CONSORTIUM for BUILDING ENERGY INNOVATION

REPORT

Title: Demonstration of Low-Cost Rapid Scalable Deployment of Optimal Controls for Buildings and Chiller Plants in MSCB

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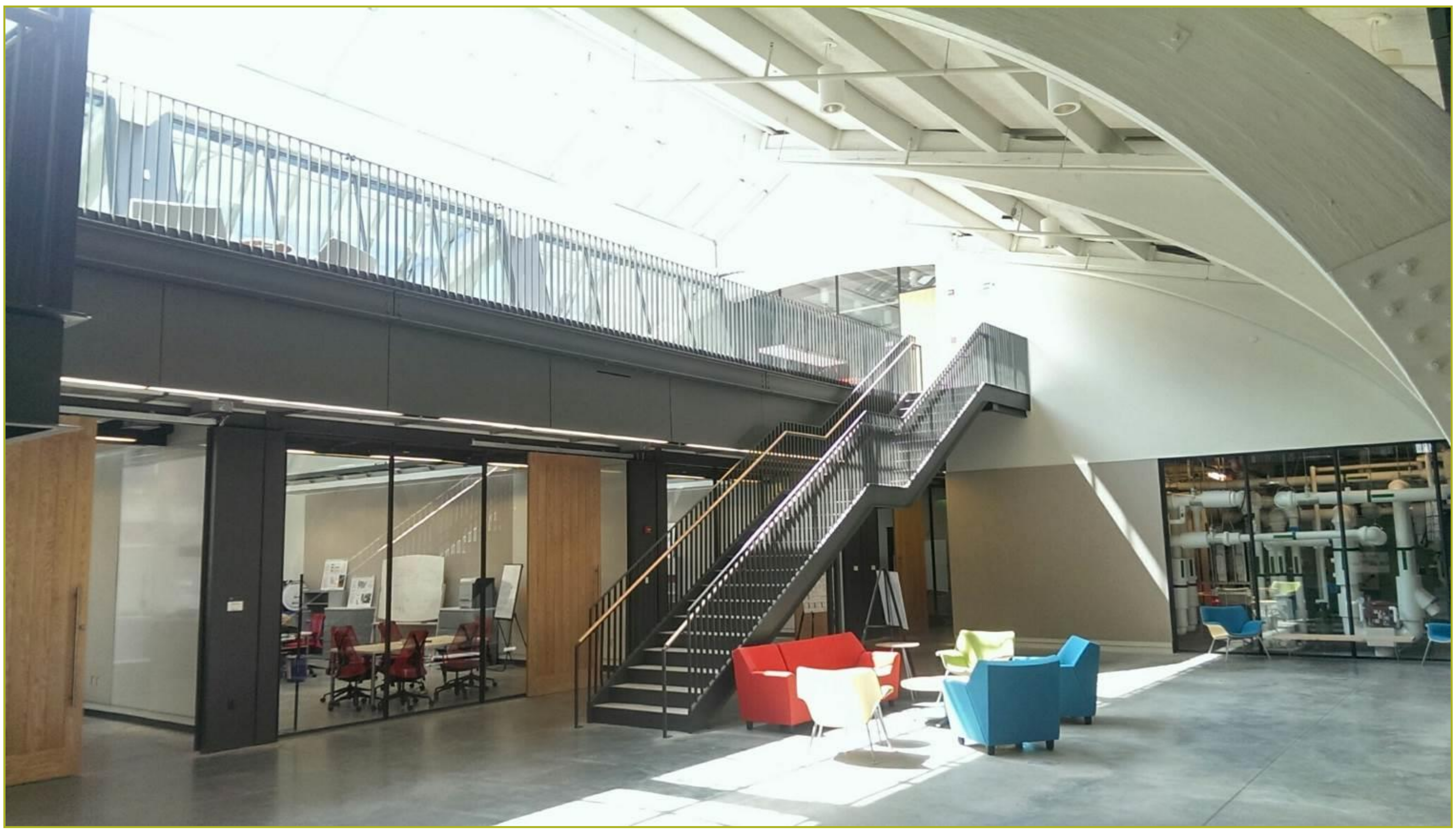

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Report Abstract

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%. 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 report presents a framework and results of using model-based design (MBD) 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 and implemented in the hardware-in-the-loop (HiL) platform. Baseline and optimization-based control algorithms were deployed in Automated Logic Corporation (ALC) controller hardware with their performance monitored through WebCtrl in real-time.

The first contribution of this work is the development of Modelica-based high-fidelity whole-building level dynamic model that successfully integrates different chiller plants, air-handling units, and building envelope and zone models. The building types of medium office and large hotel were selected and modeled in details. In particular, the building envelope and zone models were developed based on a direct translation of the selected DOE EnergyPlus reference building models, which are widely accepted in the building modeling community. The chiller plant was modeled with physics-based components such as chillers, pumps, valves, and pipes that include typical dynamics in a real chiller plant. Both primary-only and primary-secondary configurations were modeled and considered in the controls evaluation. The air handling unit was modeled based on the component models from Modelica Buildings Library developed by LBNL and includes a finite-volume based cooling coil model capable of calculating latent heat transfer.

Another significant contribution is the investigation of 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.

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D2.7.1 - Documentation of the Installation and Commissioning Process and Demonstration of the Cost-Effectiveness of Scalable Advanced Controls for MSCB Chiller Plants

Introduction

This report 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 project 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 as well as a low-cost optimal control developed internally at UTRC. Finally, this report also documents the installation time and effort to deploy the baseline and low-cost optimal chiller plant controls in the HiL platform.

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 and Modelica Buildings Library 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 hardware-in-the-loop (HiL) platform coupling with real-world chiller plant controllers to assess baseline operation. The installation time and effort for baseline and low-cost optimal control deployment were found to be 8 hrs and 12 hrs, 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 study 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.

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 [1] 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 [2] 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.

1. Dynamic Modeling of Building Envelope and Zone Models

The building types of medium office and large hotel were developed within this project. The Modelica building models were developed following 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.

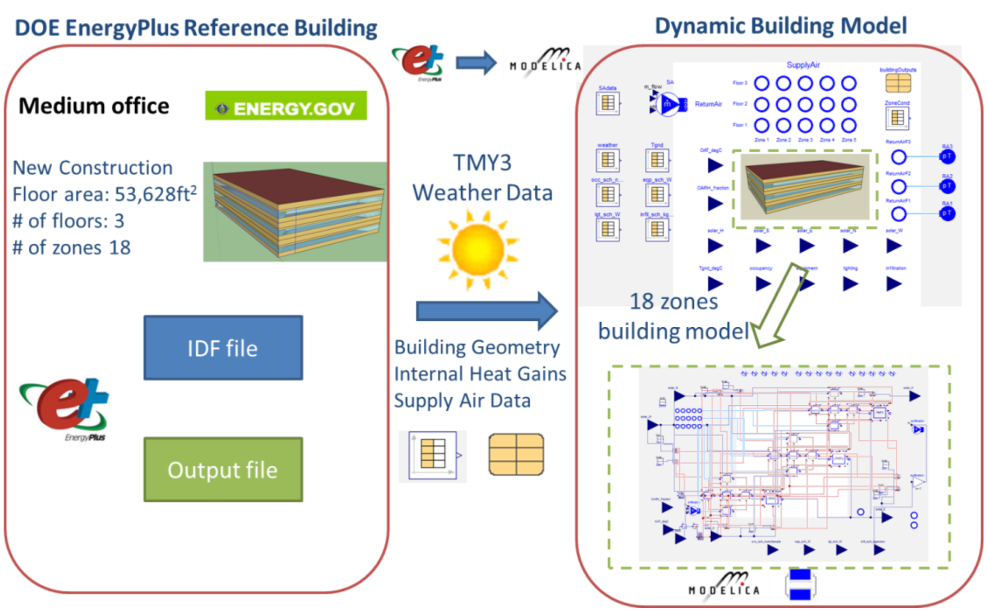


Figure 1: Illustration of dynamic modeling approach for building envelope and zone following DOE's EnergyPlus reference building (medium office)

For the purpose of chiller plant controls evaluation, a key variable is the heat flow rate (load) aggregated from the building side, which represents the amount of heat needs to be rejected by the chiller plant. Figure 2 shows the comparisons of heat flow rate between EneryPlus and Modelica model we developed using a 13 day simulation including the summer design day selected by the EnergyPlus model. Table 1 shows the mean percent errors and standard deviation of heat flow rate predictions between

EnergyPlus and the Modelica model. Overall, the developed building model shows good trend-wise predictions with standard deviations less than 5% for all three floors in the medium office building.

