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TOWARDS SEAMLESS INTEGRATION OF MODEL-BASED ENERGY PERFORMANCE SIMULATION AND MULTI-OBJECTIVE OPTIMIZATION TOOLS

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ABSTRACT

The aim of the paper is to investigate the options for using energy simulations during building operation in order to increase the overall performance and close the gap between predicted and measured energy consumption.

EnergyPlus is used to model a commercial building and simulate the overall energy performance under Danish conditions. Preliminary analysis and evaluation of the model is presented with the focus on the integration potential of EnergyPlus into a novel multi-objective optimization integration platform.

INTRODUCTION

Denmark's energy aim is to become independent of fossil fuels by 2050, through renewable energy integration as well as improving the efficiency of energy resources utilization. By applying this strategy, Denmark will also contribute to meeting the EU objective to reduce the greenhouse gas emissions with 80 - 95 % in 2050 compared to 1990 level. It was estimated that energy savings of 70 - 75 % could be attained in the Danish building sector through the implementation of cost effective and efficient measures (Danish Government, 2011).

In the last 50 years, a large number of energy simulation tools have been developed, improved and continuously used in the industry, by architects and engineers as well as in the academic environment. The U.S. Department of Energy has an on-line database providing information about 417 software tools for evaluating different aspects of energy in buildings (U.S. Department Of Energy, 2015).

Most of the available energy performance simulation tools (EnergyPlus, Modelica, TRNSYS, BSim, and others) are based on implementing the physical model approach (nodal approach) (Bueno et al., 2012). When using the physical models there is a need of significant expert knowledge to make the set-up of the model and provide realistic representation of the building (Kolokotsa et al., 2011).

Due to various factors, an evident gap exists between the intended design in terms of energy efficiency and the measured energy consumption in buildings. This gap can occur at all stages: in the design phase, when constructing and commissioning the building and during its operation. Among all, the user behavior (De Wilde, 2014) and their understanding of building's operation and control (Menezes et al., 2012) are mentioned as being major factors for the performance gap. There is an inevitable discrepancy due to modeling errors in simulations as well as experimental errors in the observations. It is important to reduce this gap in order to provide a reliable input for building certifications and deliver buildings that are robust towards environmental and operational changes (De Wilde, 2014). This will ensure a good performance over a lifetime.

A study made in the UK (The Green Construction Board, 2015), shows that the nonresidential buildings actually consume 2-3 times more energy than predicted. One of the main reasons is that the building systems are not operated as intended. The efforts to make buildings more energy efficient can lead to over optimistic predictions that will increase the performance gap. The whole building industry should be involved in the process of improving the robustness of the design and construction, not only the designers and developers. In this way the under-performance problem can be solved (Zero Carbon Hub, 2010).

Another important aspect is the feedback from measured data during operation of the building. Although data is available, a direct link between simulations and measurements is missing. One way to align the predictions would be the integration of this link into the building management system (BMS).

The interest in integrating simulation models with the BMS is increasing. Executing the simulation as part of the control sequence will bring several advantages such as: the ability to address cause and effect scenarios, adapting the control to the building use and operation, taking into account the interaction between the building and exterior disturbances, the possibility of comparing different control options before making a final decision (Clarke et al., 2002). Such building energy model integration was presented in recent studies (Pang et al., 2012), (Colmenar-Santos et al., 2013), (Nouidui and Wetter, 2014). All these studies investigate different configurations of tools for building simulation and interfaces for linking the simulation to the BMS.

The applicability of current solutions for integration and real-time energy performance assessment in buildings still need substantial efforts and research on how to deal with dynamic inputs and control (Shaikh et al., 2014).

The aim of the paper is to investigate the possibility of using energy simulations during building operation in order to increase the overall performance. The building models should be used for real time simulations, energy predictions and dynamic control. A preliminary case study based on implementation in EnergyPlus simulation tool is considered.

OVERALL PURPOSE OF THE MODEL

In Denmark, all buildings should have an energy performance certificate (EPC) based on specifications issued by the Danish Energy Authority. This certificate can be obtained by using qualified experts and authorized simulation engines (Dyrbøl and Aggerholm, 2008). In most of the cases, the predictions from the energy simulations do not coincide with the actual energy consumption of the building.

