BUILDING PERFORMANCE SIMULATION USING MODELICA: ANALYSIS OF THE CURRENT STATE AND APPLICATION AREAS

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ABSTRACT

During the last years, the modeling language Modelica became increasingly used in building performance simulation. Several Modelica libraries for building components and HVAC equipment exist and many research groups use the language. This paper provides an overview about the application of Modelica. This includes modeling on different scales (e.g., urban scale, building envelope, HVAC system) and for different applications (e.g., conceptual building design, building operation). The modeling and simulation process is analyzed with respect to available Modelica libraries, how compatible these libraries are between each other and how they can be extended. Furthermore, Modelica models are analyzed with respect to the common tool chain (e.g., coupling of Modelica–based models with other programs, uncertainty and sensitivity analysis and optimization). Project examples are introduced and practical advise concerning the effective application of Modelica is given.

INTRODUCTION

Today's tasks in building performance simulation (BPS) require a flexible tool to meet diverse requirements. Many different simulation programs exist. Some of them are especially developed for BPS (e.g., IDA ICE, ESP-r, EnergyPlus, TRNSYS, WUFI®Plus) and others are more generic but also used for BPS (e.g., Dymola/Modelica, MATLAB/ Simulink, IDA SE). The decision which tool is used in a specific project is based on the questions to be answered, the experiences of the modeler, license costs, and many other aspects.

In research, the questions to be analyzed vary significantly. Applications include conceptual building design, building operation, detailed analysis of HVAC components, calculation of heat and moisture transport in building components, fault detection and diagnosis, optimization and the simulation of several buildings at an urban scale. Neither of the mentioned monolitic BPS tools provide capabilities for all of these areas. Modelica as a flexible, equation-based and object-oriented modeling language can be used to develop models that meet given requirements. This article summarizes the application of Modelica models in a research setting examplified on the basis of the requirements at the institute of the authors. However, many requirements also apply for common BPS practice.

Several Modelica libraries exist that contain simulation models for heat/cold generation, storage, distribution and delivery as well as one-zone and multi-zone building models. Some of these BPS-related libraries are introduced in the following.

The basis of most libraries is the *Modelica Standard Library* (*MSL*) including *Modelica.Fluid*, *Modelica.Thermal* and *Modelica.Media* that contain models that can be used to model the basic physical phenomena such as heat flux through a thermal resistor, pressure drop or thermophysical properties of fluids. Furthermore, simple HVAC components such as static pipes, simple generic orifices, circulation pumps and valves are included in the *MSL* (Casella et. al., 2006).

The Lawrence Berkeley National Laboratory (LBNL) develops a Modelica library called *Buildings* that contains a large number of HVAC components such as chillers, buffer storages, heat exchangers as well as controls. Furthermore, it contains a multi-zone building model (Wetter et al., 2011).

Another Modelica library for HVAC-systems and building models is developed by the RWTH Aachen. Besides many models for HVAC components and different thermal zone models, it contains a large database of manufacturer's data for building technology (Müller et al., 2010).

Recently, another Modelica library was published by the UdK Berlin (Nytsch-Geusen et al., 2013). This library also offers a large number of building and HVAC models. The developed models do not build up on the connector types such as fluid and heat ports that are used in the *MSL*. Therefore, a coupling of these models with models from other libraries requires adjustments.

The commercial Modelica library Hydronics is developed by XRG Simulation GmbH (2013). It is especially designed for the modeling of large fluid circuits and contains constant and variable speed pumps, heat exchangers and different models for liquids. The coupling of models based on the *Modelica.Thermal* library and the *Modelica.Fluid* library (only on the gaseous side) is possible.

Modelica models require a simulation environment in which the simulation is performed. Amongst others, the open-source simulation tools JModelica and OpenModelica as well as the commercial simulation environments SimulationX and SystemModeler are available on the market. For the examples presented in this paper, the commercial modeling and simulation environment Dymola is used.

