

HVAC Models coupled with hygrothermal building simulation software

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SUMMARY:

This paper describes the integration of HVAC simulation models, developed with the multi-domain modeling language Modelica, into the hygrothermal building simulation software WUFI® Plus. With the existing software a hygrothermal building simulation, considering heating, cooling and air conditioning as ideal systems, can be performed in a user friendly way. Without detailed HVAC models, the software calculates the heating, cooling, humidification, dehumidification and ventilation demand which is necessary to keep the indoor climate in user defined design conditions. This output can be used for further investigation and sizing the plant equipment. However, a direct interaction between the detailed building model and the building equipment was not possible. This is improved with the newly developed Modelica HVAC models. They were exported via the common Functional Mock-up Interface (FMI), which was analyzed to assess the most effective coupling strategy. The FMI is the definition of an open interface between different software systems. The realization of a non-iterative coupling algorithm is illustrated by means of a simulation example. Furthermore, the implementation of the HVAC models into the hygrothermal building simulation program is validated using the results from a Modelica simulation environment as reference.

1. Introduction

1.1 Building model

Traditionally, many building simulation programs were written in high level languages like FORTRAN, or C/C++ with specialized solvers and algorithms for established and approved simulations. There is and always will be the aim to improve such simulation software. One of those traditionally software is the existing hygrothermal building simulation software, called WUFI® Plus (Holm, et.al. 2004; Lengsfeld & Holm, 2007). The holistic model is based on the hygrothermal envelope calculation model developed by Künzle (1994). This detailed model calculates the coupled heat and moisture transfer in building components and is written in FORTRAN and C++. The conductive heat and enthalpy flow by vapor diffusion with phase changes in the energy equation dependent on the moisture fields. The vapor flow is simultaneously governed by the temperature and moisture field due to the exponential changes of the saturation vapor pressure with temperature. The resulting differential equations are discretized by means of an implicit finite volume method. A stable and efficient numerical solver had been designed for the solution of the coupled and highly nonlinear equations..

The building envelope can consist of many and different components, such as exterior- and interior-walls, ceilings, and floors. A multi-zone model, written in C++, links them to the whole building model. Moisture sources or sinks inside the rooms or inside the components, exchange with the envelope due to capillary action, diffusion and vapor ab- and desorption as a response to the exterior and interior climate conditions as well as the thermal parameters are taken into account. The hygrothermal behaviour of the components affects the overall performance of the building and vice versa. The multi-zone model manages the simulation and interaction, even with further models, for windows, the solar radiation in different sun incidence angles, or the building air flow. The graphical user interface and the data management of the existing software WUFI® Plus is developed in C#. The model was validated by comparing simulation results with measured data of extensive field experiments or verification with standards (Antretter et al., 2011).

To simulate the indoor climate, the multi-zone model calculates heat and moisture balances for each zone, regarding all the sources, sinks and exchanges. As long as those balances are not satisfied during a time step, the interior temperature and humidity is adapted iteratively. For example, if the heat loss through the building envelope and ventilation is more than the solar and internal heat gain, the interior temperature is decreased as long as the loss and the gain are not equal.

The user can define design conditions for the indoor climate by setting minimal and maximal values, e.g. for the indoor temperature. Without the detailed HVAC models, ideal systems are regarded, calculating the heating, cooling, de- and humidification demand with the described heat and moisture balances. The systems are defined only per maximal capabilities. If the indoor climate would exceed the design conditions, the solution algorithm tries to get the necessary deficit to equal the balances from the defined systems capabilities. Back to the example before, if a user has set a space heating capacity, the interior temperature is kept by the minimal design condition as long as the space heating capacity is enough to fulfil the heat balance. The resulting actual heating demand is the difference in the heat balance.

However, in reality, the HVAC system may not deliver the demand instantly. It may have to load the water storage and heat up the radiator before energy is provided to the space. After that, the radiator may still heat up the room even the temperature has reached the set point temperature. This inertia of a heating system, regarding the warm-up time or the overheating of a room was not simulated with the ideal system. By coupling the detailed hygrothermal building simulation with the detailed HVAC systems, described later in this paper, the indoor climate may fluctuate more and is not kept exactly at the design conditions. Furthermore, many results regarding the dimensioning and planning of the HVAC system, in direct interaction with the building envelope, can be obtained. The multi-zone model also has to manage this simulation and interaction by setting boundary conditions, such as the radiator surrounding temperature and getting output, such as the heating power of the radiator calculated with the detailed HVAC system.

