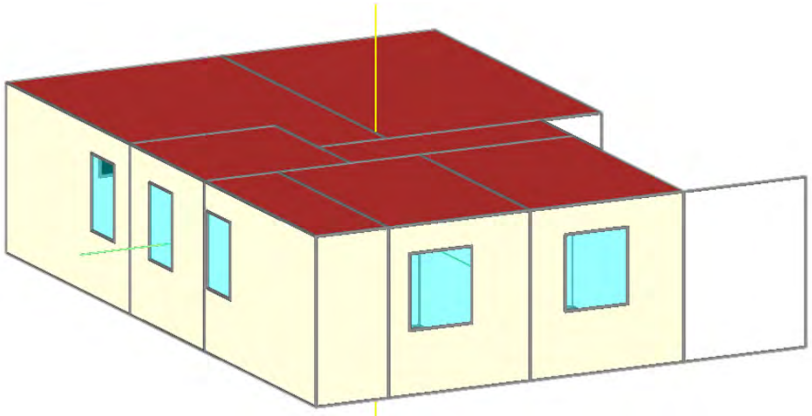
Nr.	Material/Layer (from outside to inside)	ρ [kg/m³]	c [J/kgK]	λ [W/mK]	Thickness [m]	Color
1	EPS (heat cond.: 0.04 W/mK - density: 15 kg/m³)	15	1500	0,04	0,08	
2	Concrete, C12/15	2200	850	1,6	0,02	
3	Concrete, C12/15	2200	850	1,6	0,2	
4	Mineral Insulation Board	115	850	0,043	0,05	
5	Concrete Screed, mid layer	1970	850	1,6	0,05	

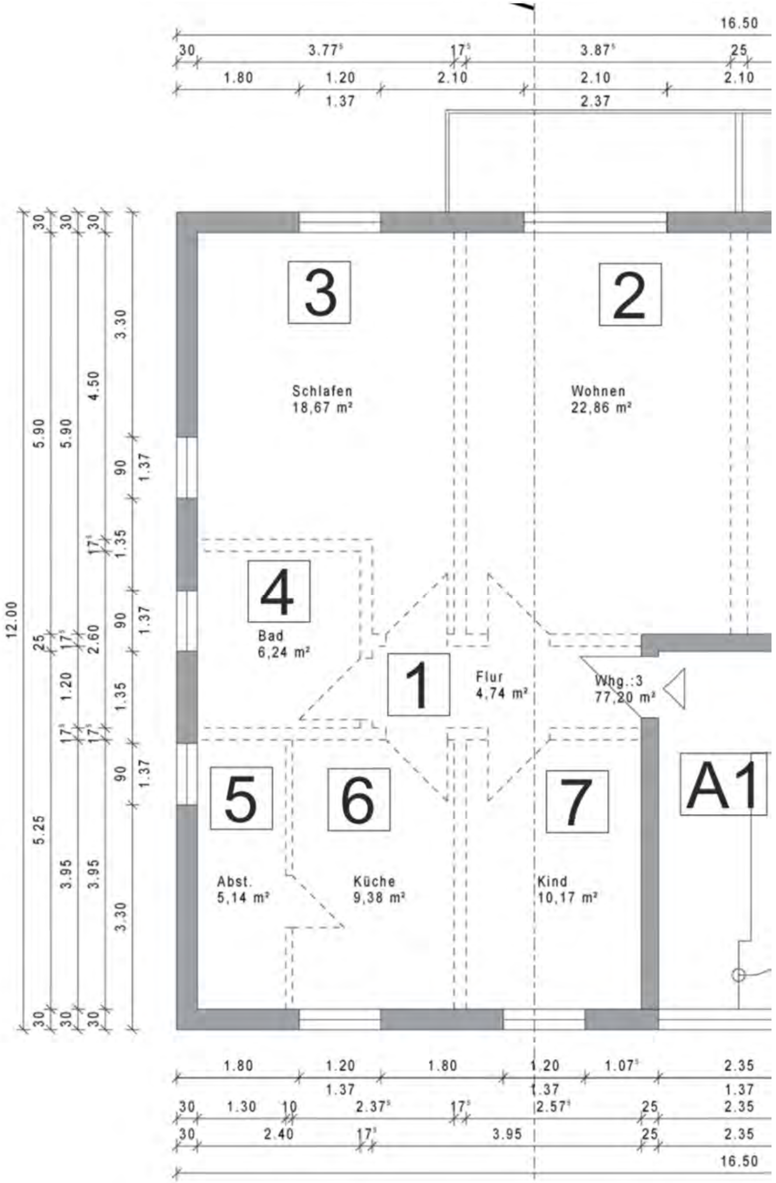
Panel Heating as Source in Component

Additional Insulation below

Fraunhofer IBP

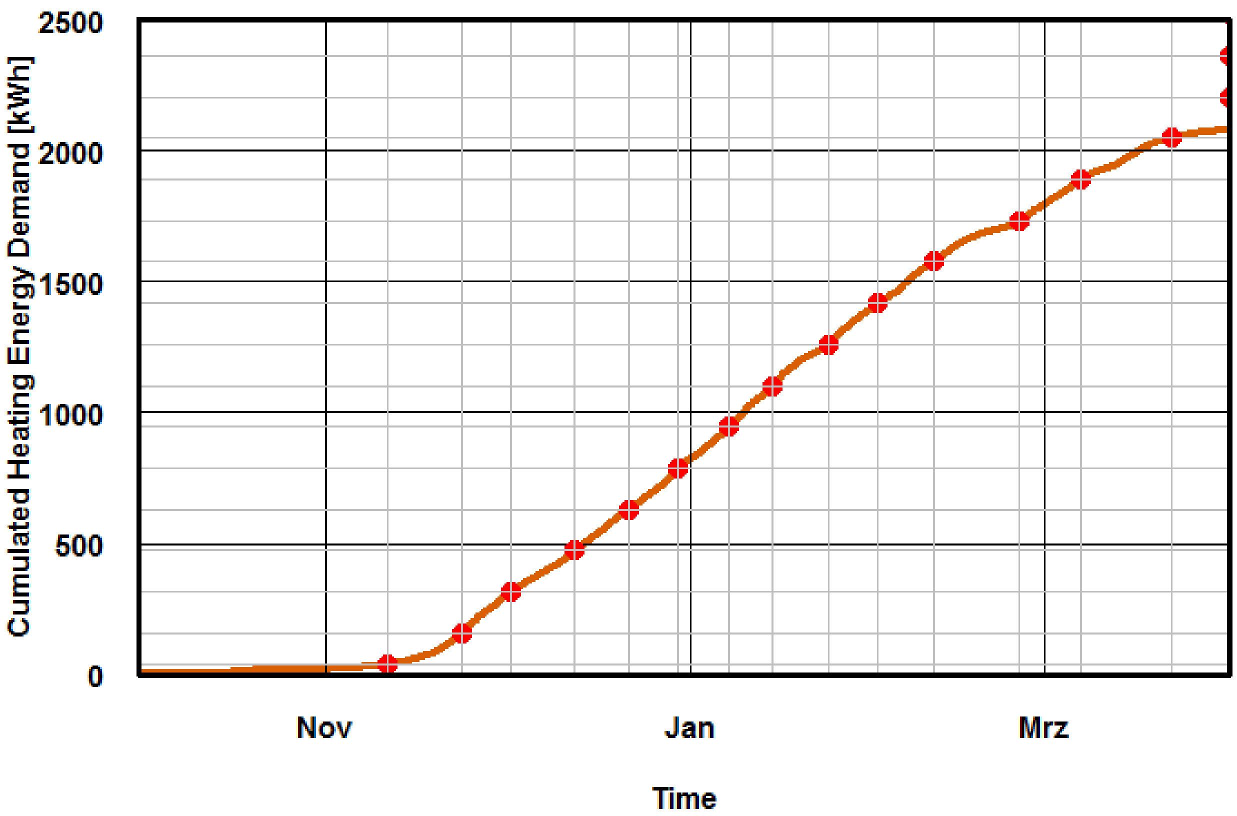
Building Model





- Apartment in a multi-family building
- 7 Zones
- Same conditions in apartment above and below
- Seperate inner load profiles per zone
- Ideal heating on 20 °C (68 F)
- Climate conditions: Germany (Holzkirchen)

Deduction of Maximum Bridgeable Times



- Cumulated heating energy demand
- Maximum take from grid

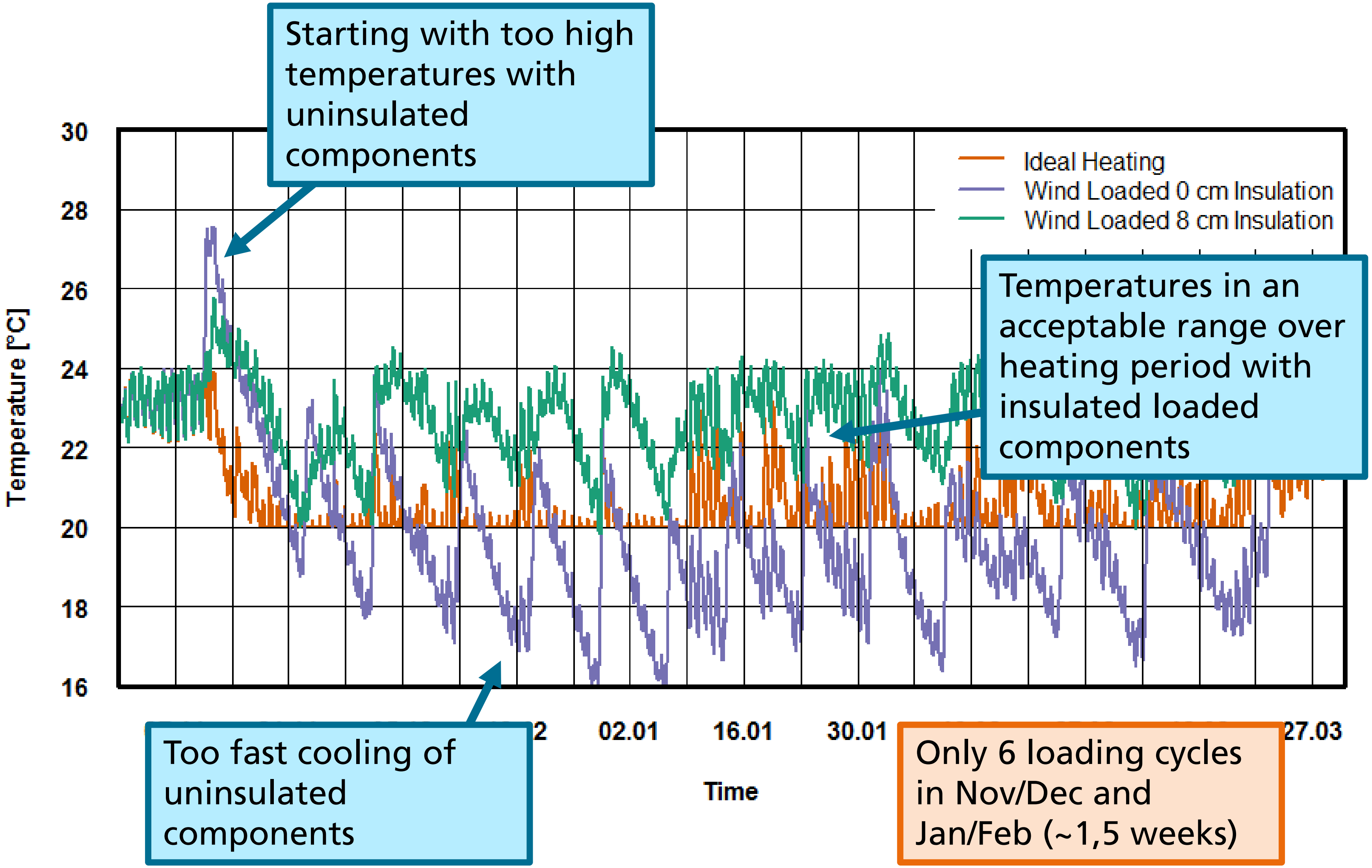
  = Area x Power per Area x Duration

  = 98.5 m² x 200 W/m² x 8 h

  = 157.6 kWh
- Mark on y-axis
- Determination of maximum times that can be bridged on x -axis

Fraunhofer IBP

Modeled Living Room Temperature



Fraunhofer IBP

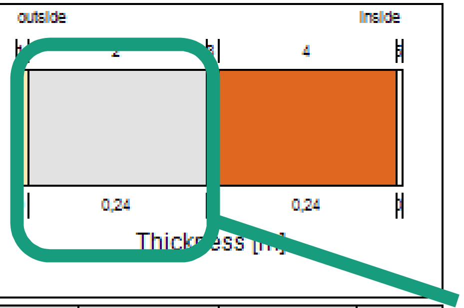
Influence of Building Thermal Envelope

Homogenous layers

Thermal resistance: 8,003 m²K/W

Heat transfer coefficient(U-value): 0,12 W/m²K

Thickness: 0,52 m



Variation of EIFS thickness

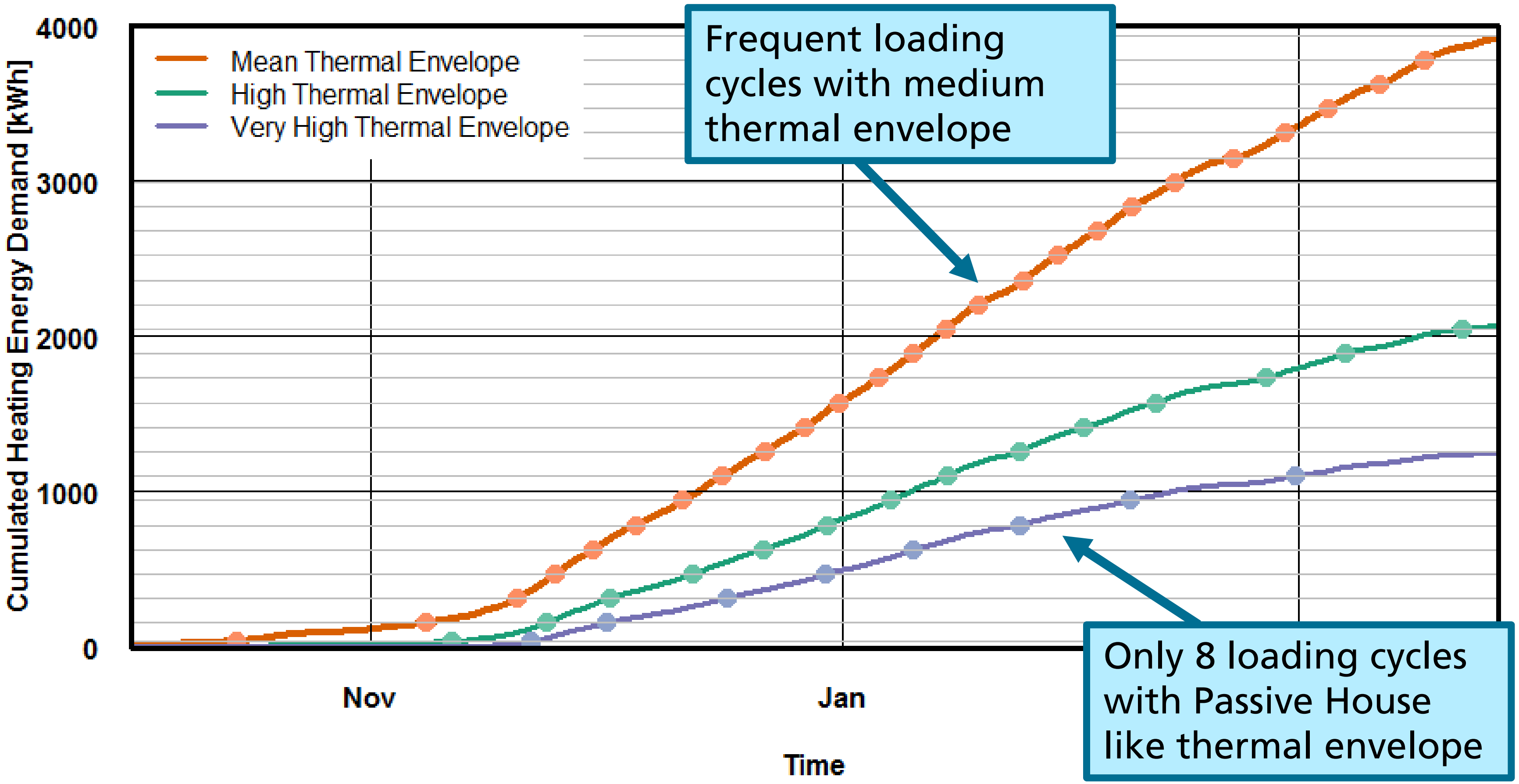
Nr.	Material/Layer (from outside to inside)	ρ [kg/m³]	c [J/kgK]	λ [W/mK]	Thickness [m]	Color
1	Mineral Plaster (stucco, A-value: 0.1 kg/m2h0.5)	1900	850	0,8	0,015	
2	Mineral Insulation Board	115	850	0,032	0,24	
3	Mineral Plaster (stucco, A-value: 0.1 kg/m2h0.5)	1900	850	0,8	0,015	
4	Solid Brick ZE	1642	899	0,577	0,24	
5	Interior Plaster (Gypsum Plaster)	850	850	0,2	0,01	

Three Thermal Envelope Qualities:

- Mean (U_{wall} = 0,48 W/m²K, U_{window} = 1,3 W/m²K)
- High (U_{wall} = 0,25 W/m²K, U_{window} = 1,0 W/m²K)
- Very High (U_{wall} = 0,12 W/m²K, U_{window} = 0,8 W/m²K)

