Building Performance Simulation

Introduction and some Fundamentals

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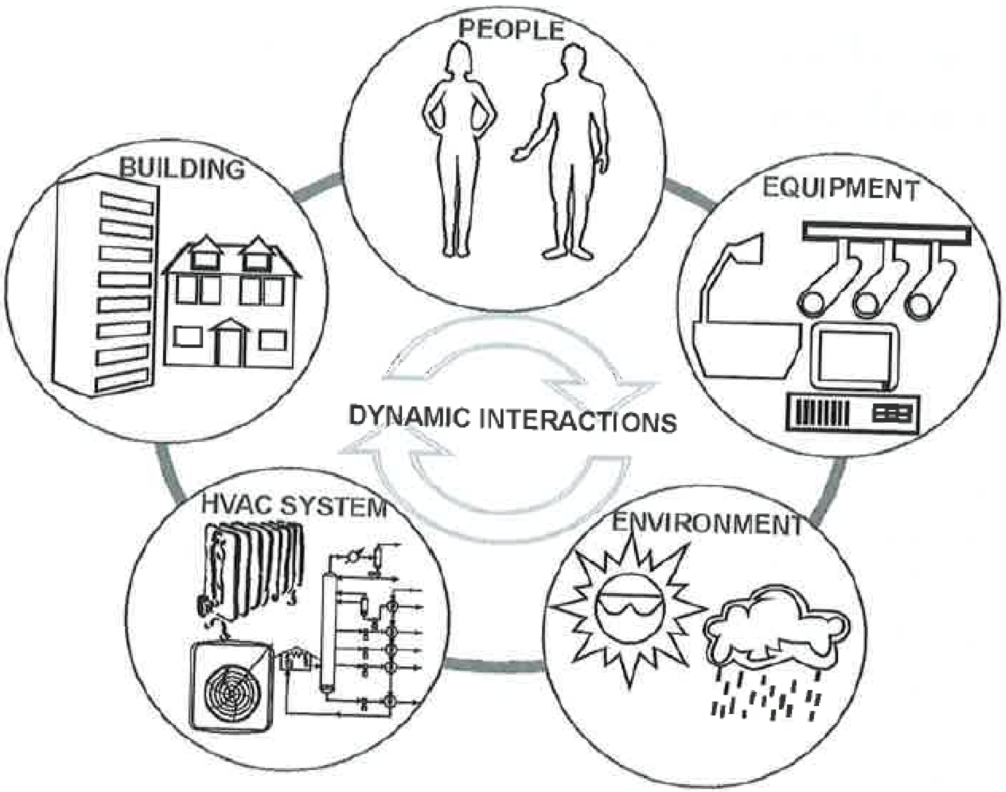
Dynamic interactions in Buildings



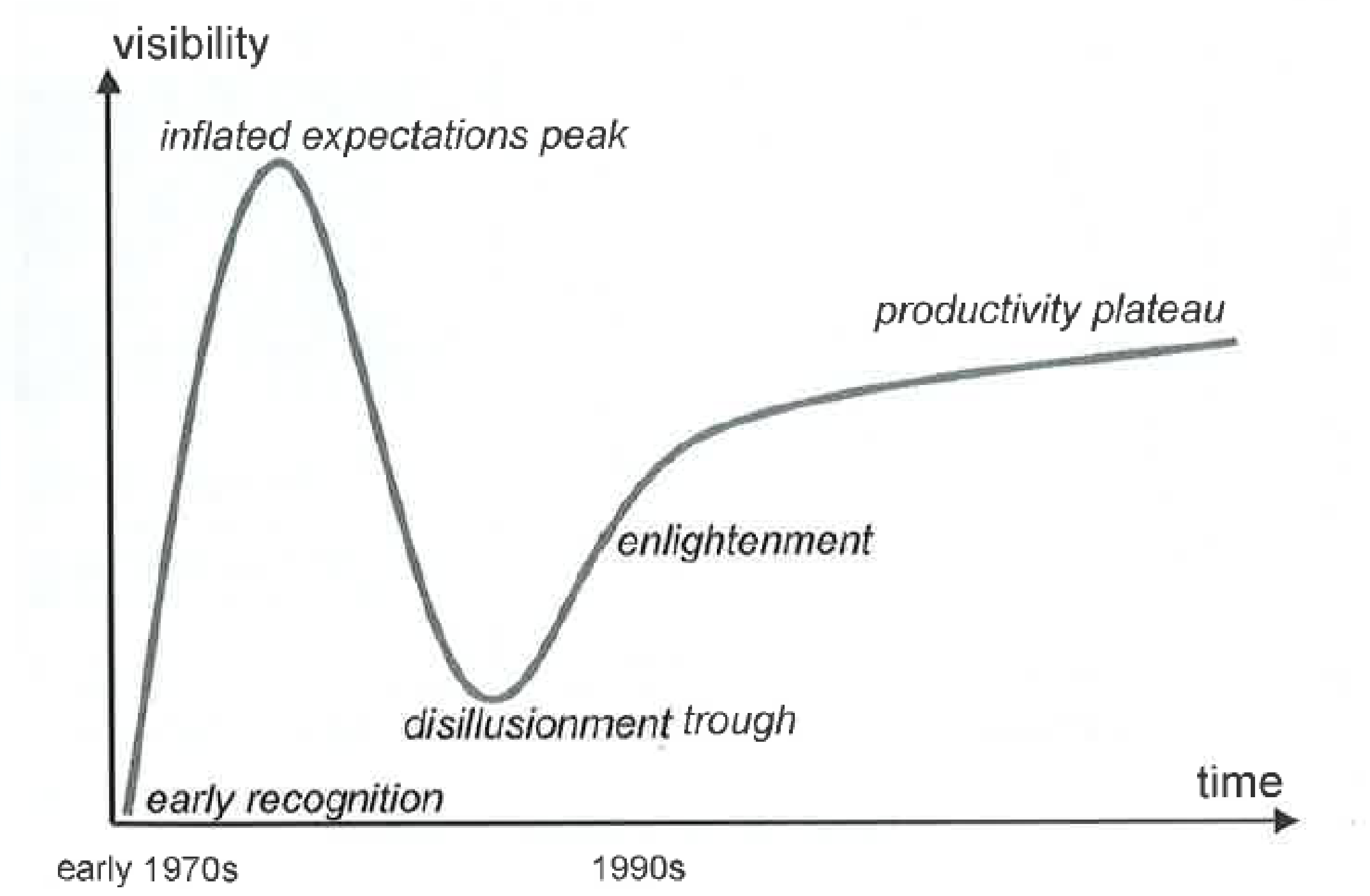
Source: Jan L. M. Hensen, Building Performane Simulation for design and operation

The behaviour of real buildings is defined by several aspects which dynamic interacts to each other:

- Building envelop
- HVAC System
- Equipment
- Occupancy
- Wheater Conditions

To built them up in a dynamic building simulation tool it's necessary to built them up in an integrated aproach of several subsystems.

Development of Building simulation



Source: Jan L. M. Hensen, Building Performane Simulation for design and operation

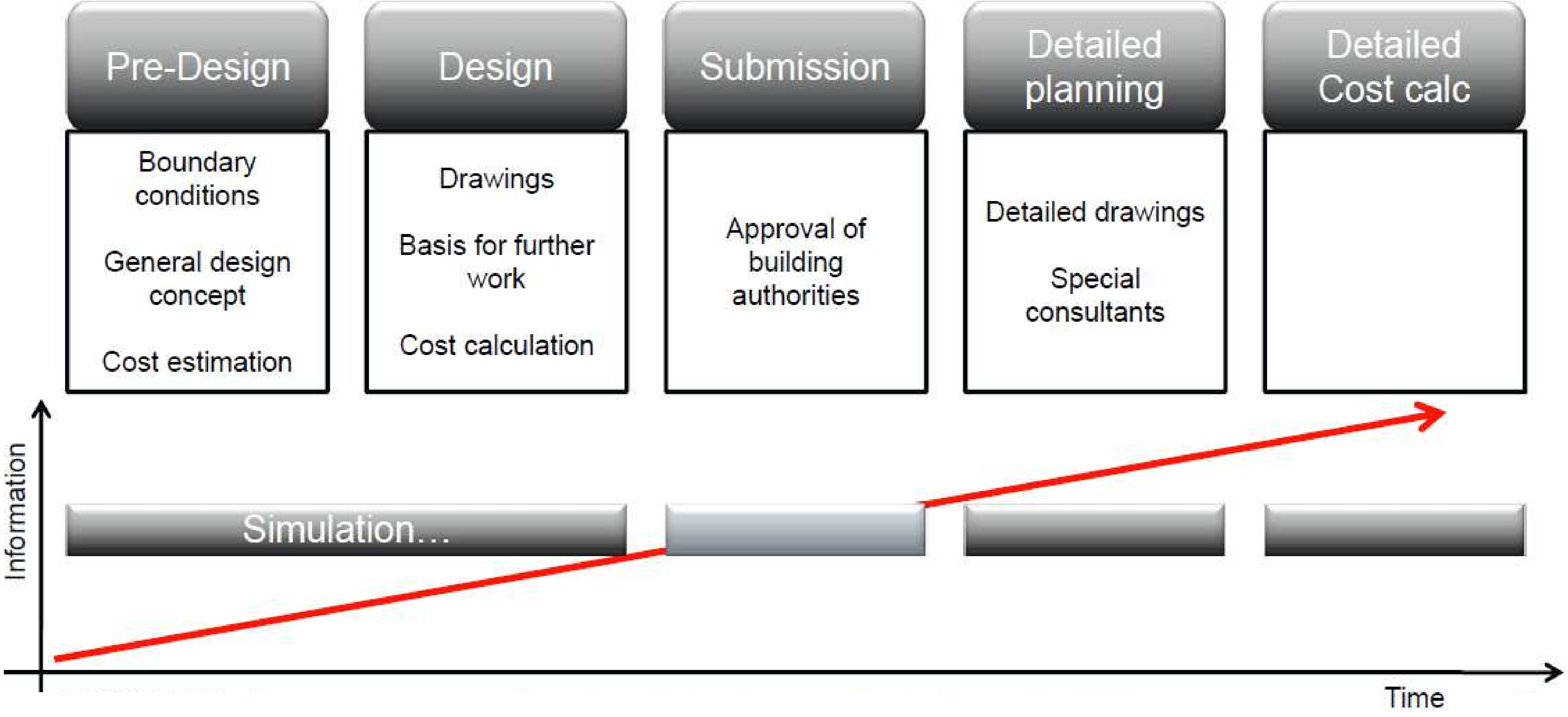
Benefits of using building simulation

- Innovative architectural designs and technologies can be:
  - Evaluated (performance, costs, comfort,…)
  - Optimized
  - Enabled

- Enables integral planning approach
- More reliable and transparent evaluation of saving potentials
- Over/ under sizing can be avoided
- Automated optimization
- Fault Failure Detection supported by simulation
- Advanced building management systems