1.2 Modelica HVAC models

The aim was to create simple but realistic HVAC models, which can be used by practitioners. Following this, only necessary and obtainable plant information is required for the simulation. Also the computation time to simulate a building should not increase to times which are no longer acceptable for practitioners. The different HVAC devices to be simulated, plant equipment for heat generation, distribution, storage and controlling include, so far:

- Condensing gas boiler – simulating the heating power output in different operation modes

- Solar thermal collector – simulating the heating power output regarding the collector orientation, inclination and shading, depending on the position of the sun and surrounding temperature
- Combined heat and power plant – simulating heating and energy power
- Heat pump
- Bore hole heat exchanger
- Thermally activated building systems (TABS) – can be added as inner source directly in the building components
- Radiators – simulate the heat flow to a room regarding mass and nominal heat power
- Storage tanks – simulation of the temperature distribution within the tank
- Control equipment – controlling e.g. the mass flow rates, depending on set point temperatures and actual room temperatures
- PV system – simulate the power output, depending on orientation, inclination and sun irradiation

During the last years, the building simulation community discovered the advantages of using Cross-industry multi-domain modeling languages (CMML) such as Modelica (Elmqvist, 1997) for the development and verification of complex simulation models. Following this the model development of the detailed HVAC systems was done with the software Dymola 2012 (Dassault Systèmes AB, 2011). It was desirable to extend the existing program with the newly developed models to be able to use both, the existing tool as well as the CMML models.

To deliver realistic and validated plant equipment models, the above mentioned sub-models are merged to complete HVAC systems, an example is shown in FIG 1. This was done to increase the usability and avoid the risk of non-feasible system configurations. Finally, the user chooses one HVAC system configuration and has to set only a few necessary parameters or import them from a database.

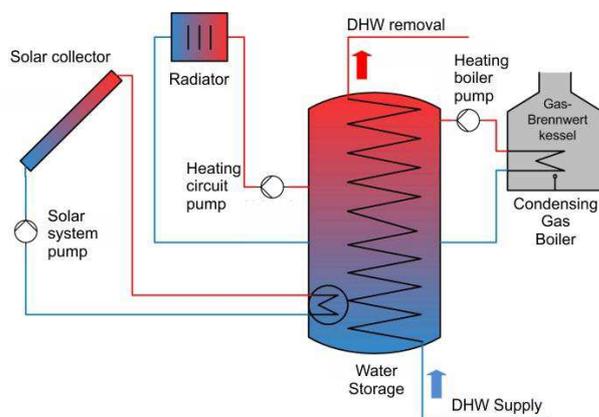


FIG 1: Exemplary HVAC configuration designed in Modelica and coupled with WUFI®Plus

2. Coupling

2.1 Preparing the HVAC models

As described above, all the different HVAC components, such as boiler, storage and solar collector are merged to whole plant equipment systems in order to increase the usability and to get feasible, proven and validated systems coupled with the building model. Each configuration can include different components, for example some include the condensing gas boiler, some others include heat pumps and some others include combined heat and power plants. The multi-zone model has to handle each of those configurations, just by changing the configuration type.

One necessary step to develop such models is to define the input, output and the parameters. Parameters are set at the beginning, respectively at the initialisation of a model. They can be computed with some other parameters, but regarded constant for the whole simulation. For example, the maximal gas-boiler output, or the maximal storage tank volume are such parameters. During the simulation the plant equipment has to interact with the building envelope, respectively the multi-zone building model. The multi-zone model has to send input, for each calculated time step. For example the actual interior building temperature and the set-point temperature is needed for the plant equipment, especially for the radiator sub-model to compute the heat flow to the room. Such time varying and simulation depending values must be sent to the plant model as input and delivered for the multi-zone model as output. Especially the model input has to be defined clearly as *input* in the model variable declaration; otherwise it is often not possible to set those values during the simulation in the exported model. Also the parameters have to be declared as *parameters* within the model. If not they might get the variability of a constant with the model export and constants cannot be changed.

One overall HVAC model exchange frame with all possible inputs, outputs and parameters for all the different kinds of included HVAC systems was defined. Each system is build up in this frame and using the inputs, outputs and parameters defined in the framework. If one configuration doesn't inherit the condensing boiler, for example, the parameters are just left empty.

