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Integrated Platform for Whole Building HVAC System Automation and Simulation

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ABSTRACT

Integrated optimal control strategies can not only reduce the overall building HVAC system energy consumption but also improve indoor air quality to ensure the economical and comfortable daily operation of buildings. However, normally it is hard to quantitatively evaluate the design-intended building HVAC automation system performance before on-site deployment. It is both very complex and time consuming because: 1) significant effort is required to develop the system steady-state or dynamic model from building and HVAC system design specifications that are typically in 2D or 3D drawings; 2) the building HVAC control strategies are designed and implemented in Building Automation System (BAS) that does not readily connect with the building HVAC system steady state or dynamic models for performance evaluation through close-loop simulation.

This paper presents the tool chain of an integrated simulation platform for building HVAC system automation and simulation and its implementation in a real use case. Firstly, building information from a Revit BIM model is automatically parsed to a building energy model in EnergyPlus. Secondly, a HVAC system model is quickly populated with a scalable HVAC system library in Dymola. Thirdly, HVAC control algorithms developed in WebCTRL® system, a BAS by Automated Logic Corporation (ALC). Finally, both the building energy model and HVAC system model are wrapped up as Functional Mock-up Units (FMU) and connected through the embedded simulator in WebCTRL to perform close-loop building automation system performance simulation.

This platform enables testing of building HVAC control strategies before on-site deployment, which reduces the labor and time required for building HVAC control development-to-deployment process and ensure the quality delivery of complex systems with innovative control strategies. A real case study for a chiller plant system in a hotel building was conducted to verify the scalability and benefit of the developed tool chain. The case study demonstrates the value of identifying both HVAC automation system control design issues and improvement opportunities for integrated optimal controls prior to on-site deployment. Furthermore, this platform can be calibrated with metered real-time data from the specific building HVAC system and serve as its ‘digital twin’ that enables future continuous monitoring and fault detection.

Keywords: Integrated platform, HVAC, Automation, Software-in-the-Loop

1. INTRODUCTION

In the United States, the buildings sector accounted for about 41% of primary energy consumption in 2010 and HVAC loads were the dominant end uses, accounting for close to half of all energy consumed by the buildings sector (U.S. DOE, 2011). A number of studies indicated that optimal control strategies and fault diagnosis can
reduce the energy waste and improve the overall building energy efficiency as well as improved air quality, resulting in improved health and cognitive function for the occupants (Akinci et al., 2011, Treado & Chen, 2013, Benga et al., 2015). Akinci et al. (2011) summarized that 25%–45% of energy used by HVAC system are wasted due to faults, including improper control logic and strategy, malfunction of controllers and controlled devices, etc. Current design and validation practices in the building industry shows the importance of a model-based design flow for building controls to verify the performance, satisfy design expectations, and reduce the on-site commissioning effort (Mehdi et al., 2011, Li et al., 2015).

There are various building HVAC simulation programs or modeling technologies to meet requirements in different design stages. For example, Revit, EnergyPlus, TRNSYS, Dymola/Modelica and Matlab/Simulink are very widely used in building, HVAC system, and controls design and simulation. However, the different models developed in different design stages and tools are not able to smoothly serve as the data source throughout the design cycle without significant manual translation efforts, making it challenging to quantitatively evaluate the design-intended whole building HVAC automation system performance before on-site deployment. Specifically: 1) the building and HVAC system design specifications are in 2D or 3D drawings that require significant manual effort to develop the building model and system steady state or dynamic models based on them. The manual model creation process can lead to numerous errors and omissions; 2) the building HVAC control strategies are designed and implemented in BAS platforms that may not smoothly connect with the building and system models for performance evaluation through close-loop simulation. Therefore, in order to do the whole building HVAC system performance simulation, it requires an environment that integrates well with computational-based rapid prototyping and system design processes to reduce cost and product time-to-market (Wetter, 2011, Burhenne et al., 2013).

This paper presents an integrated tool chain for building HVAC system simulation and control performance evaluation and its implementation in a real building case study. The case study demonstrates the values in identifying both HVAC automation system control design issues and improvement opportunities for integrated optimal controls.

