AIXLIB – AN OPEN-SOURCE MODELICA LIBRARY WITHIN THE IEA-EBC ANNEX 60 FRAMEWORK

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ABSTRACT

AixLib is a Modelica model library with focus on modeling the dynamic behavior of buildings, HVAC equipment and distribution networks to enable integrated analyses of energy systems on the scales from single building to city district. The library is available at www.github.com/RWTH-EBC/AixLib.

In this paper, we present the library and its integration within the IEA Annex 60. Possible applications are demonstrated using two use cases for the controls of a single building and for the heat demand of a city district. The paper concludes in a discussion of typical applications for AixLib and which developments we plan for the future.

INTRODUCTION

Modelica with its object-oriented and equation based approach is becoming a widely used modelling language for building performance simulation (BPS), as reflected by the IEA EBC Annex 60 project "New Computational Tools for Building Performance Simulation". Among other goals, this project aims at harmonizing the use of Modelica for BPS by means of the Annex 60 library, a common core library with basic functionalities. As explained by Wetter et al., 2015, this library is not meant to be used by end users directly, but to be merged into specialized model libraries that provide the user with additional models, further examples and documentation. Libraries using this approach and integrating the Annex 60 library include `Buildings` (Wetter et al., 2014), `BuildingSystems` (Nytsch-Geusen et al., 2013), `IDEAS` (Baetens et al., 2012) as well as `AixLib` (Fuchs et al., 2015). A major benefit of this approach is the increased collaboration on common base classes and increasing compatibility between these individual libraries. The open development of the Annex 60 library can be followed and contributed to at https://github.com/iea-annex60/modelica-annex60.

The main aim of AixLib is to provide a building performance library of Modelica models to enable integrated analyses of energy systems on the scales from single building to city district. In addition to the models from the Annex 60 library core, AixLib consists of models for building physics, HVAC models and ready-to-use data sets. The range of building models includes a more detailed high order approach (Constantin et al., 2014) as well as a low order approach to reduce computing times for city district scale simulations (Lauster et al., 2014). AixLib follows an open-source approach and encourages third parties to take part in the development and application of the library. It is published using the open source Git repository hosting service GitHub. The library can be downloaded, cloned and forked at www.github.com/RWTH-EBC/AixLib.

In this paper, we present the library's structure and the basic concepts using Modelica. We show how the Annex 60 activities influence the design of AixLib and sketch the further steps of development for the library. Two examples illustrate the benefits of using Modelica and the application of simulation models for different scales. They show how the simulation's goal influences the modelling and which decisions have to be made when designing such models. The first use case focuses on a high order model of a single building with detailed HVAC system to analyze demand side management control strategies. The second use case combines multiple low order models and idealized HVAC to calculate heat demands of an entire city district. The paper concludes in a discussion of what typical applications for AixLib are and which developments we plan for the future. With this library, we contribute to the ongoing process towards harmonized open-source tools for powerful and interconnected BPS on various scales.

INTEGRATION WITH ANNEX 60 LIBRARY

The main goal of the Annex 60 library is to harmonize the work on building performance simulation model libraries in Modelica, which had suffered from fragmentation prior to the Annex 60 efforts. In addition to its function as a platform for collaborative development between different library development teams, one important focus of the library with regard to this goal is to provide common base classes and basic functions for other libraries to use.

Especially the base class concept enabled by the object-oriented modeling approach of Modelica is a crucial factor for compatibility of models between different libraries for the end user. Prior to the Annex 60 development, e.g. different implementations for fluid connectors, media properties or energy balances would in many cases prevent using component models from different libraries to model a building energy system. In contrast, the Annex 60 library contains among other models two-port and four-port base classes that define standard connectors for fluid in- and outflow as well as energy balances. By merging these models into the respective target library, it can extend those base classes to model e.g. different HVAC components that, as a result, can then be connected to component models from other libraries using the Annex 60 base classes.

In addition, the collaborative development within the Annex 60 group allows for testing different model and function implementations and distributing the most efficient implementations into all participating libraries by means of merging the Annex 60 library into these target libraries.

With help of the Python package `BuildingsPy`, the Annex 60 library can be merged into other Modelica libraries automatically. This merging method fully integrates the package structure of the Annex 60 library into the target library's package structure. At the time of writing, in addition to a resources directory and experimental packages, the Annex 60 library contains the following main packages:

- `Airflow`
- `Boundary Conditions`
- `Controls`
- `Fluid`
- `Media`
- `Types`
- `Utilities`

In case the target library already contains a package of the same name at the same hierarchical level, both packages will be merged. If there is no corresponding package of the same name at the target library's corresponding level, the package will simply be copied into the target library.

