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Evaluation of Optimal Chiller Plant Control Algorithms in Model-Based Design Platform with Hardware-in-the-Loop

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ABSTRACT

This paper presents a framework and results of using model-based design (MBD) methodology to evaluate the benefit and trade-offs of different chiller plant control algorithms for medium-sized commercial buildings including an optimization-based algorithm that can be deployed rapidly with little installation and commission effort. A high-fidelity dynamic simulation model for selected building types and climate zones were developed with Modelica and implemented in the hardware-in-the-loop (HiL) platform for controller hardware verification purpose. Baseline and optimization-based control algorithms were deployed in a building automation system (BAS)'s controller hardware with their performance monitored through web-based interface in real-time. Through extensive model-in-the-loop (MiL) analysis with 128 case studies that cover significant amount of chiller plant load scenarios, an average energy saving of 15% was achieved for the medium office building type and 10% for the large hotel building type in selected climate zones. A simple payback analysis was conducted and the commercialization requirement of less than 3 year payback period was met.
Keywords: *Model-Based Design, Low-Cost Optimal Control, Whole-Building Dynamic Modeling, Modelica*

1. INTRODUCTION

Chiller systems account for 31% of the total cooling electricity consumption of medium-sized commercial buildings within 25k-200k square feet. In the last decade, advanced controls such as model predictive control (MPC) has demonstrated energy savings that typically range from 5% to 15% (Bengea *et al.*, 2015; Li *et al.*, 2015). However, the installation and commissioning efforts to deploy MPC into existing building automation system (BAS) are often cost prohibitive and therefore undermine the energy saving benefit it brings into the game.

This paper presents the key accomplishments in developing the model-based design (MBD) framework that enables the energy evaluation of baseline and advanced chiller plant controls in model-in-the-loop (MiL) and hardware-in-the-loop (HiL) platforms. A key feature of this paper is the various chiller plant load scenarios considered in a high-fidelity whole-building dynamic modeling environment. Another key feature is the comparison of baseline chiller plant control (fixed-setpoints) to state-of-the-art advanced control methods such as ASHRAE 90.1 and heuristic-based algorithms as well as a low-cost optimal control developed internally at UTRC.

A high-fidelity integrated building HVAC and chiller plant dynamic model with equipment-level closed-loop controls was developed with Modelica by leveraging the work from DOE's previously funded projects for EnergyPlus (Crawley *et al.*, 2001) and Modelica Buildings Library (Wetter *et al.*, 2014) and UTRC's in-house model Library. The integrated model was demonstrated to be significantly faster than real-time with Dymola's variable-step solver and was shown to be numerically robust for a wide range of operating conditions including chiller plant start-up and shut-down as well as reversed water flow scenarios during transient operation.

The integrated building HVAC and chiller plant model was later successfully deployed in HiL platform coupling with real-world chiller plant controllers to assess baseline and low-cost optimal control operation and performance. The installation time and effort for baseline and low-cost optimal control deployment were found to be 8 hours and 14 hours, respectively. The baseline and low-cost optimal control operation has been monitored for the entire weekly profile and the integrated building HVAC and chiller plant system has progressed well for multiple chiller plant start up and shut down operation without any numerical issues and meanwhile generating reasonable results.

Finally, this research investigates an extensive set of 128 case studies (that exceed the project target of 54) that provide detailed understanding on how different climate zones, plant configurations, and building types may affect energy savings. Each case study is a weekly simulation using a whole-building dynamic HVAC system model coupled with many closed-loop PI controllers and supervisory controllers at the chiller plant level. Through extensive analysis, an average energy saving of 15% was achieved for the medium office building type and 10% for the large hotel building type in selected climate zones. A simple payback analysis was conducted and the commercial requirement of less than 3 year payback period was met.

2. WHOLE-BUILDING DYNAMIC MODELING PLATFORM AND INTEGRATION

This section provides details for the building, AHU, and chiller plant modeling, respectively. The building model was developed based on a translation of selected DOE EnergyPlus reference building models using a UTRC in-house model Library. The AHU model was developed based on LBNL's Modelica Buildings Library 2.1.0 and the chiller plant models were developed based on the UTRC in-house Library. The chiller plant controls Library was developed based on Modelica Standard Library 3.2.1.

2.1 Dynamic Modeling of Building Envelope & Zone and AHU Models

The building types of medium office and large hotel were selected due to their significant coverage for medium-size building footprint. The building models were developed with Modelica following the assumptions made in the corresponding EnergyPlus reference building models from DOE. The inputs to the building model are weather profiles (OAT, OARH, and solar), building occupancy, lighting, and equipment schedules, ground temperature, infiltration flow rate, as well as heating and cooling setpoints. Figure 1 illustrates the dynamic building modeling approach where EnergyPlus model's input (i.e., IDF file) and output files were used to identify the modeling assumptions and inputs need to be incorporated in the Modelica model. For air flow distribution, the variable air volume (VAV) models were modeled directly in the building model.