→ **higher quality and reliability in the design and operation phase!**

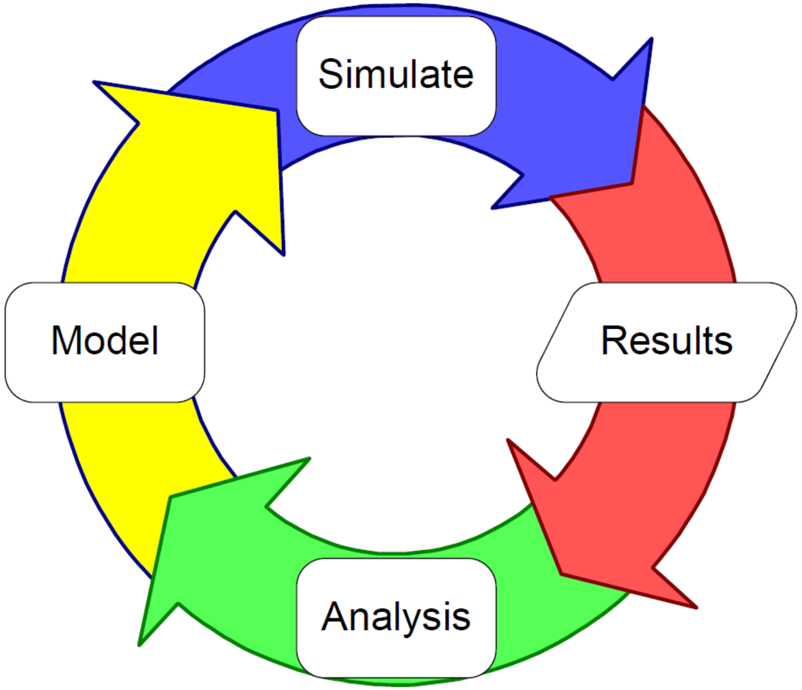
Building performance simulation in practise



Source: M. Brychta

Simulation as an iterative process

- The circle…



Source: M. Brychta

Modelling and Simulation

1) The source system…

is the real or virtual environment that is in interest of modeling – in the case of building simulation it’s the building and their environment

2) The experimental frame...

is a specification of the conditions under which the system is observed or experimented with – e.g. special wheather conditions, ventilation strategies,…

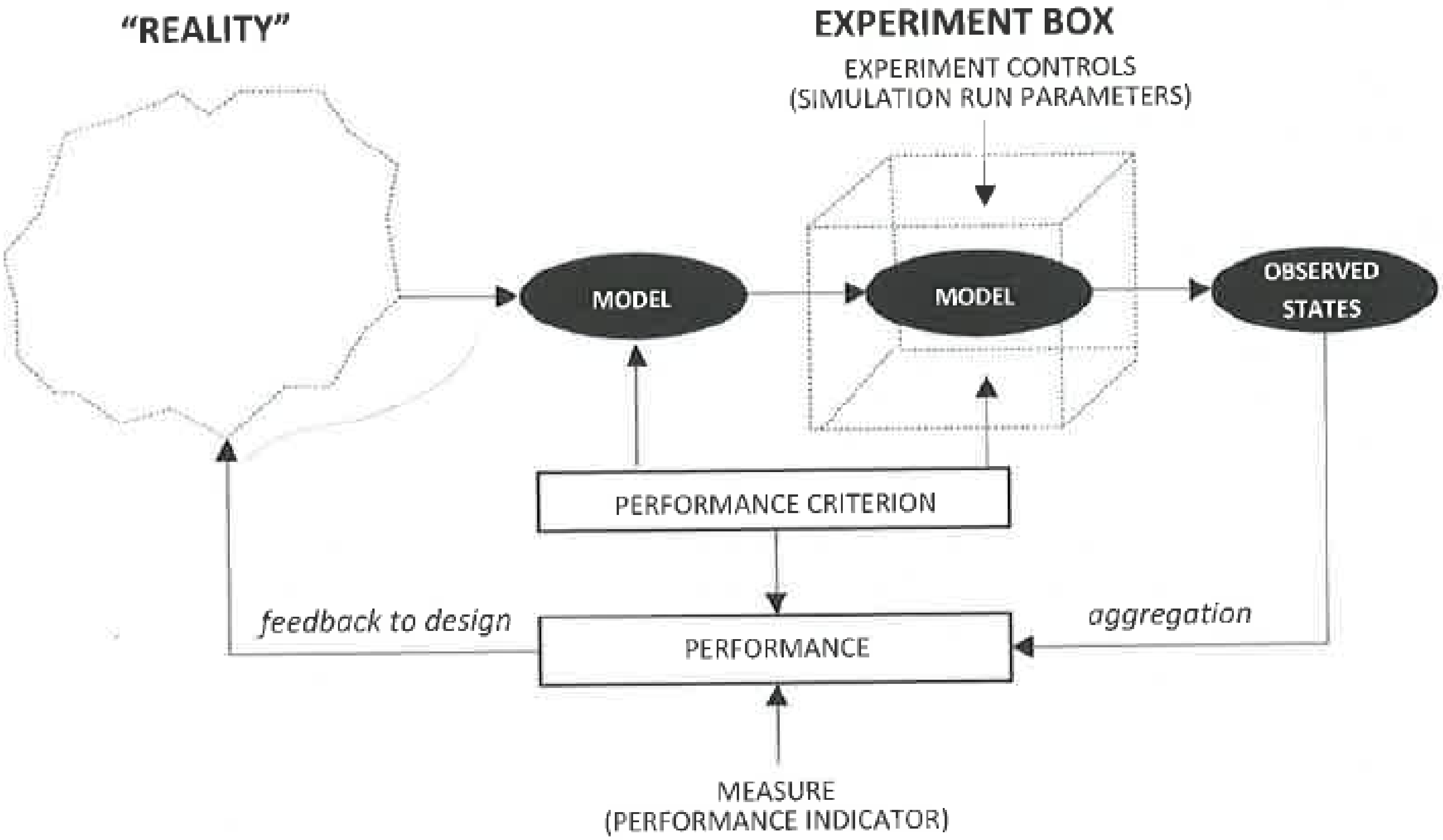
3) The simulation model…

is a set of instructions, rules, equations, or constrains for generating I/O behavior of the system – several models describe the system

4) The simulator…

is any computation system that is capable to execute the models and generate its behaviour - e.v. Simulation Studio for TRNSYS

Simulation as a „virtual“ experiment



Source: Jan L. M. Hensen, Building Performane Simulation for design and operation

Why to simulate ?

- Simulations are…
  - **faster**
  - **less expensive**
  - **more flexible**

…than experiments

- Simulations non-linear dependence on wheather
- Variations on short and long time scale

Dynamic building simulation…

…is near to first physical principles

…takes storage effects and time depending behavior of building (and their components) into account

…considers multiple thermal zones and their interaction

…calculates detailed time series of all thermal quantities

…is recommended for the investigation of new approaches

Source: W. Feist, Dynamische Gebäudesimulation

Modelling

→ **Generally:**

Systems, boundary conditions and characteristics are mainly too complex for modellig at all!

→ **Solution: analytical approach**

1) Ignoring the overall system
   → focus on subsystems
2) Understanding of the subsystems
   → under strict boundary conditions
3) Outcomes of the subsystems are recycled into the overall system
   → check their interdependency

Source: W. Feist, Dynamische Gebäudesimulation

Modelling

- A **static simulation model** is a representation of a system at a particular time

- A **dynamic simulation model** represents a system as it evolves over time, such as a conveyor system in a factory.

→ **Models always have a validity range**

Outside this range the results are uncertain!!!

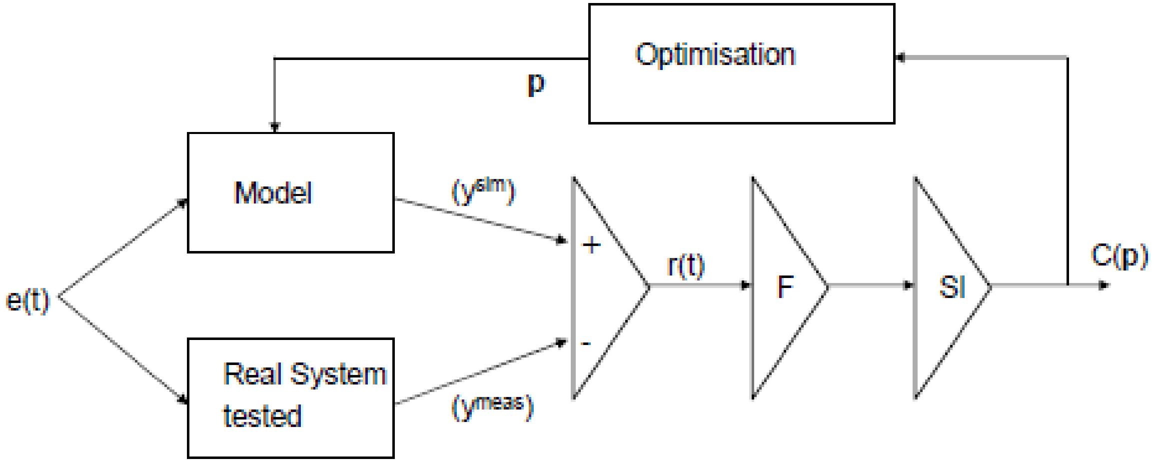
Source: W. Feist, Dynamische Gebäudesimulation

Classification of models

- **White box model**
  - Also called „physical model“
  - The whole model is made up of well-known and validated relationships between variables
- **Black box model**
  - Also called „empirical model“
  - The mathematical nature of the relationship between variables is not known (arbitary values , high-order functions, parmeters, characterisitc curves …)
- **Grey box model**
  - Mixture of white and black box model

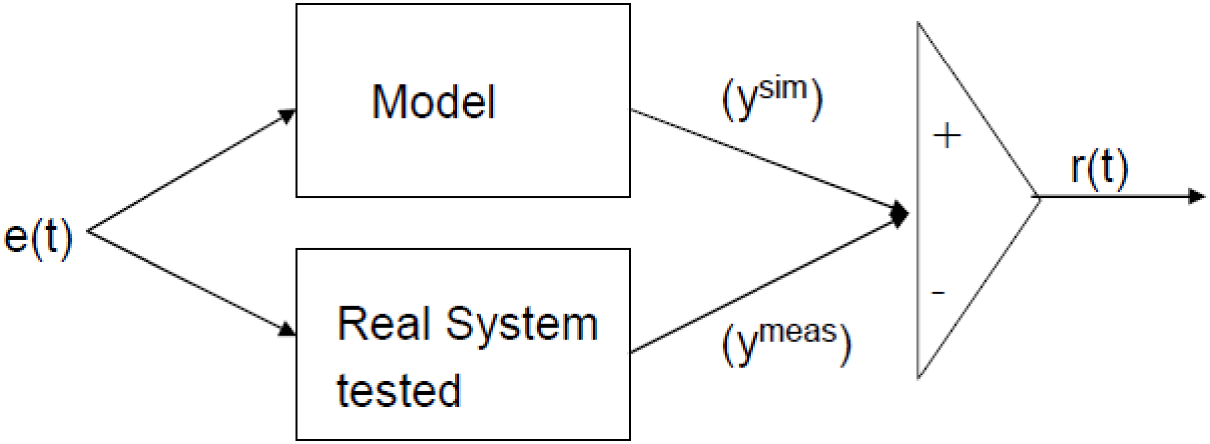
Model identification

- All models have parameter (variables/constants)
- These need to be identified for the given situation
    - To make the model simulate reality well
    - To five desired output results (e.g. design specification)
- Can be done manually or with automated tool (really an optimisation)



