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Model based co-simulation platform for integrated building system control and design optimization

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ABSTRACT

Both steady-state and dynamic simulations have been widely used by HVAC&R industry to support product/equipment development for decades. Steady-state simulation focuses on the system mass, energy and momentum balance of an equilibrium state. It is based on high-fidelity components models, and thus is suitable for system and component design optimization. Dynamic simulation studies the system transient response and is generally used for controls development and verification. It usually does not require rigorous component models of high accuracy because 1) the commonly used PID control is feedback control whose control performance evaluation doesn't require high fidelity system/plant model; 2) high-fidelity dynamic model significantly increases the number of equations and variables and creates tremendous challenge for math solver.

For supervisory control, transactive control or optimization of an integrated building system, the HVAC&R equipment is often one of the sub-components to be controlled. High-fidelity equipment models are required for accurately evaluating control strategies. In addition, building equipment manufacturers have developed a lot of high-fidelity steady-state equipment/component models per their expertise. Thus, a platform that can integrate OEM high-fidelity steady-state model with dynamic building simulation and/or electric power system & grid simulation to support the development and verification of supervisory control for integrated building systems is necessary.

In this study, ORNL's heat pump design tool (HPDM) is utilized to develop a co-simulation platform for supervisory control and optimization in integrated building systems. It is based on a model that integrates high-fidelity steady-state simulation equipment models with dynamic building simulation. A practical case of using the proposed co-simulation platform to develop and evaluate the supervisory control and optimization is presented and discussed.

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1. INTRODUCTION

Both steady state simulation and dynamic simulation have been widely used for supporting product/equipment development by HVAC&R industry for decades (TRNSYS 18, 2018, EnergyPlus 2020). The steady state simulation focus on the system mass, energy and momentum balance of an equilibrium state, is based on high fidelity components models, and suitable for system and component design and optimization. Dynamic simulation studies the system transient response and is generally used for controls development and verification which doesn't require rigorous component models with high accuracy for two reasons: 1. Actuator-level Controls are generally feedback control whose control performance evaluation doesn't require high fidelity system/component model, 2. High fidelity dynamic model significantly increases the number of equations and variables and create tremendous challenge for math solver.

The current whole building annual energy simulation rarely use the detailed steady-state simulation and dynamic simulation approaches. The high fidelity steady state simulation is computationally expensive and slows down the annual energy simulation significantly. The dynamic simulation is usually not necessary to whole building annual energy simulation since the building equipment dynamics (seconds) is much faster than building dynamics (minutes) and can be negligible. Thus, most widely used whole building annual energy simulation software/platforms, such as EnergyPlus, eQUEST … etc., are preferring to use either curve-fitting empirical or semi-thermodynamic modeling approach for building equipment simulation. However, the accuracy of these modeling strategies highly depends on quality and quantity of the data which are usually not available or often spare with limited quality.

In addition, there is increased need for evaluate the supervisory or detailed control strategies in short period or annual simulation. For example, integrated building system grid response transactive control or optimization study requires high fidelity building equipment models to allow accurate evaluate and validate the benefits of the developed control strategies. Another example is that a detailed control needs be evaluated in annual simulation to allow the integrated building manufacture to optimal design building HVAC&R system and power supply system. Moreover, building equipment manufacturers have developed quite a lot of high fidelity steady state equipment/component models per their expertise which have not been utilized or integrated into any whole building annual energy simulation. Thus, a commonly used platform, which can integrate high fidelity equipment steady state model , either from original equipment manufacturers (OEMs) or self-developed, with dynamic building simulation and/or electric power system & grid simulation while maintain reasonable computational cost to support integrated building system supervisory/detailed level control development and verification, is necessary.

To address this gap, this study utilizes the ORNL heat pump design tool (HPDM) (DOE/ORNL, 2019) to develop an integrated building system model based supervisory control and optimization co-simulation platform to integrate high fidelity steady state simulation equipment models with dynamic building simulation. This work intends to integrate the HPDM library to the Modelica modelling environment in a dynamic link library, to facilitate co-simulation between detailed build equipment models and other building elements. A practice case of using this co-simulation platform to develop and evaluate supervisory level integrated building system control and optimization is presented and discussed.