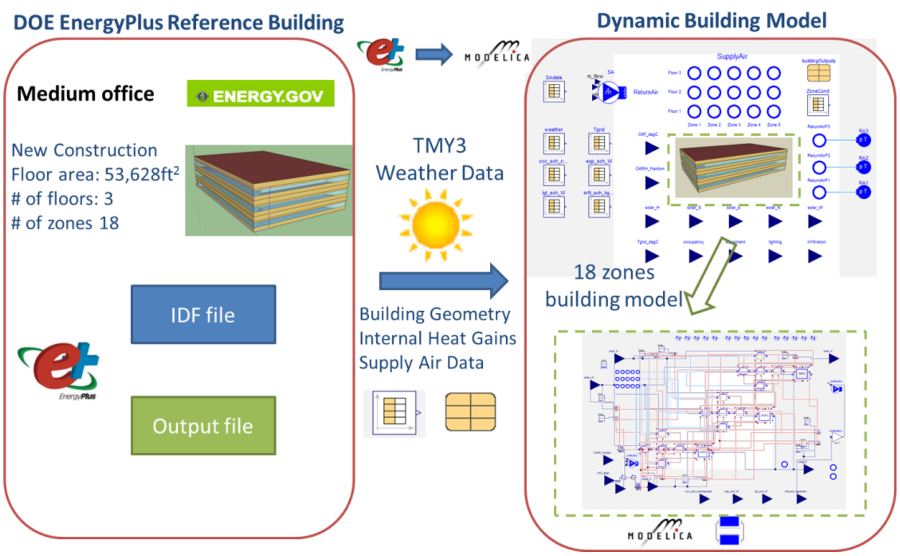
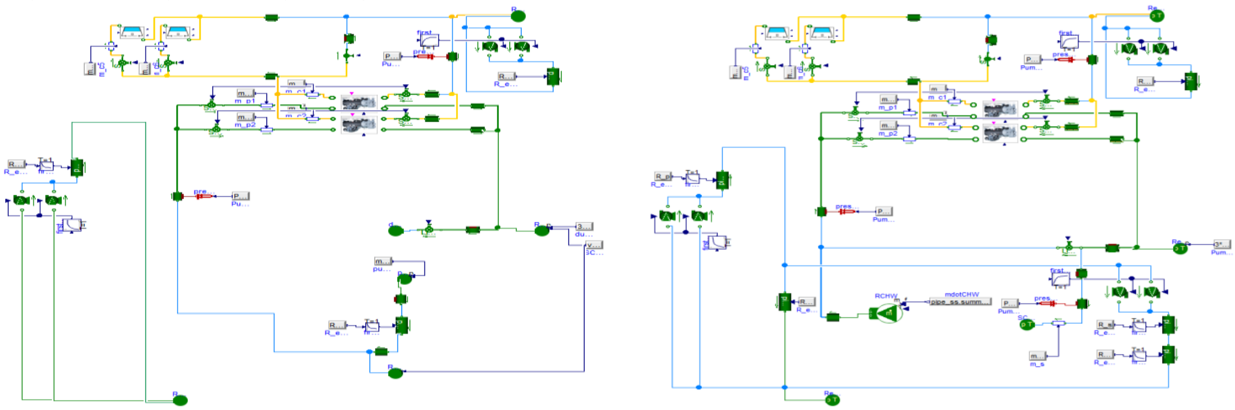


Figure 1: Illustration of dynamic modeling approach for building envelope and zone following DOE's EnergyPlus reference building (medium office)

The dynamic AHU model was developed based on LBNL's Modelica Buildings Library. The cooling coil model adopted handles both sensible and latent heat transfer with numerical discretization along the flow paths.

2.2 Chiller Plant Modeling

The chiller plant model includes dynamic models of chiller, cooling tower, pumps, and valves. These physics-based component models were adopted from UTRC's in-house Modelica Library and were validated with experimental data from UTRC's data. The chiller plant system model was built up by considering the core dynamics of chiller plant for controls evaluation. The chiller plant model consists of 2 variable-capacity chillers with the capacity determined based on building types and climate zones. Chilled-water temperature leaving the chillers is maintained at its setpoint by staging chillers and varying cooling capacity of each chiller. The cooling-water loop has 2 cooling towers with a variable-speed fan, which is used to maintain temperature of cooling water returned to chiller at its setpoint. The cooling water is circulated by two constant-flow pumps. The chilled-water loop has 2 configurations: primary-only and primary-secondary. The primary-only configuration has 2 variable-speed pumps to maintain the differential pressure. It has a bypass path connecting the pumps' outlet and return pipeline. There is a modulating value in the bypass path that is controlled to maintain a minimal flow of chilled water entering chillers. The primary-secondary has 2 water loops sharing a bypass path. The chilled water in the primary loop is circulated by 2 constant-speed pumps; the secondary loop uses 2 variable-speed pumps to maintain differential pressure between the supply and return pipelines at its setpoint. Figure 2(a) and 2(b) shows the schematic of the chiller plant model with primary-only and primary-secondary configurations.



(a) Primary-only configuration (b) Primary-secondary configuration

Figure 2: Chiller plant model layout in Dymola

2.3 Chiller Plant Control Logics

A ChillerPlantControl Library was developed based on Modelica Standard Library 3.2.1. The Library includes baseline chiller plant control logics available from Automated Logic (ALC)'s WebCtrl® program. Figure 3 shows an overview of the Library that includes chiller staging, pump and fan PI control logics.

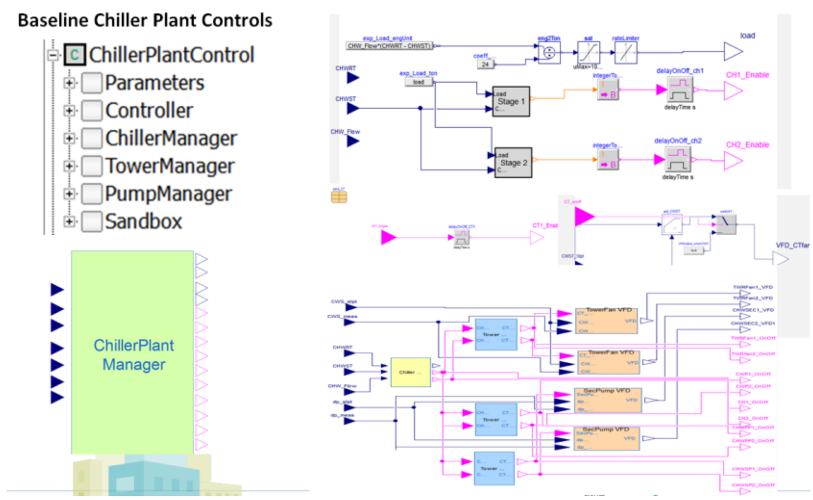


Figure 3: ChillerPlantControl Library Layout in Dymola

2.4. Integration of Building HVAC and Chiller Plant Model

In model-in-the-loop (MiL) platform, system-level coupling was tested incrementally before integrating all subsystem models together. To prepare the model for the HiL platform, each step of the subsystem integration was evaluated with fixed-step solver as well. Figure 4 schematically illustrates the coupling between building, AHU, and chiller plant model with closed-loop controls in each system and the corresponding model inputs and outputs.