The increasing importance of Modelica in the BPS community resulted in the approval of an Annex of the International Energy Agency, under the implementing agreement on Energy Conservation in Buildings and Community Systems (ECBCS). The Annex 60 has the title *New generation computational tools for building and community energy systems based on the Modelica and Functional Mockup Interface standards*. It aims to encourage a joint effort of different modelers to further extend the capabilities of BPS related Modelica modeling.

The authors aim to use Modelica models in all mentioned application areas. Different libraries are leveraged and if necessary models are extended or new models are written (e.g., adding a new HVAC component).

SIMULATION EXAMPLES

Building envelope

In the following, simple building envelope models are introduced. The main advantage of these models is that they are computationally cheap. The models can be used for various tasks (e.g., the simulation of a district with many buildings and for applying Monte Carlo (MC) techniques or optimization algorithms).

The building model is based on the so called *Thermodynamic model* (an equivalent circuit model) described in the German standard VDI 6020-1 (2001) and VDI 6007-1 (2007). However, it is partly simplified.

Figure 1 shows the equivalent circuit model of the building model. The opaque components, which are exposed to an asymmetric heat load (exterior walls, roof and bottom plate), are represented by three resistors and two capacitors. Internal building parts (e.g., internal walls and ceilings) are represented by one resistor and one capacitor. The parameters for resistors and capacitors are calculated according to VDI 6007-1 (2007).

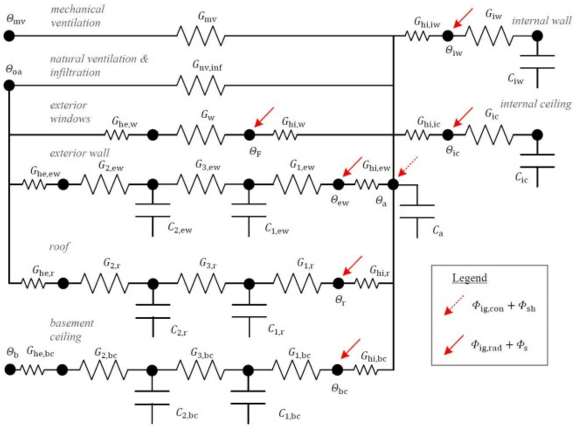

Figure 1: Equivalent circuit of the Modelica building model.

The implementation in Modelica was carried out mainly using the *MSL*. If a required model was not available in the *MSL*, own models were developed or existing models were modified. Figure 2 shows the graphical representation of the Modelica building model. By going one level deeper into a sub-model, for instance the external wall (circled in green in Figure 2), the resistors-capacitors-structure can be identified (see Figure 3).

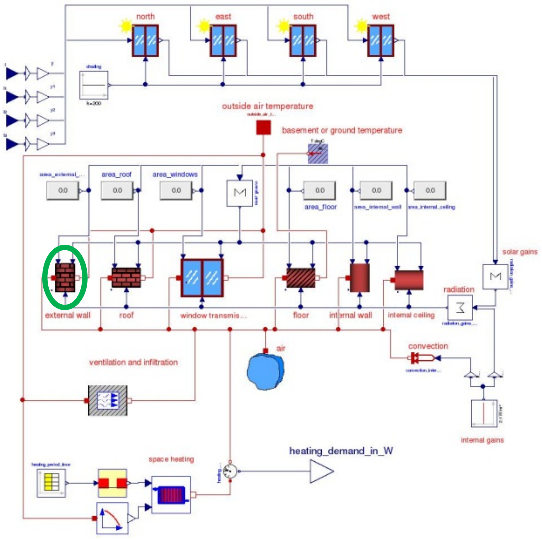

Figure 2: Graphical representation of the Modelica building model.