2. DEVELOPMENT OF MODEL BASED CO-SIMULATION PLATFORM

The model-based co-simulation platform developed in this study is a closed loop modeling and simulation to integrate the whole building and building equipment simulation with the control strategies. This platform can be used to design, develop, and evaluate the system design and control strategy before actual implementation and testing on the real system, which allows to quickly detect the controls error during evaluation and design stage. As shown in Figure 1, this platform is composed of four modules: simulation design, control strategy modeling, whole building simulation, and simulation results & virtualization.

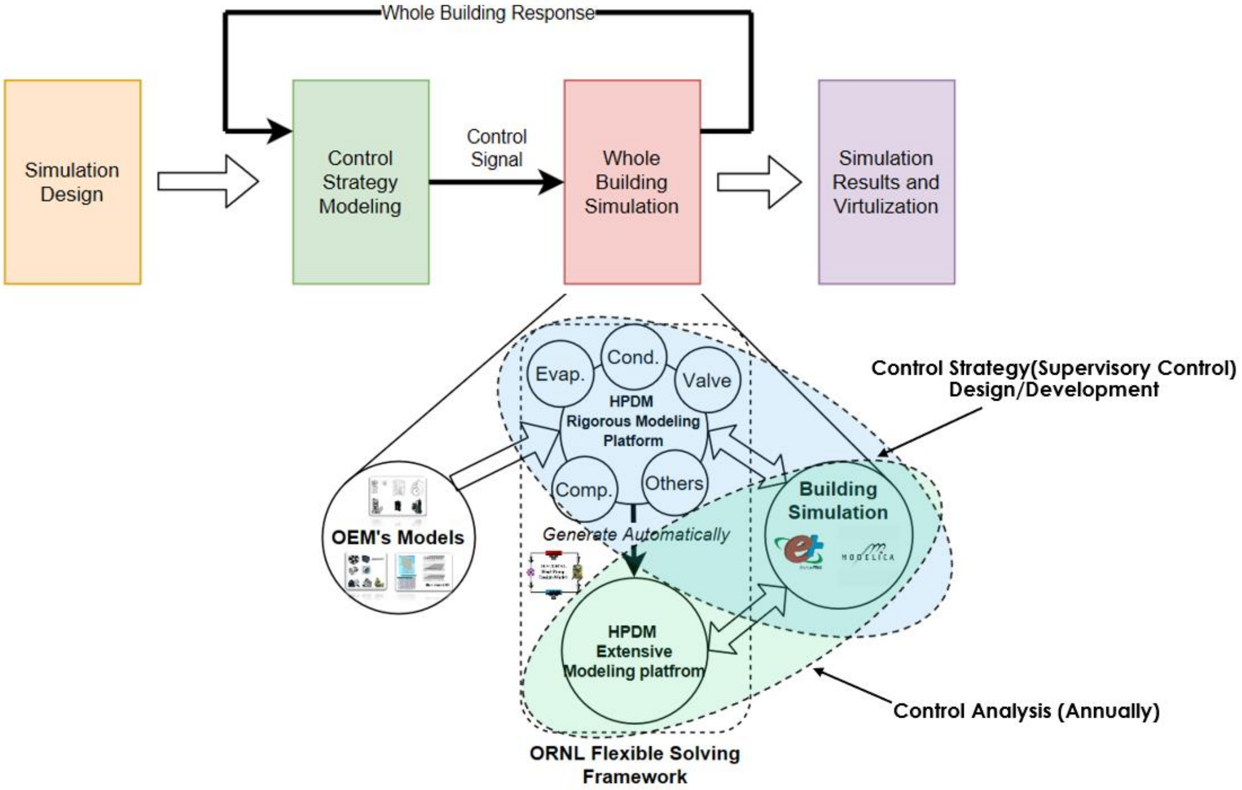

Figure 1: Schematic diagram of model based co-simulation platform

2.1 Simulation Design

Simulation design is to define a series of simulation scenarios or user cases to automatically exam different control and design strategies according to predefined test requirements and targets. It will generate input signals to the control strategy modeling modular to allow closed loop simulation between control module and building module.