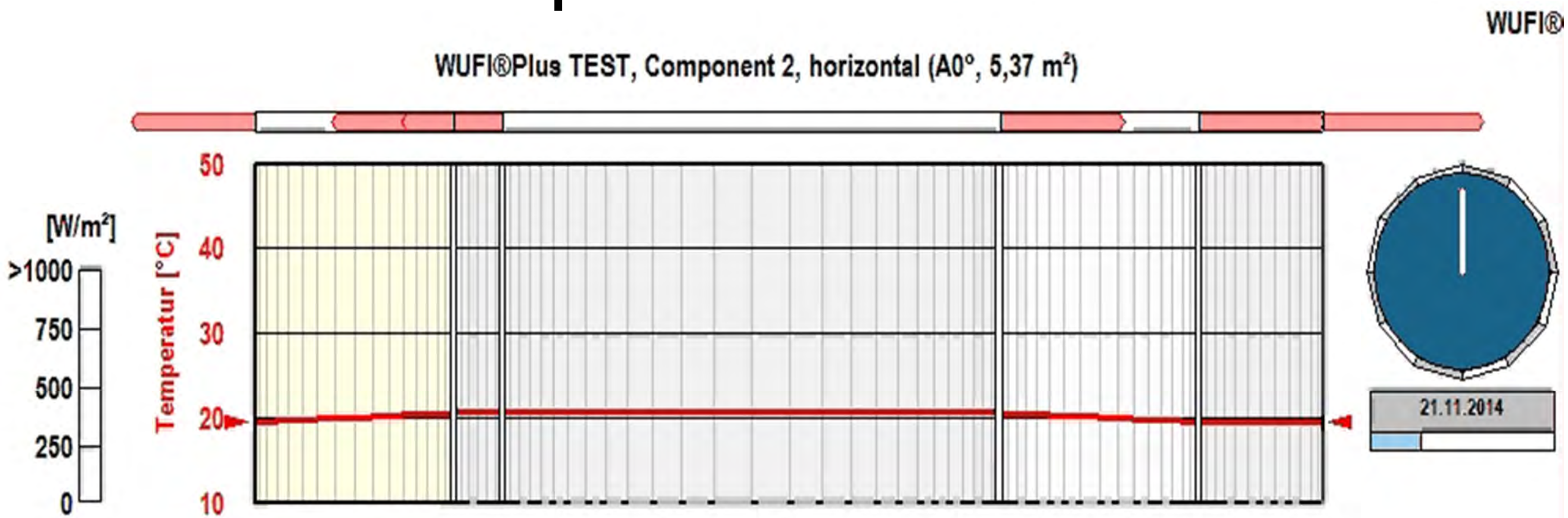
Fraunhofer IBP

Loading Cycles vs. Thermal Envelope Quality



Fraunhofer IBP

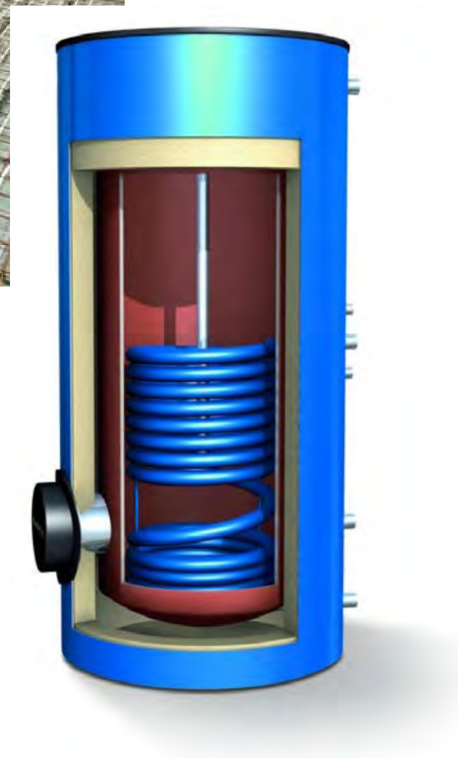
And the Loaded Components?



- High temperatures in component (around 50 °C (120 F))
- Heat flux into zones can be influenced by insulation thickness
- High thermal stress on materials
- High moisture flux toward zones on first loading cycles

Further Options

- Thermally activated components
- Hot water storage tanks
- PCM Storage
- Double insulated massive interior walls
- …



Fraunhofer IBP

First Conclusions

- It is possible to bridge 8-10 days
- A wider indoor temperature range needs to be accepted
- Sufficient thermal storage needs to be present
- Information is required for loading/unloading control:
  - thermal building performance
  - predicted weather conditions
  - current status of loaded components
- Thermal building enclosure defines the times to bridge
- Loaded internal components need to be insulated

→ Combined systems that provide "passive" gains and some control

Fraunhofer IBP

Intermittent Building Operation

Fraunhofer IBP

What is Thermal Comfort?

Thermal Comfort

is that condition of mind that expresses satisfaction with the thermal environment.

ASHRAE Standard 55

The condition of thermal comfort

is sometimes defined as a state in which there are no driving impulses to correct the environment by behaviour.

Benzinger 1979 in Hensen 1990

Fraunhofer IBP

Comfort

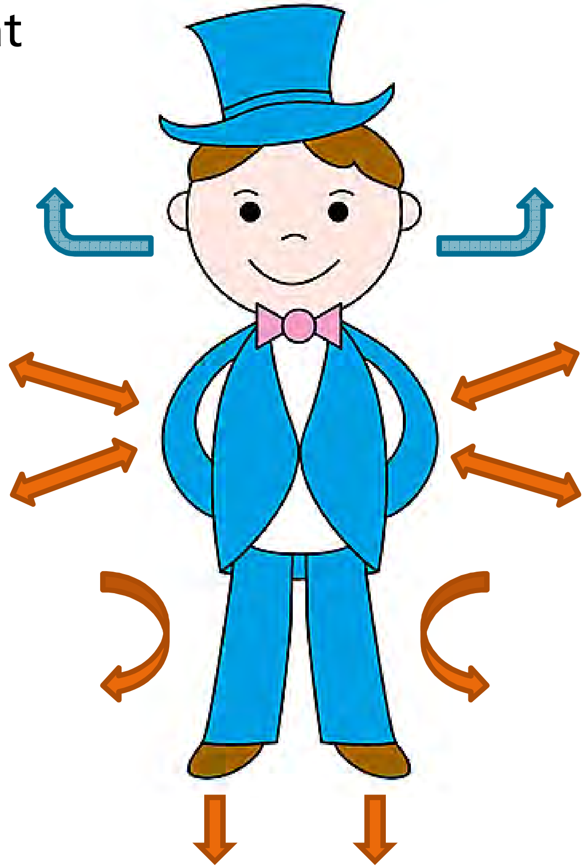
How do we manage our heat balance?

Evaporation (~ 35%)

Radiation (~ 30%)

Convection (~ 30%)

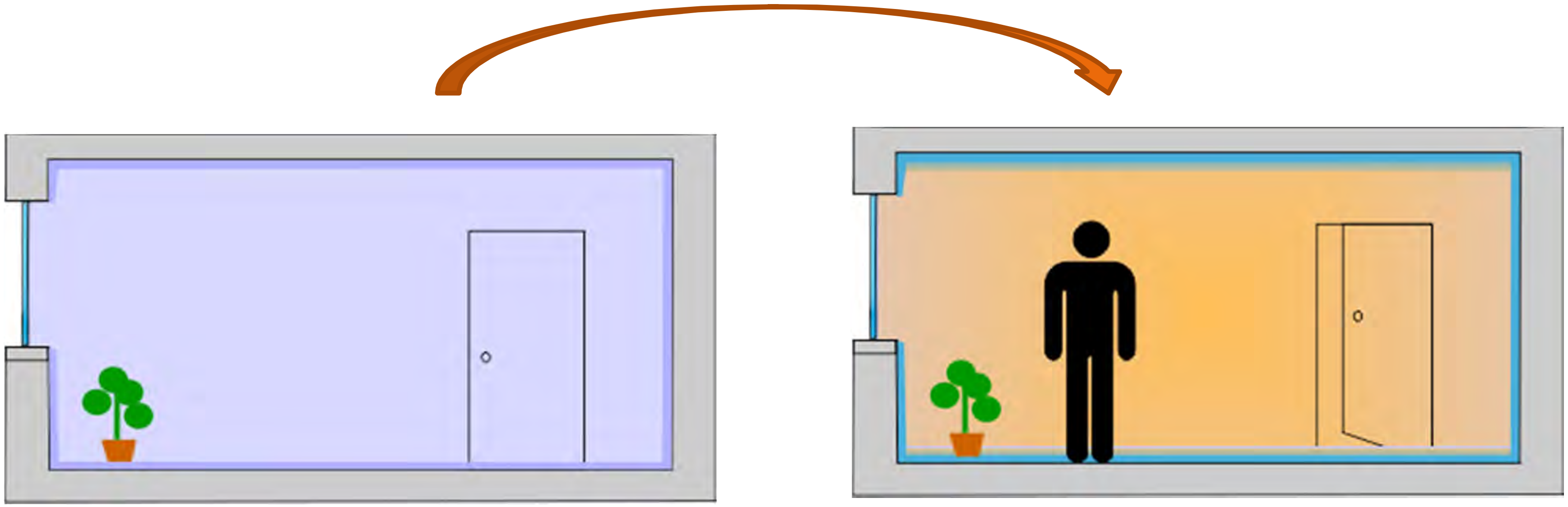
Conduction (~ 5%)



Parameters:

- Air temperature
- Radiation temperature
- Air Humidity
- Air velocity
- Clothing
- Activity

Current approach

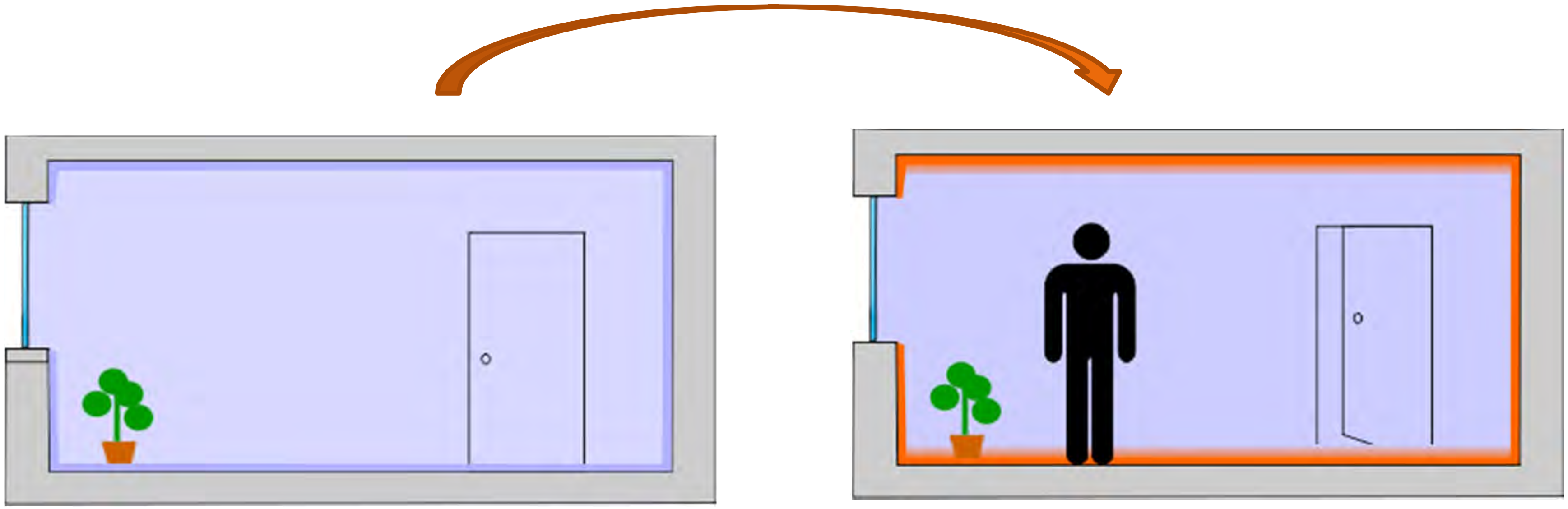


- Unconditioned space
- Cold/Warm Air and Surfaces

- Blow in cold/warm air to condition the space

→ Surface conditions change slower
→ Air temperature needs to fix it

Intermittent Heating/Cooling of a Space

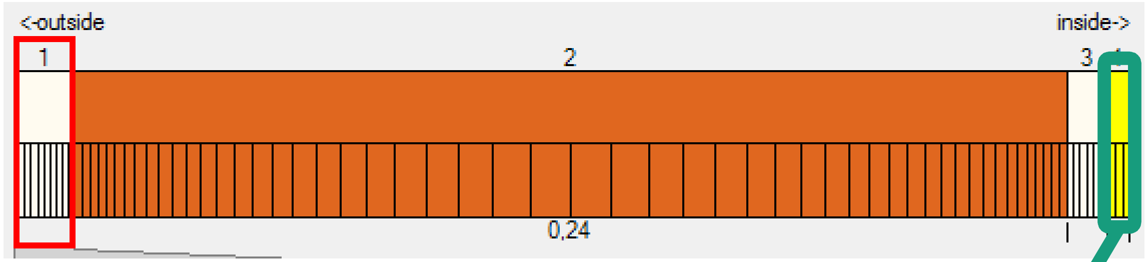


- Unconditioned space
- Cold/Warm Air and Surfaces

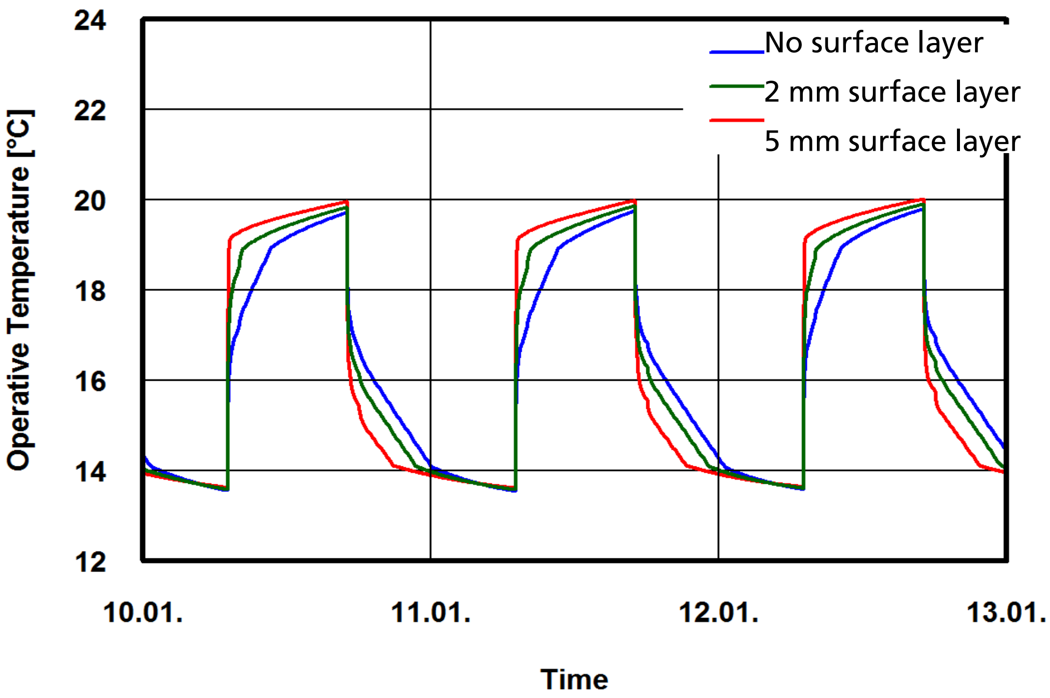
- Condition the surfaces
  - Low-e surface treatment
  - Thin internal insulation of all surfaces
  - Panel heating/cooling on exterior wall surface

Fraunhofer IBP

Operative Temperature for Thin Surface Layer



Very thin surface insulation layer



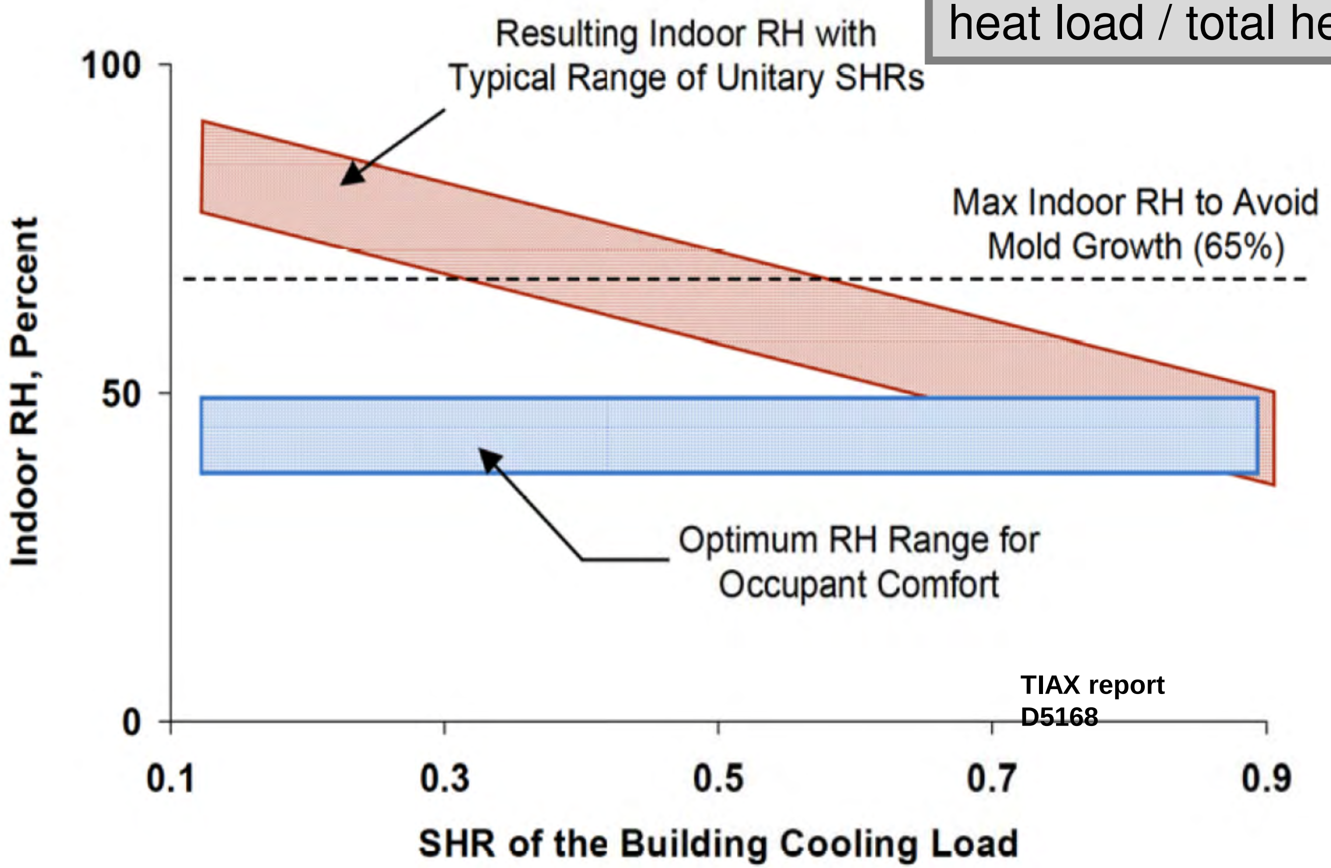
- Operative temperature faster in acceptable range
- Peak heating load is lowered

