Transient Simulations of Residential Buildings in Interaction with Combined Heat and Power Gas Technology

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Abstract

Buildings are the largest energy consuming sector in the world, and account for a one third of total final energy consumption in the world [1] and an equally important source of carbon dioxide (CO_2) emissions. To minimize the CO_2 emissions, i.e. more energy-efficient buildings, more intelligent interaction between the building, its equipment technology, energy supply grids and users behaviour is required. These challenges can only be met by increased research, using both experimental and numerical methods.
Numerical simulations can provide valuable insights in these matters, as the system “building” can be modelled and the impact of various commercially available appliance technologies on the overall performance of the system can be analysed. In this manner, the effects of technologies such as boilers, heat pumps (HP), combined heat and power systems (CHP) or heat storage and solar collector systems on the building as a whole can be investigated with the Modelica-based simulation environment Dymola.

The aim is to describe and investigate the interaction between domestic houses and conventional gas-fired technologies such as boilers and state of the art of CHP appliances and novel approaches using regenerative energies, e.g. solar power. The validation data for the created and improved models were gained from GWI’s test rigs and the GWI test house on the site of the institute. The building is equipped with a monitoring system for all mass and energy flows and temperatures on the inside and outside of the building. In addition, the weather data (wind speed/direction, total radiation intensity, temperature on all sides) are measured at the site and stored digitally. This is especially important for the validation of the model and its calculation of the convection of the building which effects the total energy loss of the system. These extensive datasets made it possible to reach an excellent matching between simulations and real system. The focus was set on the interaction of the different components, technologies, building types, weather effects, load profiles and degrees of utilisation and their effects on the total energy balance. Combining these models enables the user to simulate the transient behaviour of complete residential buildings with the implemented energy systems and furthermore to evaluate even domestic settlements.

Keywords: *CO_2 Reduction, Building; Modelica Simulation; Renewable Energy; CHP*

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1 Introduction

With the beginning of the industrial revolution in the last century mankind began to affect the world climate. The massive emission of carbon dioxide (CO_2) and other greenhouse gases increases the greenhouse effect and is changing the world climate. Even small variations in global temperatures will lead to drastic consequences of the climate on our planet. Without decisive actions in the next following decades, CO_2 emissions will increase enormously. To reduce the impact of global warming to a manageable level, the range of carbon dioxide in the atmosphere has to be limited. This can only be done by specific efforts in all fields of energy consumption. For example, the residential sector was responsible for around 40% of the total consumption of primary energy in the European Union (EU) and it is responsible for 36% of the European Union's total CO_2 emissions. Energy-efficiency and low/zero-carbon energy technologies for heating and cooling in buildings will play a crucial role in the global and local strategies against the impacts of the greenhouse effect. To reduce the consumption of energy and thus the emission of CO_2 in the field of domestic and nondomestic architecture, it will be necessary to improve existing technologies and develop new approaches. The intelligent interaction between the building, its equipment, energy supply grids, different energy sources and the behaviour of the inhabitants inside the system house are only a few examples. This paper presents and summarizes the results of research project to develop a modular system approach for residential houses with the modelling language Modelica.

The goal of the paper is to have validated modelled components in Modelica to simulate the test house and heating and air conditioning systems (HVAC) models to describe and investigate the interaction between domestic houses and conventional gas-fired technologies. Moreover is to study the possible solutions for energy consuming and producing (CHP) in a building and to discuss the optimal possible combinations between building and HVAC technologies. The House and HVAC models are the basic models to reduce up to 50 % CO_2 emissions in the city of Bottrop in Germany [2].

2 Objects and Methods

Building and HVAC technologies

The GWI's test house was used as reference object for the following described developments. It has been designed as a three levels single family house in 1998 on the premises of GWI in Essen in Germany. The building is equipped with a monitoring system for all mass and energy flows and temperatures on the inside and outside of the building. In addition, the climatic data (wind speed/direction, total radiation intensity, temperature on all sides) are measured on site and stored digitally. This is especially important for the calculation of the convection at the outer walls of the building.

Figure 1 and table 1 show a picture of the test house and a short summary of few parameters of the building are shown.

Figure 1: External View from GWI's test house [3].

