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MODELICA BUILDINGS LIBRARY 2.0

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ABSTRACT

This paper presents an update about recent additions to the Modelica Buildings library. The Modelica Buildings library is a free open-source library with dynamic simulation models for building energy and control systems. The library contains models for air-based HVAC systems, chilled water plants, water-based heating systems, controls, room and envelope heat transfer, multizone airflow, including natural ventilation and contaminant transport, and electrical systems.

The recent major additions that will be presented in this paper are a CFD model that is embedded in a thermal zone, a package for buildings to electrical grid integration, models for demand response simulation and data-driven models to predict the building load. The CFD model is an implementation of the Fast Fluid Dynamics code that allows three-dimensional CFD inside a thermal zone, coupled to building heat transfer, HVAC components and feedback control loops. The package for buildings to electrical grid integration includes models for loads, transformers, cables, batteries, PVs and wind turbines. The models can be configured for DC or AC systems with two or three phase balanced and unbalanced systems. They compute voltage, current, and active and reactive power based on the quasi-stationary assumption or using the dynamic phasorial representation. The models for demand response include a demand response client and data-driven models that predict the anticipated load of a building. This paper will explain these packages and present illustrative examples.

INTRODUCTION

The Modelica `Buildings` library is a free open-source library with dynamic simulation models for building energy and control systems. The library contains models for air-based HVAC systems, chilled water plants, water-based heating systems, solar collectors, controls, room and envelope heat transfer, multizone airflow, including natural ventilation and contaminant transport, and electrical systems.

We presented previous versions of the library in (Wetter, 2009; Wetter et al., 2014). These references also contain various examples and links to the validation of the library. This paper therefore focuses on the new additions to the library.

The library is developed in the Modelica language (Mattsson and Elmqvist, 1997). Modelica is an open-standard of an equation-based, object-oriented modeling language that has been used in various industrial applications.

Over the past two years, a significant number of models have been added. Some of these additions, and the revision of many of the existing models, were done in collaboration with the Modelica library development group of the Annex 60 project. Annex 60 is an international project conducted under the umbrella of the International Energy Agency (IEA) within the Energy in Buildings and Communities (EBC) Programme. The goal of Annex 60 is to develop and demonstrate new generation computational tools for building and community energy systems based on Modelica, Functional Mockup Interface and BIM standards.

The main additions for version 2.0 of the `Buildings` library are for modeling airflow distribution inside a room based on computational fluid dynamics, modeling AC and DC electrical systems to study the effect of buildings and renewable energy generation on the electrical distribution grid, and estimating building electrical loads, using a method that is used in demand response clients. In addition, the implementation of the `Buildings.Media` package has been simplified, and various component models have been added.

Other open-source libraries for building energy systems include `AixLib` from RWTH Aachen (Constantin et al., 2014; Lauster et al., 2014), `BuildingSystems` from UdK Berlin (Nytsch-Geusen et al., 2013) and `IDEAS` from KU Leuven (Baetens et al., 2012).

PREVIOUSLY EXISTING MODELS

The last official release of the `Buildings` library prior to version 2.0 was version 1.6. Version 1.6 contains the following main packages: `Buildings.Airflow` which computes airflow and contaminant transport among rooms and the outside (Wetter, 2006).

`Buildings.BoundaryConditions` contains models for boundary conditions such as weather data, solar irradiation and sky temperature.

`Buildings.Controls` contains blocks for continuous time controls, discrete time controls and set point scheduling.

`Buildings.Fluid` is one of the main package as it contains models of HVAC equipment, actuators, sensors and flow resistances.

`Buildings.HeatTransfer` contains models for heat conduction, convection and radiation. It also contains models for heat transfer in window systems (Nouidui et al., 2012) and in multi-layer constructions, possibly with phase change material.

`Buildings.Media` contains medium models for water and moist air.

`Buildings.Rooms` contains models for rooms that can be assembled to form buildings.

