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STRUCTURING THE BUILDING PERFORMANCE MODELICA LIBRARY AIXLIB FOR OPEN COLLABORATIVE DEVELOPMENT

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ABSTRACT

Currently, there are various efforts to formulate models for building performance simulation using the modeling language Modelica. With the International Energy Agency's Annex 60 programme collaboration is underway to build a common foundation for developing such model libraries. In this paper, we present how the incorporation of the Annex 60 library into the model library `AixLib` has changed its structure and outlook. Furthermore, we give an overview of the current state in `AixLib`'s ongoing development and conclude with two use cases to demonstrate the library's applicability for building performance simulation on building and district scale.

INTRODUCTION

Currently, there are various efforts to formulate models for building performance simulation using the modeling language Modelica. One key motivation for this approach is the high reusability of models and model components resulting from the organization of object-oriented and equation-based models in model libraries. Furthermore, the acausal modeling approach allows for assembling complex system models from component models effectively (Dizqah et al., 2015), which helps to model building energy systems from an engineering perspective.

The authors' institute has been developing Modelica model libraries for answering different research questions as well as for teaching building energy systems and their modeling to undergraduate students. These efforts include models of building envelopes as well as building energy systems. The range of building models includes a more detailed approach (Constantin et al., 2014) as well as a low order approach to reduce computing times for city district scale simulations (Lauster et al., 2014b).

Probably the most widely used Modelica model library for building performance simulation at the moment is the `Buildings` library developed by LBNL Berkeley (Wetter et al., 2014). This library has been freely available and developed under an open source policy for several years. It contains various models for building energy systems and controls. In addition, it is accompanied by a Python package named `BuildingPy` that contains methods to automate simulations and unit testing during library development.

Other modeling efforts include the `BuildingSystems` library at UdK Berlin (Nytsch-Geusen et al., 2013) and `IDEAS` at KU Leuven (Baetens et al., 2012). A strong focus of `BuildingSystems` is the idea to combine different levels of detail regarding building and energy system modeling in a combined system model. This allows for tailoring the depths of analysis to the aim of the simulation. For `IDEAS`, a special focus is set on combining thermal and electrical modeling, also on a city district scale.

All the mentioned groups work on different modeling approaches and specialize in different aspects, which helps to gain insights into the possibilities and challenges of building performance simulation with Modelica models. Yet, until recently, these efforts had not been coordinated and models had only partly been published open source. This prevented the actual potential for model and system development from being fully exploited. In order to address this shortcoming, an international collaboration is underway within Annex 60 of the International Energy Agency's Energy in Buildings and Communities Programme with the aim of developing "[n]ew generation computational tools for building and community energy systems".

As part of Annex 60, the above mentioned groups at LBNL in Berkeley, UdK Berlin, KU Leuven, and RWTH Aachen University are collaborating on the development of a common Annex 60 core library that serves as a foundation for the various specialized model libraries. By defining common base classes, main assumptions, and interfaces, this effort aims at making all libraries' component models to be compatible with each other. Base classes contain basic component models, which can then be extended to integrate more specialized functionalities. In addition, the library aims at providing a reference set of component models often used in building performance simulation. In the course of this cooperation, RWTH Aachen University has bundled its models into the model library `AixLib`. This library has been released and is now available for free use and open source development (RWTH-EBC, 2015). Furthermore, the initially released version has been redesigned and structured to use the Annex 60 library for improved open collaborative development. In this context, the aim of this paper is to give an overview of the current state of the library and describe the process of redesign in order to facilitate participation in usage and development of model libraries using common base classes. We conclude by describing two use cases that demonstrate possible applications in which the library can be a useful tool for energy modelers.

MODEL LIBRARY OVERVIEW

The `AixLib` model library contains models for building envelopes and Heating, Ventilation and Air Conditioning (HVAC) components. The building models include low and higher order models for different depths of energy analysis on building and city district scale. The HVAC component models are simplified formulations of components' behavior. They were originally designed for teaching undergraduate students, demonstrating the functionality and interaction of HVAC components with each other and with the building envelope. The simplification of HVAC component models included a fluid implementation based on constant medium properties that was not compatible with the media and fluid flow models from the Modelica Standard Library. With restructuring the `AixLib` HVAC models and many of them using the Annex 60 fluid base classes, compatibility between `AixLib` and other model libraries, especially those also using the Annex 60 core library, has been enhanced.