2.2 Control Strategies Modeling

A model representing the control logic will be developed based on control targets which define how the building and building equipment should be operated. This control model can be simulated in closed loop with the models of building and building equipment to enable rapidly and early identification of missing or inconsistent in control performance.

2.3 Whole Building Simulation

As the core of the model based co-simulation platform, high fidelity steady state and /or dynamic modeling/simulation engine of the building and building equipment are developed to represent the actual building and building equipment so that the design and control strategy can be tested and verified. This whole building simulation module is composited of three main components: building simulation, ORNL flexible solving framework, and OEM/s models.

2.3.1 Building Simulation

A dynamic model of building is created from publicly available buildings modeling, such as EnergyPlus (DOE, 2020), and building library (DOE/LBNL 1998, Wetter, et al., 2014), to simulate the dynamic behavior of the building, including building envelop, building indoor air, and weather conditions, corresponding to control inputs/outputs.

2.3.2 ORNL Flexible Solving Framework

High fidelity building equipment models are developed based on a Modelica-based equipment library and a flexible solving framework to allow integration of component simulation models, either self-developed or OEM's, into system simulation. Two modeling platforms are included this flexible solving framework,

- HPDM rigorous modeling platform: a public-domain building equipment design and modeling tools, developed and maintained by ORNL. It is a hardware-based equipment design tool promotes energy saving technologies, and provides public knowledge-base and technical support to transfer new technologies from ORNL to U.S. industry. It has a flexible component-based platform to model extensive building equipment types and complicated configurations, and comprehensive library includes information on most HVAC&R components, and many refrigerants and working fluids. In the latest version (DOE/ORNL, 2019), the capability is greatly enhanced to model extensive equipment types, and configurations and new refrigerant properties, e.g., HFO refrigerant blends and natural refrigerant like CO2. It can simulate all residential and commercial air conditioners, heat pumps, water heating and refrigeration systems, including vapor compression systems having multiple compressors and heat exchangers, and multi-split variable-refrigerant flow (VRF) systems. Regarding heat exchangers, the HPDM component model library includes fin-and-tube coil, microchannel heat exchanger for air-to-refrigerant; tube-in-tube, brazed plate, shell-and-tube, wrapped-tank coil for water-to-refrigerant. The heat exchanger models (based on a segment-to-segment approach) accept actual coil circuitry and dimensions and can represent heat transfer and pressure drop scaling factors and correlations obtained from experiments. Regarding the flow moving components, e.g., compressors and fans, HPDM correlates the performance using maps from manufacturers.
- HPDM extensive modeling platform: a reduce order building equipment modeling library through training comprehensive simulated performance data generated HPDM rigorous modeling platform using model reduction techniques, such as principal component analysis, regression analysis, machine learning based methods.

2.3.2 Original Equipment manufacturer (OEM) Models

One of the main advantages of this developed model-based co-simulation platform is to provide a quick and easy way to integrate OEM or third party simulation models/engines into this co-simulation platform through ORNL flexible solving framework.

2.4 Simulation Results and Virtualization

The simulation results will be generated through closed loop simulation and be compared with predefine desirable control performance to determine if the system and control design achieve the targets.

3. CASE STUDY

A single family house with air source integrated heat pump system is selected to demonstrate the utilization of the proposed model based co-simulation platform to support the integrated building system control. As shown in Figure 2, the model based co-simulation platform includes four main modules: simulation test module, supervisory control and design module, single family house and heat pump system module, simulation results module. The supervisory control modular receives the responses from both building and heat pump system, and generates control inputs for controlling heat pump system. The details of the building and heat pump system modeling are described as following,