Using Hygric Inertia to Flaten HVAC Demand

Fraunhofer IBP

Moisture removal capacity of standard unitary AC systems

SHR (sensible heat ratio) = sensible heat load / total heat load

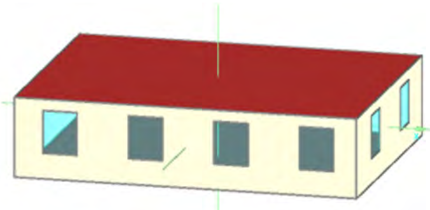


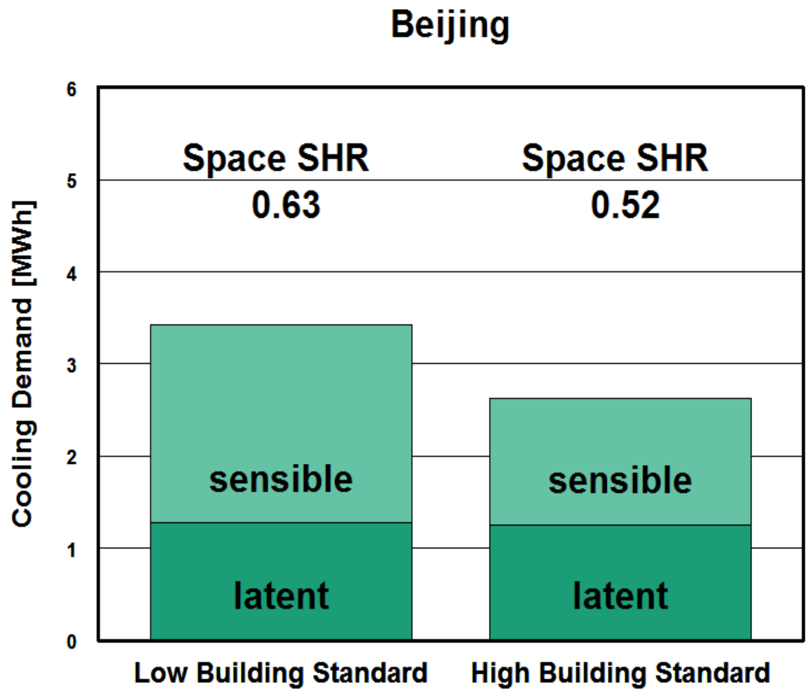
High latent loads may cause high indoor RH

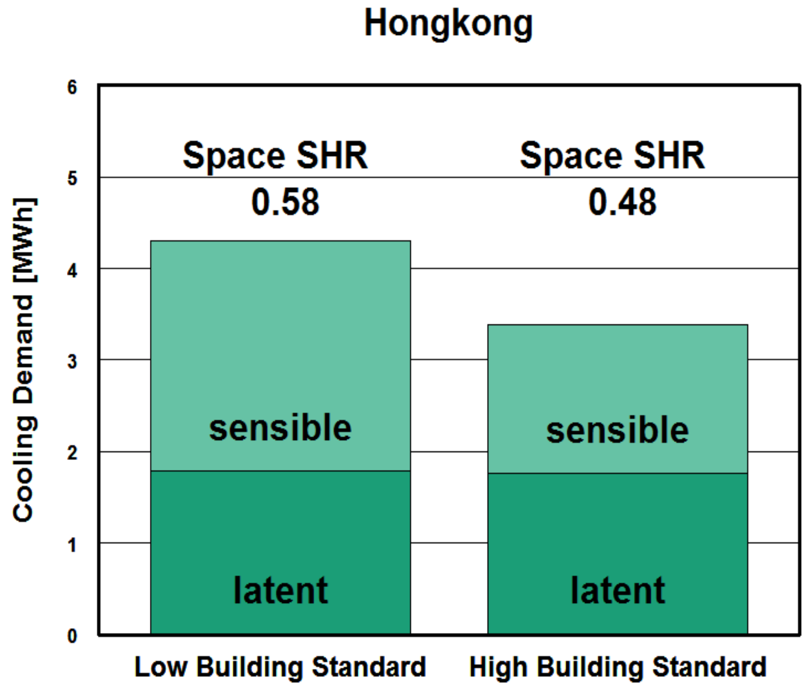
Critical threshold: SHR ≈ 0.55

Fraunhofer IBP

SHR in Apartment Building in July/August





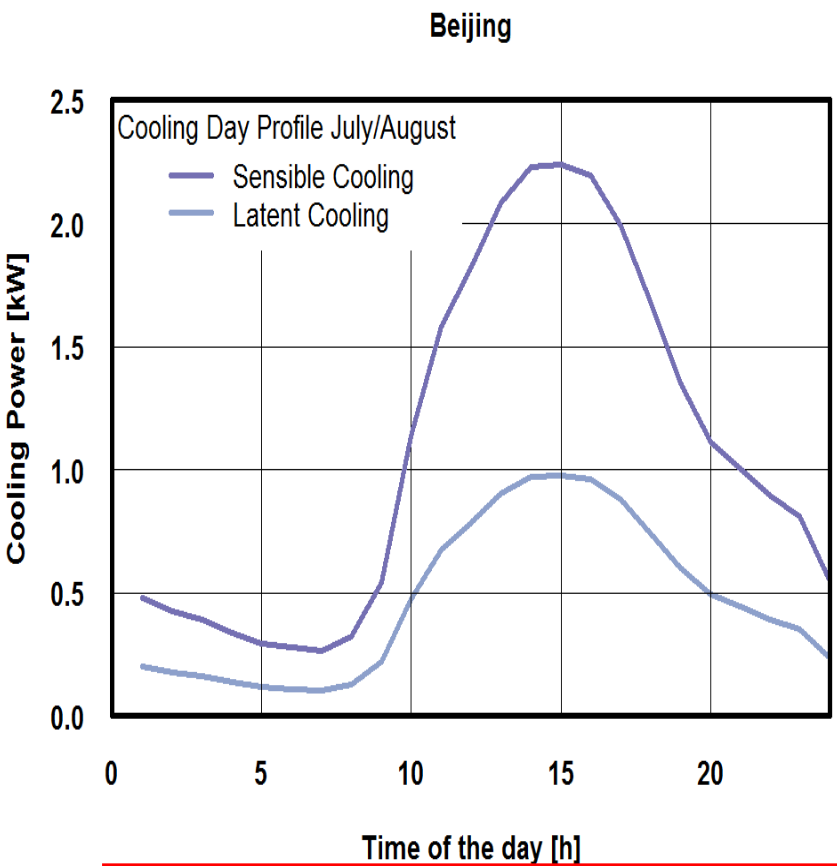


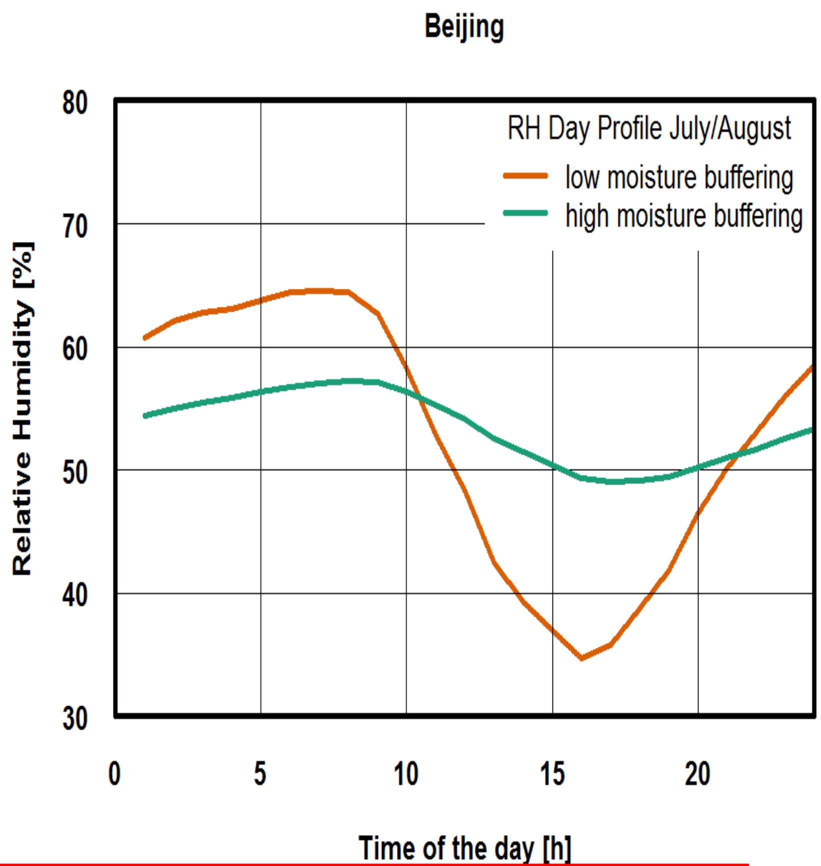
- Low Building Standard: U-wall = 1.2 W/(m²K), U-win = 2.7 W/(m²K), SHGC = 0.45
- High Building Standard: U-wall = 0.26 W/m²K, U-win = 1.3 W/(m²K), SHGC = 0.3
- Ventilation: 0.6 ACH
- Set-Points: 25°C; 50 % RH

Improving the building standard may require AC system change

Fraunhofer IBP

Moisture Buffering Effect on Daily RH Fluctuations





Moisture buffering capacity of the envelope dampens daily indoor RH cycles

Conclusions and Outlook

Fraunhofer IBP

Conclusions



- Fluctuating energy supply requires new solutions
- Long term thermal energy storage in massive buildings is one option
- Use of thermal and hygric mass for short term compensation

Fraunhofer IBP

Outlook

- In what cases is long term storage applicable/useful?
- Do I know how the building enclosure interacts with the systems?
- How do new operation modes influence durability?

- What new products/systems need to be developed/applied?
- How can I earn money on the balancing power market?

- Can we process all information from our „smart buildings“ to make them really smart (with what we know about users/use/damage/…)?

- How can we make our buildings „future proof“?

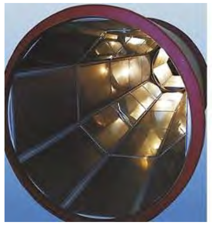
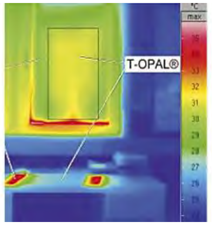
Fraunhofer IBP

Targeting future challenges – Fluctuating building operation

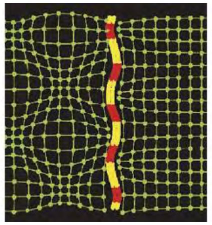
Florian Antretter – August 4th 2015

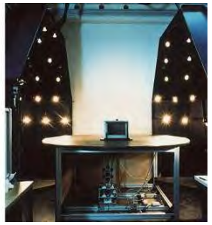
Nineteenth Annual Westford Symposium on Building Science

Auf Wissen bauen





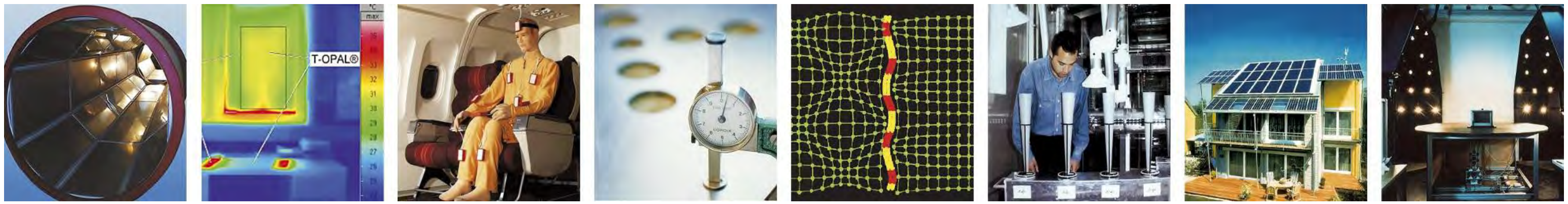



Fraunhofer IBP

How can Bavarian castles survive the rising tourist onslaught?

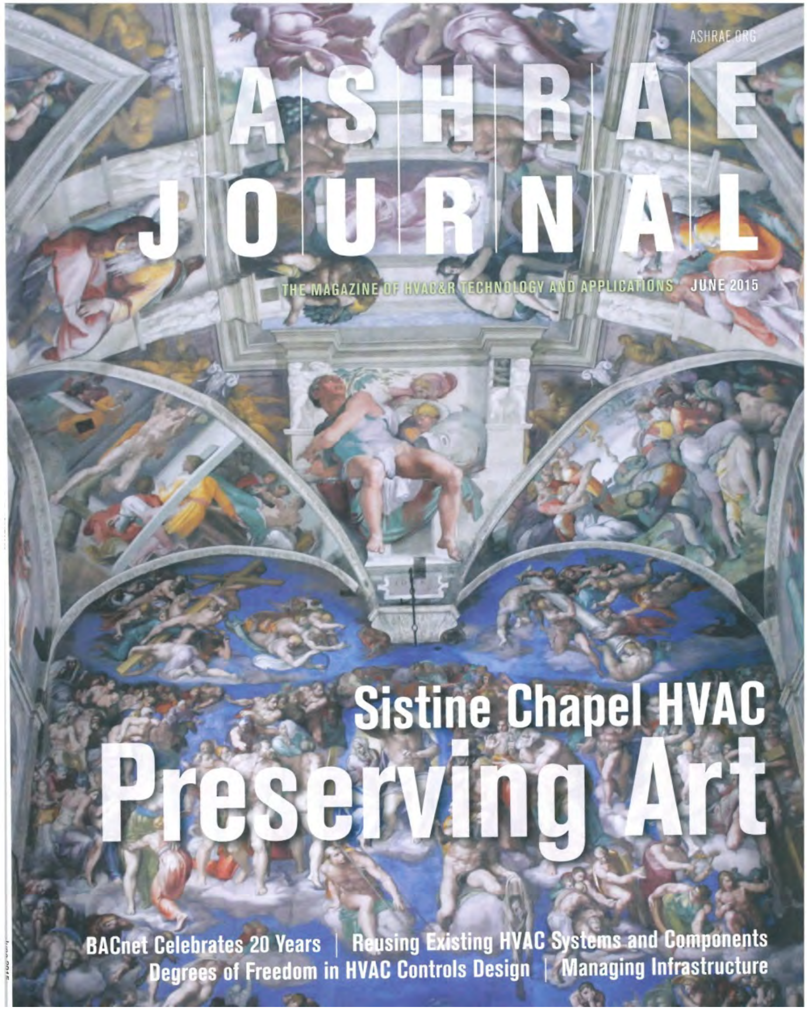
Hartwig Künzel, Ralf Kilian, Stefan Bichlmair

Auf Wissen bauen



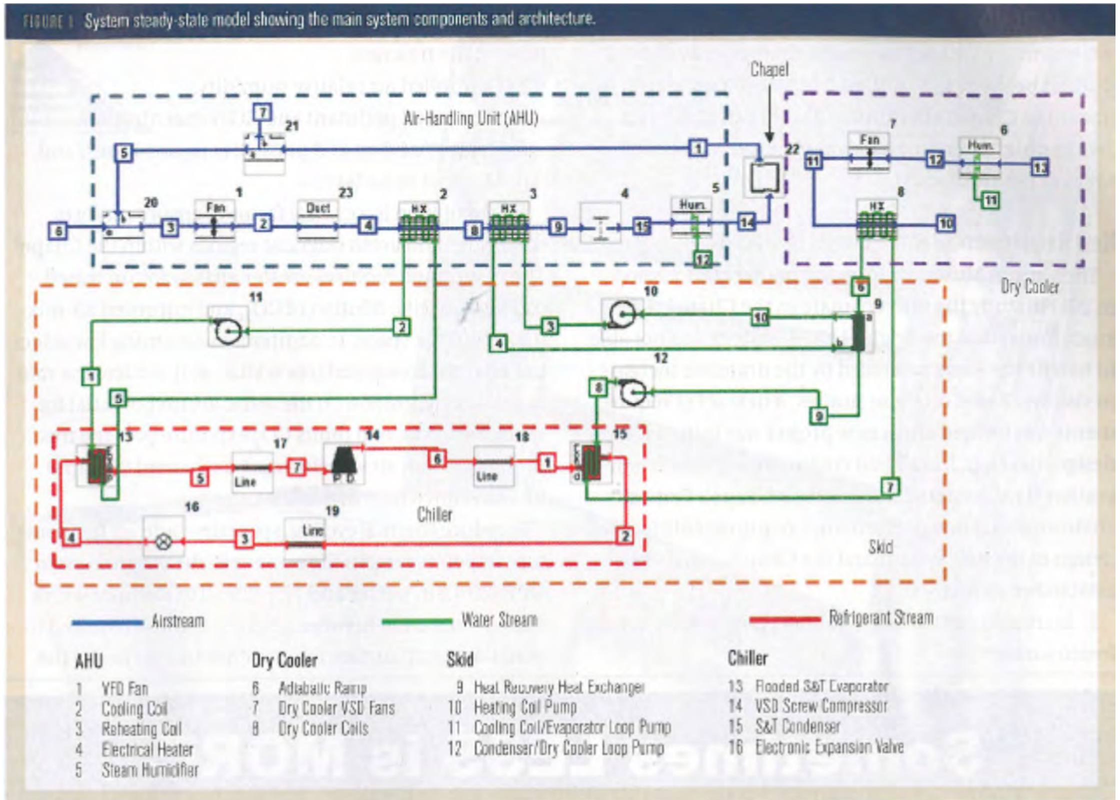
Fraunhofer IBP

Introduction – New HVAC for the Sistine Chapel in Rome



Original HVAC designed for 700 vistors per day – currently up to 2000 v/d

Introduction – New HVAC for the Sistine Chapel in Rome



Air flow capacity 15 m³/s (32,000 cfm) – Near-wall velocity < 0.5 m/s
20°C (68°F) < indoor temp. < 25°C (77°F)
50% < indoor RH < 60%
CO_2 < 800 ppm

