BUILDING DYNAMIC SIMULATION

Rendez-vous de l'ATIC

15th January 2020

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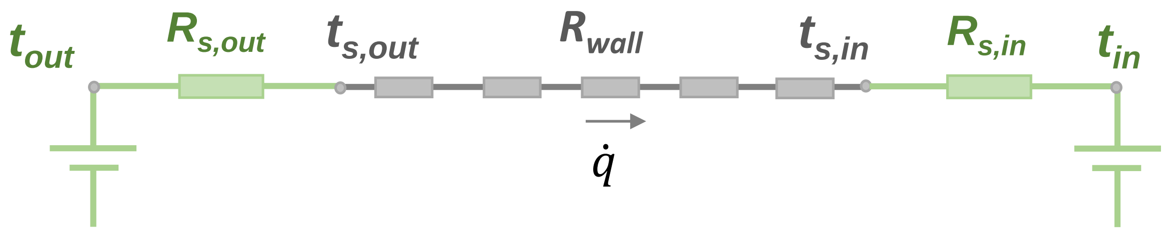
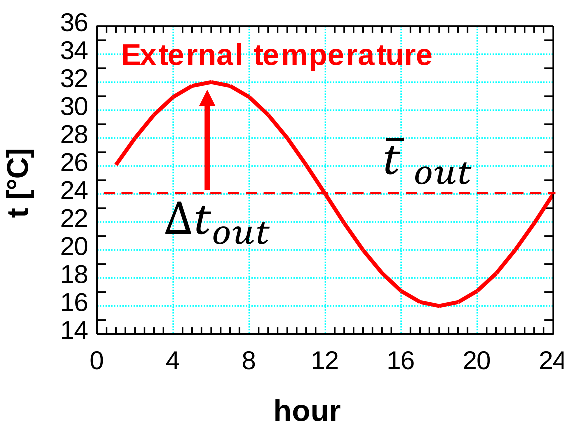
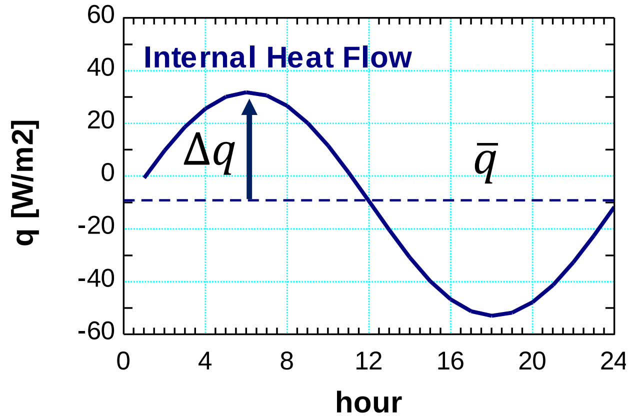
Lecturer HEPL – Researcher UCLouvain

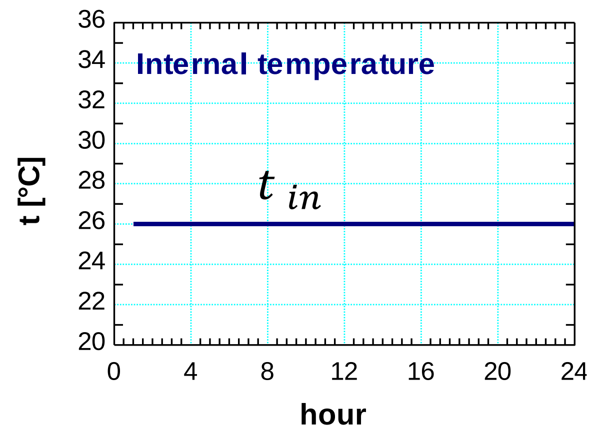
Static system



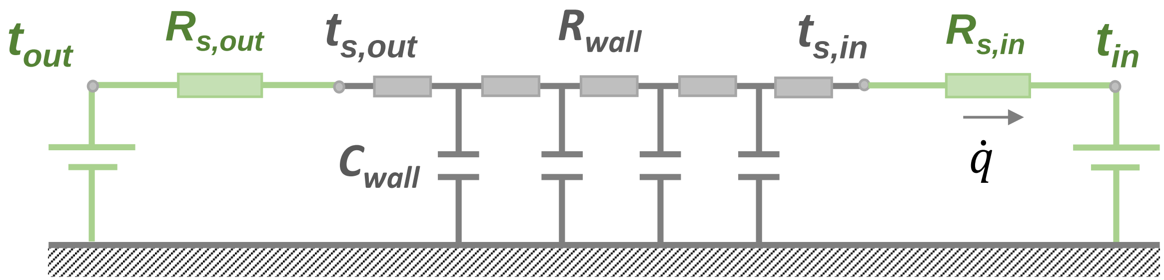
$$\dot{q} = U(t_{out} - t_{in}) \qquad \bar{q} = U(\bar{t}_{out} - t_{in}) \qquad \Delta q = U(\Delta t_{out} - t_{in})$$



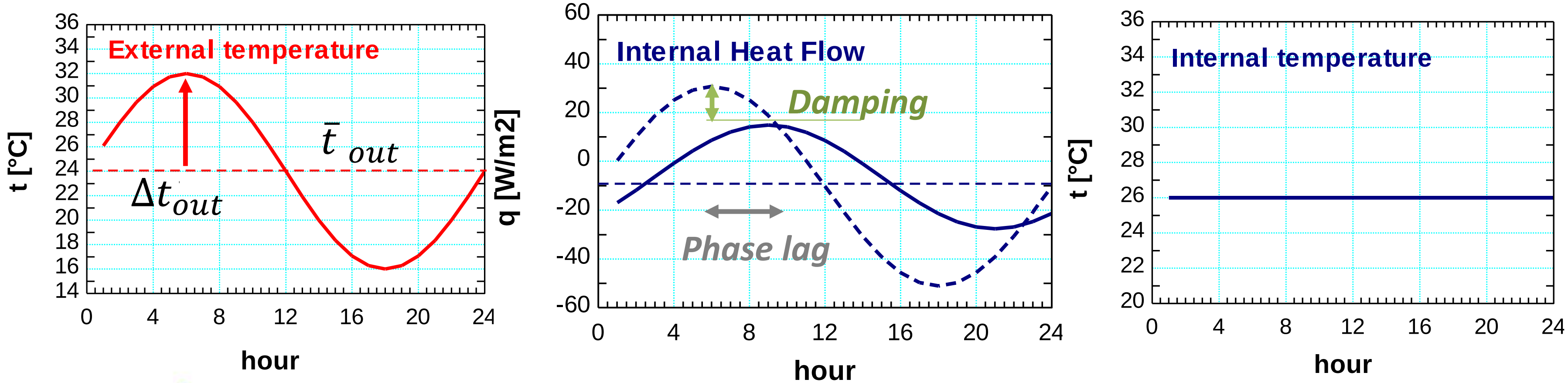




Dynamic system



$$\Delta t_{eq} = \frac{\dot{q}}{U}$$

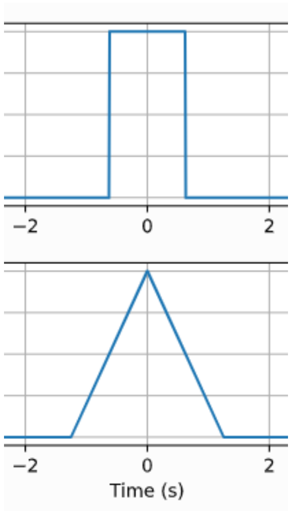


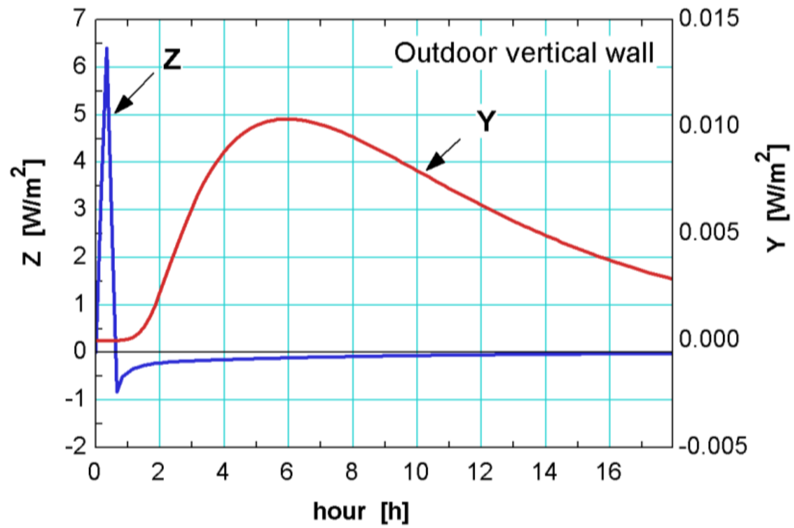
DYNAMIC SIMULATION - PRINCIPLES

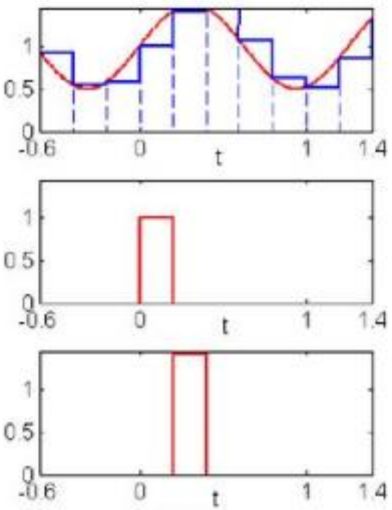
- Differential equations

$$\begin{bmatrix} \frac{dT_1}{dt} \\ \frac{dT_2}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{RC} - \frac{hA}{C} & \frac{1}{RC} \\ \frac{1}{RC} & -\frac{1}{RC} - \frac{hA}{C} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \end{bmatrix} + \begin{bmatrix} \frac{hA}{C} & 0 \\ 0 & \frac{hA}{C} \end{bmatrix} \begin{bmatrix} T_o \\ T_i \end{bmatrix}$$

- Convolution model based on response factors







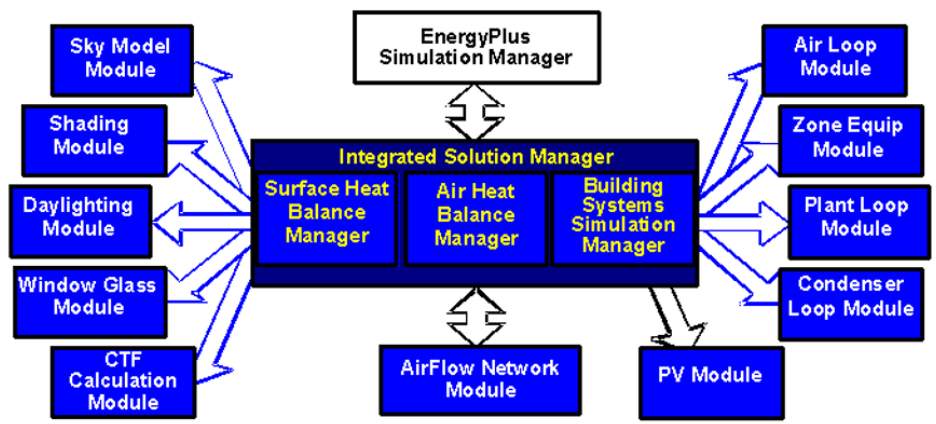
DYNAMIC SIMULATION TOOLS

BEMS team, ULg

Web : http://www.bems.ulg.ac.be

Library energy system components

- **Solar** Thermal Processes
- **Ground** Coupled Heat Transfer
- **Heat Pump** Systems
- Coupled Multizone Thermal/**Airflow** Modeling
- **Power Plant**s (Biomass,Cogeneration)
- Hydrogen **Fuel Cell** Systems
- **Wind and Photovoltaic** Systems
- **HVAC** systems
- Emerging Technology **Assessment**
- Energy System **Research**
- Data and Simulation **Calibration**
- **Optimization**



DYNAMIC SIMULATION - APPLICATIONS

System sizing

Energy Consumptions

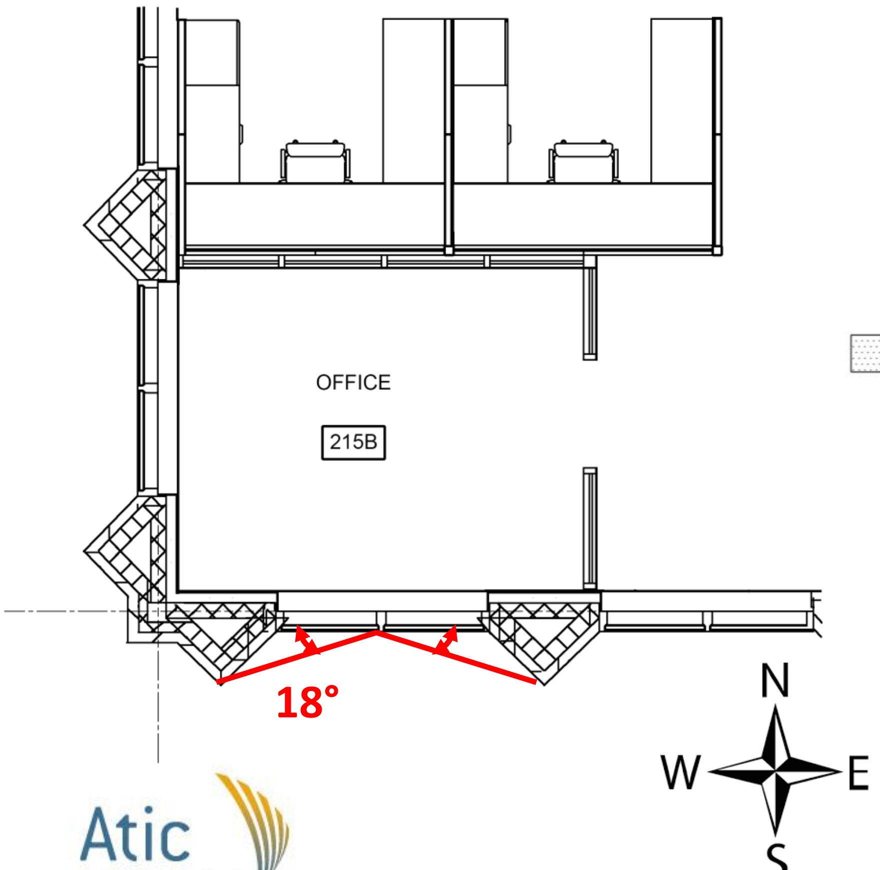
Validation

Identification

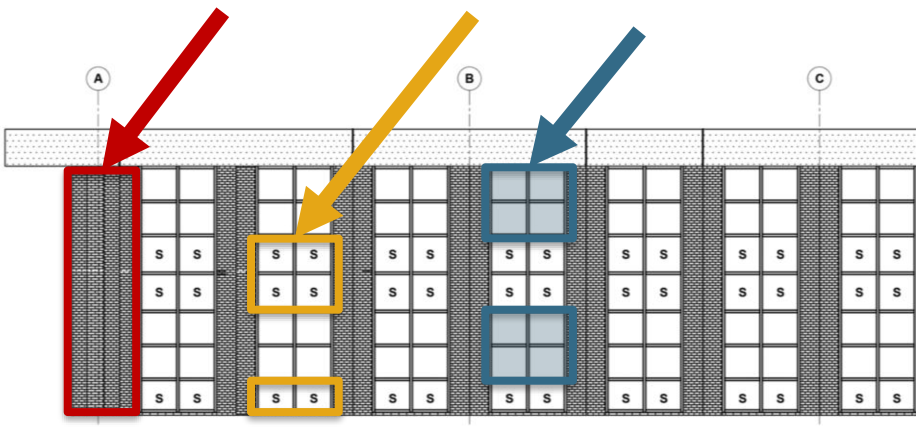
CASE STUDY

Glazing : U_w = 1,8 W/m²-K, SHGC = 0.49 frame factor 10 %

Bricks	U = 0,24 W/m²-K
Sprandel walls	U = 0,24 W/m²-K
Roof	U = 0,18 W/m²-K

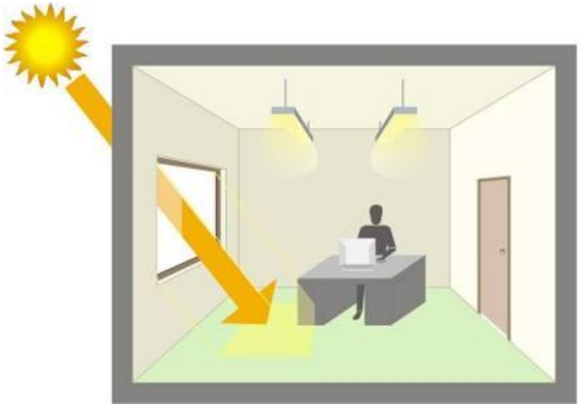


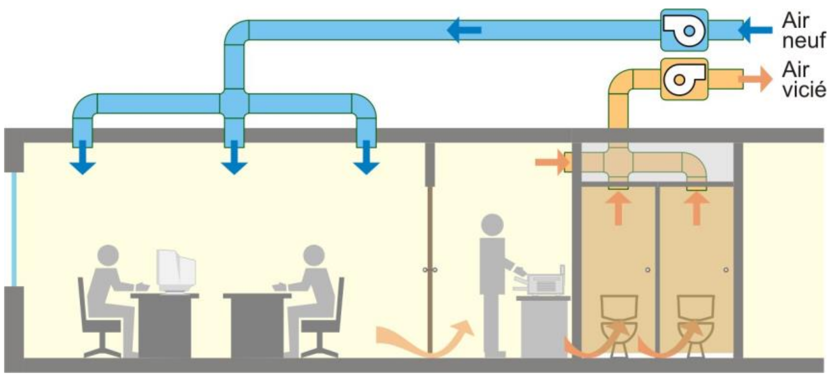
Bricks – Sprandel walls - Windows

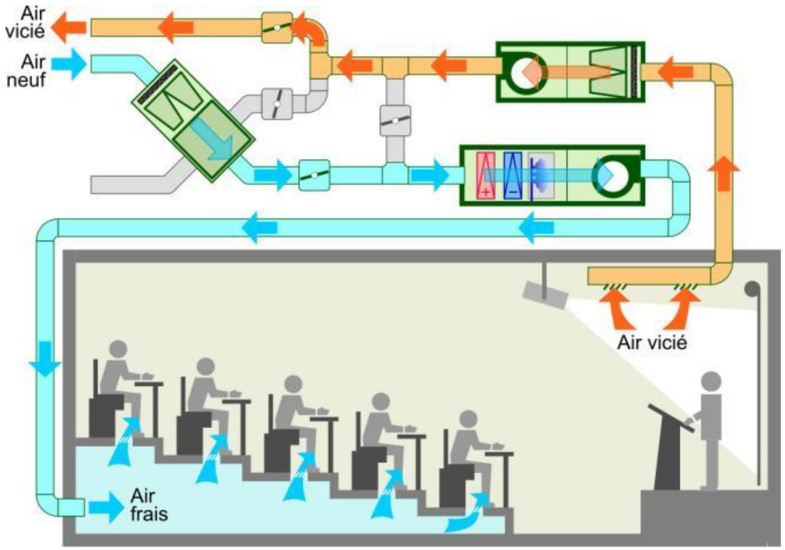


Comfort requirements

- Fresh air per occupant: 40-50 m^3/h
- Internal temperature: 20 à 26 °C
- Internal relative humidity: 40 à 60 %

