ADVANCED SIMULATION OF BUILDING SYSTEMS AND CONTROL WITH SIMULINK

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ABSTRACT

The paper presents the advanced use of S-Functions, facilitated by the Matlab/SimuLink environment. An existing indoor climate model is implemented in an S-Function, consisting of a continuous part with a variable time step and a discrete part with a fixed time step. The heating systems, including a heat pump, an energy roof and thermal energy storage (TES) are modeled as continuous systems using S-Functions. All presented models are validated. The advantages of S-Functions are evaluated and it demonstrates the powerful and flexible use of MatLab/SimuLink.

1. INTRODUCTION

SimuLink (Mathworks, 1997) is a software package for modeling, simulating, and analyzing dynamical systems. It supports linear and non-linear systems, modeled in continuous time, sampled time or a hybrid of the two. Simulink includes a block library of sinks, sources, linear and non-linear components and connectors. Each block within a SimuLink model has the following general characteristics: a vector of inputs, u, a vector of outputs, y, and a vector of states x, as shown by Figure 1. SimuLink facilitates hierarchical top-down and bottom-up modeling approaches. By double-click on blocks the level of model detail is increased. However, if a SimuLink model has a lot of blocks and a lot of levels, the model organization and how parts interact can become quit difficult to understand. S-functions (system functions) provide another way to create SimuLink models. Algorithms in MatLab or C can be implemented in S-functions. The main advantage of using S-functions is that users can build general-purpose blocks that can be used many times in a model, varying parameters with each instance of the block. SimuLink makes repeated calls during specific stages of simulation to each routine in the model, directing it to perform tasks such as computing its outputs, updating its discrete states, or computing its derivatives. Table I shows these stages. The use of S-Functions is demonstrated by the implementation of buildings systems and the building model WaVo (in Dutch: WArmte en VOcht, in English: HEat and

MOisture) in SimuLink. The main objective of WaVo is the simulation of the thermal and hygric indoor climate. A brief description of the model is given in Section 2. A more detailed description can be found in (Wit, 2001). The application of S-Functions in SimuLink is shown in Section 3 and Section 4. In Section 3, a hybrid (continuous/discrete) building zone model based on WaVo is presented. Section 4 presents a case study of an energy roof assisted heating system controlled with an on/off controller. The system includes continuous models of an energy roof, a heat pump and a thermal energy storage system (TES). In Section 5 simulation results of the presented models are confronted with measurements. The advantages of S-Functions are evaluated at the Conclusions. Finally, the complete S-function code for the presented heat pump model is given in the appendix.

2. THE BUILDING MODEL WAVO

The physics of the WaVo model is based on ELAN, a computer model for building energy design. (Wit et al., 1988). More recently, the ELAN model, together with an analog hygric model, has been implemented in MatLab. A short summary of the WaVo model is now presented, further details can be found in (Wit, 2001).

The WaVo model uses an integrated sphere approach. It reduces the radiant temperatures to only one node. This has the advantage that also complicated geometry's can easily be modeled. In figure 2, the thermal network is shown. T_a is the air temperature and T_x is a combination of air and radiant temperature. T_x is needed to calculate transmission heat losses with a combined surface coefficient. h_r and h_{cv} are the surface weighted mean surface heat transfer coefficients for convection and radiation. Φ_r is the total radiative heat input (short wave and emitted longwave from casual and solar gains, heating and cooling) and Φ_c is the convective part. For each heat source a convection factor can be given. For air heating the factor is 1 and for radiators 0.5. The factor for solar radiation depends on the window system and the amount of radiation falling on

furniture. C_a is the heat capacity of the air. L_{xa} is a coupling coefficient (Wit et al., 1988):

$$L_{xa} = A_t h_{cv}\left(1 + \frac{h_{cv}}{h_r}\right) \qquad (1)$$

Φ_{ab} is the heat loss by air entering the zone with an air temperature T_b. A_t is the total area. In case of ventilation T_b is the outdoor air temperature. Φ_{xy} is transmission heat loss through the envelope part y. For external envelope parts T_y is the sol-air temperature for the particular construction including the effect of atmospheric radiation.