A first coupling approach was to use Dymola specific export possibilities, the so called *Source Code Generation* or the *Binary File Export*. More details on this can be found in (Burhenne et.al. 2011). Finally the coupling with the *Functional Mock-up Interface* (FMI) for Co-Simulation was chosen because of its unified convention and possibilities to perform the co-simulation. Following this, all HVAC systems are exported using FMI for Co-Simulation. Those models include beside the simulation equations also a solver executing the co-simulation. The exported model is called *Functional Mock-up Unit* (FMU). It is a packed file (zip-file) containing the model binary file, a *dynamic link library* (.dll), with all the callable functions specified with the FMI application interface. Beside this model, the *modeldescription.xml* is included, containing all the necessary model information, especially the variables and parameter information.

Each input, parameter, or intern variable gets a model-unique identification number, a so called value reference number, during the export process. This number is documented in the model description file. The whole information exchange is handled via those value reference numbers. For example, the maximal boiler power with the model-variable name *qMaxBoiler*, gets the value reference number 16777216. With this number, and the transfer function `fmiSetReal(. . .)`, defined in the FMI specification, it is possible to set the value of the parameter, respectively the maximal boiler power. Even with the stiff configuration frame, the value reference numbers for the parameters and inputs change for different configurations or after a configuration is updated. It was decided not to hard-code the value reference numbers, but to develop a tool to setup the HVAC systems for the coupled simulation and merge the inputs, outputs and parameters.

2.2 Coupling the HVAC models

After a system is designed, validated and exported it can be loaded in the developed system configuration tool, shown in FIG 2 in the left bottom corner. The tool lists all the variables declared in the FMU, respectively the HVAC system. Besides the FMU variables, it also lists all the parameters, inputs and outputs provided within the graphical user interface of WUFI[®] Plus for the detailed HVAC Systems. They are partitioned per HVAC device, so each device type gets an identification number and the specified variables. For example, the gas condensing boiler has the ID 2 and the maximal heating power has the parameter index 1. Now the only thing to do, during the coupling process, is to find the variable name of maximal boiler power in the FMU (ordinary defined within the HVAC exchange framework before) and copy it behind the listed WUFI[®] Plus parameter. The tool merges the

Value Reference Number and checks the variability (input, output or parameter) and unit. It is visualised, if a connection is valid or not. The tool stores those links, and also some additional model information's, like model GUID (a unique number each exported model gets for exact identification) and the model binary file name in a HVAC configuration file.

The user of the software has not to do this. Only the model binary files, the HVAC configuration file and a FMU adapter is delivered with the software. The user only has to choose the desired HVAC system and set the values of the parameters within the graphical user interface.

The FMU adapter manages the simulation, also shown in FIG 2, without any user interaction. It gets all the parameter and input values from the building envelope model, connects them with the corresponding value reference number and sends this information to the HVAC model via the FMI-specification. It also manages the instantiation, initialisation and time step execution. Certainly it gets the outputs via the value reference numbers and sends it back to WUFI® Plus.