`Buildings.Utilities` contains a variety of packages to compute thermal comfort, to interface Modelica with the Building Controls Virtual Test Bed (Wetter, 2011), to embed Python in Modelica, for example to exchange data with hardware or web services, to compute psychrometric functions and to approximate non-differentiable functions with smooth functions.

UPDATES FOR VERSION 2.0

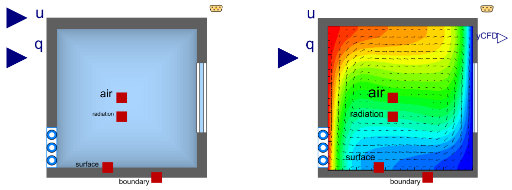
This section describes the main updates to version 2.0 of the `Buildings` library.

Computational Fluid Dynamics

The Modelica `Buildings` library version 1.6 couples the well-mixed indoor environment and the HVAC system through the connection of fluid ports and/or heat ports of the room model and HVAC component models. The room model named `Buildings.Rooms.MixedAir` simulates the indoor environment with the assumption of completely mixed air. This model can have any number of constructions and surfaces that participate in the heat exchange through convection, conduction, infrared radiation and solar radiation. Both, the model `Buildings.Rooms.MixedAir` and its window model have been validated (Nouidui et al., 2012; Wetter et al., 2011). However, the indoor air distribution can be stratified for rooms using energy efficient ventilation methods such as natural ventilation, displacement ventilation and underfloor air distribution. It also can be stratified in large spaces such as theaters and in rooms with complex air distribution such as data centers. To support the design and control of HVAC system with stratified air distribution, we implemented a new room model that computes stratified air distribution through a coupled simulation with a Computational Fluid Dynamics (CFD) program.

Model Description

Based on the existing `Buildings.Rooms.MixedAir` model, we introduced the new `Buildings.Rooms.CFD` model to compute the room air using coupled simulation with CFD. We selected the Fast Fluid Dynamics (FFD) model (Zuo and Chen, 2009, 2010) as the external CFD program. By simplifying the mathematical algorithms, the FFD is about two orders of magnitudes faster than a conventional CFD simulation. The package `Buildings.Rooms.Examples.FFD` folder provides a detailed users guide, a tutorial and some exemplar models.



(a) Rooms.MixedAir *(b) Rooms.CFD*

Figure 1: Icons of the two room models in the Buildings library.

As indicated in Figure 1, the models `Buildings.Rooms.MixedAir` and `Buildings.Rooms.CFD` are similar. This similarity allows users to easily switch the two room models for different modeling purposes. For example, `Buildings.Rooms.MixedAir` can be used during preliminary design to keep the computing time low. During detailed design, it can be replaced with `Buildings.Rooms.CFD` to increase accuracy. This replacement will preserve declarations such as the construction geometry and materials, and any connections to boundary conditions of the room. It is worth to note that the connectors of these two models differ in two aspects: First, `Buildings.Rooms.CFD` has no input connector for the shading control signal because a movable shade would require the CFD program to change the surface area of the boundaries for the shaded and unshaded window during the simulation, but this is not implemented in our CFD program. Second, `Buildings.Rooms.CFD` has the additional output connector `yCFD` that allows accessing data from CFD cells. The data from CFD cells can be temperature, velocity, mass fraction at a specific location of the room or a spatial averaged value for a certain volume, such as an occupied zone.

Our implementation uses a master-slave co-simulation, with Modelica being the master and CFD the slave. As the master, Modelica launches and terminates the CFD simulation. It also defines the coupled simulation period and the next synchronization time. The data synchronization strategy is based on a zero-order hold of the respective input signals. For more details of the implementation and validation, see Zuo et al. (2014, 2015).