2. INTEGRATED SIMULATION PLATFORM

2.1 Multi-domain Simulation Technology
Several technologies and tools are widely adopted for building HVAC system design, simulation and analysis.

2.1.1 Building Information Modeling
Building Information Modeling (BIM) is a state-of-the-art approach to design, construction, and facility management in which a digital representation of the building process is used to facilitate the exchange and interoperability of information in a digital format (Eastman et al., 2008). Building Information Models (BIMs) are electronic representation of the building parameters that can be extracted, exchanged or networked to support decision-making regarding a building or other built asset. The adoption of BIM by industry is increasing due to mandates by large building owners, its support for energy code compliance and its benefits to design and construction teams in minimizing delivery cost and time. In addition, the building simulation program (e.g. EnergyPlus etc.) can be generated using BIMs (Wetter, 2011). Automated reuse of data from BIMs for building HVAC system model development is a promising approach to improve the process by avoiding manual data input (Cao et al., 2015).

2.1.2 EnergyPlus
EnergyPlus is a whole building energy simulation program that engineers, architects, and researchers use to model both energy consumption—for heating, cooling, ventilation, lighting, plug, and process loads—and water use in buildings (Crawley et al., 2001). Based on a description of the building’s physical make-up, EnergyPlus is able to calculate the heating and cooling loads dynamically. EnergyPlus is one of the most powerful and reliable programs for annual energy analysis and thermal load simulation. However, modeling of integrated buildings requires flexible plant and equipment models, which are often case specific (Nicolai & Paepcke, 2017). Furthermore, the EnergyPlus model representation and numerical methods do not allow simulating systems with fast dynamics, nor do they allow the proper representation of controls (Nouidui & Wetter, 2014).

2.1.3 Modelica
The Modelica language is a non-proprietary, object-oriented, equation based language to conveniently model complex physical systems (Mattsson & Elmqvist, 1997). There are a number of libraries providing suitable components for modeling building systems. One of the main open-source building modeling libraries is the Modelica Buildings library of LBNL (Wetter, 2009). The building library supports rapid prototyping, as well as design and operation of building energy and control systems. However, it is not meaningful to model the entire building with sufficient physical detail in Modelica alone. The reasons are: 1) larger building complexes may involve many zones, constructions, facade elements, and thermal storage elements resulting in thousands of differential equations; 2) Modelica models may become very large and may cause problems with the generic Modelica solvers, even symbolic analysis may be extremely slow; 3) modeling the building in Modelica without suitable BIM-style data import or code generation will not be possible for complex realistic buildings, and is too time consuming and thus too expensive, and 4) manual connection of many building components with corresponding equipment and control models may be extremely time-consuming and error-prone (Nicolai & Paepcke, 2017).

2.1.4 Building Automation Systems
A Building Automation System (BAS) is used to control energy consuming equipment—primarily for heating, ventilating and air conditioning (HVAC) equipment and lighting controls. BAS controllers typically contain software that can control actuators to maintain temperature, relative humidity, pressure, and flow at a desired setpoint. The software used to program the controllers varies by BAS manufacturer. Building control system vendors usually provide architecture-specific languages for programming their platforms, along with tool chains for simulation, analysis, debugging and code generation, e.g. GPL language, EIKON, Spyder etc. (Yang et al., 2012). Highly complex, high performance HVAC systems require smart control algorithms and such iteratively learning, optimality-based control software needs sufficient closed-loop testing.

2.1.5 Software-in-the-Loop Simulation
In many cases, the building HVAC control strategies are designed and implemented in a BAS that cannot smoothly connect with the building HVAC system steady-state or dynamic models for performance evaluation through close-loop simulation. For example, Hardware-in-the-Loop (HiL) testing requires hardware infrastructure and the installation and maintenance is time-consuming and expensive. Model-in-the-Loop (MiL) requires manual translation of control logic from different vendor’s specific languages to Simulink or Modelica.

