DESCRIPTION OF AND EXPERIENCE WITH THE SPsim/ber BUILDING SIMULATION PROGRAMME

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ABSTRACT

A building simulation program has been developed and a model of a standard Swedish single family house has been built up. The model uses an explicit finite-difference method to calculate the temperatures of the next time step. The main output from the programme is energy consumption values and temperatures. The simulation program can either be run as a real time simulation tool (SPsim) or as a pure simulation tool (SPber). The paper is describing the general concept of the models used. It also gives examples of results obtained by using the program.

INTRODUCTION

When comparing the energy consumption between different possible solutions for heating and/or energy conservation in buildings, measurements in real buildings are often not the best solution. The main disadvantage is that the uncertainties of the results are often too high. Uncertainties of 50 % or more are not an unusual figure. Such an uncertainty is not sufficient when trying to distinguish between solutions that may differ less than say 10 %. The reason for the high uncertainty is that it's almost impossibly to measure all the parameters of interest. And even if that was possible, two different solutions can still not be measured in the same building at the same time. There will then still remain an uncertainty regarding either the difference in the climate or differences between the buildings. One of the largest uncertainties when measuring in real buildings is the influence of activities made by the occupants. Other disadvantages with measurements in real buildings is that they are often very expensive and takes too long time to carry out.

For this reason a building simulation program has been developed in the Delphi environment and a model of a standard Swedish single family house has been built up. The house is a two-storey building with a total floor area of 140 square meters. Thermal insulation and type of windows are as default chosen to represent the average standard of Swedish houses built in the beginning of the seventies. But the insulation standard and the type of windows can quite easily be changed. Models for several different heating systems has been developed and tested. The main output from the programme is energy consumption values. The simulation program can either be run as a real time simulation tool (SPsim) or as a pure simulation tool (SPber). Climate schedules representing different parts of the year can be given. The general concept of the models used is decribed in the methodology section.

Using the SPsim/ber simulation program, different solutions for heating and/or energy conservation may be tested under exactly the same conditions. This includes the climate, the building envelope and the activities of the occupants.

This paper gives some examples of results obtained by using the program. One example is the evaluation of a system with electrically heated radiators and poorly functioning thermostatic controls. Another example shows how the energy consumption of hydronic heating systems depends on the choice of control strategy. The third example is a study of how choosing low energy lighting equipment will influence the energy consumption of the systems studied in the first two examples. For hydronic systems both the total energy consumption as well as the electric energy consumption is then evaluated. A system using electrically heated radiators with individual ideal PID controllers and a constant set point temperature of +20 °C is in both cases used as a baseline for comparison.

METHODOLOGY

The building simulation program has been developed in the Delphi environment. The model uses an explicit finite-difference method to calculate the temperatures of the next time step [1]. Walls, floors and roofs are then represented by nodes with a certain capacitance and connected by certain resistances. The formulas used for modelling one of the walls are given in example 1 below. The window models are built up in a similar way, but they also model the transmittance and reflectance of solar radiation. A short time step ($\Delta\tau$) of 1 to 5 seconds has been used. It is therefore possible to dynamically simulate the responses of equipment with rather short time constants, such as lightweight electrically heated radiators. The model calculates conduction, convection and radiation, including solar radiation, in a fairly accurate way. It also simulates the air infiltration/exfiltration due to the temperature difference between the indoor and the outdoor air. A mechanical exhaust ventilation system is incorporated in the model. Heat/air transfers through openings due to temperature differences are also modelled. This includes permanent openings as well as doors and windows that can be opened and closed according to given time schedules. Time schedules for different types of internal loads are also given. Models for several different heating systems have been developed. This includes thermostatic valves, constant pressure pumps and hydronic piping systems. The output from the programme is energy consumption values and several key temperatures, including the operative temperature in some specified points in the house. As a check an energy balance is also made for the whole house.

The simulation program can either be run as a real time simulation tool (SPsim) or as a pure simulation tool (SPber). Real time simulation is used when a real component, e.g. a control system, that runs in real time is connected to the model. Pure simulation allows the simulation to be run at a speed of 10 to 50 time's faster than real time, depending on the time step and the processor used. Normally a period of 1 to 14 days is chosen. Climate schedules representing different parts of the year can be given. All simulations are also performed according to SP-method 1993:3 [4].