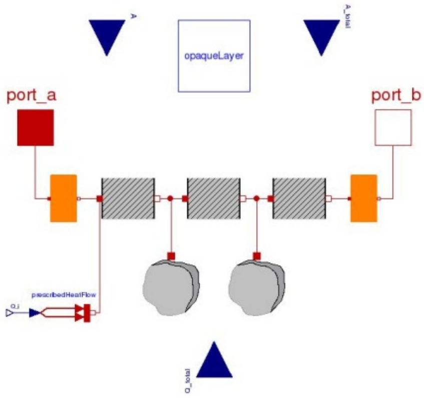

Figure 3: Graphical representation of an external wall model.

The building model was validated by comparing its results with the results of a validated building model of IDA ICE (Sahlin et al., 2004; Achermann and Zweifel, 2003). This cross-validation was carried out by determining a reference building (a 4-storey multi-family house in Freiburg/Germany) and performing an annual simulation with both models.

It was assumed that during the summer period, no heating demand is required. The summer period was defined as the period from 15th May to 14th September. For this period, no setpoint temperatures were defined in the models. For the simulation, the test reference year (TRY) data of region 12 from the German Meteorological Service was utilized (DWD, 2013).

Figure 4 shows the results of the validation simulations. The upper diagram displays the entire year and the diagrams below show two example weeks.

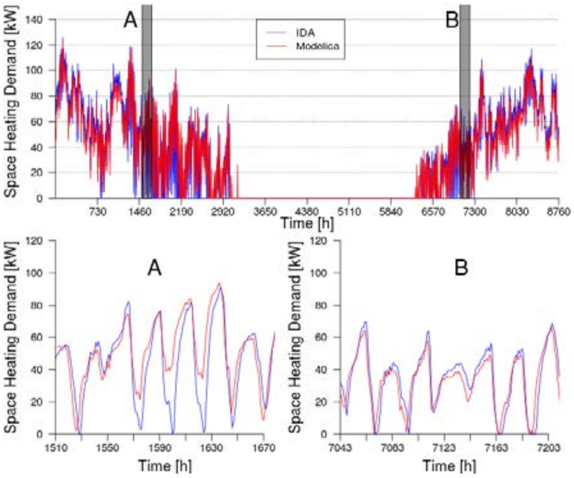

Figure 4: Results of the IDA ICE simualtion and Modelica simulation. The upper diagram shows an entire year. The lower diagrams show two representative weeks.

In addition to the visual evaluation, the discrepancies were also quantified. The summer period was not considered in the numerical evaluation. Table 1 shows the results. The coefficient of determinaton shows that generally the simulation results are in good agreement. By the mean bias error being close to 0, it can be concluded that there is no systematic error. However, the root mean square error which is 10.68 kW (mean value of the IDA ICE results is 46.24 kW) shows that there is a clear discrepancy between the two models. The comparison of the root mean square error with the mean bias error indicates that the models oscillate differently. By a visual examination of the graphs in Figure 4, it is revealed that the curve of the Modelica simulation is flatter. The IDA ICE results contain larger load swings. Nonetheless, for the purpose of this study which is simulating the space heating demand of an entire district the simplified building model can be considered as sufficient.

Table 1
Quantification of simulation result deviations. Mean value of the IDA ICE results is 46.24 kW (reference value).

MEASURE	VALUE	UNIT
Coefficient of determination	0.89	-
Mean bias error	-0.11	kW
Root mean square error	10.68	kW

HVAC equipment

In this section, a modeling and simulation example on the scale of a HVAC system for a building is shown. The analyzed building is a floating house on a lake as shown in Figure 5. The heating and cooling energy supply is realized by a brine-water heat pump system. As environmental heat source and sink the lake water is utilized by a coiled tube heat exchanger. The heat and cold delivery to the rooms is realized by a floor heating system. With the simulation model, a model-based analysis concerning the system design and system control shall be performed. The aim is to minimize the end energy consumption for the heat pump compressor as well as the circulation pumps with regard to the thermal comfort requirements. For this task, the modeling of the thermal and as well of the hydraulic behavior of the system was performed.

