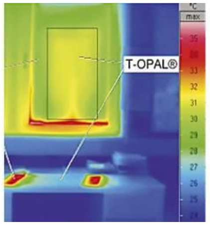
Implementation and validation of a long-wave heat exchange model

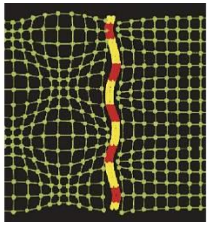
Matthias Winkler, Florian Antretter and Jan Radon

Buildings XIII – Clearwater Beach, FL – 2016-12-08

Building on knowledge



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Agenda

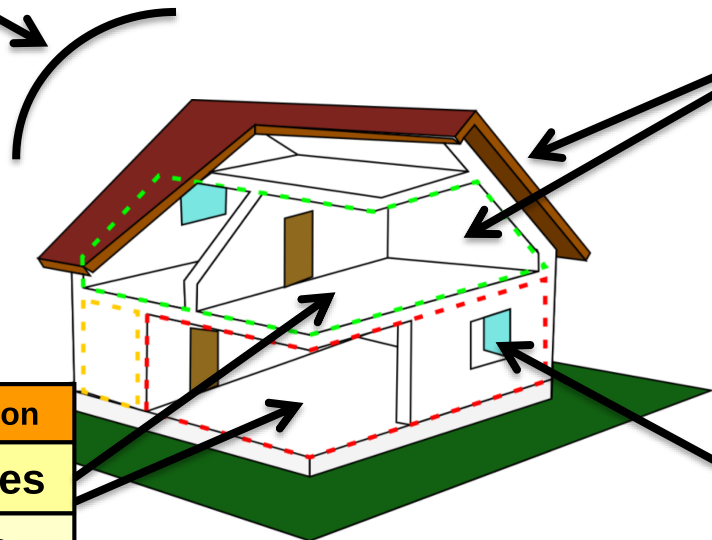
- Current Approach in WUFI® Plus
- Inner Longwave Heat Exchange Model
- Validation
- Application
- Outlook
- Conclusion

Hygrothermal Building Simulation with WUFI® Plus

Boundary condition

Outdoor climate

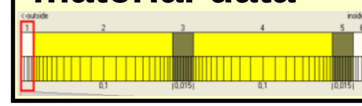
- temperature
- humidity
- radiation
- rain
- wind



Building envelope

Opaque

- layer definition
- material data



Boundary condition

Indoor climates

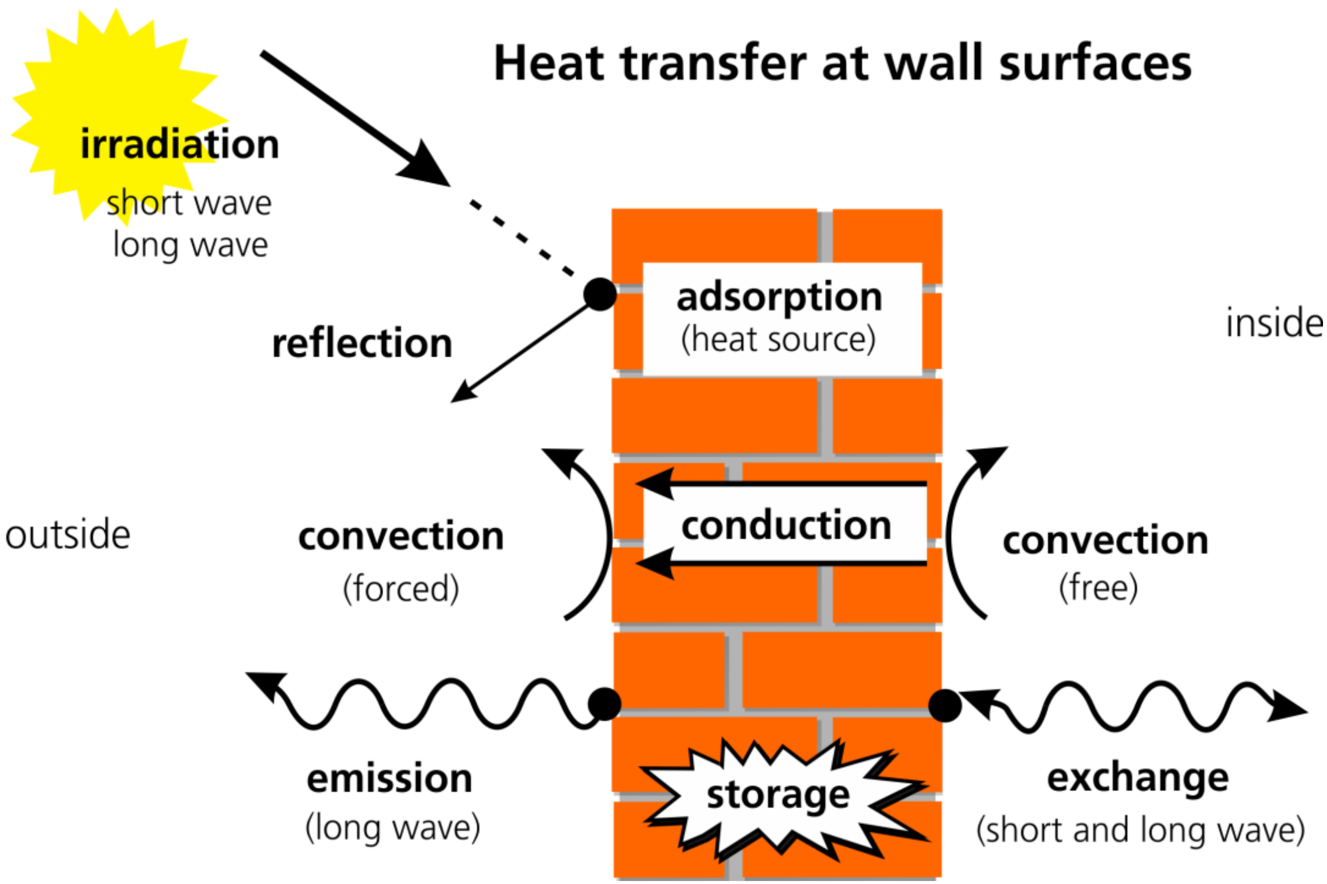
- internal sources
- ventilation
- set-points
- HVAC system