Table 1: The main Construction and energy data of GWI's test house	
Living Area	125 m²
Ground Area	85 m²
Whole Volume	930 m³
Standard of Thermal Insulation	WSVO 95
Heating Demand	70 kWh m^{-2}
Thermal insulation of walls U-value	0.24 - 0.34 $Wm^{-2}K^{-1}$
Insulation glazing U-value	2.0 - 3.5 $Wm^{-2}K^{-1}$

This overall monitoring system allows detecting and recording all resulting profiles of the different flows caused by the different technologies. This facility provides the GWI with the chance to examine the interaction of different kinds of occupants (singles, families …) and the newest combined heat and power technology.

The above mentioned house has different heating technologies implemented, thermally activated building system to carry hot/cold water, radiators located in each room in ground and upper floors. All radiators in the attic are switched off. The Cellar is heated only by the losses of the Heating systems, i.e. there are no radiators available in it. Temperatures are locally determined for the entire room.

Furthermore the hydraulic regulation is listed as following:

- Weather-compensated control
- Heating temperature limit is 15 ° C
- Heat curve 1.4
- Night shut-off 10:00 - 6:00 clock
- Maximum drinking water temperature of 65 ° C
- Operation with mixing and switching valves (1-Mixed heating circuit)

3 Modelling Approaches

The developed system of the GWI's test house consists of several models describing the entire installed gas fired technology (conventional and CHP-systems), hot water storages, hydraulic systems as pipes, radiators, circulation pumps and expansion valves.

All models were implemented using the Dymola Version 7.4 based on Modelica 3.1. Dymola is a commercial modelling and simulation environment based on Modelica language [4]. Modelica is a non-proprietary, object oriented, equation based language [5].

Two main packages were developed. In the energy supplier package many types of appliances are included, for example condensing boilers, CHP and HP which are based on the specific characteristics of the systems. The efficiency may be selected as a constant or linear interpolated. The required heat is determined by a target temperature. The pipe models are physically modelled. These were modified in the way that a detection of the energy consumption and the power output is possible. Figure 2 illustrates a modelled CHP unit using Modelica and Dymola. This Package was done by the Technical University of Hamburg-Harburg (TUHH) [5].
For example, there are three remarked systems shown in Figure 2. In red is the dynamic pipes model, i.e. Internal motor and peal load boiler presented. Two controllers in black remarked and in orange is the “State Energy” observed.

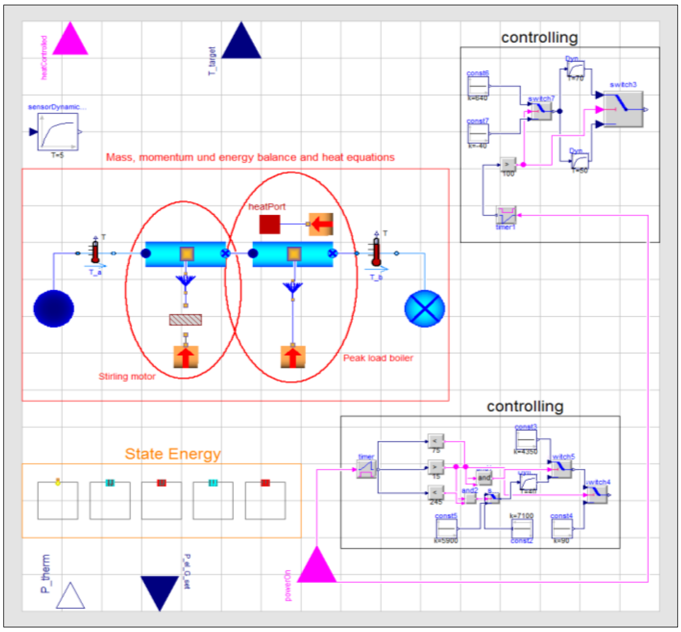

Figure 2: CHP unit in Modelica

In the pipe model is as shown in Figure 2 all the balance equations are describes. These balance equations needs to be defined for the formulation of a mathematical model. The mass, momentum and energy balance. The partial differential equations for the one-dimensional flow pipe model are as following described in Modelica [4, 5 and 6]:

Table 2: Balance equation in pipe model in Modelica	
Mass balance	$\frac{\partial(\rho A)}{\partial t}+\frac{\partial(\rho A v)}{\partial x}=0$
Momentum balance	$\frac{\partial(\rho v A)}{\partial t}+\frac{\partial(\rho v^2 A)}{\partial x}=-A\frac{\partial p}{\partial x}-F_F-A\rho g\frac{\partial z}{\partial x}$
Energy balance	$\frac{\partial(\rho u A)}{\partial t}+\frac{\partial\left(\rho v(u+\frac{p}{\rho})A\right)}{\partial x}=vA\frac{\partial p}{\partial x}+vF_F+\frac{\partial}{\partial x}\left(kA\frac{\partial T}{\partial x}\right)+\dot{Q}$
Pipe friction	$F_F=\frac{1}{2}\rho v\,\lvert v\rvert\, fS$
	x: independent spatial coordinate (flow is along coordinate x) t: time v(x,t): mean velocity p(x,t): mean pressure T(x,t): mean temperature ρ(x,t): mean density u(x,t): specific internal energy z(x): height over ground A(x): area perpendicular to direction x g: gravity constant

	f: Fanning friction factor S: circumference

The pipe model includes a thermal port which gives the possibility to distribute a given heat flow over the discretised length of the pipe. The amount of heat is given as a constant or a variable value by the input signal Q flow. The efficiency of the boiler or the CHP unit can be given as a constant value or as a variable too.

The control system adjusts the power output of the system to the needed level which is given by the heating demand of the building. Even the time response of the system as well as the communication between the CHP unit and the peak load boiler can be simulated with the presented approach. For example, let’s assume that the required heat demand of the system is 9 kWh. The examined internal engine supplies max 5.5 kWh and the peak load boiler supplies maximum 25 kWh. If the internal engine in the CHP unit reaches its maximum power level (5.5 kWh) and the energy demand of the system still can’t be satisfied, a signal is given to the peak load boiler to supply the additional needed heat (here in our example 3.5 kWh).

The last part of the CHP model as shown in Figure 2 is the State Energy component. With the help of this component, it is possible to examine and collect all interesting data like fuel flows as well as the integrated values, i.e. heat, fuel quantities, electricity consumption and electricity generation. It is like a meter for our necessary predefined information in each HVAC model.

The other main package was modelled for building and coupling between house and technologies. A one-zone and a multi zone model of the GWI’s test house including the hydraulic systems were integrated in the package. This package contains also the models for pipes, radiators and circulation pumps. This package was developed by RWTH Aachen University. Air (in rooms), weather (external environment), walls, windows and doors are also modelled in this package.

Figure 3 depicts the wall and door model. Both models provide the user with the possibility to define: Layer numbers, area and material types for each layer. In these models, the energy balance and heat transfer (conduction, convection and radiation) equations are defined. All models of this package are easy to parameterise. Various media, materials, unit type geometries are available also in this library.