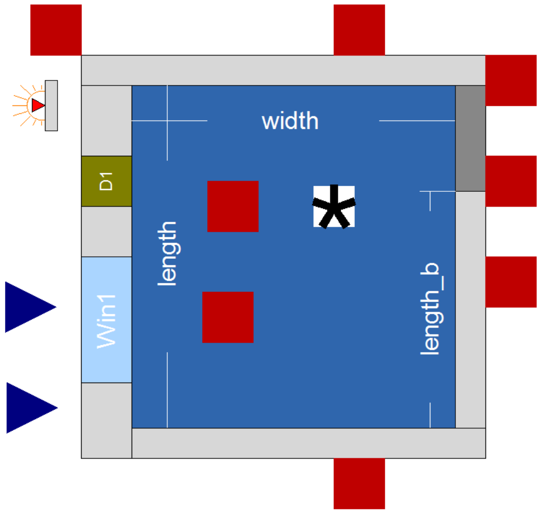

Figure 1: Scheme of a room model with thermal connectors (red squares) from `HighOrder` approach

Similar to other libraries using the Annex 60 library, AixLib not only integrates the Annex 60 library by this automatic merge, but also follows its design guidelines regarding model implementation, documentation and unit testing. More detail on how the integration of the Annex 60 library changed the structure of AixLib can be found in Fuchs et al., 2015. Furthermore, the Annex 60 library contains automated unit tests and reference results to check the library for side effects of changes and to verify its correct functioning. The unit tests are prepared by example models and `mos`-scripts that can then be automatically run in a test suite with the Python package `BuildingsPy`.

AIXLIB OVERVIEW

With the objective to model the dynamic behavior of buildings, HVAC equipment and distribution networks to enable integrated analyses of energy systems on the scales from single building to city district, AixLib contains model implementations with varying levels of detail. In many cases, analyses of a single building allow for (and may require) a more detailed modeling approach, while analyses of multiple buildings on a city district scale often rely on simplified models with a lesser level of detail. This concept applies to both the models for building physics and for HVAC components.

The AixLib adds three main packages to the Annex 60 library while integrating several sub-packages into the Annex 60 structure:

- `Building`
- `DataBase`
- `HVAC`

The models for building physics are collected in AixLib's `Building` package. The two modeling approaches with different levels of detail can be found in the sub-packages `HighOrder` and `LowOrder`, in reference to the order of states used to model the building envelope. While the `HighOrder` approach models all individual elements of the building envelope and their spatial context in high detail, the `LowOrder` approach uses a spatially aggregated model for thermal zones with less detail but also higher calculation speeds. Thus, the `LowOrder` model is a useful tool for analyses on district scale and fast parameter studies while the `HighOrder` model is designed for in-depth analyses of single buildings.

In addition, the `HighOrder` building model aims at facilitating case studies on different setups of typical building properties by means of user-friendly parametrization and pre-defined datasets. Currently, such datasets included in AixLib represent building envelope properties based on German energy saving ordinances from different years for light-weight, medium, and heavy building types. These datasets can not only be directly used by an end-user, they can also be used as a template to add own datasets according to own requirements. The model propagates these property datasets through the whole bottom-up approach in which wall elements (with optional window and door parts) are combined to room models which in turn are used to assemble building models. Fig. 1 shows the scheme of such a room model. As a result, the properties of the entire building with all its components can be varied at the top level, so that parameter studies can easily be performed once the model has been assembled. More information on the `HighOrder` building model can be found in Constantin et al., 2014.

In contrast to the high spatial resolution of the `HighOrder` approach, the `LowOrder` approach (Lauster et al., 2014) aggregates all wall elements of the same type (adiabatic interior walls and diabatic exterior walls) into one representative wall type element (Figure 2). Each element is represented by a resistance-capacitance model. The model is based on the VDI Guideline 6007 (German Association of Engineers, 2012), from which the methods for aggregation and calculation of the resistance and capacitance values are adapted. Lauster et al., 2013 give more details on the differences with the also widely used model specified in ISO 13790. With its fast simulation times, the `LowOrder` model has been shown to perform well for analyses of multiple buildings in an urban context (Lauster et al., 2014).