Building envelope

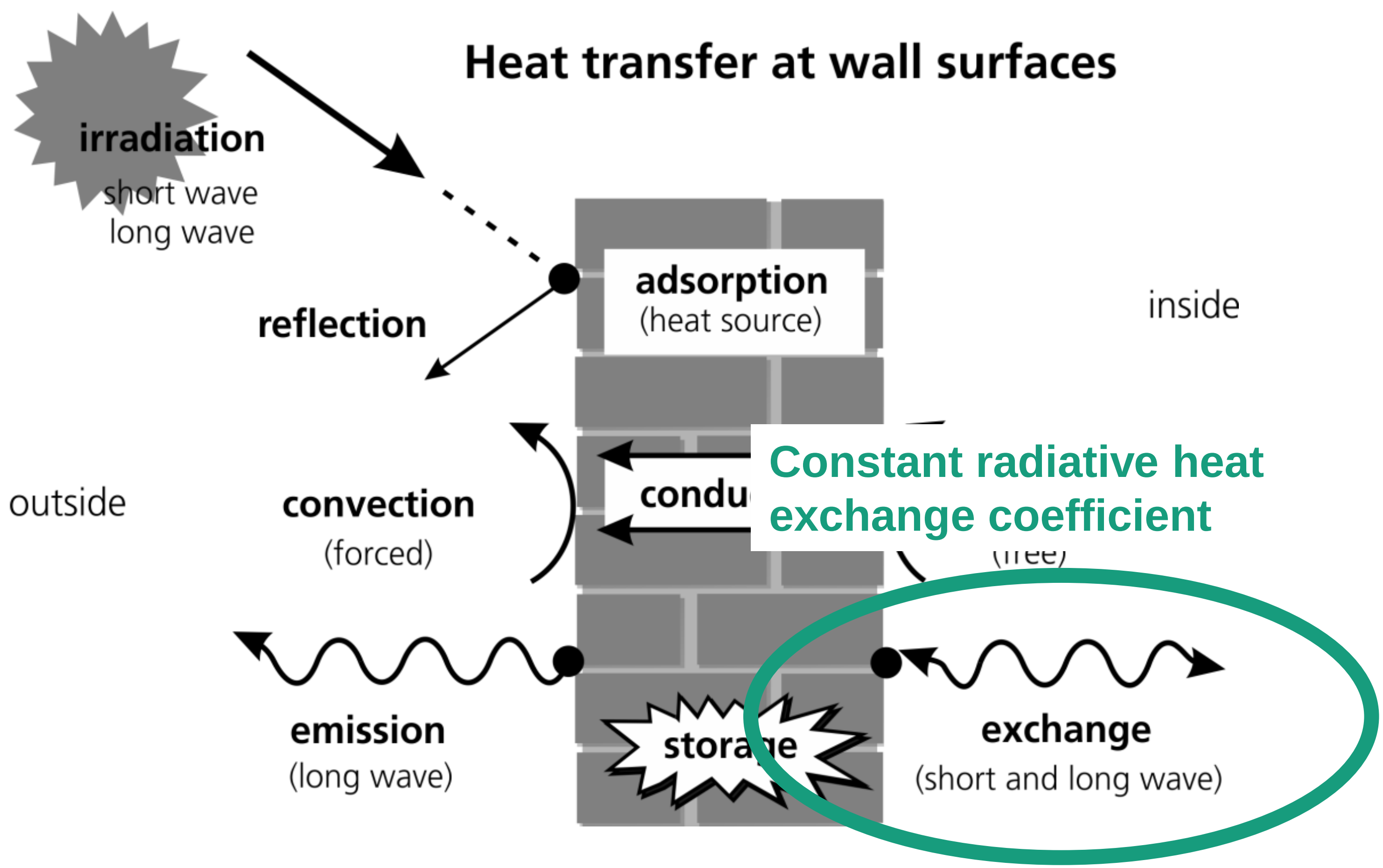
Transparent

- characteristics

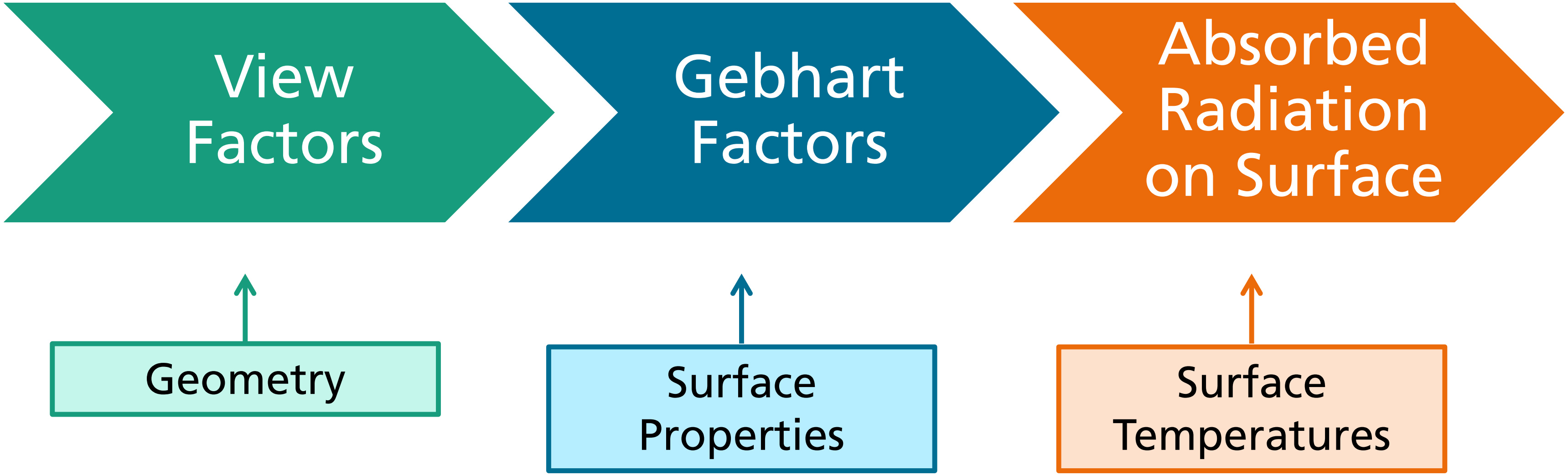
Hygrothermal Building Simulation with WUFI® Plus



Hygrothermal Building Simulation with WUFI® Plus



Calculation Method

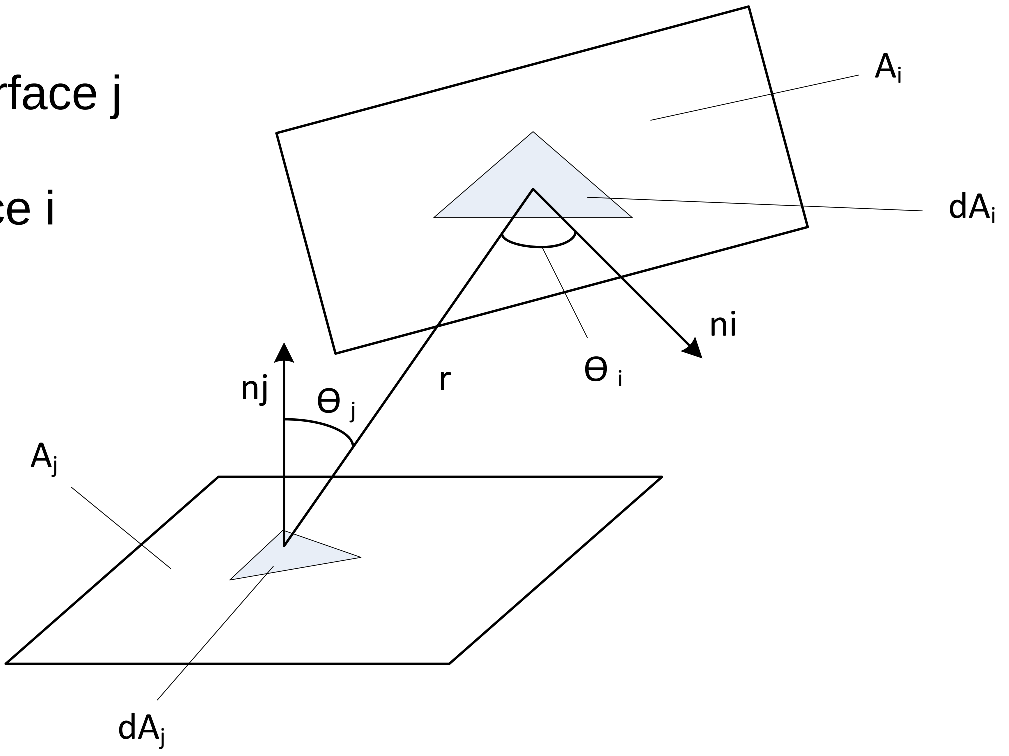


Calculation Method: View Factor

$$F_{ij} = \frac{1}{A_i} \iint_{A_i A_j} \frac{\cos\theta_i \cdot \cos\theta_j}{\pi \cdot r^2} \cdot dA_i \cdot dA_j$$

- View Factor Definition:
  - Fraction of rays
    emitted from surface i
    with direct incidence on surface j
    to
    all rays emitted from surface i

- Geometric relationship
  - Solved before
    energetic calculations



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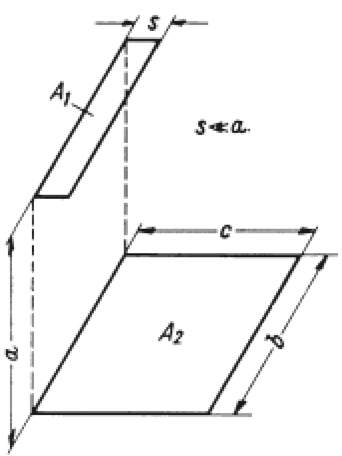
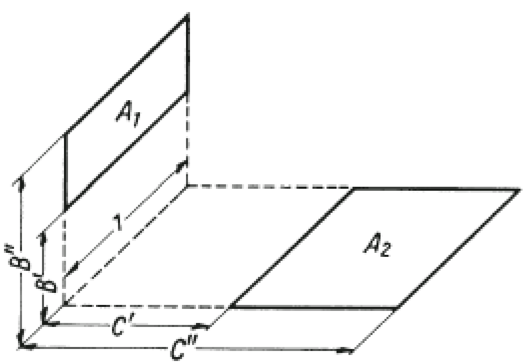
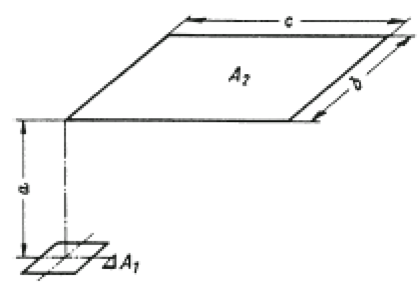
Calculation Method: View Factor