Introduction – Feasibility of a simpler approach

Visitors – heat and moisture production

Cathegory	Moisture [g/h]	Heat [W]	CO_2 [g/h]
Adult person, sitting, relaxed	43	101	30.3
Adult person, sitting, working	59	120	36.3
Adult person, middle activity	123	205	60.5

1) Getting rid of visitors or reduce their number
2) Neutralize the impacts of visitors

Fraunhofer IBP

The King’s House on the Schachen

Altitude: 1.866 m in the Wetterstein mountain range

Climate: Extreme weather with cold winters and moderate summers

Use: Open to visitors during summer, closed during winter, unheated

Construction: Wooden framework construction in Swiss chalet-style

History: Built 1869 -1872 for King Ludwig II of Bavaria

COOPERATION

Climate for Culture

Fraunhofer IBP

Location of the Schachen Mountain in Upper Bavaria

No cable car, but 4 h mountain hike >>> limited number of visitors

The King’s House on the Schachen – Ground Floor

Saloon

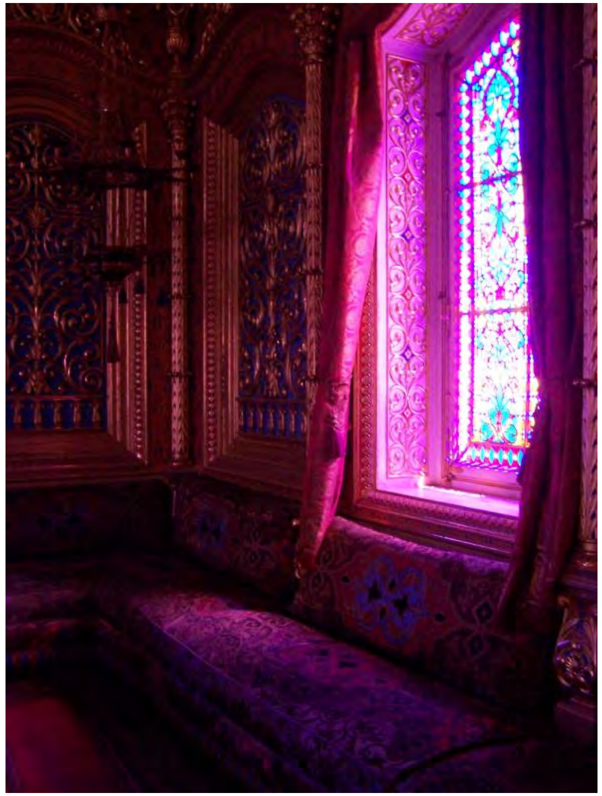
Workroom

Bedroom

Cavalier‘s room

Fraunhofer IBP

The Turkish Hall – Upper Floor



Materials: Painted wood, gilded wood, porcelain, metal, glass, feathers, textiles – cushions and carpets

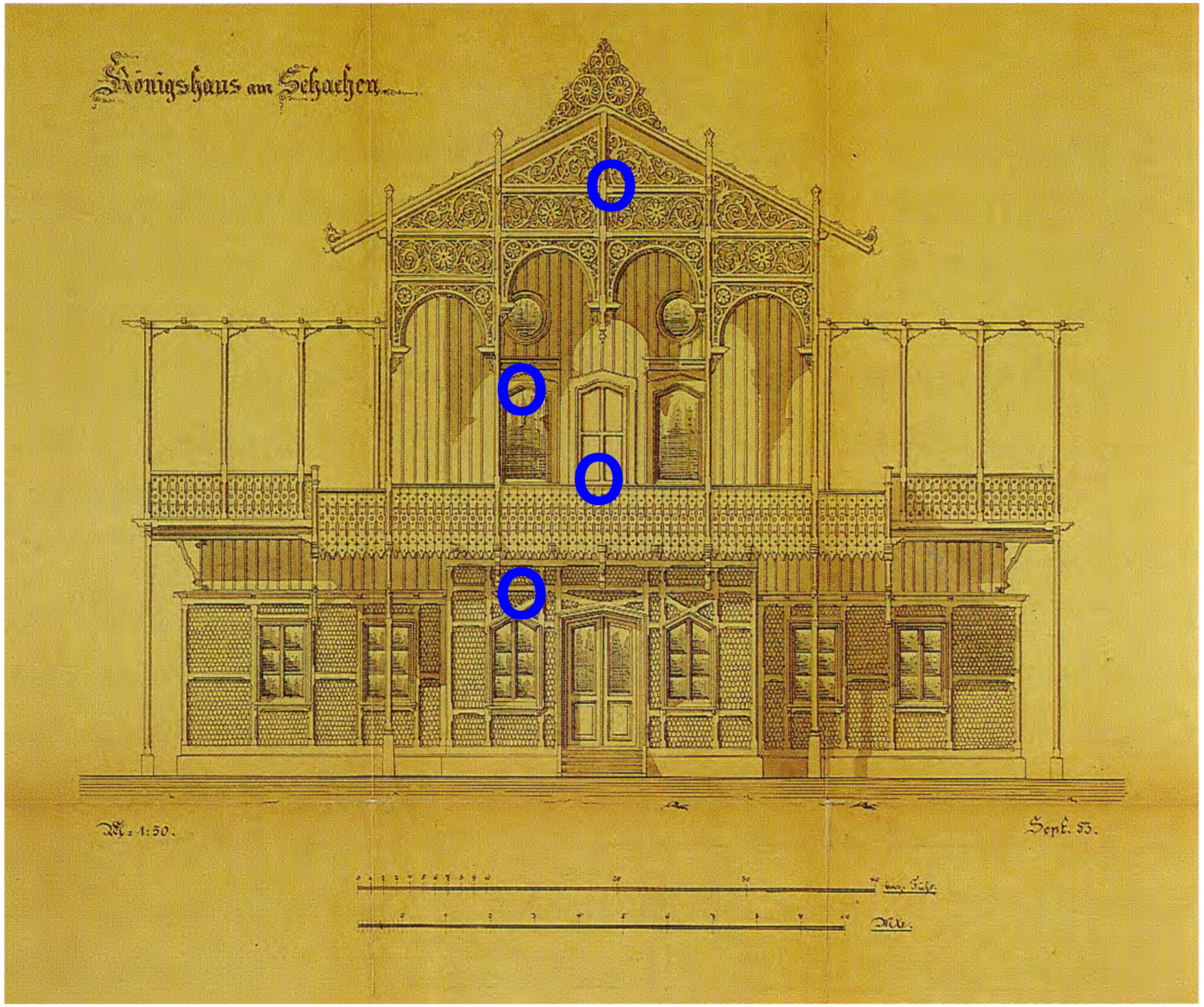
State of preservation of the furnishing

Smaller gilding defects

Warping of wall paper

Overall, wall surfaces and furnishing in the Turkish hall are in good condition

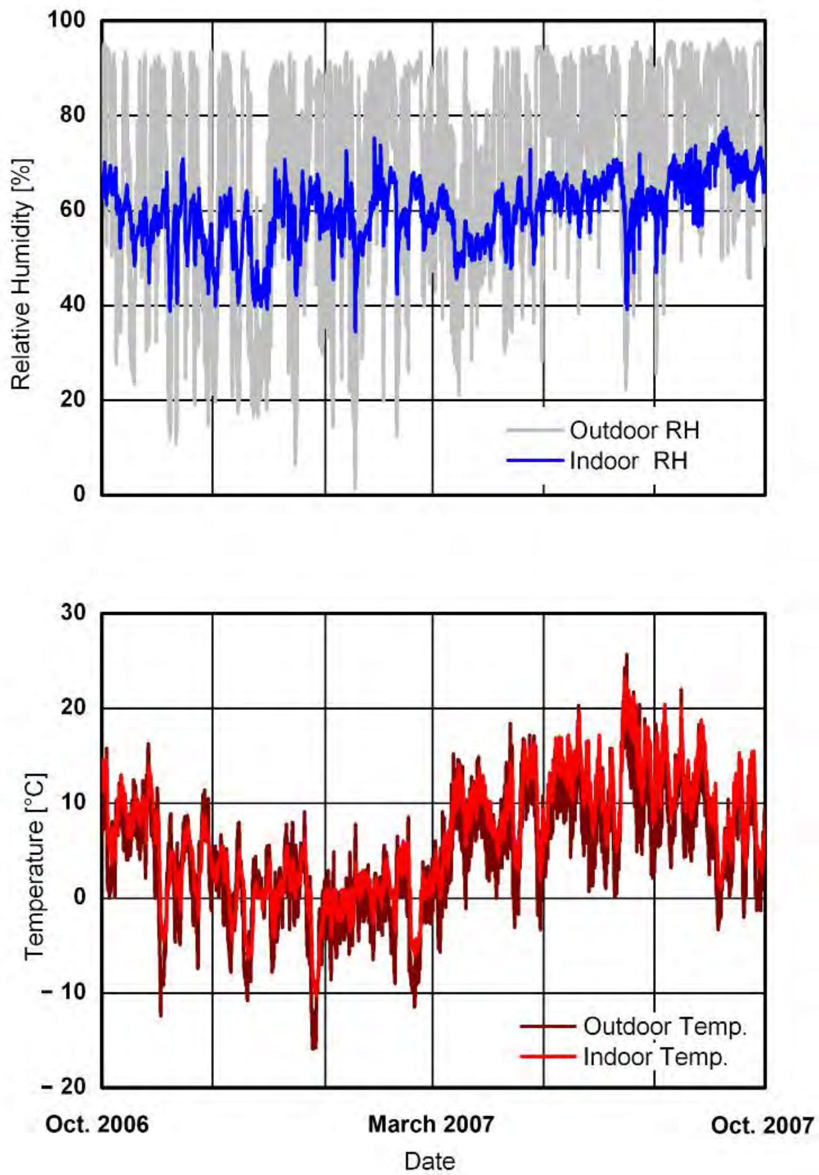
Climate measurements since summer 2006



RH, temp. outdoors
RH, temp. indoors
(since Oct. 2006)

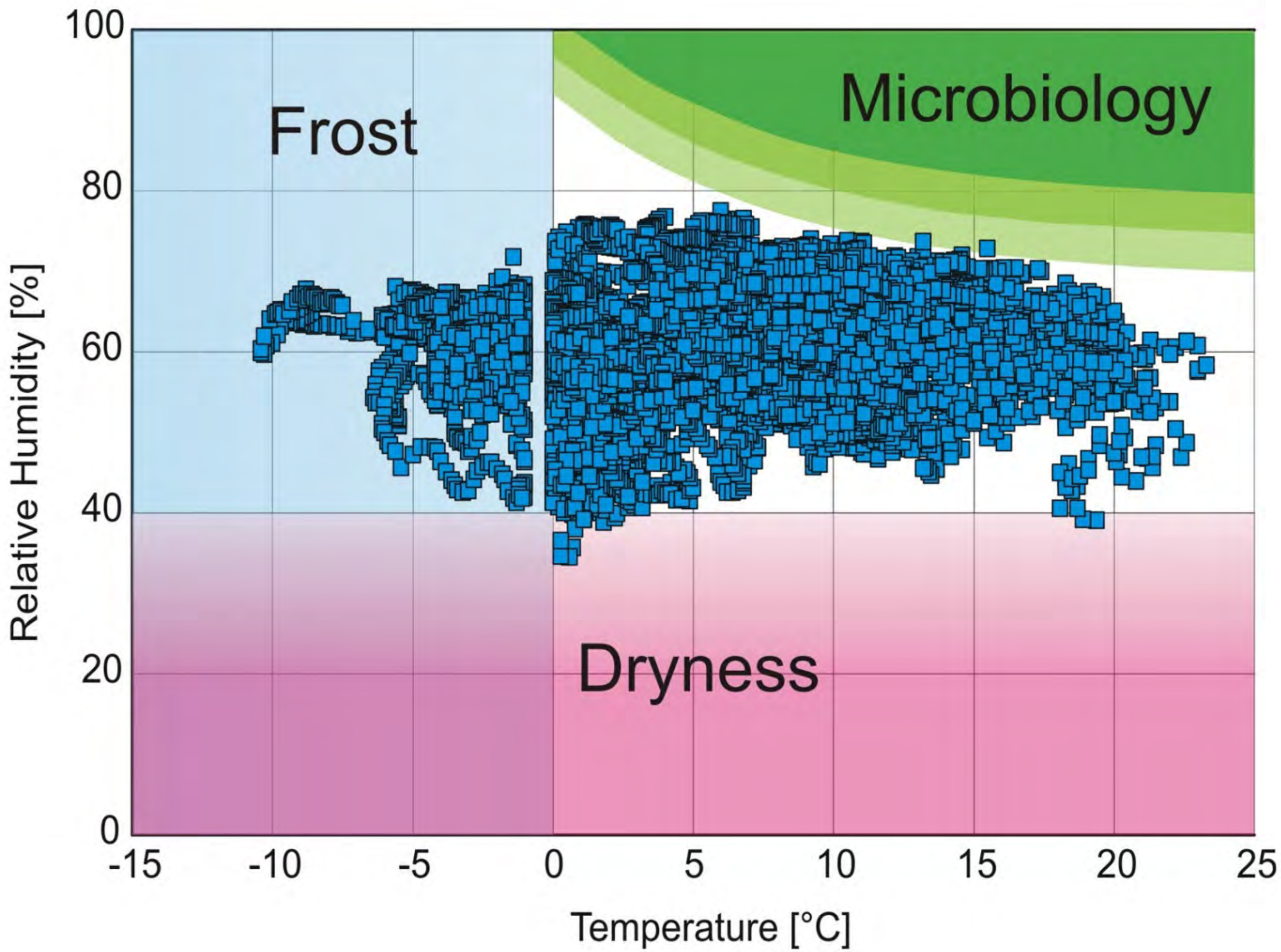
RH, temp. attic
RH, temp. ground floor
(since July 2007)

Climate measurements 2006 – 2007



Fraunhofer IBP

Risk assessment of indoor climate induced degradation



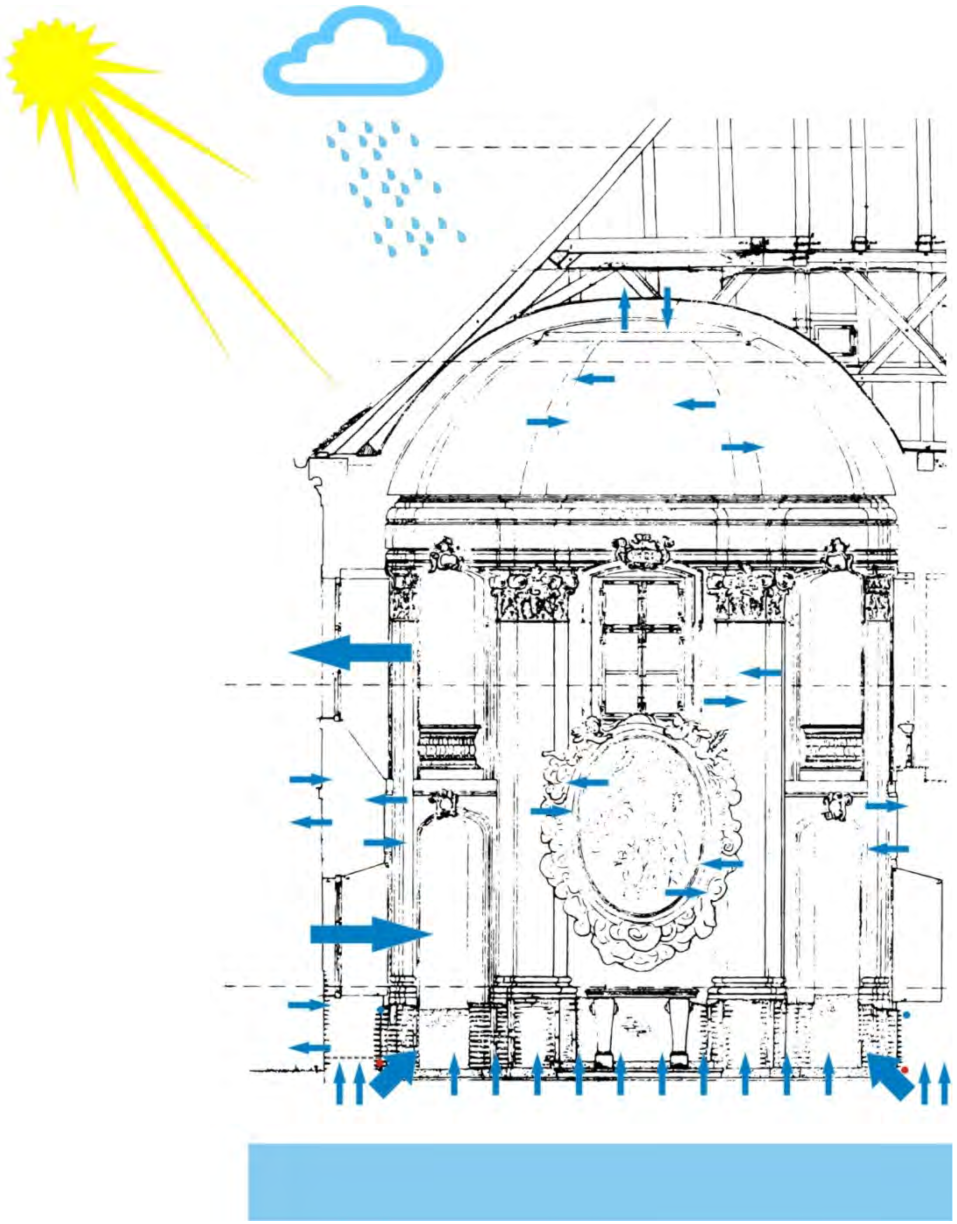
One year climate data 2006-2007

Summary on the state of preservation

- Confirmation of the overall good state of preservation of the Turkish Hall
- No heating or ventilation system
- Indoor surface materials are buffering humidity fluctuations
- Stable indoor environment helps to preserve furnishing