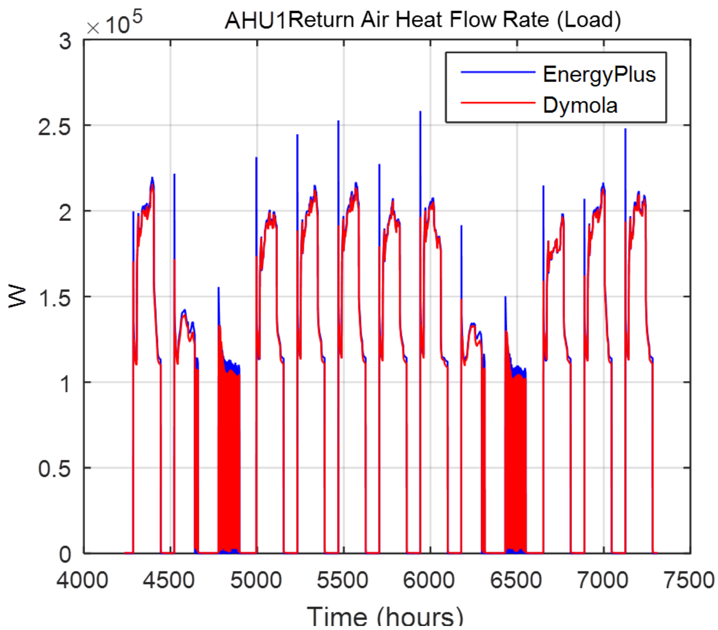


Figure 2: Comparison of return air heat flow rate from EnergyPlus model and Modelica model (medium office)

Table 1: Comparison of mean errors and standard deviation of heat flow rate between EnergyPlus and Modelica model (medium office)

Systems	Mean Errors (%)	Standard Deviation (%)
AHU1	2.33%	3.13%
AHU2	3.28%	2.84%
AHU3	7.71%	4.97%

2. Dynamic Modeling of Air Handling Unit (AHU)

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. Figure 3 shows the AHU model layout in Dymola.

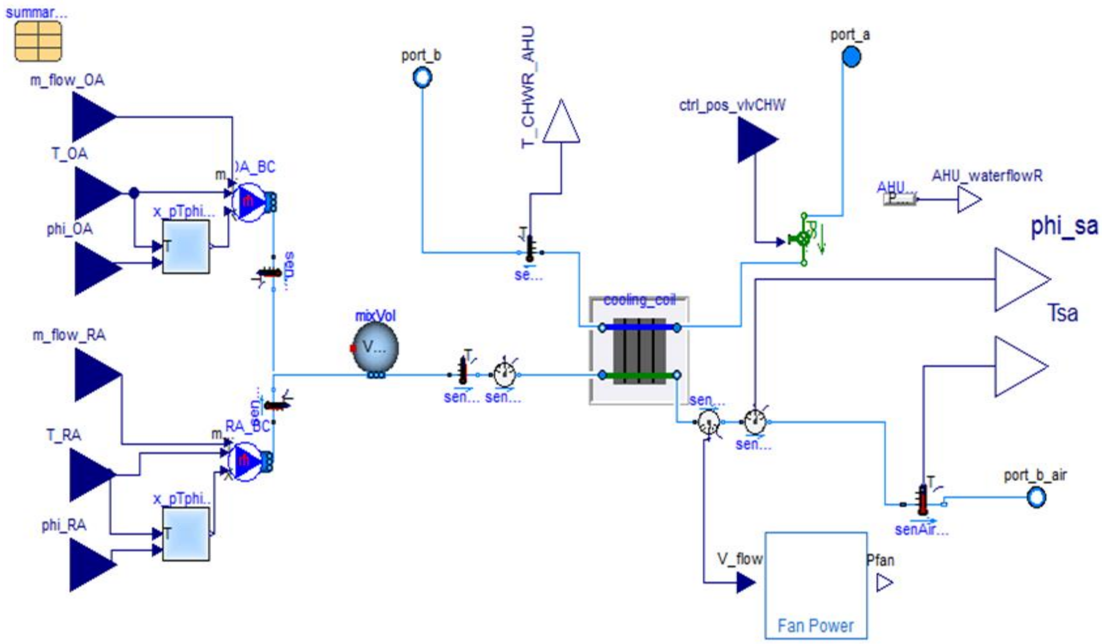
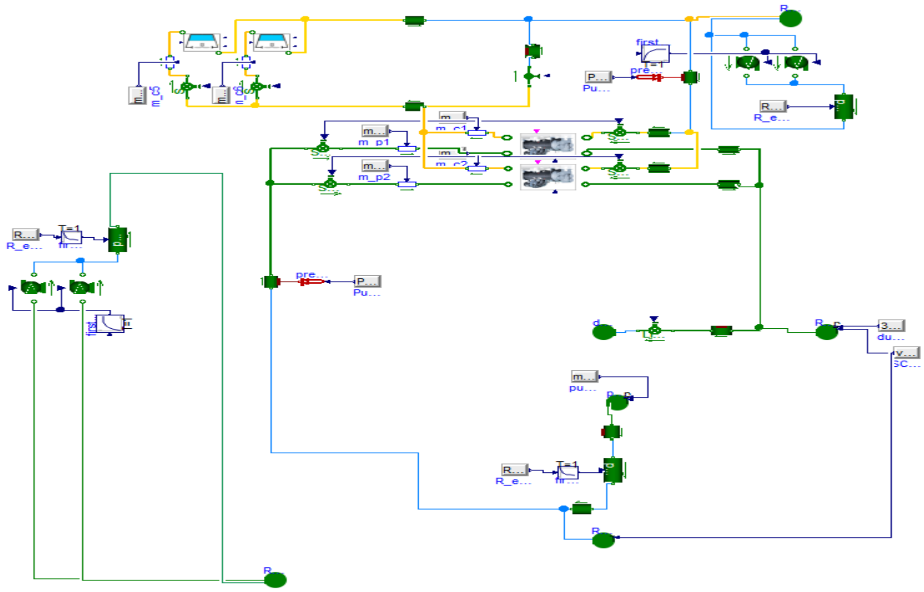


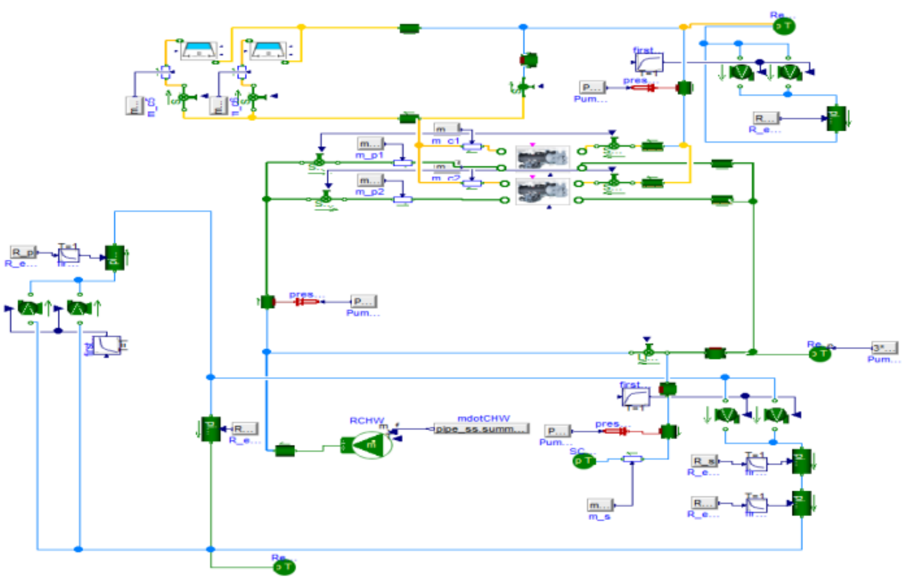
Figure 3: AHU model layout in Dymola

3. Dynamic Modeling of Chiller Plant

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. Both primary-only and primary-secondary chiller plant configurations were developed. Figure 4(a) and 4(b) shows the schematic of the chiller plant model with primary-only and primary-secondary configurations.



(a) Primary-Only chiller plant configuration



(b) Primary-Secondary chiller plant configuration

Figure 4: Chiller plant model layout in Dymola

4. Development of Chiller Plant Controls Library

A ChillerPlantControl Library was developed based on Modelica Standard Library 3.2.1, which was built based on the baseline control logics available from Automated Logic (ALC)'s WebCtrl® program. Figure 5 shows an overview of the Library that includes chiller staging, pump and fan PI control logics.

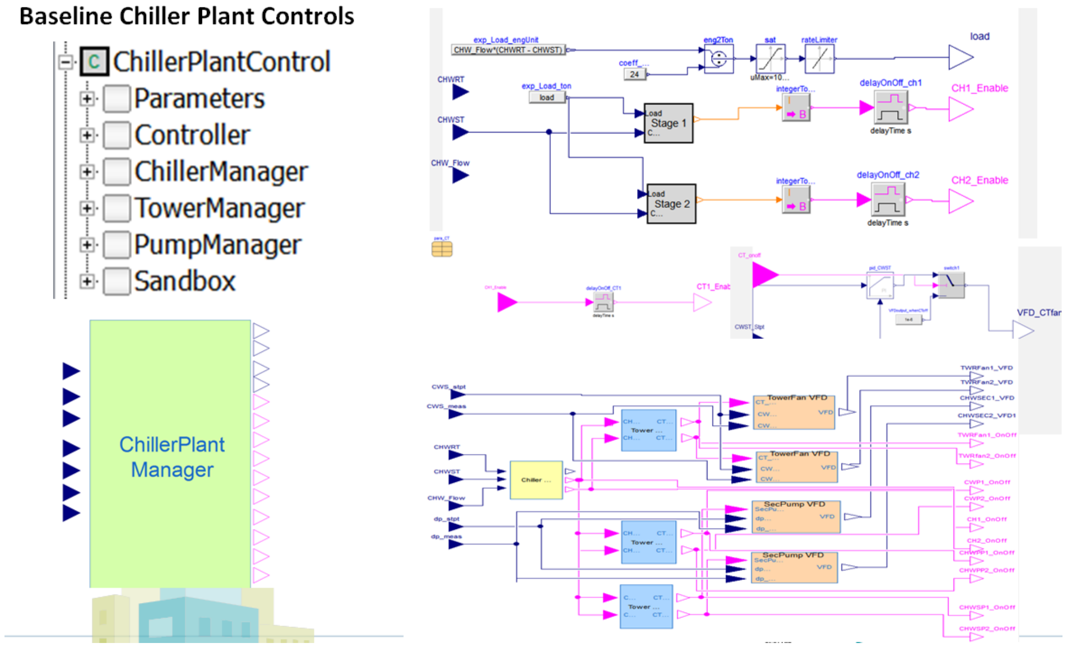


Figure 5: Chiller plant control logic in Dymola

5. 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 6 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.