Analytical solutions available, but

- limited number of shapes & positions
- Complicated / impossible analytical solutions for
  - more complex geometries
  - overshadowing





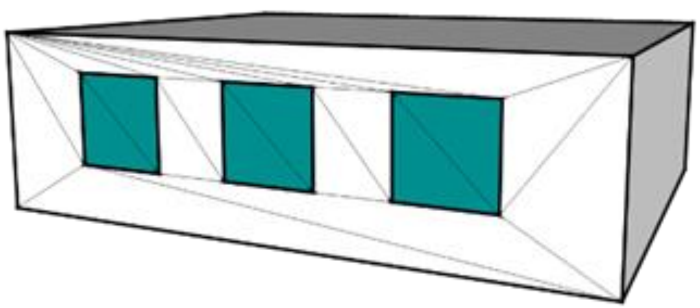


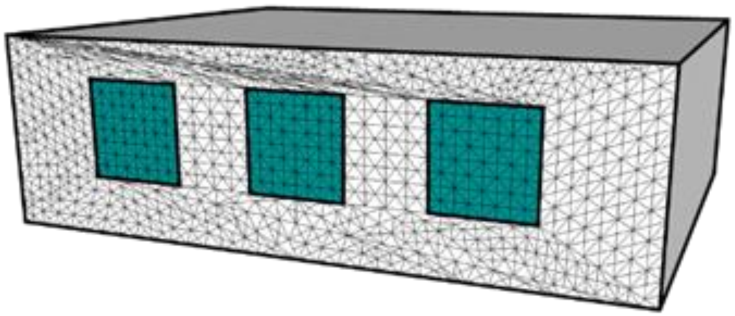
Images: VDI Wärmeatlas

Calculation Method: View Factor

→ Solution: Triangulation

- Each surface divided into small triangles
- Calculation accuracy depends on triangle size
- All visualized components included





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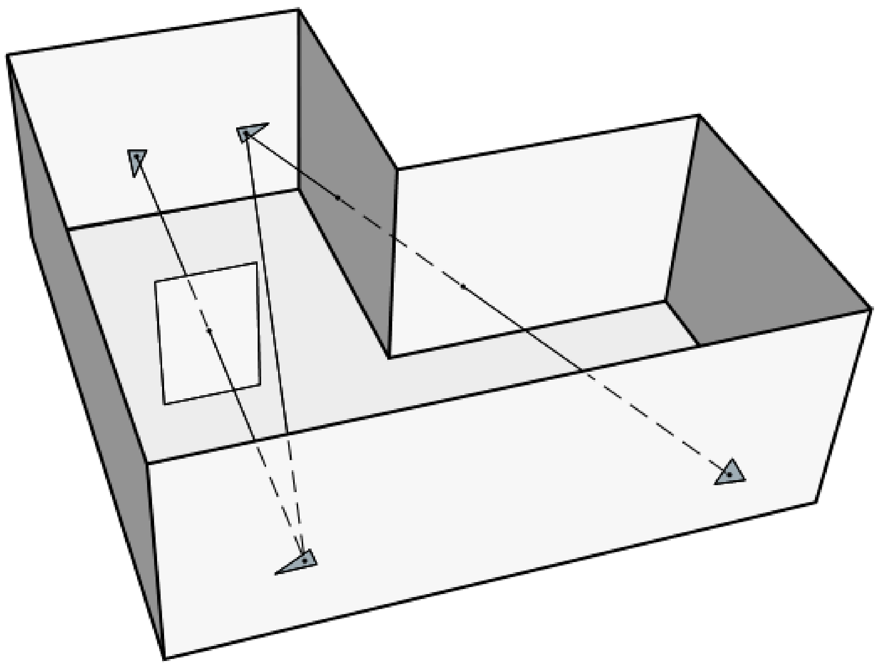
Calculation Method: View Factor

- Connecting lines for every pair of triangles
- Vector analysis to check possible crossings

→ Overshadowing from every visualized geometry



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Calculation Method: View Factor

- View Factor as fraction of connected triangles

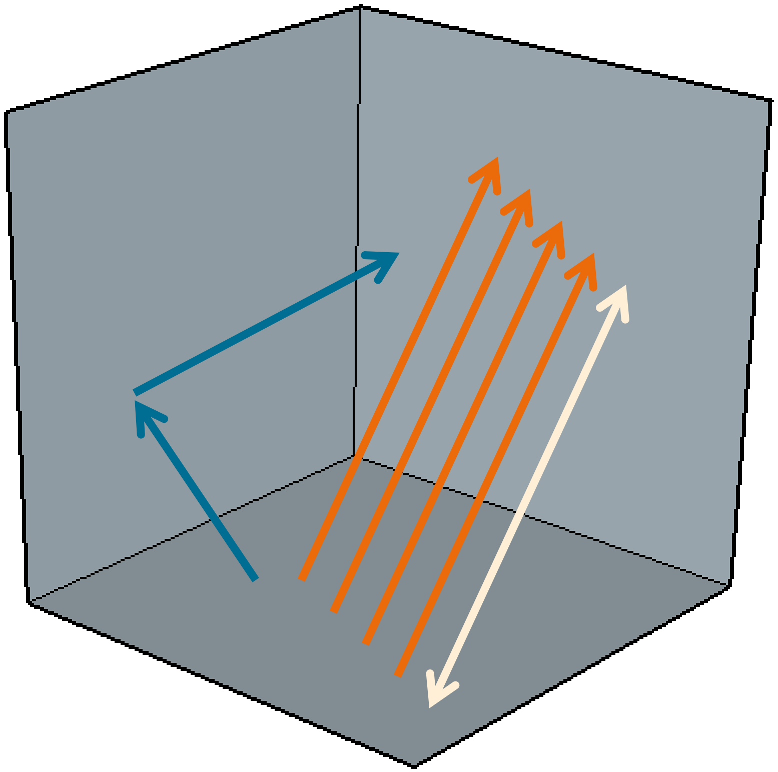
$$F_{ij} = \frac{1}{A_i} \cdot \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{\cos\theta_i \cdot \cos\theta_j}{\pi \cdot r^2} \cdot dA_i \cdot dA_j$$

- Area weighting:
  - Sum of view factors for each surface must be 1.00
  - No exact numerical solution
  - → Area-weighted distribution of remaining difference between numerical and exact solution

Calculation Method: Gebhart Factor

- Gebhart Factor
  - Fraction of energy emitted from one surface that is absorbed at another surface
  - Considers all radiation paths, including multiple and own reflections
- Calculated from the View Factor
- Includes reflectivity and emissivity of all surfaces

$$G = (1 - F \cdot \rho)^{-1} \cdot F \cdot \varepsilon$$



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Calculation Method: Longwave Radiation

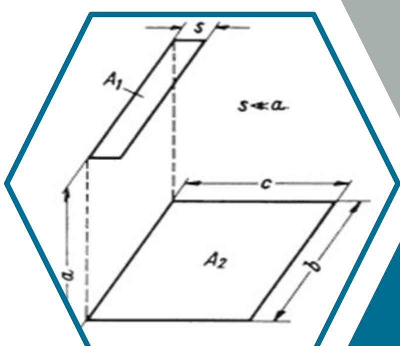
- Longwave Radiation absorbed on an interior surface:

$$I_{l,i} = \varepsilon_i \cdot \sum_{j=1}^{N} G_{ij} \cdot \sigma \cdot \left({T_i}^4 - {T_j}^4\right)$$

  - Emissivity
  - Gebhart-Factor
  - Stefan-Boltzmann constant
  - Temperatures of interior surfaces