Example

We show an example of natural convection in an empty space with a PI controller and a heater that tracks a temperature setpoint of 2°C at the center of the room. Figure 2 shows the schematic model view. The model is available at `Buildings.Rooms.Examples.FFD.NaturalConvectionWithControl`. The space is a $1\,\mathrm{m} \times 1\,\mathrm{m} \times 1\,\mathrm{m}$ box with no window. The room-facing surfaces of the east and west wall have a prescribed temperature boundary condition of $0^\circ C$ and $1^\circ C$, respectively. The other four room-facing surfaces are not connected from the outside, and hence they have a prescribed heat flow boundary condition with zero heat flow rates. The room space is discretized using a uniform grid of $20 \times 20 \times 20$ cells.

For the surfaces with temperature boundary conditions, Modelica computes the temperature and FFD computes the surface heat flow rate. For the surfaces with heat flow boundary conditions, FFD computes the

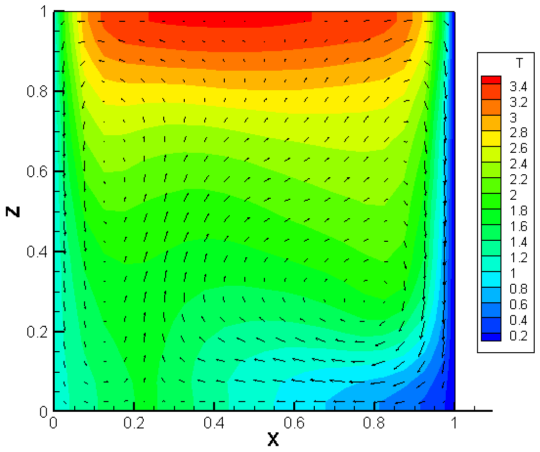


Figure 3: Temperature contours and velocity vectors on the X-Z plane at $Y = 0.5\,\mathrm{m}$ and at $t = 7200\,\mathrm{s}$ as computed by FFD.

temperature and Modelica computes the surface heat flow rate. FFD also computes the time averaged air temperature at the center of the room.

For the simulations, we used Dymola 2015 FD01 with the dassl solver, which is an adaptive time step solver. For FFD, we used a fixed time step size of 10 seconds. The two programs exchanges data every 30 seconds.

Figure 3 shows the temperature contours and velocity vectors computed by FFD. The uniform injection of heat by the controlled heating system leads to a high temperature zone near the ceiling, and a low temperature zone near the east wall since its surface temperature is $0°C$.

Electrical Grid

Residential and commercial buildings constitute about 70% of the overall electrical energy use in the United States. The increased number of PVs and other intermittent sources that may not coincide with the load of buildings impact grid stability and reliability. For these reasons, electrical models should be integrated with thermal building simulation models to assess the impact of control strategies such as demand response on the power quality of the distribution grid. The `Buildings.Electrical` package extends the `Buildings` library by providing models for different types of sources, loads, storage equipment, and transmission lines for electric power. The models can be used to represent DC, AC one-phase, and AC three-phases balanced and unbalanced systems. The models have been successfully validated against the IEEE four nodes test feeder. The results of the validation together with a detailed description of the package can be found in Bonvini et al. (2014).

Model Description

The `Buildings.Electrical` package uses a new type of generalized connector that has been introduced by Franke and Wiesmann (2014a) and that makes the library compatible with the Power Systems Library (Franke and Wiesmann, 2014b) and the Electric Power Library (Modelon, 2014).

This generalized electrical connector allows to represent electrical systems in a flexible way. The connector uses a paradigm that is similar to the one used in the `Modelica.Fluid` package. Each connector contains a package called `PhaseSystem` that contains constants and functions for a specific electrical domain. While the voltages and currents of the connectors are used to describe the boundary conditions of the models, the functions implemented in the `PhaseSystem` are used to describe the physics of the respective phase system. For example, a function is called to compute active power for given voltage and current. Different `PhaseSystem` packages are available that describe DC systems, AC single and multiphase systems that use the quasi-stationary or dynamic phasorial representations (Stankovic et al., 1999).

The `Buildings.Electrical` contains the following sub-packages.

The sub-package `Buildings.Electrical.*.Loads` contains models of resistive, inductive, or capacitive loads. The loads can be either constant or time-dependent, linear or nonlinear. The load can also be dynamic and account for electromagnetic effects.