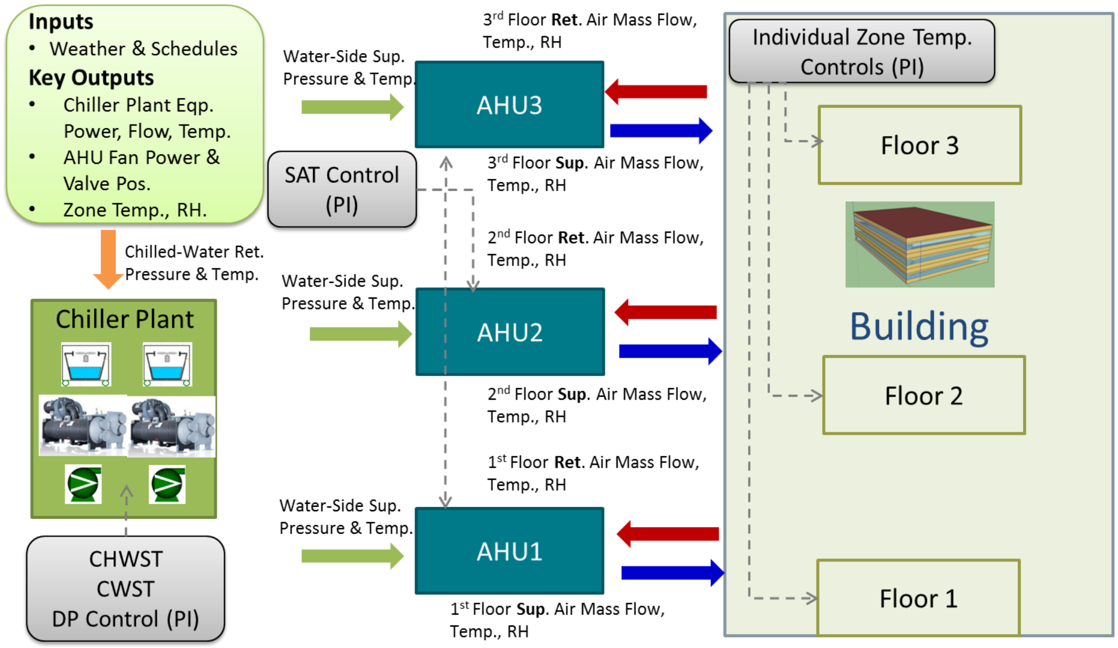
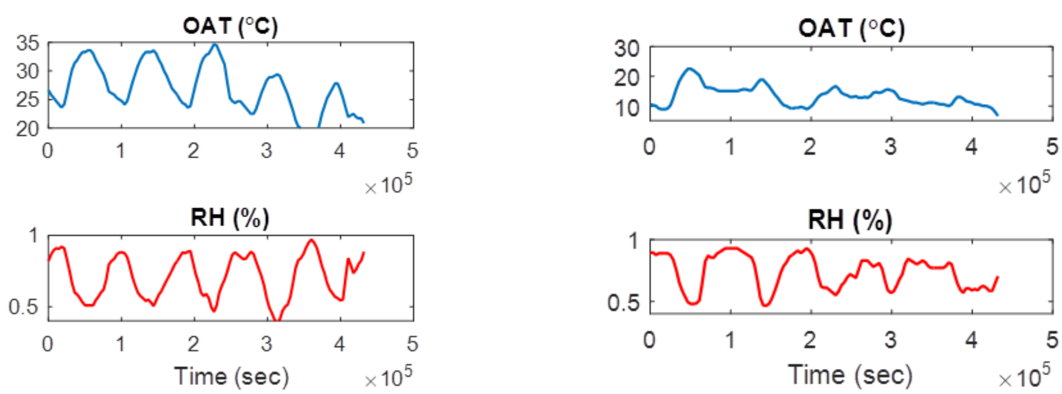


Figure 6: Schematic of model integration for building HVAC and chiller plant systems

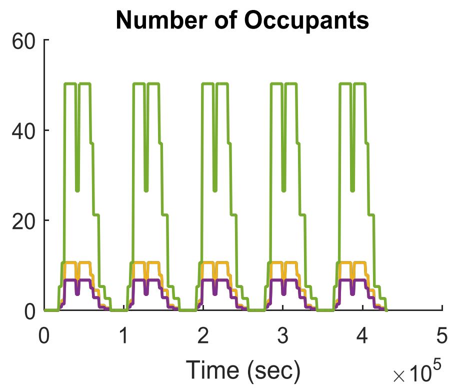
6. Model Inputs and Outputs

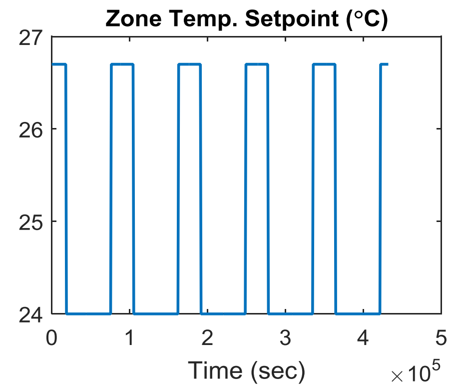
Figure 7 shows the model inputs of outdoor air temperature (OAT), relative humidity (RH), occupancy schedule for different zones as well as zone temperature sepoint schedule using Chicago weather as the example for illustration purpose. Two weekly profiles were selected in the energy evaluation phase. 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 7: Selected inputs to the integrated building HVAC and chiller plant model

Table 2 shows the baseline control setpoints selected for AHU and chiller plant systems.

Table 2: Baseline control setpoints for AHU and chiller plant systems (medium office)

Systems	Setpoints	Values
Baseline AHU & Zone Control	AHU SAT setpoint	55F
	Zone setpoint (occ./unocc.)	75F/80F
Baseline Chiller Plant Control	CHWST setpoint	45F
	CWST setpoint	80F
	Pressure diff. setpoint	30kPa

The key outputs from the integrated model include power consumption from chillers, pumps, and cooling tower fans as well as AHU fans. The building side zone temperature and RH are also logged to determine if chiller plant can provide sufficient cooling load to maintain the comfort requirements.

Baseline Control Deployment in Hardware-in-the-Loop (HiL) Platform

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.

