INTEGRATION OF HVAC MODELS INTO A HYGROTHERMAL WHOLE BUILDING SIMULATION TOOL

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ABSTRACT

A combined simulation of the building envelope and the plant equipment is more realistic than simulating both separately and has the advantage that the modeler can use one software environment instead of multiple software environments. Tools that solve the coupled heat and moisture transfer for building components already exist. In this paper a software is introduced that uses the detailed simulation models of different building components (e.g., walls and windows) to generate a whole building simulation model. Furthermore, the extension of this software with HVAC models is described. This makes it possible to take the interactions of the plant equipment with the building into account. The plant systems (e.g., heating, cooling and air conditioning systems) are modeled in the object-oriented Modelica language. The different possibilities for the integration of the HVAC models into the C-written original software are discussed.

INTRODUCTION

The application of building performance simulation software during the design process is standard to design economical buildings. Using building models which take heat and moisture transfer into account allows a more accurate assessment of the indoor environment, as well as the avoidance of moisture related problems such as mould growth or rotting components. The software WUFI®plus offers the possibility to perform these whole building simulations.

The equation-based and object-oriented modelling language Modelica (Elmqvist, 1997) can be used to model technical systems (i.e., HVAC systems). The plant equipment can be described by implicit equations which are solved by the simulation software. The advantage of this approach is that the modeler can develop own models but does not have to spend time and effort to find numerical solutions to solve the equations. This paper deals with the different ways of coupling the Modelica models with the WUFI®plus software. The processes involved happen on a very different time scale. This introduces new issues and requires new solution strategies for the overall simulation management and the time step coordination for this co-simulation. Possible strategies are discussed and the implementation is described.

Three possibilities are investigated to create the plug-in modules as well as some implementation algorithms to merge those to the existing simulation software. A first simple simulation example is introduced and the results are shown. The HVAC model of that example is a condensing gas boiler.

BUILDING MODEL

WUFI®plus is a holistic model based on the hygrothermal envelope calculation model developed by Künzel (Künzel, 1994). The hygrothermal behaviour of the building envelope affects the overall performance of a building. WUFI®plus is a building performance simulation tool which computes the coupled heat and moisture transfer in the building envelope. It takes moisture sources and sinks inside a room, input from the envelope due to capillary action, diffusion and vapour ab- and desorption as a response to the exterior and interior climate conditions as well as the well-known thermal parameters into account. The coupled heat and mass transfer for vapour diffusion, liquid flow and heat transport in the building envelope is a strong feature of the model. A stable and efficient numerical solver had been designed for the solution of the coupled and highly nonlinear equations. The conductive heat flow and the enthalpy flow by vapour diffusion with phase changes in the energy equation are strongly dependent on the moisture fields. The vapour flow is simultaneously governed by the temperature and moisture field due to the exponential changes of the saturation vapour pressure with temperature. The model was validated by comparing its simulation results to the measured data of extensive field experiments (Lengsfeld et al., 2007). Models like WUFI®plus can help to improve energy simulations because latent heat loads and their temporal pattern can be calculated more accurately. At the same time the determination of indoor air and surface conditions in a building becomes more reliable. However, the implementation of HVAC equipment in WUFI®plus was very basic. The user needed to specify the maximum value for the heating / cooling / humidification / dehumidification power that is available. Only predefined time shifts of heat flows into the zone were supported. The software is described in detail on www.WUFI.de.

HVAC MODELS

The aim of the extension of the WUFI®plus software was to create simple but realistic HVAC models which can be used by practitioners. This means that only necessary and obtainable plant information is needed for these simulations.

Systems to be simulated include:

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

The model development was done with the software Dymola 2012 (Dassault Systèmes AB, 2011).

EXPORT OF MODELICA MODELS

Existing interfaces allow the export of simulation models from Dymola. The different options are discussed in the following sub sections.

Source code generation

For each simulation Dymola generates C-code for the models. As a second step this code is compiled and then it is executed. The license feature "source code generation" allows the export of readable and compilable C-code of a developed model. These exported models can be included and instanced in another program. The interface for the exported modules is documented within the Dymola Help (Dynasim AB, 2009).