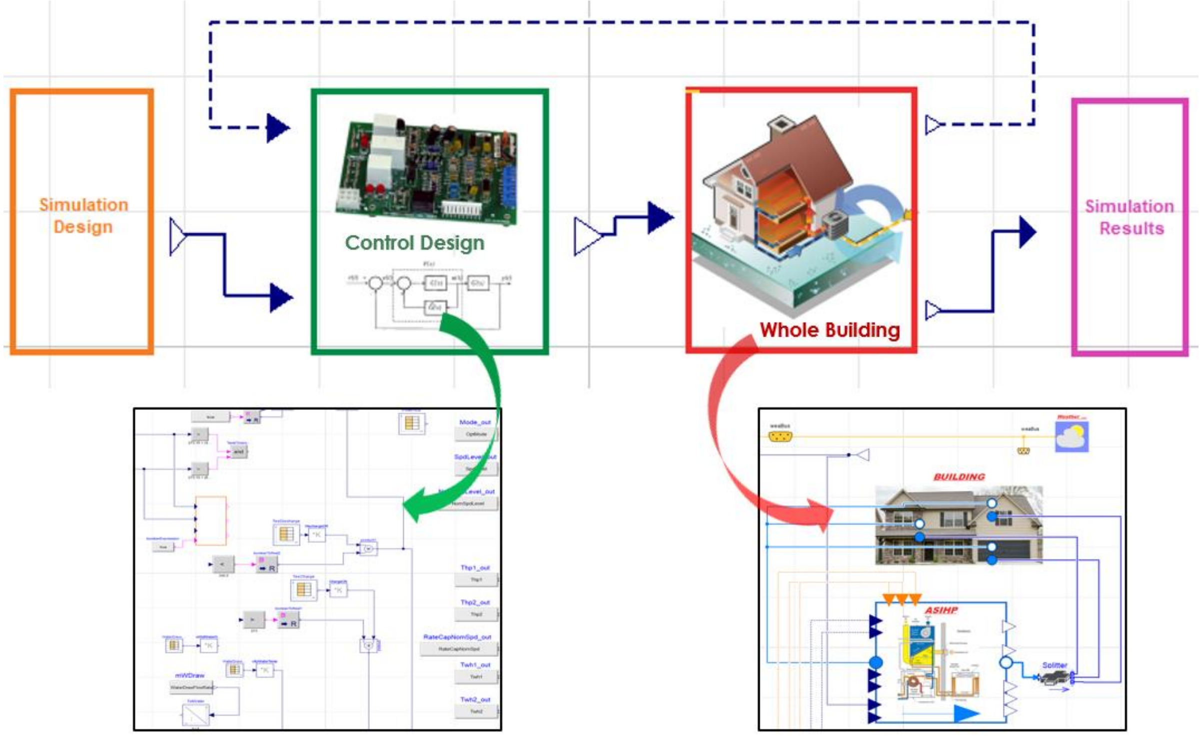

Figure 2: Model based co-simulation platform

A single family house of total 2685 square feet floor area is selected to perform the case study. For simplification, this house is divided as three thermal zones: one represents four identical bed/bath rooms, second zone is combined living /kitchen zone, and the third is sitting zone. Some envelope characteristics are given below:

- Walls: 2x6 steel frame 16” O.C., R-21 fiberglass cavity insulation + 2” XPS (R-10 continuous insulation)
- Roof: 12” steel truss 16” O.C., R-30 fiberglass cavity insulation + 3” polyiso base insulation + 0-7” polyiso tapered insulation
- Floor: 2x6 steel frame 24” O.C., R-15 fiberglass cavity insulation
- Windows
  - i. Living Room/Kitchen/Entry (23.8% window-to-wall ratio)
    1. (1) Fixed patio panel window (Type D): 46.8 sf, U-0.27, SHGC-0.21 (shaded by 6’ balcony overhang)
    2. (1) Patio Swing Door: 22.7 sf, U-0.25, SHGC-0.16 (shaded by 6’ balcony overhang)
    3. (1) Slider window (Type H): 25.7 sf, U-0.28, SHGC-0.30
    4. (1) Picture window (Type L): 12.5 sf, U-0.26, SHGC-0.32
  - ii. Bedroom/bathroom (6.5% window-to-wall ratio)
    1. (1) Slider window (Type H): 25.7 sf, U-0.28, SHGC-0.30

The internal loads schedules for living area and bedroom area are given as,

Living area:

- People: 2 people (5:00-8:00 and 17:00 – 22:00), 245 btuh/person sensible, 105 btuh/person latent
- Lighting: 75 W (5:00-8:00 and 17:00 – 22:00)
- Equipment: 2000 btuh (5:00-8:00 and 17:00 – 22:00)

Bedroom area:

- People : 2 people (0:00-5:00 and 22:00 – 24:00), 250 btuh/person sensible, 200 btuh/person
- Lighting: 50 W (4:30-6:30, 21:30-22:30)

- Equipment: 200 btuh (4:30-6:30, 21:30-22:30)

A dynamic model (Figure 3) is developed based on building library (DOE/LBNL 1998, Wetter, et al., 2014).