In order to enable usage of the Annex 60 base classes, the Python package `BuildingsPy` developed at LBNL includes a merging routine that automatically merges the Annex 60 library structure and models into an existing Modelica model library. If parts of the Annex 60 library are not yet part of the target library, these are added to the existing library structure. If both libraries follow a common structure, these parts are merged together, so that common subpackages include the original models as well as models from Annex 60.

For `AixLib`, we decided to adjust the structure of the library to better work in sync with the development of the Annex 60 library. The HVAC models in AixLib contain components for heating systems, using water as a medium and ventilation systems using moist air as a medium. For each medium different sets of connectors were originally designed. In the process of integrating the Annex 60 library, we chose two different paths for two sub-groups of HVAC component models. We changed all water-based heating system component models to follow the structure of the Annex 60 library's `Fluid` package, facilitating the use of base classes for these kinds of models. Yet, `AixLib`'s ventilation and air handling models are kept in a separate package named `HVAC`, the reason for which is described in the following sections. As the Annex 60 library does not contain building models at the current stage, the high an low order building models in `AixLib` are organized as initially designed in a package named `Building`.

Overall, the merging of the Annex 60 library into `AixLib` results in a library structure as follows:

- `Building`
- `Controls`
- `DataBase`
- `Fluid`
- `HVAC`
- `Images`
- `Media`
- `Resources`
- `UsersGuide`
- `Utilities`

BUILDING MODELS

`AixLib`'s package `Building` contains the two modeling approaches `HighOrder` and `LowOrder`. The high order approach was originally described by Constantin et al. (2014) under the library name `HouseModels` and has been integrated into `AixLib` since. The aim of these models is to serve as a user-friendly tool to simulate typical building setups in combination with building energy systems. Therefore, model components support easy parameterization and preset parameters are based on typical values derived from data by the German Federal Statistics Office and expert consultations.

The modeling approach follows a bottom-up principle in which basic components form wall elements including optional doors and windows. These wall elements can be combined to room models, from which building models can be assembled. As variables are propagated through the different model levels, it is possible to choose from a set of typical building properties at any level or alternatively define own property sets. The preset properties of the building envelope included in the library follow German energy saving ordinances from different years as well as different building thermal mass types: light-weight, medium, or heavy. Thus, it is possible to change the properties of a building with very little effort, allowing for fast case studies of building energy systems with different building types and different years of construction.

Furthermore, this part of the library includes examples of both a typical one-family dwelling (OFD) and

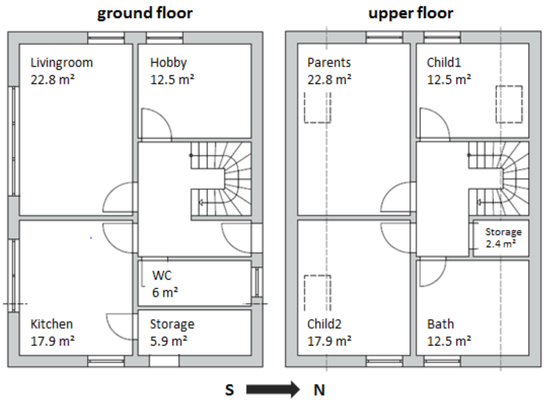

Figure 1: Floor plan of the typical one-family dwelling in AixLib

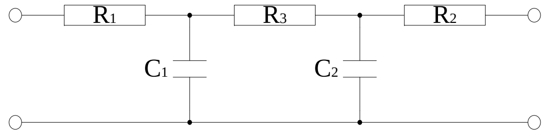

Figure 2: Resistance-capacitance concept for a multi-layer wall model

an apartment that is part of a multi-family dwelling (MFD). Thus, energy system concepts can be modeled and quickly tested in these two cases. In order to give an impression of the examle models' scale, Fig. 1 shows the floor plan of the OFD. For both building examples, the library includes models for the building envelopes as well as for a water-based heating system. The coupling of envelope model, heating system model and the boundary conditions is realized via thermal connectors for each wall element as well as air nodes for every room. The connection via thermal connectors establishes a mathematical relationship that represents the exchange of heat flows between two components with temperature differences as the driving force.