The thermal properties of the wall and the surface coefficients are considered as constants, so the system of equations is linear. For this system the heat flow entering the room can be seen as a superposition of two heat flows: one resulting from T_y with $T_x=0$ and one from T_x with $T_y=0$. The next equations are valid in the frequency domain:

$$\Phi_x = -\Phi_{xx} + \Phi_{yx} = -Y_x T_x + Y_{xy}\left(T_y - T_x\right)$$
$$\Phi_y = \Phi_{yy} + \Phi_{yx} = Y_y T_y + Y_{xy}\left(T_y - T_x\right) \qquad (2)$$

The heat flow (Φ_{yx}) caused by the temperature difference ΔT_{yx} is modeled with a fixed time step (1 hour) and response factors. For $t = t_n$:

$$\Phi_{yx}(t_n) = L_{yx}\Delta T_{yx}(t_n) + \Delta\Phi_{yx}(t_n)$$

$$\Delta\Phi_{yx}(t_n) = a_1\Delta T_{yx}(t_{n-1}) + a_2\,\Delta T_{yx}(t_{n-2}) + b_1\Delta\Phi_{yx}(t_{n-1}) + b_2\Delta\Phi_{yx}(t_{n-2})$$

$$\qquad (3)$$

The next equation for the U-value of the wall is valid:

$$A_{xy}U_{xy} = L_{xy} + (a_1 + a_2)/(1-b_1-b_2) \qquad (4)$$

For glazing, thermal mass is neglected:

$$L_{yx} = A_{glazing}U_{glazing} \qquad (a_1=a_2=b_1=b_2=0) \qquad (5)$$

The heat flow in a heavy construction is more stationary than in a lightweight construction. In such case L_{yx} will be close to zero. In the model L_{yx} is a conductance (so continuous) and $\Delta\Phi_{yx}$ are discrete values to be calculated from previous time steps. For adiabatic envelope parts $\Phi_{yx} = 0$. In the frequency domain, the heat flow Φ_{xx} from all the envelope parts of a room can be added:

$$\Phi_{xx}(tot) = -T_x\Sigma Y_x. \qquad (6)$$

The admittance for a particular frequency can be represented by a network of a thermal resistance ($1/L_x$) and capacitance (C_x) because the phase shift of Y_x can never be larger than $\pi/2$. To cover the relevant set of frequencies (period 1 to 24 hours) two parallel branches of such a network are used giving the correct admittance's for cyclic variations with a period of 24 hours and of 1 hour. This means that the heat flow $\Phi_{xx}(tot)$ is modeled with a second order differential equation. For air from outside the room with temperature T_b a loss coefficient L_v ($\rho_a c_p q_v$) is introduced. The model is summarized in figure 3.

In a similar way a model for the air humidity is made. Only vapor transport is modeled, the hygroscopic curve is linearized between RH 20% and 80%. The vapor permeability is assumed to be constant. The main differences are: a) there is only one room node (the vapor pressure) and b) the moisture storage in walls and furniture, carpets etc is dependent on the relative humidity and temperature.

The WaVo model has been subjected to the ASHRAE test (ASHRAE, 2001) with satisfactory results. For further details, see Table II.

3. THE WAVO MODEL IN SIMULINK

A major recent improvement is the development of a WaVo model in SimuLink. The model consists of a continuous part with a variable time step and a discrete part with a time step of one hour. For the HVAC installation and the room response on indoor climatic variations a continuous model is used (see figure 3). For the external climate variations a discrete model is used. The main advantages of this numeric hybrid approach are:

a) The dynamics of the building systems where small time scales play an important role (for example on/off switching) are accurately simulated.

b) The model becomes time efficient as the discrete part uses 1-hour time steps. A yearly based simulation takes 5 minutes on a Pentium III, 500 MHz computer.

c) The moisture (vapor) transport model of WaVo is also included. With this feature, the (de-) humidification of HVAC systems can also be simulated.

The heat transport part of WaVo SimuLink is also validated by the ASHRAE test (ASHRAE, 2001). The results of the WaVo SimuLink model are identical to the results of the WaVo model. The moisture transport part is not yet completely validated. Preliminary results (Schijndel et al., 2003) show a good agreement between model and measurement.

In figure 4, an example of the use of a 1-zone WaVo SimuLink model is demonstrated. The inputs of the WaVo SimuLink model are heat flow and moisture flow and the outputs are air temperature and relative humidity. In this example the air temperature is controlled by a limited PI controller and the relative humidity bounds are controlled by a humidifier and a de-humidifier.