Software-in-the-Loop (SiL) testing is an affordable approach when simulating a real-time system that requires fast iterations, to make sure that the software is able to handle the requirements. SiL testing begins with code being generated from the controller model. This code is then tested in a virtual environment, without any hardware, to test how well the software handles the simulated system. Tests are made to make sure the code works identical to the model when using different types of input conditions, functions, and mathematical algorithms. SiL, like MiL, also offers the benefit of faster than real-time simulation, making full annual analysis feasible.

2.2 FMI for Co-simulation
The sole use of stand-alone simulation tools such as EnergyPlus or Modelica-only based building modeling is not a feasible strategy for whole building HVAC system automation and simulation. The integration of different tools/models is required for this purpose. Co-simulation is a technology that can solve the multi-physics model integration. It represents a particular case of simulation scenarios in which there are at least two simulators to solve coupled algebraic equations and exchange the data with each other during simulation (Lu et al., 2016). Initiated through the Modelisar project, the Functional Mock-up Interface (FMI) standard enables engineers to exchange or co-simulate dynamic models of different domains. This way, FMI can extend the field of application of building and energy system simulation. It can furthermore help to overcome current and future limits of simulation (Schwan et al., 2017). FMI is designed for commercial simulators to transform their models to a normative form (FMI specification). With respect to the two offered operation modes, Model Exchange and Co-Simulation, we prefer Co-Simulation that allows individual FMUs to use their own dedicated solver engines. The development of the FMI standard has enabled software-in-the-Loop simulation with dynamic system models from different software environments.

As shown in Figure 1, FMI for co-simulation is based on the master-slave architecture. In the master-slave architecture, while the master coordinates the overall simulation, the slaves solve sub-problems. Slaves can directly communicate only with the master. The data exchange between subsystems is restricted to discrete communication
points. Master algorithms control the synchronization of all slave simulation solvers and the data exchange between the subsystems. The subsystems are processed independently from each other by their individual solvers during the time interval between two communication points (Blochwitz et al., 2011).

![Image](image.png)

**Figure 1: FMI for co-simulation**

### 2.3 Tool Chain
The integrated building HVAC system tool chain is critical for system design, control evaluation and performance analysis. Different simulation tools are used for building energy model, HVAC system model and control model:

- Use of a BIM model to provide detailed information on the building. Building data can be extracted from the BIM model and transferred to the building energy simulation software EnergyPlus, which can reduce the amount of time needed to set up a simulation model manually and avoid errors caused by manual input.

- Use of EnergyPlus to model the building loads. Complex building shapes can be simulated with higher simulation speed. The FMU export of EnergyPlus allows EnergyPlus to be accessed from other simulation environments, as a FMU for co-simulation.

- Use of the Modelica-based HVAC library to model building equipment (air systems/chiller plant). The adaptive airside HVAC library was developed in Dymola to handle most commonly used terminal units such as variable air volume (VAV), constant air volume (CAV), and fan coil units (FCU). It includes dynamic models of heat recovery, mixer box, coil, fan, and heat exchanger components. The coil model adopted handles both sensible and latent heat transfer with numerical discretization along the flow paths. The chiller plant model includes dynamic models of chiller, cooling tower, pumps, and valves. The HVAC system models were built up by considering the core dynamics of HVAC system for controls evaluation. Dymola supports the FMI Standard for the import and export of models, which allow the dynamic HVAC model to be accessed from other simulation environments.

- The control logic library for the HVAC system was built using EIKON logic in ALC’s WebCTRL system. WebCTRL is a JAVA based BAS that is designed to support major communication protocols such as BACnet, LonWorks, MODBUS, SNMP and concurrent operation over the same data highway, TCP/IP (Ethernet). The embedded simulator in WebCTRL, acting as a virtual LGR driver, provides all of the features of a fully functioning control system without the need of physical hardware.