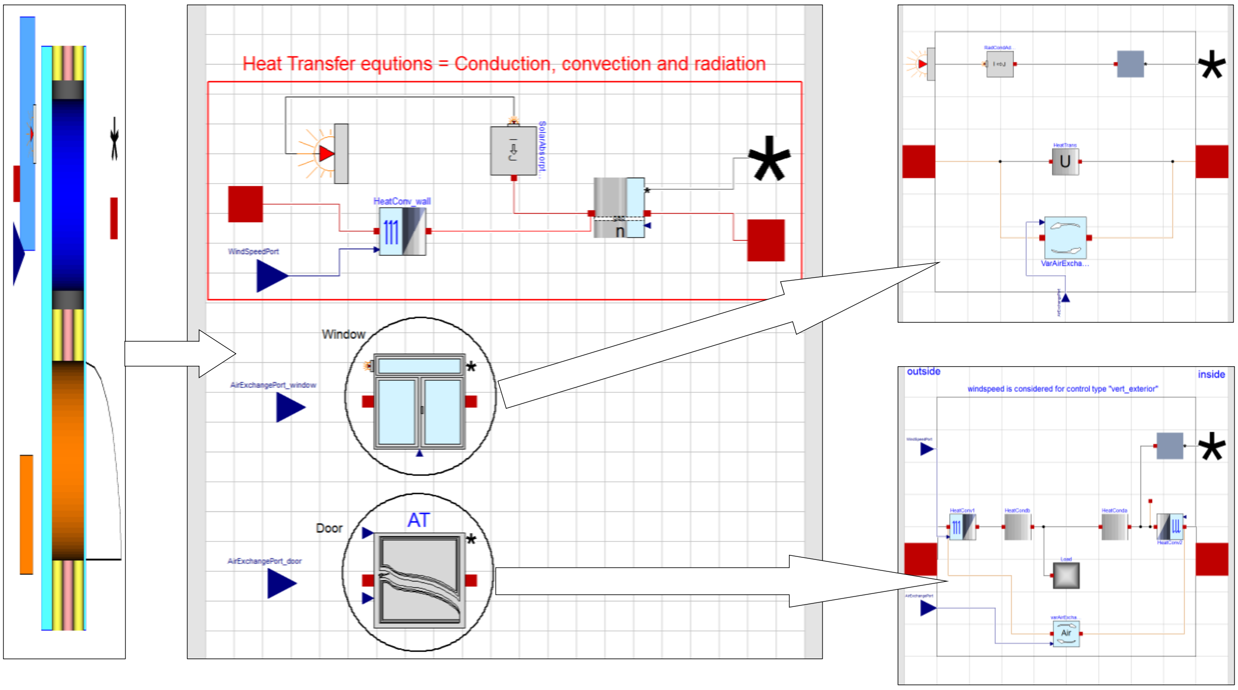

Figure 3: Outer wall model (left hand side) and window and door models (right hand side) in Modelica.

The final modelling of the GWI’s test house was achieved in two steps. The first step was to implement the different models out of the developed libraries into a one zone model of the house. Figure 4 shows the model of GWI’s test house as one zone model with its hydraulic system. This approach sums up all inner volumes (air, walls), doors and windows into a building with one big room. The building model consist a thermostat on each wall. The desired value for the room temperature is the average of the specified values of all rooms in the real building. The same procedure was applied to the heating system of the house. Pipes and radiator geometry and materials were also summarized.

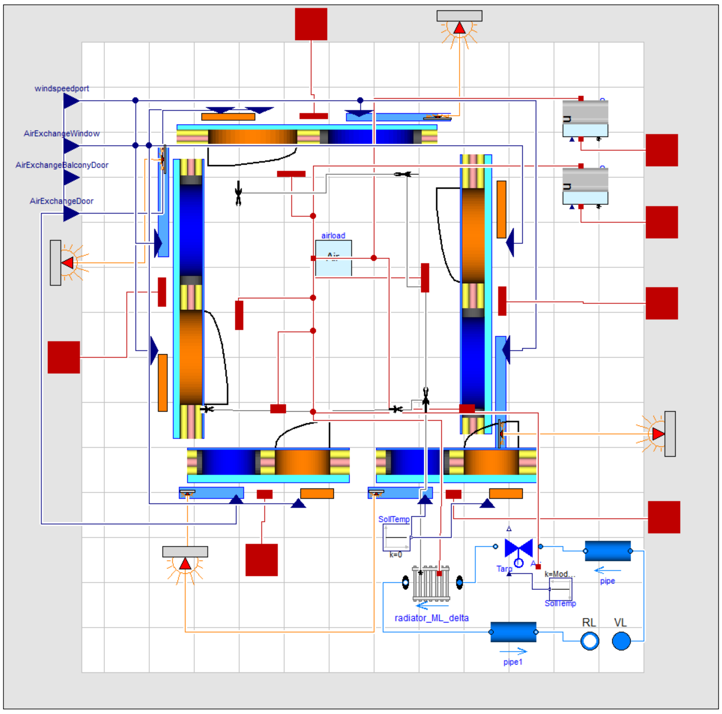

Figure 4: One zone model with the hydraulic system.

The reason for an approach with such a reduced degree of complexity is the direct dependency of the computing time and the total number of equations in the resulting differential algebraic equation system. A one zone approach is therefore much faster than a detailed zonal model due to the reduced amount of equations. This point is especially important if whole domestic settlements or a very high number of scenarios should be investigated.

All components such as walls, floors, ceilings, windows and doors are physically modelled. The following physical processes in these models are considered [6 and 7]:

- transient heat conduction through walls; a wall can consists of several layers with the same materials or with a different physical properties.
- steady-state heat conduction through sealing systems; transmission of short wave radiation through the window depends on a constant coefficient
- heat convection at outside facing surfaces depending on wind speed. Heat convection at inside facing surfaces is also described in each model
- temperature balance equations for the air volume in each room.