Based on a comparison between the Danish authorized simulation tool (Be10) and a more advanced building simulation tool (IES-VE), it was concluded that more accurate predictions can be obtained when using a full scale dynamic simulation engine (Christensen et al., 2013).

Model use during building operation

The overall goal is to develop an integration platform where building energy simulation models can be used during the operation time. The objective is to optimize the building-wide operation of decentralized building systems based on simulation models for building energy performance. The models include relevant factors such as occupant behavior, weather conditions, construction typologies, thermal properties, and properties of building systems.

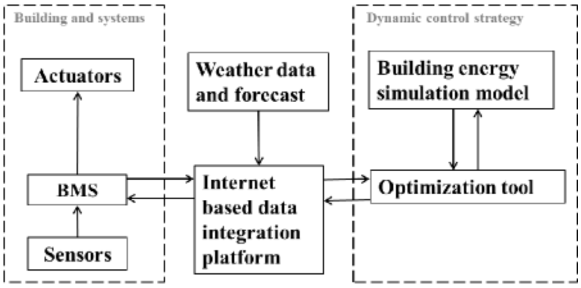


Figure 1: Overview of the integration.

The diagram of the proposed integration is shown in Figure 1.

The energy model will help the decision based optimization module by testing different proposed solutions before sending them to the BMS.

MODEL REQUIREMENTS

Following the flow diagram presented in Figure 1, the Internet based data platform is the integration point between the simulation-optimization environment and the actual building that is controlled. Because of the modular structure the overall integration platform is flexible and can be easily adapted to fit other buildings. The optimization tool will make use of the energy building model to generate optimal schedules and operating set-points in order to attain the predefined goals in terms of energy use and resources allocation. The energy simulation model needs to capture the cause and effect relationship of different elements of the system and external disturbances so that the response to different changes made in the system could be predicted. For a life cycle analysis, 1 hour timestep is sufficient to predict the overall energy consumption. However, to capture the dynamics of the system and obtain accurate predictions for each thermal zone, a shorter time step of 15 or 10 minutes is recommended (Application Guide, 2011).

Special attention should be given to the running time of the simulation. The model must provide an almost instant feedback for a fixed time horizon, based on given input data and current state of the building.

To be able to successfully integrate the simulation model, the definition configuration of the input data must be flexible enough to be able to change the simulation time, timesteps, initial conditions, schedules and set-points. The output should contain the behavior of the system based on the inputs provided.

Scenario example

As an example, having the weather forecast, the current zone temperature, the CO_2 level and the occupancy schedules of a zone as inputs, the simulation model should have the capability to calculate the energy consumption and zone temperature based on given set-points for heating, cooling and ventilation. Several simulations will be performed for different sets of set-points, based on the optimization tool suggestions for achieving economic and comfort goals.

CASE BUILDING

Building regulations in Denmark

The Danish Building Regulation 2010 (BR10) came into action on the 1st of January 2011. This regulation includes a so-called Class15 low energy building definition. In order to be a Class15 building, the total demand for energy supply including heating, ventilation, cooling, domestic hot water and lighting should not exceed 75 % of the maximum energy consumption permitted by the standard for a regular building. In August 2011, another class was introduced, Class20 to define nearly zero building. The requirements for commercial buildings are presented in Table 1.