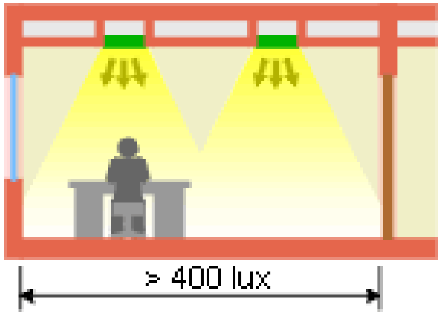




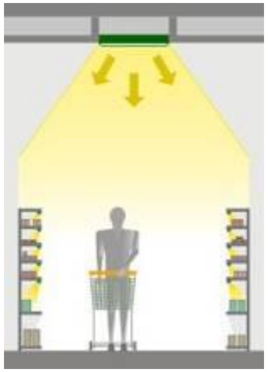


Source: www.energieplus-lesite.be

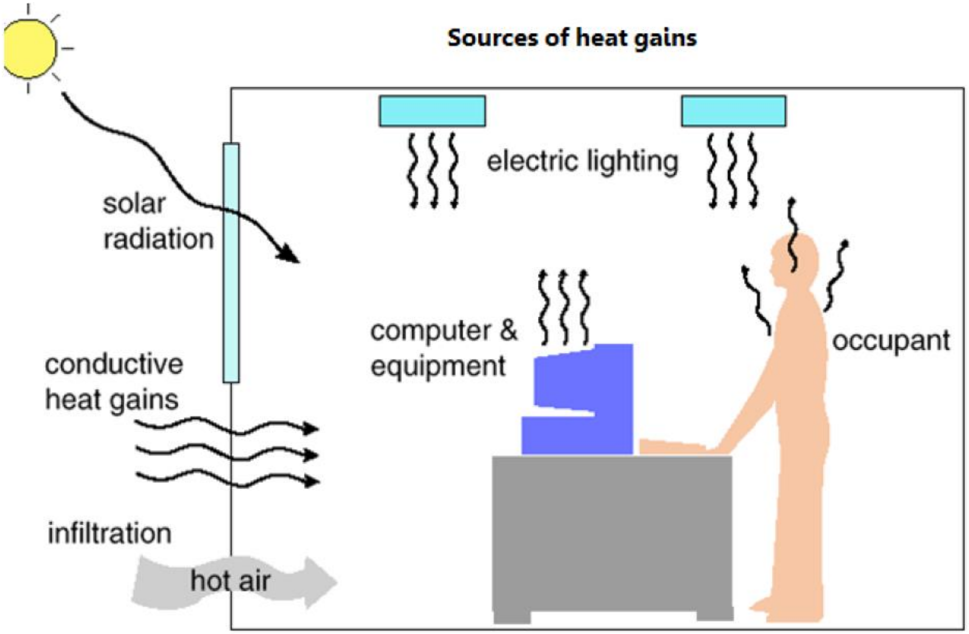
HEAT GAINS

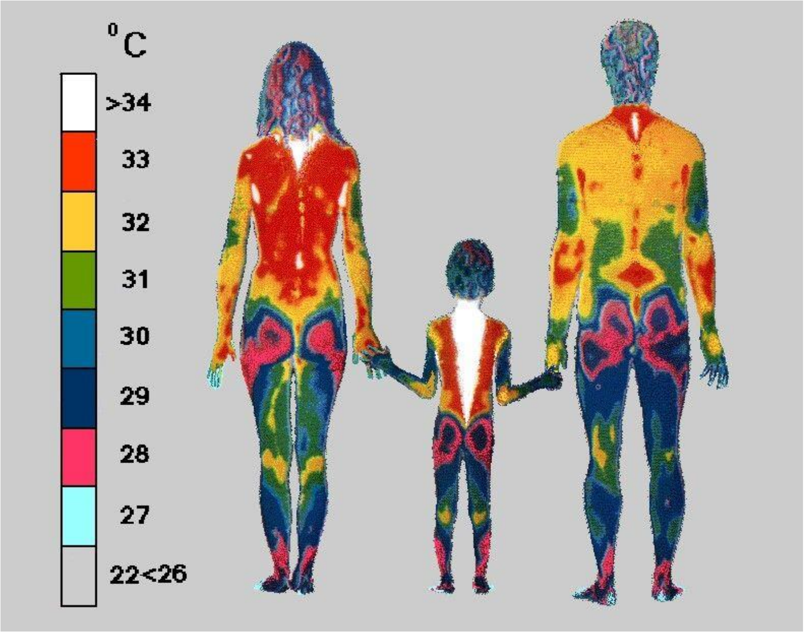


Uniforme: 10 W/m^2



Général: 20 W/m^2

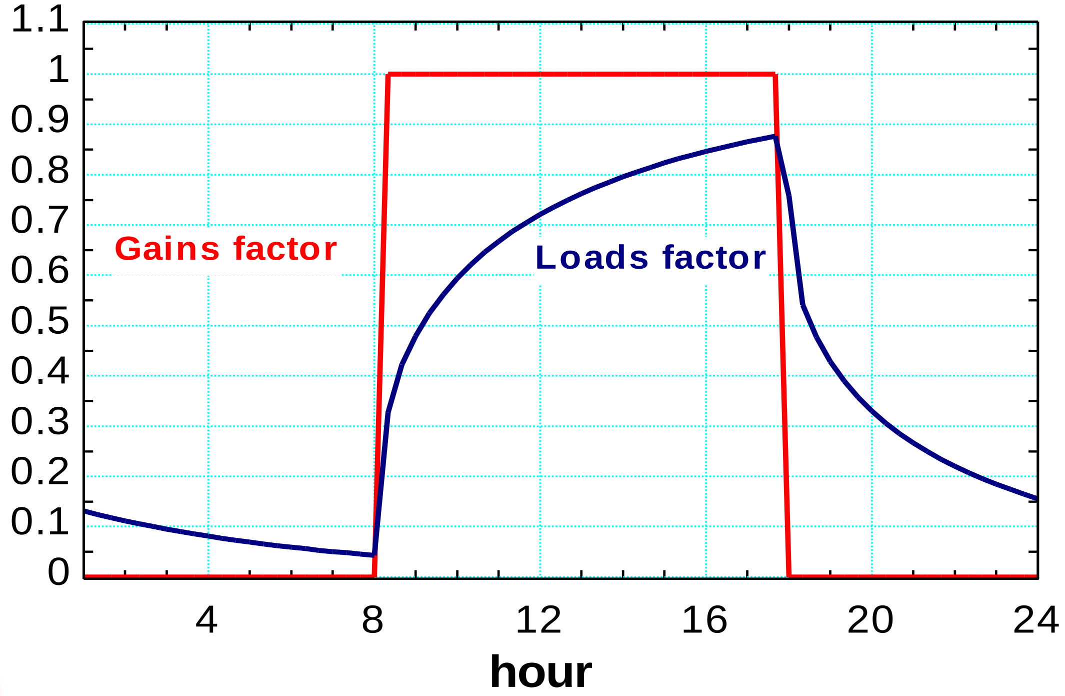




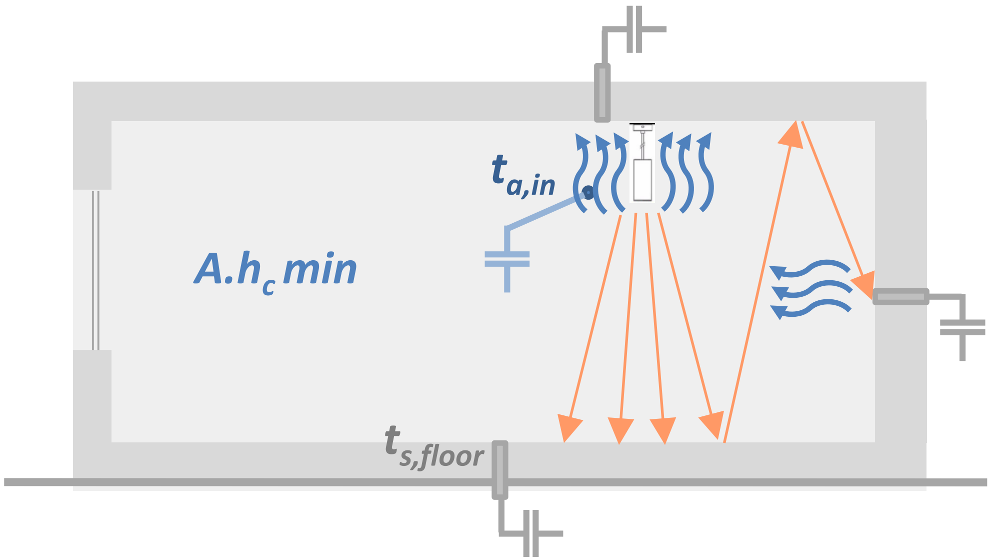
HEAT GAINS vs HEAT LOADS

$$\dot{Q}_l = f_{ad} . \dot{Q}_{l,m}$$

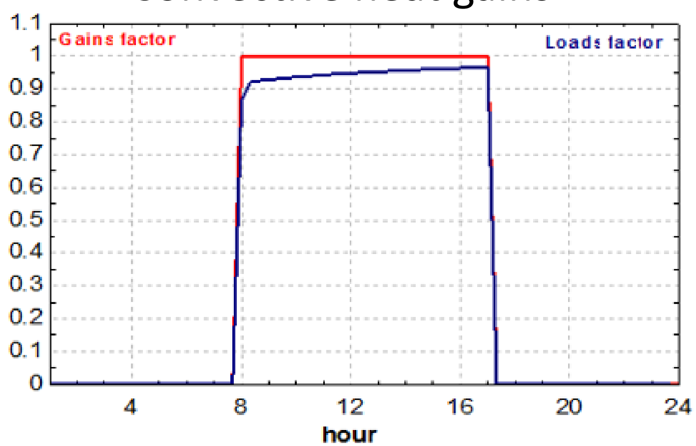
$\dot{Q}_l$	Heat gains	W
f_{ad}	Cooling Load Factor (hour by hour)	-
$\dot{Q}_{l,m}$	Heat loads	W



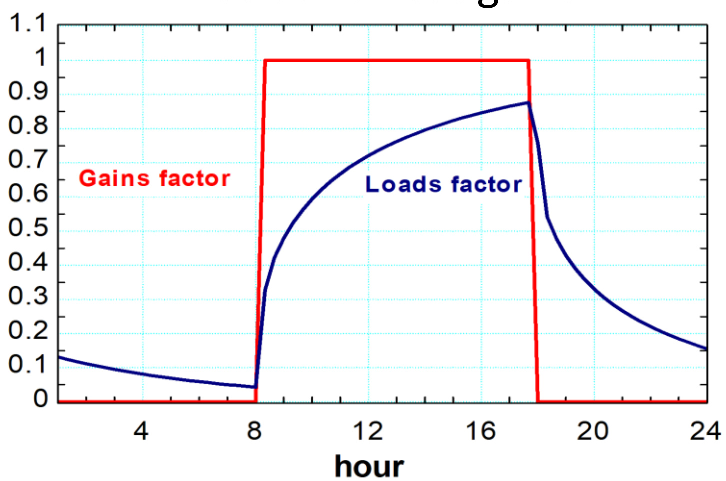
CONVECTIVE vs RADIATIVE HEAT GAINS



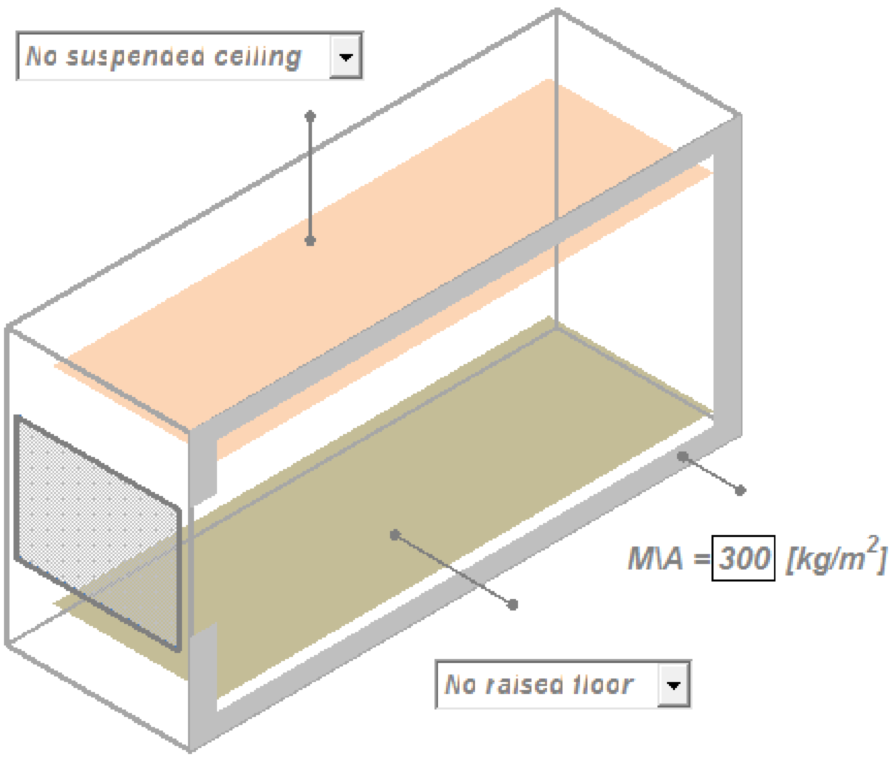
Convective heat gains



Radiative heat gains



LIGHTING AND OCCUPANCY LOADS



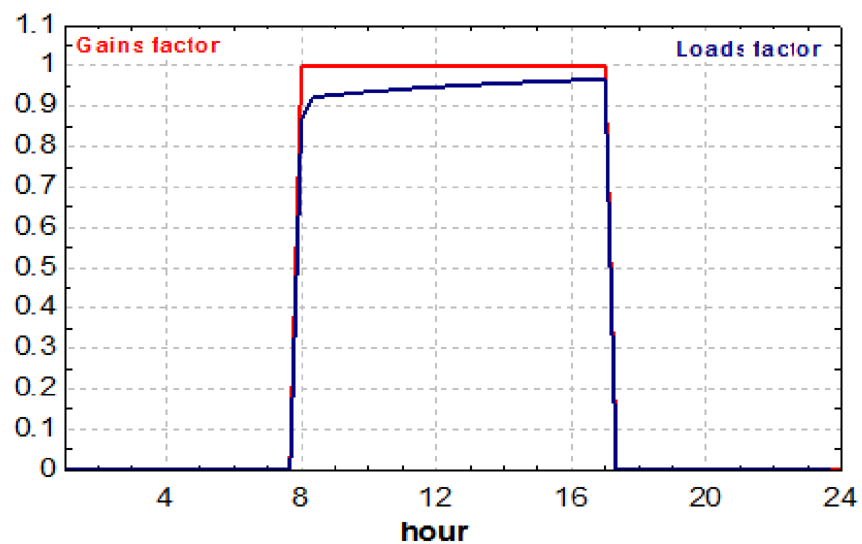
Radiative fraction of Heat gains 0

Heat gains from 8 AM to 5 PM

Plant working from 8 AM to 5 PM

Calculate

Maximum load factor: **0.97**



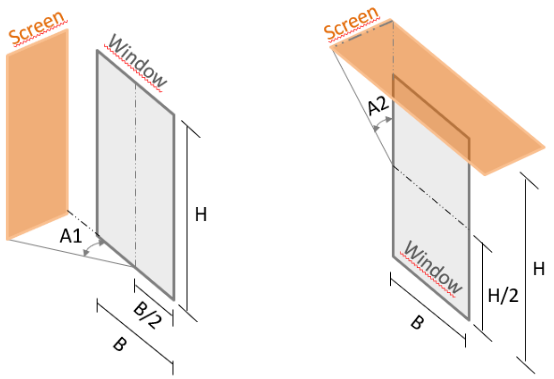
Load_factors

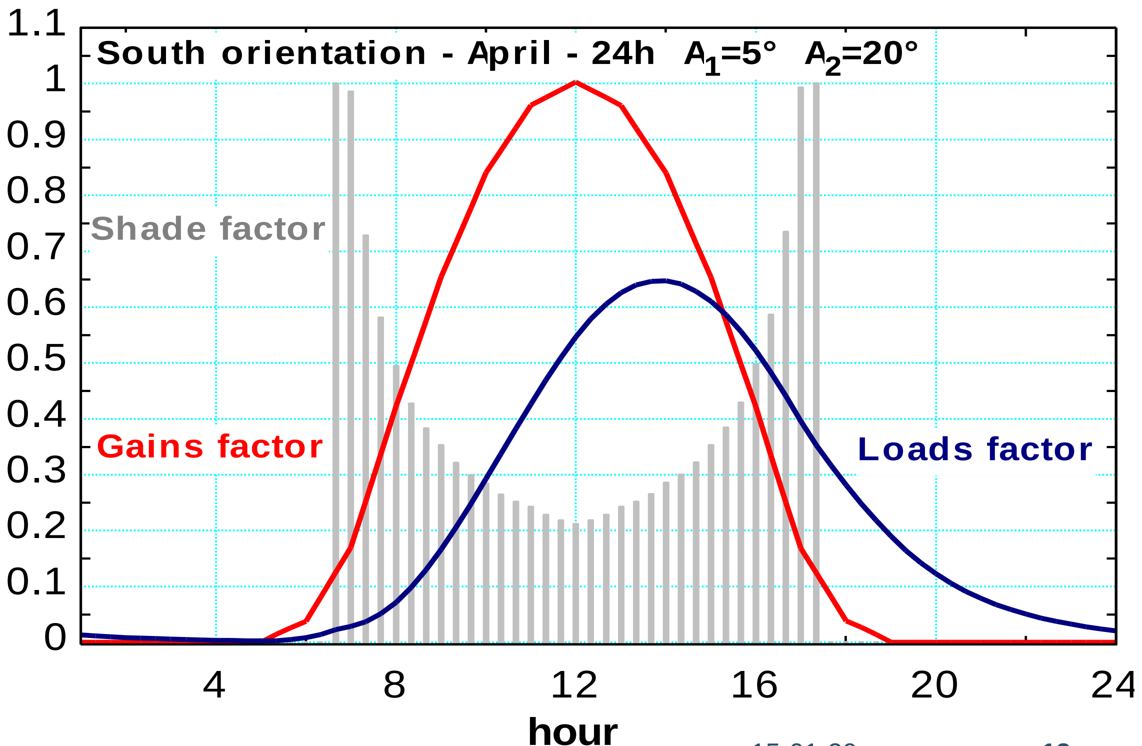
	1 $f_{ad,0}$	2 $f_{ad,1}$	3 $f_{ad,2}$	4 $f_{ad,3}$	5 $f_{ad,4}$	6 $f_{ad,5}$	7 $f_{ad,6}$	8 $f_{ad,7}$	9 $f_{ad,8}$	10 $f_{ad,9}$	11 $f_{ad,10}$	12 $f_{ad,11}$	13 $f_{ad,12}$	14 $f_{ad,13}$	15 $f_{ad,14}$	16 $f_{ad,15}$	17 $f_{ad,16}$	18 $f_{ad,17}$
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.87	0.93	0.94	0.94	0.95	0.95	0.96	0.96	0.96	0.97