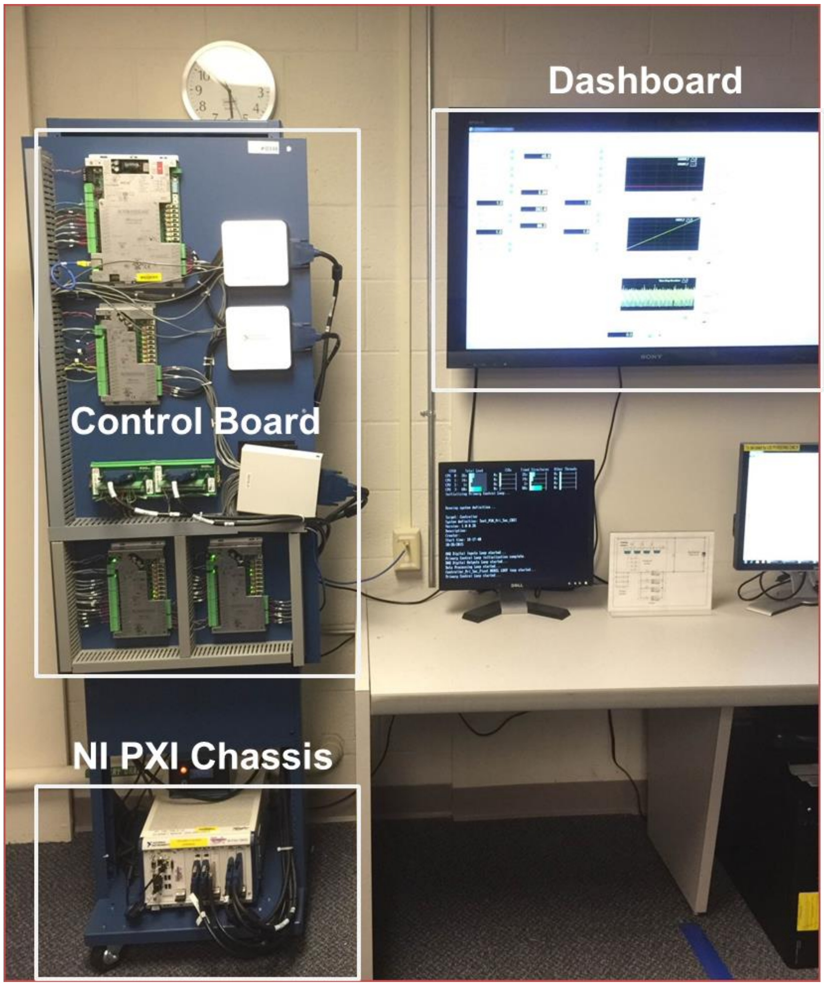


Figure 8: Hardware-in-the-Loop setup at UTRC

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

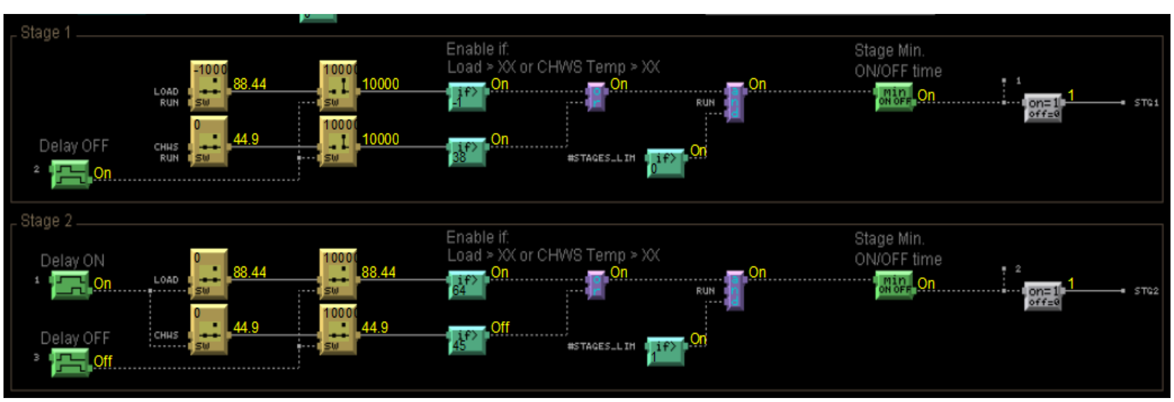


Figure 9: Chiller staging control logic implemented in WebCtrl

The installation time and effort for baseline deployment process are documented in Table 3.

Table 3: Installation time and effort for baseline control deployment process

Primary Secondary System		Time Consumed (hr.)	Remarks
Control Program Set Up	Pull control programs from PSM control library	0.5	
	Configure parameters	1	Expert judgment to configure parameters
Deployment	Configure control system network environment	0.5	Configure control board BACnet IP address, instances, etc.
	Configure control system structure	0.5	
	Deploy control program to control boards	0	Simple one click process: almost no time consumed if everything configured properly
Tuning	Tune control parameters	3	Tuning of PID gains and sequencing parameters to ensure smooth operation
	Verify operation	2.5	Ensure operation is sound and stable
Total (hr)		8	

Figure 10 illustrates the real-time trend results from HiL testing for baseline chiller plant control operation that was demonstrated to run smoothly for 3 consecutive days with reasonable results including multiple chillers start up and shut down operation without any numerical robustness issues.

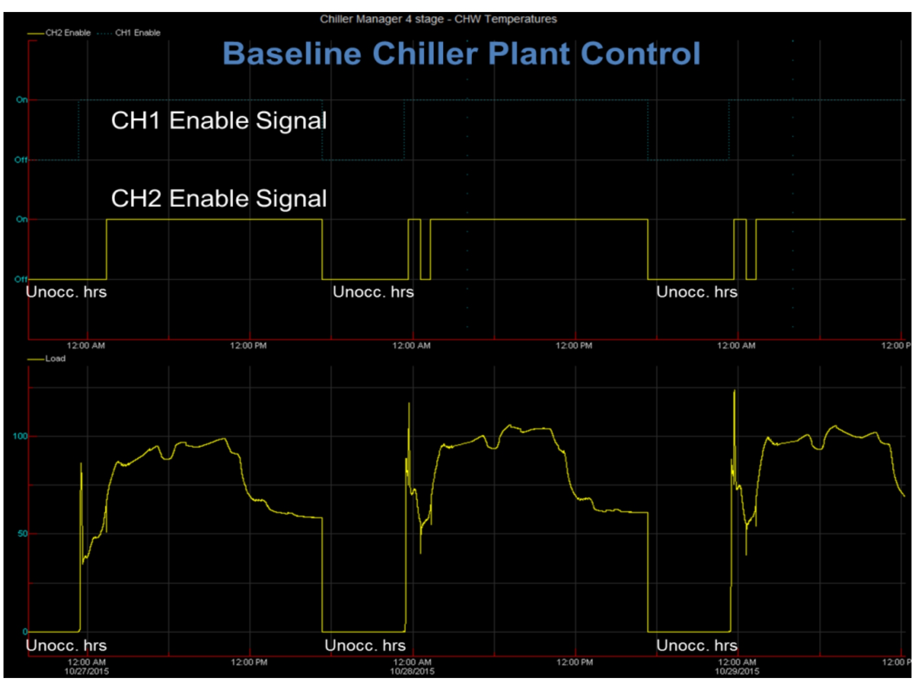


Figure 10: HiL testing results of chiller staging and load profiles monitored through WebCtrl

Low-Cost Optimal Chiller Plant Control Deployment in Hardware-in-the-Loop (HiL) Platform

In this section, the formulation of low-cost optimal chiller plant control as well as the installation and commissioning details will be described.

1. Formulation of Low-Cost Optimal Chiller Plant Control

The low-cost optimal chiller plant control applies water-side optimization 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.

The low-cost optimal chiller plant control only uses the following measurements that are typically available in practice.

- AHU mixed air temperature
- AHU supply air temperature
- AHU air flow rate
- AHU chilled-water valve position
- Chiller plant leaving water temperature

2. Installation and Commissioning of Optimal Chiller Plant Control Algorithm

As documented in [3], the cost of commissioning advanced control technology as an overlay of existing BAS systems is driven by (a) the time required to develop interfacing requirements with the BAS system and (b) level of expertise required for application commissioning. This project demonstrated a reduced time to commission and reduced needs for advanced engineering skills to deploy optimal chiller plant control algorithm through automated installation and execution of an advanced control overlay. The steps undertaken to install chiller plant controls are summarized in Figure 11.

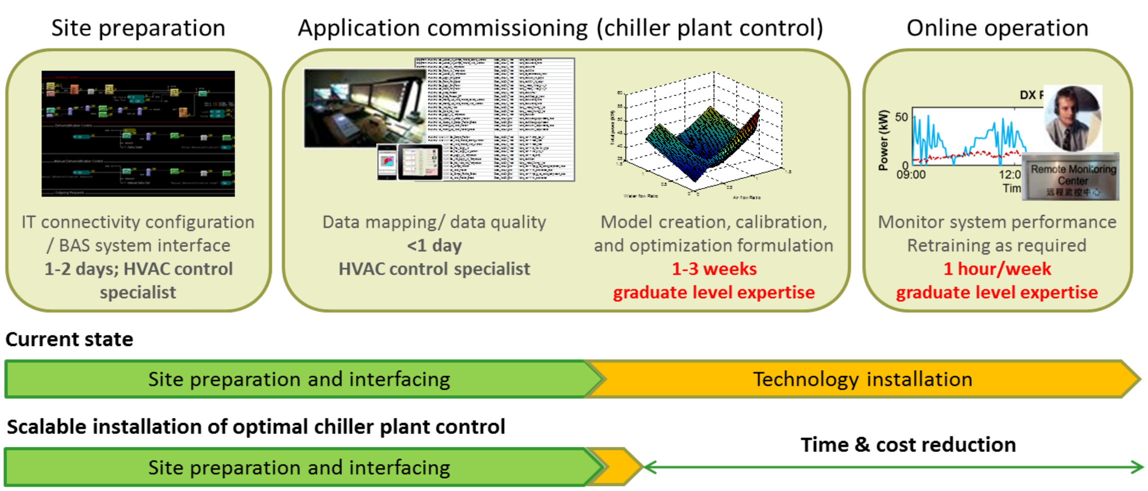


Figure 11: Illustration of installation and commissioning effort

As described earlier, for the optimal chiller plant control employed in this study, only four data points from each AHU are needed in order to formulate the optimization problem. A data-mapping step was required to determine the correspondence of the required sensor and control inputs to the associated data point addresses within the building automation system. In this case, given the limited number of data points to be used in the optimization, the task of data mapping is quite trivial and can be completed within an hour. The data mapping work doesn't require advanced engineering skills and can be executed by a HVAC contractor.

Figure 12 shows the schematic of optimal chiller plant control deployment as an overlay of BAS system. After the data mapping process, the optimal chiller plant control algorithm was written in MATLAB and communicated to Automated Logic (ALC)'s WebCtrl® server through the internet as shown in Figure 12. The hardware-in-the-loop setup for the low cost optimal control deployment is the same as the baseline system shown in Figure 8.