4. THE HEATING SYSTEM IN SIMULINK

A short introduction of the heating system is now given. An energy roof collector is cooled by a heat pump so that its surface temperature will often be below the ambient air temperature. This has the advantage that besides solar energy, also energy is gained from the ambient air. In the Netherlands the winters are mild and humid with little sunshine, so the system is very promising. In the past four years, several configurations of an energy roof with a focus on the convective heat recovery from ambient air have been investigated at the GEO test site of the University (Jong et al., 2000). The thermal energy storage (TES) is located at the cold side of the heat pump so instead of heat loss even heat gain is possible. In figure 5, an outline is given of the energy roof system. The system has two identical roof surfaces, one facing south and one facing north. This enables to investigate whether an energy roof facing north, without direct solar radiation is cost effective. Circulating the cooling fluid through the energy roof charges the TES. Discharging the TES is accomplished by passing the cooling fluid through the heat pump. (In the real system charging and discharging can be done at the same time, when the energy roof is extracting heat from outside and there is a simultaneous heat demand from the dwelling). The collector of the test site consists of a simple perforated plate designed primarily for convective heat transfer.

The measurements of (Jong et al., 2000) are used for the determination of the constants in the component models. The models are:

- Heat pump model:

$$
\left[
\begin{array}{l}
COP = k \cdot \dfrac{0.5 \cdot T_{cin} + 0.5 \cdot T_{cout} + 273.15}{(0.5 \cdot T_{cin} + 0.5 \cdot T_{cout}) - (0.5 \cdot T_{vin} + 0.5 \cdot T_{vout})} \\[2ex]
C_c \dfrac{dT_{cout}}{dt} = F_{cin} \cdot cw \cdot (T_{cin} - T_{cout}) + COP \cdot Ehp \\[2ex]
C_v \dfrac{dT_{vout}}{dt} = F_{vin} \cdot cw \cdot (T_{vin} - T_{vout}) - (COP - 1) \cdot Ehp
\end{array}
\right.
$$

$$(7)$$

Where T is temperature [^{o}C], COP Coefficient of Performance [-], k heat pump efficiency determined from the measurements at the GEO test site, (k=0.4), cw specific heat capacity of water, C heat capacity of

the water and pipes in the heat pump ($C_v = C_c \approx 10^5$ J/K),], t time[s], F mass flow [kg/s], Ehp heat pump electric power supply (1200 W). Subscript c means water at the condenser, v water at the evaporator, in, incoming, out, outgoing. The complete S-function code for the heat pump model is given in the appendix.

- Energy roof model:

$$
C_r \frac{dT_{rout}}{dt} = F_{rin} \cdot cw \cdot (T_{rin} - T_{rout}) + k1 \cdot Esolar
$$
$$
- k2 \cdot (\frac{T_{rin} + T_{rout}}{2} - T_e)
$$

$$(8)$$

Where Esolar irradiance [W/m^2], k1 and k2 empirical determined factors (k1=0.8 m^2 and k2=125 W/K). Subscript r means water at energy roof, e exterior.

Thermal energy storage:

$$
m \cdot cw \cdot \frac{dT_{bout}}{dt} = F_{bin} \cdot cw \cdot T_{bin} - F_{bout} \cdot cw \cdot T_{bout}
$$
$$(9)$$

Where m is the mass of storage [kg], Subscript b means water in TES.

The models (7), (8) and (9) are implemented in SimuLink also using S-functions. A complete example of the S-Function of the heat pump model can be found in the appendix.

5. ANALYSIS

With the parameters found from the measurements the calculated performances of the components are compared with measurements. The input for the models are: the measured incoming and outgoing mass flows, incoming water temperatures (and for the energy roof also the external temperature and the irradiance on the inclined surface). Figure 6 shows that the models of the components predict the outgoing water temperatures well: The upper left part shows the outgoing water temperature at the evaporator and condenser of the heat pump. The upper right part shows the outgoing water temperature of the energy roof system. The lower part shows the outgoing water temperature of the TES.

In figure 7, the complete energy roof system, connected to the building zone model in SimuLink, is presented. The control strategy is simple. All mass flows (water) are kept constant (0.02 kg/s) and the heat pump is controlled by the internal temperature and an on/off switch (Relay). The external temperature and the irradiance on the inclined surface are used as input for the simulation of the complete system.

In figure 8 left part, the simulated indoor air temperature using the model of figure 7, is compared with measurements. There are differences between the calculated values and the measured ones. This is probably due to a different control of the mass flows between the model and the reality, where the mass flows are also switched on and off. This has not been implemented yet and is left over for future research. Figure 8 right part, shows the temperatures for a 48 hours period. These include: Incoming and outgoing water temperatures of the evaporator and condenser, outgoing water temperature of the energy roof and internal and external air temperatures.

The model of figure 7, has successfully been used for optimizing the energy roof system (Blezer, 2003). Up to now, it may be concluded that cost-efficient application of a heat pump in a dwelling is best achieved by bivalent systems. The capacity of the heat pump is limited then to about 30% of the total required maximal heating capacity.