WebCTRL Add-on is a Java web application that runs on the WebCTRL server and accesses WebCTRL data and services through a set of Java APIs. Through this platform the WebCTRL Add-on, building model, HVAC model and control model can be connected to each other to provide software engineers an effective software-in-the-loop test environment. The Add-on allows the data exchange and communication between the building energy model and HVAC system model through using the FMI standard protocol. This software-in-the-loop test establishes a variable step size communication via TCP/IP protocol between building HVAC models and software. In this way, the controller software and simulation model can run on different computer devices or even at different locations. This software uses an external txt-file to define the required coupling interface (inputs and outputs of coupling FMU) between controller software and test models.
As shown in Figure 2, the entire work flow is: 1) Building information from a Revit BIM model is automatically parsed to an EnergyPlus building energy model; 2) With the sizing information based on the BIM load report, the HVAC system model is quickly populated with a scalable HVAC system library in Dymola; 3) Both the building energy model and HVAC system model can be wrapped up as Functional Mock-up Units (FMU) model; 4) In addition, the HVAC control program are developed in ALC WebCTRL and can be downloaded to the virtual LGR controller, embedded simulator in WebCTRL through BACnet/IP; 5) Through the Add-on platform, the building and HVAC FMU models can exchange data and communicated each other using FMI standard and they can also be connected with the controller over TCP/IP to perform close-loop simulation.

### 3. CASE STUDY

#### 3.1 Case Configuration

The above integrated tool chain was demonstrated for a new hotel building in Guangdong, China that is still in construction stage. With a cooling capacity of more than 1700 Tons, the chiller plant system will serve a >40,000-square-meter building, which was equipped with three 300-Ton lake-source heat pumps and two 700-Ton centrifugal chillers. Table 1 is the chiller plant system equipment list and Figure 3 shows the chiller plant system configuration.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Type</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chiller</td>
<td>700 Tons (Centrifugal chiller)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>700 Tons (Centrifugal chiller, VFD)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>300 Tons (Lake-source heat pump)</td>
<td>3</td>
</tr>
<tr>
<td>Chilled water pump</td>
<td>75kW(VFD), 30kW(VFD)</td>
<td>3+4</td>
</tr>
<tr>
<td>Condensing water pump</td>
<td>55kW, 18.5kW</td>
<td>3+4</td>
</tr>
<tr>
<td>Lake pump</td>
<td>18.5kW</td>
<td>4</td>
</tr>
<tr>
<td>Cooling tower fan</td>
<td>15kW</td>
<td>4</td>
</tr>
</tbody>
</table>

As shown in Figure 3, centrifugal chillers and lake-source heat pumps provide chilled water for hotel building cooling. Additionally, heat pumps provide hot water for both heating and domestic hot water. In our demo case, we
only consider the chilled water system.

![Diagram of Chiller Plant System](image)

**Figure 3:** Chiller plant system of the hotel case study

This is a new building and control engineers are required to develop the optimized control strategies for the whole chiller plant system. Thus an effective closed-loop simulation platform is needed to identify the potential issues and validate the optimal control performance. Both baseline control and optimized control strategies were developed for the comparison and evaluation. Compared with the baseline, chilled water supply temperature (CHWST) setpoint reset, condensing water supply temperature (CWST) setpoint reset and chilled water pressure difference (CHWDP) setpoint reset are included in the optimized control strategies. Table 2 shows the baseline and optimal control setpoints for chiller plant systems.

**Table 2:** Baseline and optimal control setpoints for chiller plant systems

<table>
<thead>
<tr>
<th>Setpoints</th>
<th>Baseline Control</th>
<th>Optimal Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHWST setpoint</td>
<td>45F (7°C)</td>
<td>Optimized based on load</td>
</tr>
<tr>
<td>CWST setpoint</td>
<td>82.4F (28°C)</td>
<td>Optimized based on outdoor wet-bulb temp</td>
</tr>
<tr>
<td>CHWDP setpoint</td>
<td>30kPa</td>
<td>Optimized based on load</td>
</tr>
</tbody>
</table>