In addition to the higher level modeling approach, `AixLib` also contains a low order building model that is based on the VDI Guideline 6007 (German Association of Engineers, 2012). The modeling approach is presented in detail in Lauster et al. (2014b). This approach is based on a resistance-capacitance model that aggregates all walls of the same type (outside or inside) into a corresponding one layer wall component for a thermal zone. Fig. 2 presents the concept of resistances and capacitances for a wall: a capacitance for the thermal mass of each layer, sandwiched between two resistances. The differences with the also widely used model specified in ISO 13790 are explained in more detail in Lauster et al. (2013). In the VDI model, all outside walls are lumped into a single representative outside wall element that contains one thermal capacitance and two thermal resistances, one for the connection to the outside environment and one to the indoor air volume respectively. Similarly, the inside walls are lumped to one representative inside wall element with one capacitance and only one resistance towards the indoor air volume.

The calculation of resistances and capacitances based on the properties of a given building follows the procedures described in VDI Guideline 6007. In this approach, the representative wall elements combine the thermal properties of the corresponding wall elements and take into account each wall's orientation by means of weighting factors for incoming irradiation. The model uses three capacitances for a thermal zone: outer wall, inner wall, and air node. Thus, the computational effort is reduced significantly while the model still contains the main physical principles and properties of the building's heat transfer mechanisms. For further development of the model that deviates from VDI Guideline 6007 but improves simulation performance, refer to Lauster et al. (2014a)

In order to simplify the less intuitive way of parameterizing the low order building model (values for resitances and capacitances), a dedicated parameterization tool is currently being developed at the authors' institute. This tool named `TEASER` not only aims at calculating the necessary parameters for the building model from known building properties, but also features a database of typical building setups based on statistical data. Thus, it is possible to quickly parameterize archetype buildings (e.g. office building, laboratory) with little input data like year of construction, floor area, and usage type. With the ability to export the model parameters in a structured way, using the Modelica `record` type that can be automatically imported into the model, this information can be used to set up the building model directly. An open-source release of `TEASER` is planned for 2015.

Together, both building models form a basis for dynamic building energy system simulations with varying levels of detail. Current efforts aim at further developing these model approaches and at continuing validations of the simulation results. So far, the models have been validated by cross-comparisons, the test cases given in VDI Guideline 6007, and the ASHRAE 140 validation tests. The model library contains executable examples of these validation tests for verification purposes.

MERGING WITH ANNEX 60 LIBRARY

In addition to high and low order building models, `AixLib` contains a variety of HVAC models. These were originally developed to be used for teaching building performace simulation with Modelica to undergraduate students. Due to this illustrative character, the models are comparably simplified. As part of the development in the International Energy Agency's Annex 60 program to develop new computational tools for building performance simulation, the heating system models were modified to use base classes from the newly developed Annex 60 model library. The aim is to have different model libraries use the same base classes for their fluid models, so that it is possible to use component models from different model libraries interchangeably. In the following sections, we will present this base classes approach and give an overview of the HVAC models included in AixLib.

In the initial version of AixLib the simplified HVAC component models included a fluid flow implementation based on constant medium properties that was not compatible with the media and fluid flow models from the Modelica Standard Library. With the development of the Annex 60 model library, AixLib's heating system models were changed to use base classes for fluid model implementations. These base classes define the basic mass balance and interfaces for connecting each component with other components to model the fluid flow between them. The fluid properties are defined by a Modelica medium model, which can be accessed via predefined Modelica functions.