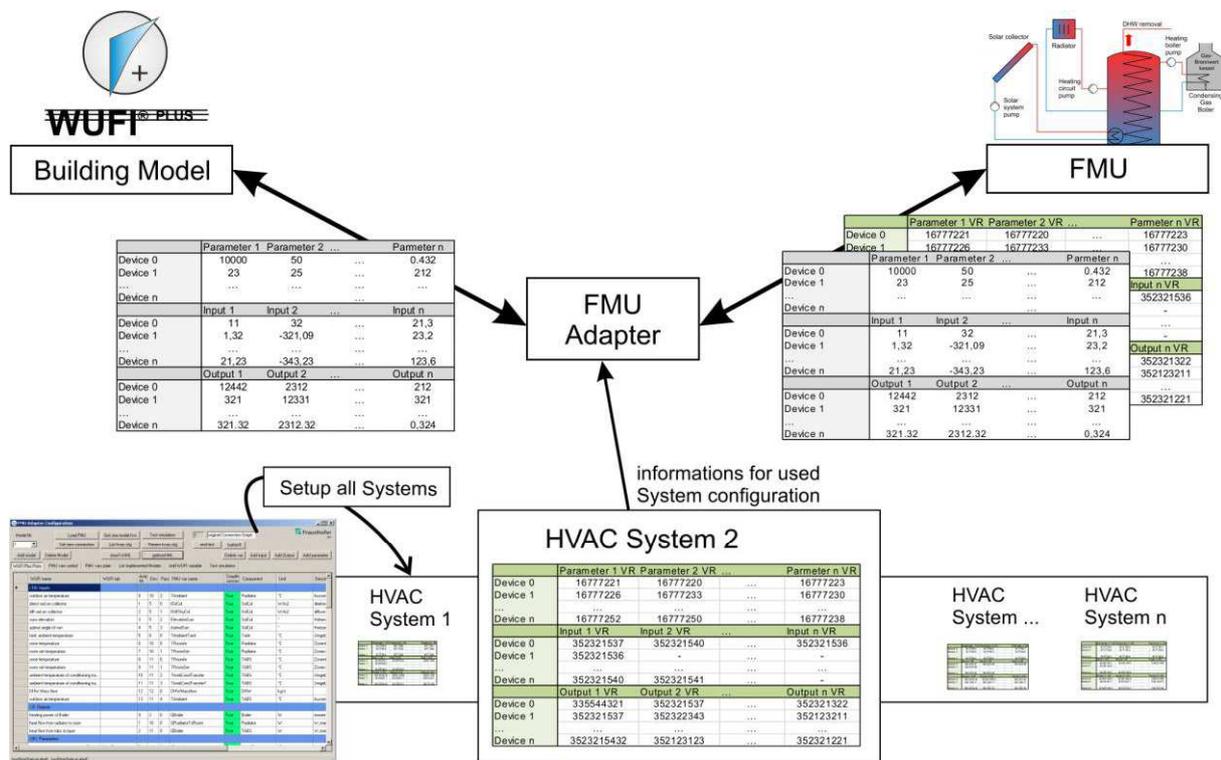


FIG 2: Coupling different HVAC Systems as FMU's with WUFI® Plus via the Coupling Tool

2.3 Simulation with the detailed HVAC models

As described before, the detailed HVAC models replace the ideal systems. Therefore, the implicit solution algorithm of the multi-zone model is replaced by an explicit method (Pazold et.al. 2012). This is required due to the unsupported rejection and repeating of time steps by co-simulation and particularly, because of the fast response to the indoor climate of the HVAC controlling devices and systems. The implicit method iterates each time step as long as the heat- and moisture in a zone is not balanced. With the explicit method, the indoor climate is adjusted for the next time step, regarding the heat- and moisture balances of an actual time step. The building model interacts with the HVAC system via a kind of *ping-pong* method. With an usual simulation time step size of one hour, to simulate one or more years, this alternative co-simulation would lead to unrealistic simulation results. Therefore, the explicit solution technique requires a decreased time step size, e.g. about five seconds. The computation of the indoor climate, and the heat and moisture field in the components has to be

done 720 times each time step. The implicit method requires only 15 to 40 iterations, respectively computations. This and of course the detailed HVAC models increase the computation time. However, the results of the small sub time steps must not be stored, the time steps don't iterate, and the hygrothermal component simulation module computes a bit faster for such small time steps, which saves some computation time. First simulations, without any further computation improvements, increase the simulation duration about 3 to 5 times. Benefits from the coupled simulation

Some improvements, regarding the hygrothermal building simulation coupled with detailed HVAC systems are mentioned in the text before. Remember the indoor climate; it will be simulated quite more realistic because of HVAC reaction times or over powering. It may not stay exact at the defined design conditions if the plant equipment is active. This will also affect the exchanges across the building components. Furthermore, the interaction between building envelope and HVAC system can be investigated in more detail. For example, the operation mode of a condensing gas boiler or a pellet boiler is simulated. In combination with the dynamic interaction between the thermal storage mass of the building, the mass of the heating distribution system and the water storage tank, the estimated efficiency of the boiler can be investigated. Additionally the power output of a solar thermal collector is simulated regarding the collector orientation, inclination and of course shading - depending on the position of the sun and surrounding components.

Besides the efficiency and heating demand investigations, the comfort assessment within different rooms or zones benefits from the detailed HVAC systems simulation. For example, the operative temperature can be assessed. By choosing a system including the thermally activated building system the dynamically simulated heating power is regarded as inner source within a building component affecting directly the heat and moisture distribution within it, the surface temperature and the heat flow into the room. This simulation can check if the area of the TABS is enough to heat up the room, with a still comfortable surface temperature.