$\Rightarrow$ many positive factors contribute to the good state of preservation

Impacts on the indoor climate

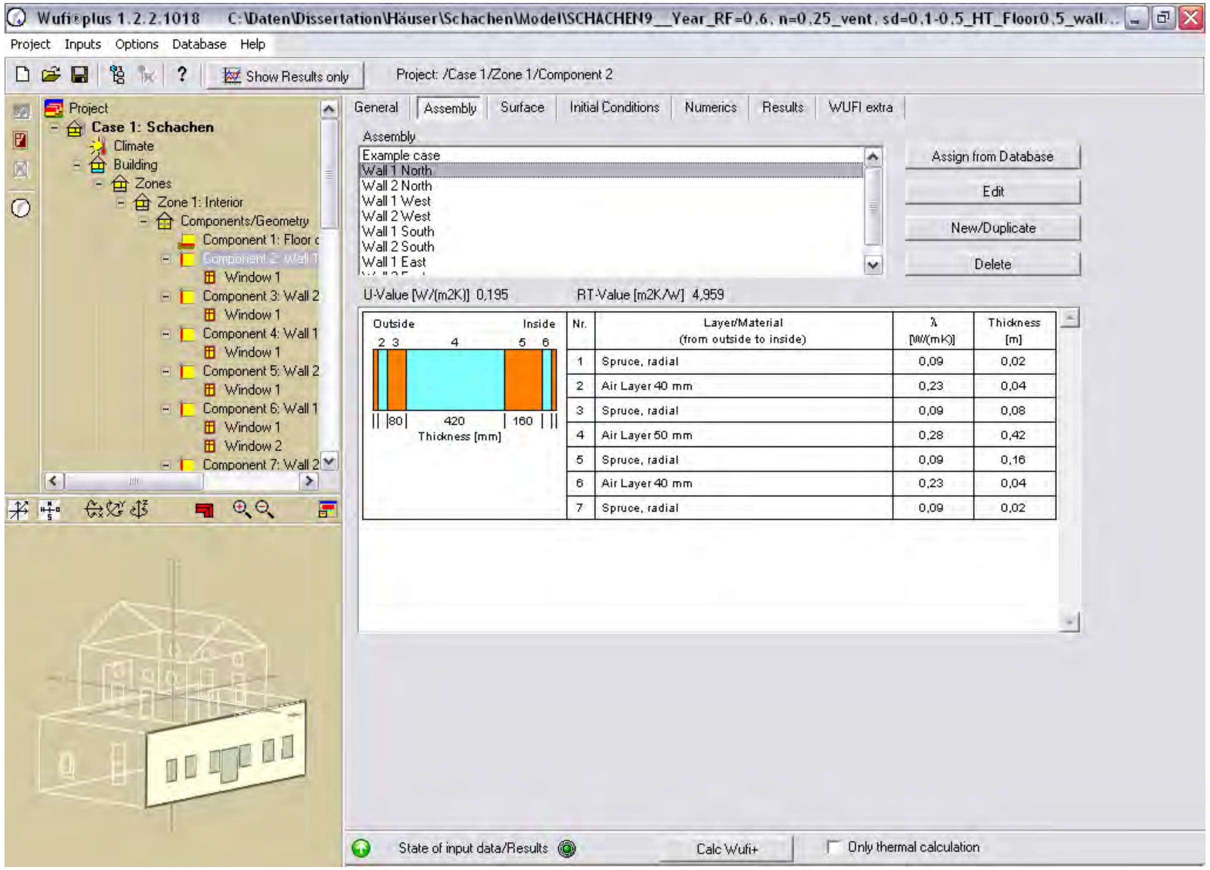


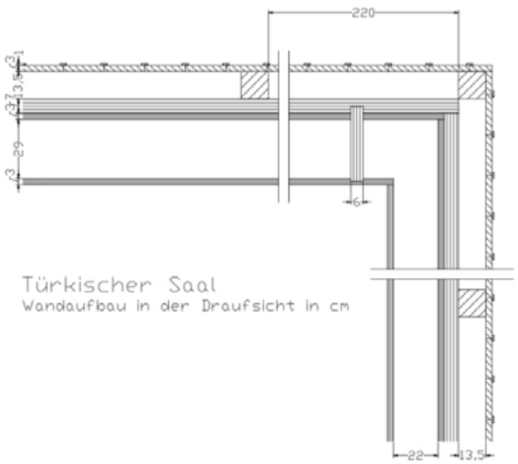
- outdoor climate
- visitors / use
- ventilation / Infiltration
- thermal inertia
- moisture buffering
- (envelope, furnishing)
- moisture / heat sources
- solar gains

Simulation of the Schachenhouse

WUFI Plus model

Composition of the building envelope





Boundary conditions

Outdoor climate

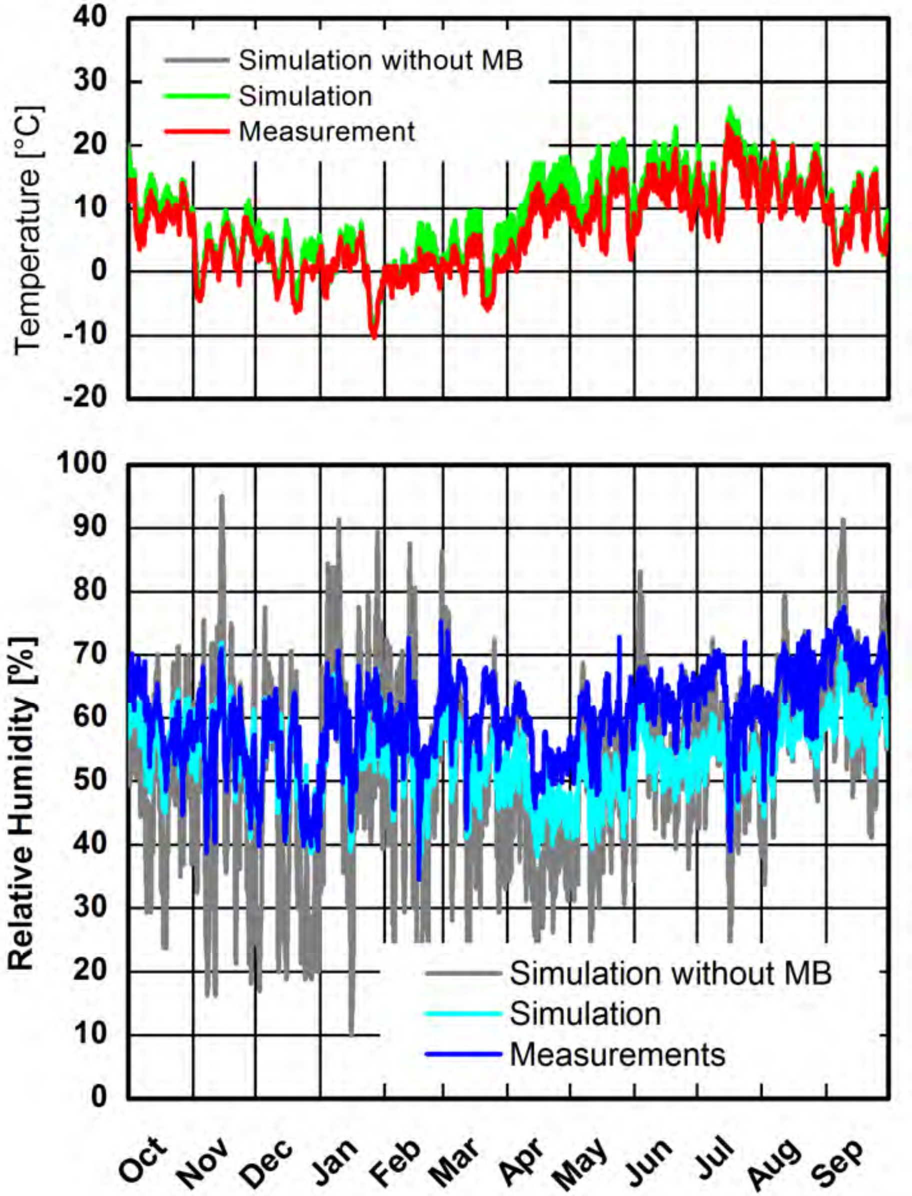
- temperature & RH measured at balcony oriented to the North
- rain, wind speed & direction from Zugspitze meteorological station
- solar radiation from Hohenpeissenberg station

Assumed air change rate 0.25 h^{-1}

Small moisture production (limited number of visitors because of mountain location, access only possible from may until september)