Example 1. *A nine-node model of one of the twenty walls in the house.*

The temperature of the outside node of wall no 1 [°C];

$$T_{y1,1}(\tau+\Delta\tau)=K_{yi}(\tau)\cdot T_{y1,1}(\tau)+\frac{\Delta\tau}{C_{yi}}\cdot\left[\frac{8}{R_y}\cdot T_{y1,2}(\tau)+h_{yi}(\tau)\cdot T_{room1}(\tau)+\beta_f\cdot I_E(\tau)\cdot\frac{A_{f1}}{A_{y1}}\cdot S_{y1,1}+\gamma_i\cdot\{F_{y1,r1}\cdot T_{r1,f}(\tau)+\right.$$
$$\left.+F_{y1,f1}\cdot T_{f1,1}(\tau)+F_{y1,y2}\cdot T_{y2,1}(\tau)+F_{y1,m1}\cdot T_{m1,1}(\tau)+F_{y1,m2}\cdot T_{m2,1}(\tau)+F_{y1,g1}\cdot T_{g1,1}(\tau)+F_{y1,b1}\cdot T_{b1,1}(\tau)+F_{y1,i1}\cdot T_{i1}(\tau)\}\right]$$

The temperature of the inside node of wall no 1 [°C];

$$T_{y1,9}(\tau+\Delta\tau)=K_{ye}(\tau)\cdot T_{y1,9}(\tau)+\frac{\Delta\tau}{C_{ye}}\cdot\left[\frac{8}{R_y}\cdot T_{y1,8}(\tau)+\alpha_{ye}\cdot I_N(\tau)+\left(h_{ye}(\tau)+\gamma_e\right)\cdot T_{out}(\tau)\right]$$

The temperature of the internal nodes of all the walls [°C];

j = [1, 20], k = [2, 8]; wall j, node k

$$T_{yj,k}(\tau+\Delta\tau)=\left(1-2\cdot Fo_y\right)\cdot T_{yj,k}(\tau)+Fo_y\cdot\left[T_{yj,k-1}(\tau)+T_{yj,k+1}(\tau)\right]$$

Where;

the Fourier-module $Fo_y=\frac{56\cdot\tau}{R_y\cdot C_y}$ *[-]*

$$K_{yi}(\tau)=1-\frac{\Delta\tau}{C_{yi}}\left[\frac{8}{R_y}+h_{yi}(\tau)+\gamma_i\right]$$ *[-]*

$$K_{ye}(\tau)=1-\frac{\Delta\tau}{C_{ye}}\left[\frac{8}{R_y}+h_{ye}(\tau)+\gamma_e\right]$$ *[-]*

SIMULATION

All simulations are compared with a **reference test house.** It's a two-storey building with the following description:

Size

Heated floor area: 140 m²
Heated volume: 336 m³
Window area: 23 m²

U-values

Walls; 0.34 W/m²/K
Roof: 0.24 W/m²/K
Floor: 0.27 W/m²/K
Windows: 2.7 W/m²/K

Ventilation

Type: Mechanical exhaust; supply terminals in all rooms except bathrooms; exhaust terminals in kitchen and bathrooms.
Air flow rate: 35 l/s (approximately 0.3 ach)

Heating system

Type: Electrically heated radiators with individual ideal PID controllers [8].
Set point: +20 °C
Power: 10.1 kW installed (7.3 kW needed at an outdoor temperature of –20 °C).

Hot water

Type: Electrically heated boiler.
Volume: 300 dm³
Power: 3 kW
Heat loss: 115 W

Household electric consumption

The mean value of internal electric loads, radiators excluded, is 727 W. Lighting is used between 7:00 and 8:00 hour's in the morning and between 16:00 and 24:00 hour's in the evening according to a given schedule.

Climate and simulation period

The evaluated climate is a +2 °C outdoor temperature that has a daily variation of ±2 K. The solar radiation corresponds to a clear day in December. Each simulation starts with all temperatures at +20 °C and the evaluation is done for the 5th of six days simulation.

Activities of the occupants

The house is assumed to be occupied by a family of two adults and two children. No one is present in the house between 9:00 to 16:00 hour's daytime. The first person leaves the house at 8:00 and the last returns at 18:00. One of the children has a friend visiting during the evening. Airing is done for 15 minutes in the bedrooms in the morning and for 15 minutes in the living room in the evening. The power supply to the radiators is not manually or automatically shut off during airing. Most of the doors, except in one of the children's rooms, are assumed to be open during the simulation.

The **1th example** is a house with thermostatic controllers that have a less optimal function than the almost perfect PID-controllers. The thermostatic controllers have in this case an on/off function and a hysteresis of 2 K.