At building level, individual zone temperature controller was implemented to adjust the zonal supply flow rate based on the temperature setpoints. Each AHU receives the information of required flow rate aggregated from each zone from the building model and provides consistent flow rate that would meet the flow requests to maintain the zone temperature within the setponts. At AHU level, there is a PI controller that measures the supply air temperature (SAT) as the feedback signal and modulates the chilled-water valve connected to the cooling coil model to maintain the SAT towards its setpoint. At chiller plant level, the AHU sides' pressure and temperature were connected to the supply and return ports of the chiller plant model so that the chiller plant's pump will provide sufficient pressure to deliver the required chilled-water flow rate to meet the SAT setpoint controls.

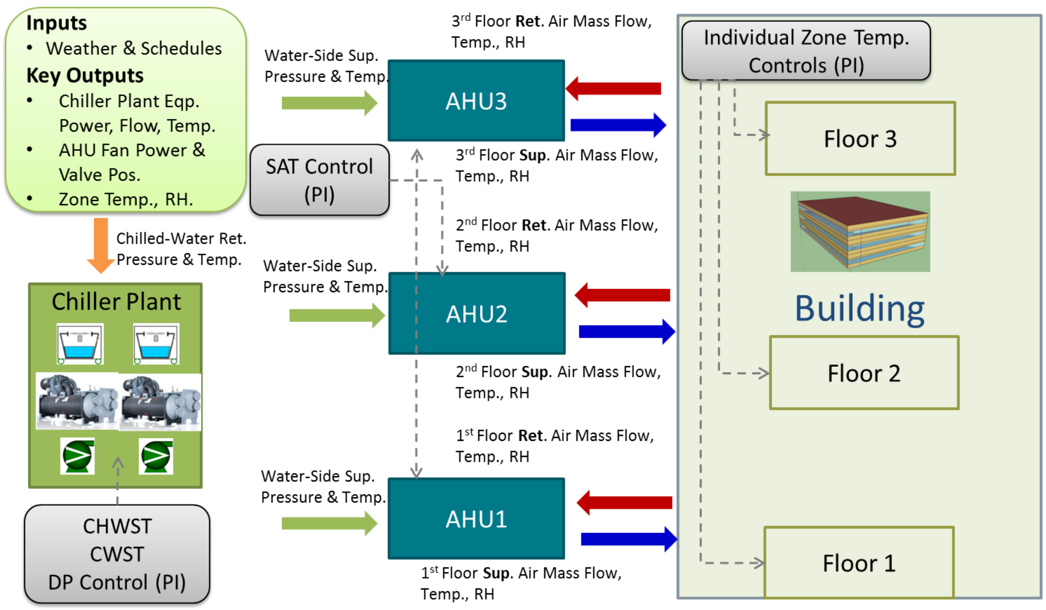
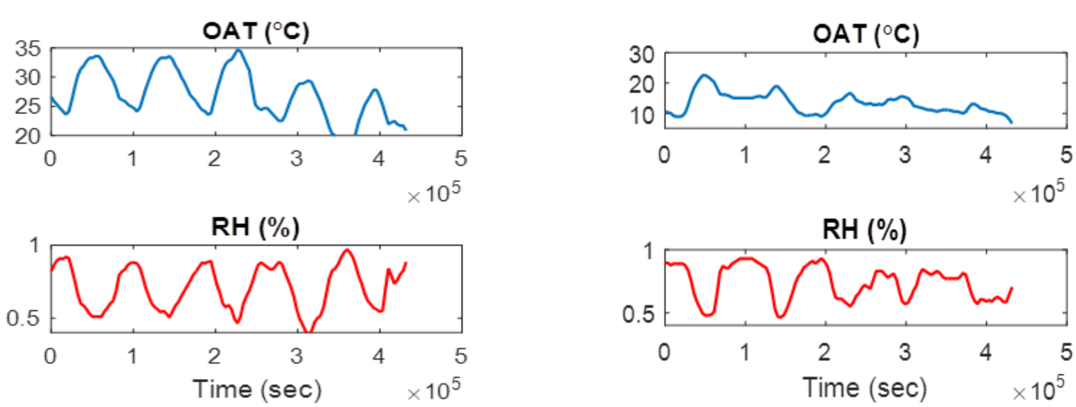


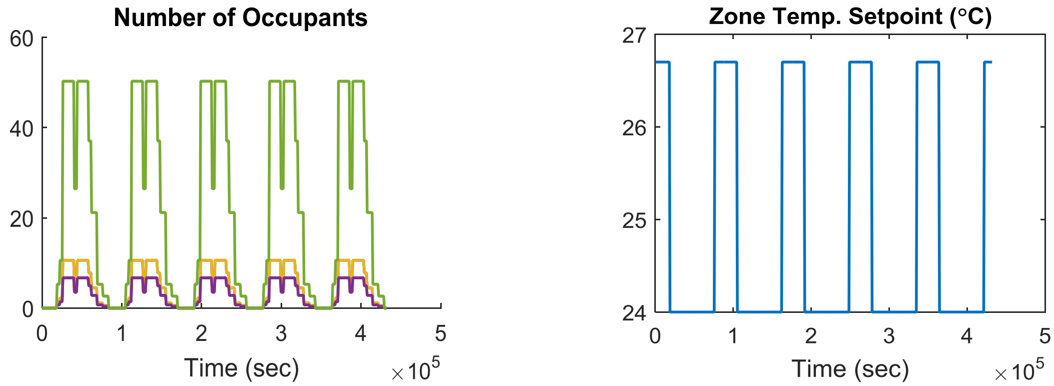
Figure 4: Schematic of model integration for building HVAC and chiller plant systems

2.5 Model Inputs and Outputs

Figure 5 shows the model inputs of outdoor air temperature (OAT), relative humidity (RH), occupancy schedule for different zones as well as zone temperature sepoint schedule using Chicago weather as the example for illustration purpose. Two weekly profiles were selected in the energy evaluation phase. The first weekly profile (July 16th to July 21st) represents a typical summer week that includes the summer design day selected by the EnergyPlus model. The second weekly profile (Oct. 2nd to 6th) represents the shoulder season week scenario.