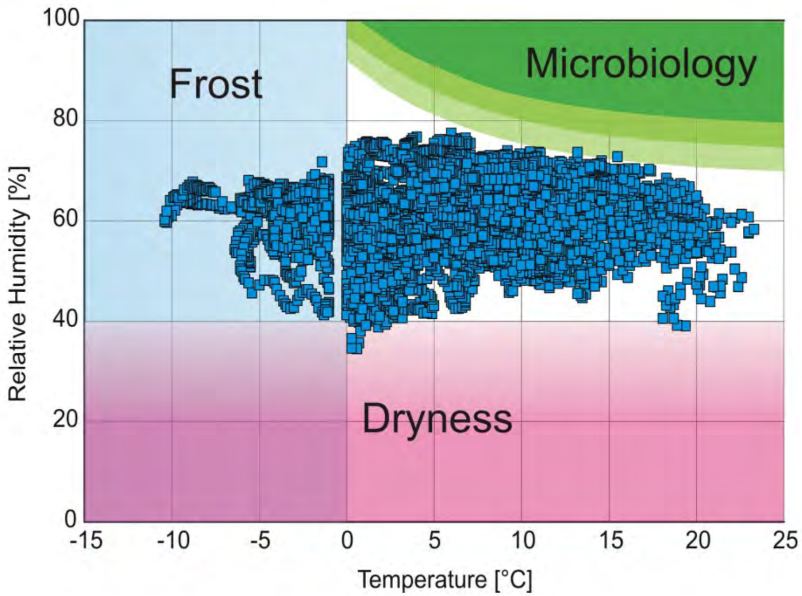
Fraunhofer IBP

Simulation – results

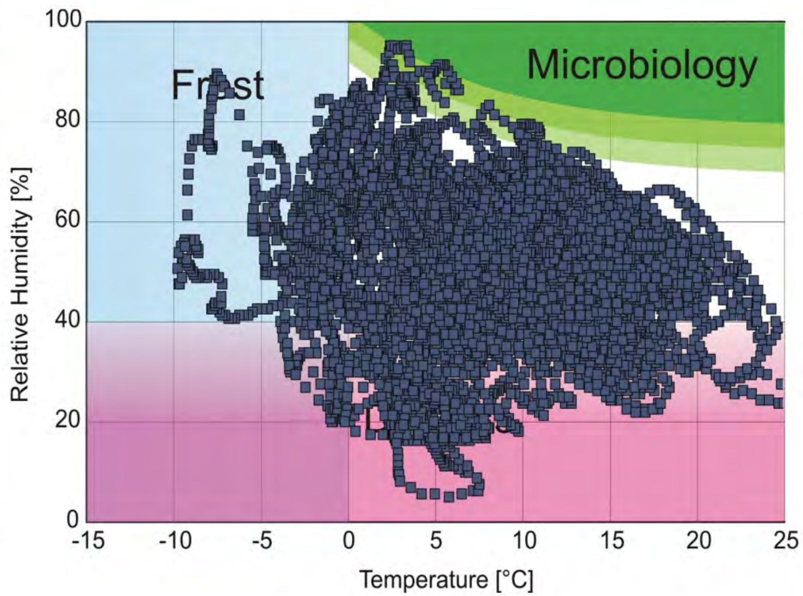


Influence of moisture buffering on RH

measured data

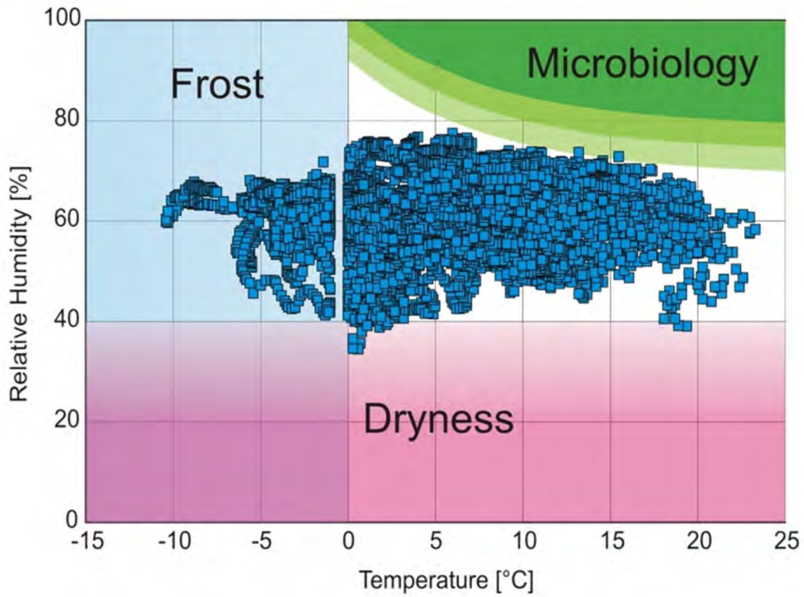


simulation without moisture buffering

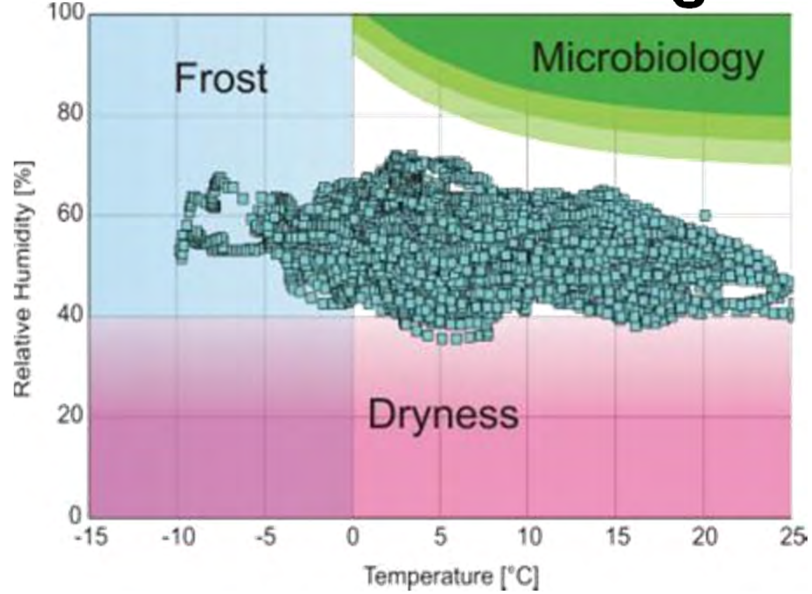


Influence of moisture buffering on RH

measured data



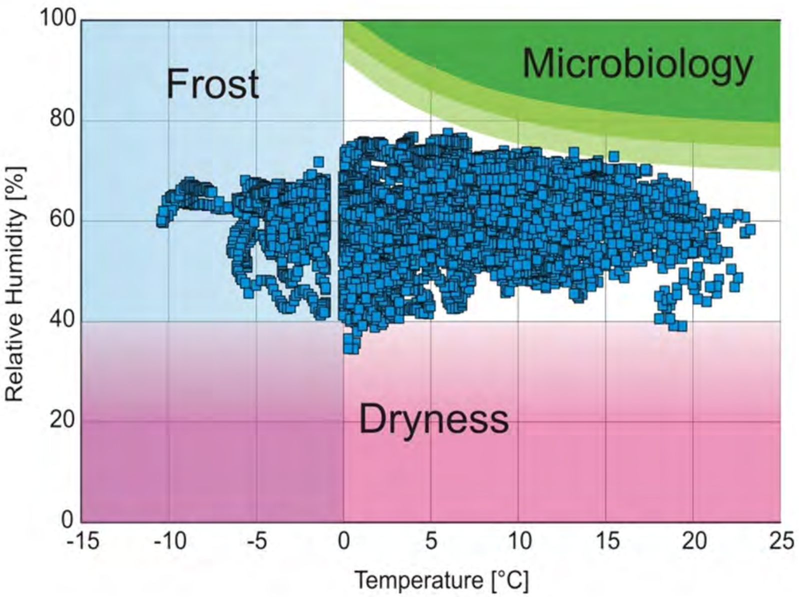
simulation with moisture buffering



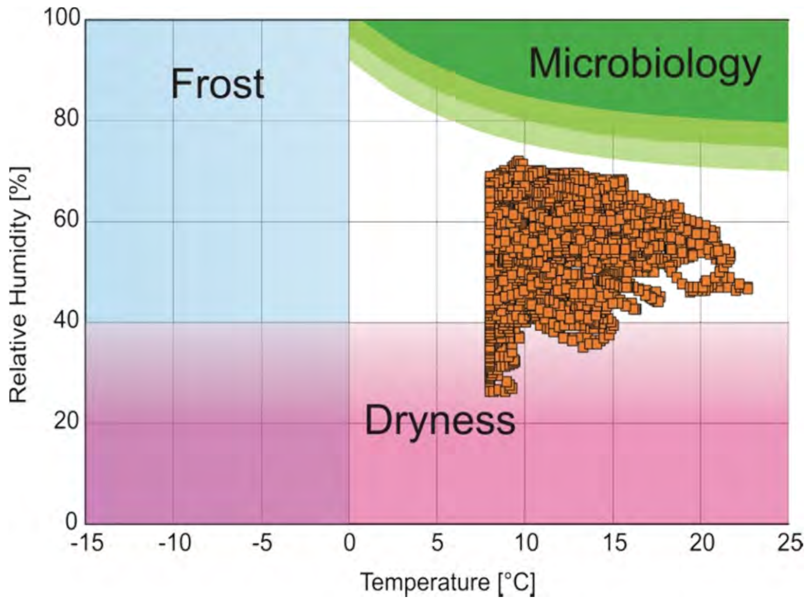
Fraunhofer IBP

Simulated change of use – heating to 8°C

measured data



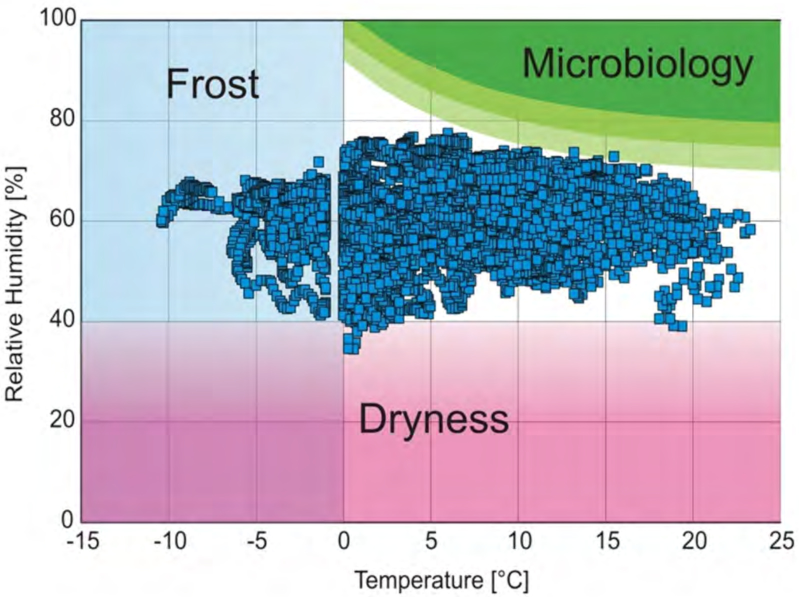
simulated change



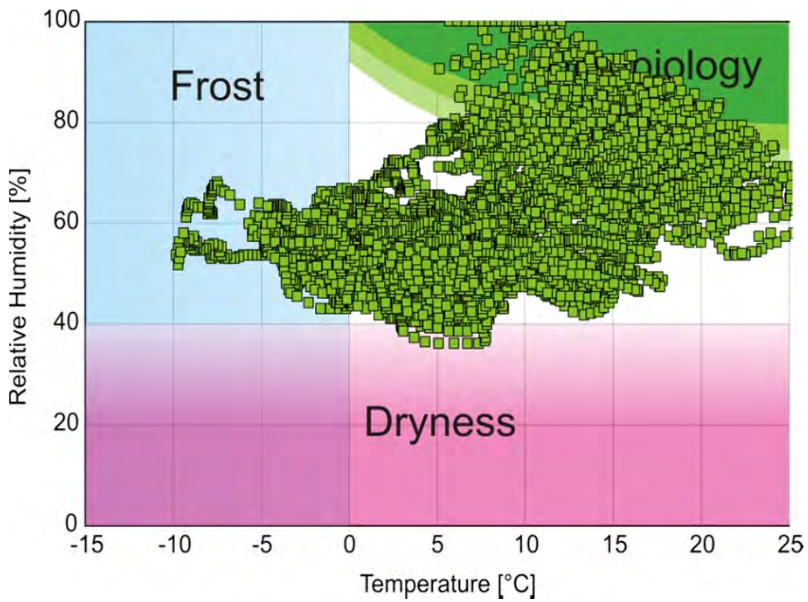
Fraunhofer IBP

Simulated change of use – 800 visitors per day

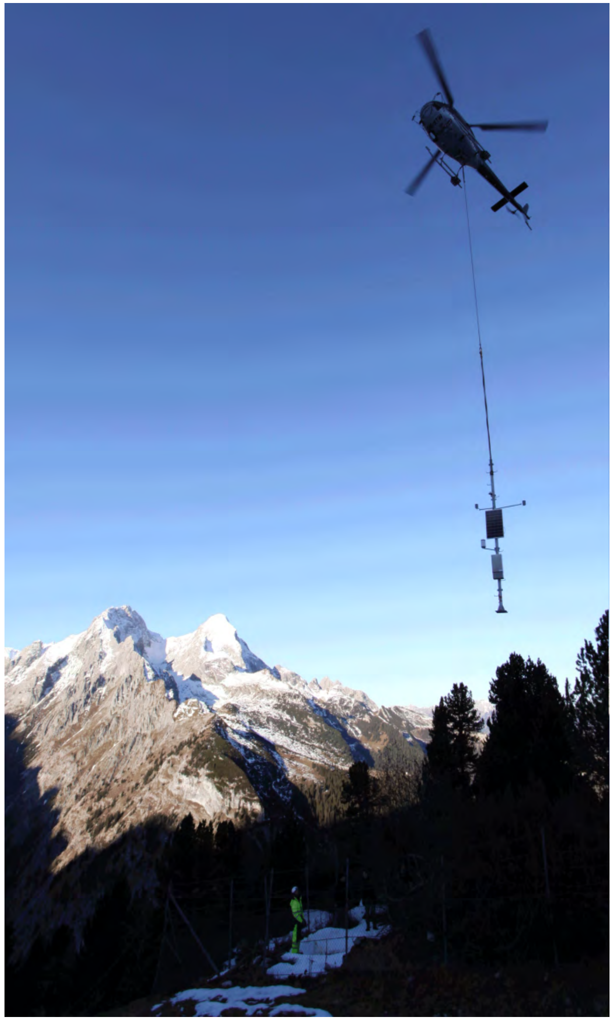
measured data



simulated change



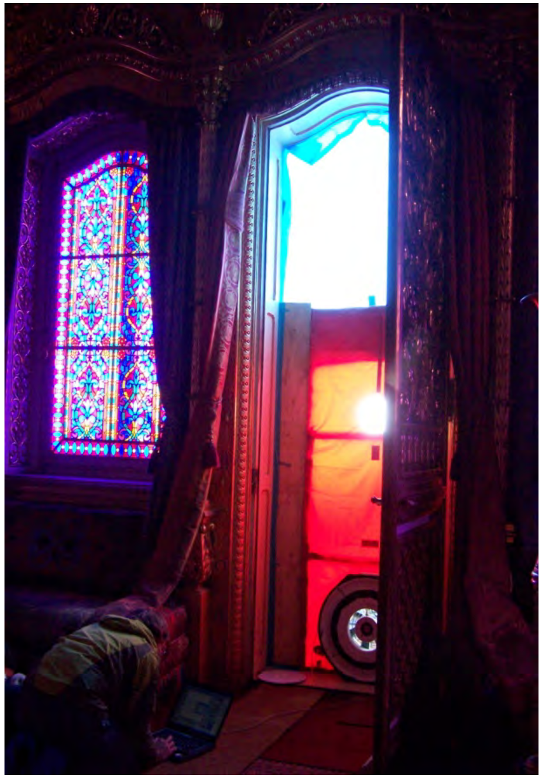
Installation of a Weather Station on the Schachen

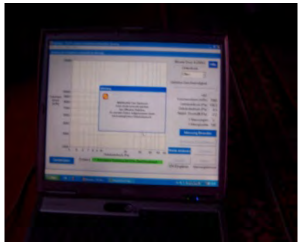


November, 19th 2009

Fraunhofer IBP

Infiltration measurements – Blower Door (failed)

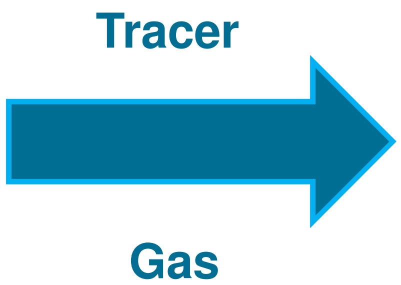





Infiltration measurements

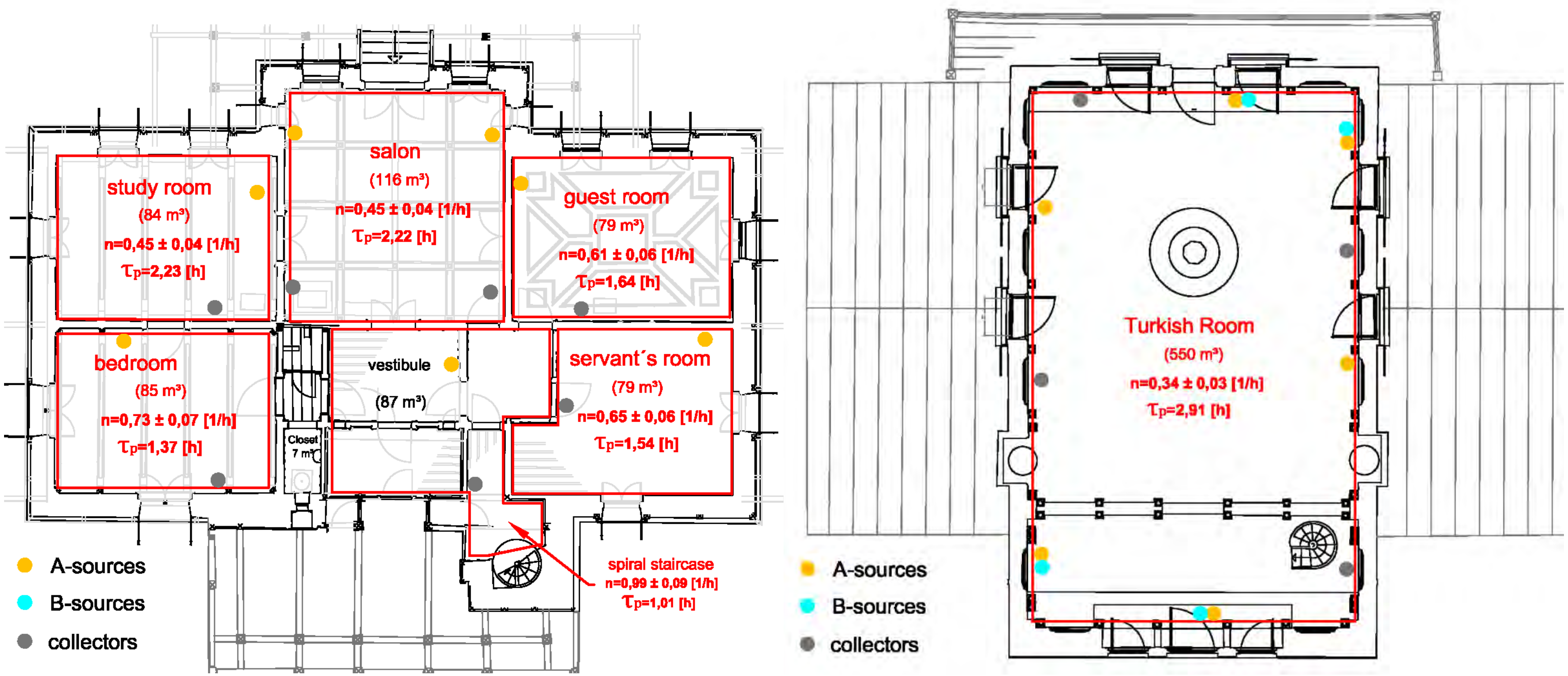
Passive sampling for measurements of air exchange rate with the outdoor air and between the floors

© Fraunhofer IBP
Source: Fluid Tracergas A / B; Constant Tracergasemission by PENTIAQ, Sweden



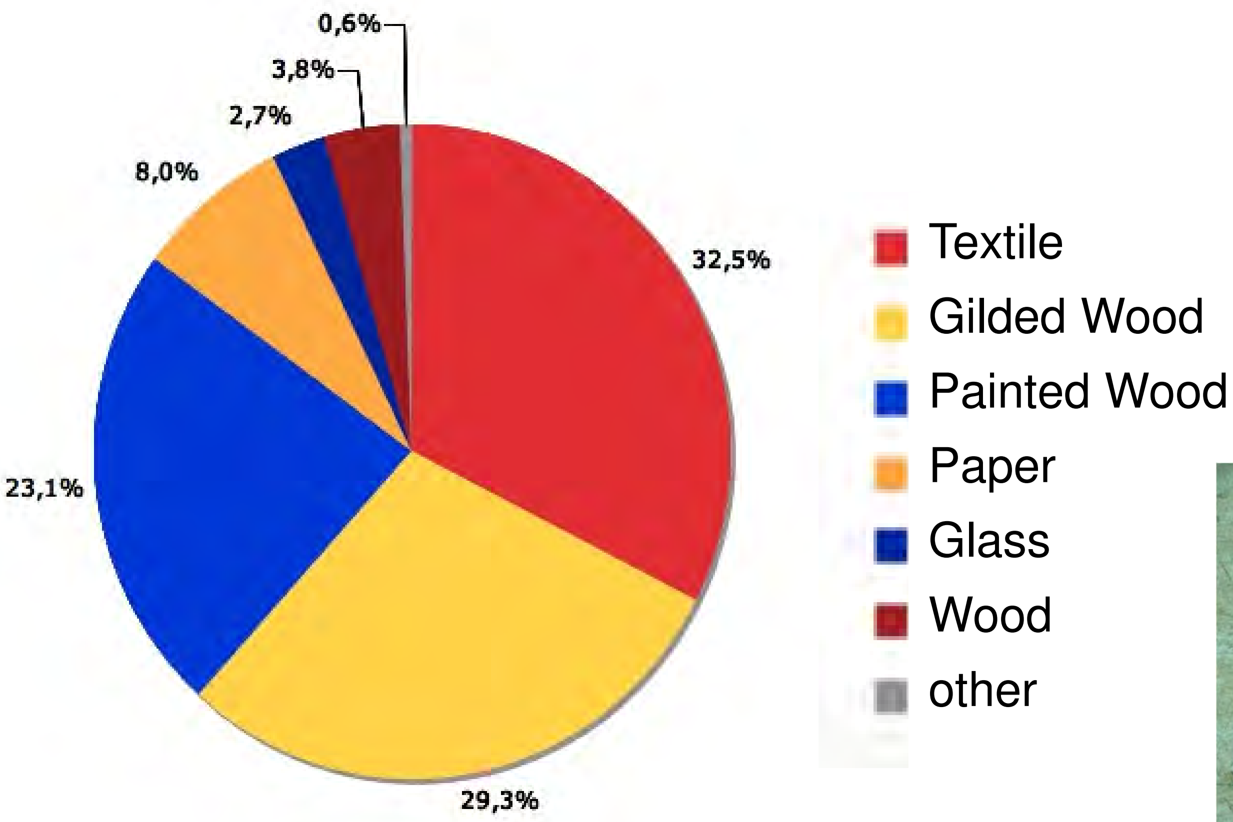
© Fraunhofer IBP
Sampler: Absorbent Material; Mass Flow into the Absorber.

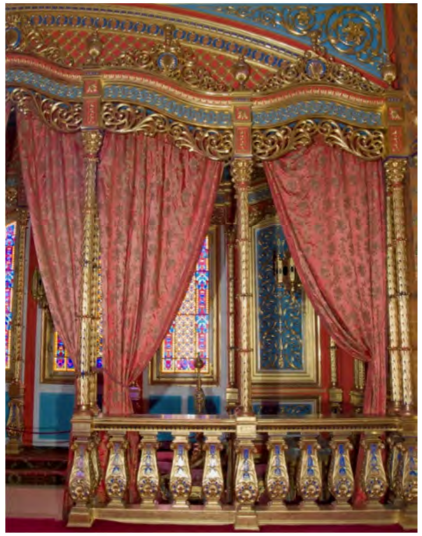
Results of the measurements of air exchange rate



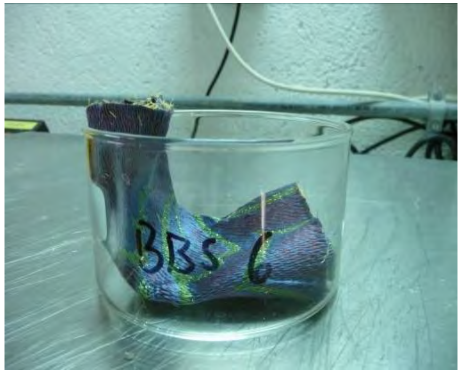
Distribution of measure equipment and results of the tracer gas measurement for each zone, Turkish Hall n = 0.34 1/h, average whole building n = 0.41 1/h

Surface materials in the Turkish Hall incl. interior furnishing





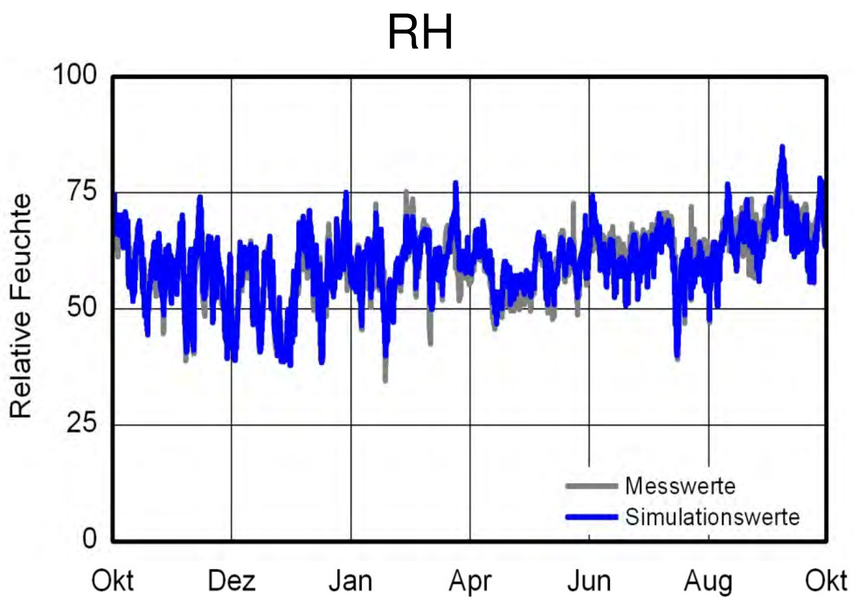
Determination of material properties

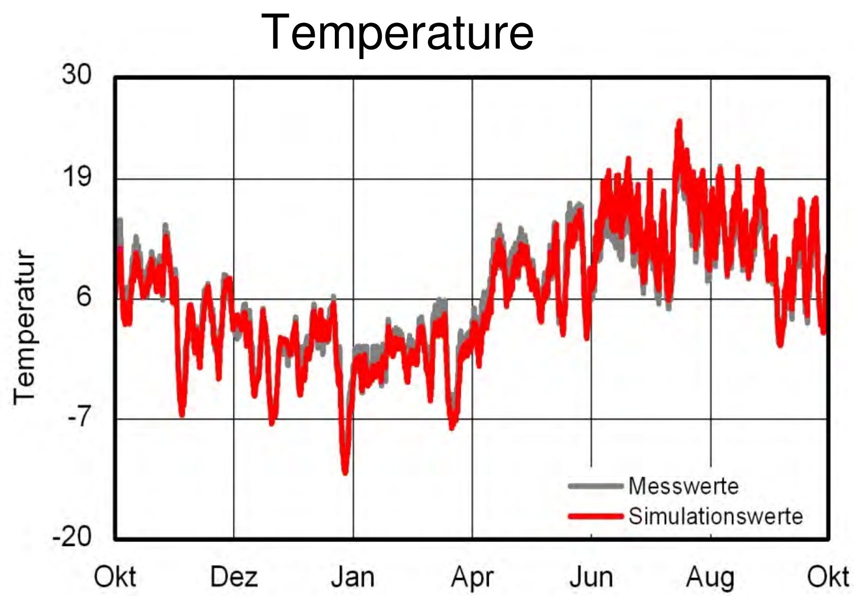


Improved Hygrothermal Building Simulation

Indoor climate in Turkish hall

– comparison between measurements and improved simulation





1.10.2009 bis 30.9.2010.