SOLAR HEAT LOADS - WINDOWS

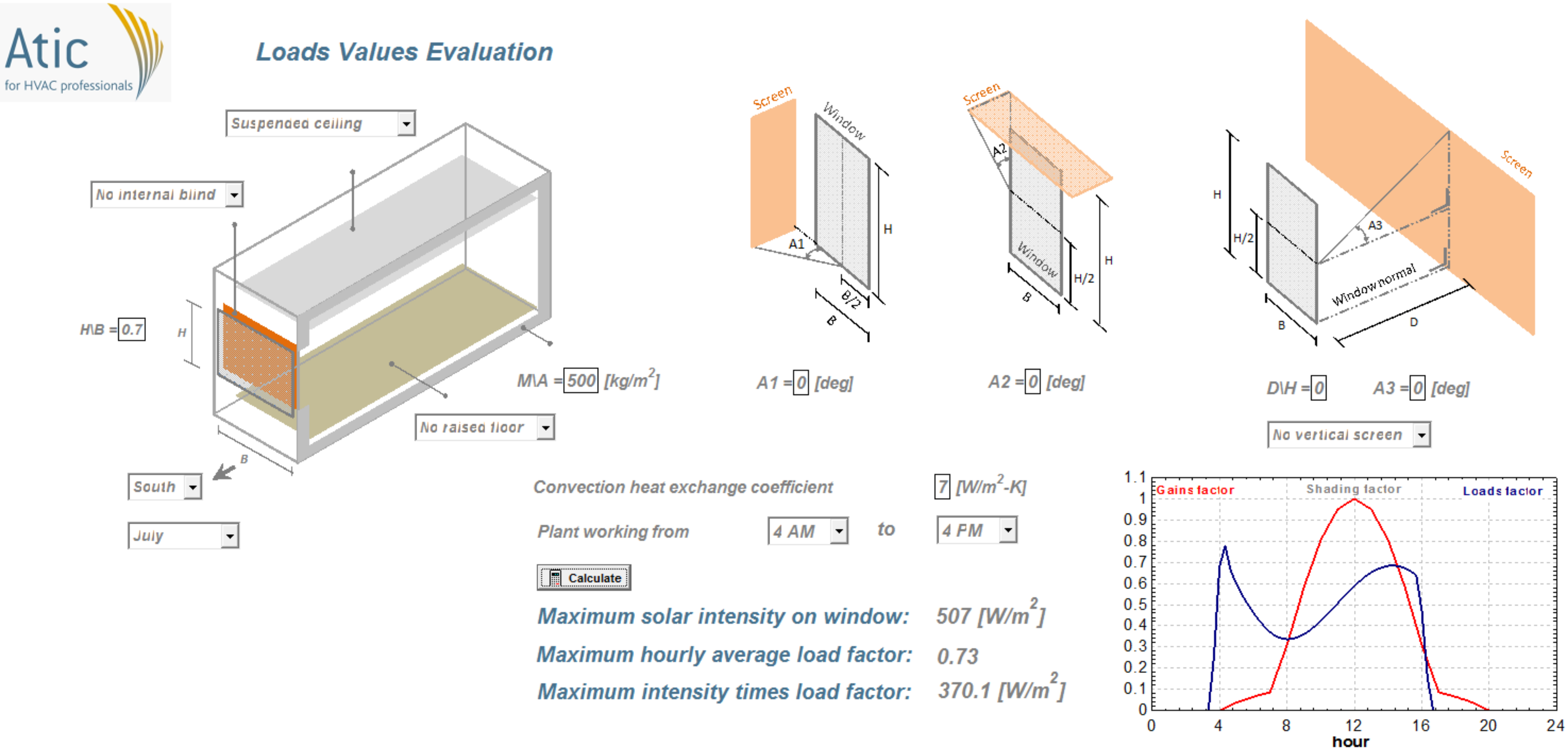
$$\dot{Q}_s = f_{ad,gl} . g . A_{gl} . \phi_{t_{max}}$$

$\dot{Q}_s$	Heat gains	*W*
$f_{ad,gl}$	Cooling Load Factor shading incl.	
$\phi_{t_{max}}$	Max total solar irradiation	*W/m²*

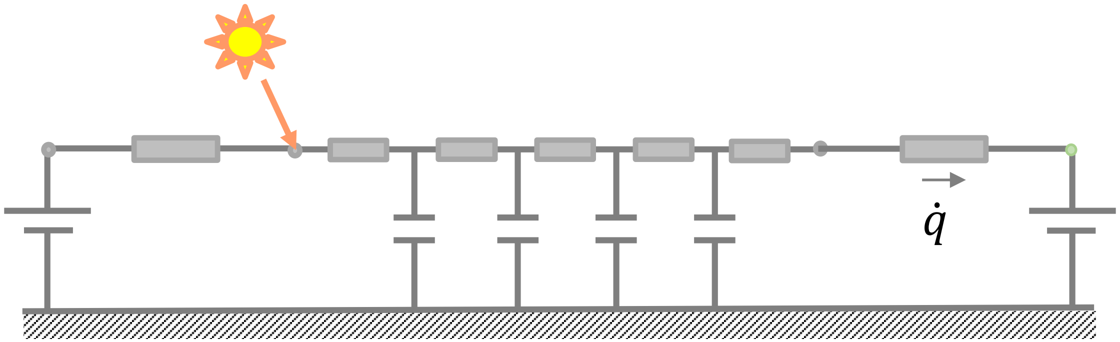


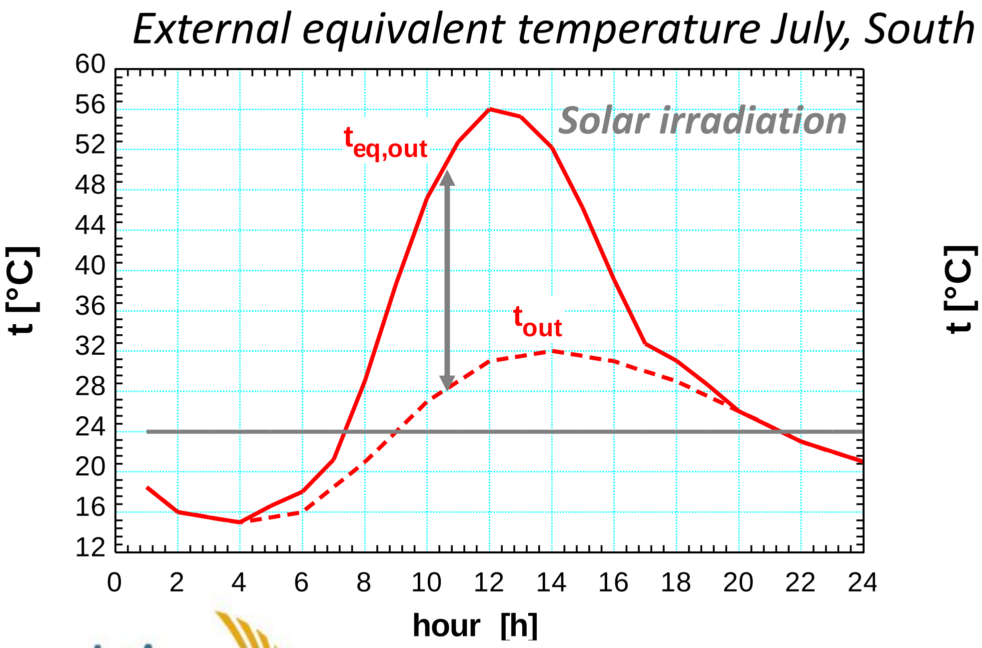


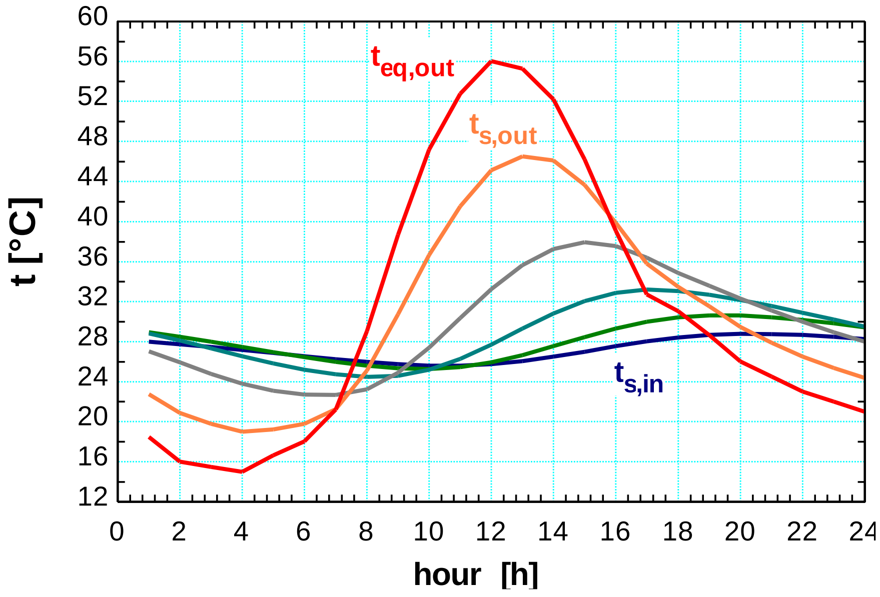
SOLAR HEAT LOADS - WINDOWS



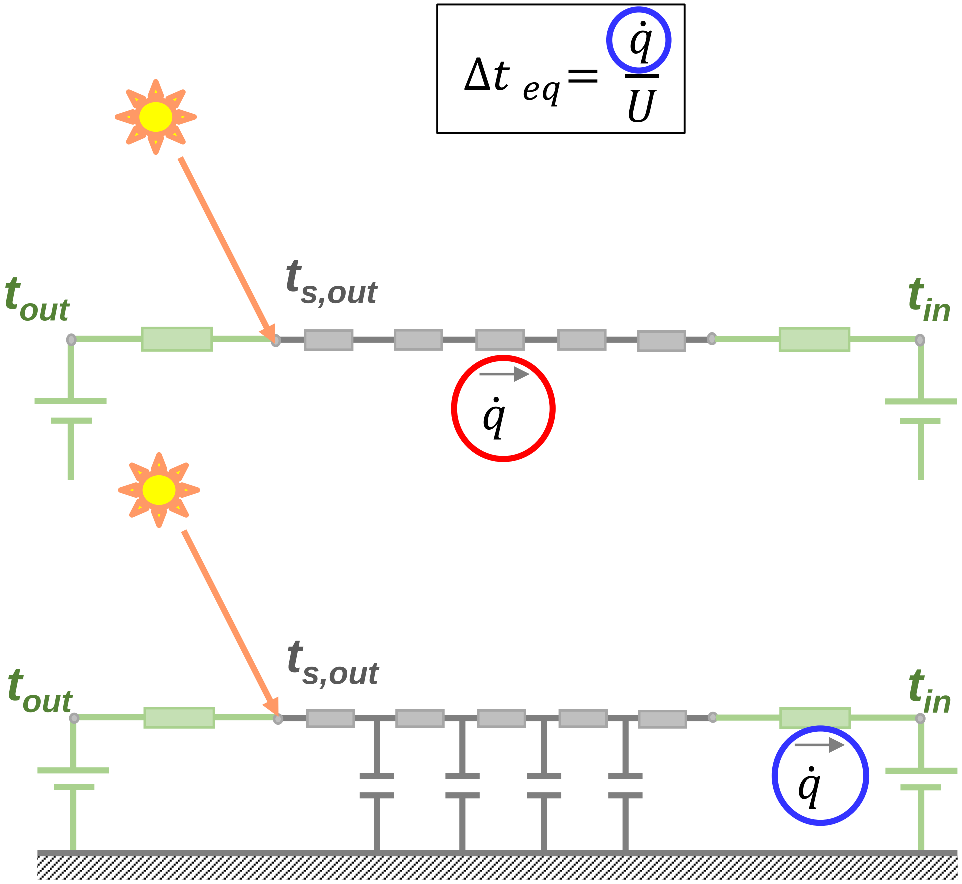
SOLAR HEAT LOADS – OPAQUE WALLS

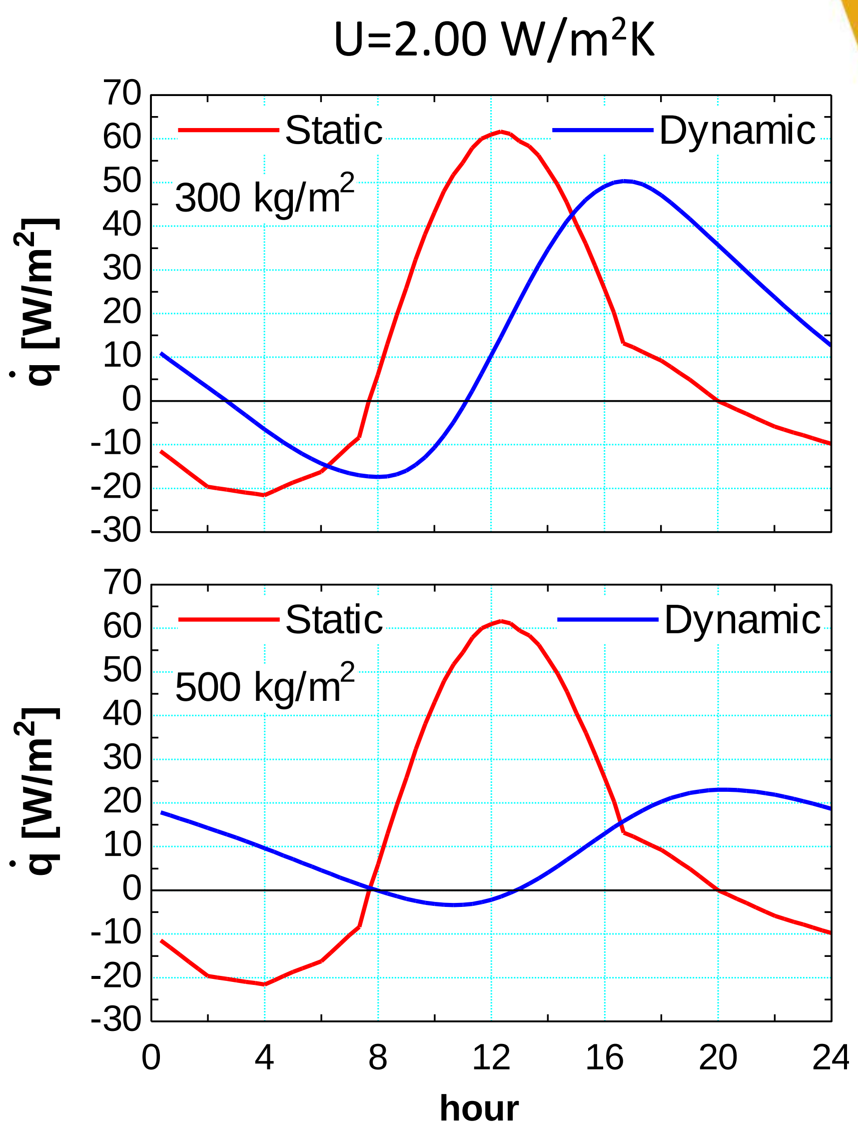




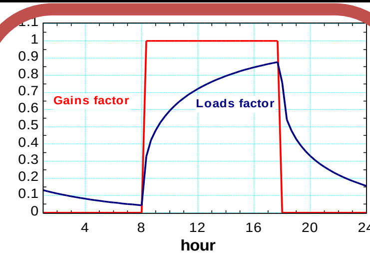
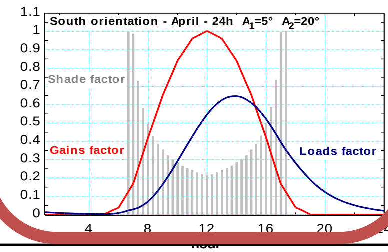
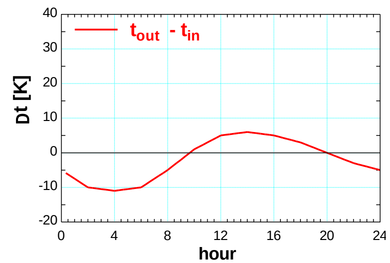
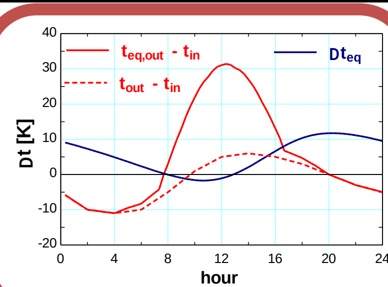