CONCLUSIONS

The next applications of S-functions in SimuLink for building systems component simulation are evaluated:

- A hybrid (continuous/discrete) building zone model capable of simulating the thermal and hygric indoor climate. The main advantages of this model are: a) the dynamics of the building systems of time scales less than an hour are accurately simulated, b) the model becomes time efficient. The building zone model is validated with the ASHRAE test (ASHRAE, 2001) and shows a good agreement

- Continuous models of a heat pump, an energy roof and a TES (Thermal Energy Storage). The main advantages of this approach are: a) a clear relation between mathematical model (system of Ordinary Differential Equations (ODEs)) and computer code in the S-functions, b) the state of art ODE solvers of MatLab gives accurate solutions. The models are compared with measurements and show a good agreement.

- A complete energy roof and building model containing all the above mentioned components with a preliminary simple control strategy. Future models will include more advanced control strategies in order to get more realistic simulation results and to validate the complete model.

The evaluation illustrates the powerful and flexible nature of Matlab/SimuLink for simulating building systems models.

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Wit M.H. de and H.H. Driessen, 1988, ELAN A Computer Model for Building Energy Design. Building and Environment, Vol.23, No 4, pp.285-289

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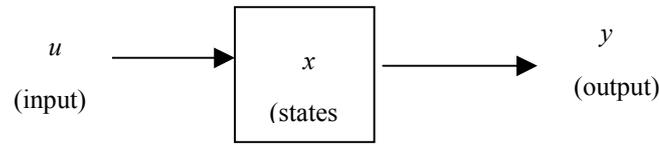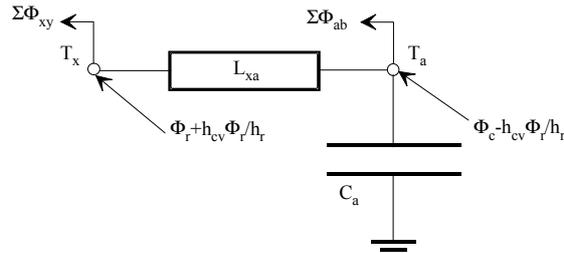
Figure 1. SimuLink block definition.

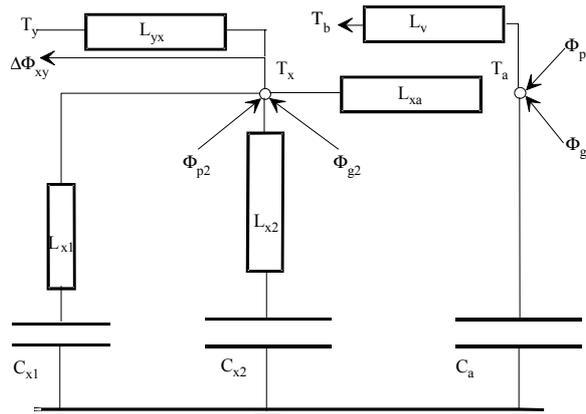Figure 2. The room model as a thermal network