The **2nd example** is a house where the electrically heated radiators have been exchanged with a hydronic heating system with ceiling panels on the first floor and radiators on the second floor. In this case two different control strategies have been investigated. One strategy is using a maximum available supply water temperature and flow rate control by means of individual thermostatic control on each panel/radiator. The thermostatic controls have a proportional P-band of 2 K and a set point of +21 °C. With a well designed system this gives approximately a mean indoor air temperature of +20 °C during the heating season, i.e. between +19 °C and +21 °C when the outdoor temperature varies between -20 °C and +20 °C respectively. The other control strategy is using a constant water flow rate and a common supply water temperature control that depends on the outdoor temperature. In both cases the house has a well-designed system that is connected to a central district heating system and is using a constant pressure water pump for the internal system. The U-value of the windows is changed to 2.7 W/m²/K.

The **3rd example** shows how the energy consumption of houses in the 1th and the 2nd example is affected by exchanging all standard lamps in the houses with so called low energy lamps. By exchanging all 40 W and 60 W lamps with 9 W and 11 W low energy lamps respectively the mean household electric consumption is reduced by 105 W, i.e. from 727 W to 622 W.

ANALYSIS

The main result from the simulation of the **reference test house** is shown in table 1 and diagrams 1-3. Table 1 shows mean, maximum and minimum values for some power consumption and temperatures, both for the whole house and for one of the rooms.

Diagrams 1-3 shows the variation of power consumption and temperature during the evaluated simulation period. Diagram 1 the power consumption for the whole house and diagram 2-3 the power consumption and temperaturesof room 1.

Table 1: *Main results for the reference house*

[W] / /[°C]	Total			Room 1		
	mean	max	min	mean	max	min
Petot	3173	6286	1870	379	1092	184
Per	2386	4616	1470	339	992	164
Peint	727	1610	340	40	100	20
Ppers	254	500	0	58	200	0
Troom	20.1	23.4	15.9	20.0	21.0	15.9
Topr	19.2	20.1	18.0	19.3	20.0	18.0
Tsr				20.0	20.3	17.5
Tfi	13.1	15.2	11.9	13.2	15.1	12.2
Tfu	2.5	4.7	0.7	2.5	4.7	0.7
Tgi				18.6	19.8	18.0
Tyi				18.4	20.1	17.5
Tyu				0.7	3.3	-1.4
Tout	2.0	4.0	0.0			
Tgnd	3.1	4.5	1.7			

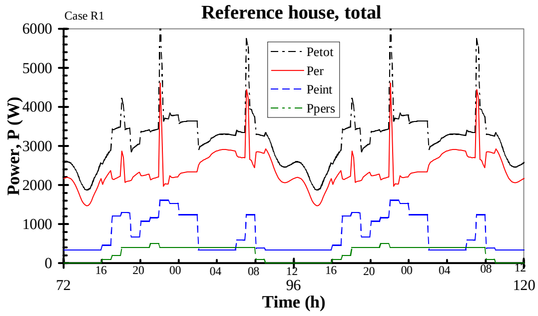

Diagram 1: *Power consumption, reference house*

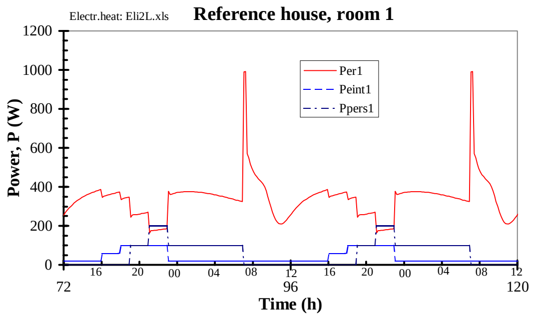

Diagram 2: *Power cons. reference house, room 1*

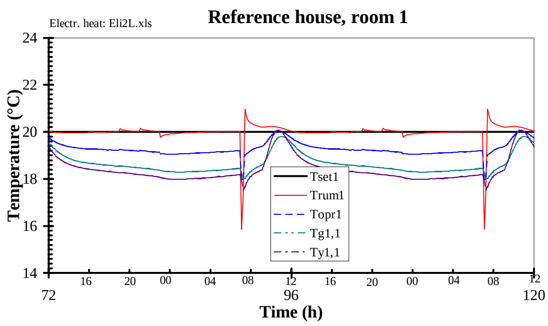

Diagram 3: *Temperatures reference house, room 1*

The mean indoor air temperature is very close to the set-point value. The mean operative temperature is about 1 °C lower, mainly due to radiation from cold surfaces. The minimum air temperature 15.9 °C is reached for a short while during the airing of the bedrooms as seen in diagram 3. The minimum operative temperature is however not lower than 18 °C, partly due to the fact that the control system increases the power output to its maximum possible value to compensate for the decrease in air temperature.