The exported model does not include the DAE (differential algebraic equation) solver, but it does provide a function to set states and inputs, to change parameters during a time step and to calculate and solve the predefined algebraic and differential system of equations for constant or variable time steps with defineable start and stop times. The integration algorithm must be provided by the source code of the main program (e.g., WUFI®plus).

Binary model export

With the license feature "binary model export" it is possible to build a compiled binary file for the implementation in another existing software. Depending on which compiler is linked with Dymola and which operating system is used, one includable binary is exported. This is the compiled C-code, exported by the "source code generation" but the functions to interact between executing software and the model are slightly different. They are explained in the file "dsmodel.h" within the Dymola Software package.

Functional Mock-up Interface

Another method to export Modelica models is the standard model description called *Functional Mock-up Interface*. FMI defines a standardized interface to communicate with so called *Functional Mock-up Units* (FMUs). These FMUs describe physical models and can be used by different simulation software packages. Modelling tools like Dymola can export developed models, or import existing FMUs to simulate them. There are three different standards of an FMU-model. The *FMI for Model Exchange* delivers a model class with all algebraic and differential equations but without DAE (differential algebraic equation) solver . Step sizes and the solver must be provided by the executing simulation software. The *FMI for Co-Simulation* standard includes the DAE solver and allows the co-simulation of two or more models, by a restricted data exchange between these models. *FMI for PLM* provides, beside the data of the other two standards, all further related data for a simulation process, such as data documentation, validation, editing, post-processing and report (Modelisar consortium, 2010). Dymola supports *FMI for Model Exchange* and *FMI for Co-Simulation* since the current version (Dymola 2012, released in June 2011). The advantage of FMI is the standardized interface.

The used parameters and variables in the model and other model information is defined in a XML file, named *modelDescription.xml* as a part of the FMU. The model equations, other model specific algorithms and the necessary computation functions are compiled and included as another part of the FMU. Within a predefined header, the functions to run the FMU are defined and can be called by an executing program. The executing program may get the variable names from the model describing XML file, or if all of the used models use the same variable names it is conceivable to declare these in a static way.

COUPLING

Initialization

First, in order to use the model, it is necessary to define external inputs and outputs. Therefore the variables of the model can be defined in Dymola as input or output to let those interact with the executing main program. The export of source code is chossen. Within the model all types of variables such as inputs, outputs and derivatives are regarded and stored in matrices. The documentation in the exported source code gives the information about the relation between the used variables, named and defined in the Modelica model, and the position in the respective matrix. For example the outdoor air temperature named "OAT", as input for the plant equipment may become position 1 in the input vector "inputs[1]" and can be accessed by the execution program code. Before the main program can run the exported Dymola model, it must initialize all used variables and allocate memory for the vectors. Here it is possible to set constant parameters for the calculation, such as maximum heating power of the boiler as well as some user defined initial values, like minimum and maximum indoor temperatures. During the initialisation some initial equations are solved and the start and end time as well as the step size of one iteration step can be set. It is possible to modify the defined inputs during the time steps.

Implementation algorithms

The software to solve the coupled heat and moisture transfer (WUFI®plus) calculates the mentioned transfers for defined schedule time steps, by iteratively solving heat and moisture balance equations (e.g., Lengsfeld et al. 2007). The plant equipment has a significant influence on the calculation, but needs more sub time steps. Both models need information exchange with each other such as indoor temperatures or actual heating power supplied by the heating system. In this paper a stategy for the coupling and especially for the information exchange between the coupled models is developed.