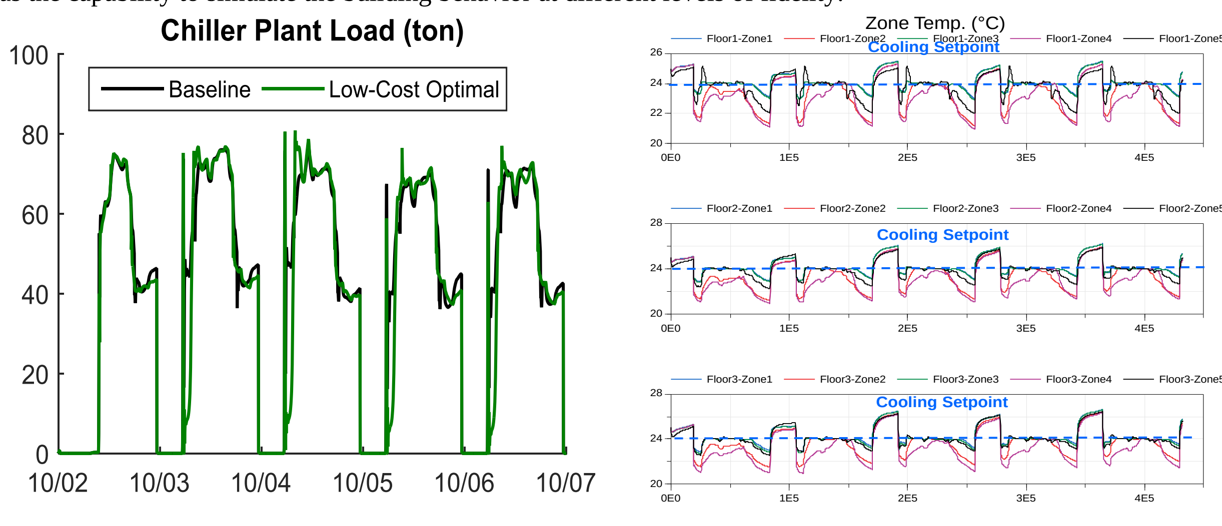
(a) Chicago summer week (b) Chicago shoulder week



(c) Occupancy schedule (d) Zone temp. setpoint schedule

Figure 5: Selected inputs to the integrated building HVAC and chiller plant model

Figure 6(a) and 6(b) present example results of whole-building dynamic model for the chiller plant load and zone temperature profiles in medium office building, respectively. The key point to illustrate is that he integrated model has the capability to simulate the building behavior at different levels of fidelity.



(a) chiller plant load profiles (b) Zone temperature profiles

Figure 6: Example simulation results of medium office during a weekly profile

3. HARDWARE-IN-THE-LOOP CONTROLLER VERIFICATION

Hardware-in-the-Loop (HiL) simulation is widely used in automotive and aerospace industries to verify control system software implementation as a part of their model based control development process. HiL allows verifying control requirements using a real controller with an emulated plant. HiL can be also useful for building HVAC system control development as real controllers can be evaluated in a more realistic environment than desktop numerical simulations. The HiL system developed for our study is depicted in Figure 7.

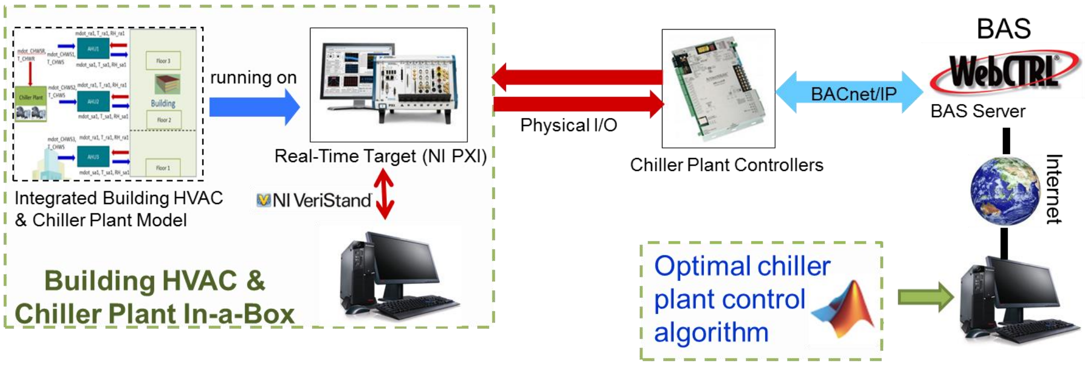


Figure 7: HiL system for building system control verification

With Matlab/Simulink support, the whole-building dynamic model discussed above is built as a real time capable Dynamic Link Library (DLL). The DLL runs on National Instruments (NI) PXI real time target. This is the same PXI hardware that is commonly used with NI LabView and Microsoft Windows. For HiL simulation, as the model is required to run in real-time, real time operating system is used instead of Windows. NI VeriStand is used in order to deploy model to the PXI system and manage simulations. Physical inputs and outputs (I/O) of the PXI system are connected to ALC controller I/O that typically involves analog and binary signals. The ALC controllers run control algorithms that are built in ALC Eikon logic builder. The control algorithm deployment to the controllers and management are done through the WebCtrl server that is connected to the ALC controllers via BACnet over IP network as well as operators via the Internet.

In new system deployment or retrofit applications, field engineers can use HiL simulation as a verification tool before deploying to a real job site. This enables to find and resolve issues in control algorithms before actual implementation so that actual commissioning of control system in the field is smoother with fewer issues. In research applications such as our study, HiL simulation can be used as a demonstration tool that is more realistic than desktop simulation. HiL simulation could even possibly replace real building demonstration when it is not available or feasible.

There are two steps needed to be carried out before running the baseline controller in HiL platform. The first step is model preparation. To enable HiL evaluation, the integrated model needs to be exported from Dymola to Simulink and then compiled as DLL file using NI VeriStand platform. The integrated model needs to be proven to work robustly with fixed-time step solver first in both Dymola and Simulink. The model preparation step usually takes several iterations since fixed-time solver has finer requirements for the dynamic models. The second step is the controller deployment, which happens after the model preparation phase and the associated time and efforts are documented below. Figure 8 shows the HiL setup at UTRC.