The main result from the simulation of the **1th example** is shown in table 2 and diagrams 1-3.

Table 2 shows mean, maximum and minimum values for power consumption and temperatures, both for the whole house and for one of the rooms. Diagrams 4-6 shows the variation of power consumption and temperature during the evaluated simulation period. Diagram 4 the power consumption for the whole house and diagram 5-6 the power consumption and temperaturesof room 1.

Table 2: *On/off-control with a hysteresis of 2 K*

[W] / /[°C]	Total			Room 1		
	mean	max	min	mean	max	min
Petot	3191	7615	400	383	1100	20
Per	2404	7205	0	343	1000	0
Peint	727	1610	340	40	100	20
Ppers	254	500	0	58	200	0
Troom	20.1	24.4	15.6	20.2	22.6	15.6
Topr	19.3	20.6	18.0	19.4	20.5	18.0
Tsr				20.2	21.1	17.4
Tfi	13.2	15.5	11.8	13.3	15.5	12.1
Tfu	2.5	4.8	0.7	2.6	4.8	0.7
Tgi				18.7	19.9	18.1
Tyi				18.5	20.2	17.6
Tyu				0.7	3.3	-1.4
Tout	2.0	4.0	0.0			
Tgnd	3.1	4.5	1.7			

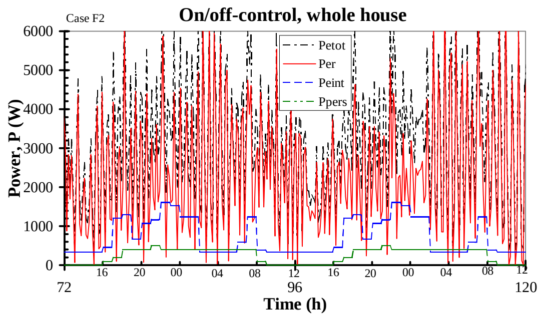

Diagram 4: *Power consumption, on/off-control*

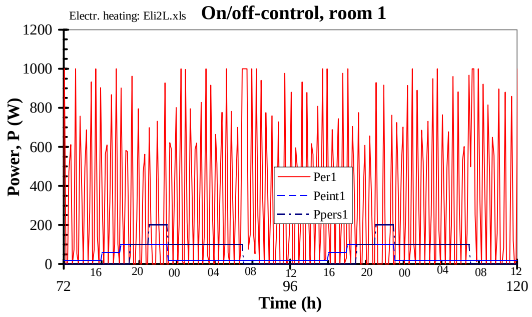

***Diagram 5:** Power cons. on/off-control, room 1*

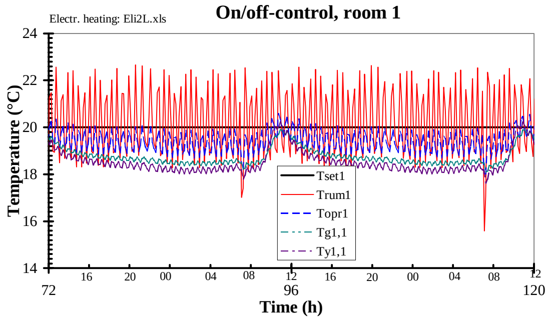

***Diagram 6:** Temperatures on/off-control, room 1*

The mean indoor air temperature is still very close to the set-point value. The mean operative temperature is also still about 1 °C lower. The minimum air temperature is also about the same but may now vary from day to day as seen in diagram 3. The minimum operative temperature is also still not lower than 18 °C. The mean power consumption is also almost the same as for the reference house. The major differences is that the maximum and minimum values are much higher respectively lower than for the reference case. Both the power outputs and the temperatures are oscillating with a much higher both amplitude and frequency. The maximum possible power output for the radiator in room 1 is reached about ten times a, whereas in the reference case it only occurs once a day (during the airing). Hence the maximum total power output of 10.1 kW may occur now and then even at outdoor air temperatures above ±0 °C.

The main result from the simulation of the **2nd example** is shown in table 3.