Linderhof Palace, Bavaria

Front view of Linderhof Palace

Rear view of Linderhof Palace

Building history

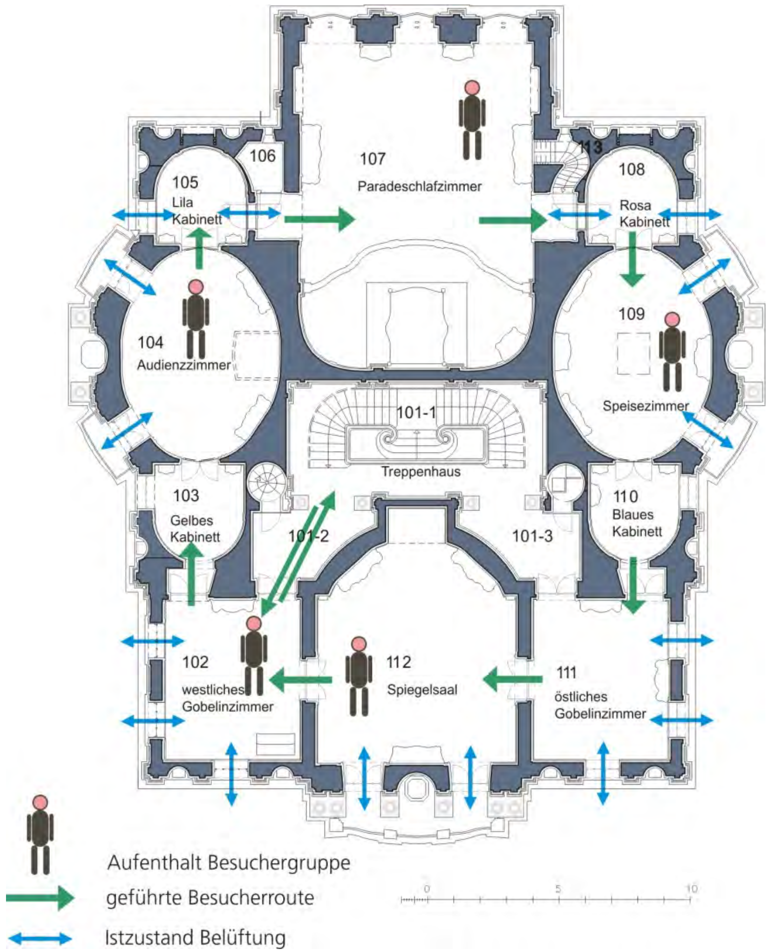
© Bayerische Schlösser- und Seenverwaltung BSV

Bedchamber of Linderhof Palace

© Bayerische Schlösser- und Seenverwaltung BSV / Firma Focus

Bedchamber of Linderhof Palace

Natural ventilation via windows and visitor tours



© Grundriss Bayerische Schlösser- und Seenverwaltung BSV

Natural ventilation and guided tour route

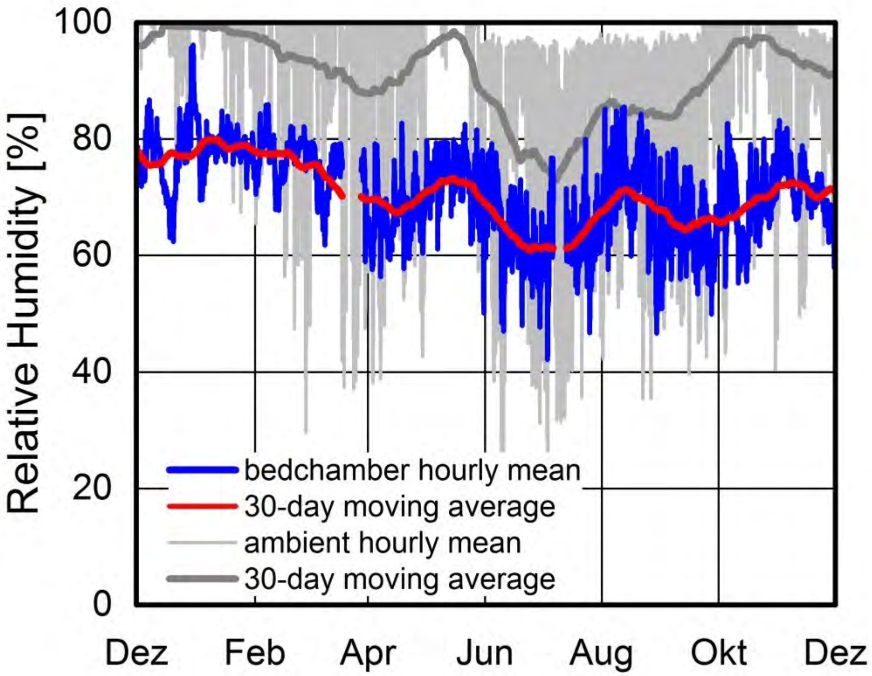
Visitor Numbers

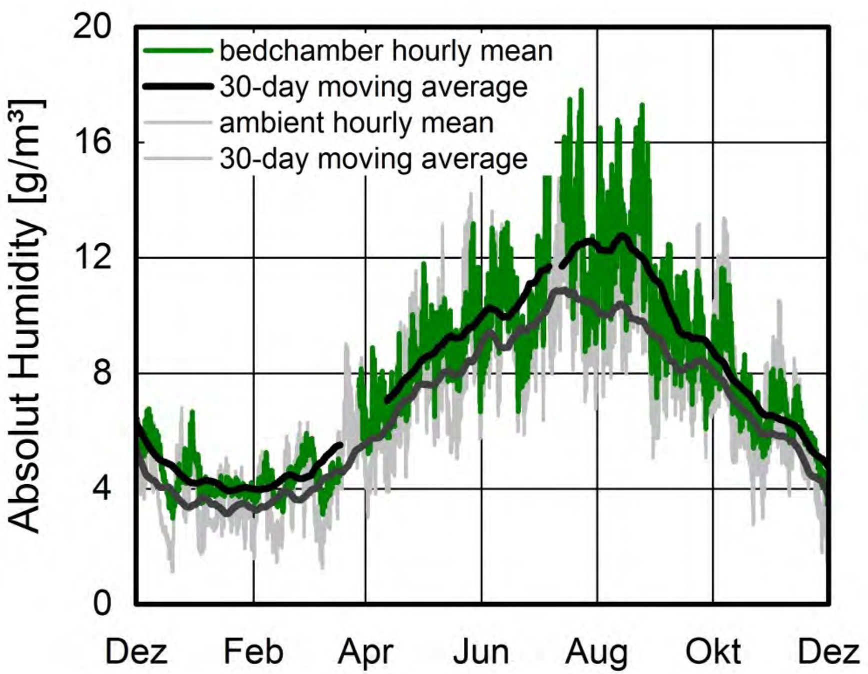
400,000 to 500,000 per year

3000 Visitors and more per day

(50% more than Sistine Chapel)

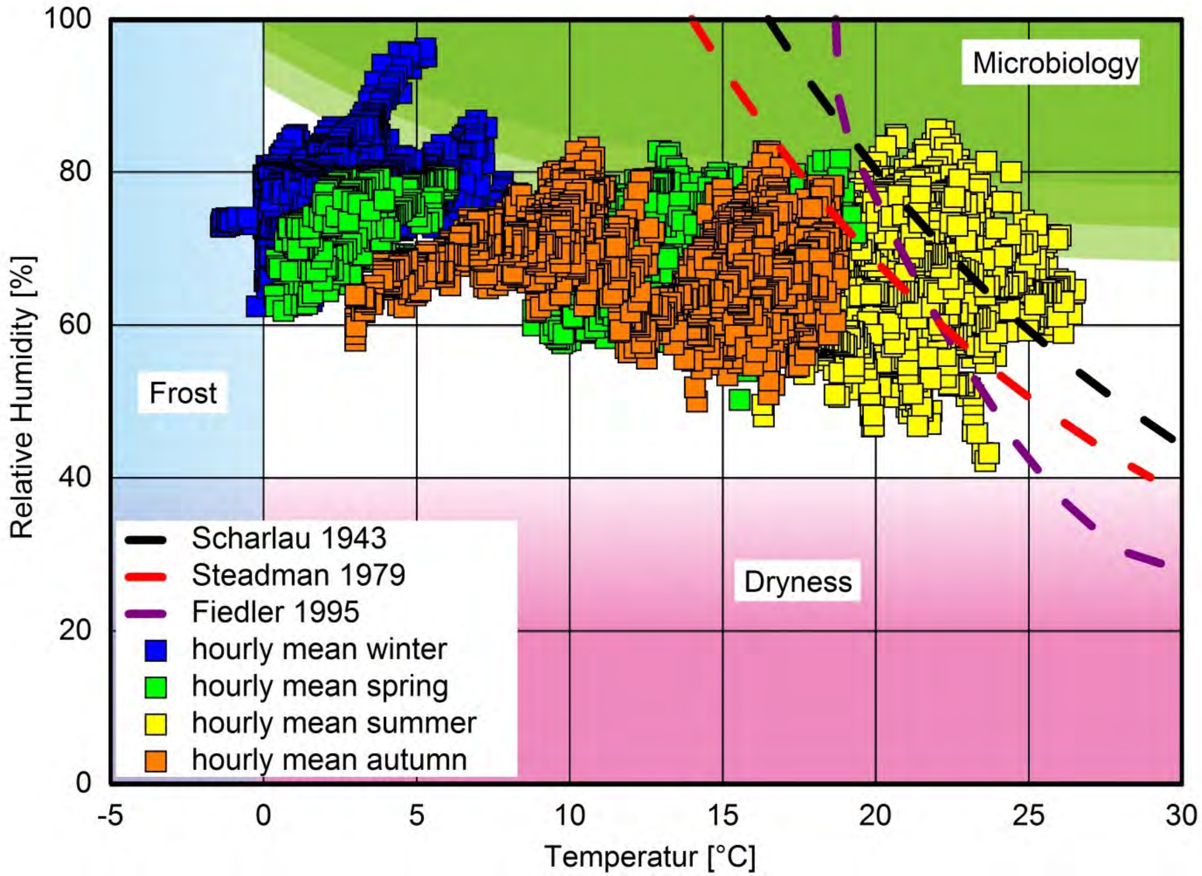
Indoor climate Parade Bedchamber





December 1st 2009 to November 31st 2010

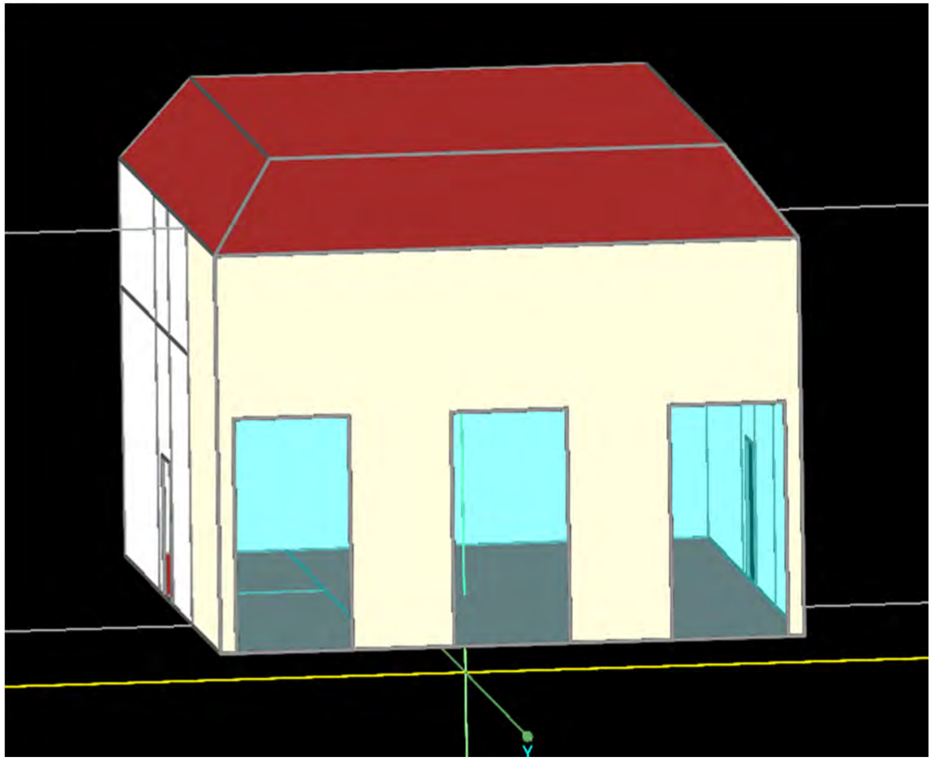
Indoor environment in the Parade Bedchamber in 2010 – Conservation risk assessment and visitor comfort



Hours of sultriness Steadman (red line)

