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Central Plant Optimization for Waste Energy Reduction (CPOWER)

ESTCP Project EW-201349

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Honeywell International, Inc.

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14. ABSTRACT

A system-level, dynamic optimization of central plants and distribution system project has the potential to save energy and cost. To assess the energy and economic benefits of the real-time optimization technology, the project team demonstrated central plant operation with optimized control at Fort Bragg. The team implemented the optimization software by connecting it with local plant control to enable real-time optimization based on current state of the plant, load and weather conditions. The technology deployed is a model-predictive run-time optimization technology to operate the generation, storage, and distribution of cooling and heating energy, while maintaining building comfort. The models are set up based on historical data and updated as new data becomes available. The optimal control commands are communicated to lower level controllers that operate the equipment in the central plant. The testing period produced energy consumption and other measurements for optimized control periods and original control periods. The analysis of the data and the issues encountered are presented in this report.

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ACRONYMS

ACS	Automation and Control Solutions (A business unit of Honeywell)
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
BACnet®	A Data Communication Protocol for Building Automation and Control Networks
BAS	Building Automation System
BMS	Building Energy Management System
BLCC	Building Life-Cycle Cost
CHP	Combined Heat and Power
CPOWER	Central Plant Optimization for Waster Energy Reduction (title of this project)
DCS	Distributed Control System
DoD	Department of Defense
DPW	Directorate of Public Works
DIACAP	DoD Information Assurance Certification and Accreditation Program
EBI	Enterprise Buildings Integrator (a Honeywell BMS)
ECM	Energy Conservation Measure
EO	Executive Order
ERDC-CERL	U. S. Army Engineer Research and Development Center's Construction Engineering Research Laboratory
ESTCP	Environmental Security Technology Certification Program
FERC	Federal Energy Regulatory Commission
FEMP	Federal Energy Management Program
GHG	Green House Gases
GPM or gpm	Gallons per minute
HBS	Honeywell Building Solutions (business unit in Honeywell ACS)
HTS	Honeywell Technology Solutions
HVAC	Heating, ventilation, and air conditioning
IAE	Integral Average Error
I/O	Input/Output
IPMVP	International Performance Measurement and Verification Protocol
LBNL	Lawrence Berkeley National Laboratory
LonWorks®	A networking protocol and platform for control applications
Mcf	1000 cubic feet (cf)
MMBtu	1,000,000 Btu (British thermal units)
MMBH	MMBtu/hr
NEC	Network Enterprise Center
NIST	National Institute of Standards and Technology
O&M	Operations and Maintenance
OVOC	Observational Voice of the Customer
PO	Performance Objective
RH	Relative Humidity

SGIP	NIST Smart Grid Interoperability Panel
UI	User Interface

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EXECUTIVE SUMMARY

Overview of technology

DoD spent close to $4.0 billion in 2010 on energy costs for its facilities. Many of DoD's fixed installations receive usable energy in the form of electric power, heating, and cooling via central plants. Central plants are currently operated to meet all demands reliably, not necessarily for fuel economy or energy efficiency. Central plants contain multiple chiller, boiler, power generation and auxiliary equipment. Each equipment operates on different efficiency curves that vary with part load, ambient conditions, and other operating parameters. In addition, the site receives real-time price signals for electricity and need to consider fluctuating fuel prices and other costs. From a systems operations perspective, an operator would be faced with huge sets of decision alternatives in order to allocate load efficiently and to operate the equipment at the most efficient and cost-effective set points. For example, at a plant with five chillers and five boilers, the operator must first select the best combination of boilers and chillers for current operation (Which combination of boilers and chillers must be ON?) and their particular load allocation (What part of the load will this equipment operate?). The theoretically possible alternatives for the first question, which chillers and boilers to set ON or OFF, are $2^5 + 2^5 = 64$. The second question deals with the choice of part-load level for each piece of equipment, considering its multidimensional and nonlinear (bi- or tri-quadratic) efficiency curves for current conditions. An operator cannot be expected to resolve this level of complexity. Additional layers of complexity are added by the physical connection and relationship among the major and auxiliary equipment.

A system-level, dynamic optimization of central plants and distribution system implemented in this project has the potential to save energy and cost. Central plants are energy intensive since they originate the energy distributed to the buildings; hence even small percentage savings can have a good payback potential. The optimization software is deployable at all central plants across DoD sites. As an example, there are 13 central plants in Ft. Bragg and 6 in Ft. Jackson. Information from a CERL colleague indicates that there are 155 heating plants in the Army installations alone. The number of cooling plants, CHP, and heating plants at all DoD sites should run to several hundreds. The optimization technology has the potential to be applied to a majority of these central plants, as well as plants serving individual buildings.