Through Modelica thermal connectors, both of these building models can be connected to models of HVAC systems to form an integrated model of the building energy system. To this end, AixLib contains different models for components of heating and cooling systems as well as for ventilation and air conditioning components.

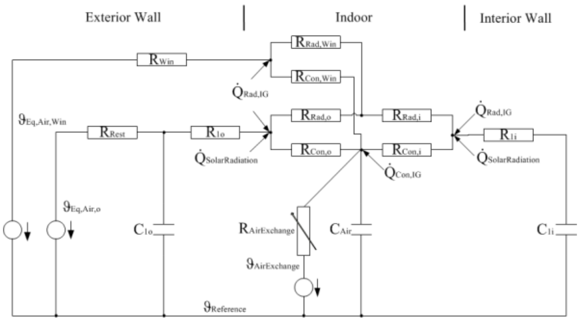

Figure 2: Thermal network of `LowOrder` model

As the Annex 60 library also contains a growing number of such component models, the user can in some cases freely choose between the AixLib and the Annex 60 implementation for a certain component. Because of the shared base classes, these models are often interchangeable, though they offer a different level of detail or modeling approach in most cases.

As the background of AixLib's development stems from German research project, the component models have a stronger focus on water-based heating systems than on cooling systems. Examples for basic component models included in the library are heat generation equipment like heat pumps, solar thermal collectors or gas boilers as well as components for the distribution and transmission of heat like pumps, pipes, valves and radiators.

For ventilation and air handling, the library similarly includes model for fans and ducts as well as models for air handling units, humidifiers and de-humidifiers. Especially the air handling unit model is designed to also work with the `LowOrder` building model, so that for city districts with a non-residential building stock (e.g. a research campus) the energy demand for air conditioning can be estimated in addition to the buildings' heating and cooling demand as a time-dependent function of the outdoor conditions.

USE CASE: DEMAND SIDE MANAGEMENT FOR AN APARTMENT

The first use case deals with an apartment in a multi-family dwelling configured as a heavy building and using the thermal insulation regulation WSchV1984. The apartment consists of two bedrooms, a living room, a corridor, a bath and a kitchen with an overall net floor area of about 70 m² (Figure 3). The heating system consists of a generation system with a boiler and a delivery system with radiators equipped with thermostatic valves.

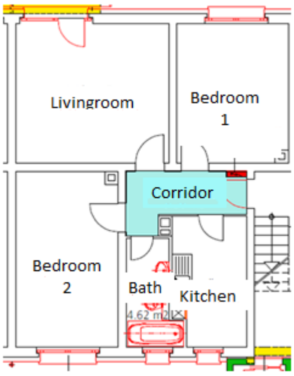

Figure 3: Floor plan of the investigated apartment

The intention of this use case is to investigate the possibilities of Demand Side Management (DSM) by overheating the apartment when it is empty. This allows storing heat within the walls and using this heat in times of high energy prices. The heat load is shifted from times of high energy prices to times of lower energy prices.

For this use case, we need to model the building physics as well as the hydraulic system in detail. The time constants within DSM concepts are within hours, thus all effects with similar time constants need to be considered. This includes a discretized modelling of thermal masses (primarily the walls) as well as of hydraulic circuits and radiators, boilers, etc. For that, we use the `HighOrder` building model with one wall model per actual wall and a layer-based discretization for each wall (each layer of a wall is modelled by two resistances and one capacitance) to model each room separately. Heat transfer through walls to adjacent rooms incorporated in this approach. The boundary conditions are defined for each room, which allows dedicated occupancy profiles per room. We combine the `HighOrder` model with detailed models for hydraulic components as pipes, valves, radiators, pumps and boiler all again representing one actual component in the "real" system and discretized in space if necessary (Figure 4).