Figure 3. The thermal model for one zone

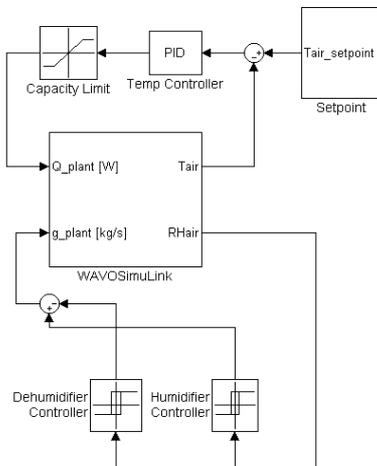Figure 4 . The WaVoSimuLink Model, including an examples controllers: a PID Tair-controller with limited heating/cooling and on/off RHair-controllers with (de) humidification.
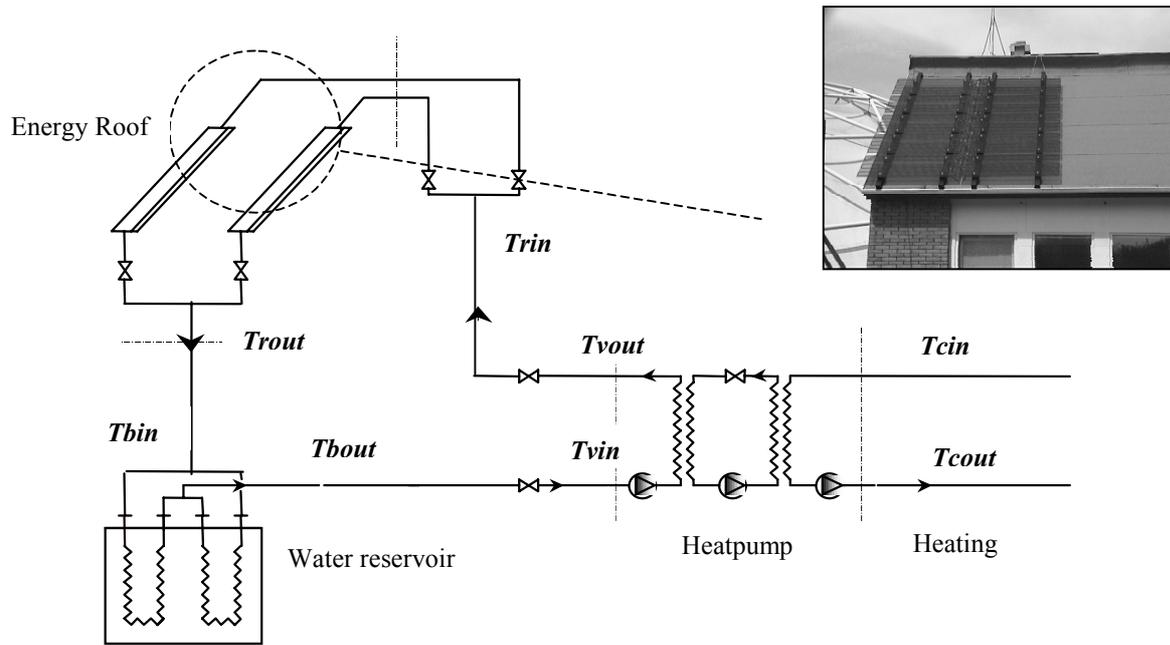
Figure 5. The energy roof system, including water temperatures (bold italic).
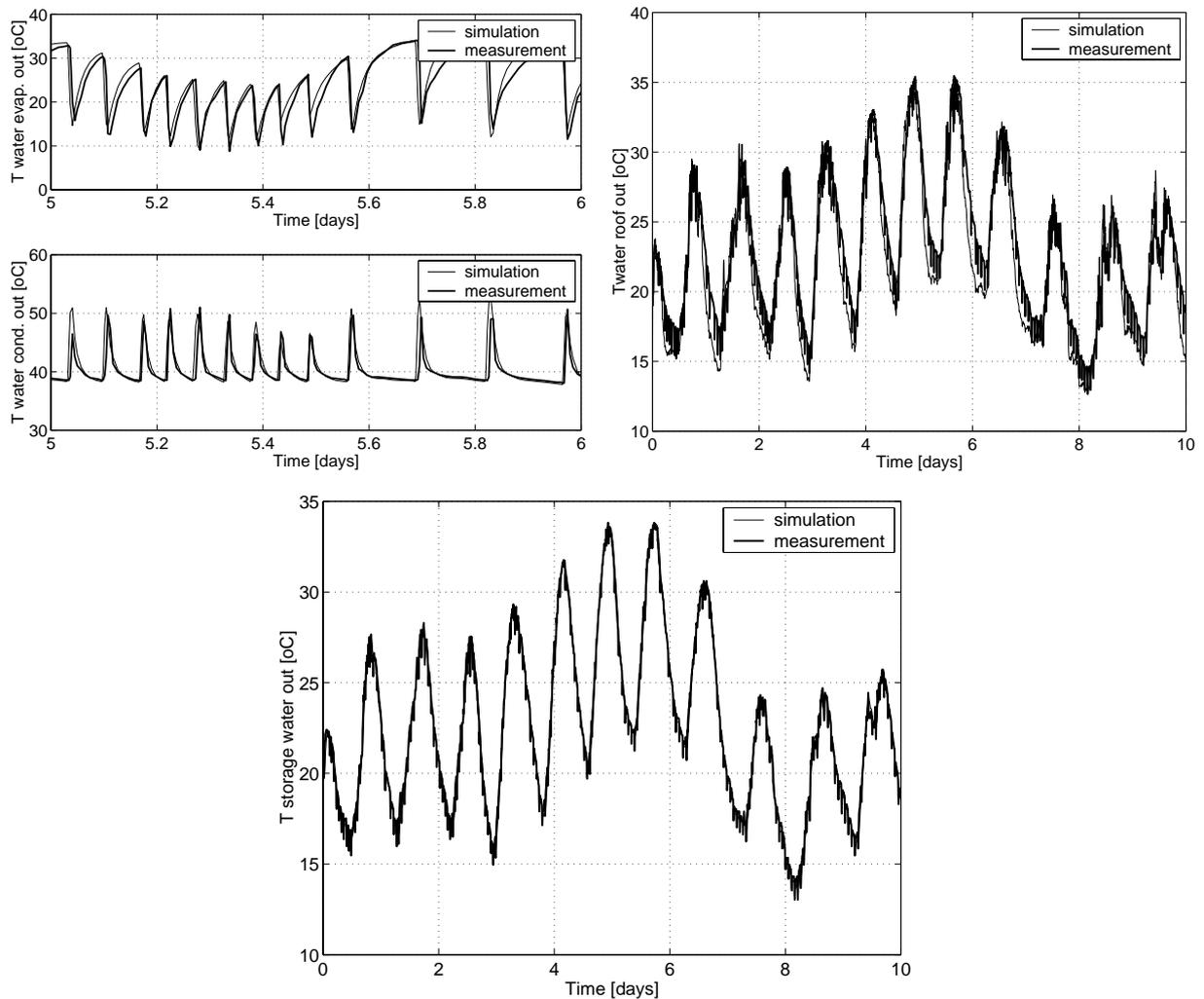