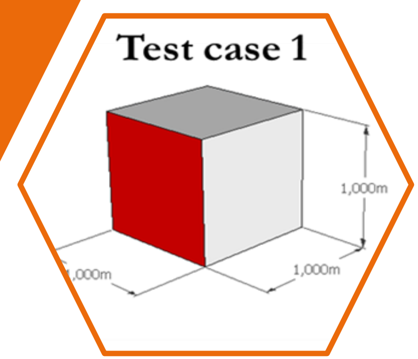
Validation

Measurments



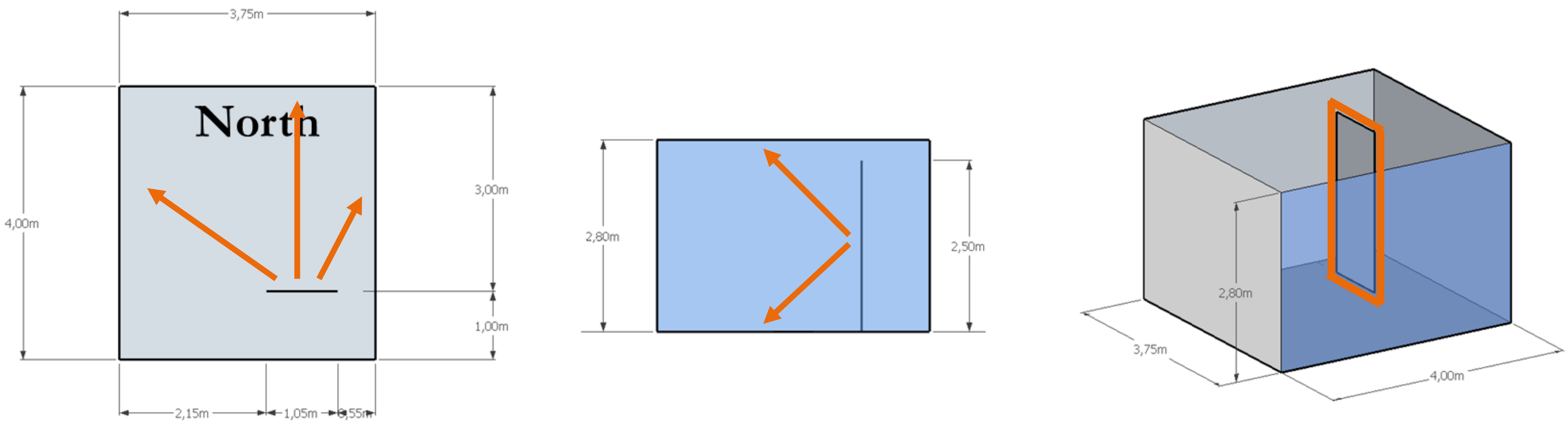
Standardized Tests

Comparative Calculations



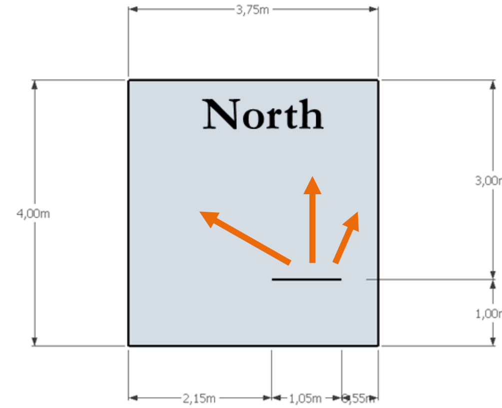
Validation: View Factors (Exemplary Room)

- Rectangular room with interior wall
  - Analytical solution (Howell, 2015)
  - WUFI® Plus calculation:
    - Accuracy levels = density of triangulation network



(a) Footprint (b) Section (c) Projection

Validation: Exemplary Room



	Analytical	WUFI® Plus		
		Low accuracy	Medium accuracy	Very high accuracy
$F_{1,ceiling}$	0,2104	0,2172 (+3.23 %)	0,2127 (+1.09 %)	0,2105 (+0.05 %)
$F_{1,wall\ west}$	0,0787	0,0795 (+1.02 %)	0,0788 (+0.13 %)	0,0786 (-0.13 %)
$F_{1,floor}$	0,2538	0,2619 (+3.19 %)	0,2618 (+3.15 %)	0,2549 (+0.43 %)
$F_{1,wall\ north}$	0,2308	0,2324 (+0.69 %)	0,2312 (+0.17 %)	0,2308 (±0.00 %)
$F_{1,wall\ east}$	0,2262	0,2353 (+4.02 %)	0,2285 (+1.02 %)	0,2264 (+0.09 %)
Sum	**0,9999**	**1,0263** (+2.64 %)	**1,0129** (+1.30 %)	**1,0012** (+0.13 %)

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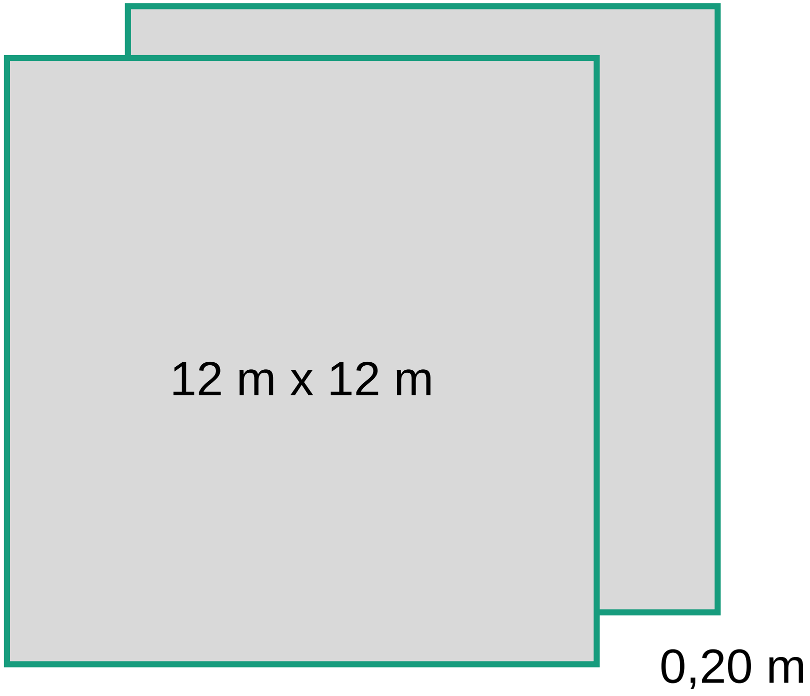
Validation: Longwave radiation two parallel plates

- Analytic solution available
  - Includes emission,
    reflection & absorption
  - Neglects side-exchanges

$$q_{1,2} = \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \cdot \sigma \cdot \left({T_1}^4 - {T_2}^4\right)$$



- Variations in boundary conditions:
  - Surface temperatures
  - Surface emissivity's

Validation: Longwave radiation two parallel plates

		Test 1	Test 2	Test 3	Test 4
Surface Temperature 1	°C	50.00	50.00	30.00	30.00
Surface Temperature 2	°C	10.00	10.00	20.00	20.00
Emissivity surface 1	-	0.90	0.90	0.90	0.90
Emissivity surface 2	-	0.90	0.10	0.90	0.10
Longw. Heat Exchange: Analytical	W/m²	207.69	25.11	49.19	5.95
Longw. Heat Exchange: WUFI® Plus	W/m²	208.29	25.11	49.34	5.95
Deviation	**%**	**+ 0.29 %**	**+ 0.04 %**	**+ 0.30 %**	**+ 0.03 %**

Validation: DIN EN ISO 13791

- DIN EN ISO 13791
  - Validation procedures for thermal building simulation software
  - Includes test cases for inner longwave heat exchange

- Test cases
  - 4 room-geometries with only opaque surfaces
  - Fixed boundary conditions
  - Validation criteria: Interior temperature