Table 3 shows mean values of power consumption and temperatures for both investigated control strategies; the variable flow rate control by means of individual thermostatic controls and the constant water flow rate with a common supply water temperature control.

***Table 3:** Different hydronic control strategies*

[W] / [°C] / / [m³/h]	Water flow rate control	Supply water temp. control
Ptot	2974	3243
Petot	791	803
Pvtot	2183	2440
Troom	20.8	22.2
Topr	20.3	21.7
Tvin	55.0	38.0
Tvut	29.0	31.0
qvtot	0.07	0.30

Due to the lower U-value of the windows the total energy consumption when using flow rate control is now lower than for the reference case even if the air temperature is higher. But when using supply temperature control the air temperatures gets so high that the total energy consumption is higher than in the reference case. Simultaneous measurements in real building support these results. Even if there is a large difference in mean water flow rate, due to well designed systems there is only a small difference between the return water temperatures of the two systems. However measurements in real buildings indicate that a real installation seldom is that well designed. Even if thermostatic controls are installed they are often given too high set points and the maximum water flow rate is adjusted to a too high value. Most hydronic heating systems therefore in practice are functioning more or less as a supply temperature control system and are often also giving too high air temperatures, which lead to an excessive energy consumption.

The main result from the simulation of the **3rd example** where low energy lamps are used is shown in table 3-4 and diagrams 7-8.

Table 3-4 shows mean, maximum and minimum values for power consumption and temperatures for the whole house with ordinary lamps used versus low energy lamps used. Table 3 for the electrically heated house with PID-controllers and table 4 for the house with hydronic heating system and flow rate.

Diagrams 7-8 shows the variation of power consumption for the whole house during the evaluated simulation period for the hydronic heating system with the flow rate control.

***Table 3:** Electric heating system, PID-control*

[W] /	Ordinary lamps			Low energy lamps		
/[°C]	mean	max	min	mean	max	min
Petot	3173	6286	1870	3169	6427	1865
Per	2386	4616	1470	2487	5033	1465
Peint	727	1610	340	622	1334	340
Ppers	254	500	0	254	500	0
Troom	20.1	23.4	15.9	20.1	23.2	15.9
Topr	19.2	20.1	18.0	19.2	20.1	17.9
Tfi	13.1	15.2	11.9	13.1	15.2	11.8
Tfu	2.5	4.7	0.7	2.5	4.7	0.7

***Table 4:** Hydronic heating system, flow rate contr.*

[W] /	Ordinary lamps			Low energy lamps		
/[°C]	mean	max	min	mean	max	min
Ptot	2974			2966		
Petot	791	1678	402	686	1402	402
Pvtot	2183	3819	1216	2280	3892	1217
Peint	727	1610	340	622	1334	340
Ppers	254	500	0	254	500	0
Troom	20.8	24.7	15.2	20.7	24.5	15.1
Topr	20.3	21.4	18.2	20.3	21.4	18.1
Tsr	20.7	21.9	17.1	20.6	21.7	17.1
Tvin	55.0	55.0	55.0	55.0	55.0	55.0
Tvut	29.0	37.4	27.2	29.2	37.2	27.2
Tfi	16.6	18.8	15.0	16.6	18.8	15.1
Tfu	2.0	5.1	-0.1	2.0	5.1	-0.1

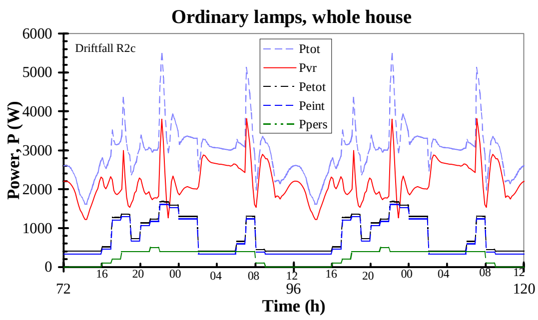

***Diagram 7:** Ordinary lamps, flow rate control*

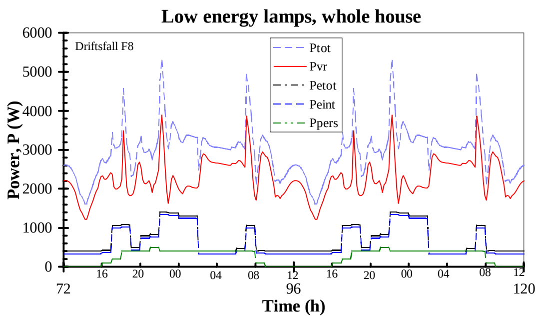

***Diagram 8:** Low energy lamps, flow rate control*

For the electrically heated house the decreased energy consumption of the low energy lamps is almost completely compensated by an equal increase in the energy consumption of the radiators, i.e. during the heating season there is almost no energy saved by using low energy lamps. But in the summer and partly in spring and autumn energy is saved. Thus in a Swedish climate only about 50% of the potential lower energy use of the low energy lamps will result in real savings when used in an electrically heated house.

