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# Object-oriented simulation of energy supply systems on the basis of renewable energy

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## Abstract

The usage of renewable energy sources has become more important in recent times mainly due to shortage of fossil fuels. Thus new challenges arise for the control and planning of heat supply systems. These systems work with different renewable energy sources (earth heat, solar radiation, exhaust air heat from building), which therefore lead to control problems with a higher rank of difficulty. The main goal of these control strategies is the reduction of operational cost as well as an increase in the rate of return for the investment.

This paper describes the simulation of a heat supply system using Dymola [13] by means of object-oriented modelling with Modelica. The final aim of such a simulation is to develop a model predictive control strategy on the basis of the proposed object-oriented model in Modelica. To develop such a control strategy it is necessary to gain knowledge about the heat demand of buildings and the power usage of its different components. The use of Computer Aided Engineering (CAE) can lead to a further reduction of development costs. A Dymola library named **RECOMB** has been created to support of modelling and simulation of such heat supply systems. The name **RECOMB** stands for **R**enewable **E**nergy **C**omponents **m**Odelling and **o**pti**M**isation of **B**uildings. The library itself consists of sub-libraries:

- Weather (chapter 1)
- Predict (chapter 2)
- HESYS (chapter 3)
- Buildings (chapter 4)

The components and the resulting models for the thermodynamic models of the sub-library HESYS

have been validated by comparing them with existing simulation software [11], [12], while the building models have been validated with help of German guidelines [9] as well as with other simulation software [8], [10].

## 1 The sub-library Weather

The sub-library Weather contains measured weather data for several German cities and a selection of other cities for validation purposes. The data has been obtained with the help of the database program Meteororm. This program can supply various climatic information (e.g. total radiation, diffuse radiation, relative air humidity, wind speed, environmental temperature, etc.) in a desired output format (every second, hourly, daily).

Unfortunately, solar radiation is only available as radiation on a horizontal surface. But outside walls of building models normally are vertical and solar panels are also tilted to maximise radiation input. Therefore, a component is needed that allows correct calculation of radiation on a tilted surface from the available horizontal radiation data.

This component is called SolarRadiationTransformer (SRT). The SRT allows correct calculation of the radiation on a tilted surface. The formula of Liu and Jordan [4] has been implemented:

$$\begin{aligned}
 G_{total, tilted} &= R_b \cdot G_{hor, beam} \\
 &+ \frac{1}{2} \cdot (1 + \cos \beta) \cdot G_{hor, diffuse} \\
 &+ \rho_{env} \cdot G_{hor, total} \cdot \frac{1 - \cos \beta}{2}
 \end{aligned} \quad (1.1)$$

where

$G_{total, tilted}$  total radiation on tilted surface

- $G_{hor,beam}$  direct radiation on horizontal surface
- $G_{hor,diffuse}$  diffuse radiation on horizontal surface
- $G_{hor,total}$  total radiation on horizontal surface
- $\rho_{env}$  reflection factor of environment
- $\beta$  angle of tilted surface

The calculated weather data is then passed on as information values to the connected models.

## 2 The sub-library Predict [6]

The sub-library Predict can be used for short-term prediction of climate data. This is essential for developing control strategies for regions where none or very few weather data can be provided. The library contains different methods to forecast climate values. Sometimes difficulties arise in data rededication, when climate data is not clearly correlated as this causes problems for most algorithms used for prediction. To handle these difficulties three different prediction methods had to be implemented:

- Persistence
- Stochastic methods, AR-modeling
- Heuristic methods
  - fast fuzzy based forecasting
  - Neural network

Prediction using the method of persistence is the simplest method of forecasting climate data. No model knowledge is needed to apply it, but it is only useful for slowly changing processes as the environmental temperature.

Autoregressive prediction (AR) is a model-based algorithm (figure 2.1). The predicted value for the next time-step is calculated by taking the preceding values into account and applying weighting factors to them. Nevertheless the most powerful method of prediction used in this library is the fast fuzzy prediction (figure 2.2.) This method compares the actual situation with situations already known from the past, which are similar to the

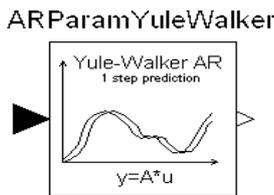


Fig. 2.1 Yule-Walker Parameter estimation

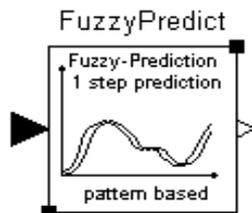


Fig. 2.2 Prediction using Fuzzy logic

current one and then generates the new value. Since the algorithm uses known patterns from situations already occurred in the past, the method belongs to the group of pattern based prediction methods.