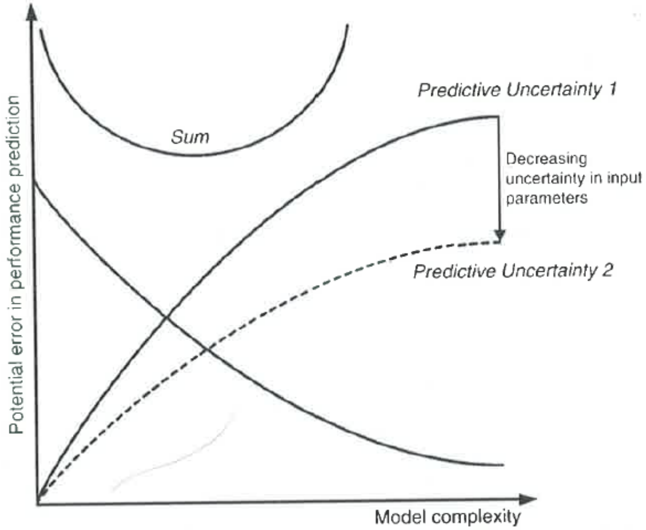
Model validation

- **Models need to be validated against reality**
  → to measure their accuracy
  → as part of the process of model development
  → to gain insight into the models validity range



Model optimizaton

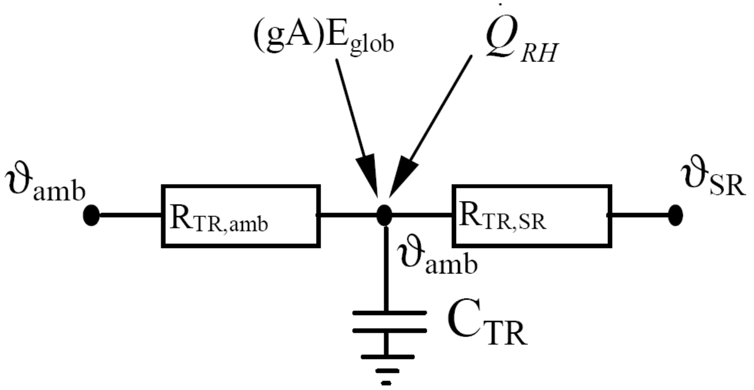
- **Very similar to parameter identification**
- **Different „objective functions“ as goals**
    - Minimum costs
    - Best performance / cost ratio
    - Best performance
    - ….

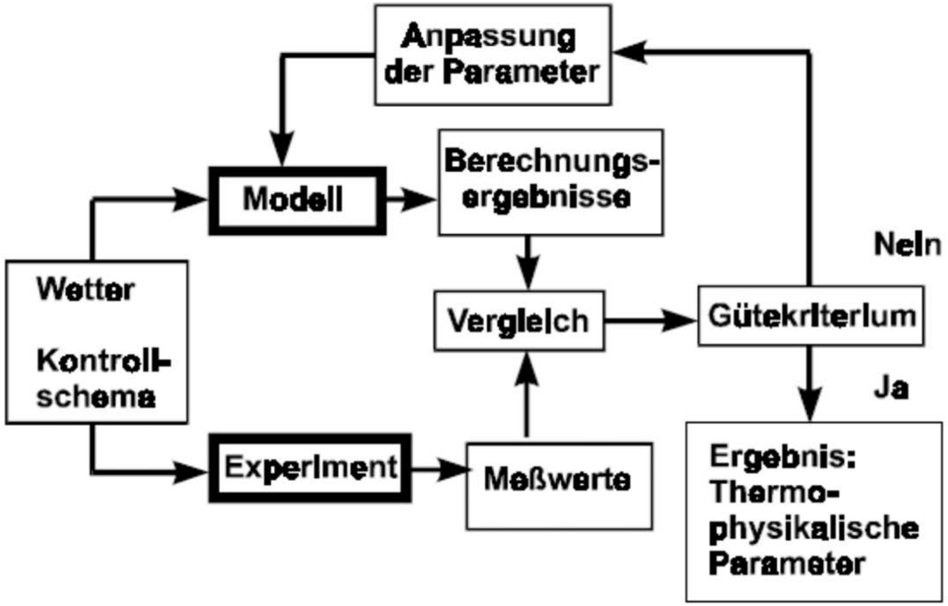


- **Can be done manually or automatically**
    - GenOpt is a free tool that can be used with many simulation programs
    - Several different algorithms

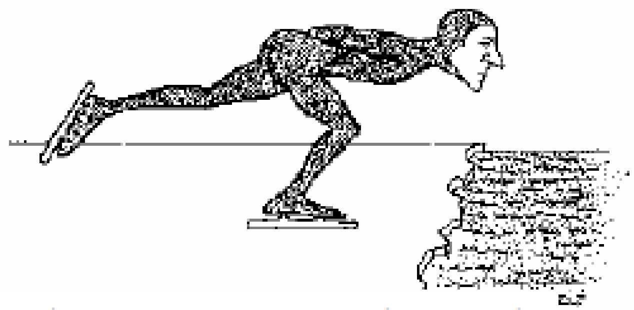
Data evaluation – Modelling – Calibration

- Data evaluation by experiment
- Dynamic modelling
- parameter identification

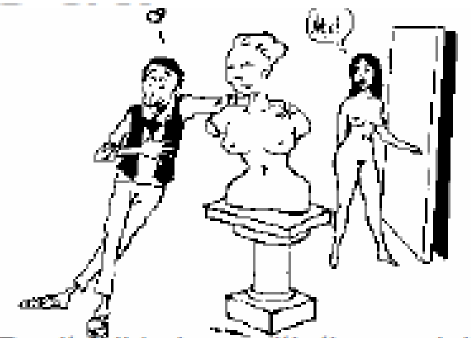




Be careful…



Extrapolation can give unexpected results



Don't fall in love with the model

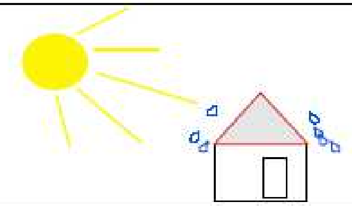
Source: Ljung & Glad (1991).
Modellbygge och simulering

Don't make reality fit the model

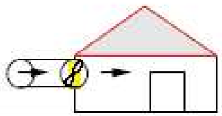
Don't be afraid to try several models

Source: Ch. Bales

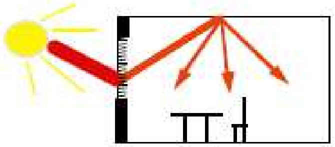
Type of simulations for buildings



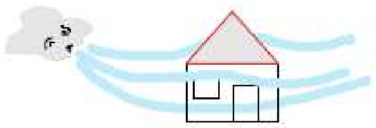
→ Thermal balancing (envelope and ambient)



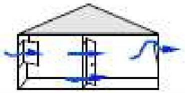
→ Building component simulation



→ Daylight and artificial light simulation
(Dialux, Relux, Radiance)



→ Moisture and acustic simulations
(Comsol, Delphi, Wufi,…)



→ Ventilation simulations
(Comis, Contam,…)

→ Room flow simulations (CFD)
(Ansys Fluent,…)

Dynamic building simulation – some available tools…

BLAST
Bsim
DeST
DOE
ECOTECT
Energy-Win
Energy Express
Energy 10
EnergyPlus
eQuest
HAP
HEED
IDA ICE
IES
DynBil
SUNREL
Tas
TRACE 700
TRNSYS
ESP-r

→ Important first task is to choose the right tool!

e.g.: D. B. Crawley et al.,

“Contrasting the capabilities of building energy performance simulation programs“,

Building and Environment 43 (2008) 661–673

http://apps1.eere.energy.gov/buildings/tools_directory/alpha_list.cfm

Recommended books/papers

Building and HVAC Simulation:

- Feist Wolfgang: Thermische Gebäudesimulation, kritische Prüfung unterschiedlicher Modellansätze, C.F. Müller, 1994
- Henson Jan L.M., Lamberts Robert: Building Performance Simulation for Design and Operation, Spon Press, 2011
- “Advanced Building Simulation”, A. Malkawi (auf OLAT)
- “The ESP-r Cookbook and The ESP-r Cookbook Exercises”, ESRU Publication, University of Strathclyde, Glasgow. http://www.esru.strath.ac.uk/ (auf OLAT)

Tools Überblick:

- Crawley, et al, CONTRASTING THE CAPABILITIES OF BUILDING ENERGY PERFORMANCE SIMULATION PROGRAMS (auf OLAT) http://apps1.eere.energy.gov/buildings/tools_directory/pdfs/contrasting_the_capabilities_of_building_energy_performance_simulation_programs_v1.0.pdf

IBPSA

International Building performance simulations association

- http://www.ibpsa.org/

- Webinares and publications are offered

- Regulary Conferences (national/international) with student competitions
- Exchange and Networking with other experts in the field
- Journal on Building Performance Simulation

Models and Numerics

Heat transfer

Room models

Radiative energy flows

Window modeling

Thermal load prediction

- Thermal load and energy performance prediction by
  - Conduction
  - Convection
  - Radiation

  → All three modes of heat transfer occur simultaneousely!