Validation: DIN EN ISO 13791

Exterior Wall

Te = 30 °C

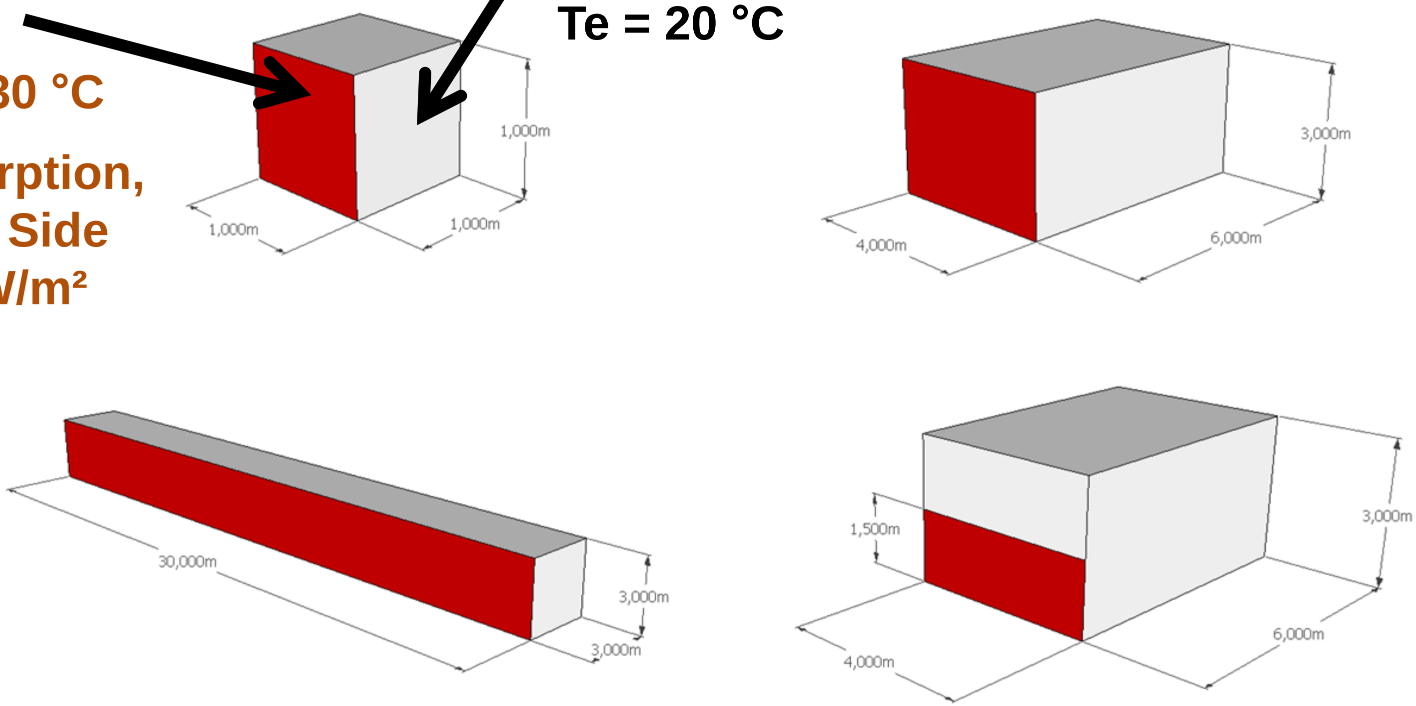
Absorption, Inner Side 100 W/m²

Partition Walls

Te = 20 °C

Test case 1

Test case 2



Test case 3

Test case 4

Validation: DIN EN ISO 13791

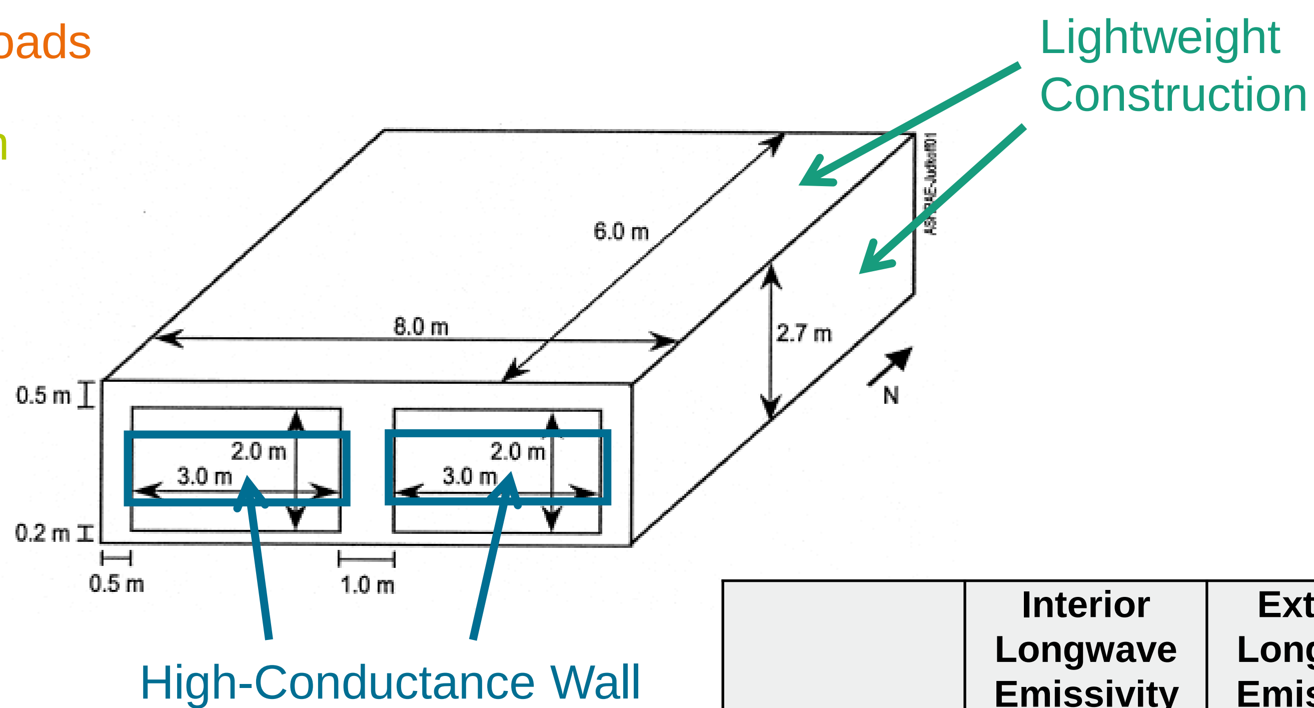
		Test 1	Test 2	Test 3	Test 4
DIN EN 13791	°C	34.4	30.4	38.5	25.5
WUFI® Plus	°C	34.3	30.1	38.3	25.0
Deviation	**K**	**0.1** ✓	**0.3** ✓	**0.2** ✓	**0.5** ✓

- Validation criteria:
  - Maximum allowed deviation: 0.5 K
  - Validation according to DIN EN 13791 successful