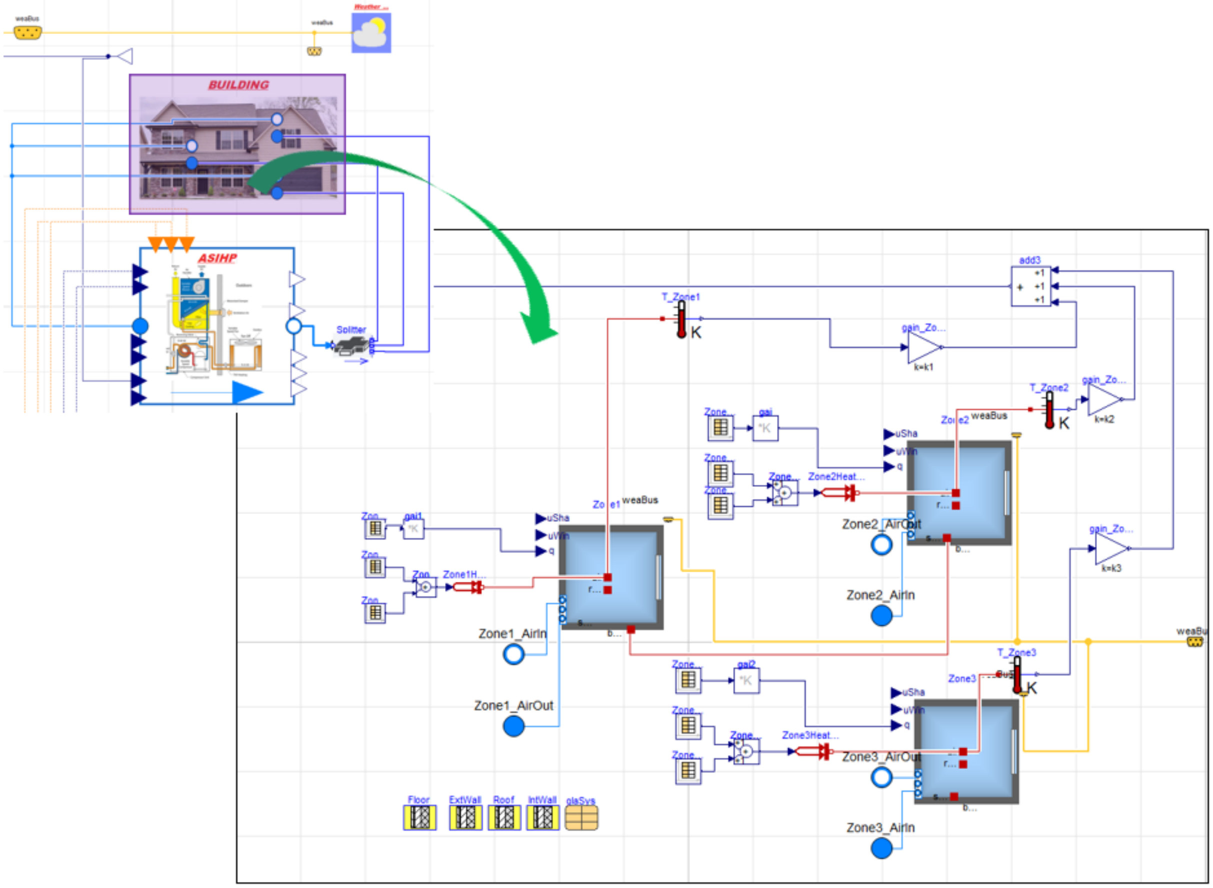

Figure 3. Dynamic model of a single family house

An air source integrated heat pump is designed to provide both cooling and heating load for this studied single family house. As shown in Figure 4, the air source integrated heat pump is simulated with ORNL HPDM tools (DOE/ORNL, 2019, Shen, et al., 2014] under a flexible solving framework.