Heat transfer calculation in Dymola through the wall, door or Window (1-Dimention) is presented as in table 4 [4, 5 and 6]:

Table 3: Used Heat transfer equation in models in Modelica	
Heat conduction	**Box**: G = k*A/L k: Thermal conductivity (material constant) A: Area of box L: Length of box

	Cylinder: G = 2*pi*k*L/log(r_out/r_in) pi: Modelica.Constants.pi k: Thermal conductivity (material constant) L: Length of cylinder r_out: Outer radius of cylinder r_in: Inner radius of cylinder
Heat convection (Laminar along a plate)	Gc = A*h h = Nu*k/x; Nu = 0.453*Re^(1/2)*Pr^(1/3) h: Heat transfer coefficient Nu: = h*x/k (Nusselt number) Re: = v*x*rho/mue (Reynolds number) Pr: = cp*mue/k (Prandtl number) x: distance from leading edge of flat plate rho: density of fluid k: thermal conductivity of fluid (material constant)
Heat Radiation	Small convex object in large enclosure: Gr = e*A e: Emission value of object (0..1) A: Surface area of object where radiation heat transfer takes place
	Two parallel plates: Gr = e*A e: Emission value of object (0..1) A: Surface area of object where radiation heat transfer takes place
	Two long cylinders in each other (from inner to the outer cylinder): Gr = 2*pi*r1*L/(1/e1 + (1/e2 - 1)*(r1/r2)) r1: Radius of inner cylinder r2: Radius of outer cylinder L: Length of the two cylinders e1: Emission value of inner cylinder (0..1) e2: Emission value of outer cylinder (0..1)

To get more accurate results and to study the exact response of house according to the weather a multi zone model was needed. In this model, all the hydraulic and the individual rooms of a building were modelled. This means that every single zone has been as in reality modelled; the terms, conditions can be set in detail for each zone. In our case the GWI test house built from a kitchen, two bathrooms, a living room, three bedrooms, attic and cellar and it has overall four levels. Every room was modelled as a separate zone. Even the unheated basement and the roof space were integrated. With every additional zone the number of equations increases. This leads to slow down the simulation and increases the possibility for the occurrence of errors. User profiles (internal loads and ventilation behaviour) were specified via a table for every room.

4 Measurements and Application Example

The measurements were used for model validation and the following data were registered:

Table 4: The main Construction and energy data of GWI's test house

Measurement variable	**Location**	**Unit**
Room temperature	In each room	°C
Radiator flow und return temperature	At each radiator	°C
Ambient temperature	At each wall side	°C
Flue gas temperature	In flue gas flow	°C

Boiler flow and return temperature	In Boiler	°C
Hot water storage tank inlet and outlet temperature	In the inlet and the outlet of a storage tank	°C
Gas amount	Gas meter	m³
Current gas flow rate	Gas pipe	m³/h
relative air humidity	In front of the house	%
Wind speed and it direction	In front the house	m/s and degree
Solar direct and indirect radiative power	In front of the house	W/m^2

The measurements were originally available at irregular points in time, in 3-5 second step. These data was prepared for comparison with the simulated data.

Detailed weather data in 15 seconds steps for the whole years were obtained from the weather-station in front the house, i.e. ambient temperature, wind speed and direction, radiation power and relative humidity.

The heat demand of the building is supplied by a reference device (fuel cell, peak load boiler). All other systems are following this reference device. In that way each system is guided by the same reference value. Because the heat demand of the building is already accommodated by the reference device all other systems use a recooling system as a heat sink.

All models were validated based on the measurements in GWI test house and test rigs. A vast number of parameters were compared like the mass flow rate, the flow temperature, the reverse flow temperature, the electrical power, the thermal power and the fuel consumption of each heating technology. Furthermore the validation of the GWI's test house is presented. After the Validation of each model it would be possible to make a parameter variation to study the energy balance in the both HVAC and building systems. Figure 5and 6 shows the agreement of the measured and simulated return temperatures and the thermal power in GWI test house.