Technology and Demonstration project details

To assess the energy and economic benefits of the real-time optimization technology, the project team led by Honeywell undertook the demonstration of the technology at Fort Bragg. The team implemented the optimization software by connecting it with local plant control to enable real-time optimization based on current state of the plant, load and weather conditions. Honeywell has developed a suite of optimization and control technologies specially targeting the supply, distribution, and demand of energy. For this project, we employed a model-predictive run-time optimization technology to operate the generation, storage, and distribution of cooling and heating energy, while maintaining building comfort. Based on the inputs of upcoming loads, price signals, central plant performance models, and building response, a mixed-integer evolutionary optimizer algorithm solves the schedules and setpoints for the major equipment in the central plant. The optimization solution was integrated with the plant control system and operated continuously in a supervisory capacity, during periods when the optimizer was enabled by the site staff. In operation, the schedules (equipment on/off commands) and setpoints (supply temperature or speed) were transmitted by the interconnections put together for the project site plant, through the local control system to the plant equipment. The optimizer also acts as the controller for the sequence of operations to be performed for an equipment to be operated correctly: for example, before a chiller is switched on, the cooling water valve and chilled water valves are opened; then the cooling water pump and chilled water pumps are started; the cooling tower fan is started; and then the chiller is commanded to be switched on.

Operation and Results

As part of the project, we teamed with University of California, Berkeley, to develop a simulation system and models of the chiller plant, heating plants, weather, and the building load. The simulation system was developed in Simulink™ and Matlab™. The simulation system was used for testing the optimizer software prior to deployment to rectify operational issues, parameter configuration issues, and other unforeseen conditions. The simulation software was connected with the optimizer software using OPC server protocol. We ran a number of simulations with the setup, to thoroughly test and fix optimizer software functions and bugs. This simulation-based test platform let us test the software before it is deployed on site, before controlling a real physical plant. The objective of the simulation was to test optimizer functionality of commanding schedules and setpoints based on real time inputs; the model granularity allows for this, but not the type of full control functionality needed on site, such as the sequence of commanding valves and pumps.

Both the chiller and heating plants are overseen 24/7 by roving operators who care for several plants on site. In the current scenario, the heating plant is controlled manually, which means control of the start and stop of boilers, and temperature setpoints. In the chiller plant, all control is automatic and has been programmed as different sequences by a skilled control technician. We installed and commissioned the optimizer at the CMA heating plant in Fort Bragg first. The site could not provide us access to automated on/off or temperature control for the boilers because of warranty issues involving the boiler manufacturer (English Boiler) and the boiler control (Allen Bradley). This situation meant that we provided the optimizer outputs only as recommendations to the plant operators, who must then manually start or stop a boiler or change its supply temperature setpoint. We worked with the plant manager, operators, and control technician to develop a process so that the operators can follow the optimizer commands at the plant.

The optimizer was installed and commissioned at the chiller plant next, with appropriate changes to the local control system to allow interconnection of the optimizer to the plant equipment and sensors, and to allow switching between the original automatic control and the optimizer control. We brought the optimizer online by following a systematic and thorough testing and commissioning process. Our observations and later analysis showed that the optimizer's outputs were appropriate, as would be expected for energy use minimizing actions. The optimizer was handed over to the site staff, after training the operators, site resource manager, and other site personnel, and providing the appropriate user manuals. Honeywell ACS Labs in Minneapolis continued providing remote phone support as well as on-site support to running the plant under optimizer control.

The running of the optimizer during the demonstration period was dependent on the chiller plant equipment being in good operating condition (not experiencing maintenance issues forcing manual operation, etc.), availability of site staff with time to monitor the operation periodically since optimizer controlled operation is a large departure from current practice. We went through several periods of troubleshooting and updating of the software, to manage site expectations and the difficult transition from R&D to production prototype. The optimizer software has been available and connected at the chiller plant since April 2015 to May 2016, and was enabled to operate the plant for some periods during that time. We have data from July 2015 through May 2016. After removing invalid and shorter duration data, the data analysis shows the optimizer operated on site for 39 days (24-hour periods) in several continuous periods. During the same period, the data shows 164 periods of original control days.

Our rigorous baseline characterization uses the original control data during the demonstration period. We built several regression models of energy consumption considering different combination of factors and algorithms. The factors considered were weather parameters, indoor temperatures, and week day type. The baseline models were evaluated for accuracy and the best fit models were used for comparing the actual energy consumption during optimized operation and expected energy consumption from original control operation. With this approach, we found that with all the data available, the optimized control of the plant did not reduce the energy consumption in the plant, and in most cases is within one standard deviation error of the expected usage with original control. This very unexpected result led to further analysis to diagnose the problems; our analysis showed a number of discrepancies in the input data to the optimizer software which are explained in detail in the performance assessment section. The optimizer works on real time sensed data to know the state of the plant, forecast loads and calculate optimal operating commands. Poor quality or outright incorrect sensed data will not result in optimal outputs.