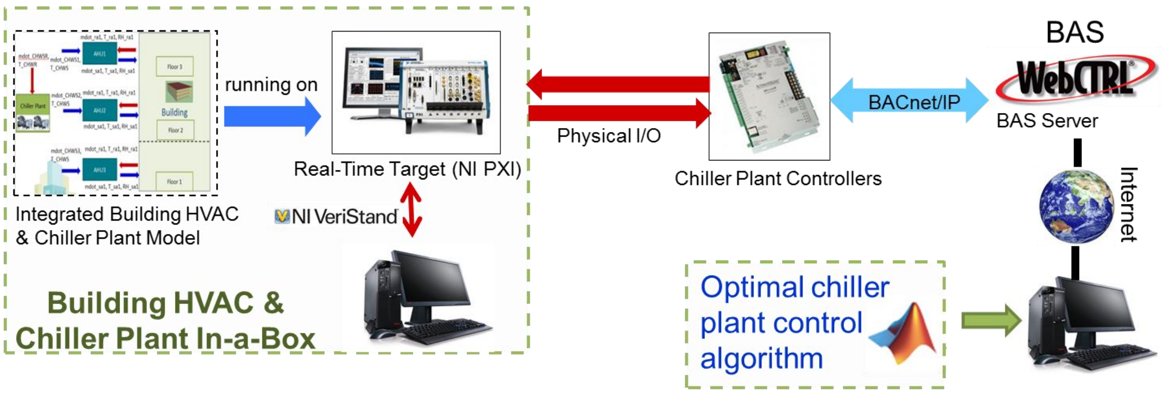


Figure 12: Optimal chiller plant operation monitored through WebCtrl®

The chiller staging logic remains the same for the optimal chiller plant algorithm and baseline system as shown in Figure 9. The installation time and effort for optimal control deployment process are documented in Table 4.

Table 4: Installation time and effort for low-cost optimal control deployment process

Primary	Secondary System	Time Consumed (hr.)	Remarks
Control Program Set Up	Pull control programs from PSM control library	0.5	
	Configure parameters	1	Expert judgment to configure parameters
Deployment	Configure control system network environment	0.5	Configure control board BACnet IP address, instances, etc.
	Data mapping of additional points for optimal control	1	Only 4 additional points per AHU need to be mapped.

	Configure control system structure	0.5	
	Deploy control program to control boards	0	Simple one click process: almost no time consumed if everything configured properly
Tuning	Tune control parameters	7.5	Tuning of PID gains and sequencing parameters to ensure smooth operation Tuning of parameters for optimal chiller plant controls
	Verify operation	3	Ensure operation is sound and stable
	Total (hr)	14	

Table 5 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 5: 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 13 shows the chilled-water temperature setpoint commanded by the low-cost optimal control during HiL testing.

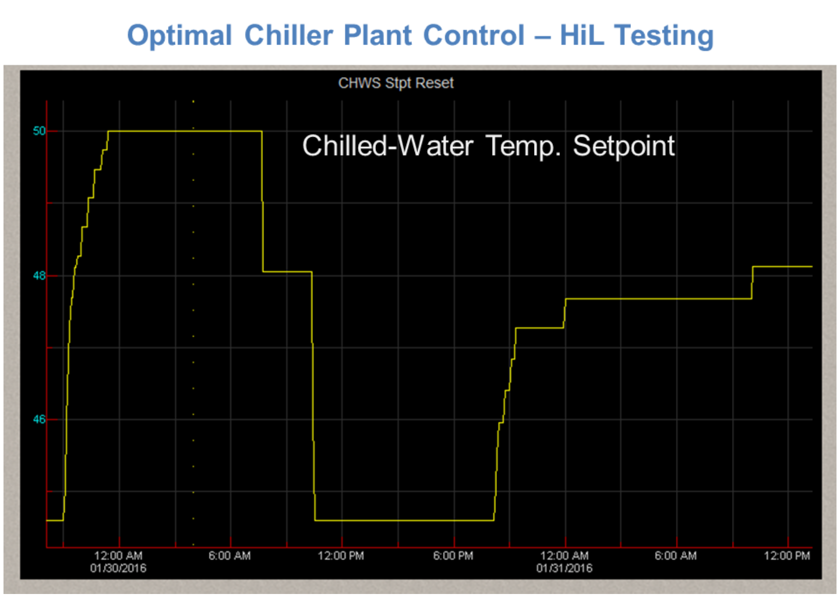


Figure 13: Low-cost optimal chiller plant control operation monitored through WebCtrl®

For each weekly simulation profile, sanity check was performed to examine the AHU supply air temperature and zone air temperature controllers' tracking performance to evaluate if cooling load and comforts can be maintained for low-cost optimal control compared to baseline system operation. As an example, Figure 14 shows the comparison of AHU supply air temperature control between baseline and low-cost optimal control. As can be observed, even if the chilled-water supply temperature was raised by the optimal control, the air-side cooling load can be still maintained very well.

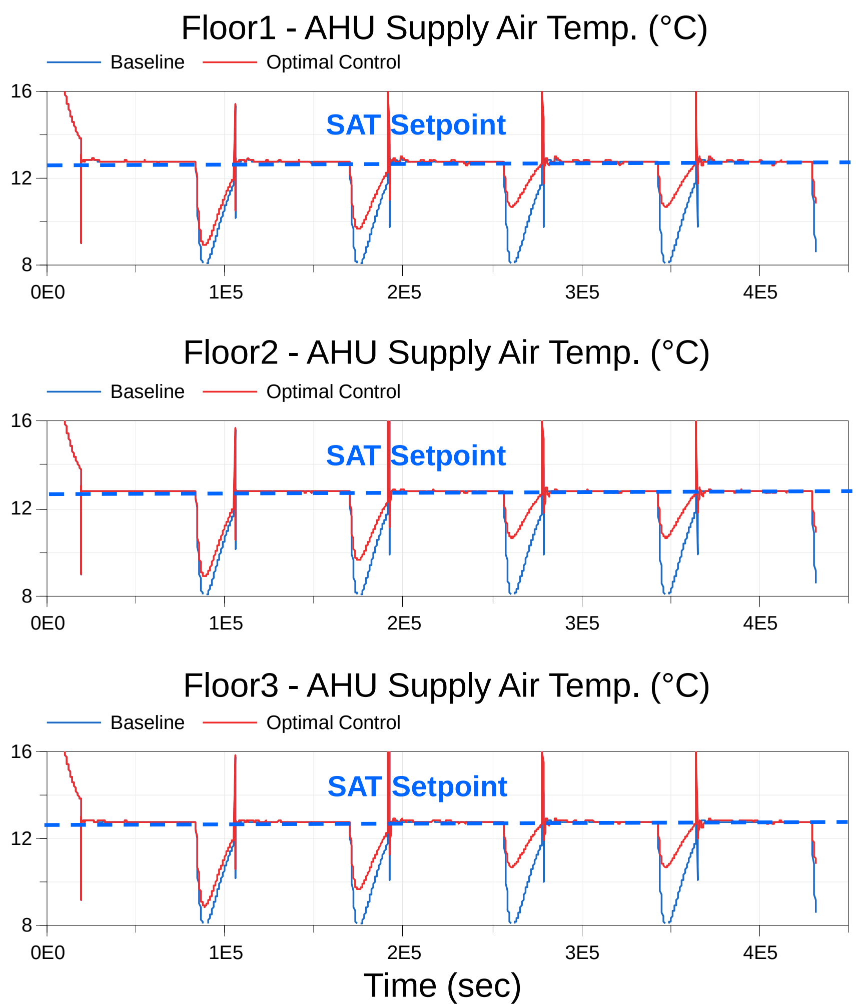


Figure 14: Comparison of AHU supply air temperature between baseline and optimal control

Figure 15 shows the zone temperature profile during the operation of optimal chiller plant control. As can be observed, the zone temperature of all 15 zones (medium office) were maintained very well relative to the cooling setpoint, which indicates the zone-level comfort was not affected by the operation of chilled-water supply temperature variation introduced by the optimal control algorithm.

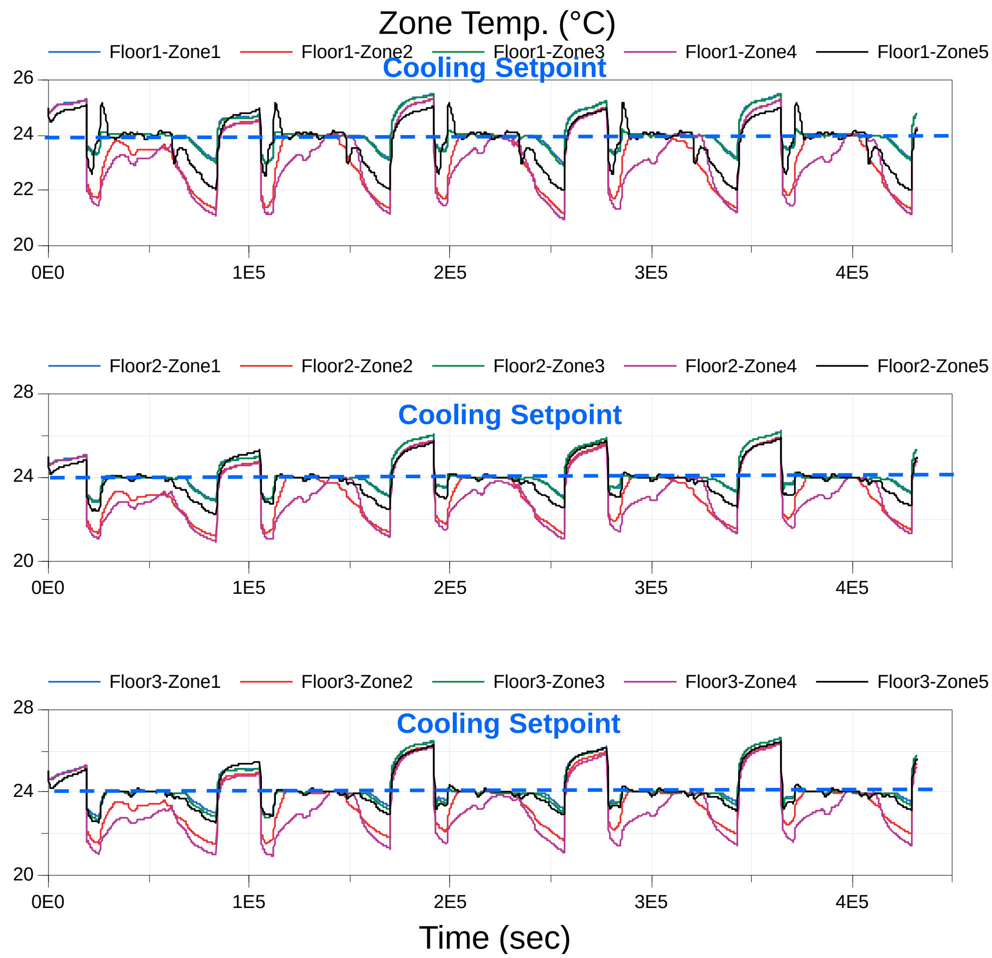


Figure 15: Zone temperature profile when optimal chiller plant control is operating