Figure 5: Floating house on a lake in Kalkar, Germany

The modeling of the system components is based on the fluid and thermal connector concept provided by the *MSL* (Franke et. al., 2009). These connector types were used as interfaces of the component models and enable the communication between different models. Models with fluid connectors use pressure and temperature as potential variables and mass flow rate as flow variables. Models with thermal connectors use temperature as potential variable and the heat flow rate as flow variable. As already mentioned, different model libraries for HVAC systems exist that contain models for heat/cold generation, storage, distribution and delivery. For this example, models such as pipes, orifices, fluid volumes, thermal resistors and thermal capacities were utilized from the *MSL* (i.e., *Modelica.Fluid*, *Modelica.Thermal* and *Modelica.Media*). Other HVAC components were used from the *Buildings* library provided by Wetter et al. (2011) such as variable speed pumps and buffer storages. Non-existing or non-suitable component models were modeled from scratch using the *MSL* as basis. The modeling of the components was partly realized by implementing the equations for the investigated physical processes, using empirical equations and correlations from literature or deducing characteristic lines and curves from measurement data or manufacturer's data sheets.

As an example, the modeling of the heat pump of the introduced system is presented here. The heat pump model was built up as a black-box-model based on characteristic curves for COP and heating power dependent on the temperature levels on the evaporator and condenser side. The data points such as heat flow rates, electrical power consumption and temperatures were obtained from the data acquisition system in the real building which has a measurement frequency of 90 seconds. The measurement data set for the whole heating season in 2011/2012 were filtered for quasi-steady-state operating points of the heat pump in which the energy balance for evaporator, condenser and compressor energy was below a defined threshold of 100 W. For the characteristic curves for the COP as well as for the heating power, a layer-equation according to Equation 1 is used:

$$COP = a \cdot T_{\text{prim}} + b \cdot T_{\text{sec}} + z_0 \qquad (1)$$

The identification of the parameters a, b and z_0 was realized using a nonlinear surface approximation. The relevant data points represented as black dots as well as the deduced regression curve is shown in Figure 6. The *COP* (dependent on the fluid side evaporator and condenser temperatures) can be determined with a coefficient of determination of 0.88.

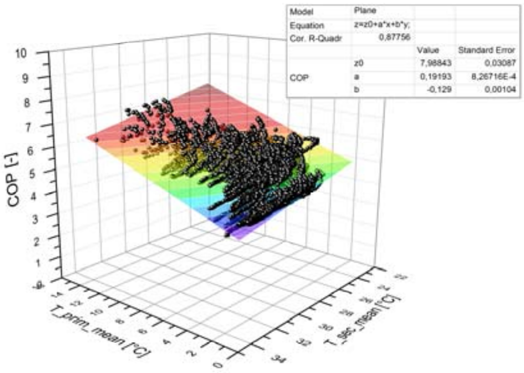

Figure 6: COP dependent on evaporator and condenser temperature levels

The electrical power consumption of the compressor can be derived from the definition of the *COP* as ratio between heating power and electrical power consumption. The cooling power at the evaporator is derived based on the energy balance of the heat pump which is considered to be adiabatic.

For the modeling of the hydraulic network, a detailed on-site audit has been conducted to identify the pipe, orifice, valve and pump geometries and data for the hydraulic components of the system. Manufacturer's data sheets for heat exchangers, heat meters etc. were also consulted to obtain nominal pressure drops at nominal volume flow rates. This data was used for the parameterization of the hydraulic model components that were used from the *Modelica.Fluid* respectively *Buildings* libraries (static pipe, simple generic orifice). All pipe lengths and pressure loss coefficients for independent valves, orifices and fittings in one section of the hydraulic network were aggregated into one hydraulic resistance to keep the number of equations in the system model small.