Thus, models using the base classes are compatible with models from the Modelica Standard Library. Furthermore, the user can easily change the fluid properties by selecting a different medium model to be used without the need to further modify the component model itself. On the one hand, this allows for using the same component model with different media, e.g. a pipe model for water that also serves as an air duct model with a medium definition for air. On the other hand, this approach enables users to switch between different models for the same medium with varying levels of detail and resulting computational effort.

In the course of the Annex 60 collaboration, AixLib has been enhanced by merging the Annex 60 core library into AixLib. As a result, all models for heating and cooling equipment that use water as a medium have been redesigned to extend from a suitable Annex 60 base class. Thus, these models can be used with different Modelica media implementations and are compatible with heating and cooling equipment models from other libraries that are also based on the Annex 60 base classes, i.e. the libraries Buildings, BuildingSystems, and IDEAS. As described above, merging the Annex 60 library into AixLib is done automatically using the BuildingsPy package. AixLib includes a Python script making use of BuildingsPy's merge functionalities that initiates the merge process by seaching for both libraries in the local system's environmental variable MODELICAPATH. Thus, if MODELICAPATH is set correctly, this merge script can be executed from any working directory.

In addition to base classes, the Annex 60 library also contains a set of HVAC component models. These models are part of ongoing collaborative library development and may in the future be used as a reference model set for HVAC system simulation in addition to being useful for benchmarking the base class and media implementations in the library. With merging the Annex 60 library as a core part into another model library like AixLib, these component models are also introduced into the target library. In the case of AixLib for many of these components two versions exist, one from Annex 60 and one from the AixLib itself. With the current state of AixLib this results largely in two corresponding model sets. Having two models for the same component is a temporary solution. It is planned to develop benchmark use cases which can be used to compare the performance of the models and help in reaching an informed decision over which model is better suited for a particular application. We expect some models to be replaced by the Annex 60 versions, because of their current very basic modeling, while others may continue to be used when the application does not require a high level of detail.

In the course of structuring AixLib to incorporate the additional models and base classes from the Annex 60 library, it was an essential design decision which models to convert to use the fluid base classes. For the heating system models described in the following section, the decision was taken to convert all models, as the difference in level of detail justified maintaining the two complementary model sets on a common foundation of the base classes. As the modeling approach for ventilation components was very different from the Annex 60 approach, the incorporation of base classes was not feasible. These models were left unchanged.

HEATING SYSTEMS

Originally, the heating system models in AixLib relied on a simplified definition of media properties and simplified fluid connectors that did not allow for mixing of different media or change of media properties during simulation and were not compatible with the Modelica Standard Library approach. With the development of the Annex 60 library, all these models have been redesigned to use the Annex 60 library base classes. Thus, it is now possible to use media models from the Modelica Standard Library, the Annex 60 Library or other libraries with each component model according to the respective aim of the simulation.

The available heating system component models in AixLib represent the main components as in a real system. These include different models for heat generation, distribution and consumption. A general assumption is that heat is distributed in a water circuit, as is mainly the case in German buildings. On the consumption side, there is a radiator model that calculates the convective and radiative heat flows transferred to the room depending on the hot water flow and radiator type. The radiator type can be defined by means of a data record specifying the design parameters: length, height, depth, as well as nominal power at standard flow, return and room temperatures. In addition, the consumption side of a heating system model can be ideally represented by a fluid volume model with a thermal connector to a thermal energy source.

Regarding the heat distribution circuit, `AixLib` includes component models for the pump, pipe elements and hydraulic resistances. The pump model is based on tables that specify boundary curves for operation points regarding volume flow and head of the pump. The model allows for the selection of a control strategy between constant and varying pressure difference over the pump. In addition, a Boolean input can set the pump to a night setback mode following the minimum curve defined in the pump table. With these options, the pump model can illustrate basic modes of operation without being very detailed or complex. Similarly, the pipe model was designed in order to illustrate a relation between mass flow rate and pressure loss modeled using the Hagen-Poiseuille equation. As it was only implemented for demonstration of this principle, the pipe model does not take flow regimes into account but always assumes a turbulent flow. For a more realistic modeling of pipe flow, other libraries like the `Modelica Standard Library` already contain such pipe models. In order to be able to account for pressure losses, e.g. from bends, in a simple way, the hydraulic resistance model can be used given a pressure loss factor.