3. Application example



FIG 3: Application example test building

The effect of a coupled simulation is shown in this chapter. One exemplary case is chosen to show some of the results of a HVAC model and the interaction with the building envelope and the indoor climate. Therefore one small house, with one full storey and a developed attic is investigated as shown in FIG 3. The treated floor area of the building is 118 m² and the net volume 281 m³. It should be located in Lund, Sweden, with the respective climate. The heat transfer coefficient (U-value) of the timber constructed and insulated exterior wall is 0,15 W/m²K, of the roof 0,17 W/m²K and of the windows 1,76 W/m²K. The overall window area is 18,6 m², including window frames. Furthermore, standard internal loads for two residents are regarded. The air change rate is set constant to 0,4 per hour. The reference case is simulated with an ideal heating system with over dimensioned heating power. In a next step, the ideal system is exchanged with the detailed exemplary HVAC system shown in FIG 1. It includes a condensing gas boiler and a solar collector for heat generation, a storage tank and a radiator for heat distribution. The main parameters for the system are listed in TABLE 1.

TABLE 1. Parameter list for application example HVAC devices

| | | | |
|--|---|----------|----------------------|
| condensing gas boiler | Maximal boiler power | 5 | [kW] |
| | Boiler and circuit mass | 50 | [kg] |
| | Temperature of tank which requires loading by boiler | 60 | [°C] |
| | Maximal mass flow of boiler supply | 0,1 | [kg/s] |
| | Top border temperature of tank | 70 | [°C] |
| Solar collector | Intercept (maximum) of the collector efficiency | 0,8 | [-] |
| | First-order coefficient in collector efficiency equation | 3,5 | [W/m ² K] |
| | Second-order coefficient in collector efficiency equation | 0,015 | [W/m ² K] |
| | Area of solar thermal array | 6 | [m ²] |
| | Length of collector | 3 | [m] |
| | Orientation of array (positive east from north) | 180 | [°] |
| | Inclination angle of array | 35 | [°] |
| | Required temperature diff. between collector and tank | 10 | [°C] |
| | Maximal temperature of tank | 90 | [°C] |
| Maximal mass flow of collector circuit | 0,05 | [kg/s] | |
| Water storage tank | Thermal storage capacity | 400 | [Liter] |
| | Diameter tank | 0,5 | [m] |
| | Heat transfer coefficient tank fluid to ambient (relative heights of inlets, outlets and sensors) | 0,25 | [W/m ² K] |
| | Thermal conductance of heat exchanger 1 | 500 | [W/K] |
| | Thermal conductance of heat exchanger 2 | 500 | [W/K] |
| Radiator | Nominal heat power of the used radiators | 2 | [kW] |
| | Mass of radiator including water | 100 | [kg] |
| | Radiator exponent | 1,281 | [-] |
| | Maximal radiator mass flow | 0,1 | [kg/s] |
| DHW | Domestic hot water profile (time scheduled) | variable | [kg/s] |

As described before, the building is simulated twice. Once with the ideal heating system and in the next step with a coupled detailed heating system, described in this paper. The results of both simulations are compared and some additional results, only obtainable with the detailed system are shown.

The graphs in FIG 4 show the indoor air temperature and FIG 5 show the heating power, which was required to keep the indoor air temperature within the design conditions. The reference simulation with the ideal system calculates a quite constant minimum indoor temperature, because of the design condition at 20°C. The simulation with the coupled heating system gives a more fluctuating indoor temperature, because of the detailed simulation of the heating system. The system includes a thermostat, with a hysteresis, setting the heating circuit mass flow rate following the indoor temperature and set point temperature. The behaviour of the whole system, including supply and return temperature of the radiator is simulated. Exemplary, in FIG 6 the water temperature within the water storage at the bottom, the middle and the top of the storage volume is shown. Such new results, only available with the detailed system, may be used to adjust the storage capacity and properties to the whole building.