The sub-package `Buildings.Electrical.*.Sources` contains models of ideal voltage sources and ideal power generators. Renewable energy sources such as PV panels or wind turbines are part of this sub-package.

The sub-package `Buildings.Electrical.*.Conversion` contains models for transformers and AC/DC or DC/AC converters. The transformers are modeled using different levels of fidelity from simplified ones based on efficiency coefficients to detailed ones that describe the magnetic and core losses. The three-phase unbalanced transformers allow connecting the primary and secondary sides of the transformer either with a Y or D configuration.

The sub-package `Buildings.Electrical.*.Storage` contains models for batteries and simplified battery state of charge controllers. For AC systems the models account also for the efficiency of AC/DC conversion and allows to specify the power factor.

The sub-package `Buildings.Electrical.*.Lines` contains models that represent transmission and distribution lines in the DC or in AC domains. The models range from simple ohmic resistances to detailed models that account for the inductive and capacitive effects of the cables. The cables can be automatically sized, or the user can select from a collection of commercial cables.

Example

Figure 4 shows a model of a net zero energy (NZE) residential neighborhood. The model is available as `Buildings.Electrical.Examples.`

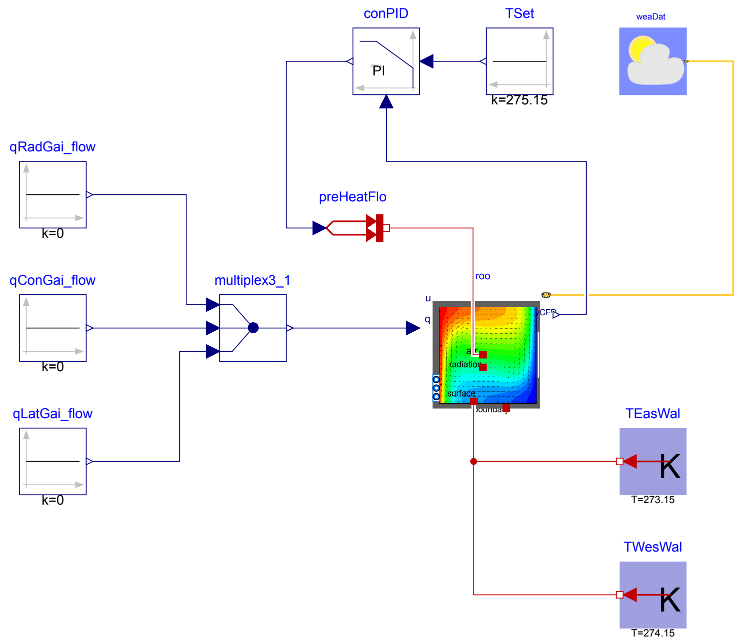


Figure 2: Schematic view of the Modelica model for natural convection with a heater and feedback control. The yellow line carries weather data, the red lines are for temperature and heat flow rate and the blue lines are input/output signals for internal heat gains and control signals.

`RenewableSources`. It is composed of seven residential units that are modeled as inductive loads. Each unit has a PV system and, in addition, the neighborhood has a wind turbine that supplements the energy provided by the PVs. The neighborhood is located in San Francisco, CA, and uses the standard weather data for this location.

The nominal voltage of the neighborhood is $V_{nom} = 480\,V$ and the nominal load of each residential unit is assumed to be $P^{load}_{nom} = 3.5\,kW$. The nominal power of the PVs is $P^{PV}_{nom} = 3.5\,kW$ and hence equal to the nominal load of the residential unit. In order to reach the NZE target, the nominal power of the wind turbine is $P^{wind}_{nom} = 14\,kW$ and therefore it is four times the nominal load of a residential unit.

The model represents the neighborhood using three-phase balanced models since this analysis does not focus on the possible asymmetries caused by the connection of the loads and sources on different phases. To make the model more realistic, the efficiencies of the PVs, their orientation and tilt angles are all different. Also, the power factor and the time series that represent the load of each house varies among the houses.