Finally, a method using neural networks has been implemented. This neural network works on the basis of a multi-layer perceptron to forecast the actual weather data (figure 2.3). Important filters to remove trends as well as modules for scaling values and to calculate statistical values for time series have been implemented into the sub-library Predict. To make full

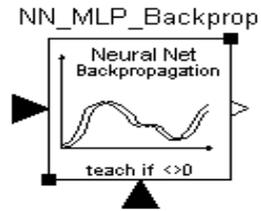
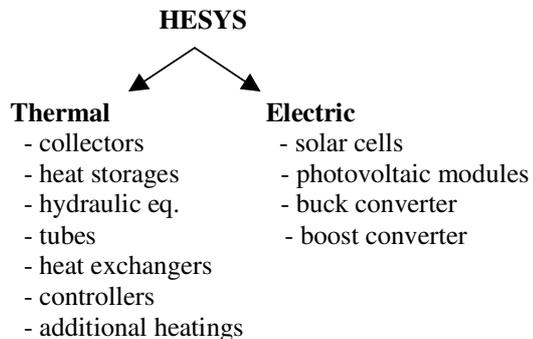


Fig. 2.3 Neural network prediction

use of the Modelica language options, some parameter calculations are carried out using external C/C++ functions. The implemented methods of forecasting have been validated on short-term prediction with the available data from the program Meteororm. In connection with the long-term data provided by weather institutes and databases, the combination of the two forms of climate prediction leads to a powerful tool for controlling and maximising the output of solar thermal and photovoltaic constructions. Again the predicted data is passed on as information values to the connected models.

## 3 The sub-library HESYS

This library contains all components necessary to model and simulate **Heat and Energy Supply SYSTEMS**. Together with the sub-library Buildings (chapter 4) this is the core of the library **RECOMB**. The library itself is divided into two sub-libraries to separate those elements necessary to model and simulate solar-thermal systems, heat pumps and conventional heating from elements necessary to model photovoltaic systems.



Unlike other model libraries, the components of HESYS have been modelled especially for controlling aspects, as it is the main aim to develop efficient control strategies for the use of renewable energies. This aspect is also shown in the design of the connectors. For the use of the sub-library Thermal a HeatPort Connector as it can be seen in figures 3.1 – 3.3 has been implemented, which contains three variables. To completely describe the energy flow, only two variables would be sufficient (temperature  $T$ , heat flow  $\dot{Q}$ ), but in this case the mass flow  $\dot{m}$  has also been integrated. This is due to the fact that the mass flow later will become the actual control variable:

```

partial connector HeatPort
  "Thermal port for 1-dim. heat transfer"
  SIunits.Temp_K T "Port temperature";
  flow SIunits.HeatFlowRate Q_dot;
  flow SIunits.MassFlowRate m_dot;
end HeatPort;
    
```

Fig. 3.1 Heat Port Connector in Modelica

```

connector HeatPort_in
  "Thermal port for 1-dim. heat transfer"
  extends HeatPort;
end HeatPort_in;
    
```

Fig. 3.2 Heat Port In Connector in Modelica

```

connector HeatPort_out
  "Thermal port for 1-dim. heat transfer"
  extends HeatPort;
end HeatPort_out;
    
```

Fig. 3.3 Heat Port Out Connector in Modelica

The connector for the photovoltaic components of the sub-library Electric is based on the connectors from the general electric library from Modelica PositivePin and NegativePin. This also allows the use of components defined in that library. To demonstrate the use of some of the basic elements of the sub-library HESYS two simple examples, one for each of the underlying sublibraries, are shown.