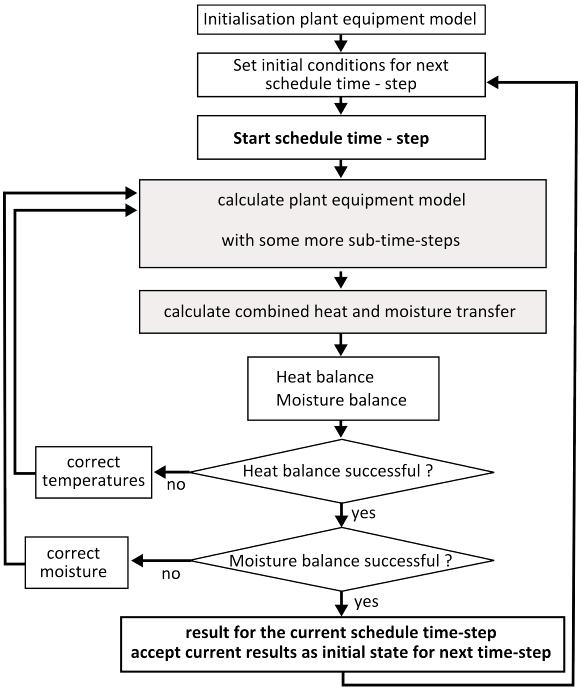
Initialisation plant equipment model
Set initial conditions for next schedule time - step
Start schedule time - step
calculate plant equipment model with some more sub-time-steps
calculate combined heat and moisture transfer
Heat balance
Moisture balance
Heat balance successful ?
correct temperatures
no
yes
Moisture balance successful ?
correct moisture
no
yes
result for the current schedule time-step
accept current results as initial state for next time-step

Figure 1: One by one algorithm

A simultaneous solution is not possible, because each model relies on results from the other model. The different models must interact during schedule time step iterations and adjust variables (e.g., temperature and moisture in the heated zone or return temperature in HVAC equipment) for convergence.

The first approach assumes, that the plant equipment model computes first and the results are used as input for the heat and moisture transfer calculation. Both models must repeat the calculation of one time step and have to correct initial values until all balances are satisfied. The correction of the variable values must be considered because it may lead to convergence for one model but in combination with the other model it may oscillate. This "one by one" algorithm is shown in Figure 1.

The plant equipment models need some more sub-time steps during one superior schedule time step. The plant models must compute the same sub time steps for each iteration, until convergence is reached. Therefore, within every iteration step the exported Dymola model must be reset to the initial values of the current iteration step. This may cause problems calculating the time derivatives in the model. A simpler solution is to make a new calculation of the exported Dymola model for every iteration step, however this may cause more computation time and memory management problems. All variables specifying the actual system state must be accessible in order to be stored globally after every calculation step and set as initial condition for iterations in the next time step.

Another way to merge the plant equipment configurations and the existing software is to establish one more iteration loop in which both models interact. The main program initiates some assumptions, the plant model may compute as a result. The calculation of the combined heat and moisture transfer in building parts as well as the heat and moisture balance in the building during one simulation time step is computed in the existing way. After that, the plant model starts the computation with the results of the last satisfied results calculated at the previous time step. The plant model may also have some more sub time steps and may be instanced at the beginning of every iteration step. The reset to initial conditions may be done as in the "one by one" algorithm (described in the previous paragraph). After the iterative time step calculation is made and results are globally stored, the exported C-code deletes the occupied memory. After this only one instance of the plant model exists. At the end, before the next schedule time step, the main program computes the difference between the assumptions and the results of the plant model. If the difference between the assumptions and the results is too big, these new results are used for further steps in a new iteration loop until the discrepancy is small enough for the predefined accuracy. This "parent iteration loop" algorithm is shown in Figure 2.