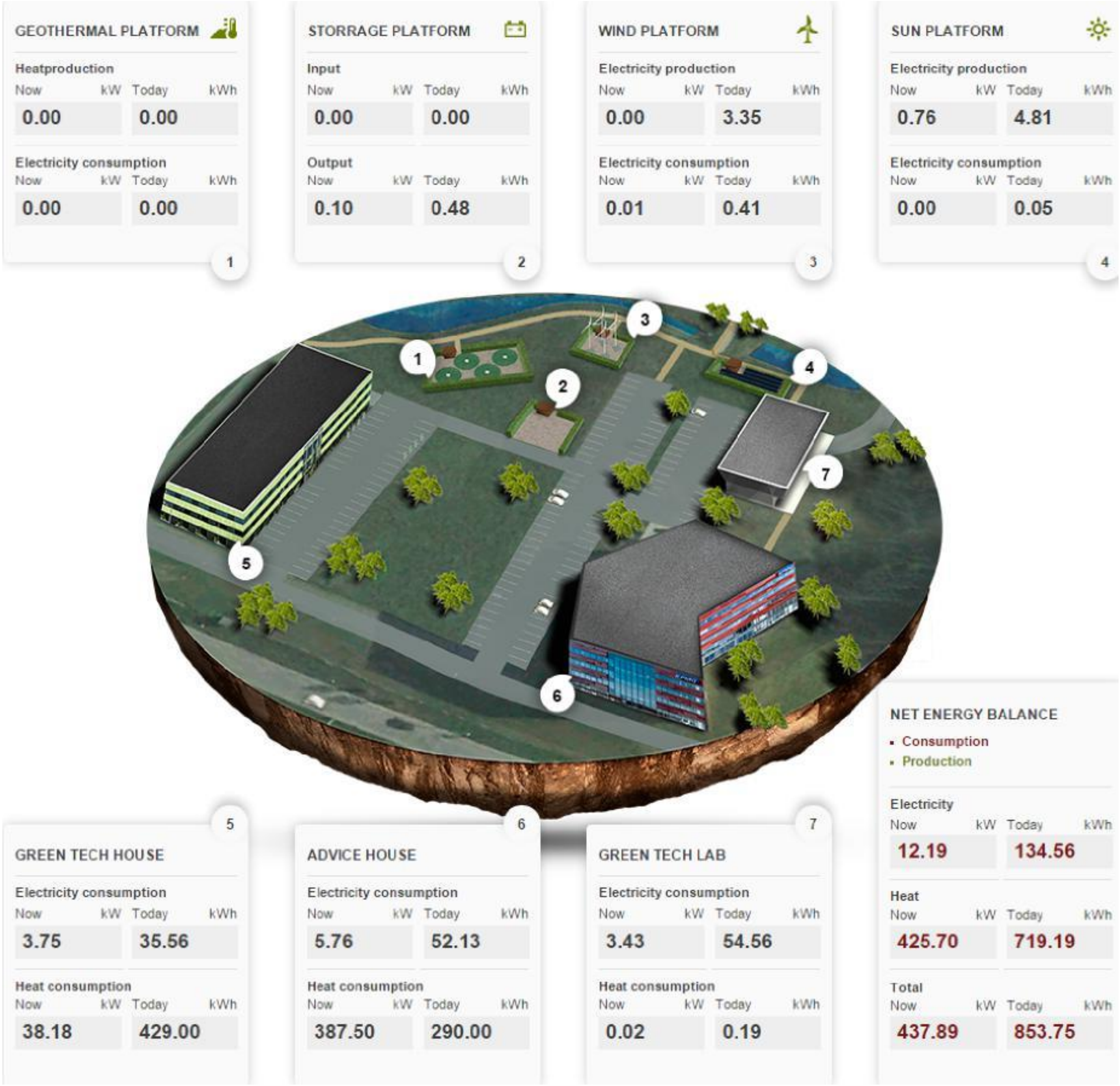
Table 1
Annual energy frame for commercial buildings in Denmark

ENERGY USE [kW h m^{-2}**year]**		
BR10	Class15	Class20
71.3 + 1650/A	41+ 1000/A	25

A represents the area of the building.

General description

To test the applicability of the proposed integration solution, an initial case study of the Green Tech House (GTH) is considered. This building is part of the Green Tech Center Micro Grid Living Lab shown in Figure 2. This facility is located in Vejle, Denmark, comprising 3 main buildings (5, 6, 7 in Figure 2), a geothermal platform (1), a storage



GEOTHERMAL PLATFORM 1

Heatproduction	Now kW	Today kWh
	0.00	0.00
Electricity consumption	0.00	0.00

STORRAGE PLATFORM 2

Input	Now kW	Today kWh
	0.00	0.00
Output	0.10	0.48

WIND PLATFORM 3

Electricity production	Now kW	Today kWh
	0.00	3.35
Electricity consumption	0.01	0.41

SUN PLATFORM 4

Electricity production	Now kW	Today kWh
	0.76	4.81
Electricity consumption	0.00	0.05

GREEN TECH HOUSE 5

Electricity consumption	Now kW	Today kWh
	3.75	35.56
Heat consumption	38.18	429.00

ADVICE HOUSE 6

Electricity consumption	Now kW	Today kWh
	5.76	52.13
Heat consumption	387.50	290.00

GREEN TECH LAB 7

Electricity consumption	Now kW	Today kWh
	3.43	54.56
Heat consumption	0.02	0.19

NET ENERGY BALANCE

- Consumption
- Production

	Now kW	Today kWh
Electricity	12.19	134.56
Heat	425.70	719.19
Total	437.89	853.75

Figure 2: Green Tech Center online data platform. Building 5 is the Green Tech House. (Green Tech Center, 2015)

platform (2), a wind turbine (3) and a solar platform with solar panels (4). The 3-storey building (5) considered as a case study, includes a 3500 m^2 area with a commercial Living Lab and various demonstration spaces equipped with different smart energy solutions.