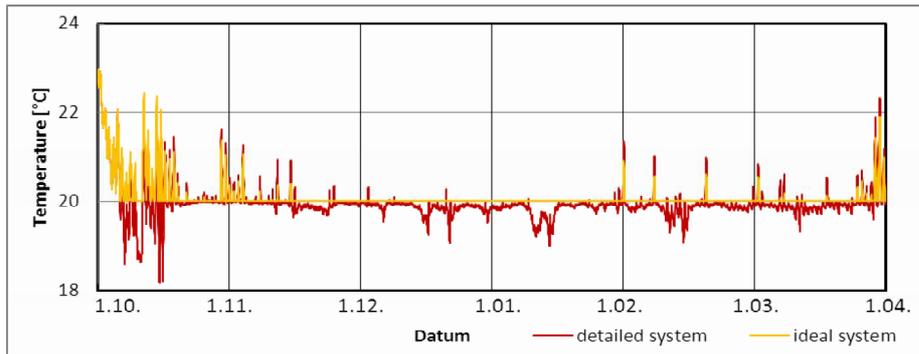


FIG 4: Comparison of the simulated indoor temperature of the application example building calculated with the ideal and the new detailed system. Because of the radiator hysteresis and the detailed heating system, the indoor air temperature fluctuating more and is not kept constant at the design condition at 20°C

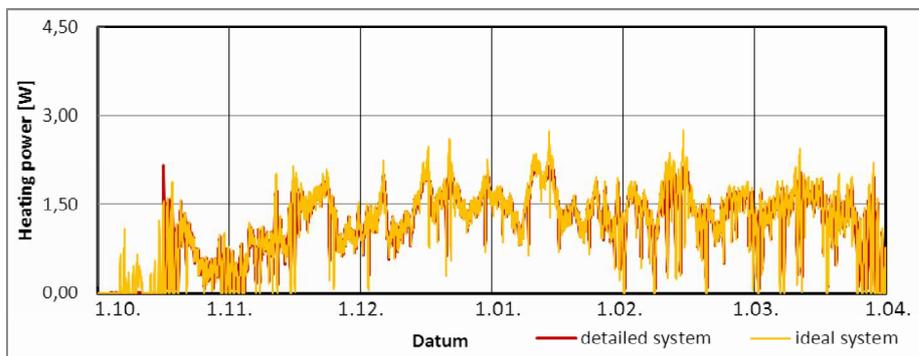


FIG 5: Simulated heating power, respectively heat flow from the radiator to the room, calculated with the ideal system compared to the simulation with the detailed system.

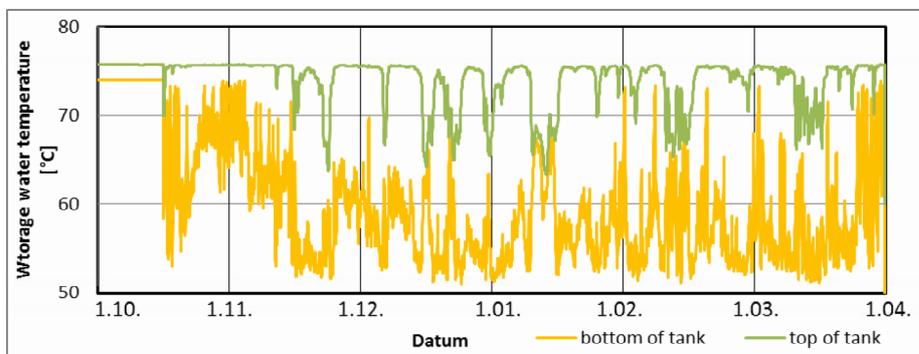


FIG 6: Further detailed system results, exemplary the simulated water temperature inside the water storage at different heights.

4. Conclusion

Cross-industry multi-domain modeling languages (CMML) provide a fast way to design and simulate different HVAC devices which are merged to pre-defined whole system configurations. Exporting those models with the standardized Functional Mock-up Interface (FMI) can be used to couple them with existing software, written in high level languages. However, some rearrangements of the existing software are necessary to adopt the models, respectively to implement the FMI functionality. The hygrothermal building model with a specialized solver and the HVAC systems are complex proven models, validated and stable for many kinds of simulations. The described coupling using the co-

simulation approach seems to be a reasonable technique to merge those models. The input and output of the different exported FMUs, acting as sub-models, can be defined using the developed tool. With the tool, it is possible to couple new or updated models without recurrent modifying of the source code of the existing software. A still acceptable computation time and realistic simulation results, e.g. a quite equal heating power to keep the indoor climate at the design conditions, leads to the conclusion, that the described coupling is a suitable and confiding method to improve the hygrothermal building simulation.

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