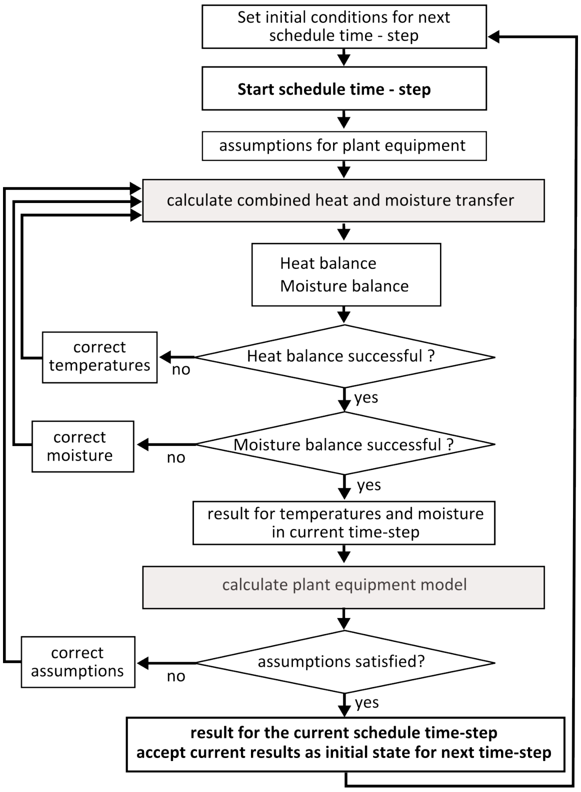
Set initial conditions for next schedule time - step
Start schedule time - step
assumptions for plant equipment
calculate combined heat and moisture transfer
Heat balance
Moisture balance
correct temperatures
no
Heat balance successful ?
yes
correct moisture
no
Moisture balance successful ?
yes
result for temperatures and moisture in current time-step
calculate plant equipment model
correct assumptions
no
assumptions satisfied?
yes
result for the current schedule time-step
accept current results as initial state for next time-step

Figure 2: Parent iteration loop

One upcoming problem of this coupling method might be the results of the sub time steps from the plant equipment model. The WUFI®plus software needs one value (e.g., net heating power) for one schedule time step. But the plant model provides more sub values for this, resulting from its own time step. The values must be averaged for the use in the building executing algorithm. Another problem is the mentioned correction of integration variables. This might lead to convergence problems because of oscillating values.

The main disadvantage of the two ways of coupling mentioned so far is that the plant system and the building are calculated seperately and this causes a lot of iterations and convergence problems. However, there is a third approach, which turned out to be the most efficient. This merging called “Heat and moisture balance including plant equipment (HVAC)”, is shown in Figure 3.

Heat provided or removed from a room is, in thermal balance terms, a heat source or heat sink. The same is valid for moisture. Hence, at some iteration state, all building parameters, especially air moisture and temperature are assumed. Also heating, cooling, humidification and dehumidification requirements are quantitatively defined to keep the required indoor conditions. All these parameters are put into the plant calculation for the current time step. Starting from the initial time step the plant calculation gives an answer to the current environmental and HVAC requirements. The plant model provides information about the amount of heat or moisture, which it is capable to provide or remove. Also the effects of thermal inertia are taken into account.

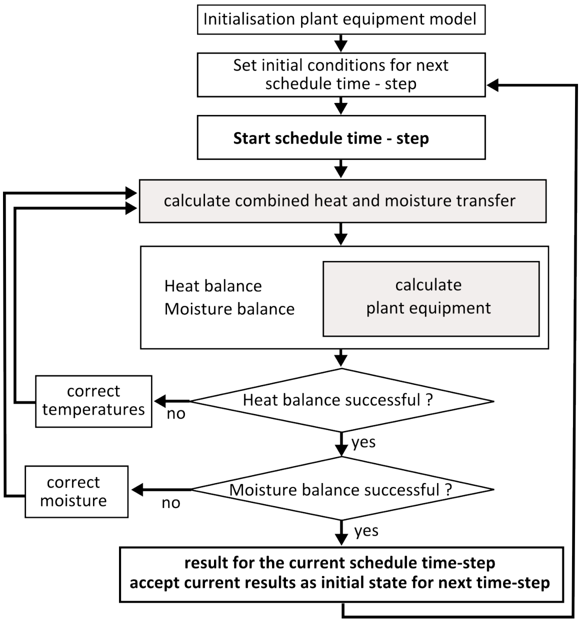
Initialisation plant equipment model
Set initial conditions for next schedule time - step
Start schedule time - step
calculate combined heat and moisture transfer
Heat balance
Moisture balance
calculate plant equipment
correct temperatures
no
Heat balance successful ?
yes
correct moisture
no
Moisture balance successful ?
yes
result for the current schedule time-step
accept current results as initial state for next time-step