SOLAR HEAT LOADS – OPAQUE WALLS





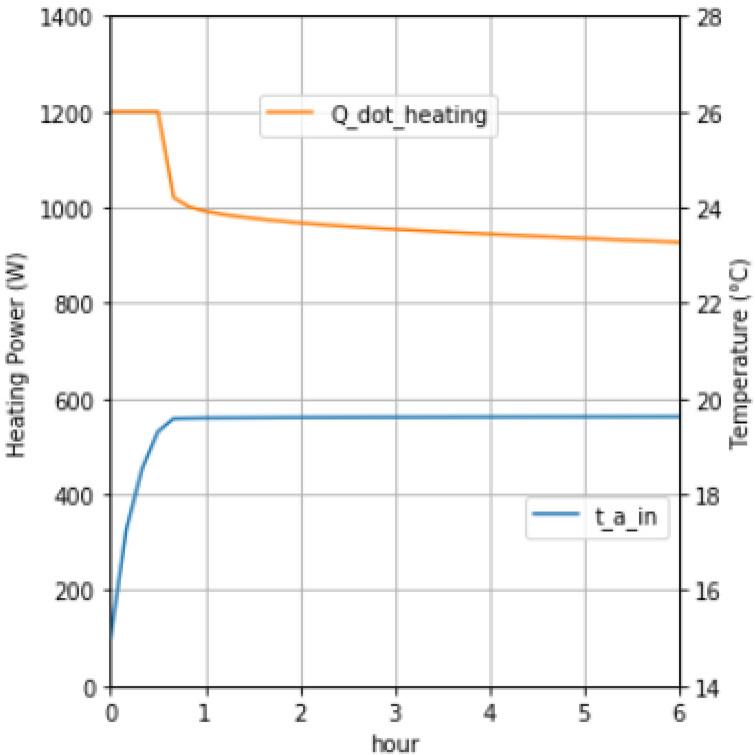
HEAT GAINS

	Heat Gains	Load Factor	Heat Loads
Occupants **Lighting** **Equipment**	Radiative		$\dot{Q} = f_{ad} \cdot \dot{Q}_{rad,max}$
	Convective		$\dot{Q} = f_{ad} \cdot \dot{Q}_{conv,max}$
Windows	Radiative		**Internally accessible mass** $\dot{Q} = f_{ad,gl} \cdot g \cdot A_{gl} \cdot \Phi_{s,max}$
	Transmission		$\dot{Q}_{tr} = AU(t_{out} - t_{in})$
Opaque walls	Radiative + Transmission		$\dot{Q}_{tr} = AU\Delta t_{eq}$ **Total mass**

COOLING SYSTEM SIZING

Hour (summer)		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	0	1
Hour (solar time)		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Step 100% radiative CLF		0,18	0,14	0,11	0,09	0,07	0,07	0,28	0,43	0,54	0,63	0,7	0,75	0,8	0,83	0,86	0,88	0,9	0,91	0,73	0,57	0,45	0,36	0,28	0,23	0,18
Light & occ radiative loads (W)	144	26	20	16	13	10	10	40	62	78	91	101	108	115	120	124	127	130	131	105	82	65	52	40	33	26
Step 100 % convective CLF		0,09	0,07	0,06	0,04	0,04	0,25	0,65	0,72	0,78	0,82	0,85	0,88	0,9	0,92	0,93	0,94	0,95	0,96	0,36	0,28	0,22	0,17	0,14	0,11	0,09
Light & occ convective loads (W)	216	19	15	13	9	9	54	140	156	168	177	184	190	194	199	201	203	205	207	78	60	48	37	30	24	19
South Solar CLF - July		0,01	0	0	0	0	0	0,02	0,04	0,06	0,08	0,09	0,1	0,11	0,11	0,11	0,11	0,11	0,11	0,1	0,08	0,06	0,04	0,02	0,01	0,01
South Solar heat loads (W)	832	8	0	0	0	0	0	17	33	50	67	75	83	91	91	91	91	91	91	83	67	50	33	17	8	8
West Solar CLF - July		0,04	0,02	0,01	0,01	0	0	0,01	0,03	0,04	0,06	0,07	0,07	0,08	0,08	0,08	0,08	0,08	0,11	0,22	0,31	0,32	0,22	0,12	0,07	0,04
West Solar heat loads (W)	1094	44	22	11	11	0	0	11	33	44	66	77	77	88	88	88	88	88	120	241	339	350	241	131	77	44
South brick wall DTE- July (K)		6,4	5,9	5,2	4,4	3,5	2,6	1,6	0,5	-0,4	-1,3	-1,9	-2,3	-2,1	-1,5	-0,4	1	2,5	4,1	5,4	6,4	7	7,3	7,2	7	6,5
South brick wall (W)	1,34	9	8	7	6	5	3	2	1	-1	-2	-3	-3	-3	-2	-1	1	3	5	7	9	9	10	10	9	9
South spandrel wall DTE- July (K)		-4,7	-6,8	-9,3	-10,3	-10,9	-10,2	-9,1	-6,8	-1,7	6	13,2	18,4	21,8	22,4	20,8	17	12	6,4	4,5	2,7	0,6	-1,1	-2,6	-3,7	-4,7
South spandrel wall (W)	1,34	-6	-9	-12	-14	-15	-14	-12	-9	-2	8	18	25	29	30	28	23	16	9	6	4	1	-1	-3	-5	-6
West brick wall DTE- July (K)		9,6	9,1	8,4	7,5	6,4	5,2	4	2,7	1,6	0,5	-0,3	-1	-1,3	-1,4	-1,2	-0,8	0	1,2	2,7	4,5	6,3	7,9	9,1	9,7	9,6
West brick wall (W)	0,89	9	8	7	7	6	5	4	2	1	0	0	-1	-1	-1	-1	-1	0	1	2	4	6	7	8	9	9
West spandrel wall DTE- July (K)		-4,7	-6,8	-9,3	-10,3	-10,9	-10,2	-9,1	-6,8	-4	-1	2,1	4,4	6,4	12,7	20	25,2	28	27,6	23,8	16,1	3,1	-1	-2,6	-3,7	-4,7
West spandrel wall (W)	1,34	-6	-9	-12	-14	-15	-14	-12	-9	-5	-1	3	6	9	17	27	34	37	37	32	22	4	-1	-3	-5	-6
Roof DTE - July (K)		-4,3	-6	-8,4	-9,9	-10,6	-8,8	-3,1	5,7	16,3	27	36,6	44,1	48,9	50,6	49,2	44,9	38,3	29,9	20,6	11,4	4,1	0	-1,9	-3,3	-4,3
Roof (W)	1,51	-7	-9	-13	-15	-16	-13	-5	9	25	41	55	67	74	77	74	68	58	45	31	17	6	0	-3	-5	-7
External dry temperature (°C)		21	18,5	16	15,5	15	15,5	16	18,5	21	24	27	29	31	31,5	32	31,5	31	30	29	27,5	26	24,5	23	22	21
DT dry- July (K)		-5	-7,5	-10	-10,5	-11	-10,5	-10	-7,5	-5	-2	1	3	5	5,5	6	5,5	5	4	3	1,5	0	-1,5	-3	-4	-5
Windows transmission gains (W)	12,05	-60	-90	-121	-127	-133	-127	-121	-90	-60	-24	12	36	60	66	72	66	60	48	36	18	0	-18	-36	-48	-60
Infiltration sensible gains (W)	11,00	-55	-83	-110	-116	-121	-116	-110	-83	-55	-22	11	33	55	61	66	61	55	44	33	17	0	-17	-33	-44	-55
Total heat load (W)		-20	-127	-214	-239	-270	-210	-46	104	243	400	532	620	712	744	769	761	744	740	655	638	539	342	157	53	-20

HEATING SYSTEM SIZING



- Transmission losses:
  - 400 W
- Ventilation & Infiltration :
  - 180 W with recovery HX
  - 720 W no recovery HX
- Heating restart
  - 620 W
- Total
  - 1200 W with recovery HX
  - 1700 W no recovery HX

DYNAMIC SIMULATION - APPLICATIONS

System sizing

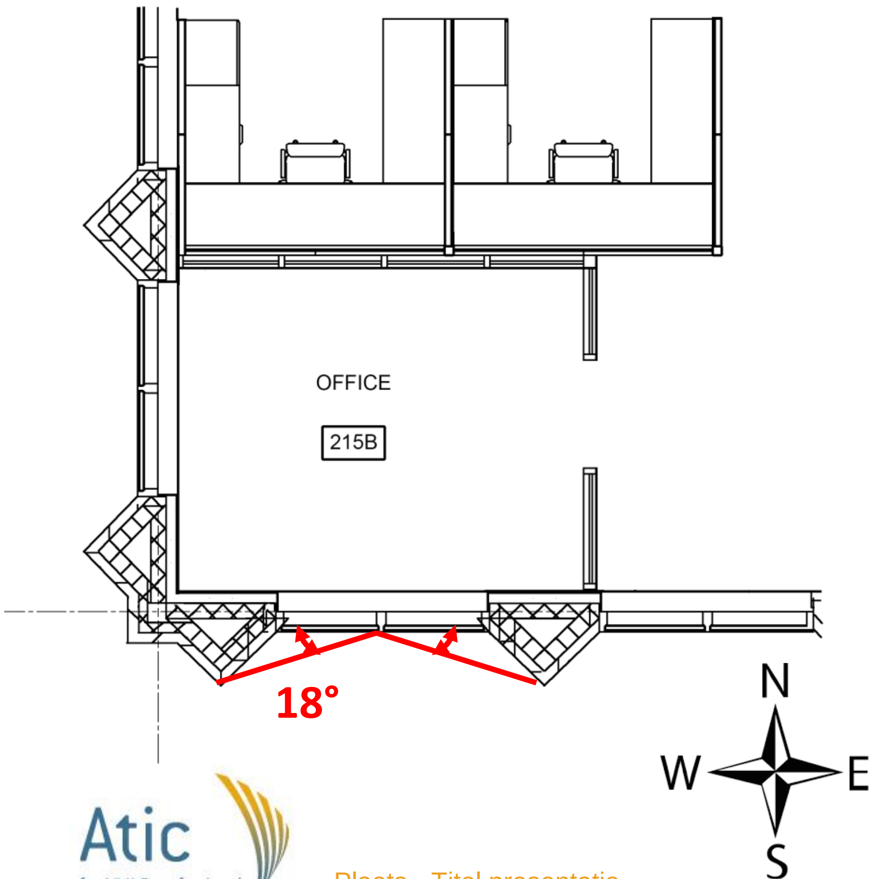
Energy Consumptions

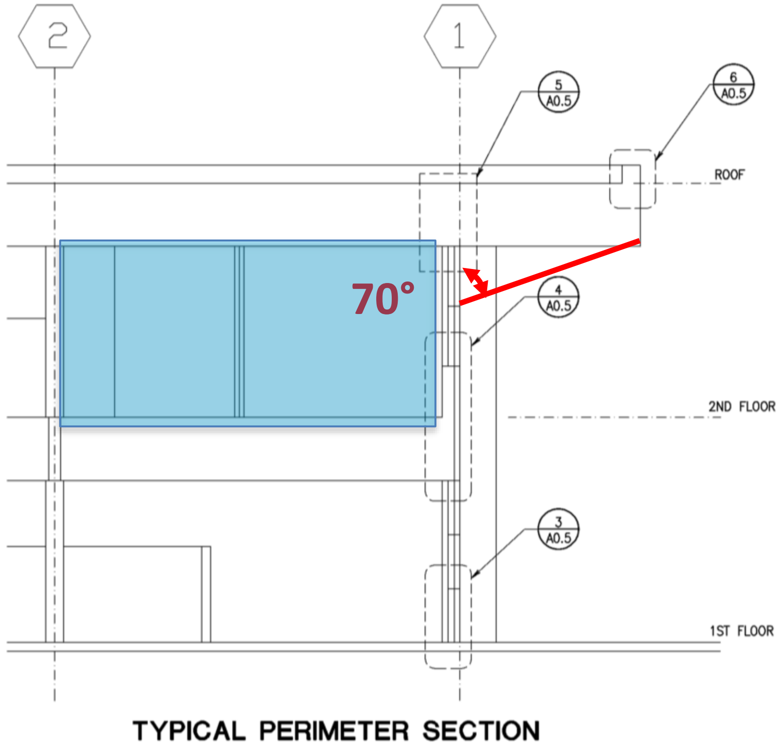
Validation

Identification

CASE STUDY

Glazing : U_w = 1,8 W/m2-K, SHGC = 0.49 frame factor 10 %





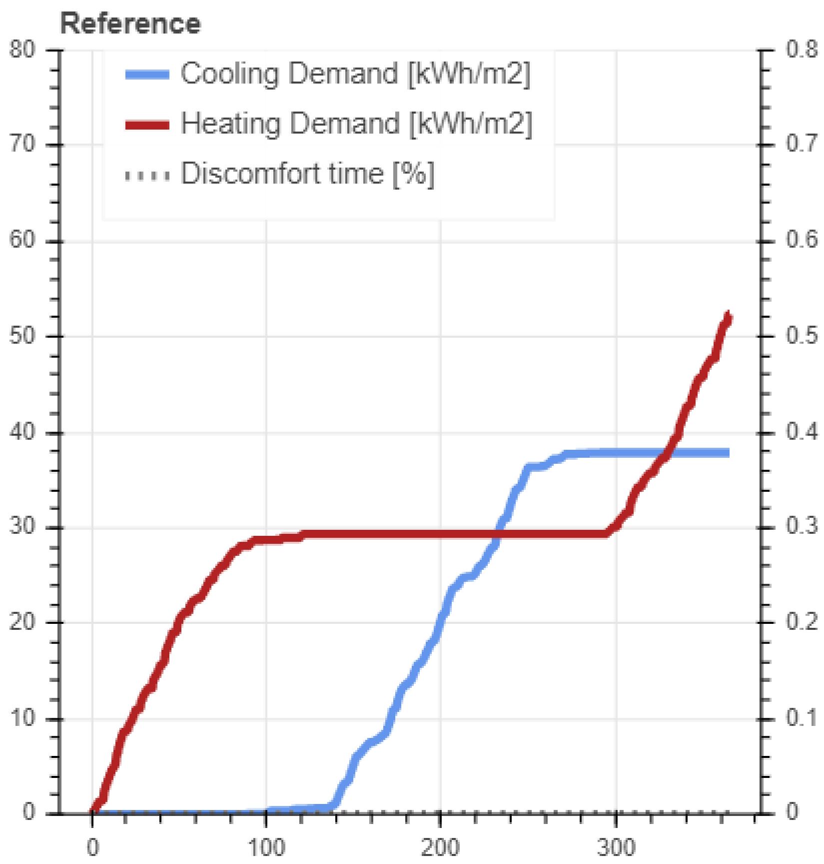
IMPROVEMENT STEPS

- Reference:
  - Suspended ceiling and raised floor, no solar screens
- Envelope :
  - Accessible thermal mass
  - Solar shading
- System control improvement:
  - Daytime free cooling : bypass of the heat recovery exchanger
  - Night free cooling
  - Optimized free cooling control

Envelope :

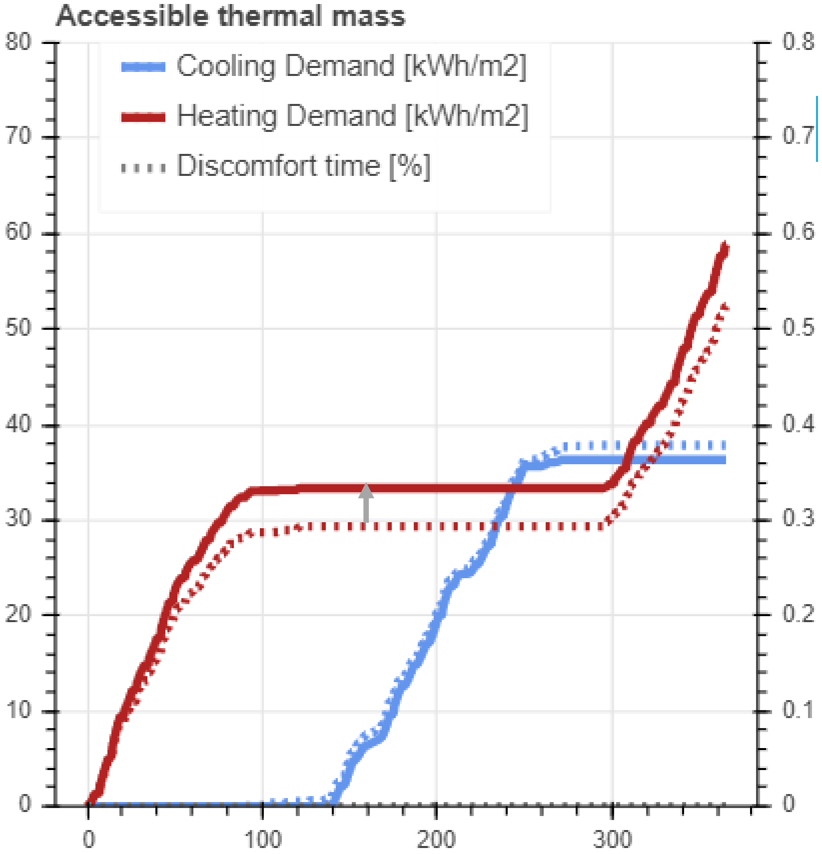
  - Extra insulation thickness for external walls (+ 5 cm)