Validation: ASHRAE 140 - Class I Test Procedures

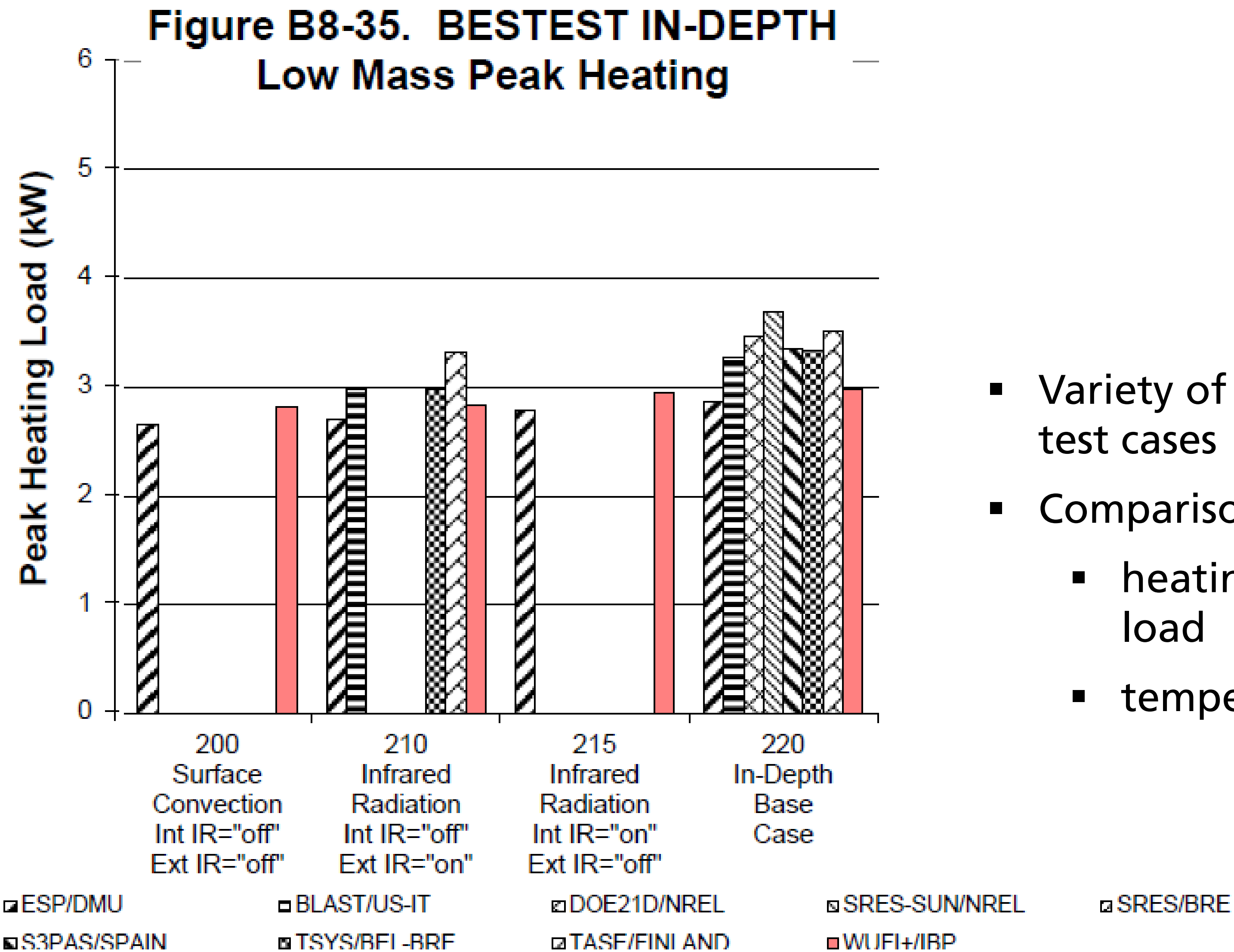
No Internal Loads

No Ventilation



	Interior Longwave Emissivity	Exterior Longwave Emissivity
Case 220	0.9	0.9
Case 215	0.9	0.1
Case 210	0.1	0.9
Case 200	0.1	0.1

Validation: ASHRAE 140 (Example Results)



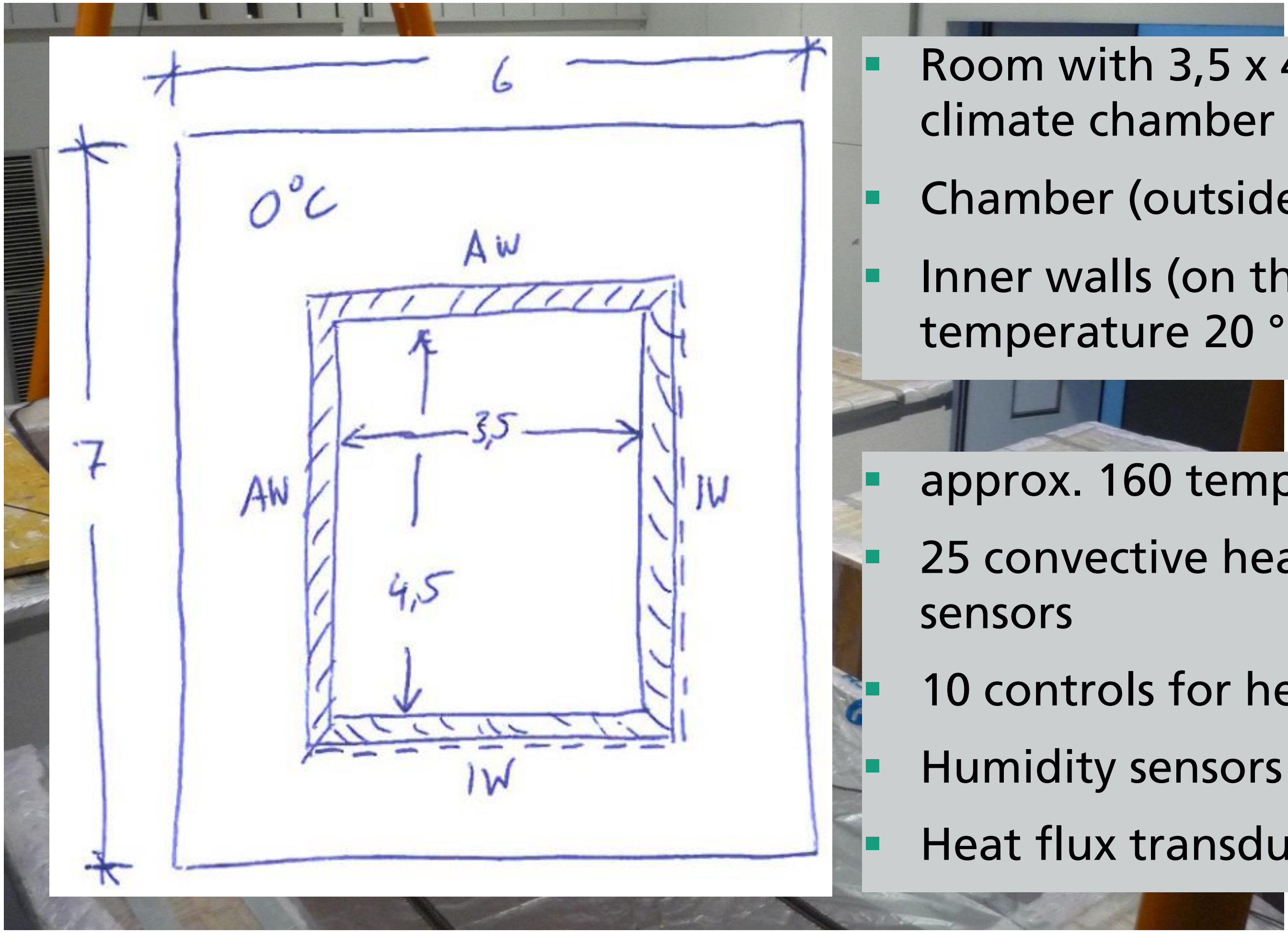
- Variety of different test cases
- Comparison values for
  - heating/cooling load
  - temperature

Validation and Application Experiment

- Impact of interior thermal insulation and intermittent heating on
  - Interior climate conditions
  - Energy savings
  - Comfort
- Varying interior insulation systems and types
- Comparison of heating systems
- Influence of interior surface coatings