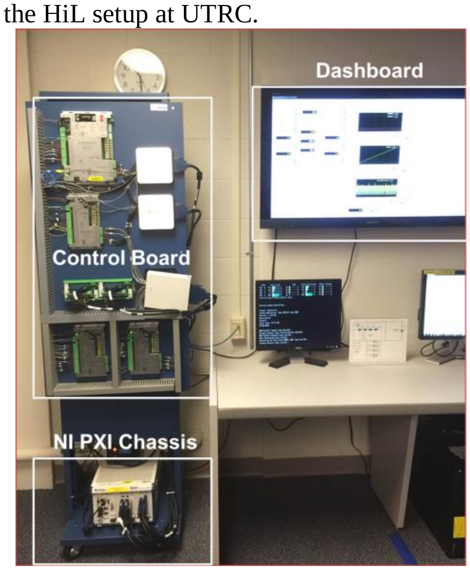


Figure 8: Hardware-in-the-Loop setup at UTRC

The baseline chiller plant control logics are available from Automated Logic (ALC)'s WebCtrl®. Figure 9 shows the chiller staging control logic.

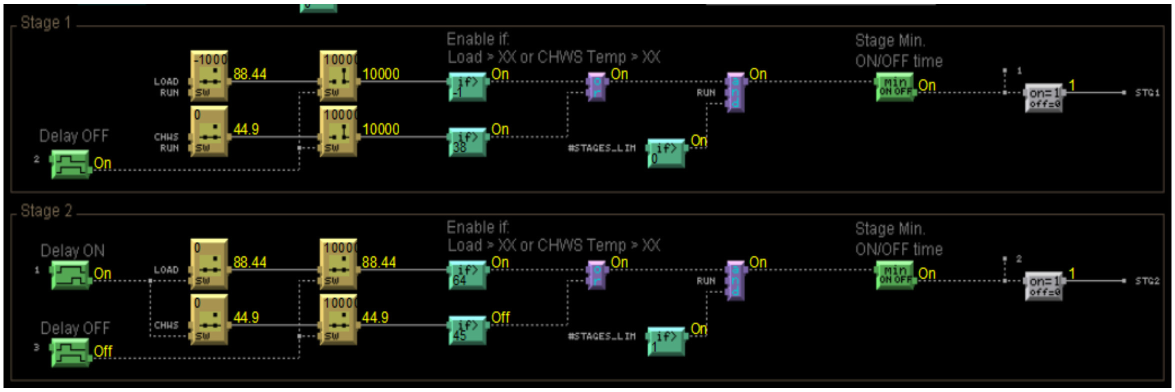


Figure 9: Chiller staging control logic implemented in WebCtrl

Table 1 shows the control setpoints selected for AHU and chiller plant systems. The optimal chiller plant control algorithm will manipulate the chilled-water supply temperature (CHWST) based on the estimation of air-side loads.

Table 1: Baseline and optimal control setpoints for AHU and chiller plant systems

Setpoints	Baseline	Optimal Control
AHU SAT setpoint	55F (12.78°C)	55F (12.78°C)
Zone setpoint (occ./unocc.)	75F/80F (23.9/26.7°C)	75F/80F (23.9/26.7°C)
CHWST setpoint	45F (7°C)	Optimized
CWST setpoint	85F	85F
Pressure diff. setpoint	30kPa	30kPa

Figure 10 shows the chilled-water temperature setpoint commanded by the low-cost optimal control during HiL testing.

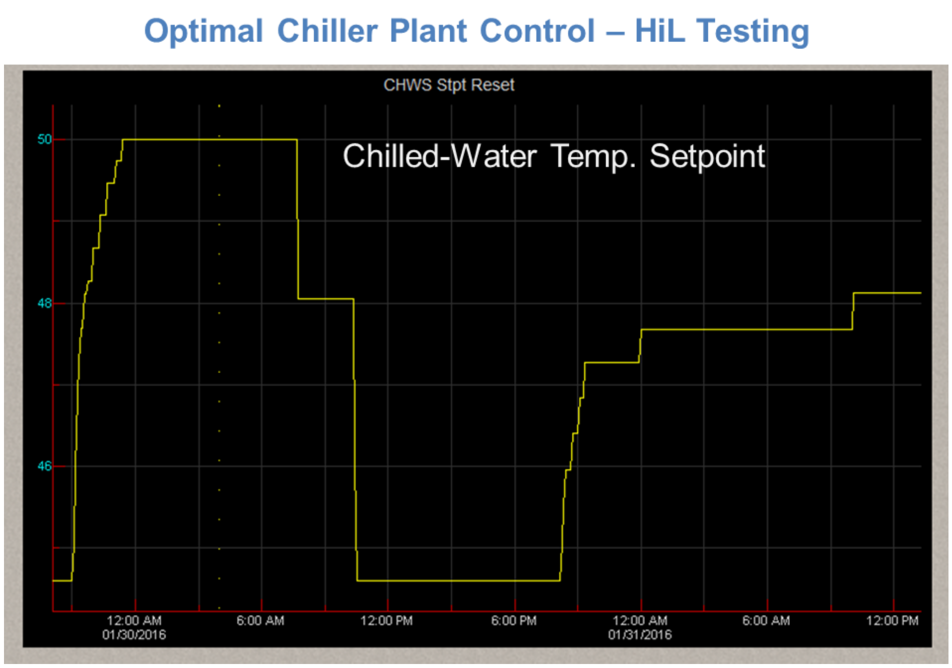


Figure 10: Low-cost optimal chiller plant control operation monitored through WebCtrl®

4. RESULTS AND ANALYSIS

This section presents the energy evaluation results by comparing different chiller plant controls and return of investment analysis for the low-cost optimal control.

4.1 Case Configurations for Case Studies

As described above, the baseline chiller plant control provides a constant chilled-water temperature setpoint of 7°C. The low-cost optimal control is realized by determining the maximum leaving chilled water temperature setpoint based on air-side load estimation. An online learning algorithm is employed to estimate the cooling coil parameters, which is used as a constraint in the optimization formulation to determine the degree of freedom to lift chilled water temperature setpoint. Table 2 provides a summary of the 4 case configurations exploited in our case studies. Each case configuration is represented by a high-fidelity whole-building HVAC system dynamics model that includes the chiller plant, AHUs, VAVs, zones, and the respective local PI controllers for each subsystem as well as supervisory controls at the chiller plant based on the Modelica platform.