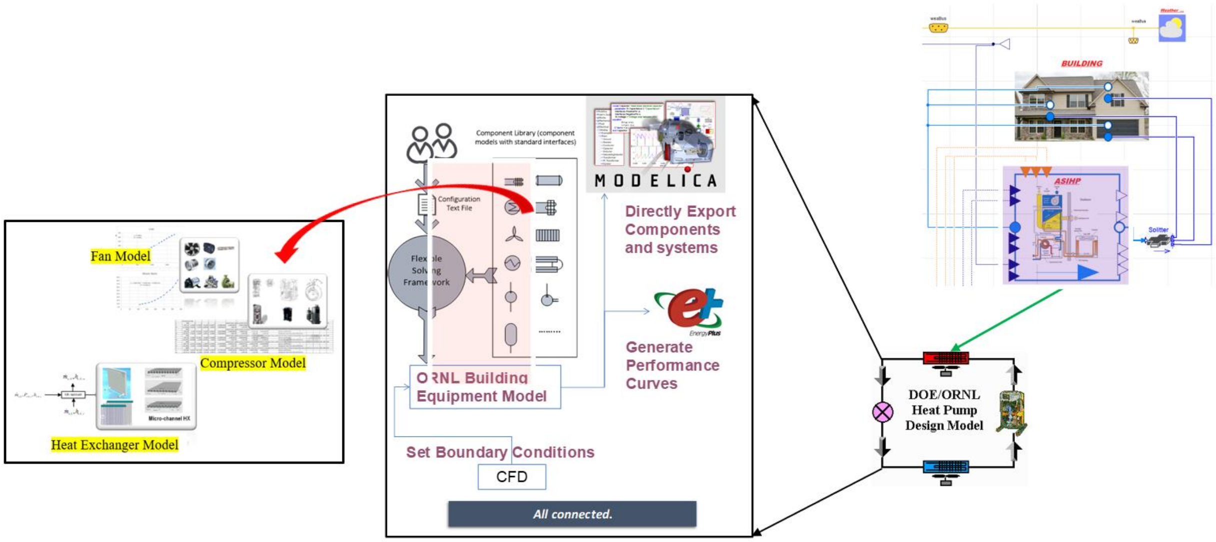

Figure 4. Air source integrated heat pump system model

4. SIMULATION AND ANALYSIS

Based on the model based co-simulation platform, we investigated a grid-responsive control strategy to take advantage of the low-cost electricity during night-time. It maintained the same comfort level, i.e. the same temperatures for the ASIHP to turn on, while allowing larger temperature bands for over-cooling, or over-heating when the electricity cost is low. This will utilize the low-cost electricity to provide hot water storage, precooling/preheating the building ahead of high price hours. Table 1 below described the temperature settings in space cooling, space heating and water heating modes, respectively for the normal ASIHP control and grid-responsive control.

Table 1: Normal and grid-responsive thermostat settings

Control targets	**Space Cooling**		**Space Heating**		**Water Heating**	
	Day	Night	Day	Night	Day	Night
Normal	73-77°F		68-72°F		110-125°F	
Grid-Responsive	73-77°F	70-77°F	68-72°F	68-75°F	110-125°F	110-140°F

As a comparison, Figure 5 depicts ASIHP’s return air temperature profiles in Phoenix, AZ for a cooling week (July 1-7), respectively for the normal and grid-responsive controls. It indicates that the grid-responsive control allowed larger temperature band and cooled the building to lower temperatures during night hours. Figure 6 shows the hot water tank top node temperature profiles, resulted by the two control strategies.