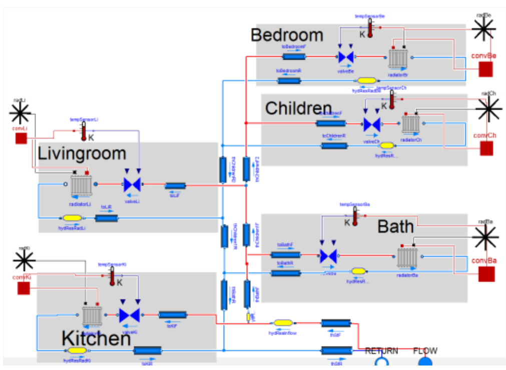

Figure 4: Hydraulic distribution system of investigated apartment

The following simple demand side scenario is simulated: two hours before the users return home after work, from 16:00 until 18:00 the house is pre-heated by setting a higher set temperature. Once the users arrive the temperature is set back. The usual set temperatures are 20°C during day time and 18°C during night time, from 22:00 to 6:00. A reference case, without DSM, uses only these set temperatures. During the short pre-heating period in the afternoon, energy will be stored in the buildings mass and given back to the room gradually over time.

Figure 5 shows the profiles for air temperature and the radiator power in the living room for both cases. For the DSM case the radiator power is lower throughout the day, around 14% less after the pre-heating, while at night there is no need for the thermostatic valve to open. Considering that period after 18:00 is considered peak time, with a flexible energy tariff cost reductions are achievable with such a strategy.

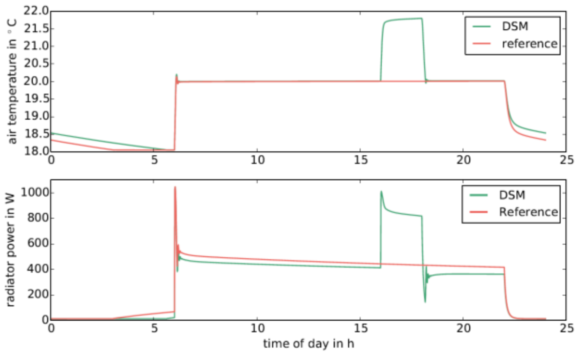

Figure 5: Simulation results for demand side management use case

USE CASE: HEAT DEMAND OF A CITY DISTRICT

Subject of this use case is a research campus with 200 buildings of different use (office and lab), year of construction and net floor area. All buildings are connected to a local heating grid. The aim is to predict heat loads for the years 2020 to 2050, considering a renovation rate of 1.7 % per year. Such predictions help to evaluate energy savings potential and design central heating systems that are not oversized in future scenarios.

To model such a complex city district, the AixLib provides the `LowOrder` building model that allows fast simulation times while focusing on predominant physical phenomena. Data acquisition is often elaborate on district scale, which leads to a sparse information density. A building model incorporating details of minor importance is hard to parameterize on such a basis and can hardly supply additional benefits considering the high uncertainties in data acquisition. In addition, the LowOrder model still provides sufficient accuracy and successfully passes verification tests such as those according to VDI 6007 (German Association of Engineers, 2012) and ASHRAE 140 (ASHRAE, 2011) and shows good agreement with measurements done by Annex 58 (Strachan et al., 2015).

The `LowOrder` model comes with a dedicated workflow automation tool and parameterization algorithms in the programming language Python, called TEASER. This tool integrates the `LowOrder` model into high-level Urban Energy Modelling (UEM) tools at our institute as well as provides interfaces to information models such as CityGML as well as application programming interfaces (API). Similar to AixLib, TEASER will be released as an open-source project at www.github.com/RWTH-EBC/TEASER.

Using TEASER and AixLib, we set up one model per building with seven zones each (divided by the usage, e.g. office, laboratory, floor, etc.). Each building model is customized by its net floor area, year of construction, building height and building type. These properties influence the wall constructions, material properties, geometric dimensions and boundary conditions (internal gains). Internal gains and weather conditions are given in hourly time steps to allow dynamic investigations. The building models calculate indoor air temperatures and heat loads using several models from the `HVAC` part of AixLib, including a mode based Air Handling Unit (AHU) model and ideal heater and cooler models. With a workstation (12 cores, 2.9 GHz, 32 GB RAM, Dymola 2016 FD 01), the one-year simulations for all 200 buildings with an hourly output time step took less than 8 hours.

The investigated research campus operates extensive measurements what allows a detailed comparison of simulation results and measurement on campus scale. Figure 6 shows daily values of heat load for simulation and measurement for the entire building stock. The simulation shows good agreement with the measurement even in times of high variations. The trend, mean values and variances (based on hourly values) of both curves are similar with some overestimation of the heat loads in the simulation for summer times. This is mainly related to dehumidification in the AHU's to condition laboratory zones. The visual impression of high agreement is verified by a coefficient of determination of $R^2=0.91$.