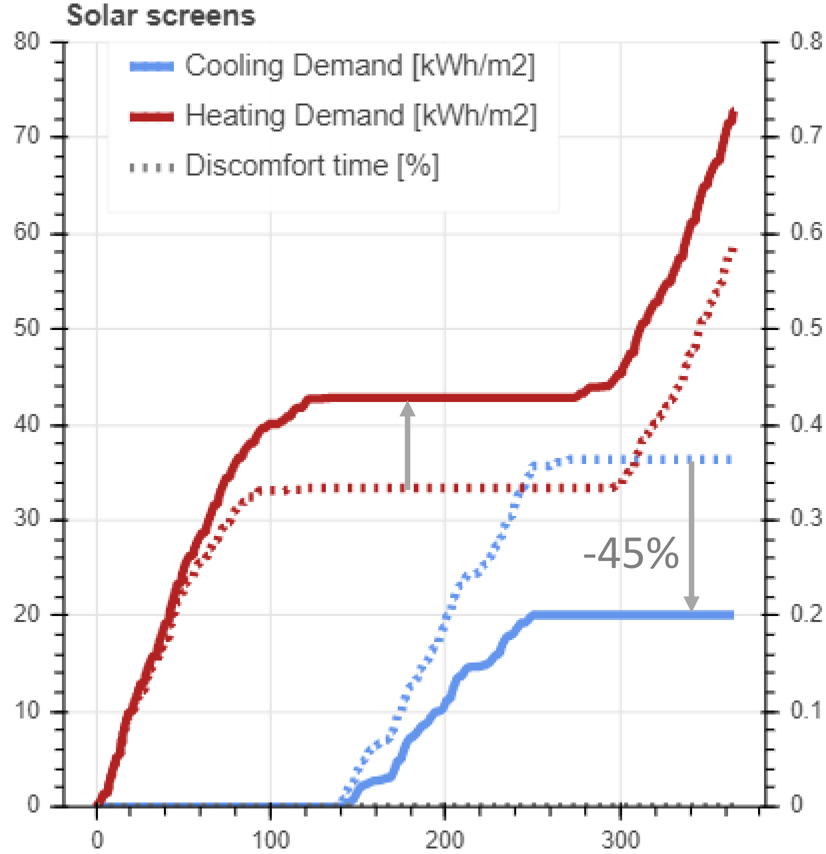
REFERENCE



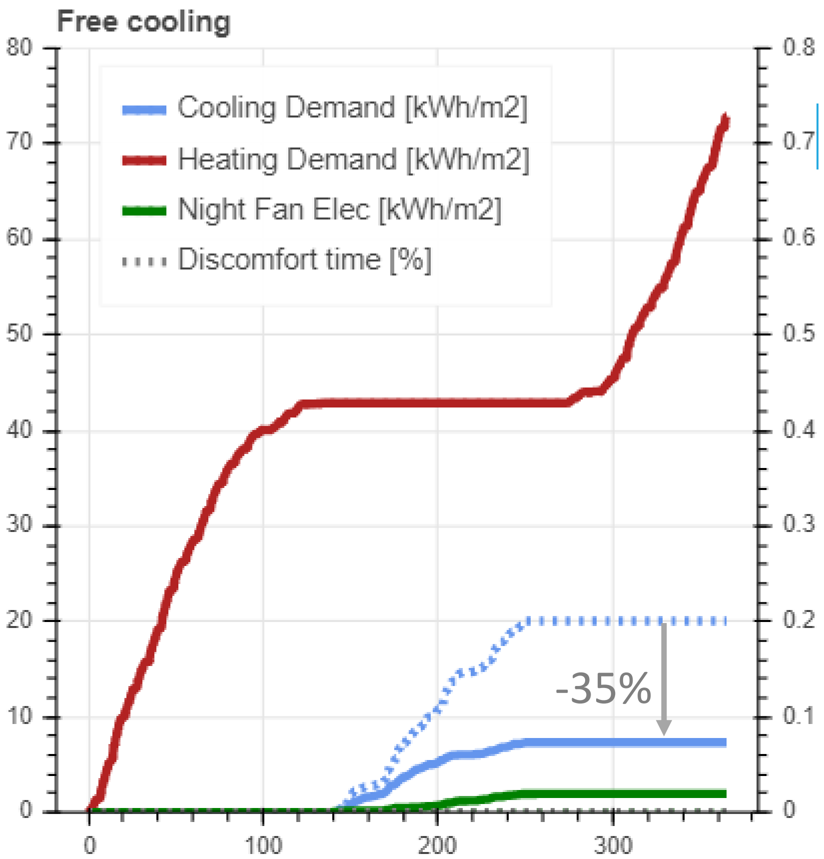
- Average weather data
- Temperature set points :
  - Summer 26°C / 30°C
  - Winter 21°C / 16°C
- Occupancy:
  - 8 h – 18 h
  - 7.5 m^2/occ
  - 40 m^3/h.occ fresh air
  - 6 W/m^2 lighting
  - 10 W/m^2 appliances
- Heat recovery exchanger