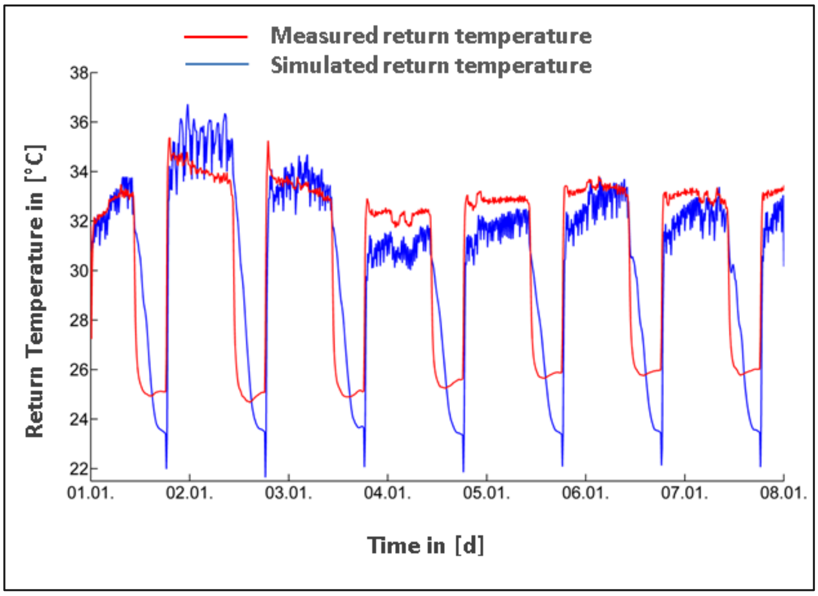

Figure 5: Comparison of measured with simulated return temperatures in the GWI's test house.

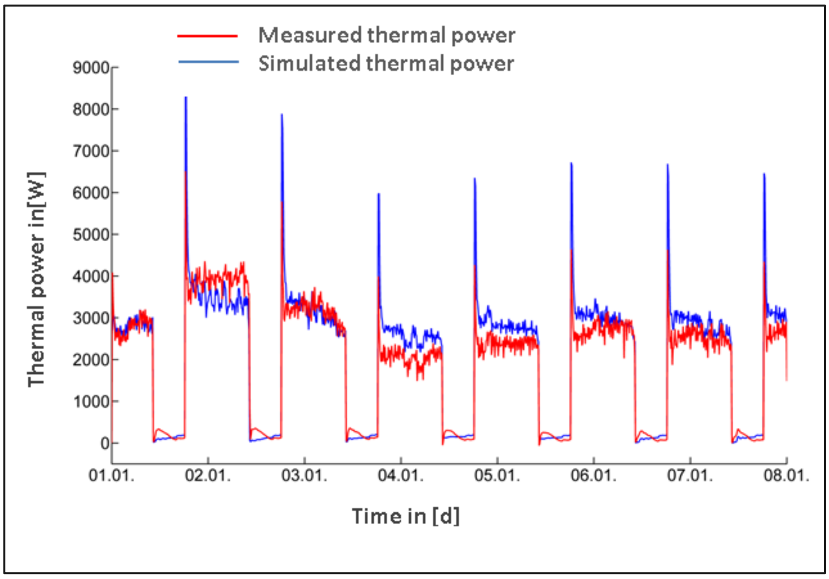

Figure 6: Comparison of measured with simulated thermal powers of the GWI's test house.

We will now present an application's example of a heating system with a one zone building which is part of our second package, as mentioned above. One of the applications of these packages is used to compare CHP Technologies at the same weather; user and building conditions. A comparison of different isolations of the building was also discussed in the final report of the "Modelica-Simulation des Systems Nutzer/Gebäude/Anlagentechnik" project [6]. Figure 7 shows a Modelica model of the heating system with one zone model.

The red marked square in Figure 7 shows the model of a CHP unit inclusively its peak load boiler and the circulating pump. Every component in this system can be set as desired. The heat supplier is connected to a thermal energy storage tank. This allows the CHP unit to reduce working hours and the amount of on and off switches. Two temperature sensors in the bottom and on the top of the storage are modelled. These sensors are necessary to compare the temperatures inside the storage tank. The right orange box on the lower right corner of the Figure shows the heat distributor and the water supply with a separated thermal storage from the heating plant system and the flow/return pipes to the building. The nominal supply water temperature was set by a scheduled CSV table according to VDI 4655 [9]. Three inhabitants were assumed.