Energy Analysis of Different Chiller Plant Controls

This section presents the energy evaluation results and return of investment analysis for the low-cost optimal control.

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 6 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 6: Summary of case configurations in the case studies

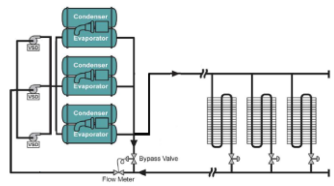
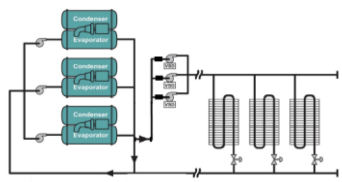
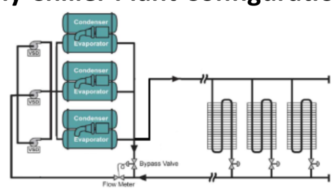
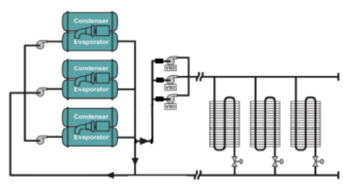
Case Configurations	Case Configuration Definitions
Case Configuration 1	**Medium Office + Primary-Only Chiller Plant Configuration**  
Case Configuration 2	**Medium Office + Primary-Secondary Chiller Plant Configuration**  
Case Configuration 3	**Large Office + Primary-Only Chiller Plant Configuration**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

Table 7 lists all the weather profiles tested for each case configuration:

Table 7: 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 16 through 18 show the outdoor air temperature, relative humidity (RH), and wet-bulb temperature, respectively.

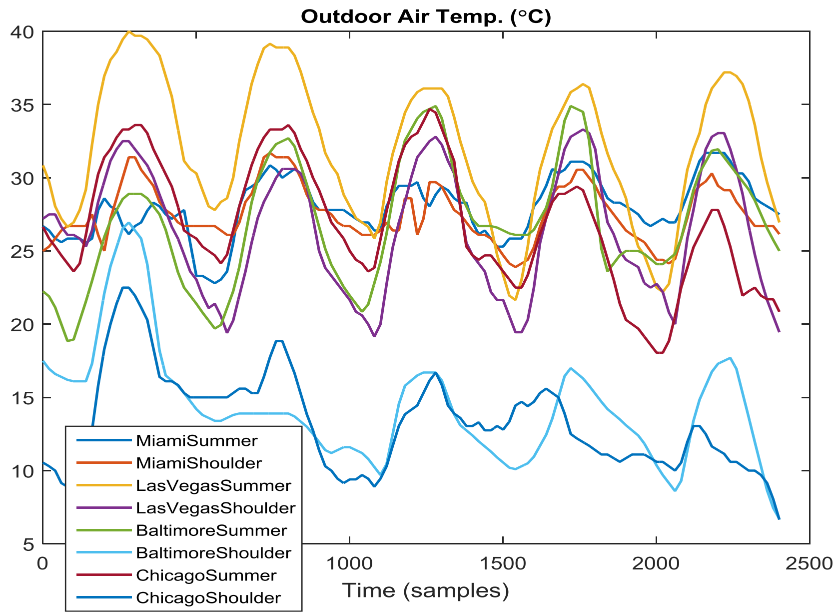


Figure 16: Outdoor air temperature of all test cases in Table 7

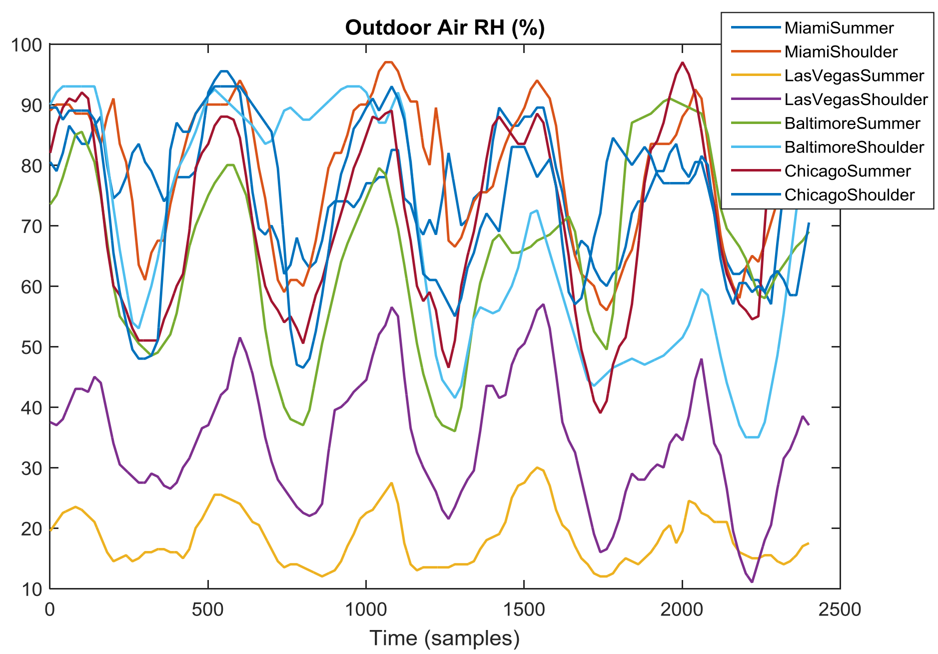


Figure 17: Outdoor air RH of all test cases in Table 7

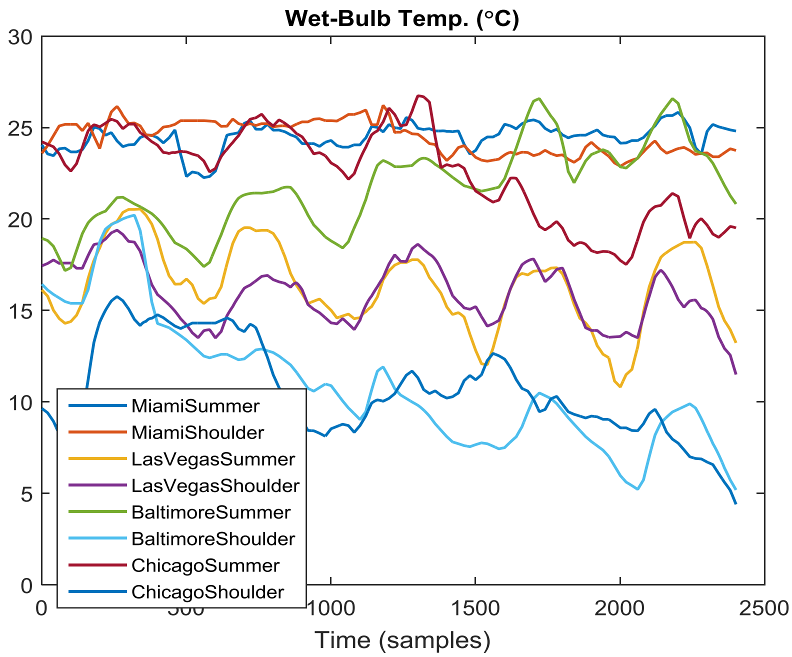


Figure 18: Outdoor air wet-bulb temperature of all test cases in Table 7

2. Comparison of Low-Cost Optimal Chiller Plant Control with Baseline System

Figures 19 to 22 show the total chiller plant energy consumption and energy savings from the low-cost optimal control for the 4 case configurations in Table 6. Compared to other test profiles across all case configurations, the higher energy savings in the shoulder season for test 6 (Baltimore Shoulder) and test 8 (Chicago Shoulder) were achieved when the 2nd chiller was turned off most of the time. The average energy saving based on the results below will be presented in the next section.