For the house with a well-designed hydronic heating system the total energy consumption is also almost the same during the heating season. But in this case the electric energy saved by using the low energy lamps is exchanged with non-electric energy. If this energy is supplied by means of a cheaper and/or more efficient energy source, e.g. a heat pump, then almost 75% of the potential lower energy use of the low energy lamps will result in real savings.

For a less well designed hydronic system the use of low energy lamps will probably result in only a neglectable influence on the heating system. In that case almost all of the potential lower energy use of the low energy lamps will appear to result in real savings. And indeed the consumption of electric energy will be lower. But that system will of course still have a too high total energy consumption compared to a well designed system.

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CONCLUSIONS

Less perfect controllers, e.g. of the type on/off, do not increase the total energy consumtion. But, they do frequently require higher power output than a more optimal controller. They do also to some extent decrease the thermal comfort.

Well designed hydronic heating systems with variable flow control by means of individual thermostatic controllers result in good thermal comfort and an almost optimal energy consumption. Hydronic heating systems with constant air flow rate and a common supply water temperature control do in most cases result in too high indoor air temperatures, and consequently in a too high energy consumption.

Depending on the heating system only 50% to 75% of the potential lower energy use of the low energy lamps will result in real savings.

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NOMENCLATURE

A brief description of the symbols used in your paper.

τ =	present time	[s]
$\Delta\tau$ = 1-3	time step	[s]
R_y = 2,8	thermal resistace	[m² K/W]
C_y = 2000	internal capacitance	[J/(m² K)]
C_{yi} = 9000	inside nod capacitance	[J/(m² K)]
C_{ye} = 22000	outside node capacitance	[J/(m² K)]
γ_i = 5,5	inside radiation koeff.	[W/(m² K)]
γ_e = 4,0	outside radiation koeff.	[W/(m² K)]
α_{ye}= 0.5	wall solar rad. absorbtion	[-]
β_f= 0.76	window solar rad. transm.	[-]
$h_{yi}(\tau)$=	inside convection koeff.	[W/(m² K)]
$h_{ye}(\tau)$=	outside convection koeff.	[W/(m² K)]
$I_N(\tau)$=	solar rad. north vert. surf.	[W/m²]
$I_E(\tau)$=	solar rad. east vert. surf.	[W/m²]
$P_{tot}(\tau)$=	total power consumption	[W]
$P_{etot}(\tau)$=	total electr. power consumpt.	[W]
$P_{vtot}(\tau)$=	total hydr. power consumpt.	[W]
$P_{eint}(\tau)$=	internal electr. power consumpt.	[W]
$P_{pers}(\tau)$=	power output, present persons	[W]
$T_{opr}(\tau)$=	operative temperature	[°C]
$T_{sr}(\tau)$=	sensor temperature	[°C]
$T_{vin}(\tau)$=	supply water temp.	[°C]
$T_{vut}(\tau)$=	return water temp.	[°C]
$T_{out}(\tau)$=	outdoor temperature	[°C]

$T_{gnd}(\tau)=$	ground temperature	[°C]
$T_{room}(\tau)=$	mean room temperature	[°C]
$T_{room1}(\tau)=$	air temp. room 1	[°C]
$T_{fi}(\tau)=$	inside window surf. temp.	[°C]
$T_{fu}(\tau)=$	outside window surf. temp.	[°C]
$T_{r1,f}(\tau)=$	temp. radiator 1, front	[°C]
$T_{gi}(\tau)=$	inside floor surf. temp.	[°C]
$T_{yi}(\tau)=$	inside wall surf. temp.	[°C]
$T_{yu}(\tau)=$	outside window surf. temp.	[°C]
$A_{f1}(\tau)=$	area window1	[m²]
$A_{f2}(\tau)=$	area window2	[m²]
$S_{y1,1}(\tau)=$	solar radiation distr. ratio	[-]
$F_{y1,r1}(\tau)=$	radiation angle coefficient	[-]