For the variable speed pumps, a simulation model of the *Buildings* library was used. Herein, the user provides characteristic data for the pressure drop as well as the electric power consumption under nominal conditions (i.e., full-load operation). Operating points in between are interpolated by a cubic hermite spline. Part load operating points (relative speed between 0 and 1) are obtained by applying affinity laws for the volume flow rate, the pressure head and the power consumption as follows:

$$Q = Q_{nom} \cdot \frac{n}{n_{\mathrm{nom}}} \tag{2}$$

$$\Delta p = \Delta p_{\mathrm{nom}} \cdot \left(\frac{n}{n_{\mathrm{nom}}} \right)^2 \tag{3}$$

$$P_{\mathrm{el}} = P_{\mathrm{el,nom}} \cdot \left(\frac{n}{n_{\mathrm{nom}}} \right)^3 \tag{4}$$

Q is the volume flow rate, Δp the pressure head, P_{el} the electrical power consumption and n the speed of the pump. The index *nom* indicates nominal conditions. Based on the component models, the whole system was modeled using the GUI of Dymola. In Figure 7 the highest hierarchical layer of the thermo-hydraulic system model is shown.

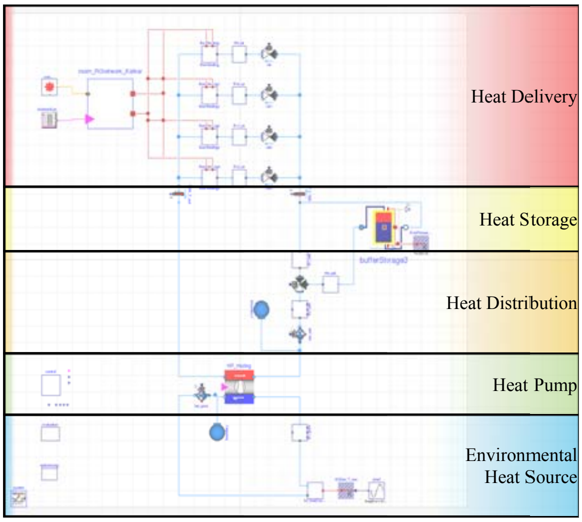

Figure 7: Overview of the thermo-hydraulic system model in Dymola

The system simulation model can be used for the optimization of control strategies for space heating by the heat pump system. For example, an optimization of control parameters for a commonly used control strategy based on a heating curve for the supply temperature dependent on the moving mean of the ambient temperature was performed. It could be shown that the energy consumption of the heat pump system with regard to the thermal comfort requirements varies between 509 and 854 kWh/a dependent on the chosen control parameter set. With optimized control parameters, a minimal end energy consumption of 509 kWh/a and a seasonal performance factor of 4.91 could be achieved.

Modeling of district heating systems

Several thermo-hydraulic models have been already implemented in order to be able to answer relevant energetic problems at district level (Nytsch-Geusen et al., 2009). The dynamic pipe model of the *MSL* is too complex for our application. We used the fundamental equations of the pipe model from the *MSL* and modified and extended the model that we can easily build up district heating networks by considering many pipes with different properties like insulation, installation depth etc. Our aim was to build a district heating pipe model that we can use to generate models for whole districts automatically by extracting the required information from Geographical Information Systems (GIS). The structure of Modelica is very suitable for this purpose. Nevertheless, we still face the problem to reduce the complexity in order to improve simulation runtime. Therefore, we aggregated parts of the district heating network with reasonable accuracy for our requirements. Figure 8 shows a map of a case study. The aim was to analyze the operation strategies of the district heating network in Weingarten, a district of Freiburg, Germany.