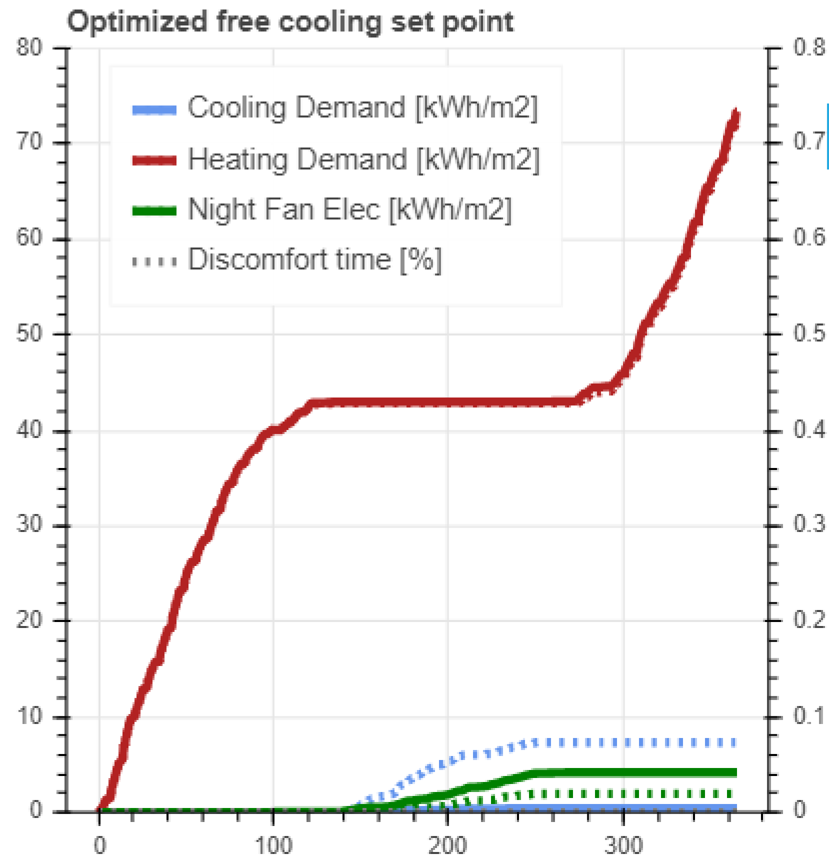
ENVELOPE IMPROVEMENTS



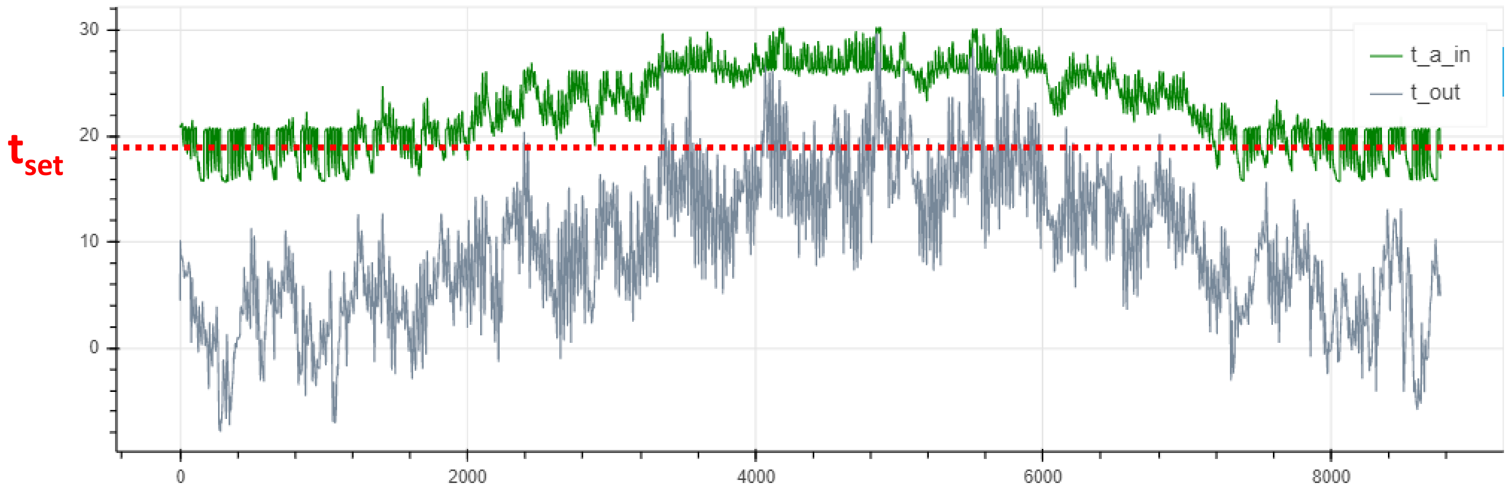


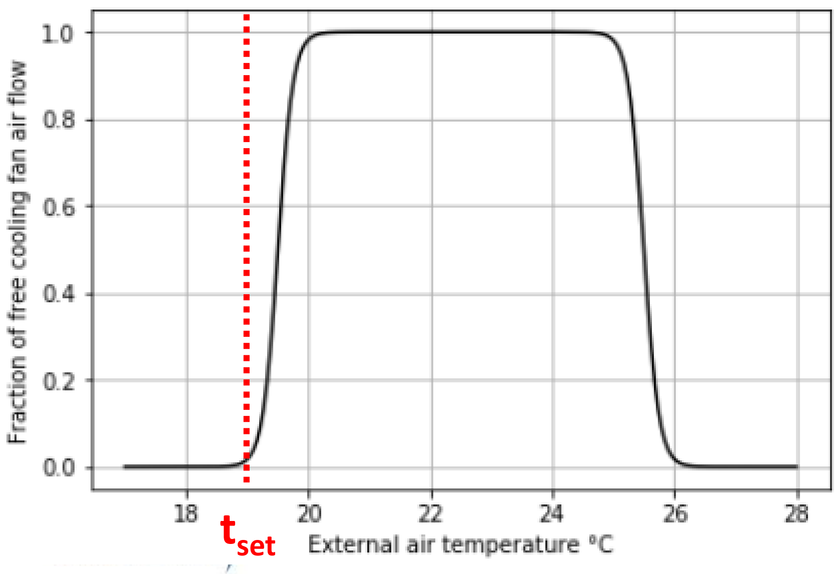
SYSTEM CONTROL IMPROVEMENT

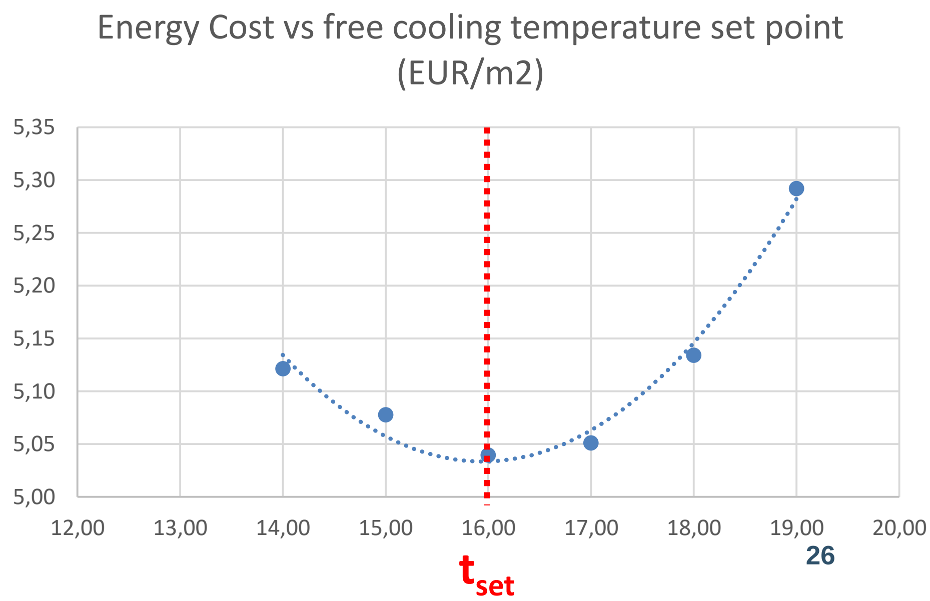




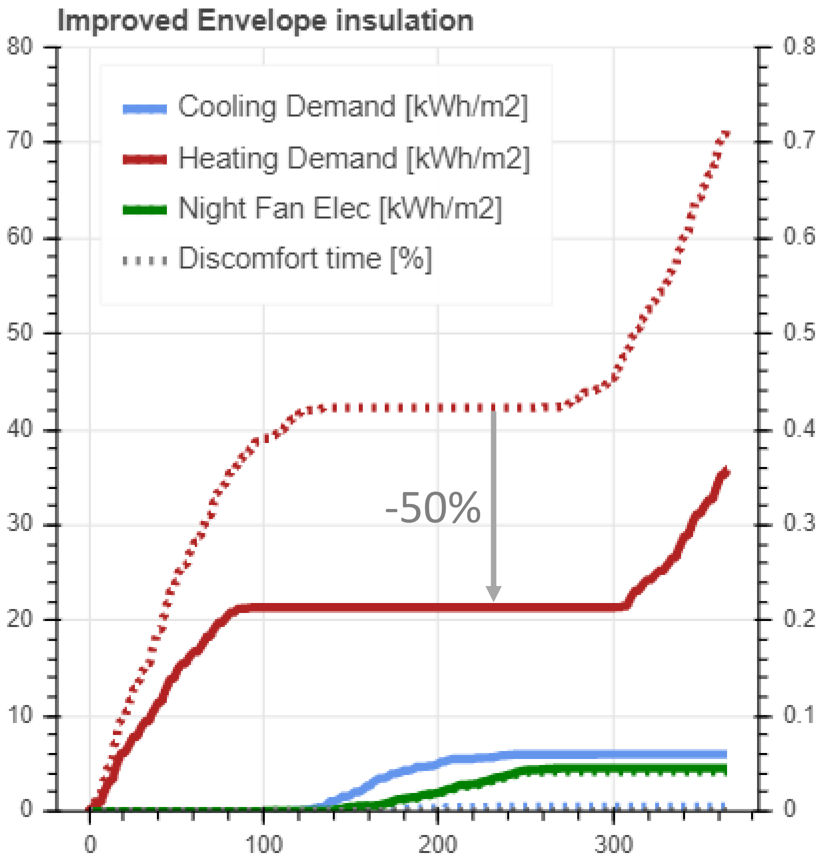
OPTIMIZATION FREE COOLING SET POINT

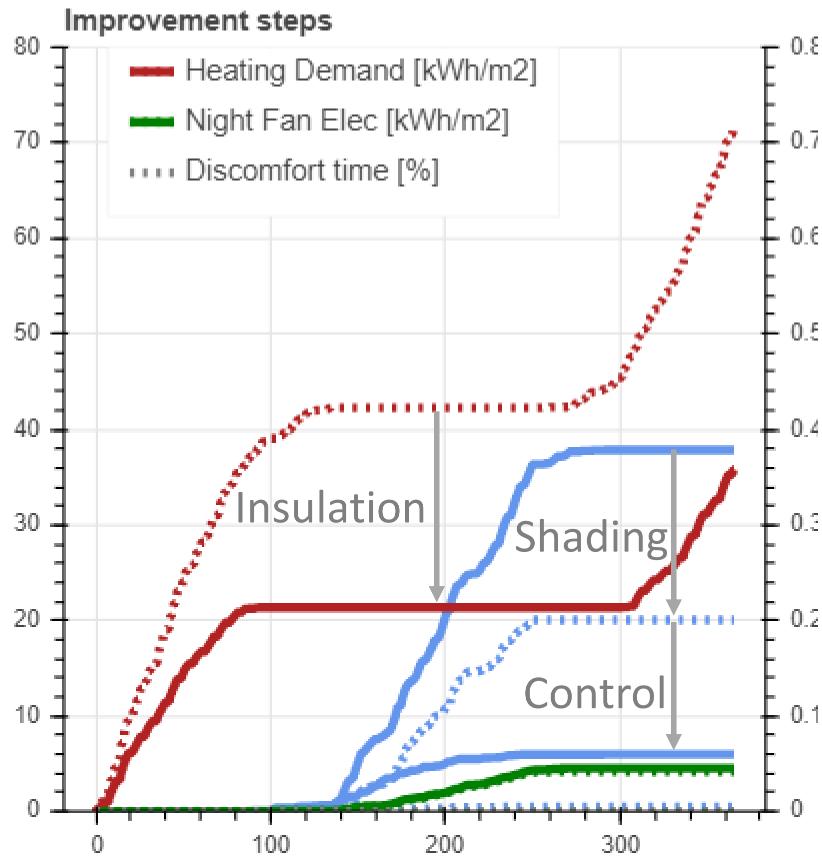




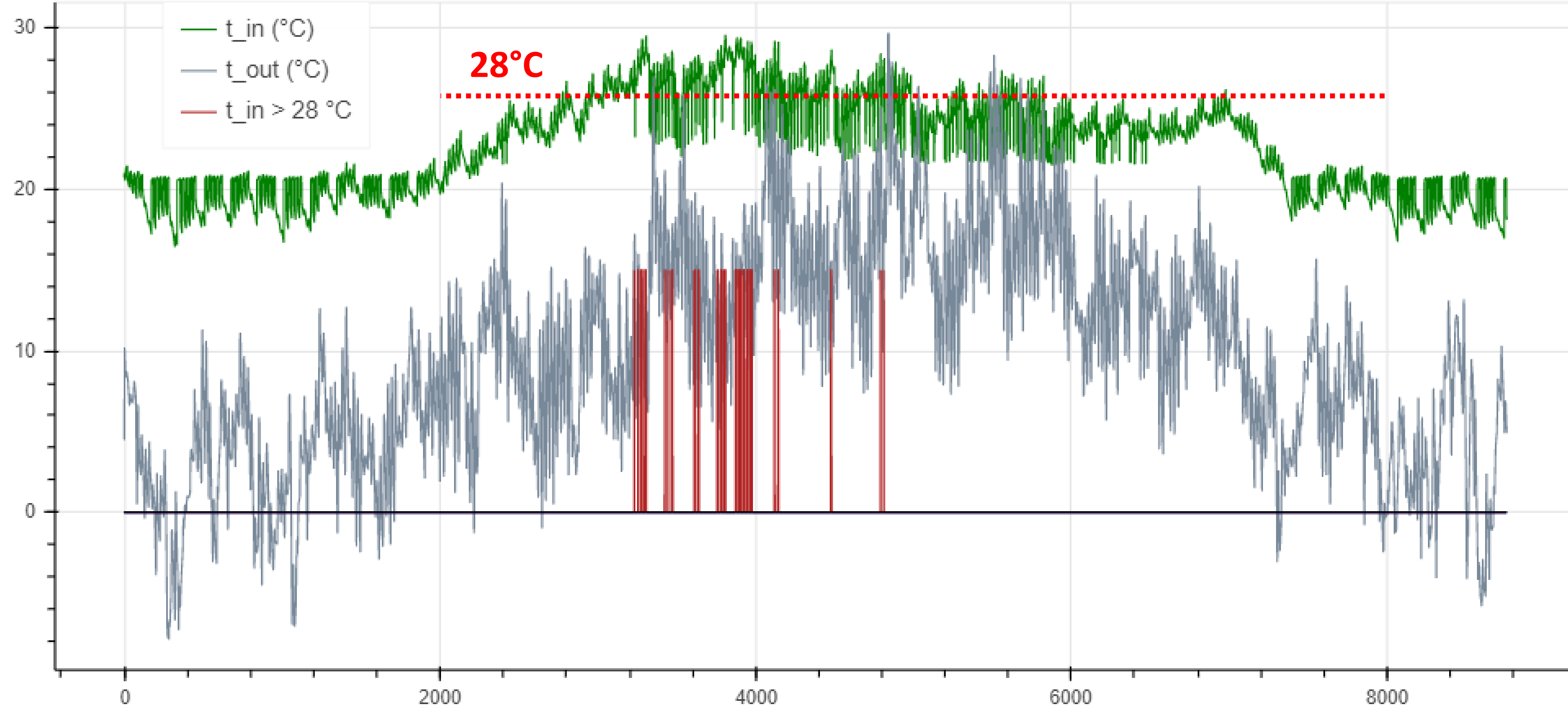


EXTRA ENVELOPE INSULATION

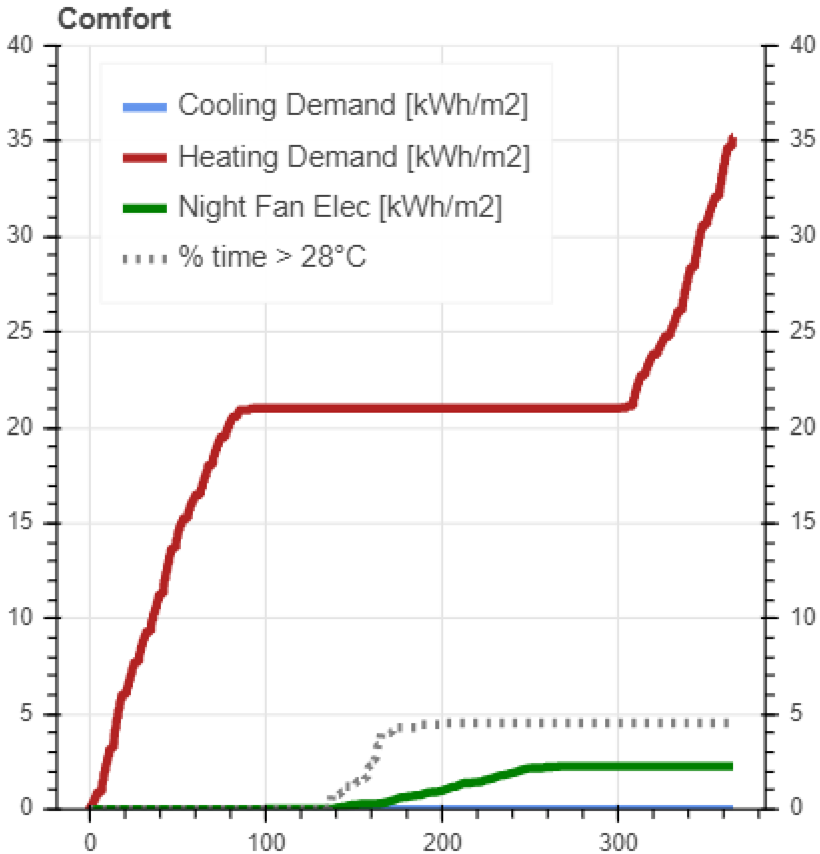


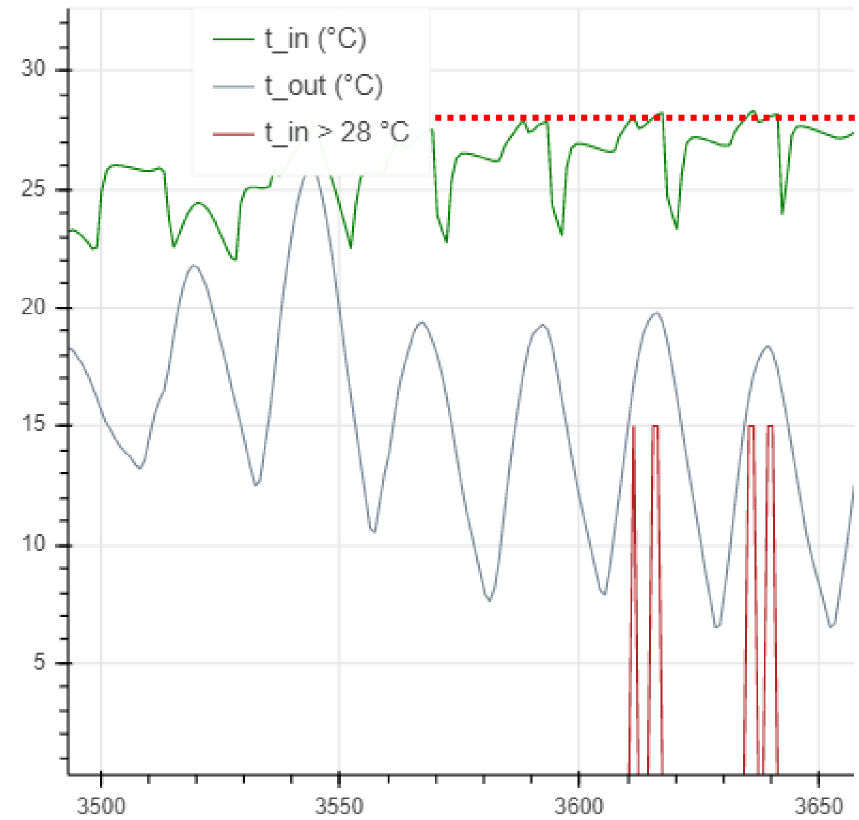


THERMAL COMFORT – NO CHILLER



THERMAL COMFORT – NO CHILLER





CONCLUSION

- Dynamic simulation of building:
  - Sizing of Heating and cooling systems
  - Prediction of energy consumption
  - Prediction of thermal comfort

- Improvements options:
  - Shading systems
  - Optimization of control >>> ROI < 15 years
  - Envelope insulation >>> ROI > 15 years

DYNAMIC SIMULATION - APPLICATIONS

System sizing

Energy Consumptions

Validation

Identification

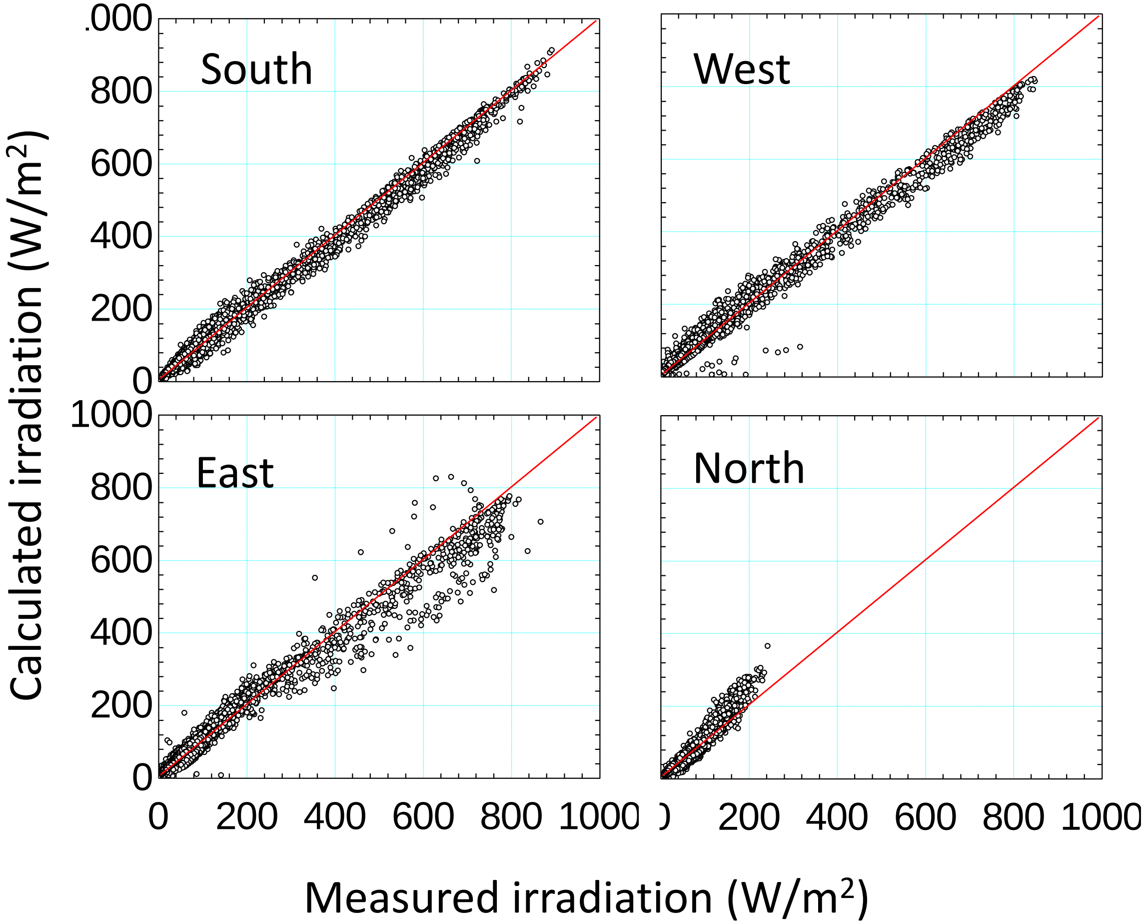
VALIDATION OF SIMULATION TOOLS

IEA EBC Annex 71 Holzkichen Twin Test Houses

VALIDATION OF SIMULATION TOOLS

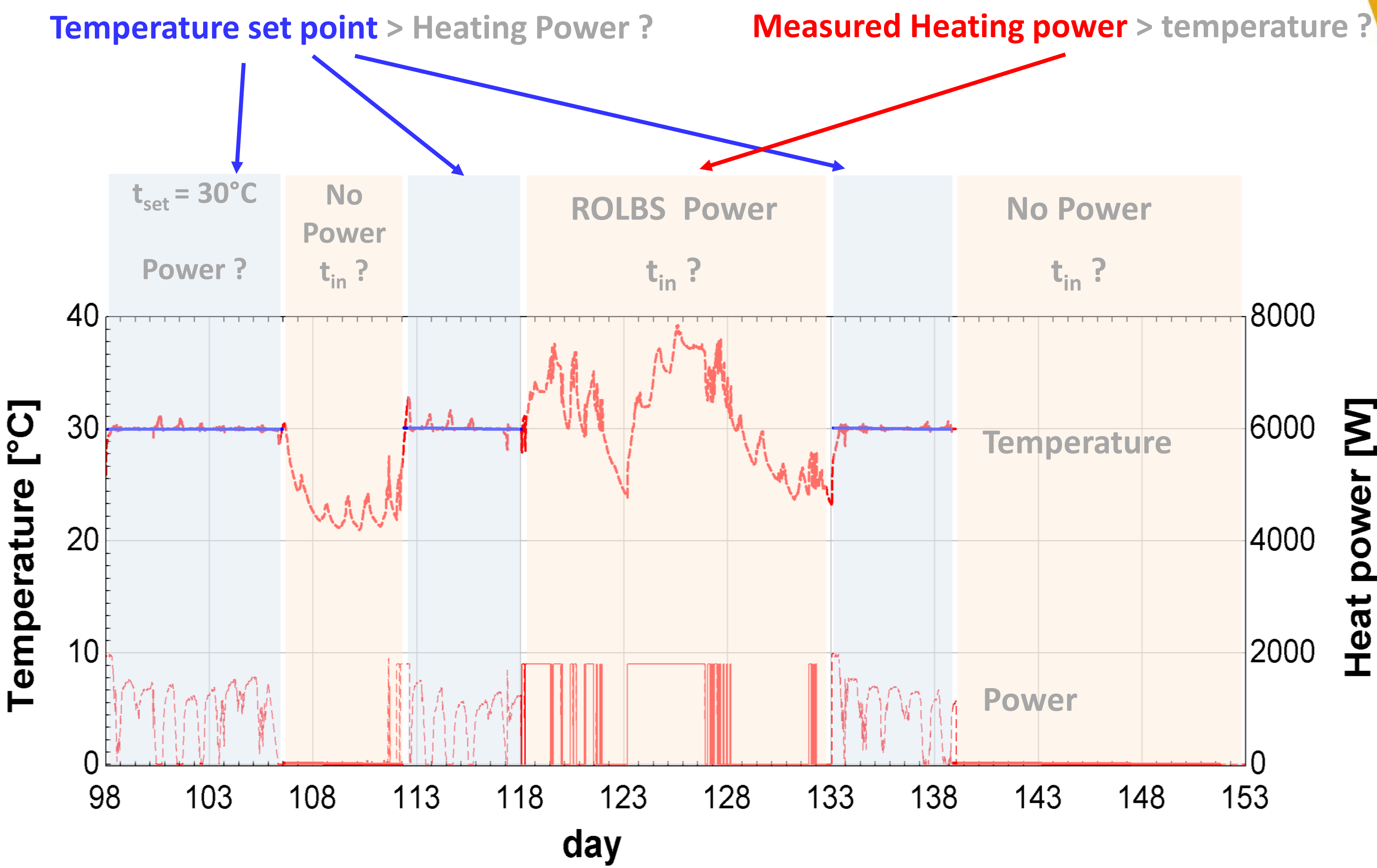
Calculated vs measured solar irradiation on facades

IEA EBC Annex 71 Holzkichen



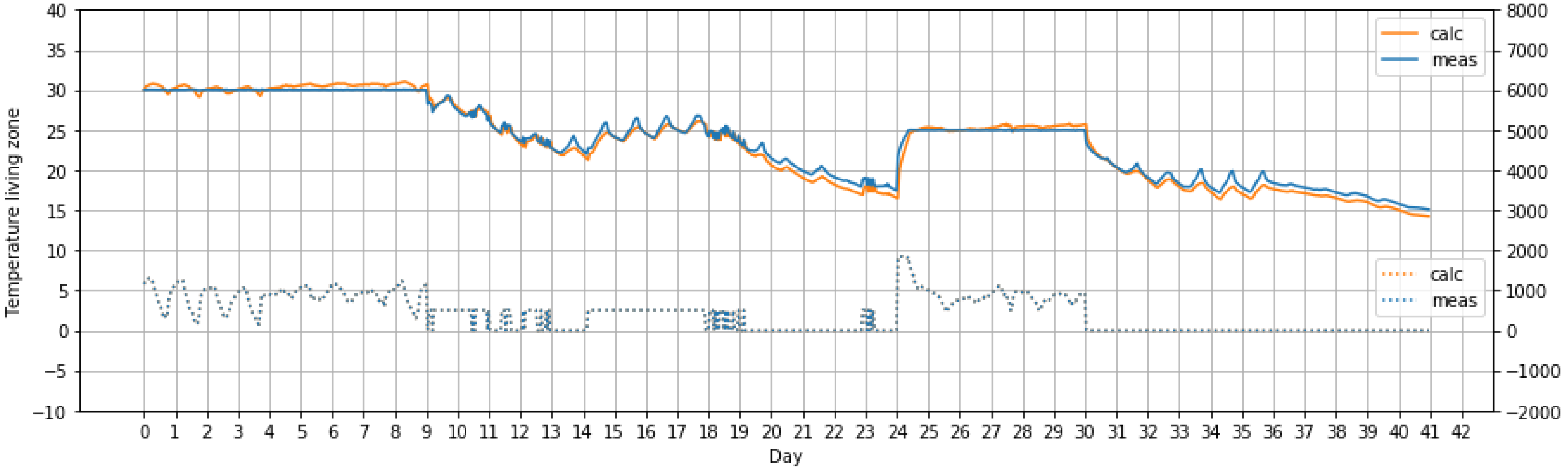
Atic
for HVAC professionals

BLIND EXPERIMENT



VALIDATION OF SIMULATION TOOLS

IEA EBC Annex 71 Holzkichen Twin Test Houses



VALIDATION OF SIMULATION TOOLS

IEA EBC Annex 71
Holzkichen Twin Test Houses

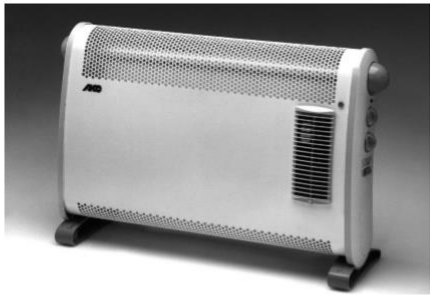
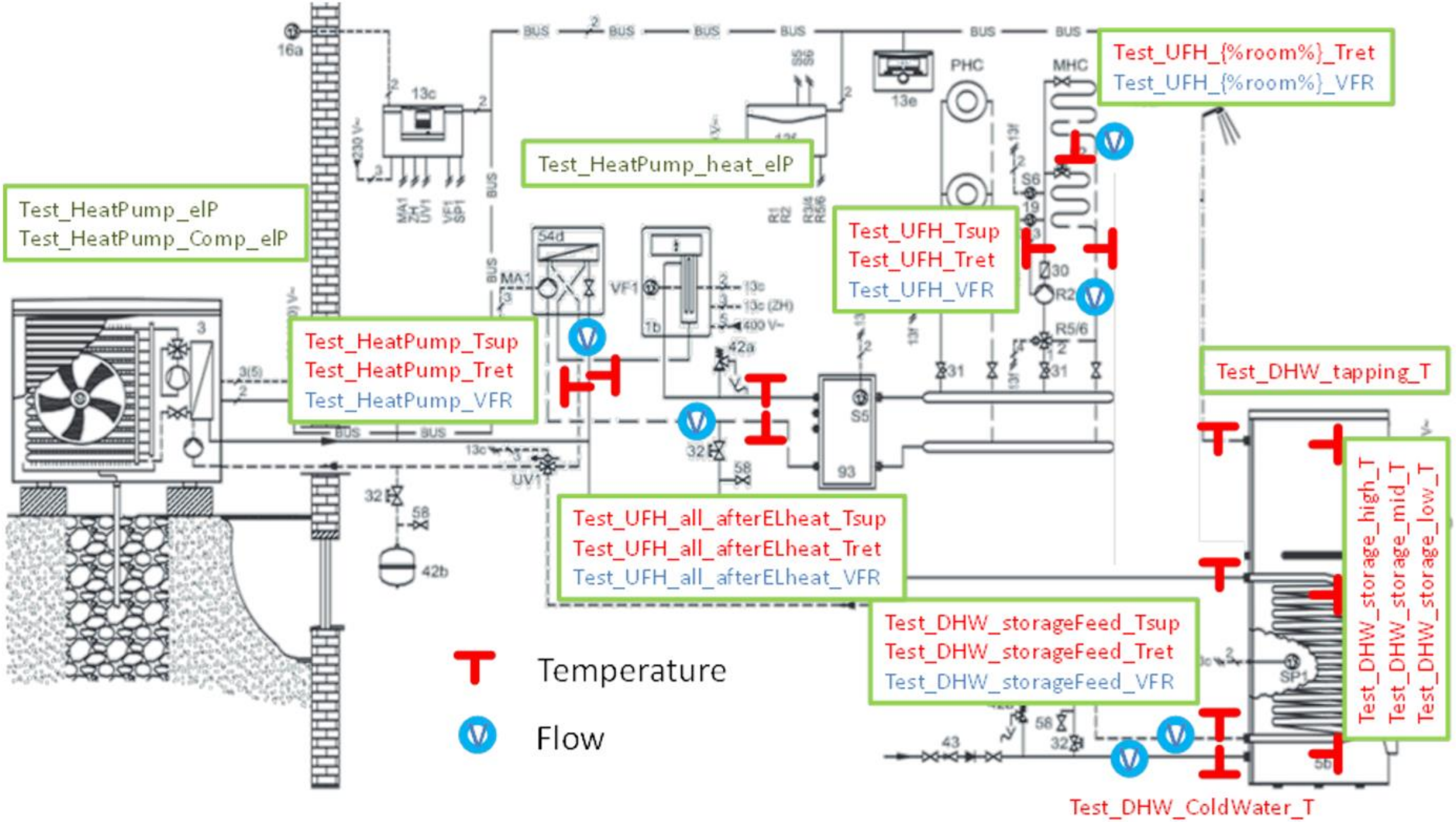


Figure 21: External installation of the Twin Houses Vaillant "aroTHERM VWL 55/2 A" air source heat pump, left in summer, right in winter.