### 3.2 Control Verification

With the integrated Sil platform, the potential control issues can be easily identified through exploring the whole system operation envelop. Figure 4 shows two examples of the identified issues before and after resolution. One example concerns the chiller staging control. At the beginning, the building load is approximately 1300 Tons. Three chillers (one 700-ton centrifugal chiller and two 300-ton heat pumps) start up one by one to meet the cooling load. Later the building load is reduced to 700 Tons. The number of operational chillers do not decrease with the reducing load. The three operating chillers now all work at a 54% PLR. This is very inefficient. After fixing the error, the new chiller staging control enables reduction of the number of running chillers with the reducing load. Two small chillers will shut down while only one big chiller works on 100% PLR to meet the load (see Figure 4a). It should be highlighted here is that this issue is most likely going to be identified only when the chiller plant reaches its full capability in summer season rather than in its on-site installation and commissioning process which is going to lead to significant energy waste as well as re-visit of on-site commissioning technician. Another example is the chilled water pump speed oscillation. This issue can be solved by implementing PID control tuning to reduce the oscillation (see Figure 4b). In total, more than six issues were identified and solved as summarized in Table 3.
**Figure 4:** Control issues solved before and after monitored through WebCTRL

<table>
<thead>
<tr>
<th>Baseline Control</th>
<th>Optimal Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>The number of chillers will not reduce with building load (see Figure 4a)</td>
<td>CHWST setpoint reset for heat pumps is too much (&gt; 5°C offset)</td>
</tr>
<tr>
<td>Pumps will be turned on when valves are still shut off</td>
<td>Chilled pump speed will vibrate in certain operation conditions (see Figure 4b)</td>
</tr>
<tr>
<td>Cooling tower fans will frequently stage on and off in some weather conditions</td>
<td></td>
</tr>
<tr>
<td>Heat pumps will not be turned on in time</td>
<td></td>
</tr>
</tbody>
</table>

### 3.3 Energy Benefit Evaluation

Besides the control commissioning, the SiL platform can also be used to estimate the energy performance of the optimized control strategies. Therefore, three representative days for summer season, transition season and winter season are selected for the energy benefit evaluation, respectively. Figure 5 shows the annual load profile and hourly load profile for the selected days. Since the project is located in the very south of China, the building requires cooling load for the whole year. In the summer time, centrifugal chillers and lake-source heat pumps are required to work together to meet the cooling load. Only centrifugal chillers are needed in the transition season and heat pumps are used in the winter season for cooling.
Figure 5: Annual load profile and hourly load profile for selected days

Figure 6: Comparison of daily average chiller plant efficiency between baseline and optimized control

With the three representative days’ simulation, the energy benefit for the implementation of optimal chiller plant control algorithm can be validated. Figure 6 shows the efficiency comparison of chiller plant system using baseline and optimized control, separately. It is obvious that with optimal control, the chiller plant energy efficiency has been significantly improved, especially for transition seasons and winter seasons. The improvement of average chiller plant efficiency has reached 2%, 17.1% and 17.3% for selected days, respectively. According to annual building load simulation, the total cooling capacity is about 7294 MWh, 6136 MWh and 165 MWh for summer, transition and winter seasons, respectively. Assuming the above average plant efficiency for each season and a cost of electricity per kWh to be $0.14 for Guangzhou, about 9.3% annual energy consumption reduction (~$44K cost saving) can be achieved in chiller plant operation by the optimized control.

4. CONCLUSIONS

This paper presents a tool chain of an integrated simulation platform for building HVAC system automation and simulation and its implementation in a real use case. The case study demonstrates the values in identifying both HVAC automation system control design issues and over 9% annual energy saving from the integrated optimal
controls. This platform enables testing of building HVAC control algorithms before on-site deployment, which reduces the labor and time required for building HVAC control development-to-deployment process and ensures the delivered quality. As the next steps, firstly, the simulation speed will be accelerated to achieve whole year simulation within minutes or hours to have more accurate annual system energy performance evaluation, as the current platform allows only real time simulation. Secondly, this platform will be deployed either in WebCTRL server or Cloud, automatically calibrated with metered data from the specific building HVAC system, and served as “digital twin” to represent design-intended system performance for on-site commissioning quality verification, intelligent operation strategy development, fault diagnostics and maintenance needs prediction.

REFERENCES


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