- Thermal load → amount of <u>heat</u>, that must be <u>removed</u> (cooling load) or <u>added</u> (heating load) to maintain a constant temperature

- Building is divided into „Zones“
  - Each Zone formes a control volume over which heat transfer into and out of the zone is analyzed

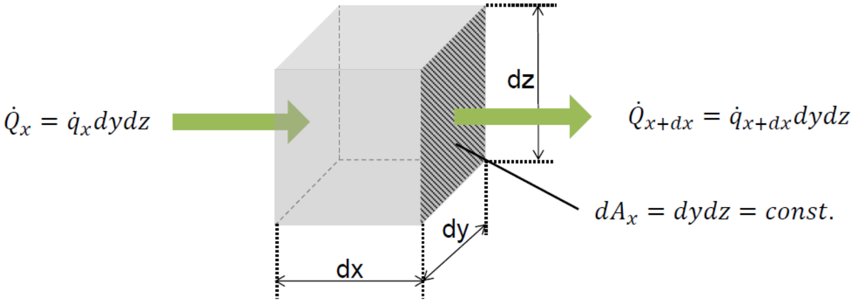
Heat transfer

Conduction (steady-state / transient)

- Important differential equations / Fourier's law
  - 1D steady-state heat conduction
    - sufficient for simple heat load calculations

$$\dot{q}_x = -\lambda \frac{\partial \vartheta}{\partial x}$$

  - Transient conduction:
    - Varying temperature
    - Varying solar radiation
    - ...



$$\frac{\partial \vartheta}{\partial t} = a\left(\frac{\partial^2 \vartheta}{\partial x^2} + \frac{\partial^2 \vartheta}{\partial y^2} + \frac{\partial^2 \vartheta}{\partial z^2}\right) \pm \frac{\dot{q}^*}{\rho c_p}$$

Heat transfer

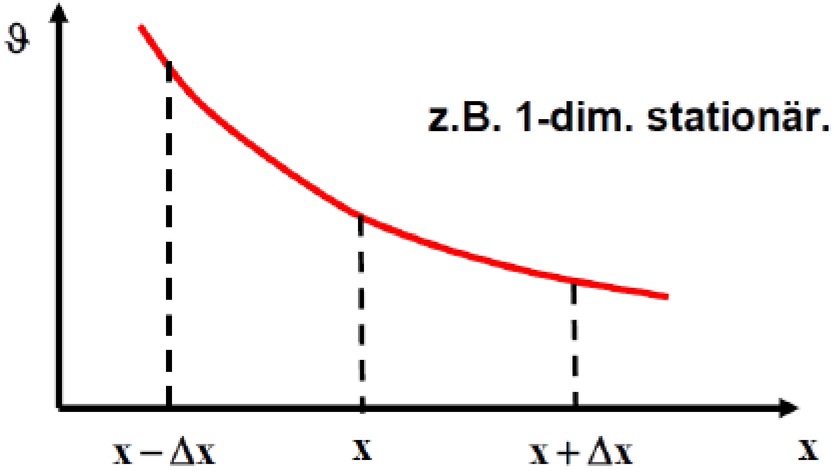
Conduction (steady-state / transient)

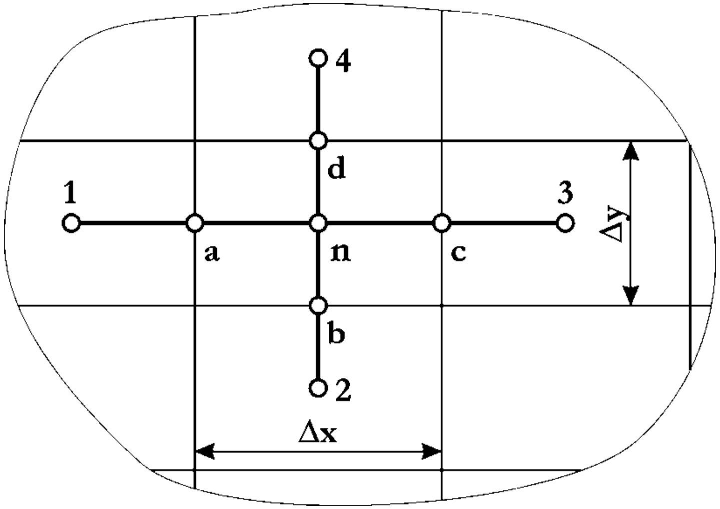
- Solving methods:

  - **Z-transform methods** (Response factor, CTF, PRF)
    - Describing the “history” of heat transfers of the last hours
    - High degree of accuracy
    - Computationally efficient
  - **Numerical methods**
    - Finite Difference / Finite Element method
    - High degree of accuracy, but less computationally efficient
    - Increased flexibility for treating deailed physical phenomenas
  - **Lump parameter methods**
    - Treating walls and windows as discrete resistances and lumped capacitances (used in conjunction with lumped zone models)

Numerical methods

Finite Difference Method





$$\frac{\partial \vartheta}{\partial x} \approx \frac{\vartheta_{x+\Delta x} - \vartheta_{x-\Delta x}}{2\,\Delta x}$$

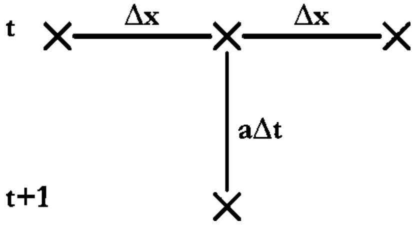
$$\frac{T_3^t + T_1^t - 2\cdot T_n^t}{(\Delta x)^2} + \frac{T_4^t + T_2^t - 2\cdot T_n^t}{(\Delta y)^2} = \frac{1}{a}\,\frac{T_n^{t+1} - T_n^t}{\Delta t}$$

Source: Prof. Streicher, UIBK

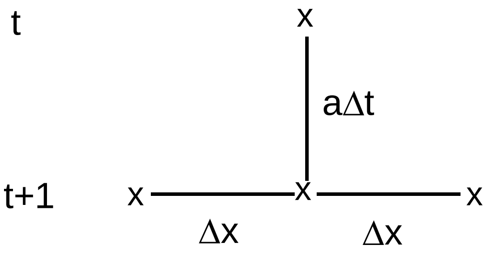
Numerical methods

Stability vs. accuracy / computational effort

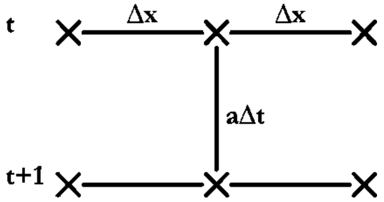
- **Explicit**
  - Stability criteria has to be defined



- **Implicit**
  - Always stable
  - but results might be underestimated



- **Crank-Nicolson**
  - Combination of both



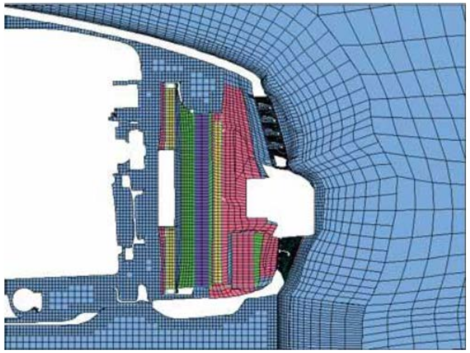
Source: Streicher, UIBK

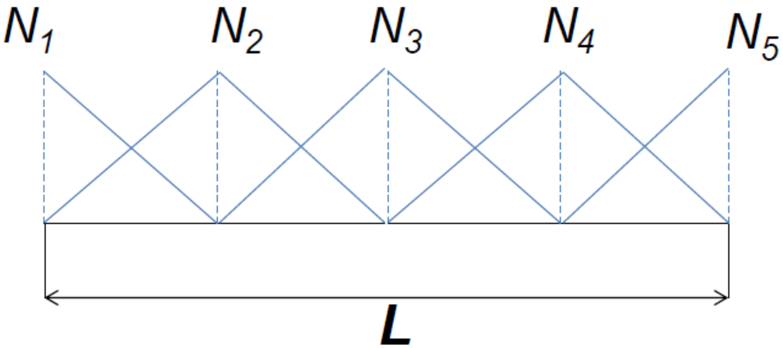
Numerical methods

Finite Element Method

This method is based on the model imagination of a continuum, which is divided into simple patches or sub-bodies („meshing“), which are connected at defined nodes.

The deformation of the infinitesimal mass points is approxi-mately described as a function of the nodes’ deformation by means of a displacement approach w.r.t. an “element type”. This enables the separation of the distributed variables into space and time variables.

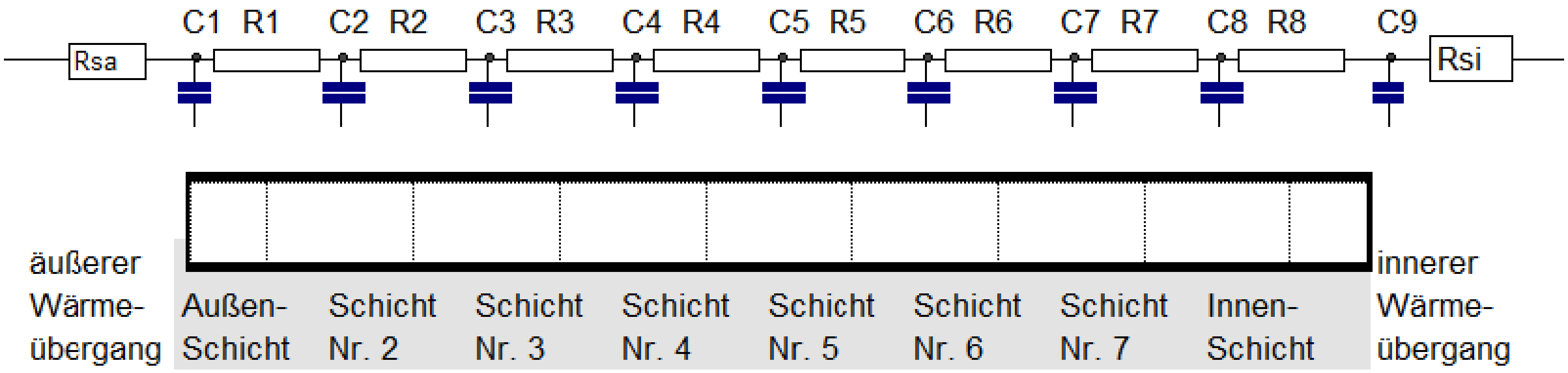




Lump parameter model

RC-model

- Beuken - model
- non - steady
- for 1D-heat transfer through walls



- 1 Resistance/Capacity-pair per wall layer
- Inner/outer resistance for (combined) heat transfer

Source: Feist, PHI/UIBK

Z-transform methods

- Conduction Transfer Functions (CTF)
    - Using Laplace q/z- transformation leads to

$$\dot{q}_{s,i} = \sum_{k=0}^{n_{b_s}} b_s^k T_{s,o}^k - \sum_{k=0}^{n_{c_s}} c_s^k T_{s,i}^k - \sum_{k=1}^{n_{d_s}} d_s^k \dot{q}_{s,i}^{k}$$

$$\dot{q}_{s,0} = \sum_{k=0}^{n_{a_s}} a_s^k T_{s,o}^k - \sum_{k=0}^{n_{b_s}} b_s^k T_{s,i}^k - \sum_{k=1}^{n_{d_s}} d_s^k \dot{q}_{s,0}^{k}$$

K	A	B	C	D
0	3.0402072E+01	8.6597596E-01	6.2473097E+01	1.0000000E+00
1	-2.8791436E+01	8.7958309E-01	-6.1044043E+01	-5.5725114E-03
2	1.4382785E-01	8.9032318E-03	3.2541274E-01	1.0083948E-07
3	-1.0589132E-06	4.0042651E-07	-4.7183532E-06	
SUM	1.7544627E+00	1.7544627E+00	1.7544627E+00	9.9442759E-01