For heat generation, `AixLib` includes models for boilers, solar thermal collectors, and heat pumps. All of these models are table-based with reference to a database of records. By choosing the corresponding table, it is possible to configure the boiler model with efficiency curves of a constant temperature boiler, a low-temperature boiler, or a condensing boiler. In the same way, there are different records for different types of solar thermal collectors from simple absorbers to flat-bed, concentrating, and vacuum collectors. The heat pump model uses two tables to calculate the electric power and heat flows of the condenser depending on the source and sink temperatures. As these models use fairly simplified approaches to model basic operation, they are not suited for in-depth analyses but rather for quick comparisons and demonstrations of differences between various heat generation equipment in a heating system.

For a more in-depth analysis of heating systems, it is an advantage that the merging process of the Annex 60 library into `AixLib` introduces not only the aforementioned base classes, but also additional component models. These models represent a basic set of heating system components that in many cases use more detailed model formulations than the illustrative models originally included in `AixLib`. Furthermore, the Annex 60 library is not static, but continues to be developed by an international working group. Thus, with structuring `AixLib` to use the Annex 60 library at its core introduces a complimentary set of component models. This is an advantage in addition to the increased compatibility with other model libraries following a similar approach.

VENTILATION AND AIR HANDLING

A major difference between the heating systems and the ventilation and air handling models is the accounting of different substances in given concetrations in the medium, so called species. While heating system models are assumed to use only water as a single-species medium, it is crucial for ventilation and air handling models to take into account the concentration of water in the air medium. The original `AixLib` approach had the species concentration calculation coded into each ventilation and air handling model in order to stick with the approach of having a simple fixed medium implementation. A change in medium would mean a redesign of each model. In this sense, the models contained a second-species extension compared to the heating system models. Thus, a redesign for the ventilation and air handling models to use the Annex 60 base classes would not have been feasible, especially as the resulting models would have been very similar to the corresponding models already introduced to the library by the Annex 60 library merge. As a result, the current `AixLib` contains the Annex 60 ventilation and air handling models as well as the original simplified models for similar purposes. Thus, it is possible to quickly assemble air handling systems with the simplified approach as well as work on a more detailed system model with the Annex 60 models, similar to the approach for heating system modeling.
The simplified set of ventilation and air handling models contains component models for a fan and for air ducts to assemble air duct networks and move the air flow through. In addition, there are models for a steam humidifier and a dehumidifier in order to condition the air regarding its water content. Further models include an ideal heater/cooler and a recuperation heat exchanger as well as utility models for volume flow controllers, sensors, and air volumes.
As the more versatile Annex 60 models can be used with different media implementations, the distinction between heating system models and air handling models is not as pronounced as it is with the more simplified models. As a result, the pipe and pump model can be used as duct and fan models by changing the medium model to an air representation. More specialized air handling models include also a humidifier and air dampers. In future work, cross-comparisons and testing of use cases will show whether both modeling approaches will be kept as parts of the library or whether future development will lead to focus on one of these approaches for all applications.

EXAMPLE USE CASES

This section demonstrates possible use cases for the `AiXLib` model library in order to suggest useful applications for possible library users. As with the model description above, possible use cases can focus on the evaluation of building envelopes and on HVAC

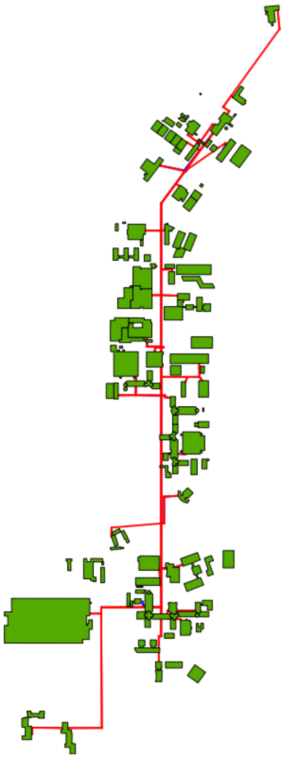

Figure 3: Layout of a reference district with 32 buildings

systems. In addition, a combination of both can be achieved by connecting HVAC system models to room air nodes of building envelope models. In the following, we will describe an example use case for heat demand simulation on city district scale and a use case evaluating the influence of heating system efficiency on the fuel demand of an apartment in a multi-family dwelling.