Figure 5 shows the ratio between the energy produced by renewables and the energy consumed by the residential units over one year. As can be seen the ratio approaches one after one year and therefore the system meets the NZE target. Figure 5 also shows that in order to reach a ratio that is close to the NZE target at the end of the year, there is a period between spring and autumn in which the energy produced by renewables has to be higher than the energy consumed. This period has an impact on the voltage quality in the neighborhood. Figure 6 shows how the voltages measured in three different nodes of the neighborhood vary with respect to the power generated by the renewables over the power consumed. The lower two plots show the voltage at the three nodes as a function of wind speed and horizontal global irradiation. As expected, the measured voltage increases as the power generated by the renewable increases. The highest voltage is V_3, which is at the point where the wind turbine is connected and the sensor `sen3` is located.

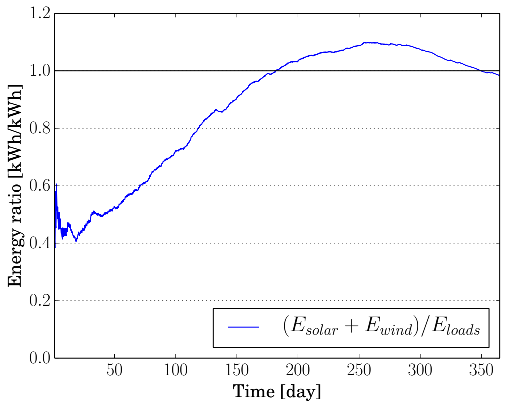


Figure 5: Ratio between renewable energy sources and energy consumed by the neighborhood and the target ratio for the NZE goal.

Demand Response and Electrical Load Prediction

Model Description

The model `Buildings.Controls.DemandResponse.Client` is a data-driven

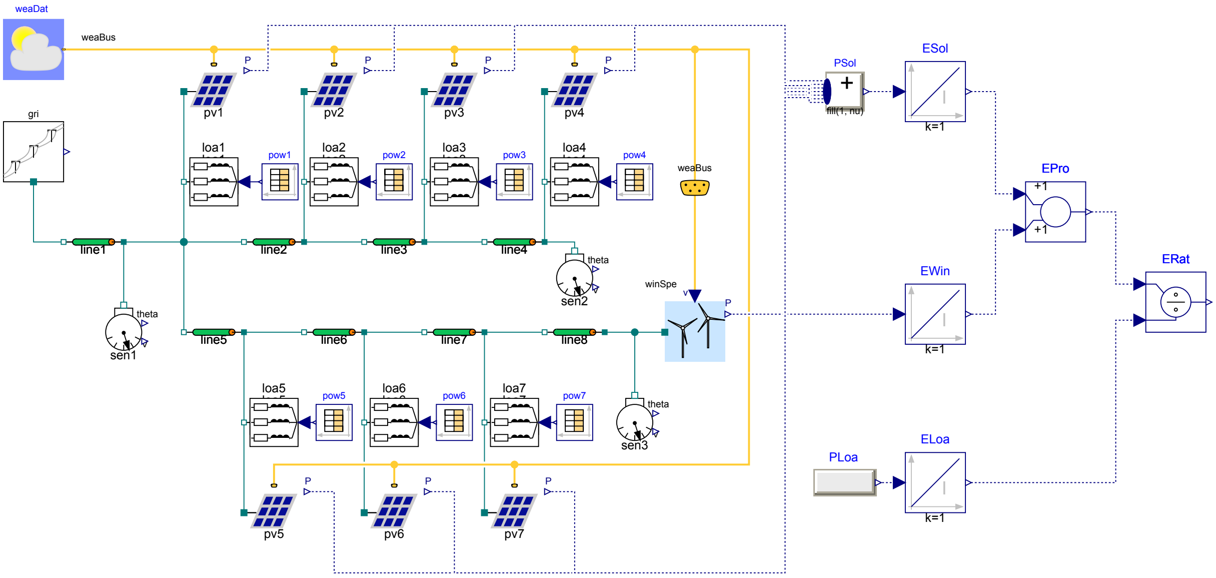


Figure 4: Neighborhood model with renewable energy sources. The yellow lines are weather data, green lines are electrical lines, and dashed blue lines are for post-processing.