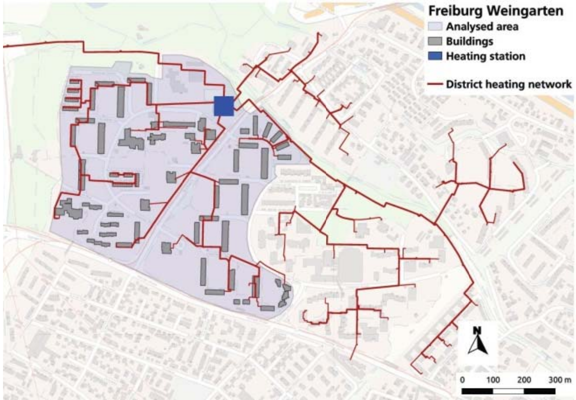

Figure 8: District heating network in Weingarten-Freiburg; Data: Freiburger Stadtbau GmbH, badenovaWÄRMEPlus

The local utility company provided the topology of the network by means of GIS data. The GIS data contains all necessary inputs for the simulation (e.g., diameter, length, type of insulation). An import-export interface for GIS and Modelica based on Python was developed in order to generate pipe models with specific properties automatically. The final arrangement and the connection of the separate models need to be done manually in Dymola. In this case study, we focused on the heat distribution by using ideal heat sources and sinks as shown in Figure 9.

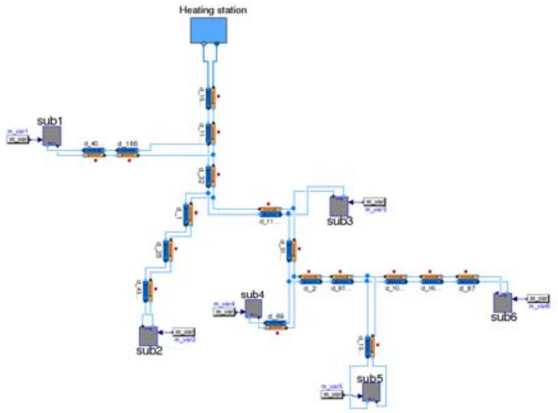

Figure 9: Model of a district heating network

Figure 10 shows simulation results of distribution heat losses with the following supply strategies:

- Strategy A: Status Quo; Heating curve with max. 110°C supply temperature; current state of substation; average return temperature of 70° C
- Strategy B: Heating curve with max. 90°C supply temperature; substation and return temperature equal to strategy A
- Strategy C: Heating curve with max. 90°C supply temperature; maintained substation; reduced average return temperature of 50°C

The simulation results show that a small reduction of heat losses could be achieved by decreasing the supply temperature (Strategey B). However, strategy C results in higher energy savings because the return temperature was also significantly decreased. Lastly, the return temperature depends mainly on the quality of the substation.