The building is constructed so that the ground floor includes technical rooms, canteen, conference rooms, classrooms and entrepreneurial offices for rent for short or extended periods. The other two floors are designed as office spaces. Each floor has 60 permanent workplaces. The maximum occupancy capacity of the building is 149 people.

The building is connected to a district heating network, and has the possibility of integrating a heat pump, wind turbine and solar panels. In terms of energy use, the building is designed to comply with Class15. The interest in modeling this specific building comes from the fact that it offers full access to all building design documentation as well as the constructed building and services employed during operation. Due to the wide range of facilities that are offered, the building is suitable for testing various configurations and scenarios.

Control strategies

According to the documentation of the building design and operation, the control of the building is based on 8 working hours a day, 5 days a week. There are 3 different operation modes:

- Comfort - The room temperature is controlled by a desired set point e.g. 21 °C, when the space is occupied during the working hours;
- Standby - The room temperature is controlled by the same set point as comfort, with an accepted fluctuation of ± 2 °C for heating and cooling, when the space is not occupied in the working hours;
- Night - The room temperature is controlled by the same set point as comfort, with an accepted fluctuation of ± 4 °C for heating and cooling, during the night period.

On-line data platform

Figure 2 shows the accumulated data for each of the components. The building is equipped with various sensors and energy meters. All data are logged and centralized into an on-line data platform accessible to users.

At the building level there are energy meters for:

- Heat consumption,
- Ventilation power consumption,
- Total power consumption.

At a more detailed level, for each of the rooms in the GTH the following data are available:

- CO2 level,
- Room temperature,
- Room temperature control set points,
- Cooling/Heating set points,
- Illuminance,
- Occupancy,
- Radiator valve position.

A weather station is installed in the area of the Green Tech Center making the acquisition of all weather data possible.

IMPLEMENTATION

The implementation is based on the Building Information Model provided by the designers. Several iterations were needed in order to clarify all aspects of the building related to material properties and components used for construction. Even if the building is newly constructed and most of the documentation is available, some data were difficult to find, and required a significant amount of time.

Especially for this case study, besides the high complexity of the building, there are several companies involved in the commissioning of different systems. This hampers the process of finding the responsible persons to deliver all the documentation, raising strategic and communication issues.

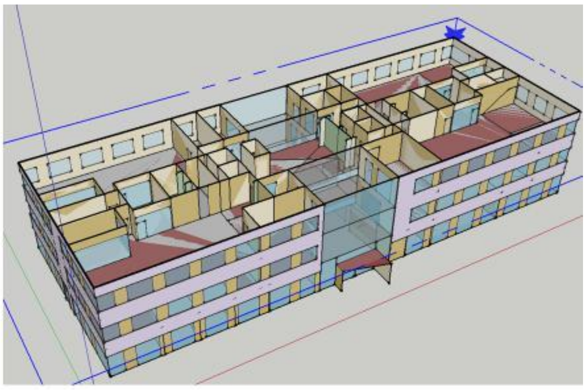


Figure 3: Building implemented in SketchUp

The GTH building shown in Figure 3 is simulated in EnergyPlus using SketchUp and Open Studio plug-in. After defining the geometry of the building in SketchUp, the thermal properties of the building construction elements and the thermal zones specifications are added in Open Studio. The internal loads implemented at this stage are lights and occupants.

The model contains 107 spaces, each one assigned to a thermal zone. Based on the HVAC system, 84 of the zones are conditioned. Each space corresponds to one room with the exception of the open space in the middle of the building, which is divided into several spaces bounded by air walls. This layout of the zoning was adopted based on the consideration that the control of the building should be performed individually for each room.

The temperature is controlled based on the implemented schedules. All conditioned zones have thermostats. For simulations, the reference year weather file from Copenhagen is used.