Figure 3: Heat and moisture balance including plant equipment (HVAC)

In general the plant calculation iterates internally with its own time step and solver. The aim is to deliver or remove the defined amount of heat and moisture to satisfy the design conditions at the current external building iteration. For this reason some variables are adjusted (e.g., mass flow and/or return temperature). If design conditions can not be achieved because of limited plant capabilities, the internal air temperature and moisture are corrected and the same procedure is repeated. When the overall heat and moisture balance converged the calculation is done for the calculation step. At this point current results are accepted as initial state for the next time step. Besides starting a new calculation to restore the initial plant conditions at every time step and iteration another approach can also be applied. It relies on copying of the corresponding matrices including current and last accepted calculation states of the plant instance. This procedure was applied for the exemplary calculation in this paper.

The described algorithm is certainly not free of convergence issues, but in a similar way the simulations are performed in WUFI®plus which has proved numerically stable so far. Heat/moisture sources/sinks are casual values irrespectively if they are assumed or delivered by a detailed HVAC simulation.

SIMULATION EXAMPLE

The plant equipment for the exemplary simulation consists of a condensing gas boiler. At this stage no radiator model is included because the calculations were done to analyze whether the coupling strategy works or not. The main equation of the boiler model is

$$m\, c_{p,boiler} \frac{dT_{boiler}}{dt} = Q_{heat} + \dot{m}\, c_{p,fluid}\, T_{return} - \dot{m}\, c_{p,fluid}\, T_{flow}$$

The condensation effect is modeled by using empirical data (BBT Thermotechnik GmbH Buderus Deutschland 2005, page 9). The effect depends mainly on the part load factor (p) of the boiler and the return temperure of the heating system (T_{return}). The boiler is able to vary the heating power from 15 till 100 % of its nominal power. Splines were used to describe the empirical data of the condensation effect. The efficiency can be calculated with the following equations:

$$\eta(T_{return}) = \begin{cases} -0.30\, T_{return} + 113.40 + b\,; & for\ T_{return} \leq 48\,°C \\ -1.7 \cdot 10^{-4}\, T_{return}{}^{3} + 3.8 \cdot 10^{-2}\, T_{return}{}^{2} - 2.77\, T_{return} + 163.34 + b\,; & for\ 48°C < T_{return} < 62°C \\ -1.9 \cdot 10^{-2}\, T_{return} + 98.16 + b\,; & for\ T_{return} \geq 62\,°C \end{cases}$$

where the dependency of the dynamic efficiency on the part load factor (p) is taken into account via the caluculation of the return temperature (T_{return}) with:

$$T_{return} = \begin{cases} T_{return,model} - a\ ;\ for\ \ T_{return,model} \geq 30°C \\ 30°C\text{ - } a\ ;\ for\ \ T_{return,model} < 30°C \end{cases}$$

The factors a and b are adjustment factors and can be calculated according to

$$a = (-1.18(p - 0.15) + 1)\, 6.90$$

$$b = (-1.18(p - 0.15) + 1)\, 0.64\,.$$

The equations lead to the following Figure where the dynamic efficiency of the gas boiler is plotted for a one year building simulation:

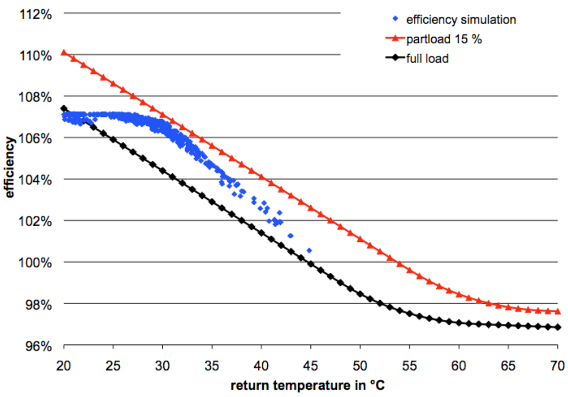

Figure 4: Part load efficiency during a simulation. Note that the efficiency has a maximum value of 107 % and that the basis for calculating the efficiency was the lower heating value (and not the upper heating value) which leads to values higher than 100 %.