In the first use case, the use of `AixLib` mainly concerns the low order building model described in the section Building Models. While the higher order building model in `AixLib` can represent a building in significantly more detail, the low order building model is a useful tool for estimating heat loads of a larger number of buildings. In part, this is due to its shorter simulation times and, with the help of the aforementioned tool TEASER, its fast and easy parameterization, even if only little data about the building stock is known. As mentioned above, the low order model uses a resistance-capacitance approach to estimate heat and cooling loads as a time series. For this time series, the time resolution depends on the resolution of the input data and the chosen simulation output step. With the focus on heat demand series of a city district, a yearly simulation with an hourly time-step is a practical choice, as weather input data is often available in hourly time-steps.

As a use case for a city district we want to evaluate the district's heat demand. For the use case two scenarios are developed: a reference case using the current state of the district and a retrofit case in which the building envelopes have been retrofitted. Figure 3 shows a reference district with 32 buildings supplied by a district heating and cooling network. In order to estimate the district heating network's heat load, `AixLib`'s low order building model can be used to simulate each building's performance and output the hourly heat demand for one year. The simulation time for this group of buildings is 11 minutes on 12 cores and thus also allows for simulating different variations for comparisons. In this example use case, we parameterize each building using TEASER, giving only the minimum input data like year of construction, floor area, height, and usage type. From this minimum input data, TEASER derived resistances and capacitances of the buildings with the help of statistical data and parameterized corresponding building models accordingly.

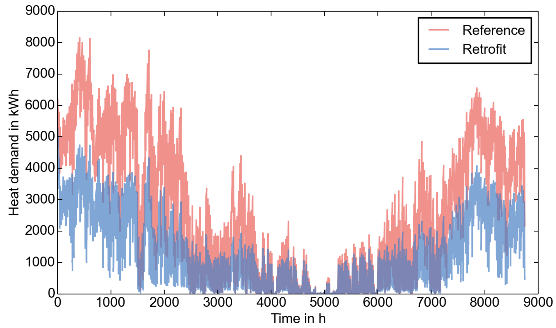

Figure 4: Simulated heat demand of all buildings in the district

In another simulation run, all building models were parameterized to use retrofitted building envelope properties with increased insulation. A comparison of these two simulation results shows the influence of building retrofits on the heat load of the district heating network. In this example, simulating the buildings with the retrofit data predicts a reduction in overall heat demand from all buildings of 49.7 % compared to the reference case. Figure 4 shows the hourly values of the heat demand for both cases. For the supply plant of the district heating network, such a reduction in heat demand would have significant effects. Thus, this use case illustrates how the low order building model can be used to estimate heat loads on city district scale for various building retrofitting scenarios and its effects on a centralized heat supply.

As a second use case, we present a combined model of the building envelope, the heating system and the outside environment's influence by example of one apartment in a multi-family dwelling as shown in Fig. 5. To model the building envelope, we use the higher order building model, while the heating system model is built from `AixLib` model components. For this illustrative example, the boundary conditions at the inner walls are considered adiabatic. For the outside wall we consider radiation through windows as well