Figure 3.4 shows a collector array with a size of  $A = 4m^2$ . The basis for the model of the collector is the static general collector model [1]:

$$\dot{q}_{abs} = a_0 \cdot G_0 - a_1 \cdot (T_{out} - T_{env}) - a_2 \cdot (T_{out} - T_{env})^2 \quad (3.1)$$

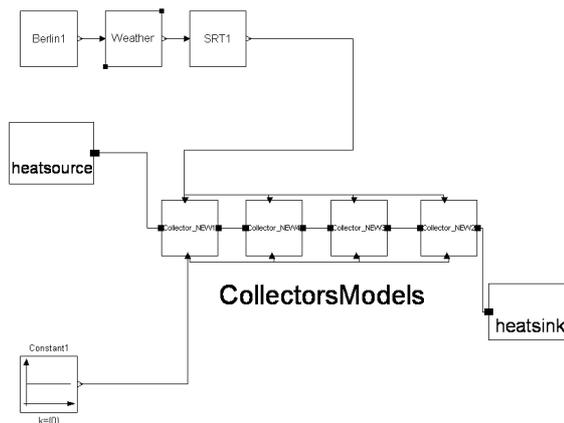


Fig. 3.4 Dymola/Modelica model of a collector field with 4 collectors in series

where

- $a_0$  optical efficiency factor
- $a_1, a_2$  thermal loss coefficients
- $\dot{q}_{abs}$  specific absorbed heat flow per  $m^2$  collector size
- $G_0$  total radiation on surface
- $T_{out}$  fluid temperature at collector exit
- $T_{env}$  environmental temperature

The parameters used to obtain the results shown in figure 3.5 resample a Prinz Lux 2000 collector. The

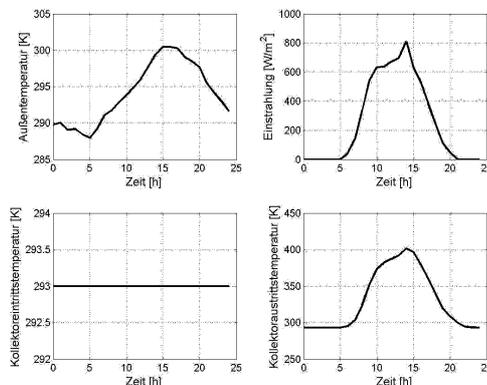


Fig. 3.5 Simulation results of a collector field

upper left graphic shows the environmental temperature over a one-day horizon and the graphics in the upper right the radiation on the collector surface. The two lower graphics show the temperature of the fluid entering the collector (left) and at the exit. The benefits can be seen clearly, as the fluid reaches temperatures around 100 degrees Celsius at the collector exit during noon.

The photovoltaic module as it can be seen in figure 3.6 consists of 36 solar cells connected in series.

The simulation model looks similar to the model of the collector array seen in figure 3.4.

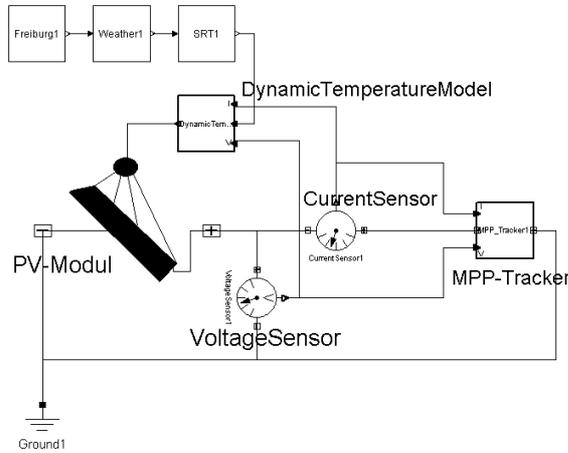


Fig. 3.6 Dymola simulation model of a photovoltaic module

The simulation shows, that several factors influence the output of a photovoltaic module, e.g. the temperature of the module itself and the point of maximum performance, obtained from the specific solar cell characteristics. For simulation purposes a solar cell can be considered a diode in its behaviour and 2-diode-model can be used to calculate current and voltage of the cell [1]:

$$0 = I_{ph} - I_{s1} \cdot \left( \exp\left(\frac{U + I \cdot R_s}{m_1 \cdot U_T}\right) - 1 \right) - I_{s2} \cdot \left( \exp\left(\frac{U + I \cdot R_s}{m_2 \cdot U_T}\right) - 1 \right) - \frac{U + I \cdot R_s}{R_p} - I \quad (3.2)$$

where

- $R_p$  current losses along the borders of the cell
- $R_s$  voltage drop
- $I_{ph}$  photo current
- $I_{s1}, I_{s2}$  satisfactory currents
- $m_1, m_2$  diode specific parameters
- $U_T$  voltage drop depending on temperature
- $I$  current through cell
- $U$  voltage drop over cell

The results can be seen in figure 3.7.