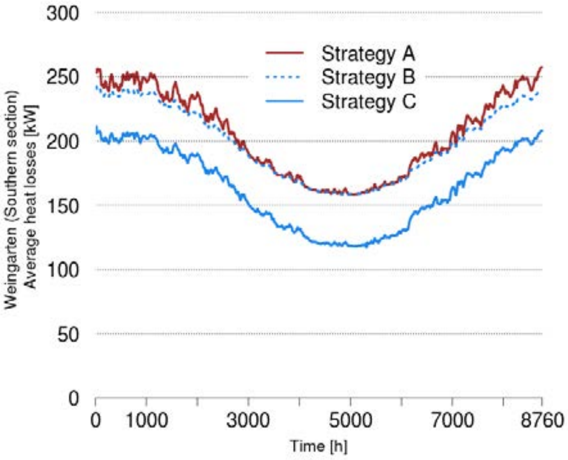

Figure 10: Simulation result for heat losses with different strategies

Using Modelica Models in Conjunction with Existing Programs

Given the existing BPS programs and their capabilities it is desireable to couple Modelica models with these programs. This has the advantage that valuable programs can be used in an Modelica context and vice versa. In the following an example of such a coupling is introduced. WUFI®Plus is a holistic, model-based, on the hygrothermal envelope level calculation tool developed by Künzel (1994). The hygrothermal behavior of the building envelope affects the overall performance of a building. WUFI®Plus is a BPS tool that computes the coupled heat and moisture transfer in the building components. These components are combined to a whole building model. Until now, the HVAC equipment of the software was considered as ideal heating and cooling system. Current activities aim to implement realistic models into WUFI®Plus to simulate HVAC systems. These models are written in Modelica. The building envelope and the HVAC system influence each other significantly. This makes a separate simulation of both systems inaccurate and introduces special requirements for combining both in a co-simulation. The decision to implement the Modelica models into the existing software rather than model the building envelope with Modelica was made because of the big user community that is familiar with the existing GUI and other user specific requirements. A possible way to include Modelica models into an existing BPS program is the Functional Mock-up Interface (FMI) for Co-Simulation. More details can be found in Pazold et al. (2012).

The aim is to implement simple but realistic HVAC models, which can be used by practitioners. This means that only necessary and obtainable plant information is required for these simulations. The computation time to simulate a building should not increase to times which are no longer acceptable for practitioners.

HVAC components to be simulated include:

- Condensing gas boiler
- Solar thermal collector
- Combined heat and power plants
- Heat pumps
- Bore hole heat exchangers
- Thermally activated building systems (TABS)
- Radiators
- Storage tanks
- Control equipment
- PV systems

There are many HVAC configurations with different devices and different parameters and in consequence, many Functional Mock-up Units (FMU). WUFI®Plus have to interact with the HVAC system configuration which is chosen by the user of the software. A FMU adapter (Figure 11) is written in the object-oriented language C++ to manage dynamic FMU instantiation, initialization, setting input, getting output and execute time steps. Therefore, the adapter gets the information about the different kinds of configurations and their parameters (their value references).

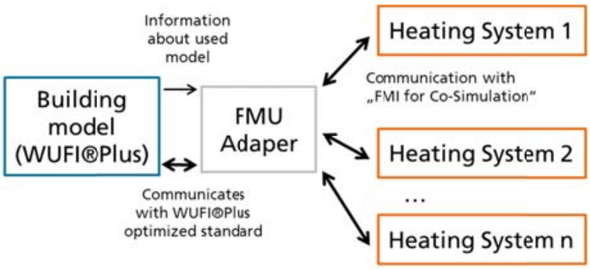

Figure 11: Communication between building model and heating systems (source: (Pazold et al. 2012))

Tool Chain

BPS often requires a tool chain to facilitate given tasks. This includes the pre and post processing of simulation data, uncertainty analysis (UA), sensitivity analysis (SA) and optimization. Different tools can be used to perform these tasks (e.g., MATLAB, Phython, GenOpt and R).
In the research group of the authors R is used as tool to supplement BPS. R is a language and a program for statistical computing and graphics. R runs on different operating systems and is available as a free software under the GNU General Public License (R Core Team 2012). R can be used for generating random numbers, performing statistical computations as well as arithmetic calculations, managing parallel simulations on different cores of computers, processing simulation input and output and result visualization. We use R to perform uncertainty and sensitivity analyses as well as optimization with Modelica models. Modelica models are well suited for this application because the models can be modified to fit the analysis requirements. Furthermore, numerical noise can be reduced to a minimum level to not influence the analysis results.

CONCLUSION

This paper investigated the application of Modelica for typical BPS problems. It is an analysis based on the project requirements at the research group of the authors. However, the authors believe that many research groups cope with similar applications.

Different application areas and levels of detail have been introduced and the capabilities of Modelica models have been illustrated. Modelica is a very flexible modeling language and suits for most tasks in common BSP practice. However, extending and developing models requires a basic understanding of DAE systems and solvers for these systems. Otherwise models might be developed that contain numerical instabilities. Hence, the better flexibility of Modelica comes at the cost that modelers have to take care about things that they do not have to take care about when using traditional monolithic BPS programs.

Future activities have to focus on collaborations between researchers using Modelica to avoid that developments in Modelica have to be duplicated by different research groups. The mentioned ECBCS Annex 60 is a step into this direction.

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