Table 2: Summary of case configurations in the case studies

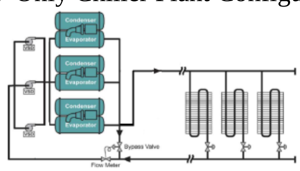
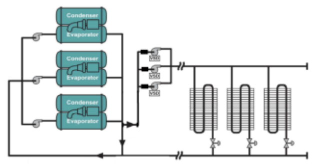
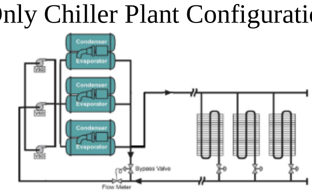
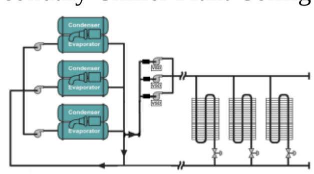
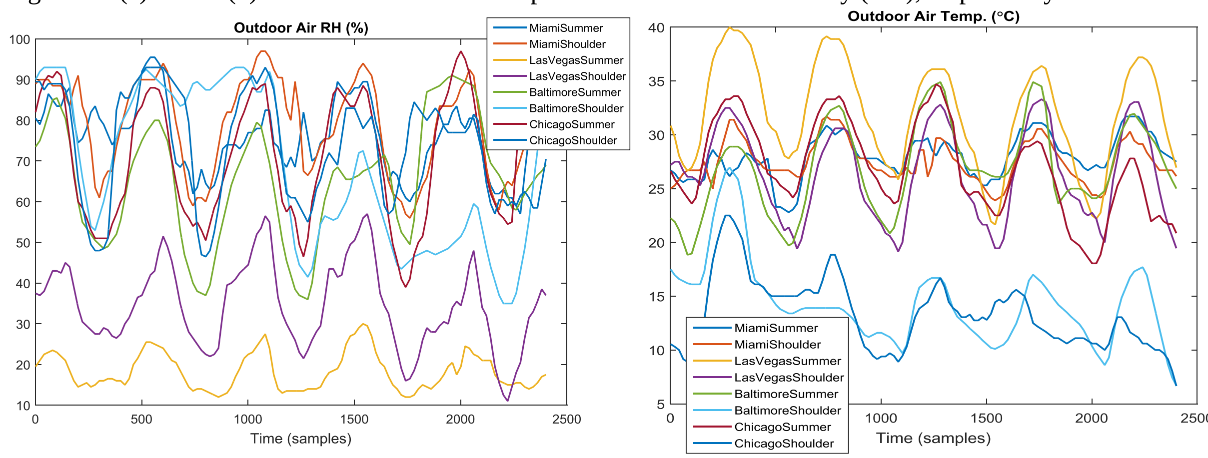
Case Configurations	**Case Configuration Definitions**
Case Configuration 1	Medium Office + Primary-Only Chiller Plant Configuration  
Case Configuration 2	Medium Office + Primary-Secondary Chiller Plant Configuration  
Case Configuration 3	Large Office + Primary-Only Chiller Plant Configuration  
Case Configuration 4	Large Office + Primary-Secondary Chiller Plant Configuration  

Table 3 lists all the weather profiles tested for each case configuration

Table 3: Weather profile scenarios for all test cases in a given case configuration

Test Cases	**Test Case Scenarios**
Test 1	Miami Summer
Test 2	Miami Shoulder
Test 3	Las Vegas Summer
Test 4	Las Vegas Shoulder
Test 5	Baltimore Summer
Test 6	Baltimore Shoulder
Test 7	Chicago Summer
Test 8	Chicago Shoulder

Figures 11(a) and 11(b) show the outdoor air temperature and relative humidity (RH), respectively.



(a) Outdoor air temperature (b) Outdoor air relative humidity (RH)

Figure 11: Outdoor air conditions of all test cases in Table 3

4.2. Comparison of Different Chiller Plant Control Algorithms with Baseline System

Figures 12 to 15 show the total chiller plant energy consumption and energy savings from the OAT-based reset, trim-respond, and the low-cost optimal control algorithms respectively for the 4 case configurations in Table 2. Table 4 shows a summary for the 4 different chiller plant control algorithms employed in this case study.

As can be observed from Figures 12 to 15, the OAT-based reset algorithm shows consistent savings across all the case configurations but is less effective in terms of achieving higher energy savings as seen from the low-cost optimal control. The trim-respond control algorithm yields comparable performance as the OAT based reset algorithm but the performance is less consistency in terms of overall energy savings achieved across all the case configurations. Note that the energy waste for trim-respond algorithm in the hotel primary secondary case configuration is mainly due to two reasons. The first reason is by trimming the CHWST setpoint up and down over time, the chiller staging will be affected and the cases with more energy consumption typically has more frequent staging behaviors of the 2nd chiller and therefore chiller 2 has more on time compared to the baseline. The second reason is by lifting the CHWST setpoint the pump will consume more power. In the case of hotel building (larger than the office), the trade-off between chiller powers and pump powers are more pronounced and therefore caused the fact that the increase of pumps' energy is more than the reduction of chillers' energy.

Table 4: Summary of chiller plant control logics employed in the case studies

Control Algorithms	Descriptions
1. Baseline Control	Constant chilled-water supply temperature (CHWST) setpoint of 7°C. Staging logic based on chiller plant load.
2.OAT-Based Reset (ASHRAE 90.1)	A linear schedule to reset CHWST setpoint based on outdoor air temperature (ASHRAE 90.1). Staging logic based on chiller plant load.
3.Heuristic-Based (Trim-Respond)	Trim-Respond logic resets CHWST setpoint based on the demand measured by AHU's chilled-water valve position. One request is generated when one chilled-water valve position becomes greater than a prescribed threshold (e.g., 90%). Staging logic based on chiller plant load.
4. Low-Cost Optimal	Maximize CHWST setpoints while performing real-time load estimation. Staging logic based on chiller plant load.