Again, the two upper graphics show the environmental temperature (left) and the radiation on the surface of the photovoltaic module (right) over 24 hours. The lower left graphics shows the temperature on top of the photovoltaic module and the power produced during that particular day can be seen in the graphics in the lower right corner of figure 3.7.

As it is the overall aim of the project to maximise the use of renewable energy sources both introduced models are only a smaller part of a system. In figure

3.4 the heat sink in reality is in most cases a water tank, the main purpose of which is to provide heated water to a connected household. This so heated water is then available for domestic use or to supply floor or ceiling heating, both becoming more popular in low-energy houses.

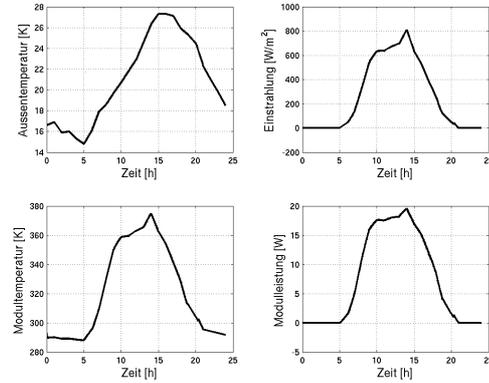


Fig. 3.7 Simulation results of a photovoltaic module

To simulate the heat demand of a regular household, the sub-library also offers components to model complete heat supply circuits, including tubes, pumps, flow-heaters and storages. One of the major parts in these systems is of course a water storage tank. At the moment two common types of storages tanks are available. A mixed-liquid storage tank, where the hot water is supposed to be mixed ideally with the colder water of the storage as well as the more frequently used stratified storages including a stratification charger to minimize heat losses. The latter ones are better in terms of cost and energy savings, since hot water is injected into a corresponding layer of water with almost identical temperature in the tank. This leads to less extra conventional heating. Nevertheless mixed-liquid tanks are still widely used due to their lower investment costs. If there is no internal or external heat exchanger used, the change in storage temperature can be calculated [3]:

$$\frac{dT_{storage}}{dt} = \frac{\dot{Q}_{collector} - \dot{Q}_{used} - \dot{Q}_{loss}}{c_{p,storage} \cdot \rho_{storage} \cdot V} \quad (3.3)$$

where

- $\dot{Q}_{collector}$  heat flow from the collector
- $\dot{Q}_{used}$  heat flow from storage to user
- $\dot{Q}_{loss}$  heat loss through walls, top and bottom of tank
- $c_{p,storage}$  specific heat capacity of stored fluid

$\rho_{\text{storage}}$  density of stored fluid  
 $V$  Volume of storage tank

A complete solar thermal model with storage tank can be seen from figure 3.8.

In the same sense, the energy produced by the photovoltaic components can be used. The energy can be used directly to feed domestic energy sinks (e.g. TV, bulbs) using buck or boost converters.

The results obtained from both the solar thermal and the photovoltaic models have been compared with results from other common simulation software packages like T-Sol [12] and the Simulink Toolbox CARNOT [13]. The results justify an approach using the modules from the sub-library HESYS.

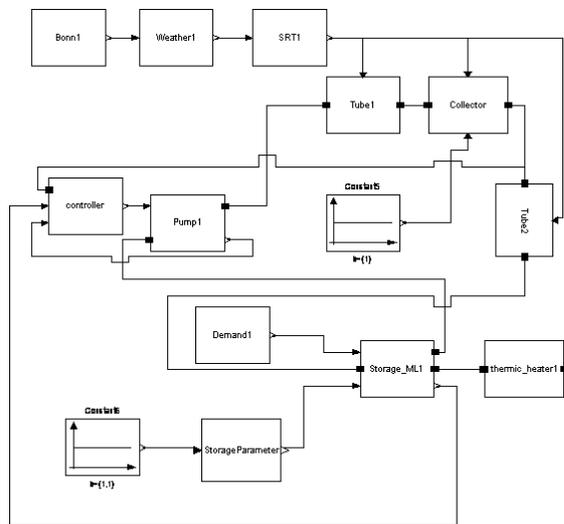


Fig. 3.8 Dymola simulation model of a simple heat supply system

## 4 The sub-library Buildings [5]

An essential part in developing efficient control strategies to work with renewable energy components is to have high knowledge about the thermal behaviour of the actual energy sink. In this case, a building, not necessarily a low-energy house, is considered to be the main energy consumer. Therefore, the sub-library Buildings contains components (walls, windows, models of exchange of radiation inside rooms) to build realistic models of any kind of buildings.