In this paper the source code generation feature of Dymola was used to export the boiler model. This feature provides the C code of the model. As a second step significant changes were made in the code (division into initial and time step calculation, global matrix storage, copying of the matrices). An additional unit (header file + code) of about 200 lines was included. Furthermore some changes in the main calculation loop were made to enable iterative calculation. The exported code shows certain structural regularity so that the header file can be used for every model. The whole code consists of several thousand lines. Hence, additional effort to couple the programs was little compared to programming the HVAC models from scratch in C. The software WUFI®plus is programmed in C++. So the only possibilty to merge these two modules was to create a dynamic link library (dll) and link it to WUFI®plus during the calculation.

After some experiments with different merging scenarios had been made the heat and moisture balance including plant equipment (HVAC) algorithm (Figure 3) was chosen.

As already mentioned, the analyzed model does not include a radiator, which couples the boiler and the heated zone. To do the calculations a simple radiator model has been assumed. Heating power currently emitted to the zone is equal to the formula:

$$\dot{Q}_e = (T_{flow} - T_{return}) \cdot \dot{m} \cdot c_{p,fluid}$$

No distribution and emission losses and no heat storage are taken into account. Hence, the return temperature can be calculated using the formula

$$T_{return} = T_{flow} - \frac{\dot{Q}_{net}}{\dot{m} \cdot c_{p,fluid}}$$

where $\dot{Q}_{net}$ [W] is the current heating demand calculated by WUFI®plus.

The flow temperature T_{flow} is calculated in the boiler model using a heating curve to determine the set point of the flow temperature according to the outside air temperature.

Input parameters are

T_e outdoor air temperature [°C],

T_{return} return temperature [°C],

$\dot{m}$ fluid mass flow [kg/s],

$c_{p,fluid}$ specific heat capacity [J/(kgK)] and

$\dot{Q}_b$ maximum boiler power [W].

T_{flow} is firstly assumed on the basis of the heating curve. The return temperature depends on the current space heating demand of the zone. If the boiler power is high enough to cover heat demand in the current time step, no additional internal iterations are needed. Otherwise it is iterated as long as the difference between the assumed T_{flow} before and after the boiler calculation differs not more than 0.1 K.

A small one storey residential building was used for the calculation (Figure 5). The building is assumed to be typical for contemporary standard in Europe.

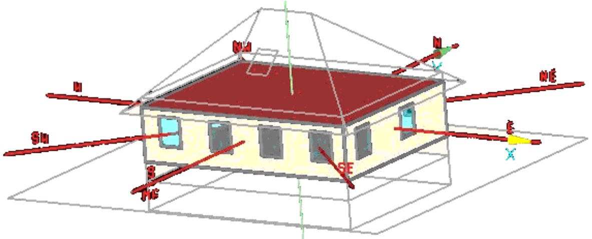

Figure 5: Exemplary building used for the calculation with WUFI®plus software (heated zone depicted opaque).

The calculations were carried out for the time period 15 Jan. – 15 Feb. with the climate of Holzkirchen (close to Munich, Germany). The time step for building was 360 sec (0.1 h) and the time step for the boiler model was 36 s. These time steps are resonable for the desired level of accuracy.

Due to simplicity of the HVAC model, no difference in calculation time was noted (compared to WUFI®plus with ideal heating device). The number of iterations of WUFI®plus was also not significantly higher than without the boiler. Only one more iteration step, in comparison to the calculation without plant (assuming ideal heating mode) has been noticed, usually after a rapid change of the outdoor air temperature.