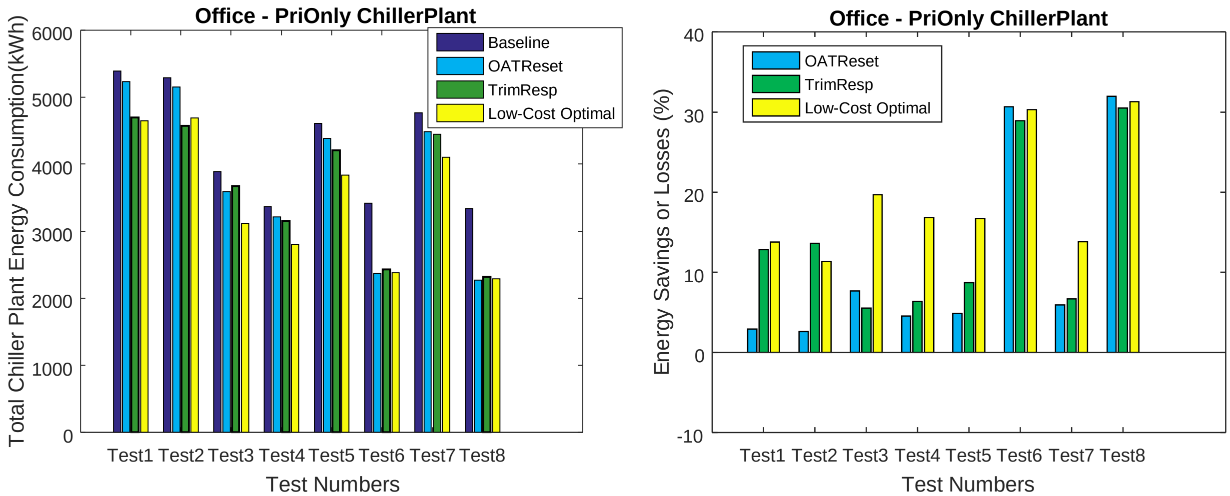


Figure 12: Comparison of energy consumption among baseline, OAT-reset, trim-respond, and low-cost optimal controls and respective energy savings to baseline (case configuration 1 – office & primary only chiller plant)

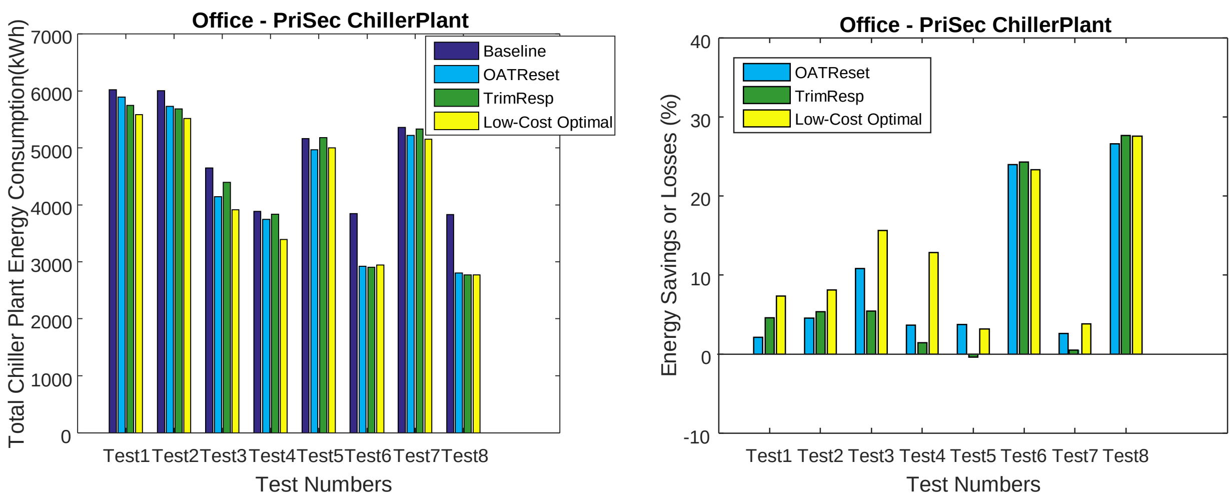


Figure 13: Comparison of energy consumption among baseline, OAT-reset, trim-respond, and low-cost optimal controls and respective energy savings to baseline (case configuration 2 – office & primary secondary chiller plant)

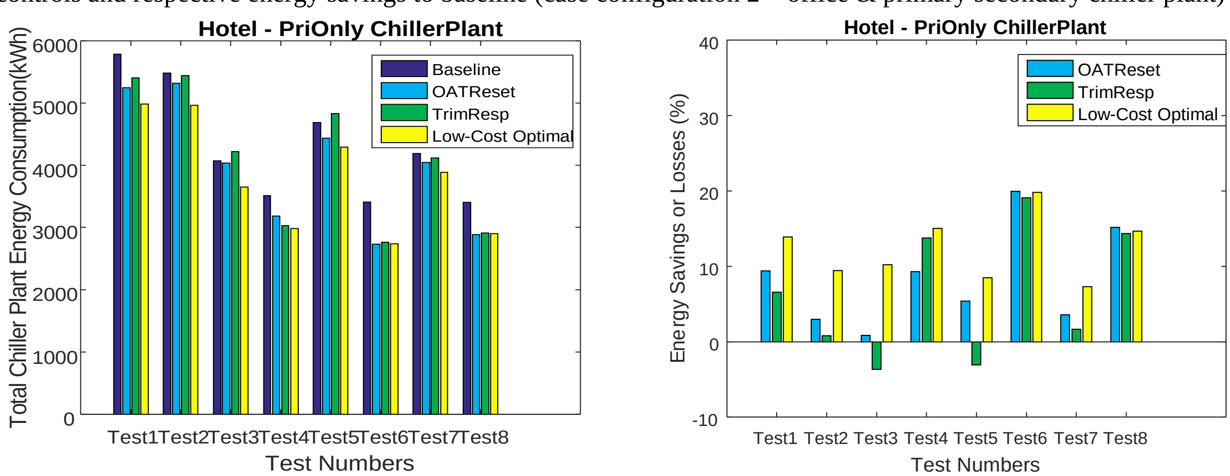


Figure 14: Comparison of energy consumption among baseline, OAT-reset, trim-respond, and low-cost optimal controls and respective energy savings to baseline (case configuration 3 – hotel & primary only chiller plant)