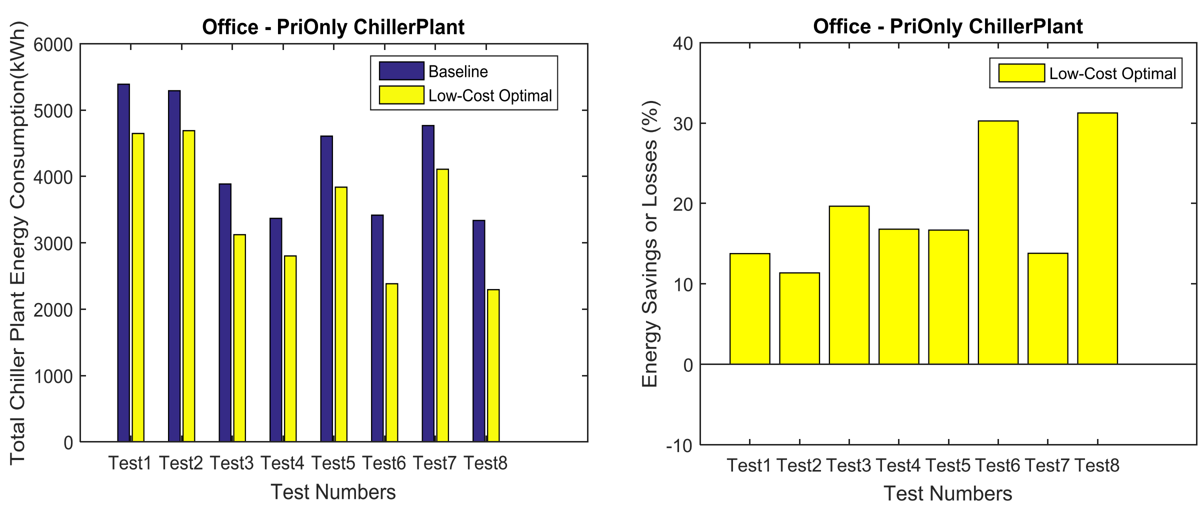


Figure 19: Comparison of energy consumption of baseline and low-cost optimal control and energy savings (case configuration 1 – office & primary only chiller plant)

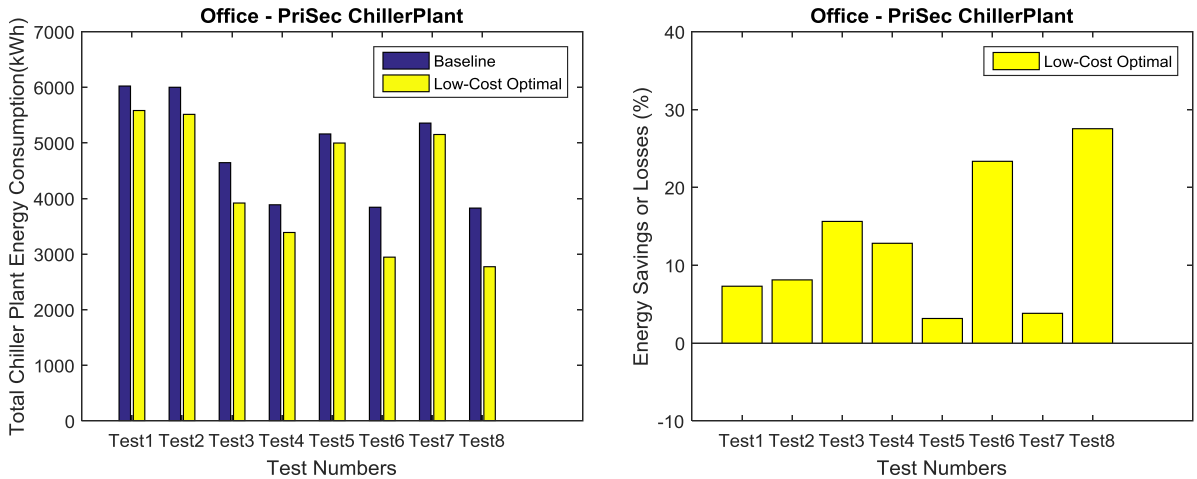


Figure 20: Comparison of energy consumption of baseline and low-cost optimal control and energy savings (case configuration 2 – office & primary secondary chiller plant)

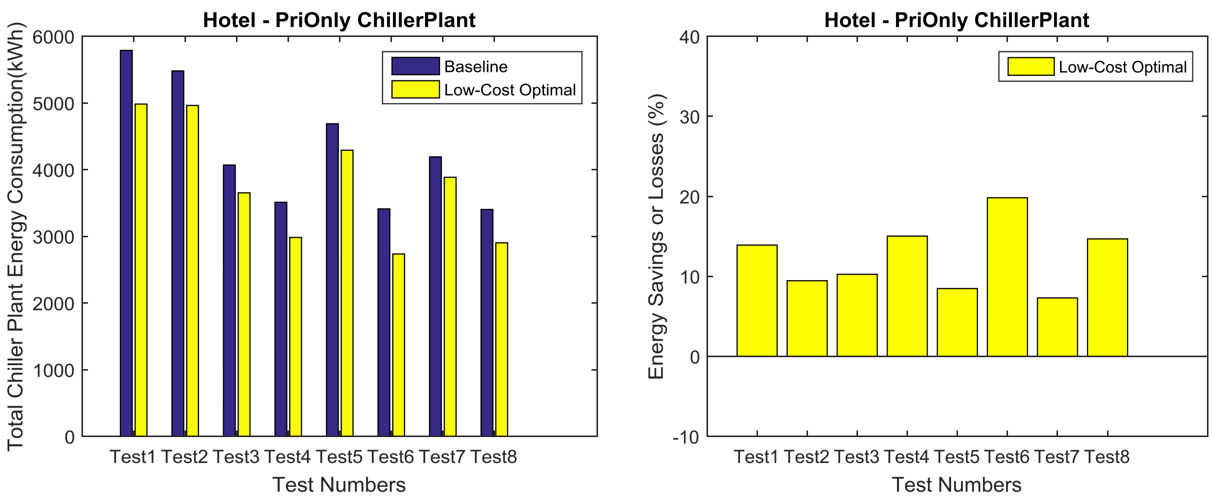


Figure 21: Comparison of energy consumption of baseline and low-cost optimal control and energy savings (case configuration 3 – hotel & primary only chiller plant)

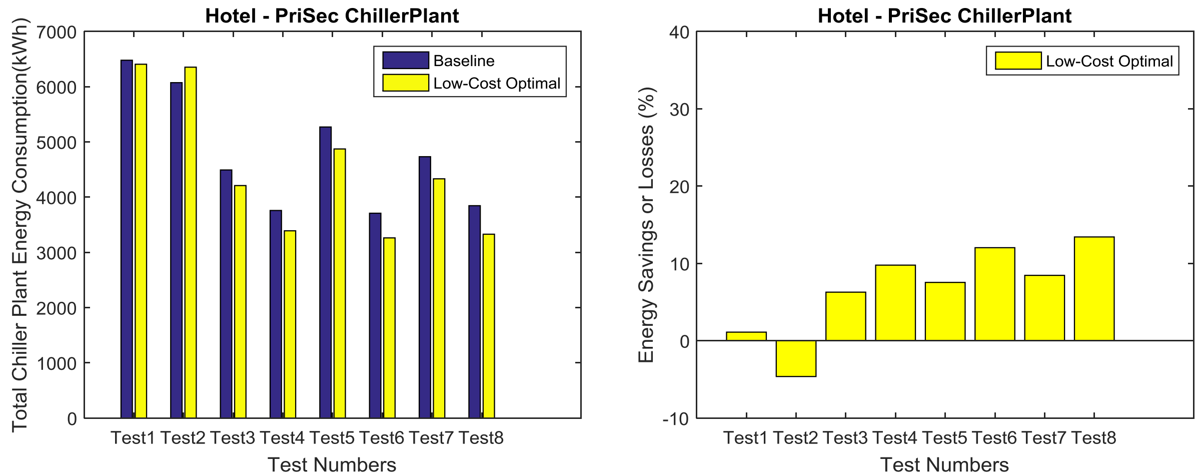


Figure 22: Comparison of energy consumption of baseline and low-cost optimal control and energy savings (case configuration 4– hotel & primary secondary chiller plant)

3. Comparison of Different Chiller Plant Controls with Baseline System

Figures 23 to 26 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 6. Table 8 shows a summary for the 4 different chiller plant control algorithms employed in this case study.

As can be observed from Figures 23 to 26, 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 8: Summary of chiller plant control logics employed in this study

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.