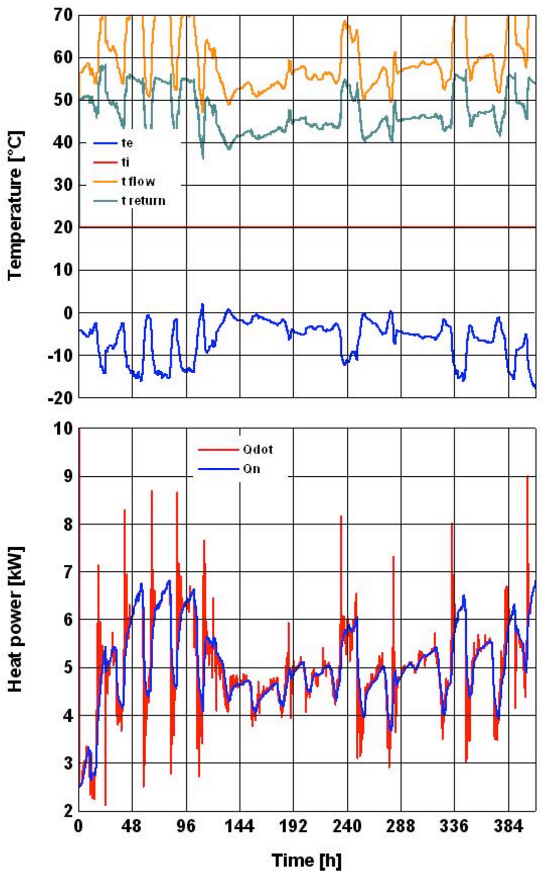

Figure 6: Exemplary results, above: outdoor and indoor air temperature as well as flow and return temperature, below: required net heating power of the building (Qn) and boiler power (Qdot).

Figure 6 shows the results averaged to an overall time step of 0.1 h. The upper diagram shows the inner and outer air temperature as well as the flow and return water temperature in the boiler model. The lower diagram shows the boiler response to the outdoor air temperature and the heating demand. Local peaks reflect increased heat used to warm up the thermal mass of the boiler after the supply temperature has been raised. At the beginning the maximum power (10 kW) is used to heat up the system from the assumed 20 °C to above 55 °C. When the flow temperature decreases the boiler power is lower than the zone heating demand.. Hence, in terms of typical boiler performance, expected and plausible results were obtained.

DISCUSSION

Complicated systems, like multi-zone building models heated or cooled by different plants exhibit many unknown variables in the model. This leads to numerical problems, as great linear and nonlinear systems of equations must be solved at every time step. Therfore modelling of the building with an existing software and HVAC separately with a so called “weak coupling” seems to be a reasonable alternative. Exported C code of the plant model can be used to supplement the building model. In general merging of the two analyzed models can be made only in an iterative way. That means, that at least one model (building or plant) must be able to restart time step calculations with the same initial states. After the converging criteria is achived time step results are stored and used as initial state for the next step calculation. Such a possibility does not explicitly exist in exported Dymola C code. Therefore some deep intrusions into the code were necessary. It has been found, that declaring and storing of global matrices, instead of local, and copying them respectively back and forth enables to carry out calculations in an iterative way. However, one serious issue remains unsolved: To avoid numerical problems in the calculation of the time derivative of the temperature the time in consecutive calls must ascent, even during iterative calculations. This can eventually lead to an overflowing of the declared time variable.

CONCLUSION

The presented results illustrate the integration possibilities of HVAC models into an existing software. The HVAC equipment consisting of a condensing gas boiler is very simple and does not fully reflect the real central heating system. As a next step more realistic plant models will be coupled to WUFI®plus and the effectiveness of explanined coupling strategy will be further investigated.

The possibility to export C code from Dymola enables the coupling of the existing building simulation software with Modelica HVAC equipment models. Exemplary simulations show, that reliable results can be obtained by attaching HVAC models in this way. However, some changes of the exported code must be made to adopt the source code for the calculations. The authors believe, that the merging of different models with exported C code in an iterative way can be very interesting for various applications. Therefore it would be worth considering by software developers to enable the set back of the results to the previous time step in the exported C code. After that the incorparation of models to software like WUFI®plus would be much easier. The *Functional Mock-up Interface for Co-Simulation* (Modelisar consortium, 2010b) is expected to support this set back. However, this export option is supported since the software version Dymola 2012 which was released in June 2011. This coupling option could not be tested in the framework of this paper. As a next step this way of coupling will be tested and compared with the existing results.

ACKNOWLEDGEMENT

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