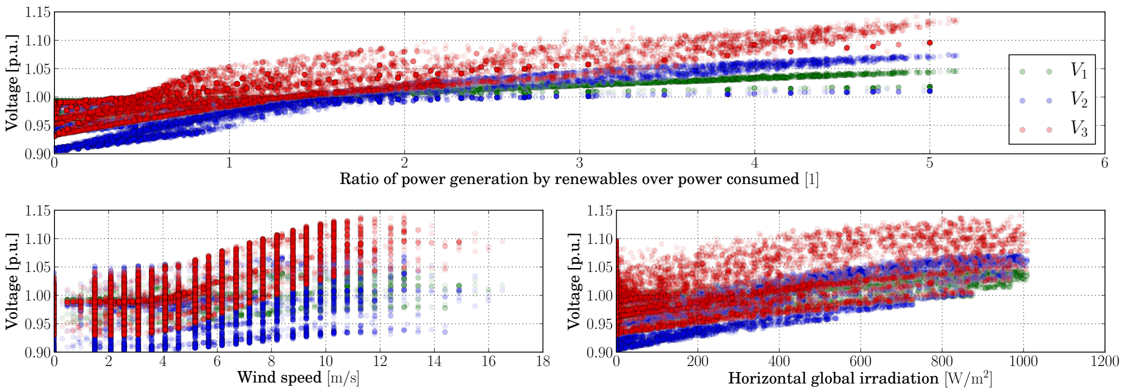


Figure 6: Voltage levels in three different nodes of the neighborhood as a function of the power generated by renewables, the wind speed and the horizontal global irradiation. The different colors represent voltages of the sensors `sen1`, `sen2` *and* `sen3` *in Figure 4.*

demand response client that predicts the future load and allows to apply a load shedding factor. It takes as a parameter the number of samples in a day, such as 96 for 15 minute sampling. Inputs to the model are the consumed energy up to the current time instant, the current temperature, the type of the day, which may be a working day, non-working day or holiday, a boolean signal that indicates whether it is a demand response event day, and a boolean signal s that if true causes the load to be shed. An input signal y determines how much of the load will be shed if $s =$ true, otherwise y is ignored. Output of the model is the prediction of the power that will be consumed in the current sampling interval. The load can be predicted for multiple future time intervals.

The load prediction is computed in the data-driven model `Buildings.Controls.Predictors.ElectricalLoad`. It allows to compute either an average baseline or a linear regression with respect to outside temperature. For both, optionally a day-of adjustment can be made.

The baseline is computed as follows: Separate loads are computed for any types of days as defined above. The average baseline is the average of the consumed power of the previous $n_{his} \geq 1$ days for the same time interval and the same type of day. If configured to use a linear regression, then the predicted power is a linear function of the current outside temperature, with slope and intercept computed using a regression over the past n_{his} days, again for the same time interval and type of day.

A boolean input signal s_h allows to no longer carry out the prediction for this day until midnight. This is needed as during a demand response event day, any time interval after the demand response signal has been received should be excluded from the baseline prediction, as the building likely is controlled in a non-typical manner. Storing history terms for the baseline

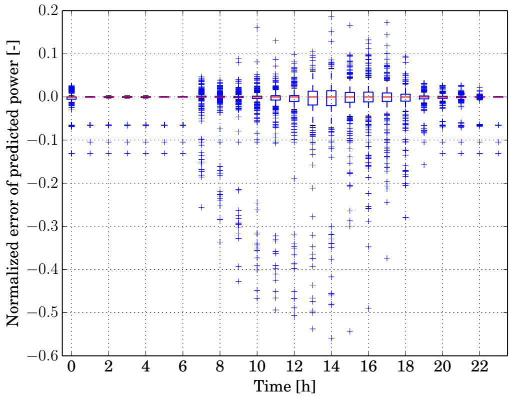


Figure 7: Prediction of weather-based regression model.

resumes automatically at midnight.