The analysis of the data showed that there were no adverse effects to comfort conditions in buildings. We also show that equipment short cycling, although more frequent than in original control, was still within guidelines provided by the site and able to be adjusted with user provided parameters. The effectiveness of the user interface and the optimizer software architecture had mixed results. By the end of the demonstration period, the site lead (Honeywell Building Solutions) had become familiar with the optimizer software and its different tools and very comfortable putting the optimizer in control and letting it operate without supervision overnight and several days continuously. However, the end users expressed concerns regarding the cycling of equipment as well as non-intuitive commands the optimizer produced.

Analysis and Recommendations

The inability to achieve energy and cost savings during the demonstration period stems from a few causes: (1) incorrect inputs to the optimizer that were caused by communication disruptions or incorrect configuration changes, (2) the complexity and prototype nature of the software meant it needed monitoring and support from skilled application engineers, but DoD site restrictions meant no remote access to the workstation was possible; (2) data driven plant equipment models were potentially not learnt well because of problems experienced by the optimizer to operate stably for longer periods with all equipment components for varied reasons; (3) the transition of complex software from R&D to production prototype needed development of additional software tools and training of staff (4) the software's architecture and implementation scheme to control the full plant from the supervisory layer causes two problems (a) the optimizer software had to put in place safety measures to prevent unsafe operation because of potential network communication problems (b) the site staff were uncomfortable with a supervisory level algorithm controlling lower level components in real time.

The effectiveness of the program is in the successful commissioning of a very complex supervisory level optimization software that continuously receives real time sensor data, computes optimal operating points and commands plant equipment in real time. The testing provided valuable lessons for improvement of the software, user experience and transitioning to DoD sites. Below are our recommendations:

(1) Re-architect the software to separate the supervisory and local control layers; the supervisory layer providing high-level operating schedules and setpoints which are then managed and controlled by the local control layer. This will not only improve the software ease of implementation and performance, but eliminate safety concerns due to network communication issues, and also vastly improve the operational staff's comfort with the software.
(2) Phase in the commercial transition with less complex plants, e.g. chillers only without additional energy sources
(3) Develop standard implementation tools to quickly and reliably configure the software and connect it to the local control on site.
(4) Improve user experience by providing explanations of major actions by the optimizer
(5) Improve cycling frequency by considering equipment cycling as a cost in the optimization objective function.
(6) Secure remote access to the optimizer will enable a few expert engineers to provide troubleshooting for the complex software.

1.0 INTRODUCTION

Executive Order (EO) 13514 (now replaced by EO 13693) gave requirements for improving federal government efficiency by decreasing fossil fuel dependence . EO 13693 [6] provides goals to maintain Federal leadership in sustainability and greenhouse gas emissions reductions; specifically the goal to promote building energy conservation, efficiency and management by reducing building energy intensity by 2.5% annually through end of FY 2025. The Department of Defense goal is to reduce greenhouse gas emission by 34% from FY 2008 to FY 2020 from sources it owns or controls, including fossil fuel combustion and fugitive emissions [2]. DoD spent nearly $4.0 billion in 2010 on energy costs for its facilities [3]. Many of DoD's fixed installations receive usable energy in the form of electric power, heating, and cooling via central plants, which are excellent candidates for improvements in operational efficiencies because of their aggregation of energy production and distribution and their impact on the energy use profile of a military installation.

Honeywell's predictive, automated optimization for central plants has significant potential to cost-effectively reduce energy consumption and costs, by choosing the right operating points for all equipment, considering real time pricing and several other factors, in real time.

1.1 BACKGROUND

The implemented technology is intended to address the operational efficiency of central plants that provide heating and cooling to several buildings in military installations. DoD central plants currently do not use automated optimization. Discussions with experienced central plant operators and energy managers about current operations make it clear that opportunity exists for capturing efficiency savings from operational optimization.

Central plants are currently operated to meet all demands reliably and not necessarily for fuel economy or energy efficiency. Plant operators run the equipment according to a pre-set, fixed strategy. However, plant equipment efficiencies vary with load and external conditions such as ambient temperature. In addition, central plants have multiple chillers, boilers, and power generation equipment, which may differ from each other in capacities and performance curves. The ability to select the most efficient equipment for a load would offer great benefits.