Figure 6. Simulation and measurement of the outgoing water temperature of: the heatpump (upper left), the energy roof (upper right) and TES (lower).
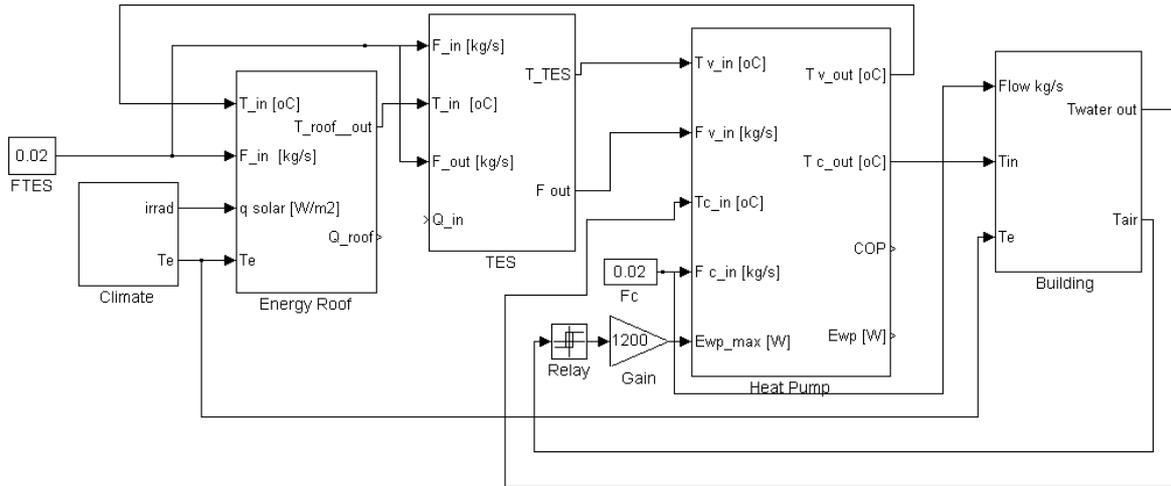
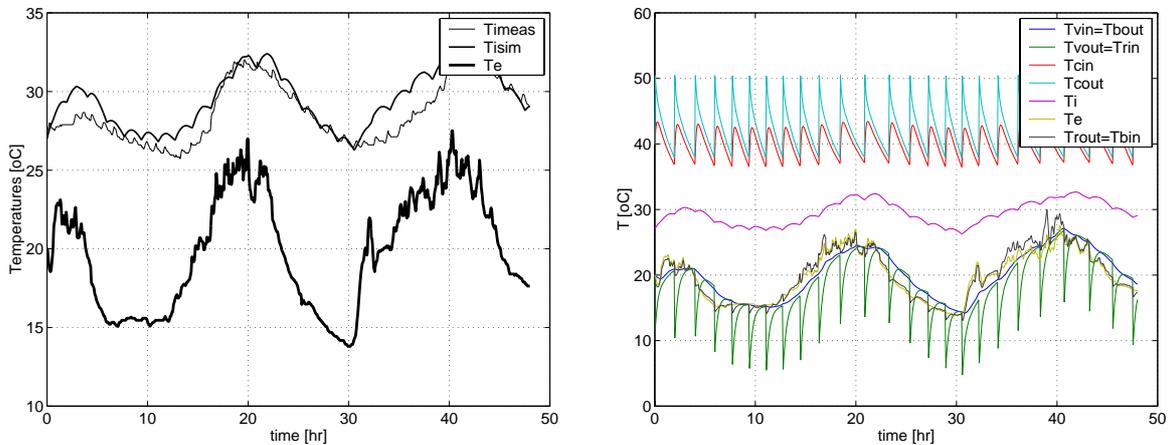Figure 7. The complete energy roof system in SimuLink.