There exist already several libraries to simulate thermal behaviour, even one designed with Modelica [10]. Still the authors decided to develop one of their own. This again was driven by the control approach, as it was necessary to connect the components from the HESYS with building components as well as with the controllers.

Nevertheless, both libraries share similarities, for example the modelling of heat transmission between walls or other heat emitting elements inside a room (machines, persons). The library allows the use of the two-star model [7], which approximates the heat transmission. This model is very efficient for non-rectangular rooms or rooms with additional heat emitters. For validation purposes, exact models to calculate heat exchange between opposite or perpendicular heat radiation emitting elements [9] are implemented as well.

Major differences can be found in the implementation of walls of windows. Even though a wall can easily be divided into objects for different layers, it is considered to be a better approach to implement a wall as a single object. This allows a more exact realisation of a wall consisting of different layers.

Starting from the partial differential equation from Fourier:

$$\rho \cdot c_p \cdot \frac{\partial T}{\partial t} = -\lambda \cdot \frac{\partial^2 T}{\partial r^2} + \dot{q}_i \quad (4.1)$$

with

$\rho$  density of material  
 $c_p$  specific heat capacity  
 $\lambda$  heat conductivity  
 $\dot{q}_i$  heat flux density  
 $T$  absolute temperature

it is useful to then generate a discrete approximation of this equation. In [5] it is shown that it is more accurate to use an implicit method for differentiating. Therefore, the reverse quotient for differentiating is used to calculate the temperature distribution through the wall. Since a wall normally consists of layers of different materials, it can be physically justified to consider each wall layer a numerical layer. This leads to the following system

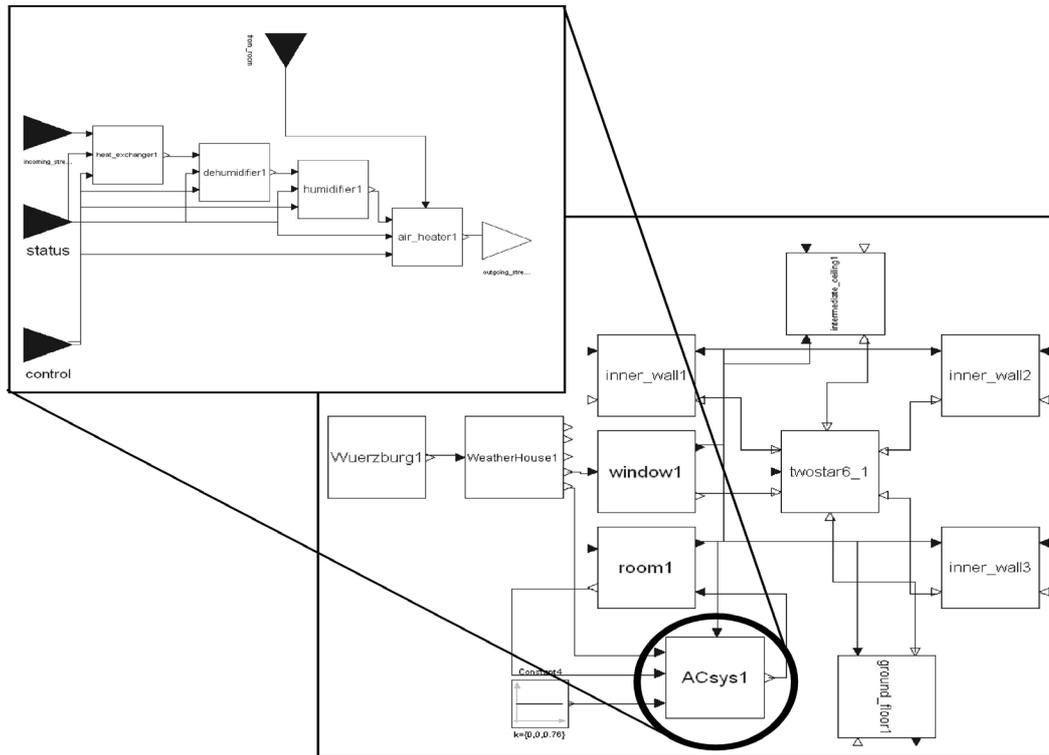


Fig. 4.1 Dymola simulation model of a simple room with air conditioning

of equations for heat conduction inside a wall element:

$$\frac{dT_i}{dt} = \begin{cases} \frac{a_1}{d_1^2} \cdot (T_2 - 2 \cdot T_1 + T_{outside}) & \text{if } i = 1 \\ \frac{a_i}{d_i^2} \cdot (T_{i+1} - 2 \cdot T_i + T_{i-1}) & \text{if } 1 < i < n \\ \frac{a_n}{d_n^2} \cdot (T_{inside} - 2 \cdot T_n + T_{n-1}) & \text{if } i = n \end{cases} \quad (4.2)$$

with

- a thermal diffusivity
- d thickness of layer
- n number of layers

The temperatures on the inside and the outside of the wall can be calculated using the heat balances on these surfaces:

$$0 = \dot{Q}_{convection, outside} + \dot{Q}_{longwave} + \dot{Q}_{shortwave} + \lambda_1 \cdot \frac{A}{d_1} \cdot (T_1 - T_{outside}) \quad (4.3)$$

$$0 = \dot{Q}_{convection, inside} + \dot{Q}_{longwave} + \dot{Q}_{shortwave} + \lambda_n \cdot \frac{A}{d_n} \cdot (T_{inside} - T_n) \quad (4.4)$$

where

- $\dot{Q}_{shortwave}$  heat transmission caused by short-wave radiation
- $\dot{Q}_{longwave}$  heat transmission caused by long-wave radiation
- $\dot{Q}_{convection}$  heat transmission caused by convection on inside or outside of element
- A area of wall
- $d_1, d_n$  thickness of first/last wall layer
- $\lambda$  heat conductivity of wall layer
- T absolute temperature

The same approach is used for the model of the windows. As originally low-energy houses have been considered, a window can also be seen as a wall element with, in case of double-glazing, at least three layers, where the intermediate layer is a vacuumed space or filled with gas. But heat transmission through a layer of glass is different to that of a wall. To generate an exact model this

has to be considered. Shortwave radiation does normally not get absorbed in glass layers. Nevertheless, after being absorbed by objects in the room it is transformed and emitted as long-wave (heat) radiation. For this radiation, glass layers are impenetrable. This leads to a natural heating of the room and this effect is commonly known as the greenhouse effect. Furthermore, for glass layers reflection and absorption between layers has to be considered. This is accomplished by using the ray-tracing method.

Another major part of the sub-library next to model buildings is to model the interior behaviour of a room. This is again done with respect to the overall aim of developing the control strategies. To minimise conventional heat sources, low energy houses also make use of heat recovery in air conditioning systems. Hence, these systems obviously have an influence on the total heat absorbed or emitted inside a room. Therefore, it has to be implemented in a complete model as well as conventional heat suppliers like radiators. The sub-library allows to model realistic air conditioning systems, which can be extended to a heat recovery system due to the object-oriented nature of the simulation environment.

Another extension of the available library is the possibility to simulate the room behaviour with respect to hygienic factors. The general purpose of the library was also to generate a room climate that is generally considered comfortable by a human being. Therefore in addition to heat transmission, emission and absorption, factors for relative humidity, moisture on the insides of walls and air pollution by CO<sub>2</sub> have to be considered.

Furthermore, it is possible to control the room behaviour with simple PID – controllers as well as with state space controllers. This already leads to a good impression of the total heat consumption of a single room or house under different requirements of comfort.

The models generated using the sub-library Buildings have been validated using an exemplary configuration for a room under certain conditions obtained from [9] as well as comparing the results with those from the “Baukonstruktionslehre” (BKL) – house introduced by Feist [7]. The Verband Deutscher Ingenieure (VDI) offers a range of examples in one of their guidelines to compare total heating and/or cooling load or for a selected week of rooms under defined conditions. Figure 4.2 shows the complete model of the VDI example 13 as it appears in Dymola.