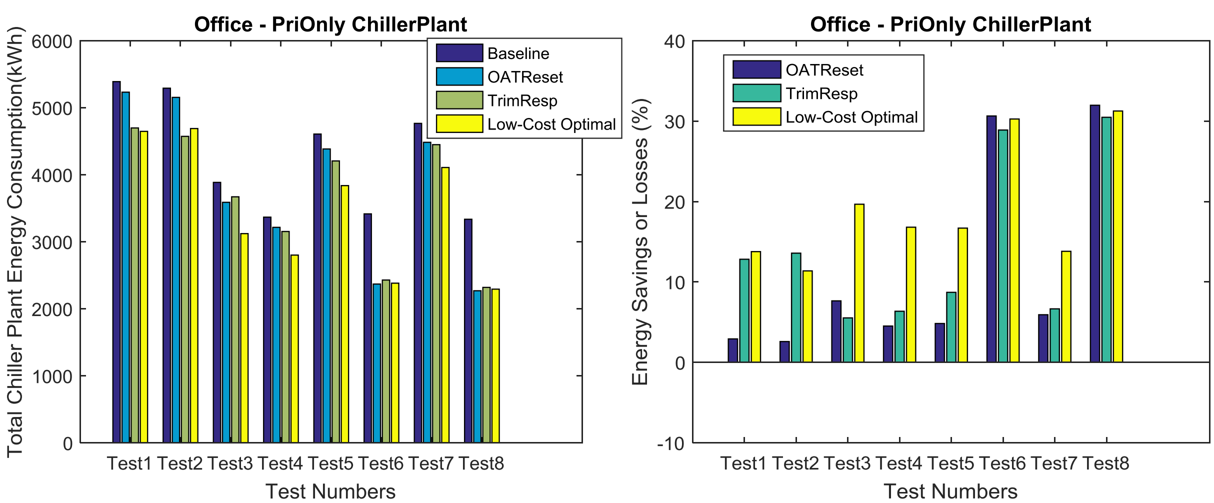


Figure 23: Comparison of energy consumption among baseline, OAT-reset, trim-respond, and low-cost optimal controls and respective energy savings to baseline (case configuration 1 – office & primary only chiller plant)

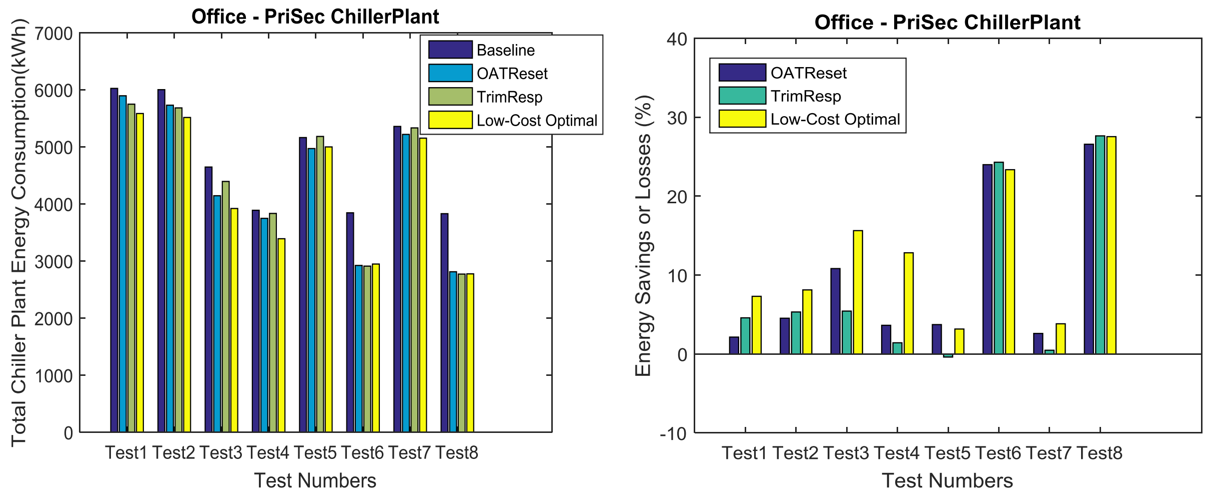


Figure 24: Comparison of energy consumption among baseline, OAT-reset, trim-respond, and low-cost optimal controls and respective energy savings to baseline (case configuration 2 – office & primary secondary chiller plant)

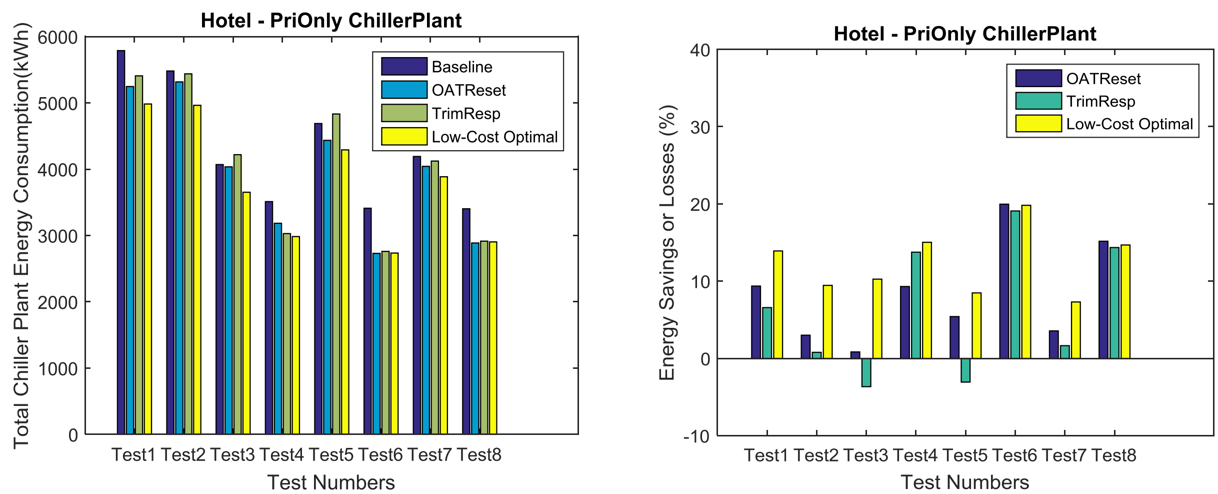


Figure 25: Comparison of energy consumption among baseline, OAT-reset, trim-respond, and low-cost optimal controls and respective energy savings to baseline (case configuration 3 – hotel & primary only chiller plant)

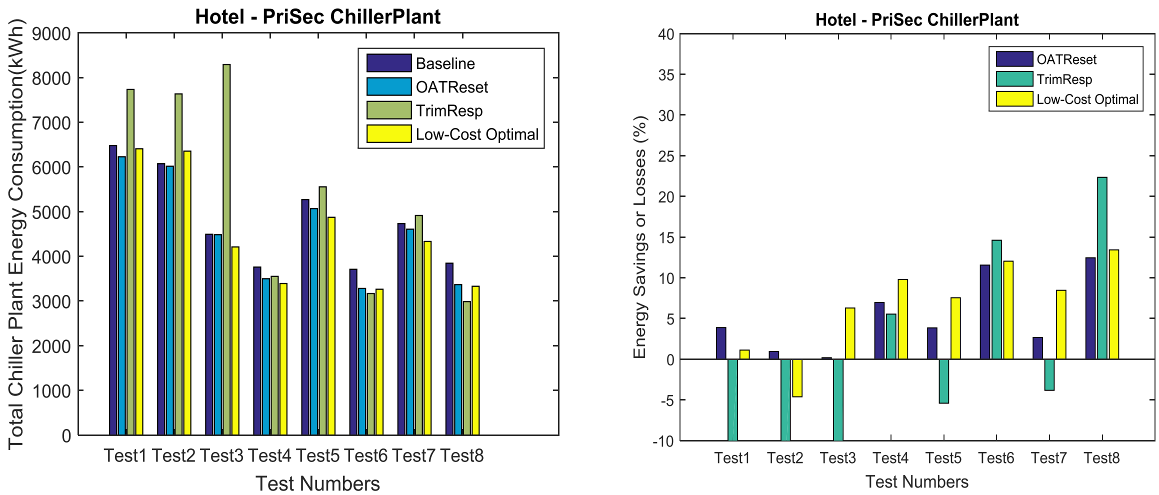


Figure 26: Comparison of energy consumption among baseline, OAT-reset, trim-respond, and low-cost optimal controls and respective energy savings to baseline (case configuration 4 – hotel & primary secondary chiller plant)

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 27 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.

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

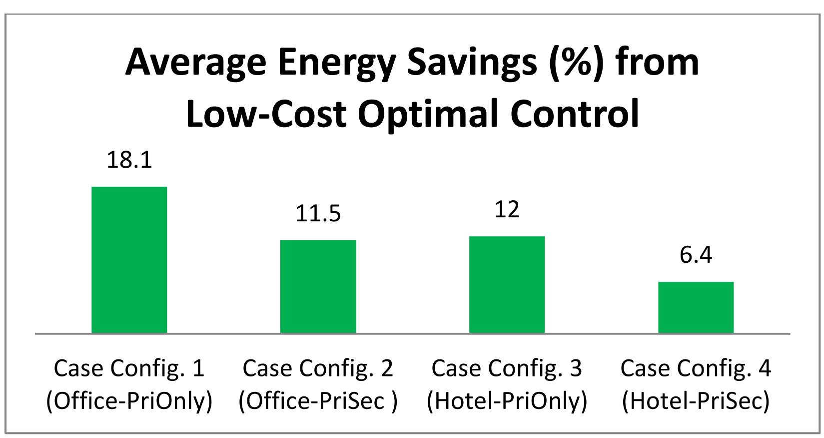


Figure 27: Average energy savings achieved by low-cost optimal control in all case configurations

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 at approximately $1150 (14 hrs., see Table 4) based on an hourly rate of $82 for HVAC contractor [3].

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 [3], and a cost of electricity per kWh to be $0.126 [3], 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.

Conclusion

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.

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.

References

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[2] Wetter, M., Zuo, W., Nouidui, T. S., & Pang, X. (2014). Modelica buildings library. *Journal of Building Performance Simulation*, 7(4), 253-270.

[3] CBEI Project 2.3 BP4 Final Deliverable, Pre-commercial demonstration of cost-effective advanced HVAC controls and diagnostics for medium-sized commercial buildings, April 2015, United Technologies Research Center.