Figure 8. The indoor air temperature, measured & simulated (left); Simulation of the total system (right)

Table I. Stages in S-functions (Mathworks, 1997): C = Continuous, D = Discrete, O = Output, t = time).

Simulation stage	S-Function Routine	Flag	Computation
Initialization	mdlInitializeSizes	flag = 0	$x = x_0$
Calculation of outputs	mdlOutputs	flag = 3	$x = x_C + x_D$, $y = f_O(t,x,u)$
Update discrete states	mdlUpdate	flag = 2	$x_D = f_D(t,x,u)$
Calculation of derivatives	mdlDerivatives	flag = 1	$dx_C/dt = f_C(t,x,u)$

Table II Comparison of the room model with some cases of the standard test (ASHRAE, 2001):

Case Nr. Simulation of	hr of occ.	model result	min.test	max. test
600ff mean indoor temperature [^{o}C]	NA	25.1	24.2	25.9
600ff min. indoor temperature [^{o}C]	79	-17.9	-18.8	-15.6
600ff max. indoor temperature [^{o}C]	6951	64.0	64.9	69.5
900ff mean indoor temperature [^{o}C]	NA	25.1	24.5	25.9
900ff min. indoor temperature [^{o}C]	80	-5.1	-6.4	-1.6
900ff max. indoor temperature [^{o}C]	5871	43.5	41.8	44.8
600 annual sensible heating [MWh]	NA	4.9	4.3	5.7
600 annual sensible cooling [MWh]	NA	6.5	6.1	8.0
600 peak heating [kW]	74	4.0	3.4	4.4
600 peak sensible cooling [kW]	6949	5.9	6.0	6.6
900 annual sensible heating [MWh]	NA	1.7	1.2	2.0
900 annual sensible cooling [MWh]	NA	2.6	2.1	3.4
900 peak heating [kW]	79	3.5	2.9	3.9

APPENDIX

A complete example how to model a system of ODEs with an S-function of Simulink is shown for the heat pump model. The first step is to define the input-output definition of the model. This is presented in Table III.

Table III. The input-output definition of the heat pump model

Variable name	Input (u) / Output (y)	Description
T_{vin}	u(1)	Incoming water temperature at the evaporator [^{o}C]
F_{vin}	u(2)	Incoming mass flow at the evaporator [kg/s]
T_{cin}	u(3)	Incoming water temperature at the condenser [^{o}C]
F_{cin}	u(4)	Incoming mass flow at the condenser [kg/s]
Ehp	u(5)	Power of electrical supply [W]
k	u(6)	efficiency [-]
T_{vout}	y(1)	Outgoing water temperature at the evaporator [^{o}C]
T_{cout}	y(2)	Outgoing water temperature at the condenser [^{o}C]
COP	y(3)	Coefficient Of Performance [-]