Physical basics

- Stefan-Boltzmann law
  - theoretical (1884, Ludwig Boltzmann)
  - experimental (1879, Josef Stefan)

    Correlation: $E_{ges} \sim T^4$

  - Total radiant emmitance ideal black body

    $E = \sigma\ (T^4 - T^4)$

  - resulting energy exchange btw. non-ideal black absorbers

    $E = \sigma\ \varepsilon\ (T_A^4 - T_B^4)$

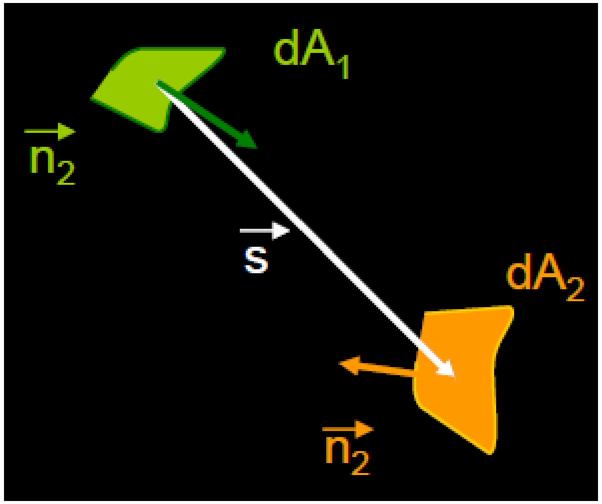
    $\sim 5{,}6\ W/m^2K\ (T_A^4 - T_B^4)$ ...in case of T ~ 18°C

Radiation exchange between surfaces

- $q_{Str} = F_{AB} * \sigma\,(T_A^4 - T_B^4)$

$$F_{AB} = \frac{1}{\frac{1}{\varepsilon_A} + \frac{1}{\varepsilon_B} - 1}$$

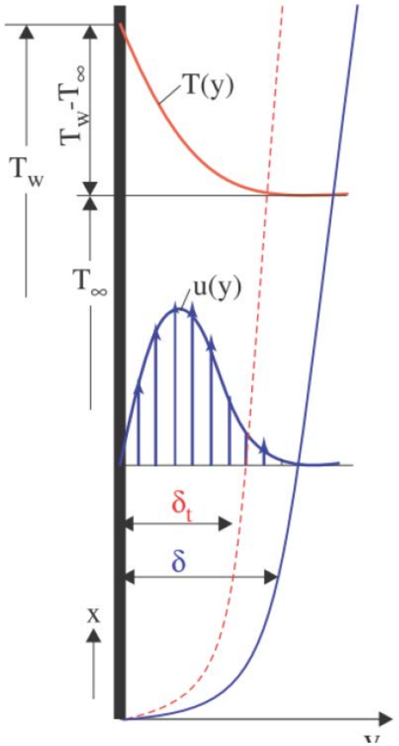
$$d\varphi_{12} = \frac{\cos\theta_1 \cos\theta_2}{\pi s^2} dA_2$$



Source: Feist, PHI/UIBK

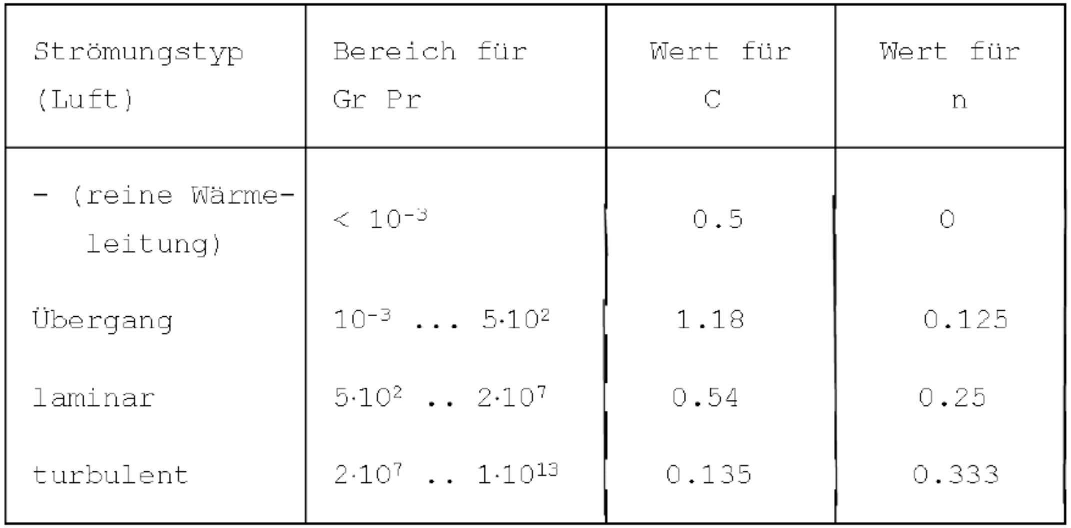
Convective heat transfer

- Based on semi-empirical models



$$Q_c = h_{c,i}\,A\left(T_{surf} - T_{air}\right)$$

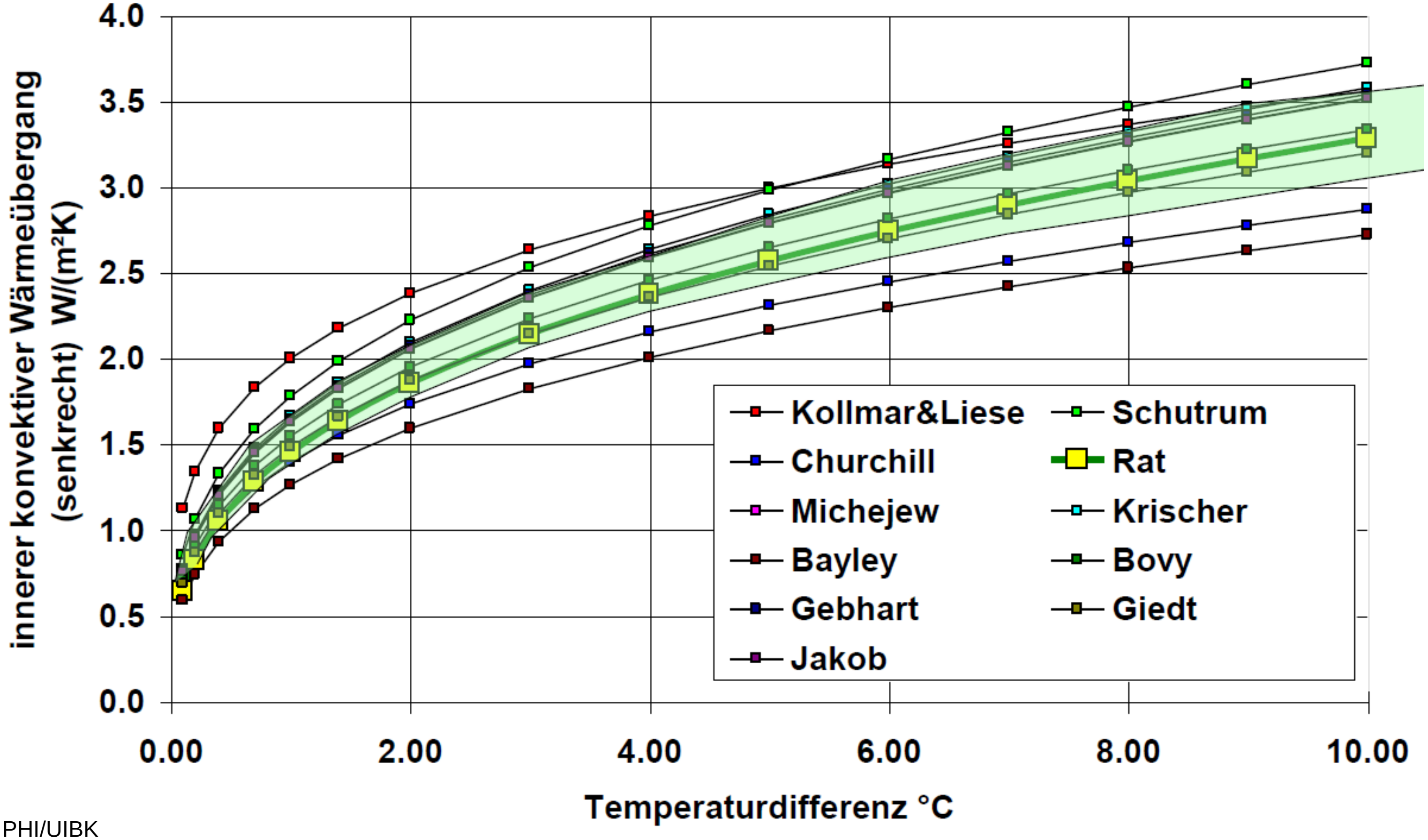
$$h_{c,i} = Nu_i\left(\frac{\lambda_{g,i}}{d_{g,i}}\right)$$



Strömungstyp (Luft)	Bereich für Gr Pr	Wert für C	Wert für n
- (reine Wärme-leitung)	$< 10^{-3}$	0.5	0
Übergang	10^{-3} ... $5{\cdot}10^{2}$	1.18	0.125
laminar	$5{\cdot}10^{2}$ .. $2{\cdot}10^{7}$	0.54	0.25
turbulent	$2{\cdot}10^{7}$ .. $1{\cdot}10^{13}$	0.135	0.333