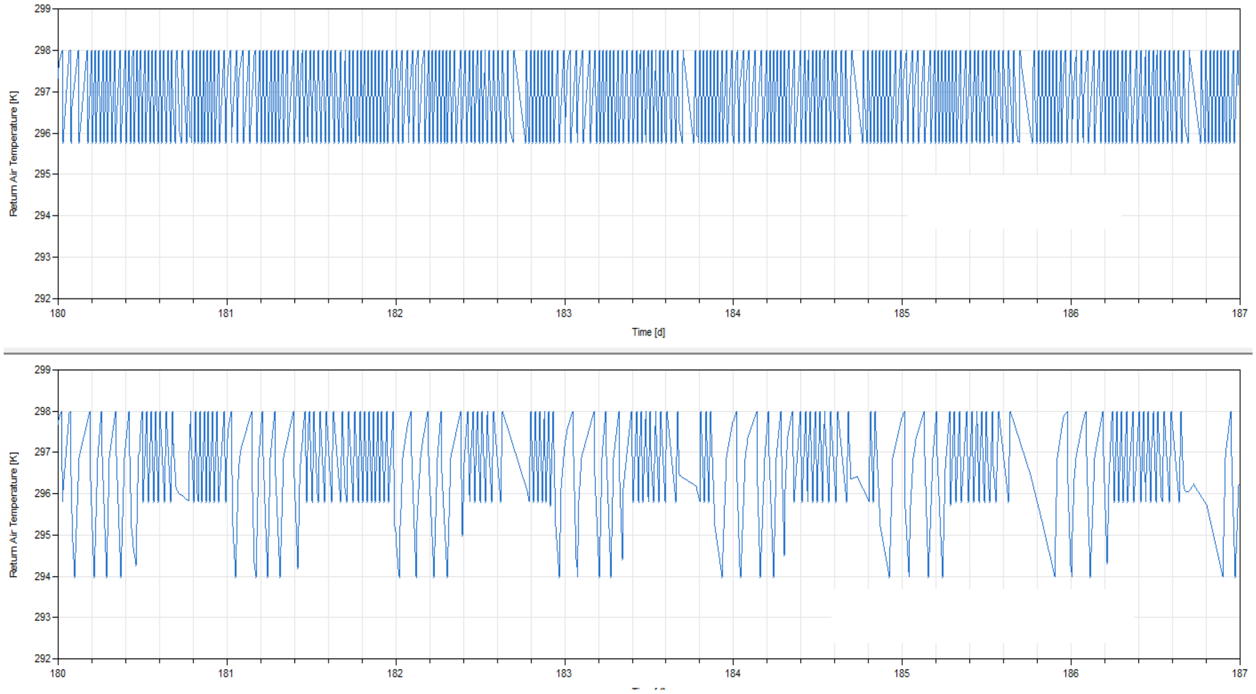

Figure 5: Return air temperature profiles in Phoenix, AZ, within a cooling week, normal vontrol versus grid-responsive control.