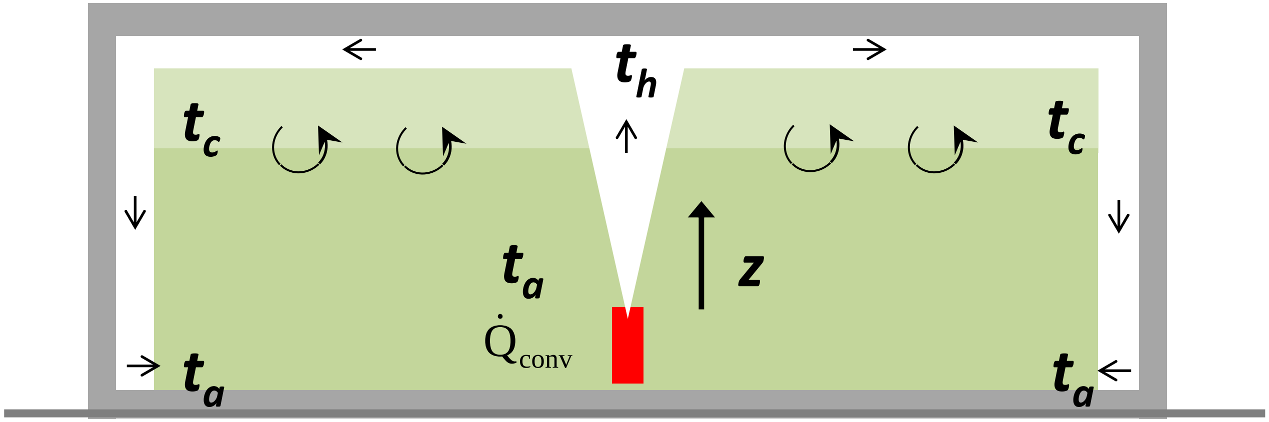
VALIDATION OF SIMULATION TOOLS

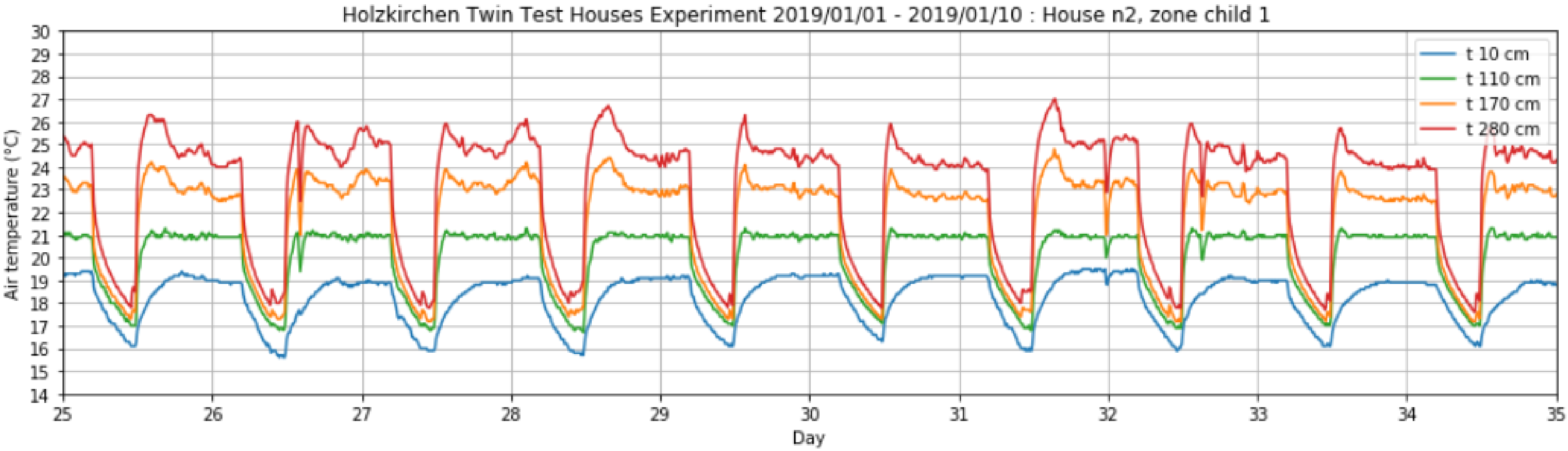
IEA EBC Annex 71 Holzkichen Twin Test Houses

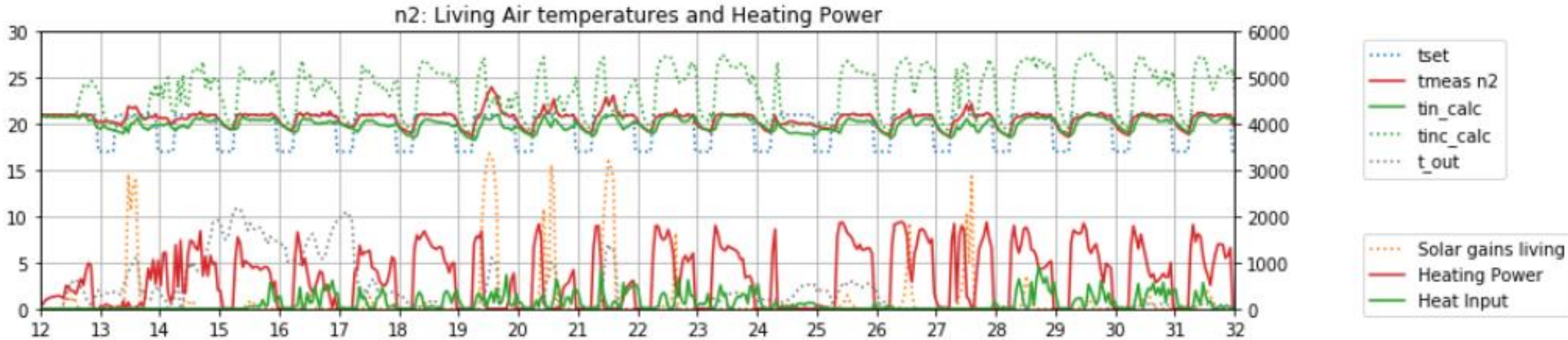


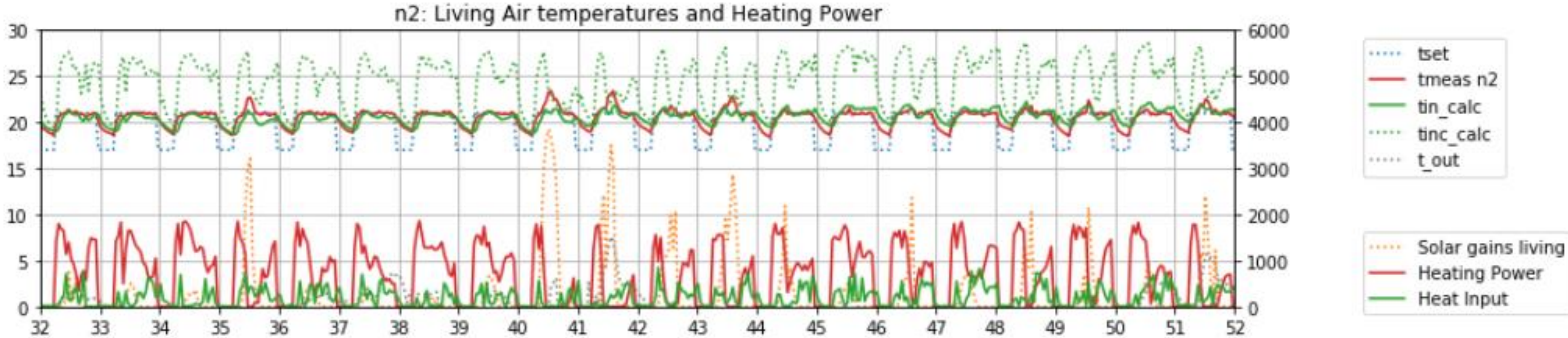
SRATIFICATION EFFECT

- Child1 zone electric radiators : 5 °C on average, 10°C maximum






n2: Living Air temperatures and Heating Power
tset
tmeas n2
tin_calc
tinc_calc
t_out
Solar gains living
Heating Power
Heat Input
0 5 10 15 20 25 30
0 1000 2000 3000 4000 5000 6000
12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32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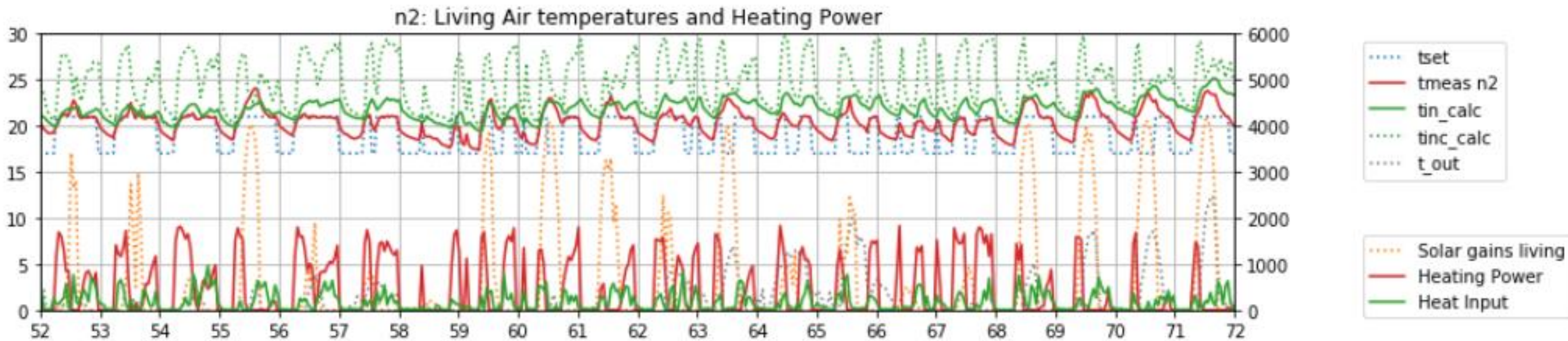
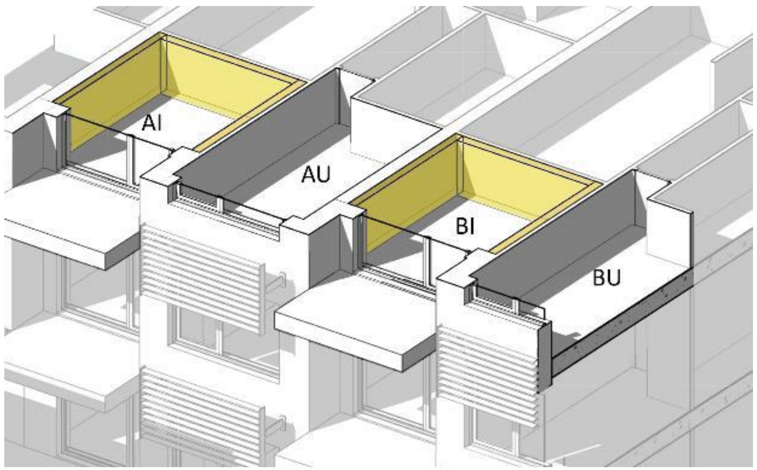
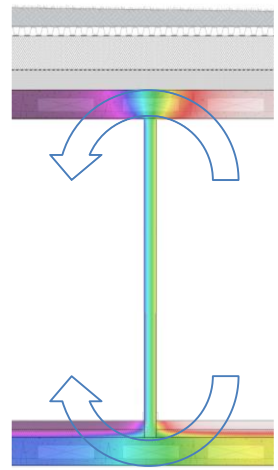
Solar gains living
Heating Power
Heat Input
0 5 10 15 20 25 30
0 1000 2000 3000 4000 5000 6000
32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52

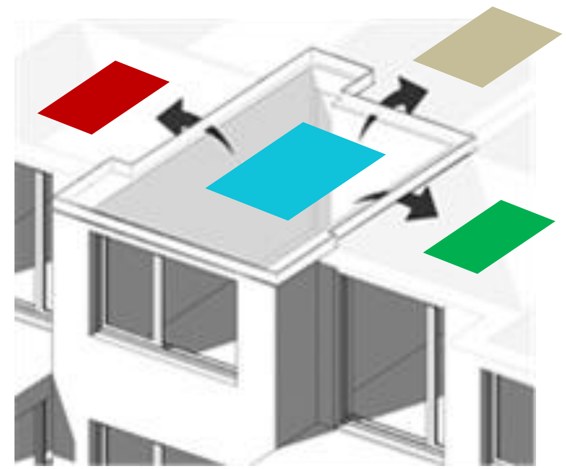

n2: Living Air temperatures and Heating Power
tset
tmeas n2
tin_calc
tinc_calc
t_out
Solar gains living
Heating Power
Heat Input
0 5 10 15 20 25 30
0 1000 2000 3000 4000 5000 6000
52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72

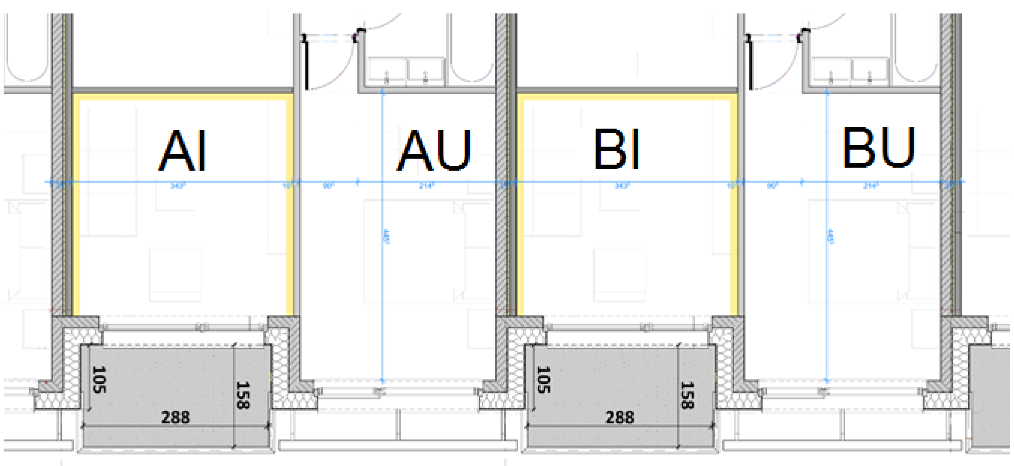
INTERNAL THERMAL BRIDGES

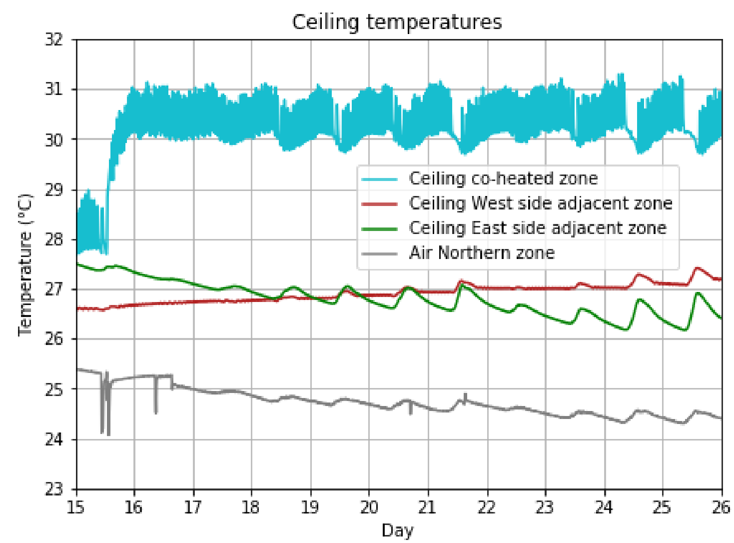
Saints Pierre et Paul, Neder-Hover-Heembeek, Cam(b)bridge Project supported by innoviris