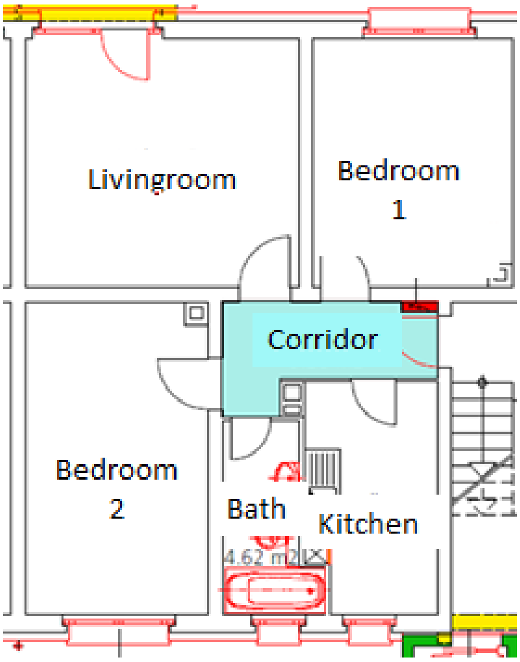

Figure 5: Floor plan of the example apartment

as heat transfer to the outside environment depending on the temperature difference between indoor and outdoor air.

Furthermore, we assume the apartment to be supplied with heat from its own gas boiler. A pump drives the water flow from the boiler to distribute heat to five rooms, each equipped with a radiator and a thermostatic valve controlling the water flow to keep the the room air temperature at a given set point. The radiator is connected to the room via two thermal connectors, one for radiative and one for convective heat transfer respectively. This way it is possible to combine the heating system model with the building model and evaluate the whole system in an integrated simulation.

For this use case we estimate the fuel demand when using different types of boilers. As mentioned in the section Heating Systems, the boiler model allows for changing the efficiency curves to represent a standard constant temperature boiler, an improved low-temperature boiler, and a more efficient condensing boiler. In this example, we performed yearly simulations of the system with each of these boiler types to compare the differences in fuel demand for the apartment's heat supply. As shown in Fig. 6, the different efficiency curves for the boiler types have a significant effect on the predicted fuel demand to supply the apartment with thermal energy.

These example use cases are meant to illustrate applications for a user of `AixLib`. With the first use case, we showed the applicability of using `AixLib`'s low order model for heat demand simulations for larger groups of buildings. The second use case showed how the higher order building model can be coupled with HVAC equipment models in order to evaluate the dynamic behavior of the entire building system in one integrated model. Here, the model was able to serve as a tool to quickly estimate the influence of heating equipment properties on the fuel demand of the building. Further use cases can include more detailed studies of building energy systems as well as interactions between buildings on a district scale.

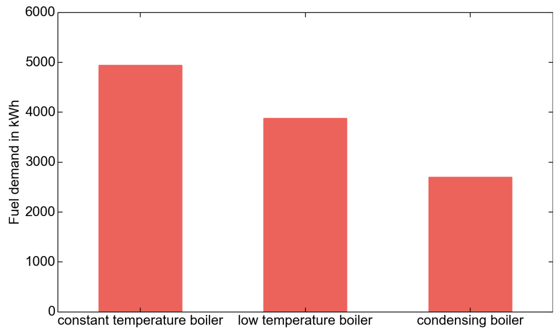

Figure 6: Simulated fuel demand for one apartment with different boiler types

CONCLUSIONS

With the International Energy Agency's Annex 60 programme collaboration is underway to build a common foundation for developing model libraries for building performance simulation in Modelica. To this end, several developer groups work together on an Annex 60 model library containing base classes, type definitions, and reference models for HVAC components. In this paper, we presented how the incorporation of the Annex 60 library into our model library `AixLib` has changed its structure and outlook. Furthermore, we gave an overview of the current state in `AixLib`'s ongoing development and concluded with two use cases to demonstrate the library's applicability.

Possible fields of application for the model library are building performance simulations on building as well as on city district and urban scale. For the low order model, the short computation times allow for simulations of groups of buildings as well as for optimization and parameter studies that require several simulation runs. With the upcoming release of the open source parameterization tool TEASER, these functionalities of the low order building model will be further enhanced.

With the high order building model, more detailed analyses of a single building is possible. In this context, the capabilities of the model to represent different building standards depending on year of construction and thermal mass, the model is well suited to test HVAC equipment in different building environments. This allows for development of robust building energy concepts by using simulation for testing different operation modes before real world implementation. Future work on the library will include ongoing integration of the Annex 60 developments, enhancement of model components and validation examples. With the open source release and the structuring to use common base classes, `AixLib` is now open for collaborative development and free use by researchers and practitioners in building performance simulation.

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