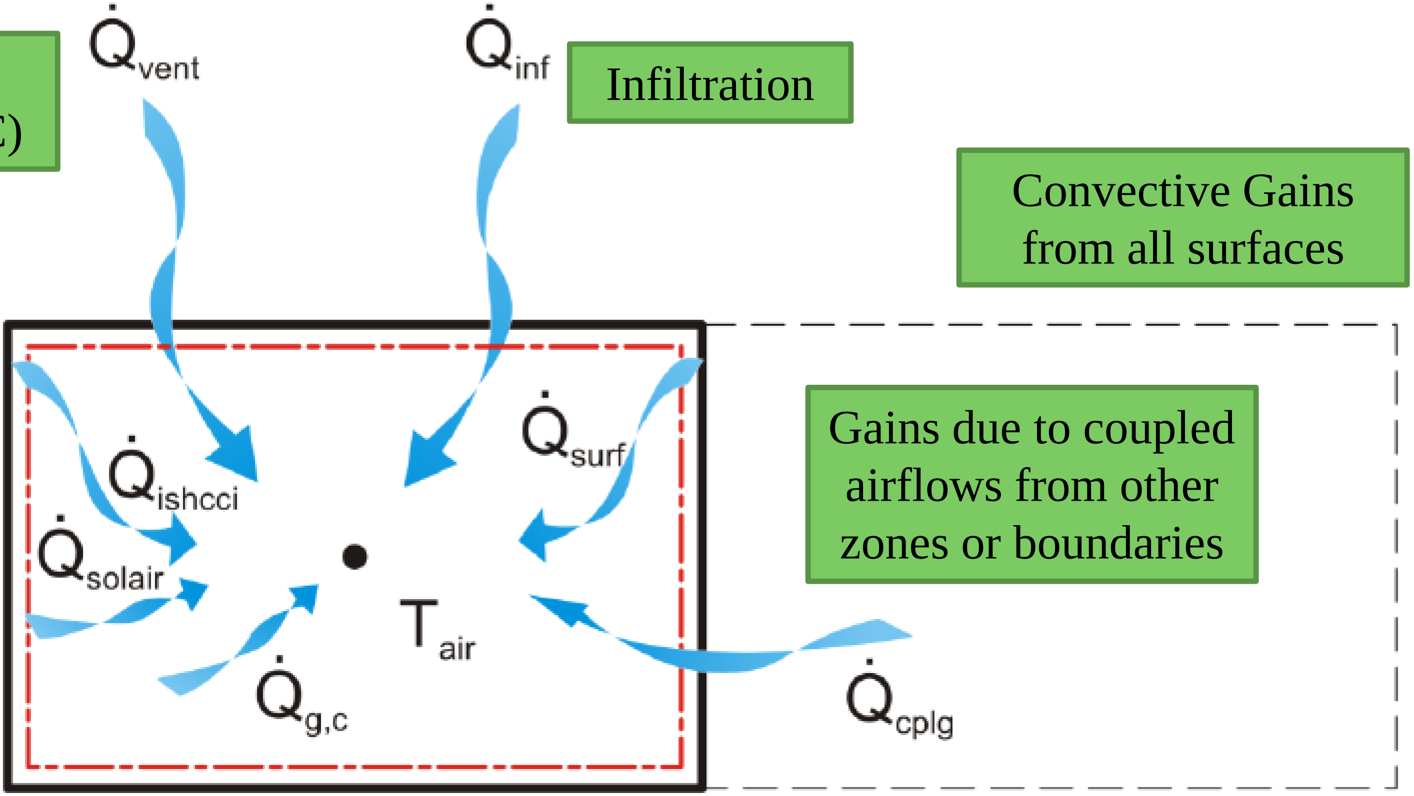
Source: Feist, PHI/UIBK

Convective heat transfer



Source: Feist, PHI/UIBK

Energy balance on the room air node



Mechanical Ventilation (HVAC)

Infiltration

Convective Gains from all surfaces

Convective Gains from Solar Radiation and Shadings

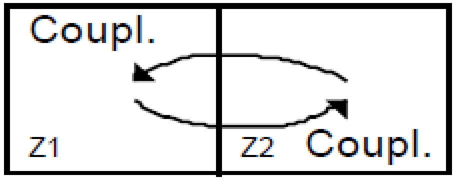
Gains due to coupled airflows from other zones or boundaries

Internal convective gains (people,equipment, etc.)

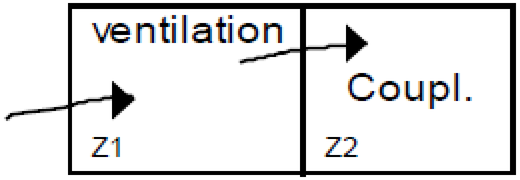
$$\dot{Q}_i = \dot{Q}_{surf,i} + \dot{Q}_{inf,i} + \dot{Q}_{vent,i} + \dot{Q}_{g,c,i} + \dot{Q}_{cplg,i}$$

Source: TRNSYS17 Documentation

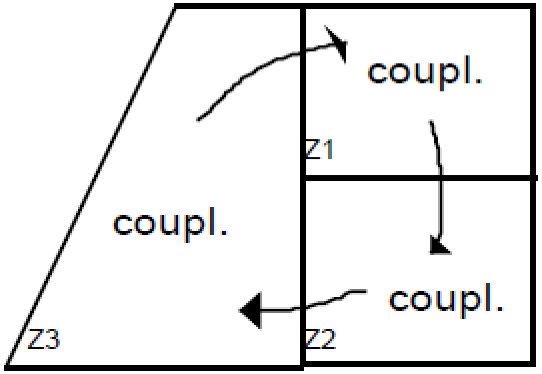
Coupling airflows



interzonal airchange



cross ventilation



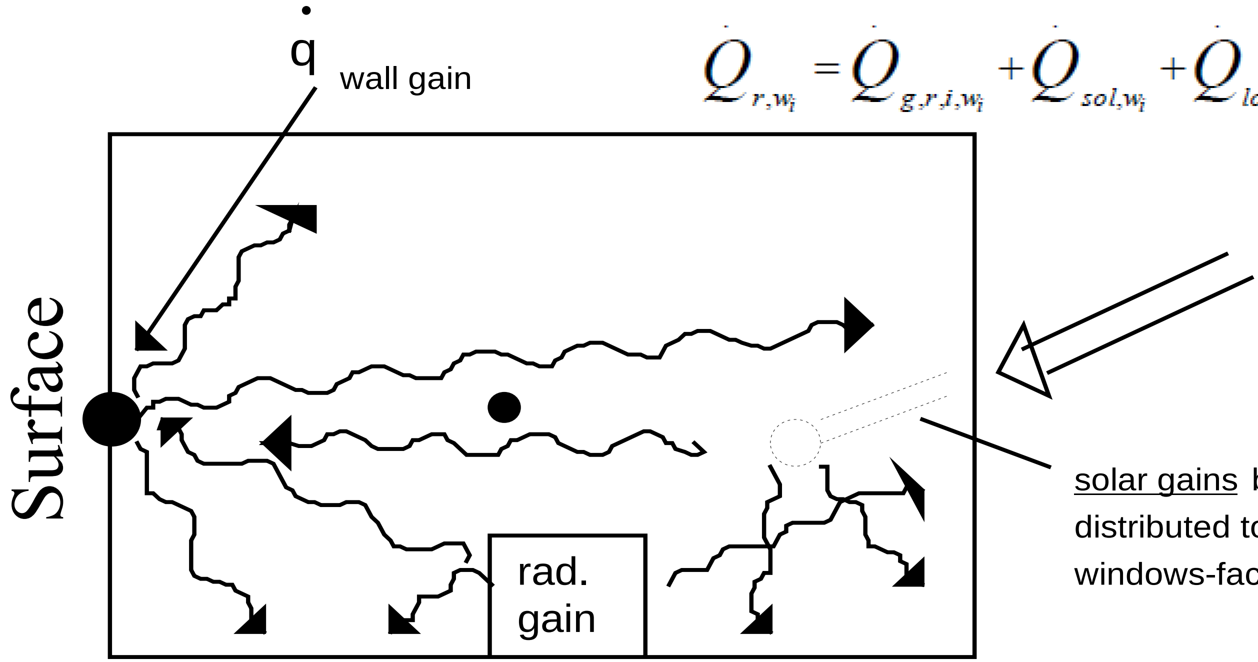
Ventilation circle

Source: TRNSYS17 Documentation

Radiative energy flow

for one wall with it‘s surface temperature node

$$\dot{Q}_{r,w_i} = \dot{Q}_{g,r,i,w_i} + \dot{Q}_{sol,w_i} + \dot{Q}_{long,w_i} + \dot{Q}_{wall-gain}$$



solar gains by windows are distributed to all walls and windows-faces

Total Radiative Gains to Each Surface =

- \+ *internal radiative gains* inside the zone received by the wall
- \+ *solar gains through windows* received by the wall
- \+ longwave *radiation between* this wall and all other walls and windows
- \+ *user specified* heat flow to the wall surface (wall gain)

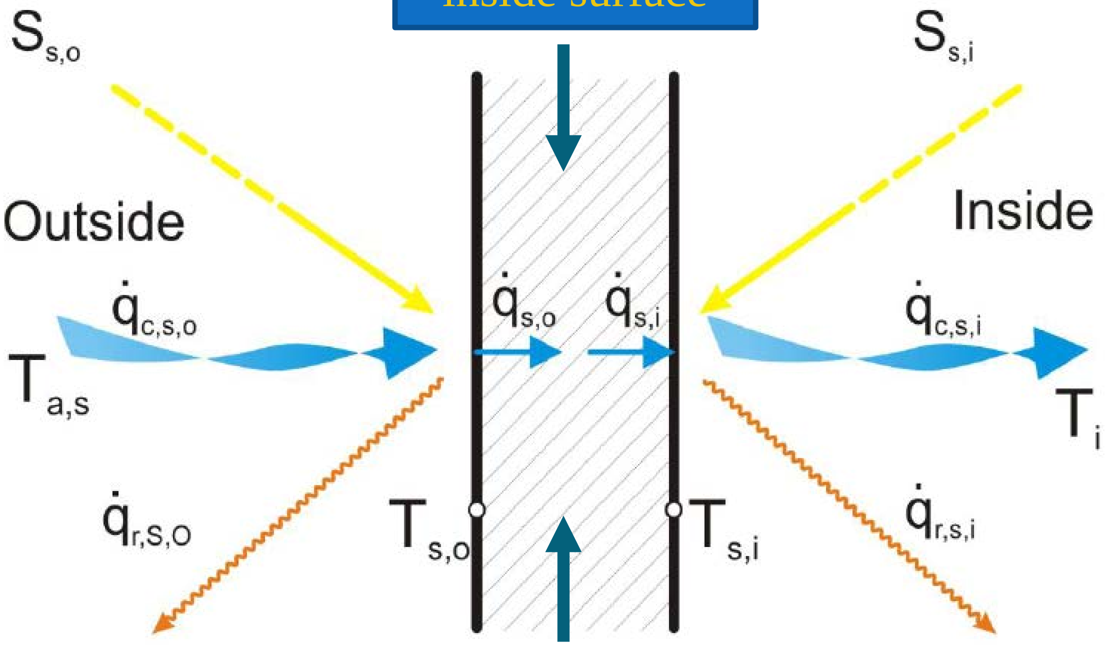
Source: TRNSYS17 Documentation

Energy flows in the wall (or window)

Solar radiation absorbed outside

conduction from the wall at the inside surface

Solar radiation absorbed inside



convection to the outside surface from the boundary / ambient

convection from the inside surface to the zone air

net radiation with all surfaces outside

conduction into the wall at the outside surface

net radiation with all other surfaces within the zone

Longwave radiation exchange in room

- Approximation des langwelligen Strahlungsaustausches im Raum durch das 2*-Modell
- Annahmen:
    - Strahlungsaustausch zwischen zwei Oberflächen indirekt über Zwischen-absorption an einem dem Raum ausfüllenden Körper
    - ohne thermische Masse
    - mit unendlicher Wärmeleitfähigkeit
    - und ideal schwarzer Oberfläche

- **1 Strahlungsknoten** (Strahlungsaustausch zwischen Flächen)
- **1 Raumluftknoten** (bildet konvektive Wärmeübergänge zwischen Raumluft und Bauteiloberflächen ab)