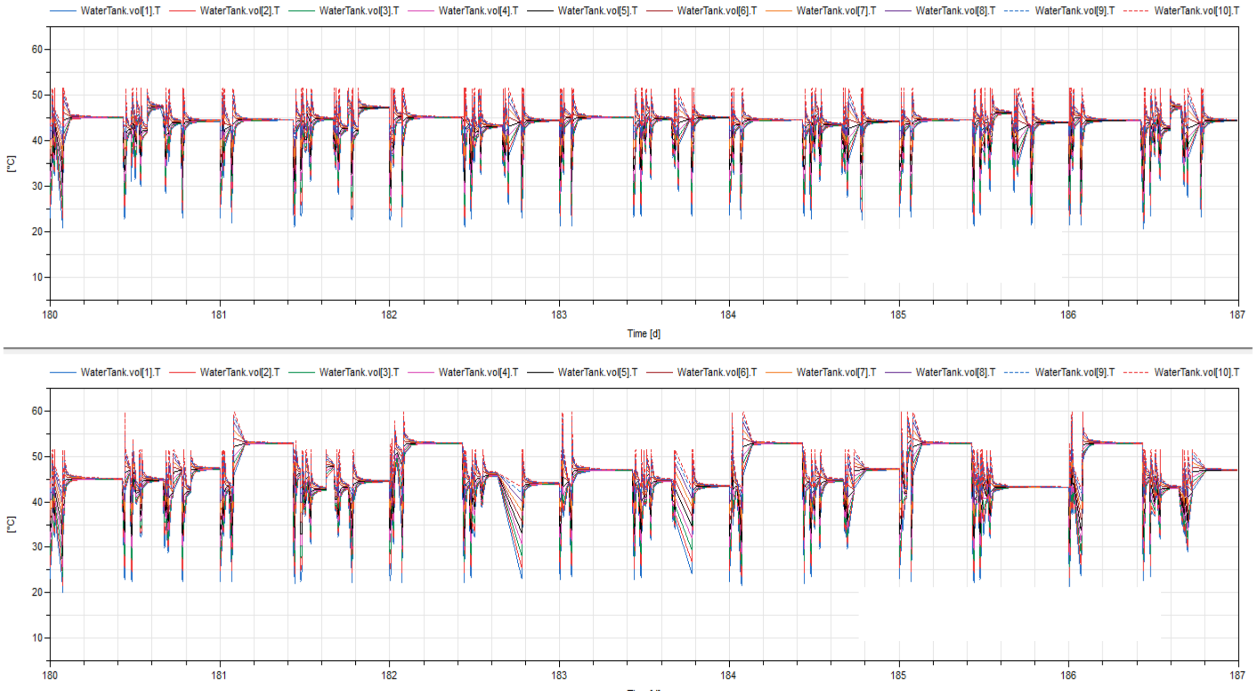

Figure 6: Hot water temperature profiles (top node), normal control versus grid-responsive control.

We conducted annual building energy simulations in five US cities, i.e. Chicago, IL; Phoenix, AZ; San Francisco, CA; Knoxville, TN; New York City, NY. Table 2 summarizes the energy consumptions and electricity costs. It demonstrates that the grid-responsive control strategy can reduce electricity costs up to 9%.

Table 2: Annual energy consumptions and utility costs in five US cities

		Chicago	Phoenix	San Francisco	Knoxville	New York
Normal Control	**Power Consumption,** kWh	7242	11941	8766	8621	8084
	Power Cost, $	682.1	1122	830	807	763
Grid-Responsive	**Power Consumption,** kWh	7027	10984	8045	8024	7661
	Power Cost, $	655	1027	755	751	714
Relative Savings	**% power saving**	-3.0%	-8.0%	-8.2%	-6.9%	-5.2%
	% power cost saving	-3.91%	-8.51%	-8.99%	-6.93%	-6.32%

5. CONCLUSION

Utilizing the ORNL heat pump design tool (HPDM), an integrated building system model-based supervisory control and optimization co-simulation platform is developed in this study to integrate high fidelity steady state simulation equipment models with dynamic building simulation. This work is to integrate the HPDM equipment library into the Modelica modelling environment through a dynamic link library, to facilitate co-simulation between detailed build equipment models and other building elements. A practice case is presented through development of a single family house with air source integrated heat pump system modeling platform and based on it to investigate a grid-responsive control strategy which takes advantage of low-cost electricity during night time and maintained the same conform level, i.e. the same temperatures for the ASIHP to turn on, while allowing larger temperature bands for over-cooling, or over-heating when the electricity cost is low. This utilized the low-cost electricity to provide hot water storage, precooling/preheating the building ahead of high price hours. In addition, annual building energy simulations in five US cities, i.e. Chicago, IL; Phoenix, AZ; San Francisco, CA; Knoxville, TN; New York City, NY, have been conducted to demonstrates annual electricity costs reduction up to 9% with the grid-responsive control strategy.

REFERENCEs

DOE/ORNL, 2019, Heat Pump Design Model, https://hpdmflex.ornl.gov/hpdm/wizard/welcome.php
DOE, 2020, EnergyPlus Engineering Reference, Version 9.3, https://energyplus.net/documentation
DOE/LBNL, 1998, Modelica Building Library, https://simulationresearch.lbl.gov/modelica/
Rice, K., Shen, B., Munk, J., Ally, M., and Baxter, V., 2014, Development of a Variable-Speed Residential Air-Source Integrated Heat Pump, 11thIEA Heat Pump Conference 2014, May 12-16, Montréal (Québec) Canada
Shen, B., New, J., and Baxter, V., Air source integrated heat pump simulation model for EnergyPlus, Energy and Buildings, Volume 156, 2017, Pages 197-206, ISSN 0378-7788
TRNSYS 18, 2018, https://sel.me.wisc.edu/trnsys/features/trnsys18_0_updates.pdf
Wetter, M., Zuo, W., Nouidui, T.S., and Pang, X., Modelica Buildings library. Journal of Building Performance Simulation, 7(4), 253–270, 2014. DOI: 10.1080 /19401493. 2013.765506

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