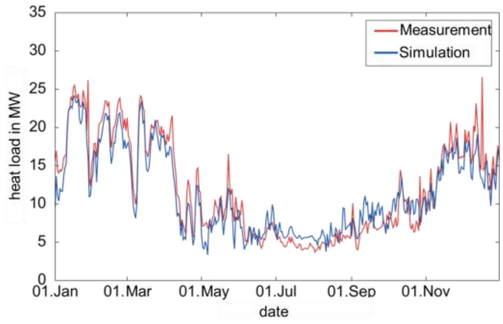

Figure 6: Comparison of simulation results and measurement

To predict heat loads in 2020 to 2050 with the given renovation rate, we used a functionality in TEASER to automatically retrofit buildings to a given renovation standard. Depending on the simulated year, a corresponding number of buildings are considered as retrofitted in the simulation. In this way, we determined heat load duration curves for pre-defined reference years (2020, 2030, 2040 and 2050). Figure 7 shows the annual load duration curves in hourly time steps as well as the energy savings within the decades. Comparing 2020 and 2050, 47% of heat demand could be saved with the given renovation rate. Even more important, the duration curves tend to flatten over the decades, leading to a higher relative share of base load. The shape of duration curves influences the dimensioning of heating systems as Combined Heat and Power units (CHP) that work efficiently and economic in base load without start-ups and shut-downs or part load operation.

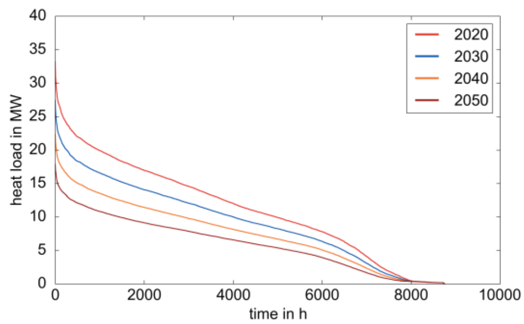

Figure 7: Annual load duration curves

CONCLUSIONS AND FURTHER APPLICATIONS

The presented use cases gave an overview of some of the capabilities and possible applications for AixLib as a model library for building performance simulation on scales from a single building to urban districts. While the first use case showed, how the more detailed building model can be used to investigate control strategies like Demand Side Management in a building, the second use case demonstrated the applicability of AixLib's low order model for scenario analyses regarding the dynamic heat demand of a district.

In addition to the presented use cases, AixLib is continuously used in different research projects, resulting in new models and functionalities being added to the library. Currently, some key areas of development include improved methods to automatically generate models for urban energy systems, the addition of further component models, the modeling of exergy losses as well as the modeling and evaluation of new control strategies for building and district energy systems.

In combination with TEASER, we plan to further integrate our urban energy and building stock models into the Urban Energy Modelling research field and extend our approaches for statistic parameter estimation. This goes hand in hand with the activities within the Annex 60 regarding the development of adaptive `ReducedOrder` models with a flexible number of wall elements and variable spatial discretization of these wall elements. These new models will extend the existing `LowOrder` calculation core in AixLib and allow smooth variations of the model's order.

In addition to TEASER, further workflow automation tools for urban energy systems modeling are planned for upcoming open-source releases. This includes the Python packages uesgraphs and uesmodels. While uesgraphs aims at providing an open graph model framework to describe different network contexts within an urban energy system, uesmodels contains methods to automatically create Modelica models for district heating and cooling networks based on AixLib components. In combination with building models from TEASER output, this approach allows for creating dynamic system models of urban energy systems with significantly reduced manual effort.

Also, as presented by Stinner et al., 2015, we currently work on alternative implementations of thermal energy system models using a newly developed connector. These implementations focus on energy flows instead of mass flows and feature high user friendliness ("plug-and-play"). The aim is to use the same calculation cores for the actual energy system components while extending either standard fluid connectors in one variant or the developed plug-and-play connector in the other variant.

ACKNOWLEDGEMENT

We gratefully acknowledge the financial support by BMWi (German Federal Ministry of Economic Affairs and Energy), promotional reference 03ET1177A.

This work emerged from the Annex 60 project, an international project conducted under the umbrella of the International Energy Agency (IEA) within the Energy in Buildings and Communities (EBC) Programme. Annex 60 will develop and demonstrate new generation computational tools for building and community energy systems based on Modelica, Functional Mockup Interface and BIM standards.

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