→ Beide Anteile sind sauber voneinander getrennt

Characteristics of room nodes

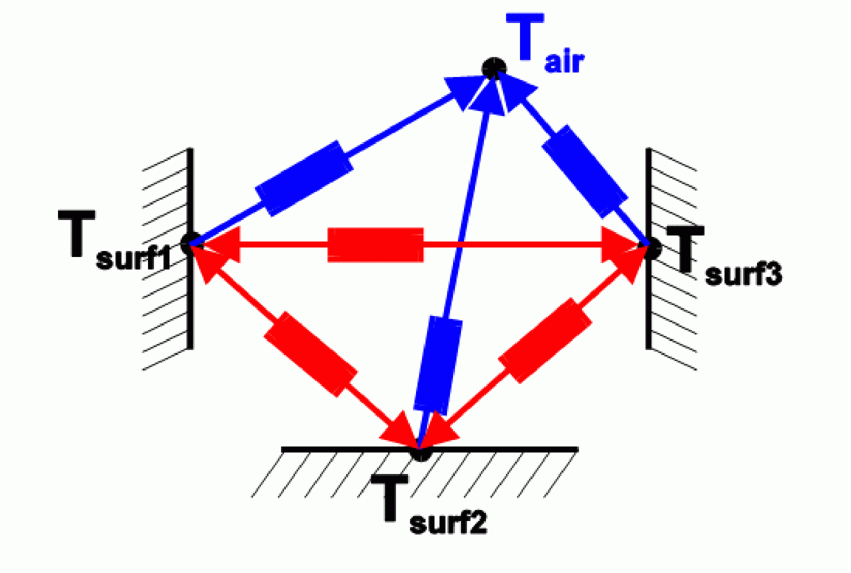
- Radiation node
  - Strongly dependent on incident solar radiation
  - Directly coupled with surfaces of the enclosure
  - Thermal mass of the surfaces
  - high time constants

- Convective mode
  - Strongly dependent on infiltration and ventilation
  - Weak coupling th the surfaces of the enclosure
  - Neglegtable thermal mass of the zone air
  - low time constants

Longwave radiative resistance networks

- 3D Model
  - Convection / radiation solved separately
  - Exact solution
  - Numerically expensive
  - E.g. in TRNSYS 17.1 / 3D

radiative
convective



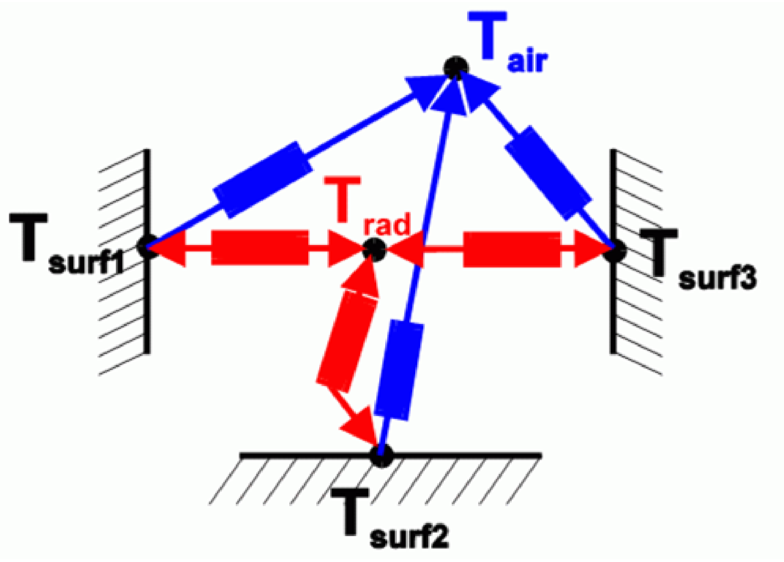
Source: TRNSYS17 Documentation

Longwave radiative resistance networks

- 2 Node Model
  - One radiation node, one air node
  - exact for three walls
  - Good results

  - E.g. in Dynbil / ePlus

radiative
convective

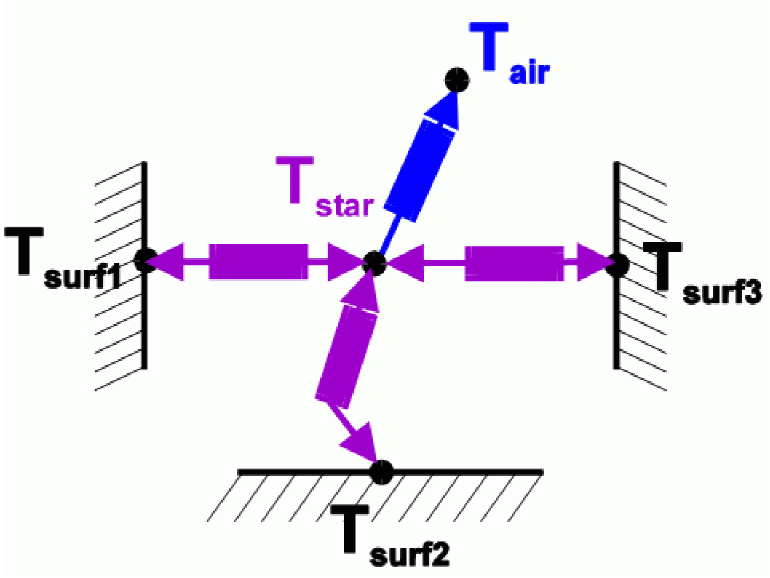


Source: TRNSYS17 Documentation

Longwave radiative resistance networks

- Star-node model
  - Combined rad/con heat transfer

  - E.g. in TRNSYS 16



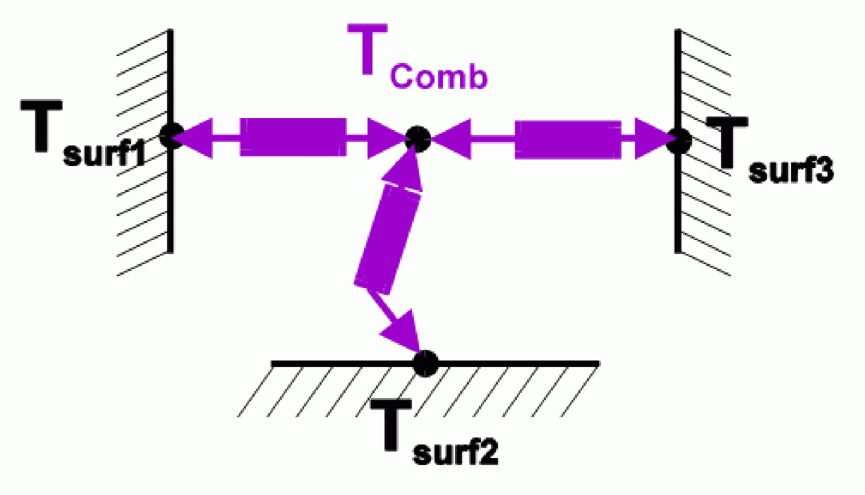
A artificial temperature node (T_{star}) determines the the convective heat flow from a wall surface to the air node and the radiative heat flow from a wall surface to other wall and window elements.

Source: TRNSYS17 Documentation

R/C Models

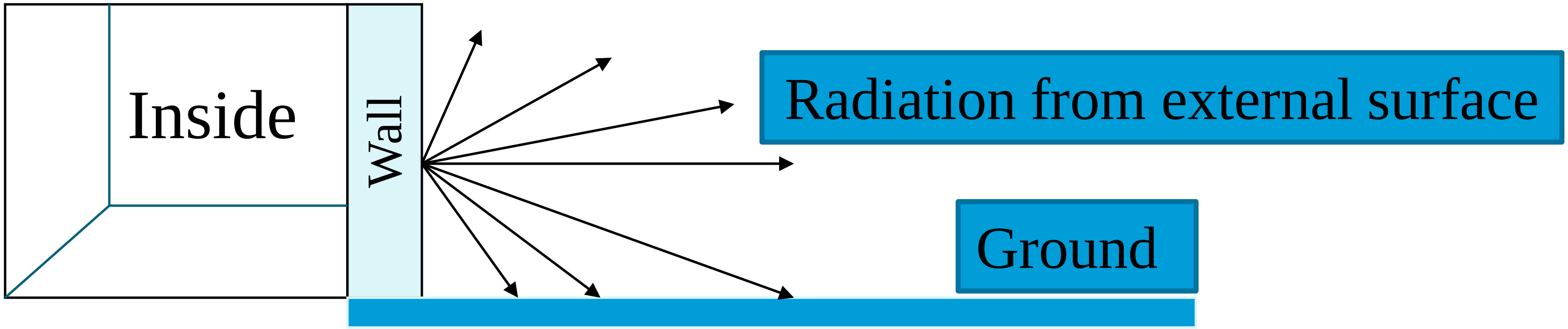
- 1 Node Model
  - Convection / radiation combined
  - Can lead to huge deviations

  - E.g. in ??