TESTS AND RESULTS

Building compliance

The building is designed to comply with Class15 standard, see Table 1. Based on the EPC the overall energy consumption is 40.04 kW h m^{-2} for one year.

Ideal loads simulation

To simulate the energy performance of the GTH, EnergyPlus is used (Crawley et al., 2000). This simulation engine fully integrates the building and its HVAC system. It is using the multi zone approach to calculate the dynamic heat and mass balance of the building (Crawley et al., 2001).

To get an idea about the overall energy consumption of the building the first simulations were performed using ideal loads. This assumes that each conditioned zone has an HVAC system that supplies the required amount of heating/cooling directly to the zone so that the specified limits in terms of temperatures, humidity, air quality and other constrains could be reached.

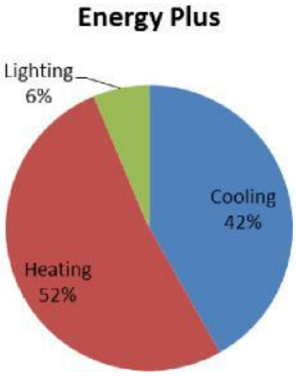


Figure 4: Annual end use breakdown results from EnergyPlus.

The annual end energy use breakdown results from EnergyPlus for the ideal loads simulation is shown in Figure 4.

The results of the energy predictions for the GTH are summarized in Table 2.

Table 2: Energy prediction for GTH building

ENERGY USE [kW h m^{-2}**year]**				
	Heating	Cooling	Lighting	Total
Energy Plus	37	30	4.4	71.4
Design	28.8	7.6	3.7	40.01

There is a considerable difference between the pre-designed calculation and EnergyPlus simulation predictions. It can be noticed that the overall energy consumption of the building is approximately 73 % more than it was predicted in the design phase. The main discrepancy is for the cooling predictions. To be mentioned here is that the big difference for the cooling demand is also due to the fact that in the simulations made by the designers, a default value of 24 °C is set for the cooling set point, which is not in accordance with the building design documentation.

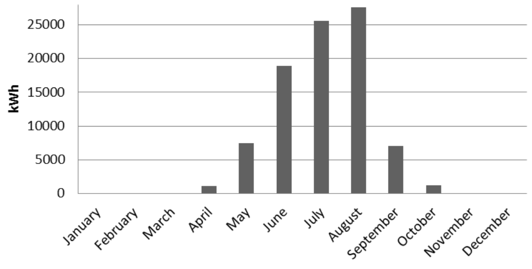


Figure 5: EnergyPlus results - one year prediction for cooling energy consumption.

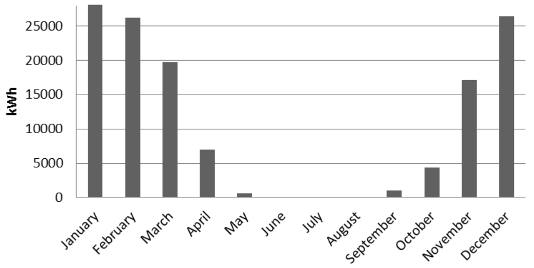


Figure 6: EnergPlus results - one year prediction for heating energy consumption.

In Figure 5 and 6 the predictions for cooling and heating energy consumption are shown. In accordance with the weather conditions, the energy is used primarily for heating during winter, and for cooling during summer.

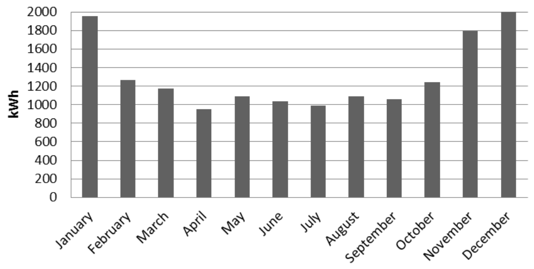


Figure 7: EnergyPlus results - one year prediction for lighting energy consumption.

The energy consumption for lighting is shown in Figure 7. There is constant lower energy consumption during spring and summer compared to winter months, and increases in the transition between the cold and warm season due to daylight variation. The highest energy consumption for lighting is exhibited during winter, approximately double the summer consumption. An increase of the energy use when implementing the actual HVAC system and all equipment specifications is expected, due to additional energy consumption of components and losses which are not taken into account by the ideal loads simulation.