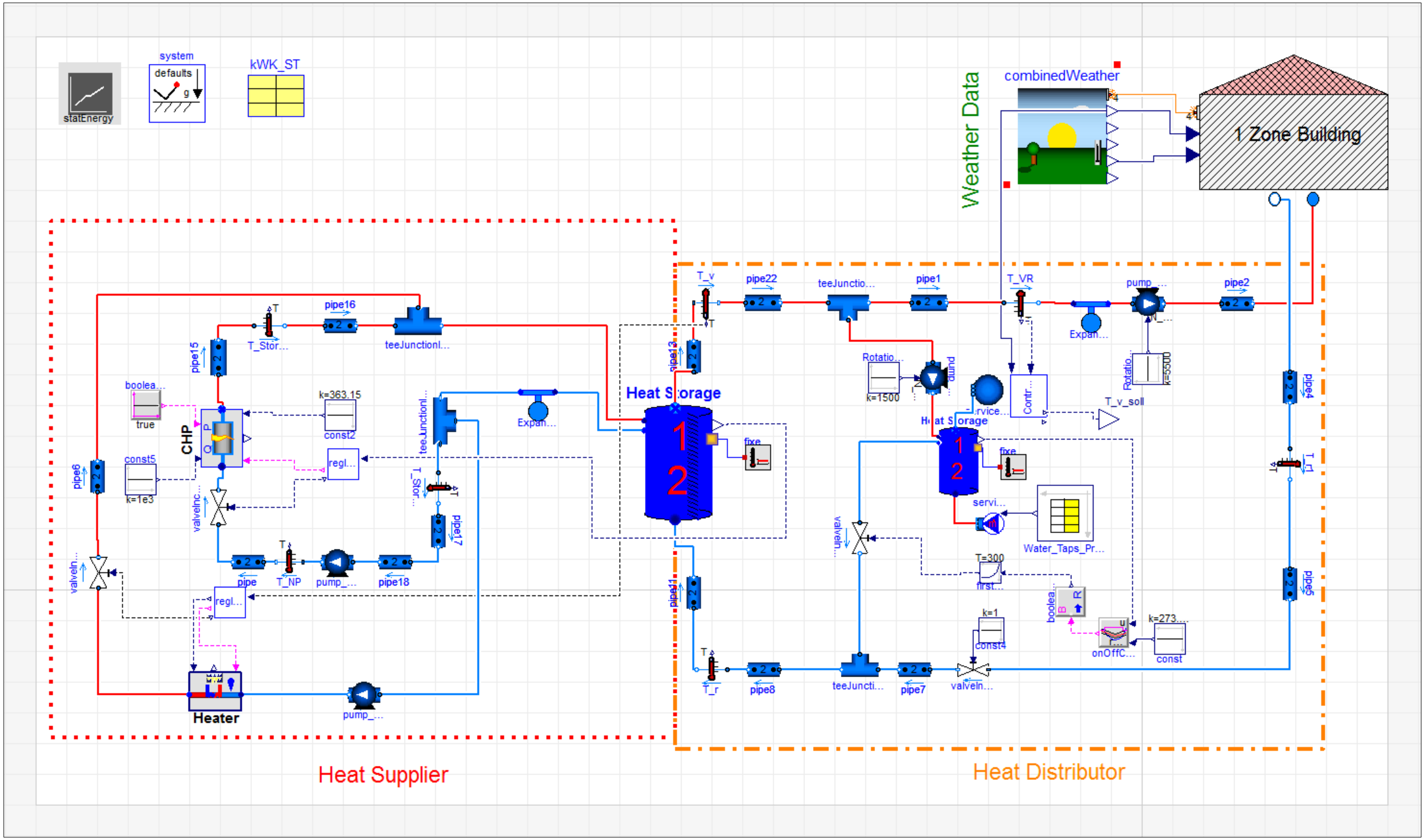

Figure 7: Multi zone model with the hydraulic system. in Modelica

The average temperature of the air was set to be 19°C inside the air load model. Figure 8 shows the building i.e. room temperatures and the outside air temperature over one year. The weather data were taken from the German test reference year (TRY) [10] from the year 2010 and in zone 5 (Essen in Germany).