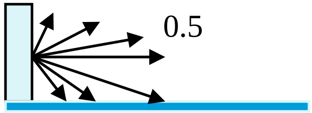


Source: TRNSYS17 Documentation

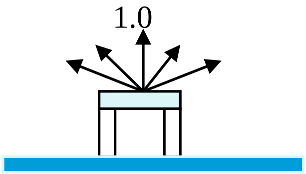
Radiation calculation from external



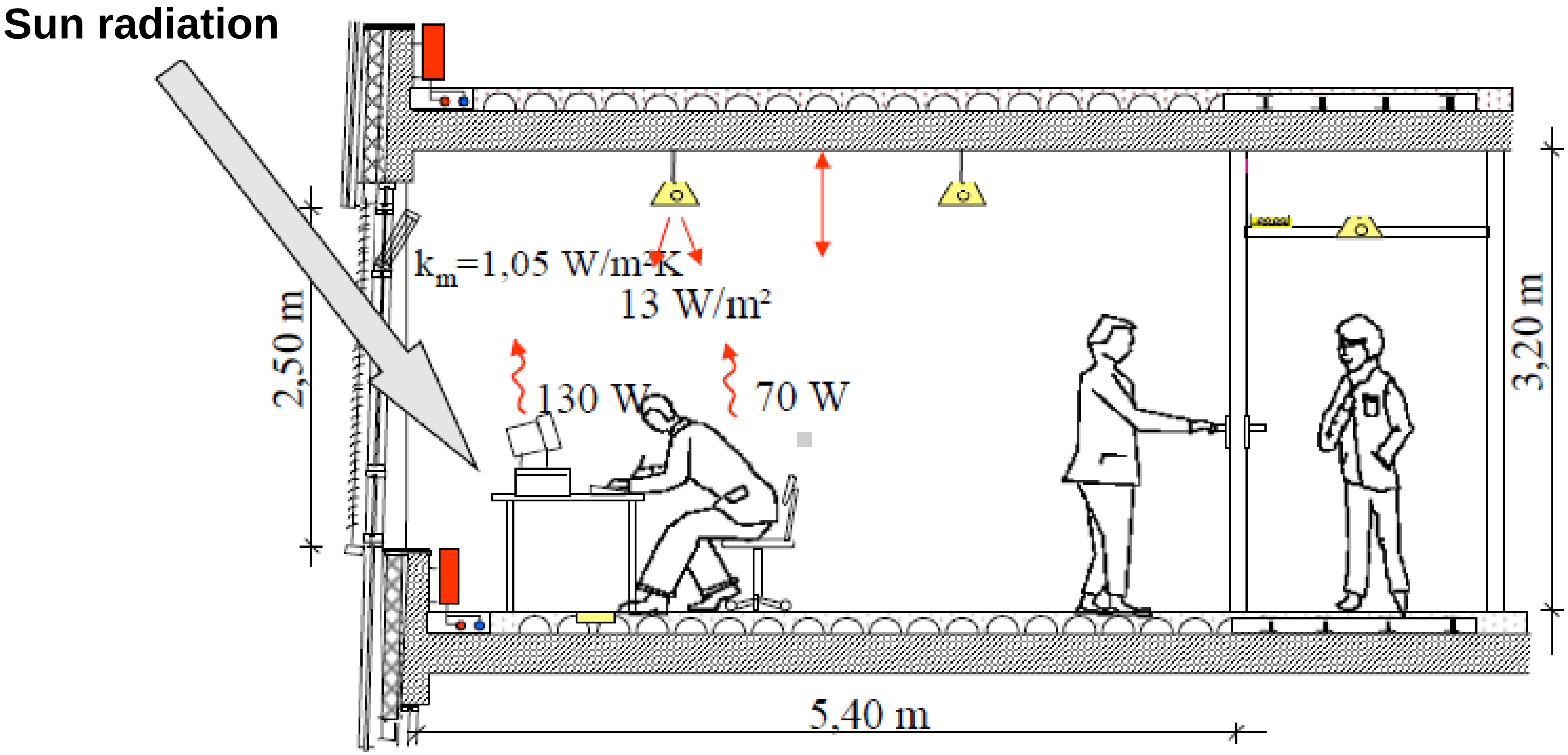
- External surfaces radiate energy in all directions
- Amount of radiation depends on temperature difference
- A large portion of the radiation is to the sky
- The temperature of the sky (used to calculate radiation amount) is calculated by a utility component (Type 69)



- Fsky = fraction of radiation that goes to sky
- = 0.5 for vertical wall on flat plane
- = 1 for flat roof that only radiates to the sky



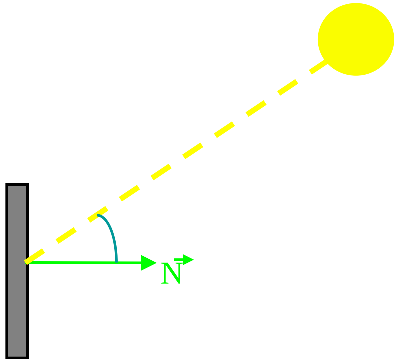
Different room gains



- Gains by sun radiation
- Gains by persons in the room
- Gains by Equipment (PC,…)
- Gains by artificial lighting

Building model input

- Ambient Temperature
- Ambient Relative Humidity
- Sky Temperature
- For each Orientation:
  - Incident Beam Radiation
  - Incident Total Radiation (Beam plus Diffuse radiation)
  - Incident Angle
    - Angle (measured from normal) at which beam radiation hits surface
- Certain building characteristics defined in building file
  - Ex. ventilation, infiltration, shading controls, etc.
  - Values passed to Type 56 from other components



Effects of People in BPS

- …named „Occupancy level"
- **„passive effects":**

  …concerns the hygro-thermal effects by people in buildings. It depends on the „mere" prensence of people in the building. Depending on people's activity, beside sensible and latend heat they also release water vapour, carbon dioxide and odours. Data input mainly by external sources (occupancy load scedules) derived from measurement results of metabolic rates.
- **„active effects":**

  …refers to peoples control actions on windows, shades, luminaires, radiators and fans. These control actions have a significant impact on buildings hygro-termal and visual performance.

  → lot of empirical studies done to study occupancy effects

Zoning

…from the architectural model to the thermal model

- **Keep it as simple as possible!**
The user effort, complexity and computation time increases significantly with the number of zones and not necessarily accuracy!!

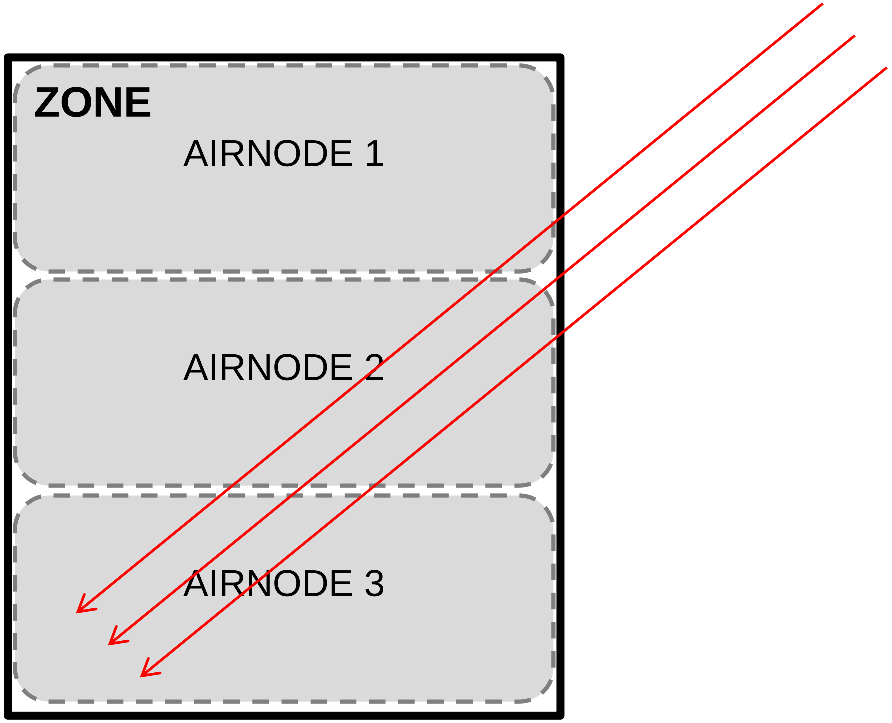
- **A thermal model doesn't have to look like an architectural model!**
…but has to model the thermal behavior. For most cases the geometry can be simplified.

- **The zoning depends on the expected results of the simulations!**
Similar areas with respect to solar gains, construction, utilization and conditioning show the same thermal behavior and can often be combined into one zone for emery simulations. For detailed analysis of comfort and detailed temperatures it is recommended to simulate "special areas" as separate zones.

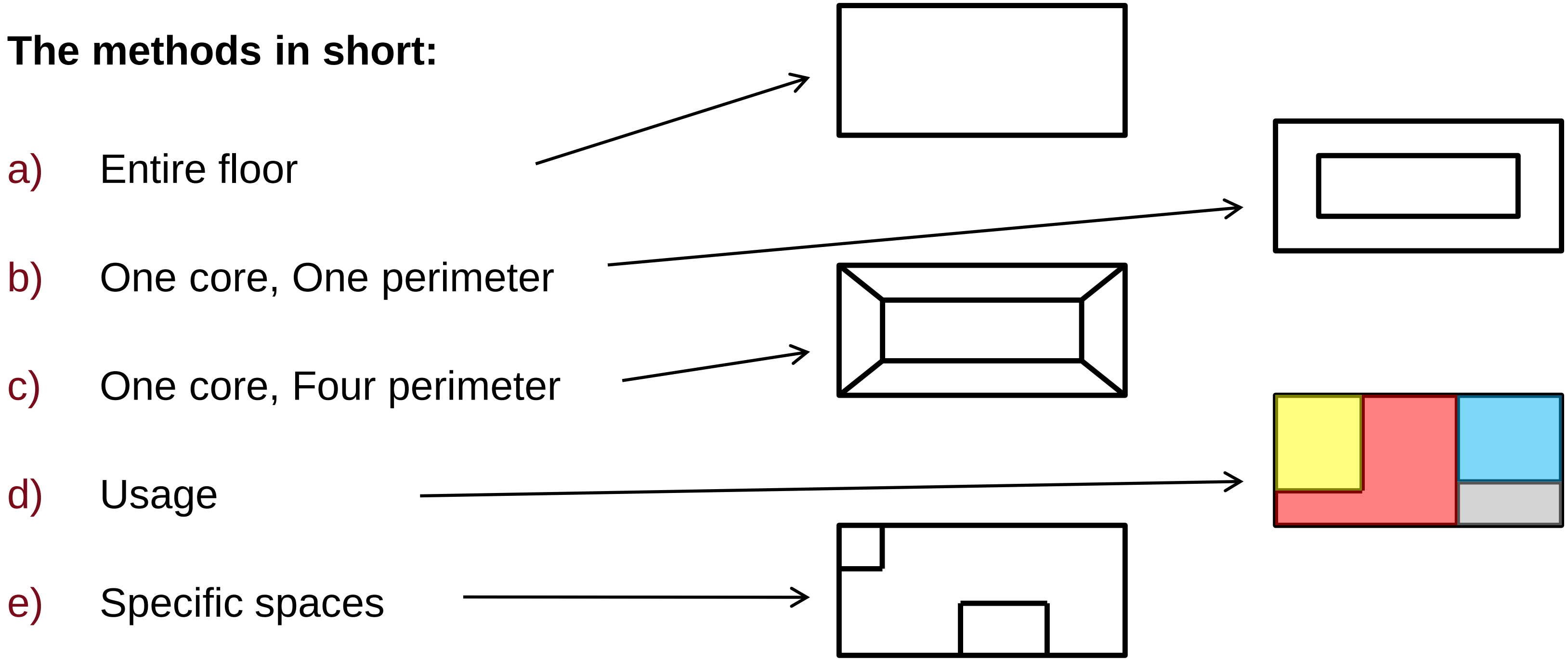
Thermal zoning

some hints…

- Use exterior dimensions for drawing the 3D models / zones
- One thermal zone can consist of multiple (up to 99) air nodes



Choose the appropriate zoning method



The methods in short:

a) Entire floor

b) One core, One perimeter

c) One core, Four perimeter

d) Usage

e) Specific spaces

Thermal zoning

Basic approach

a. **Entire floor**

+ Simple	- Low level of detail: e.g trbls with core - perimeter

b. **One core – One perimeter**

+ Simple geometry	- No effects of orientation, low level of detail,

c. **One core – Four perimeter**

+ Effects of orientation, general appr.	- Distribution of loads, HVAC, profiles

d. **According to usage**

+ Internal loads, HVAC homogenous	- Low level of detail

e. **Specific spaces**

+ Only „interesting“ zones	- Selection of zones

Thank you for your attention!

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