- Sultriness hours in total 1295 h
- Sultriness during opening hours 630 h

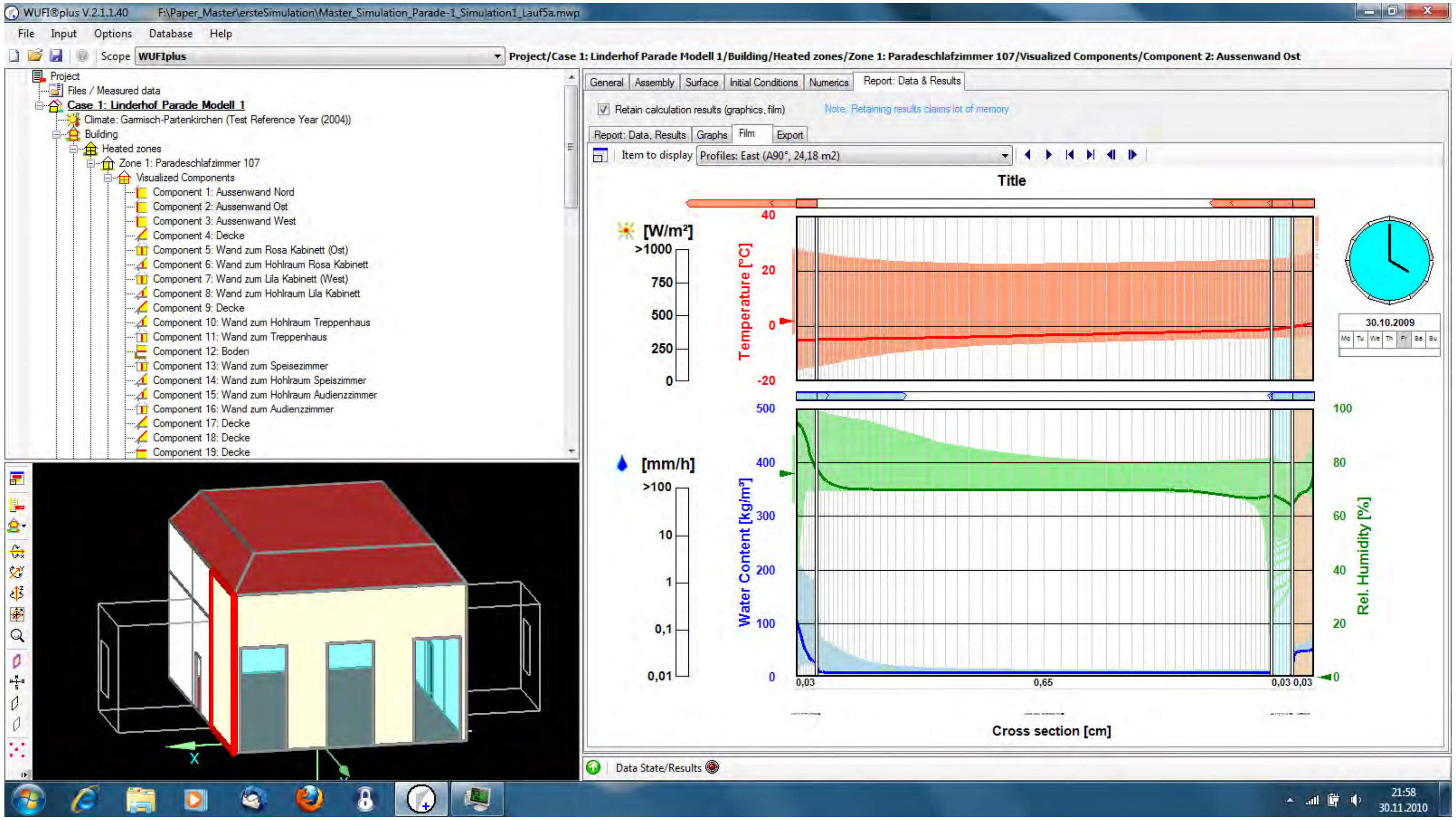
WUFI Plus simulation model



Simulation model - Parade Bedchamber

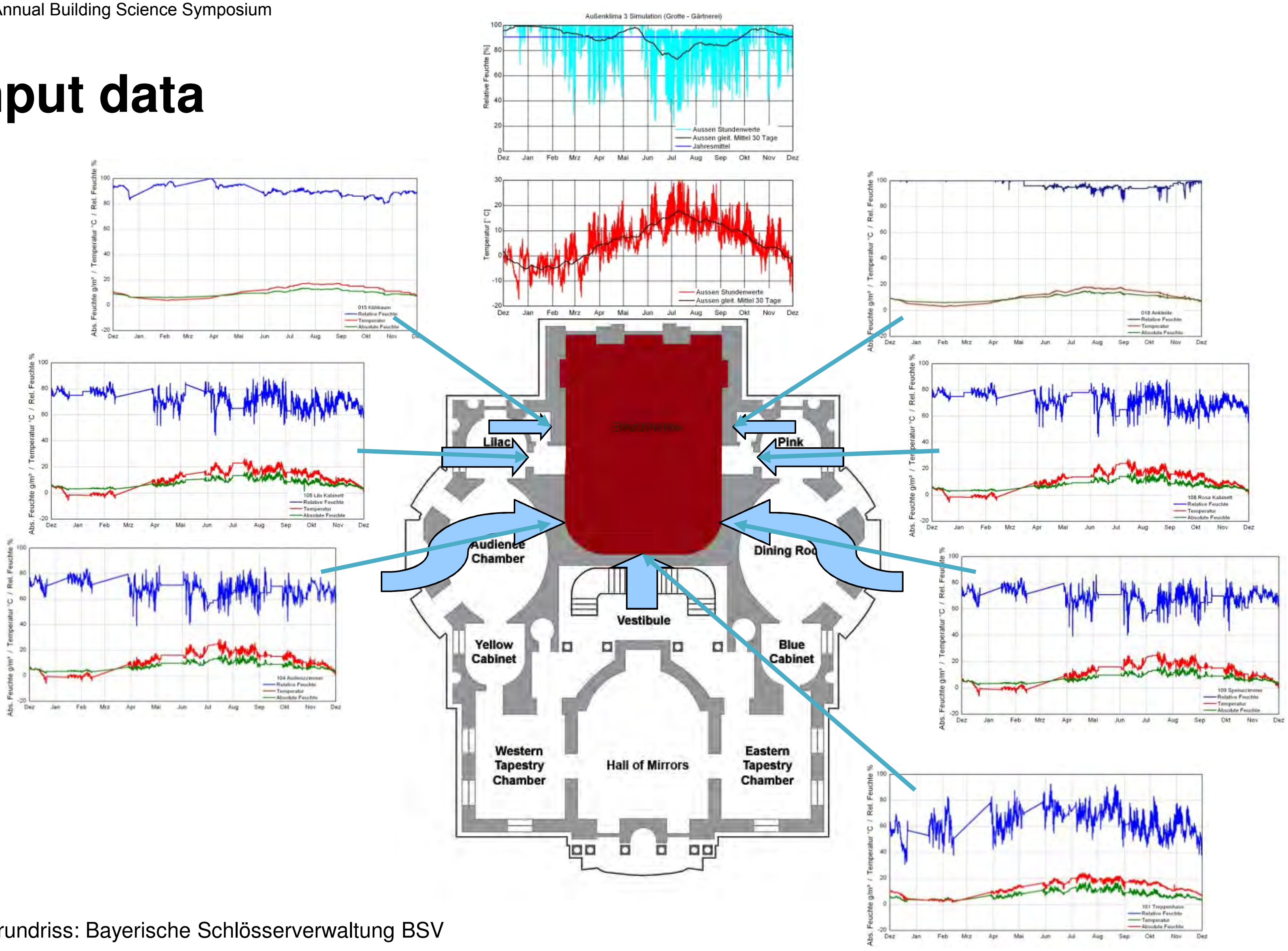
Rear view Linderhof Palace

Hygrothermal simulation of the bedchamber



Hygrothermal simulation of the room climate of the bedchamber

Input data

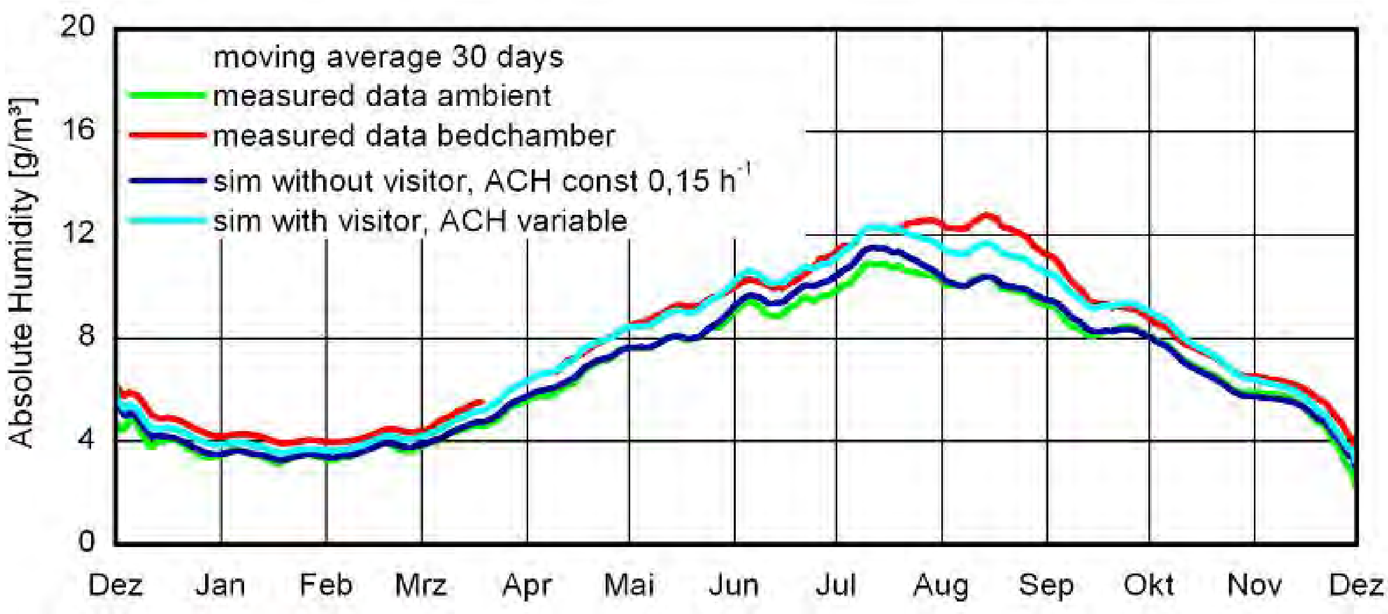


© Grundriss: Bayerische Schlösserverwaltung BSV

Parade Bedchamber and adjacant climates
01.12.2009 bis 01.12.2010

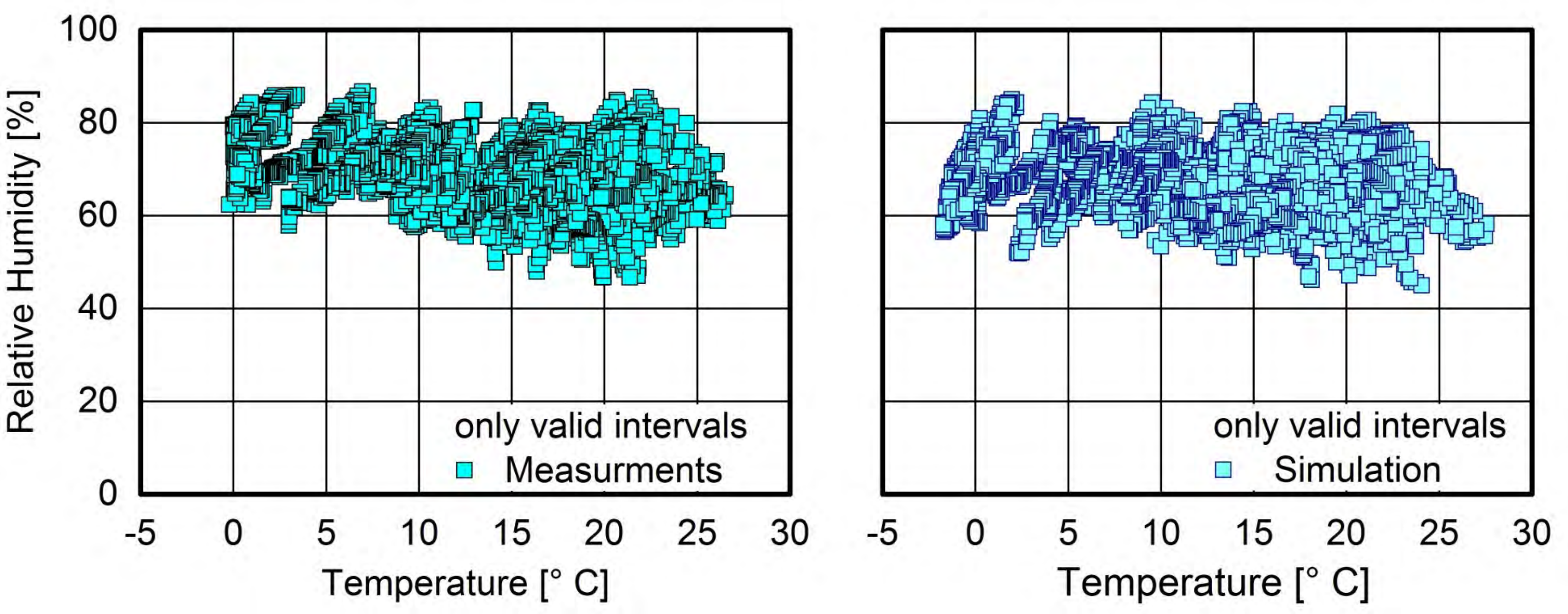
Comparison simulation vs. measurements

Scenario with / without Visitors

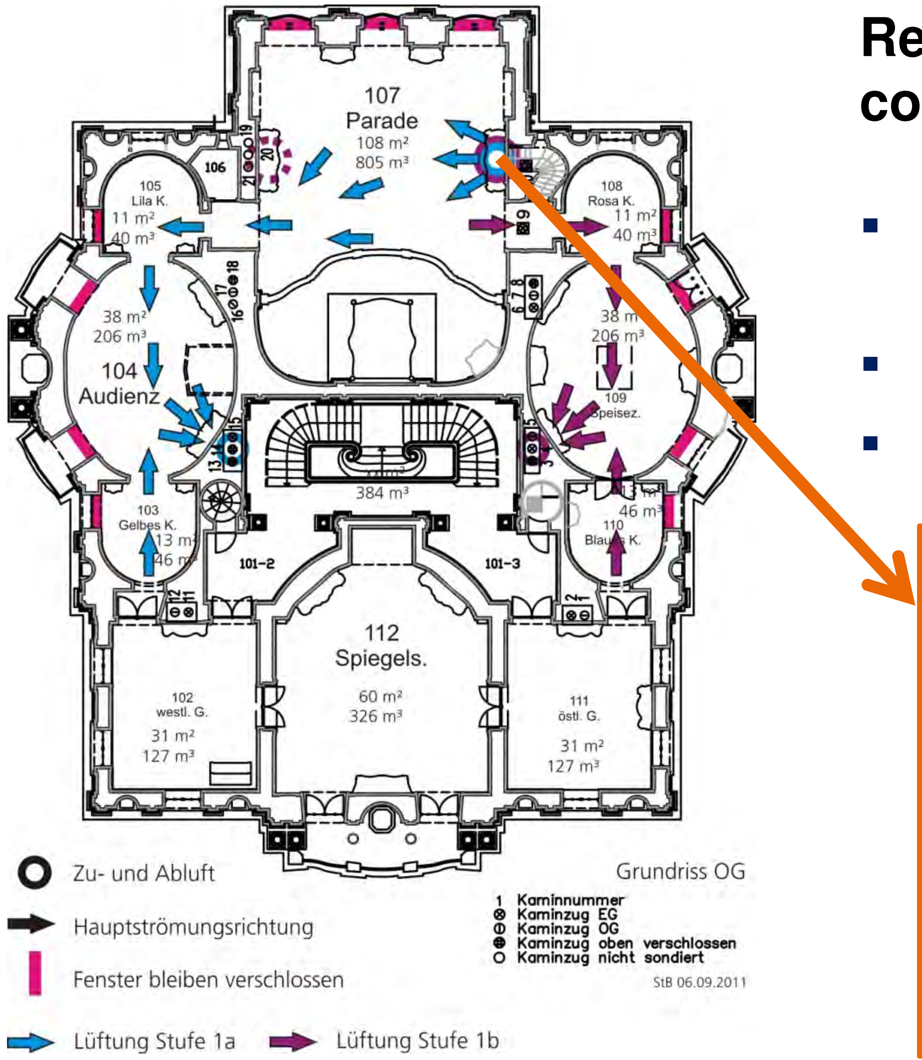


Scenario of absolute humidity with vistiors and without visitors, period from 12/2009 to 12/2010.

Comparison measurements vs. simulation



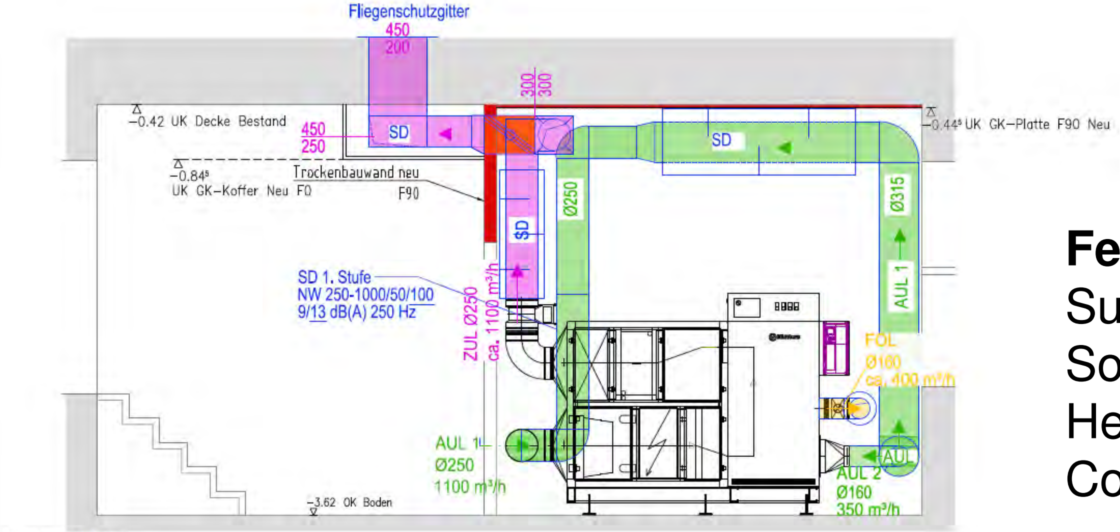
Climate concept – Stage 1a and 1b



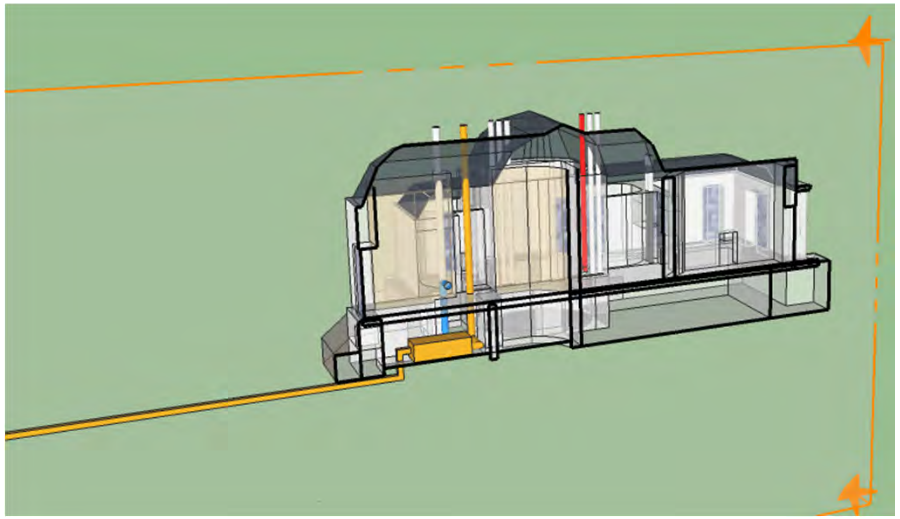
Reasons for a new climate control concept at Linderhof

- Mean RH above 70 % (Parade Bedroom, north side)
- Large short term fluctuation of RH
- Degradation problems visible

Climate control unit



ANSICHT A-A 1:25



Features of HVAC-system:
Supply air 1200 m³/h
Sorption dehumidification
Heating (frost-free)
Cooling (sorption enthalpy)

Earth tunnel
→ pre-cooling
→ pre-heating
→ dehumidification ?

Climate control unit

Neuschwanstein Castle

5000 Visitors and more per day

Fraunhofer IBP

Neuschwanstein Castle, Throne Hall

Climate for Culture

Fraunhofer IBP

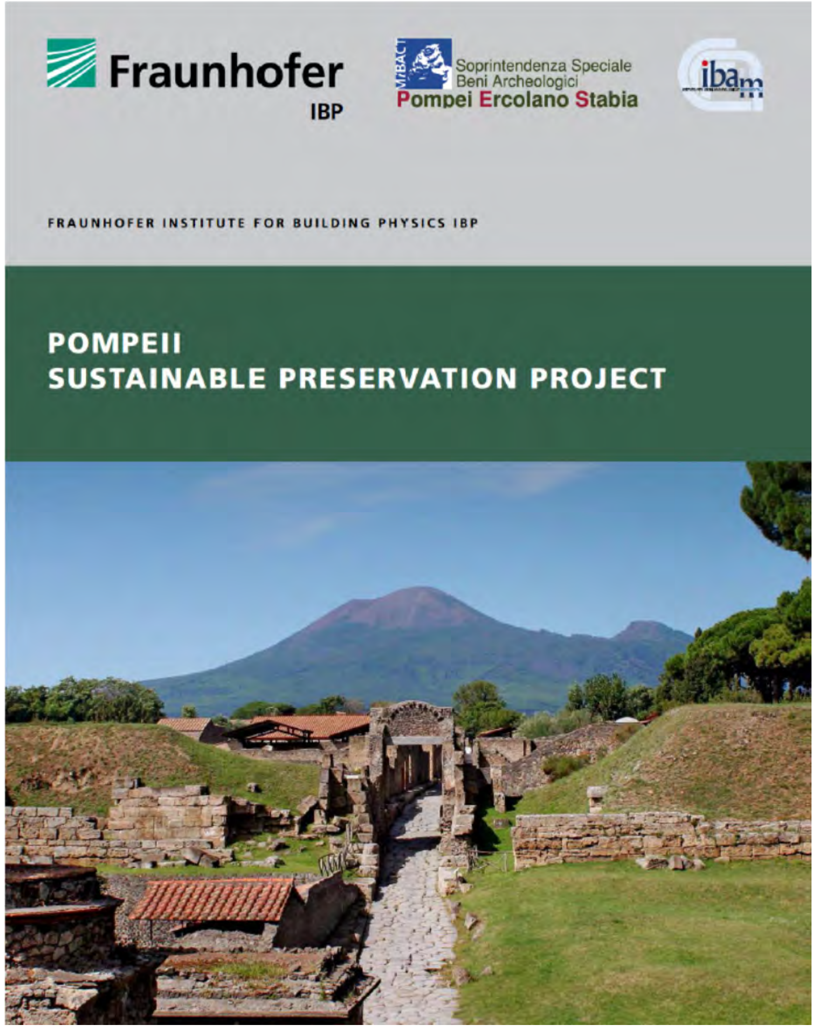
45

Fraunhofer IBP

Challenge: installing and removing sensors on precious interior finishes

Reversible glue: Cyclododecane (evaporates after sensor removal)

New preservation project: Pompeii



www.pompeii-sustainable-preservation-project.org/