INTEGRATION EVALUATION

The presented energy simulation model should be integrated with the optimization tool and used during the operation of the building. To fulfill the requirements for integration purpose, several aspects were considered.

Co-simulation usage

EnergyPlus offers the possibility of exporting the model as a Functional Mock-up Unit (FMU) (Nouidui, 2014). Using this format it is easy to establish a co-simulation environment by coupling the energy simulation model with the optimization tool. The FMU will be imported in the optimization tool, which will be the master. It will initiate the simulation model by configuring the input file and read the output.

Initialization

One of the main requirements for integration is that the optimization tool needs to instantiate the simulation at any given time. Analyzing this aspect, the simulation in EnergyPlus can be started and ended only at midnight (Berkeley Lab, 2015). This is one very important aspect that will be a limitation for how the model can be used in an optimization context.

In terms of defining variables for providing dynamic inputs to the simulation, EnergyPlus does not offer the full flexibility needed. From the external interface it is allowed to set actuators, schedules and global variables linked to the EnergyPlus energy management system (Application Guide, 2011). However, it is not possible to change the state variables, as for example the room temperature, which is one of the main parameters to be evaluated in the proposed integration.

The timesteps can be set to 1, 2, 3, 4, 5, 6, 10, 12, 15, 20, 30, and 60 minutes which give a satisfactory range of options.

Output variables

The behavior of the system can be analyzed and evaluated based on the output information supplied by the FMU. This information is sufficient for the optimization purpose.

Running time

Several tests were performed using EnergyPlus version 8.2 to evaluate if the runtime of the simulations is applicable for our control scenarios.

The timestep used for simulations is 10 minutes. Full exterior and interior radiation is taken into account for solar distribution. The running time of the simulation is 20 min and for one year; 3 min and 45 s for 1 week; 3 min and 39 s for 3 days; 3 min and 33 s for one day. For the considered case, the startup period of Energy-Plus is 205 s, as shown in Figure 8.

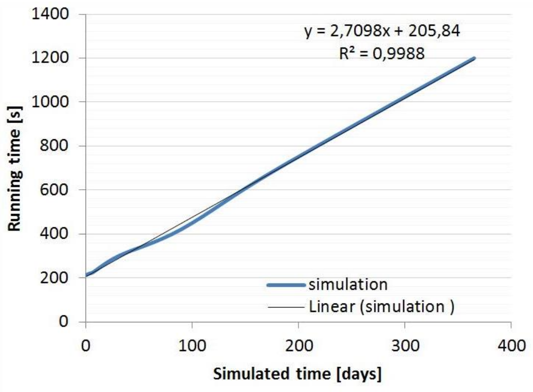


Figure 8: EnergyPlus run time.

The blue line represents the running time of Energy-Plus depending on the number of days simulated. The black line shows the linear fit of the data.

Based on these results, it is required to lower the complexity of the building model considered, and develop a reduced model not only to decrease the running time, but also to ensure an easier control and optimization procedure.

CONCLUSIONS

In this paper, initial development of a building energy model was presented. The purpose of the model is to evaluate the overall energy consumption of the building and to investigate the possibility of using an energy simulation model in developing a novel multi-objective integration platform for optimizing the end use energy in buildings.

The building used as a case study is designed to comply with Class15 standard. Initial evaluations of the developed model show a significant gap between the implementation in EnergyPlus and the EPC of the building. This gap can be reduced using intelligent optimization techniques such as the proposed integration solution. The overall performance of the building can be improved by coordinating the end use energy consumption in a better way, providing optimal schedules and setpoints.

EnergyPlus offers a good integration potential in terms of co-simulation using the FMU, but it does not fulfill all requirements with respect to model initialization and simulation time. Thus, EnergyPlus cannot be used for the proposed integration solution.

Because the investigations related to the integration part are in the initial stage, alternative tools are also considered. One of them is Modelica, with the recent developed Buildings Library (Wetter, 2013). Modelica cannot support very complex buildings with a large number of thermal zones. Hence, the building model needs to be reduced. A model reduction can be conducted based on the developed EnergyPlus model.

As further work, regardless of the simulation tool used, the HVAC and building systems needs to be implemented so that the model could be used for optimization and integration with the BMS. Afterwards, a full validation and calibration of the model needs to be conducted at the whole building level. For this purpose, the on-line data platform available is going to be used.

ACKNOWLEDGMENT

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