DYNAMIC SIMULATION - APPLICATIONS

System sizing

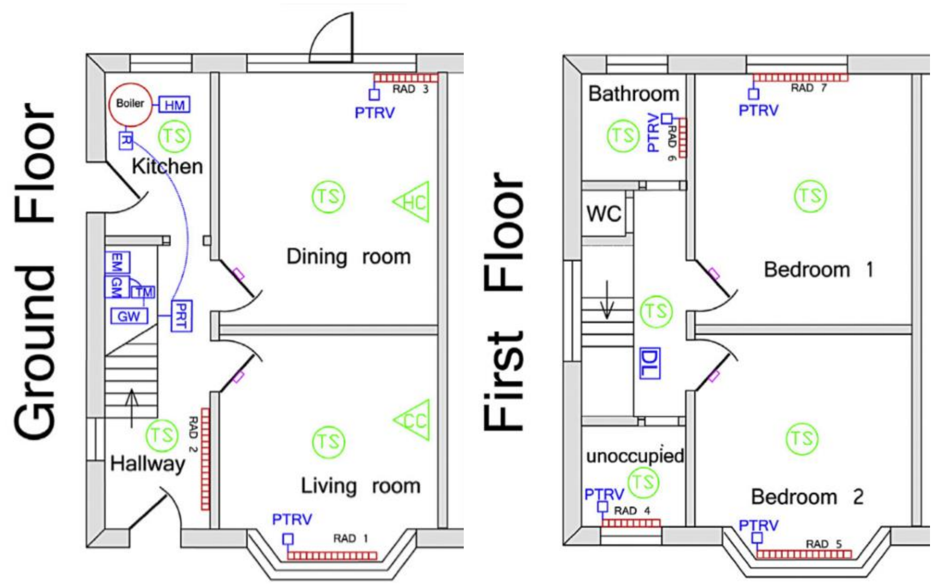
Energy Consumptions

Validation

Identification

PARAMETRIC IDENTIFICATION

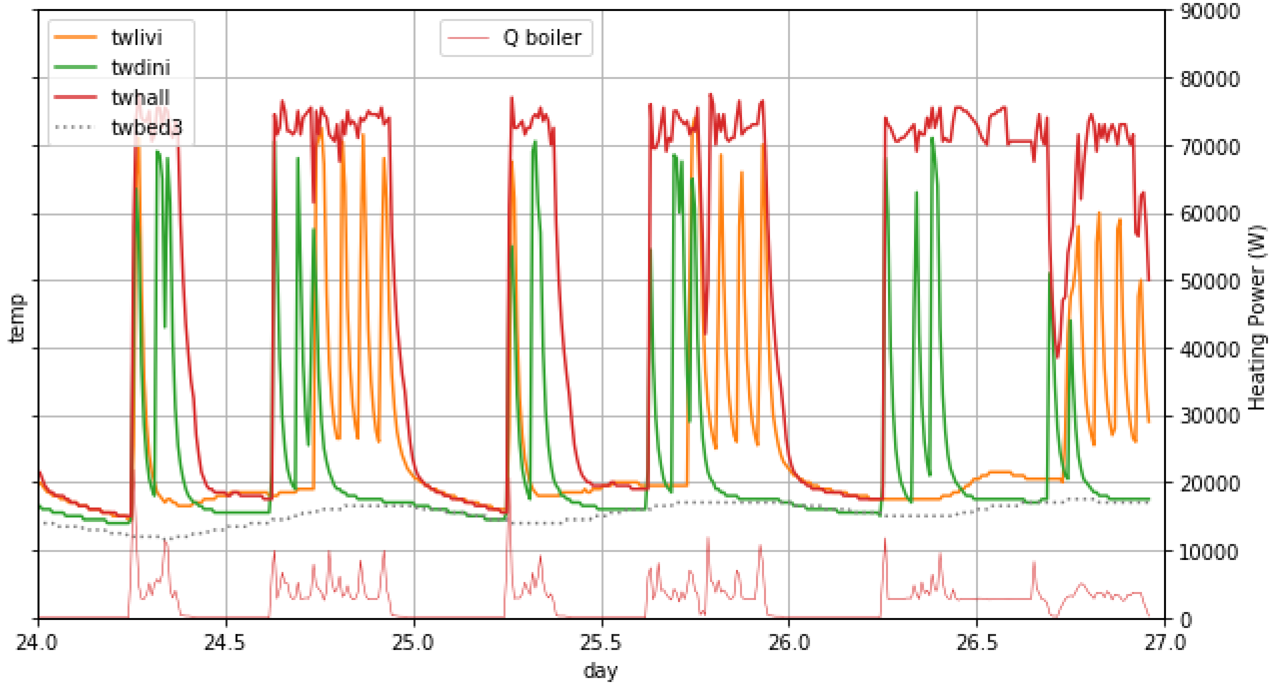
IEA EBC Annex 71 Loughborough case

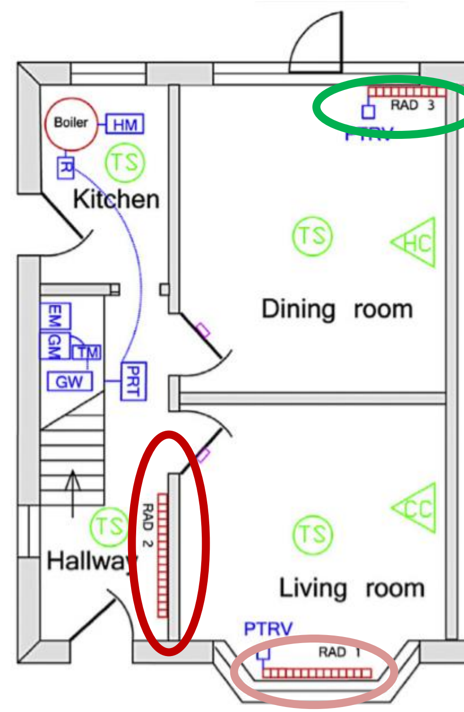


- Use of the monitored radiator temperatures to split the boiler heat output into the different building zones
- Multi-zone modelling using internal temperatures measured by zone

PARAMETRIC IDENTIFICATION

Use of monitored radiator temperatures to split boiler heat output into the zones





Morning Afternoon & Evening

Ordinary day Week-end

Radiators AU’s – 4 days static analysis

$$\dot{Q}_{rad} = m_w \frac{d\theta_w}{dt} + AU\,(\theta_w - \theta_{in})^n$$

$$m_w = 0.011\,\dot{Q}_n \qquad \dot{Q}_n = AU\left(\theta_{w,n} - \theta_{in,n}\right)^n$$

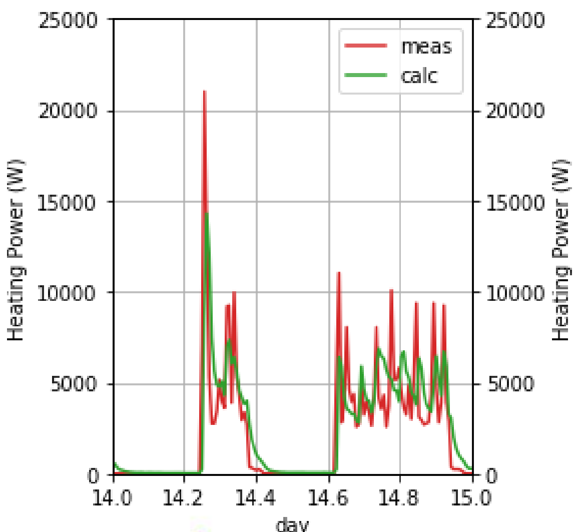
$$\dot{Q}_{rad} = AU\left(0.011\,.\left(\theta_{w,n} - \theta_{in,n}\right)^n \frac{d\theta_w}{dt} + \,(\theta_w - \theta_{in})^n\right)$$

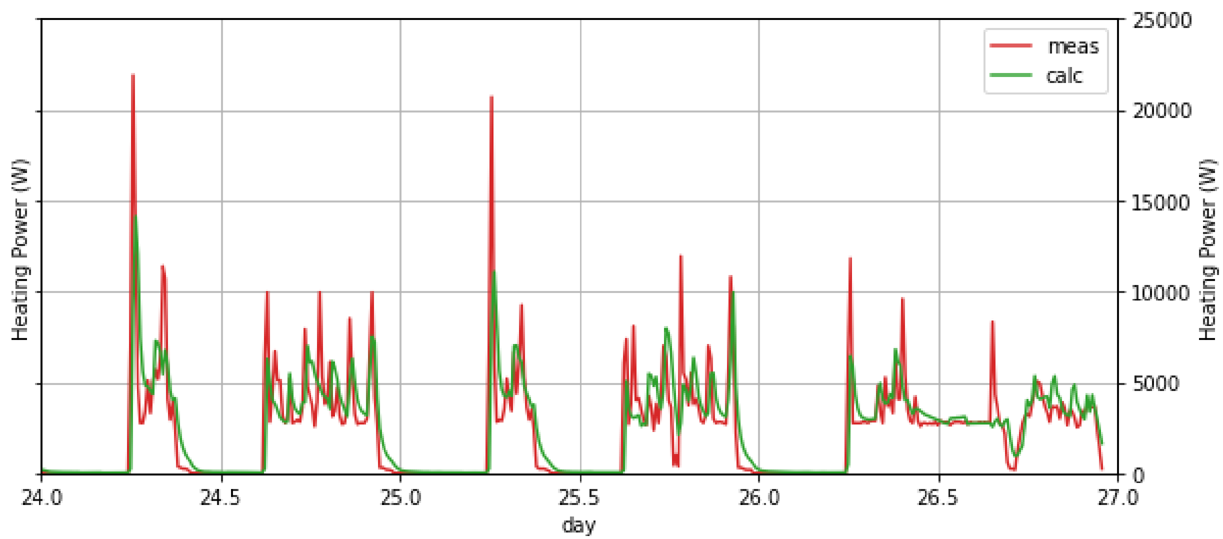
$$n = 1.3$$

$$\theta_{w,n} = 70\,°$$

$$\theta_{in,n} = 20\,°$$

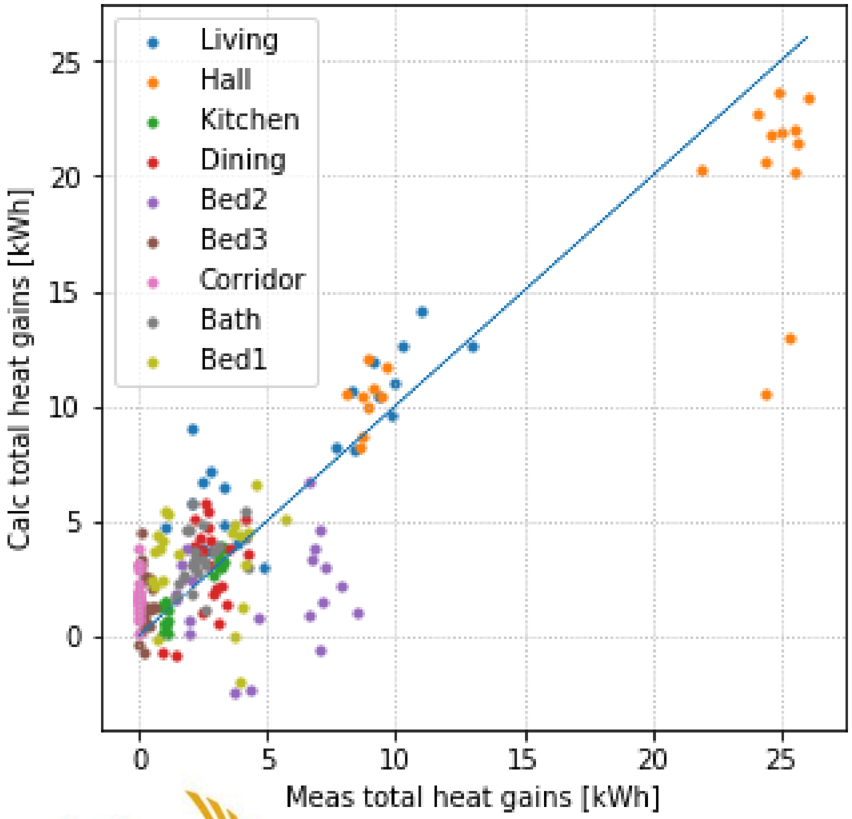
Radiator	AU [W/K]	$Q_{rad,n}$ [W]
Living	15.39	2488
Hall	17.13	2770
Dining	16.13	2608
Bed2	17.6	2846
Bath	9.94	1608
Bed1	12.96	2095

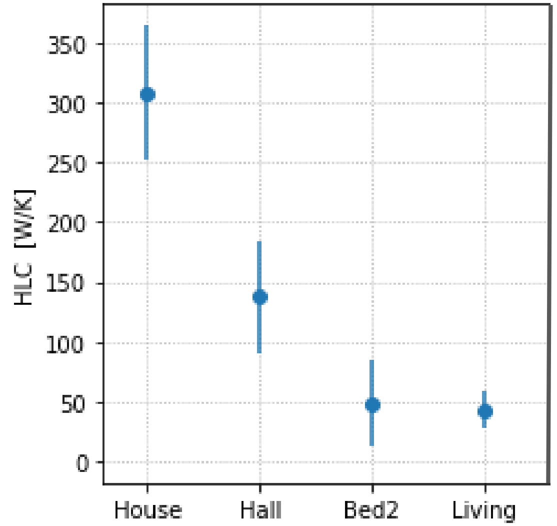




Zones HLC's – 10 days static analysis

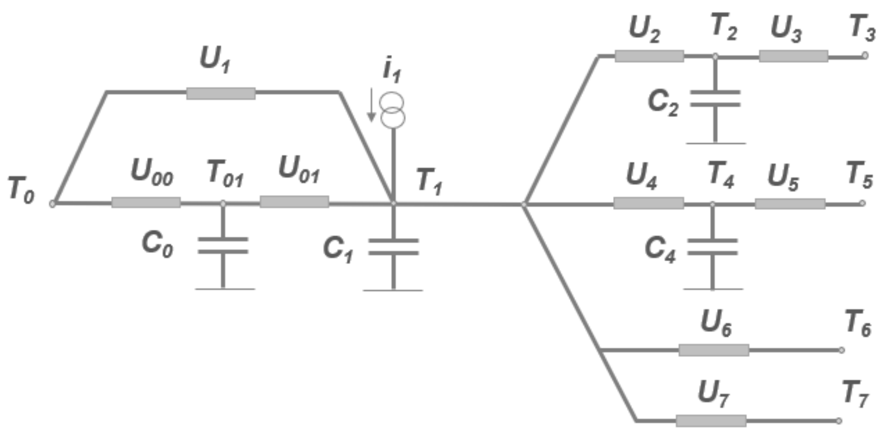
$$\dot{Q}_{rad} + \dot{Q}_{in} + \dot{Q}_{sol} = HLC\ (\theta_{in} - \theta_{out})$$





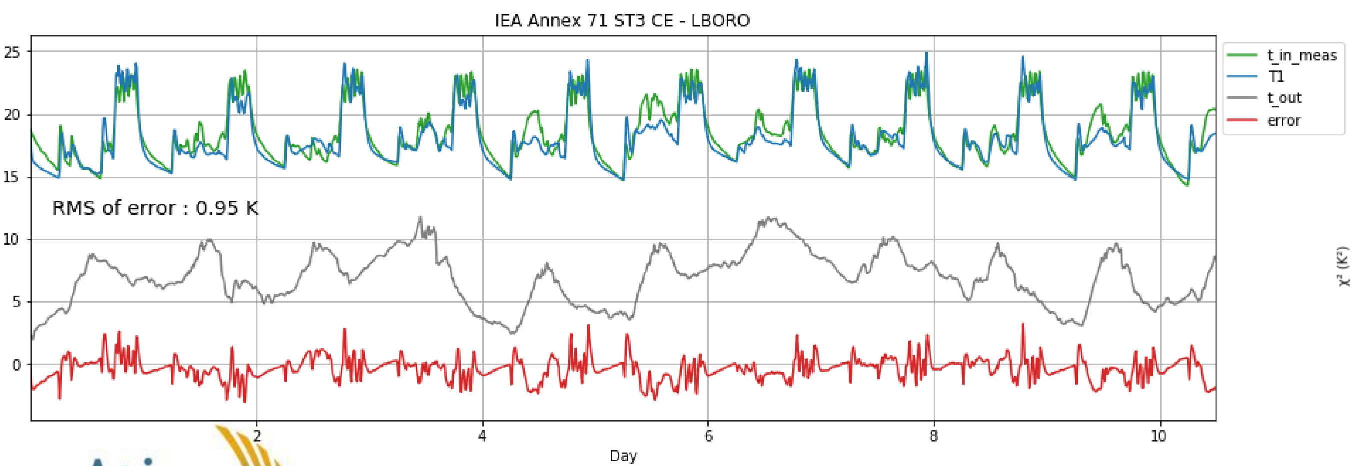
Zone	HLC [W/K]	HLC std [W/K]
House	308.04	56.38
Hall	137.88	47.17
Bed2	48.64	35.83
Living	43.11	15.21

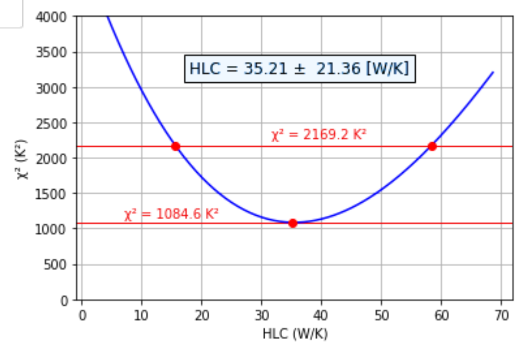
Living zone – 10 days dynamic analysis



T0	External
T1	Living
T3	Hall and Dining
T5	Neighbor 18°C
T6	Bed2
T7	Hall
facs	Solar gains factor
fach	Heat input factor
facm	Ventilation coupling factor

U00	[W/K]	0.02
U01	[W/K]	296.01
U1	[W/K]	35.21
tau0	[h]	18155
tau1	[h]	0.17
tau2	[h]	46.81
facs	[-]	1.51
fach	[-]	1.50
facm	[-]	2





CONCLUSION

- Validation of dynamic simulation tools:
  - Assessment of solar heat gains
  - Modelling of air stratification effect
  - Presence of internal thermal bridges

- Parametric identification:
  - Towards Effective Performance Assessment
    - Building Envelope Heat Loss Coefficient
    - Efficiencies of HVAC systems
  - Assessment of uncertainties associated to measurements