The second step is to formulate a mathematical model by a system of ODEs. This is done using (7). The third step is to implement the mathematical model into a (S)ystem function, a programmatic description of a dynamic system. Details about this subject can be found in (Mathworks, 1997). Figure 9 shows the program code of the S function and the final SimuLink model.

```
function [sys,x0,str,ts] = wpsfun2(t,x,u,flag)
%WPSFUN2 Heat pump
%u(1)=Tvin [oC], u(2)=Fvin [kg/s], u(3)=Tcin [oC],
 %u(4)=Fcin [kg/s], u(5)=Ehp [W], u(6)=k [-]
%y(1)=Tvout [oC] (=x(1)), y(2)=Tcout [oC] (=x(2))
%y(3)=COP
switch flag,
 case 0,     [sys,x0,str,ts]=mdlInitializeSizes;
 case 1,     sys=mdlDerivatives(t,x,u);
 case 3,     sys=mdlOutputs(t,x,u);
 case { 2, 4, 9 },
   sys=[];
end
function [sys,x0,str,ts]=mdlInitializeSizes
sizes.NumContStates  = 2; % Number of Cont. states
sizes.NumDiscStates  = 0; % Number of Disc. states
sizes.NumOutputs     = 3; % Number of Outputs
sizes.NumInputs      = 6; % Number of Inputs
x0 = [10; 10];          % Initial values
function sys=mdlDerivatives(t,x,u)
    Tvm=(u(1)+x(1))/2;
    Tcm=(u(3)+x(2))/2;
    COP=u(6)*(273.15+Tcm)/(Tcm-Tvm);
    Cc=200000;Cv=200000;cv=4200;cc=4200;
    xdot(1)=(1/Cv)*(u(2)*cv*(u(1)-x(1))-(COP-1)*u(5));
    xdot(2)=(1/Cc)*(u(4)*cc*(u(3)-x(2))+COP*u(5));
    sys = [xdot(1); xdot(2)];
function sys=mdlOutputs(t,x,u)
    Tvm=(u(1)+x(1))/2;
    Tcm=(u(3)+x(2))/2;
    COP=u(6)*(273.15+Tcm)/(Tcm-Tvm);
 sys = [x(1); x(2); COP];
```
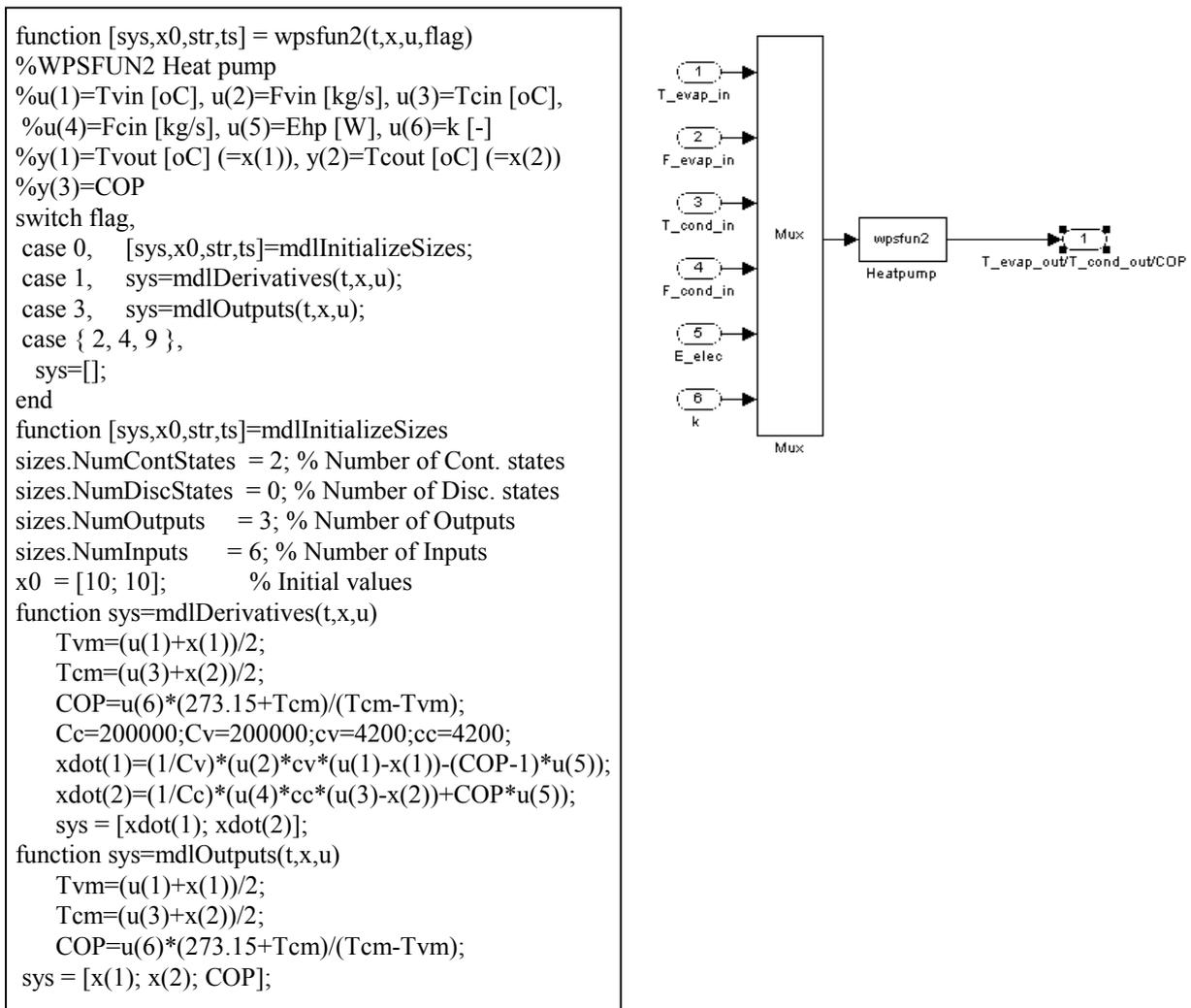

Figure 9. The code of the heat pump model used at the S function (left side) and the SimuLink model (right side).