Optionally, a day-of adjustment can be made to correct the above prediction with the measured consumption of the previous hours.[1]

The day-of adjustment is computed as follows: First, the average power P_{ave} consumed over the day-of time window, typically 1 to 4 hours prior to the demand response event, is computed using one of the above regression models. Next, the average power P_{his} is computed for the past n_{his} days. Then, the adjustment factor is computed as $a = \min(a_{max}, \max(a_{min}, P_{ave}/P_{his})$, where a_{min} and a_{max} are parameters for the minimum and maximum adjustment factors. The predicted power is then multiplied by the factor a to better take into account the current electrical consumption of the building.

Example

Figure 7 shows the box plot for the weather-based regression model with $n_{his} = 10$ days, 15 minute sampling, and day-of adjustment with $a_{min} = 0.8$ and $a_{max} = 1.2$. The boxes extend from the lower to upper quartile values of the data, with a line at the median. The whiskers extend from the box to show the first and third quartiles. For better visualization, we only plotted the prediction at the full hours, rather than at 15 minute intervals as were used in the predictions. Input was the total electric consumption of building 90 on the LBNL campus as simulated by an EnergyPlus model. The outlayers with large negative error are during heat waves when the building consumes more power than the regression model estimated.

Media

The media package has been simplified from the previous nine air models, of which many were experimental, to two models for moist air, optionally with trace substances such as for CO_2 or VOC, and two models for water. These are the same models as are used in the `Annex60` library (Wetter et al., 2015).

The models `Buildings.Media.Air` and `Buildings.Media.Water` are the recommended media for typical applications as they lead to the smallest systems of coupled nonlinear equations. `Buildings.Media.Air` implements a moist air model with the Boyle-Mariotte gas law $\rho/\rho_{stp} = p/p_{stp}$, where ρ is the mass density, p is the pressure and stp are standard temperature and pressure conditions. The model `Buildings.Media.Water` implements a water model with constant density.

More detailed models that generally cause higher computing time are in `Buildings.Media.Specialized`. The model `Buildings.Media.Specialized.Air.PerfectGas` uses the ideal gas law, and `Buildings.Media.Specialized.Water.TemperatureDependentDensity` uses a 3rd order polynomial to compute the mass density as a function of temperature.

The previous media models have been moved to `Buildings.Obsolete.Media` and will be removed in future versions.

Minor updates

The following minor updates have been made.

The fan and pumps models now use performance data from records, and data are provided for various pumps from Wilo SE.

Two new valve models have been added: A two-way valve in which the K_v value can be specified by a table for different valve openings, and a pressure-independent two-way valve in which the mass flow rate, for sufficiently large pressures, is $\dot{m} = y\,\dot{m}_0$, where $y \in [0,\, 1]$ is a control signal and $\dot{m}_0$ is the design flow rate.

The new model `Buildings.Fluid.HeatExchangers.HeaterCooler_T` is a heater or cooler whose outlet fluid temperature is equal to its control input. Optionally, the maximum heating or cooling capacity can be specified, and the set point can be tracked either ideally or with a first order response.

CONCLUSIONS

The Modelica `Buildings` library has been significantly extended between version 1.6 and 2.0, increasing the number of models, blocks and functions from 416 to 668. It now allows to combine models of thermal building simulation, including HVAC, with models of electrical distribution systems and prediction models as are used in demand response clients. The library has been extended with a CFD model that allows combining room heat mass transfer through opaque materials and the window with computational fluid dynamics in a room. This combined model can then be connected to HVAC system and control models.

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[1] Some literature call this morning-of adjustment, but we call it day-of adjustment because the adjustment can also be in the afternoon if the peak is in the late afternoon hours.

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