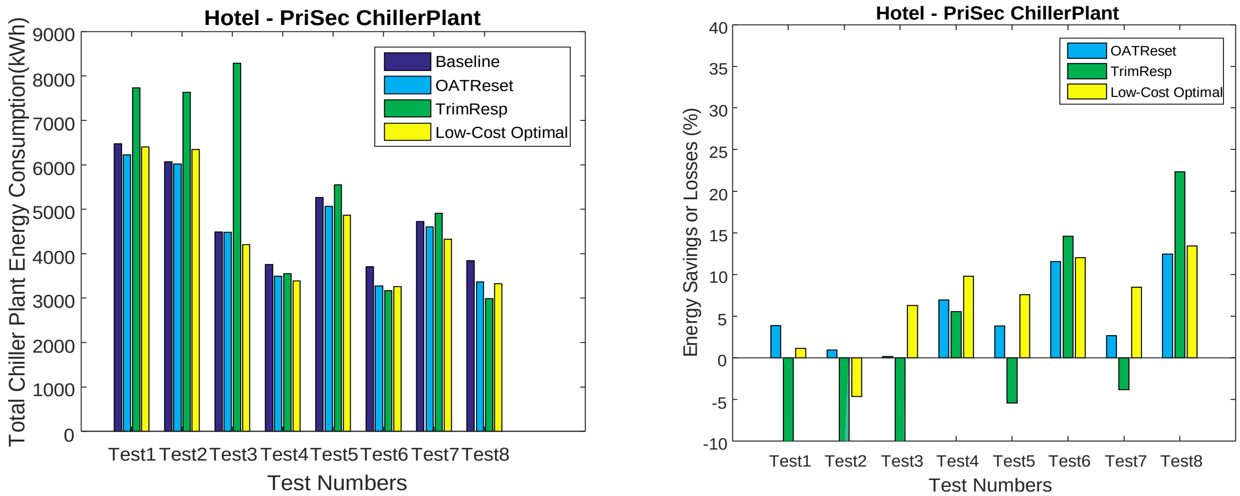


Figure 15: Comparison of energy consumption among baseline, OAT-reset, trim-respond, and low-cost optimal controls and respective energy savings to baseline (case configuration 4 – hotel & primary secondary chiller plant)

4.3 Return of Investment Analysis for Low-Cost Optimal Controls

This section presents a summary of the cost-benefit evaluation for the implementation of optimal chiller plant control algorithm. As demonstrated in the previous section, reduced energy consumption has been observed while the thermal comfort in the building zones has been maintained.

Figure 16 shows the average energy saving achieved by the low-cost optimal control across all the case configurations. The equation below was used to calculate the average energy savings for each configuration.

$$Average = 100(\sum_{test\ no.}^{1\ to\ 8} E_{total,base} - \sum_{test\ no.}^{1\ to\ 8} E_{total,optimal})/\sum_{test\ no.}^{1\ to\ 8} E_{total,base}$$

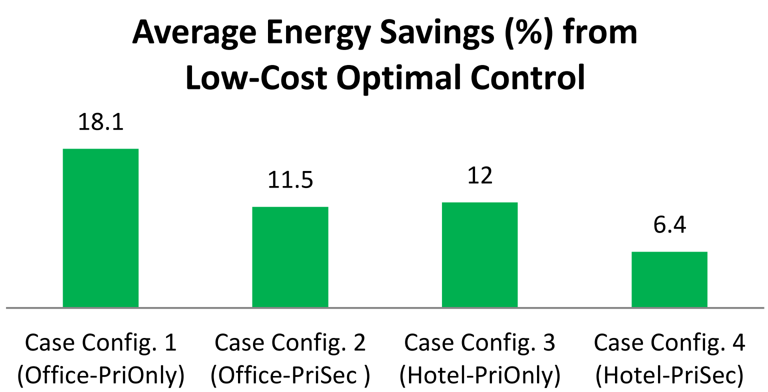


Figure 16: Average energy savings achieved by low-cost optimal control in all case configurations

The cost associated with the time required for a future commercial deployment of an optimal chiller plant control application, including customer engagement and site preparation, data mapping, and application installation and commissioning, is estimated to be approximately $1150 (14 hours) based on an hourly rate of $82 for HVAC contractor (CBEI, 2015).

An annual simulation of the medium office building model was conducted in EnergyPlus to determine the annual cooling energy consumption of the baseline system. As a result, the annual cooling capacity is determined to be 82.1 megawatt hour (Mwh) for the climate zone of Miami. Assuming an average chiller plant COP of 3 (CBEI, 2015), and a cost of electricity per kWh to be $0.126 (CBEI, 2015), and ~12.5% energy consumption reduction in chiller plant operation, then 100% of the installation cost can be recovered in 3 years, which is less than the target of 3-year payback period and meets the commercial requirement identified for this project.

5. CONCLUSIONS

In summary, the scalable low-cost optimal chiller plant control algorithm has successfully demonstrated its effectiveness through an extensive set of 128 case studies covering a variety of chiller plant load variations with each case being a weekly simulation of whole-building dynamic HVAC system models with closed loop local controls and supervisory chiller plant controls. In particular, 4 case configurations were studied in details for both Office and Hotel sites and primary only and primary secondary chiller plant configurations. For each case configuration, the chiller plant control algorithms were evaluated in typical summer and shoulder weekly profiles across the climate zones of Miami, Las Vegas, Baltimore, and Chicago, respectively. In addition, the deployment of low-cost optimal controller hardware was verified using the hardware-in-the-loop (HiL) platform and the commissioning time and effort of baseline and low-cost optimal controller were evaluated through HiL as well.

A detailed analysis through model-in-the-loop (MiL) platform suggests a promising average energy saving of ~15% for medium office building across both primary only and primary secondary chiller plant configurations. For large hotel building, an average energy saving of ~10% is achieved for both primary only and primary secondary chiller plant configurations. Through simple payback analysis, the low-cost optimal chiller plant control can be paid back in less than 3 years which exceeds the commercial requirement identified in this project.

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