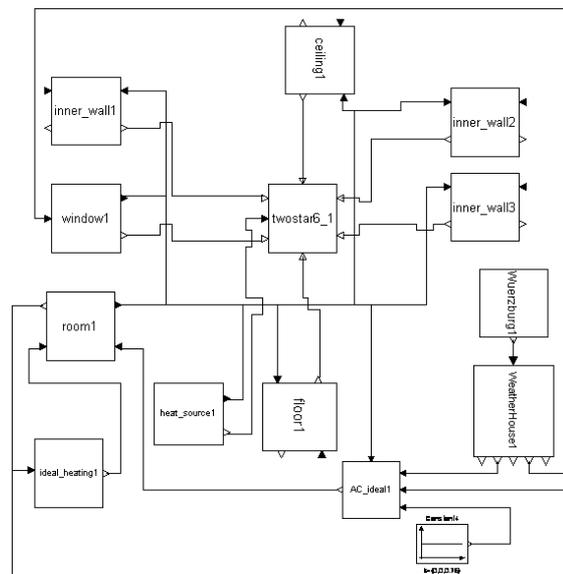


Fig. 4.2 Dymola simulation model of the VDI example room 13

The VDI has used five different simulation programs to get results for the maximum heating and cooling load as well as for the total heating and cooling load over a one-year period. The results have been grouped into a minimum, a maximum and an average. A model can be suggested as validated, if the simulated values for the mentioned are in between the range of the other five simulation programs.

As it can be seen from figure 4.3 the model build with components from RECOMB fulfil this requirement, as only the maximum value for the cooling load violates the constraint by eight per cent.

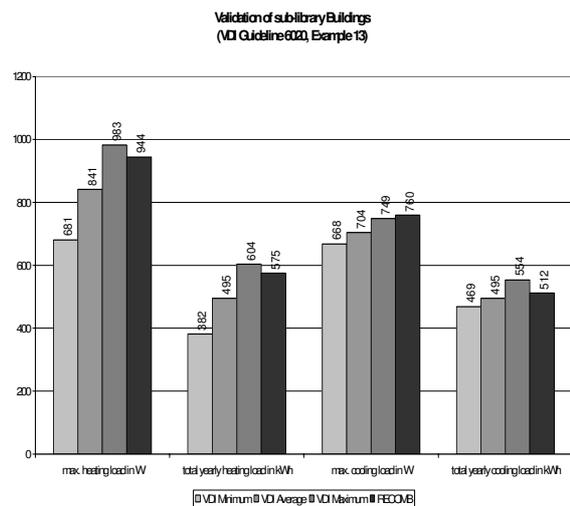


Fig. 4.3 Validation results VDI - RECOMB

Comparing the results with the BKL – Vergleichshaus, has also validated the model. The difference is, that the BKL Vergleichshaus is actually a three 2-level houses in a row, sharing one side. Thermodynamically speaking, the one in the middle is the most interesting one, as it is connected to the other houses on its east and west side. Only the front (facing south) and the back (facing north) are in contact with the environment as well as the roof. Figures 4.4 shows the different temperatures in the ground floor and the 1<sup>st</sup> floor as they appear in the middle section of the BKL – Vergleichshaus. It can be seen that the temperature in the top room (upper trajectory) varies more than the temperature in the lower room. Also due to extra heat gains during the summer through the flat roof the temperature in 1<sup>st</sup> floor is higher than in the ground floor room.

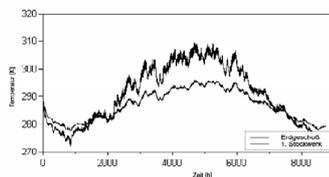


Fig. 4.4 Room temperatures for the BKL - Vergleichshaus

## 5 Further work

The development of the introduced library RECOMB is an ongoing process and is far from completion. As has been mentioned briefly in the introduction, the overall aim of this library is to develop powerful and efficient control strategies to minimise the use of conventional heat resources. Therefore, a major part in the near future will involve developing modules to calculate optimal control trajectories to work with the heat and energy supply systems and/or air conditioning systems inside rooms. This might eventually lead to re-designing some of the already existing modules.

Also the library aims to give help to another area important for maximising the benefits from renewable energy resources. Already being developed but far from being presentable, the authors currently work on modules to help determine the optimal size of a heat and energy system, e.g. optimal size of a collector field for a normal houses.

Finally, as seen from the introduced figures of the library, the graphical output of the models has to be improved to offer the user an easier way of generating simulation models. Well-designed

icons for buildings and heat and energy supply components will further improve the usability of the library.

## 6 Acknowledgements

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