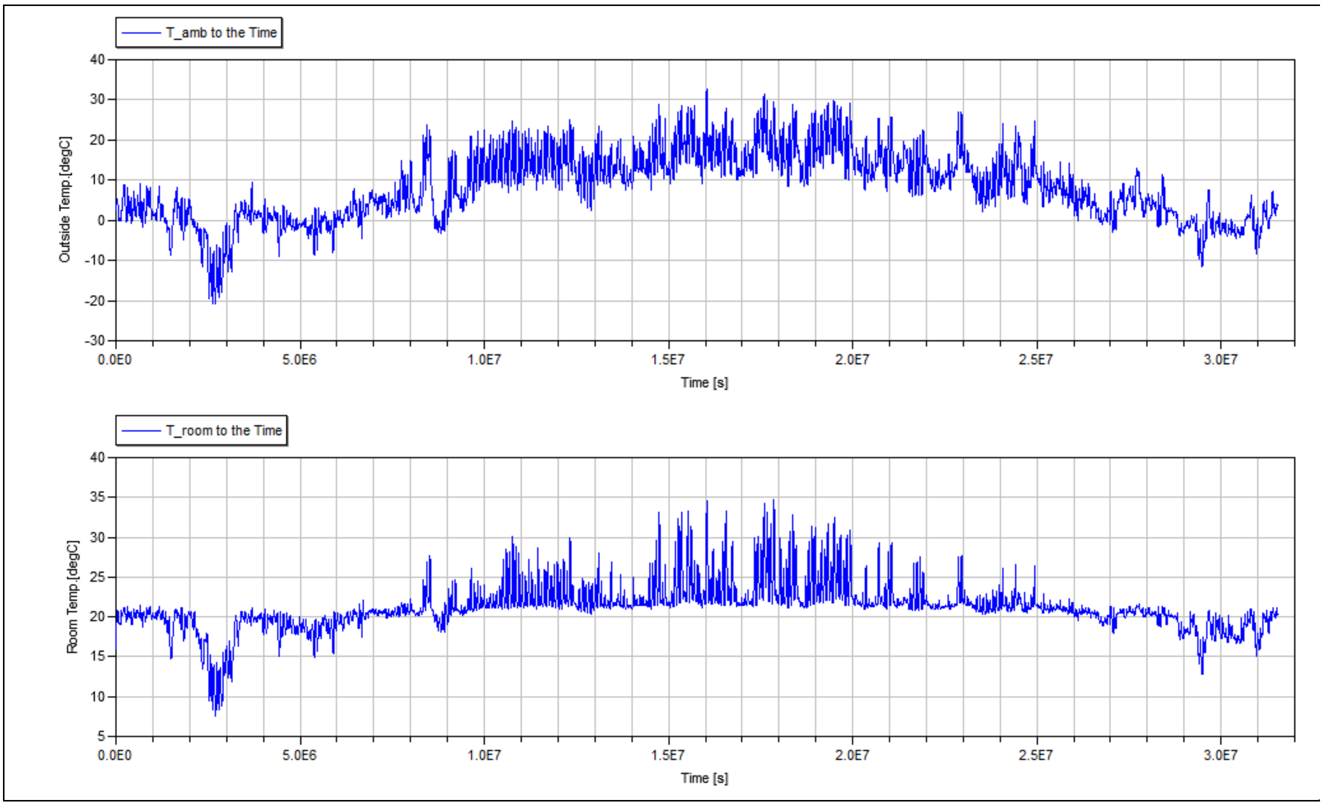

Figure 8: Top: Simulated room (inside) temperature model. Bottom: Outside Temperature in Essen (TRY 2010 Zone 5)

5 Summary and conclusions

In the last years, many models describing various technologies were developed using Modelica. HVAC applications are one area where the potential of this modelling approach can be successfully exploited.

In this article, a newly developed library is presented which contains models for a variety of domestic heating and decentralized small-scale heat and power generation appliances. This includes both conventional gas-fired technologies such as boilers and CHP appliances and novel approaches using regenerative energies, e.g. solar power. All component models were validated using measured data from test rigs.

These models were combined in a system of a complete residential building, based on GWI's test house facility. Using measured data from the test house as well as realistic user behaviour profiles, the response of the system "house" to these conditions was simulated and compared to the measured response of the test house. The comparison shows a satisfactory agreement between simulated and measured results.

The presented paper shows that the developed models for single components and entire systems are capable of presenting the behaviour of real domestic architecture. The now existing libraries can be used to numerically investigate different scenarios, also allowing simulation-based optimization approaches. The aim is to get a deeper understanding of the interactions of different energy systems and the resulting possibilities for the so called "deutsche Energiewende".

6 Acknowledgements

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