- Methods:
  - Measurements
  - Building and component simulation

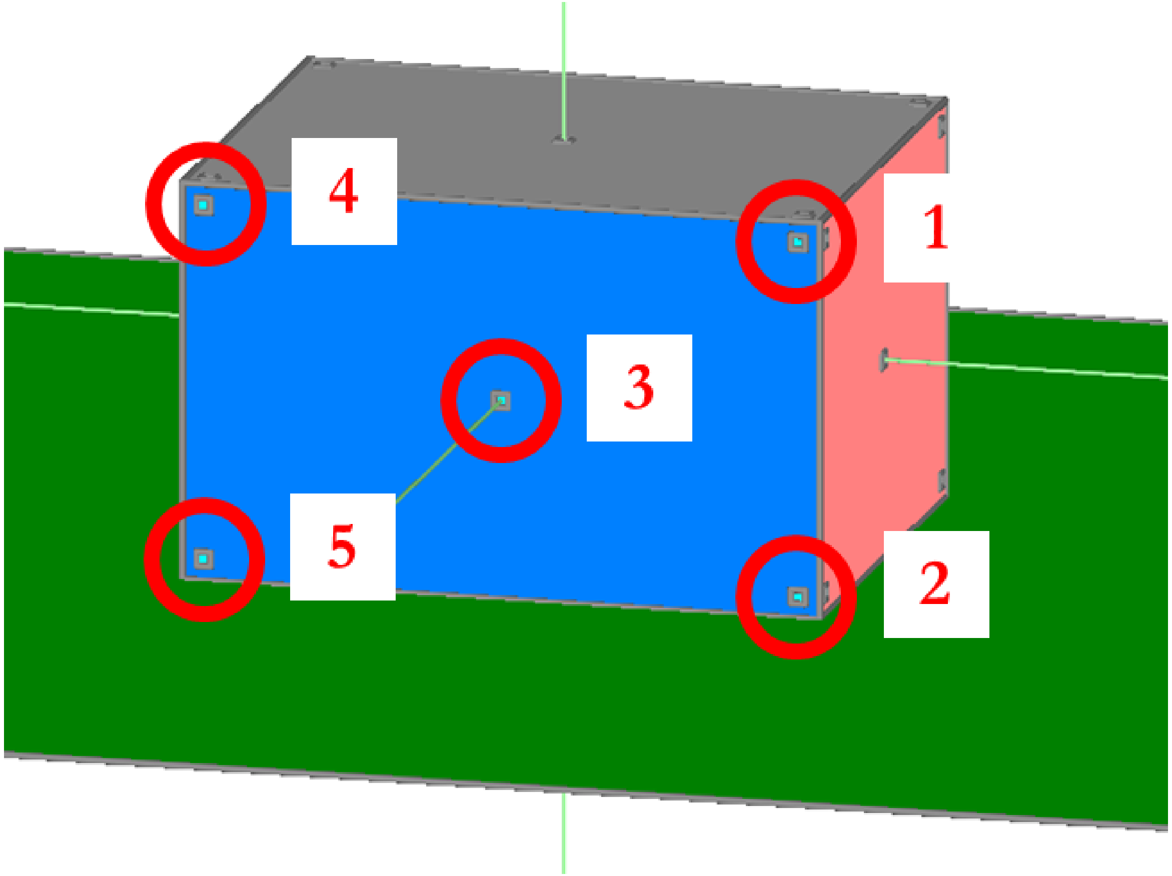
Validation and Application Experiment



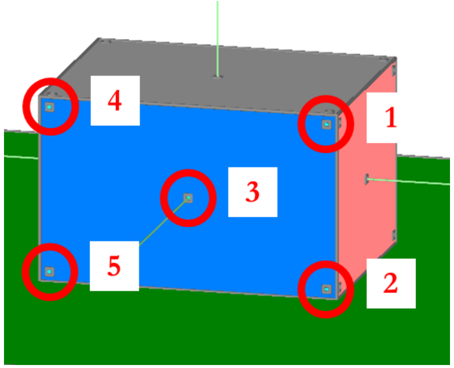
- Room with 3,5 x 4,5 m in big climate chamber
- Chamber (outside) temperature
- Inner walls (on the outside) temperature 20 °C

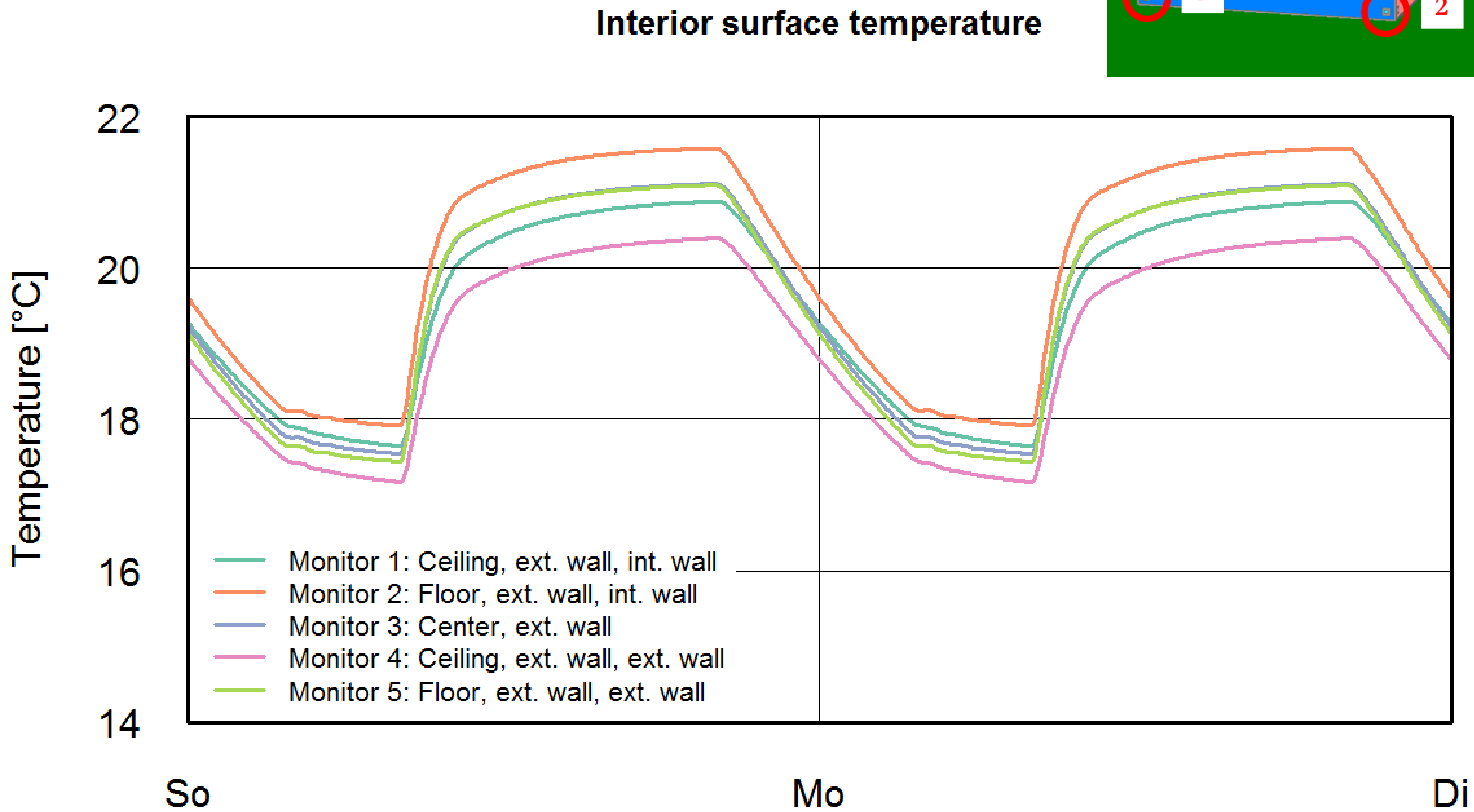
- approx. 160 temperature sensors
- 25 convective heat transfer sensors
- 10 controls for heating surfaces
- Humidity sensors
- Heat flux transducers

Validation and Application Experiment

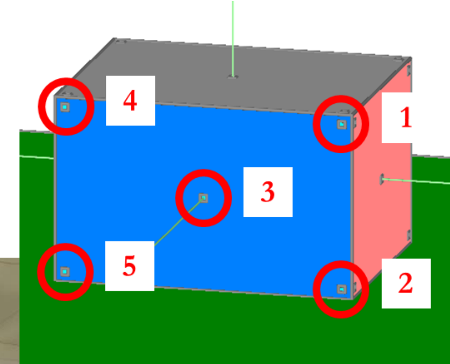


Validation Experiment – Expected Range





Experiment Instrumentation



Experiment Instrumentation

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Application Experiments - Goals

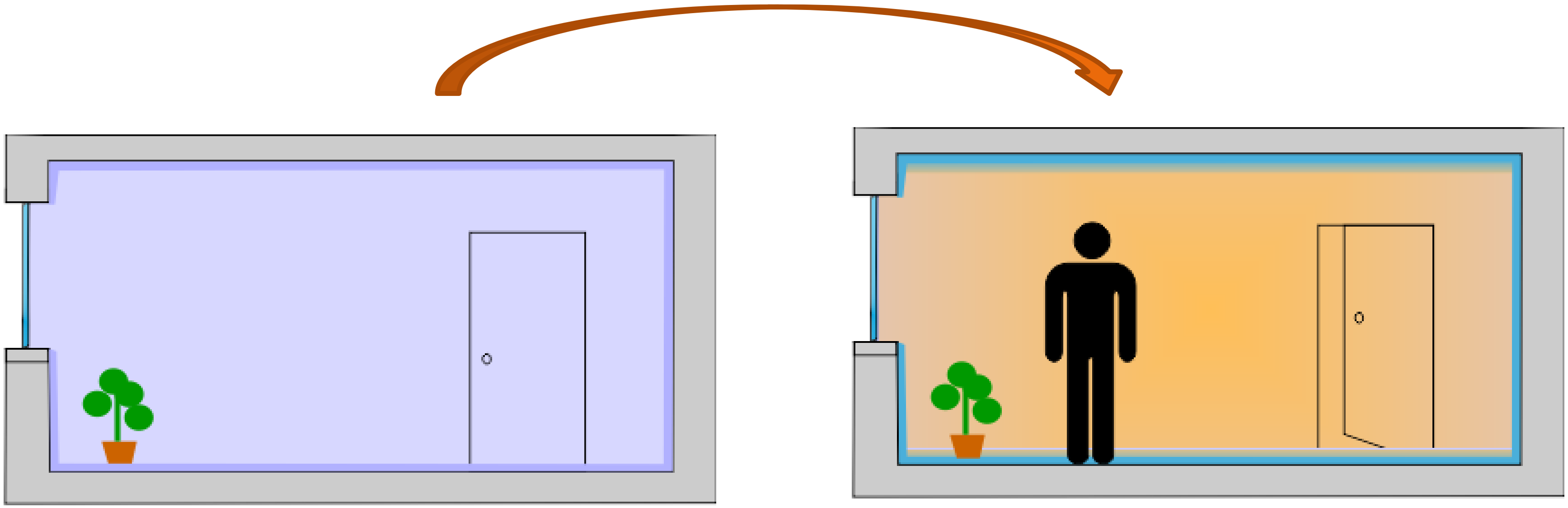
Development of efficient strategies for intermittent building use, e.g.:

- Quick reacting panel heating systems
- Insulation of massive components (also interior)
- Coatings for inner surfaces (e.g. low-e)

→ Assess options with experiment und simulation

→ Take restraints (e.g. humidity, comfort) into account

Current approach



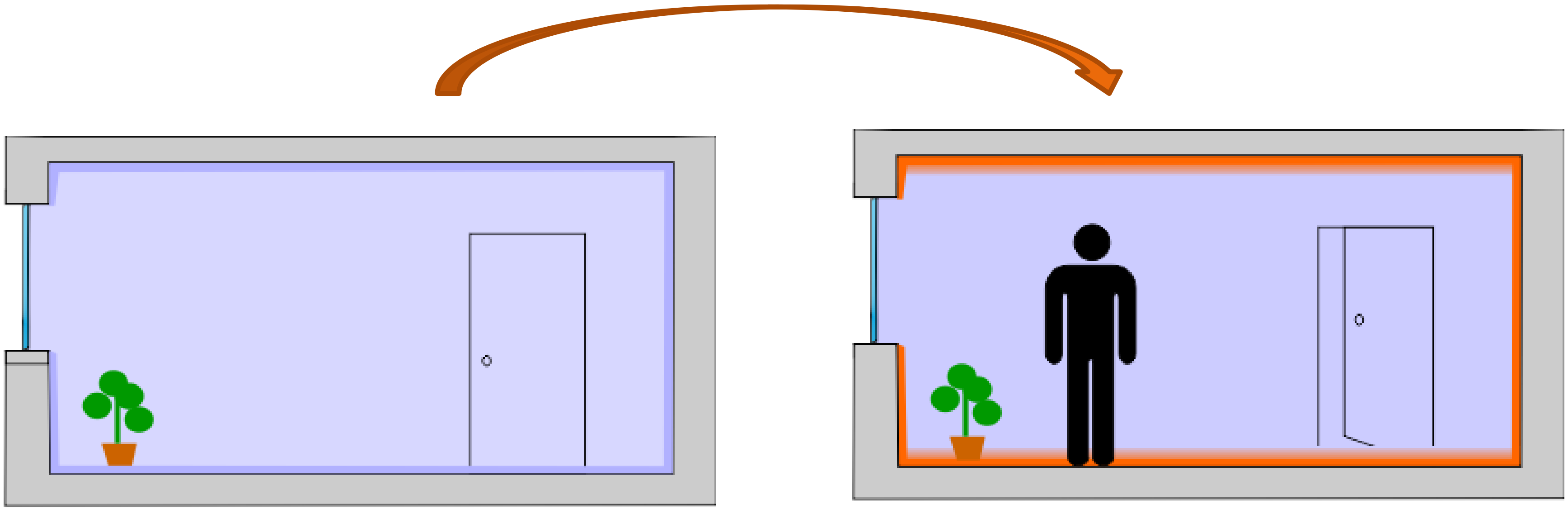
- Unconditioned space
- Cold/Warm Air and Surfaces

- 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

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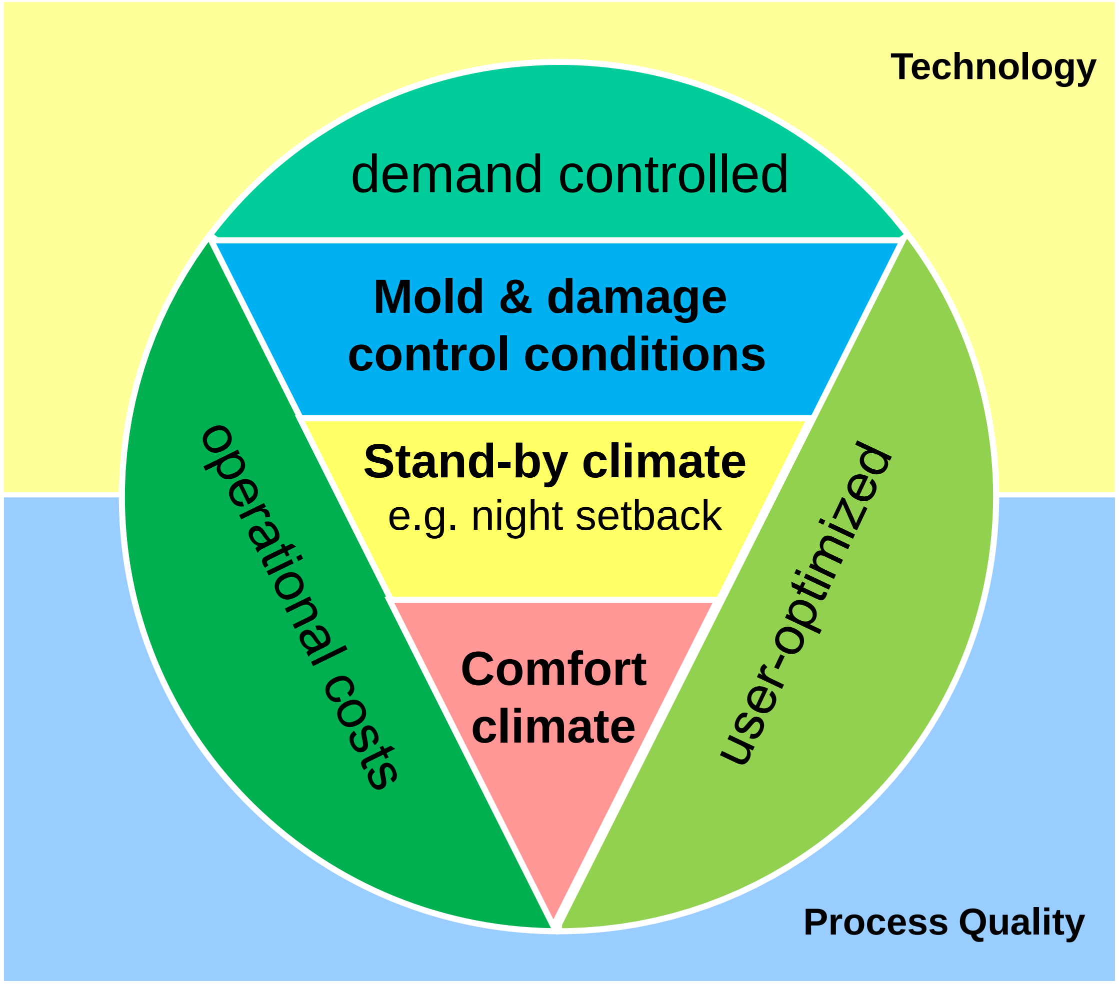
Where do we want to get?



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Summary and Conclusion

- Model for interior longwave heat exchange implemented in WUFI® Plus
- Model successfully validated:
  - Comparative calculations with analytical solutions
  - Validation tests from international standards (DIN, ASHRAE)
- Measurements will be used for further validations
- Validated model will be used for development of new and innovative demand responding space conditioning strategies

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Contact:

Florian Antretter

florian.antretter@ibp.fraunhofer.de

+49 8024 643-242

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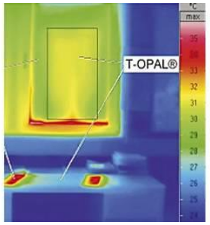



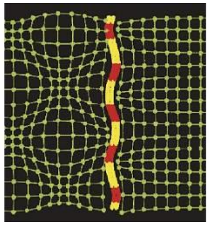


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