An operator motivated to maximize system efficiency is faced with a huge set of alternatives. For example, at a plant with five chillers and five boilers, the operator must first select the best combination of boilers and chillers for current operation (Which combination of boilers and chillers must be ON?) and their particular load allocation (What part of the load will this equipment operate?). The theoretically possible alternatives for the first question, which chillers and boilers to set ON or OFF, are $2^5 + 2^5 = 64$. The second question deals with the choice of part-load level for each piece of equipment, considering its multidimensional and nonlinear (bi- or tri-quadratic) efficiency curves for current conditions. An operator cannot be expected to resolve this level of complexity.

Additional degrees of freedom are introduced by auxiliary equipment such as pumps and cooling towers, which are large consumers of energy. Supply water temperatures, condenser water temperature, and flow rates can improve system operating efficiency and are even less intuitive quantities for an operator grappling with system efficiency.

A central plant optimization system automatically computes the lowest cost (and highest efficiency) equipment schedules and setpoints for the generation and distribution system while satisfying multiple constraints. Such energy optimization brings economic value by optimizing the system for energy efficiency and utility rate structures.

1.2 OBJECTIVE OF THE DEMONSTRATION

The objective of the project was to implement advanced optimization software that will control the operation of a central cooling and a central heating plant, and measure the resulting energy and cost savings.

The overarching objectives of the field demonstration were to:

Validate the performance of the central plant optimization in practice: We identified a set of seven performance objectives, described in section 3, that formed the basis to validate the performance, costs and benefits of this technology.

Obtain insights to provide guidelines for DoD practices in operating central plants: The energy savings and cost savings insights and the implementation costs from the demonstration (PO3, PO5) are intended to provide guidance for adoption of optimization technology. The performance objectives dealing with the testing, correct interconnections, minimum comfort criteria and short cycling provide a basis for best practices as well as monitoring requirements for future implementation at adoption sites. Plant operator and manager training needed for proper dissemination of the technology will be guided by the insights from the demonstration.

Facilitate technology transfer: The performance data and implementation know-how gathered from this demonstration will play a key role in the technology transfer process; by providing insights into the process, people and organizations involved in delivering value to the end customer and user; by providing software improvement recommendations based on performance data and issues encountered.

Provide additional benefits of energy, cost and emissions savings to the specific DoD site.

Deliver the results of the project in the form of data analysis, results and conclusions in the final report.

1.3 REGULATORY DRIVERS

This project addresses the following drivers:

Executive Order (EO) 13514: Sections 1, 2.a.i, 2.a.ii, 2.b.iii, 2.g, 8 [1]

EO 13514 sets the policy that U.S. Federal agencies shall increase energy efficiency. It provides requirements for setting goals for reducing energy intensity of buildings, reducing greenhouse gas emissions, ensuring that all new buildings achieve net-zero energy by 2030, and managing existing building systems to reduce the consumption of energy.

EO 13423 [4]: Section 2. (a) improve energy efficiency and reduce greenhouse gas emissions of the agency, through reduction of energy intensity by (i) 3 percent annually through the end of fiscal year 2015, or (ii) 30 percent by the end of fiscal year 2015, relative to the baseline of the agency's energy use in fiscal year 2003.

EO 13693 [6]: EO 13693 provides goals to maintain Federal leadership in sustainability and greenhouse gas emissions reductions; specifically the goal to promote building energy conservation, efficiency and management by reducing building energy intensity by 2.5% annually through end of FY 2025.

The CPOWER project directly addressed these EOs, since the main objective of the CPOWER demonstration was to achieve reduced energy consumption and as a result, reduced greenhouse gas emissions. Reduced consumption was addressed with the advanced optimization applied to central plants that supply cooling and heating to buildings.

The demonstration also helps cost-effective deployment of renewable energy, since facilities should employ all possible cost-beneficial energy efficiency measures before installing capital-intensive renewable energy generation sources.

DoD Policy: DoD's Strategic Sustainability Performance Plan [2] sets out DoD's priority to invest in reducing energy from traditional sources (Energy Management in Fixed Installations), sets a target to reduce Scope 1 and 2 GHG emissions by 34% between FY 2008 and FY 2020. The plan says that energy efficiency in facilities will be one of the ways the GHG target will be met and sets a goal of reducing energy intensity by 3% each year from FY 2006 through 2015 and by 1.5% per year from FY 2016 through 2020. Providing a fixed installation as a test-bed for demonstrating innovative technologies is stated as a way to tap into emerging technologies while helping them be commercially viable.

This policy was addressed through the CPOWER project's control of central plants, which offers the potential for reducing energy use and GHG emissions.

EO 13327: Section 3.b.ii. prioritizes actions to be taken to improve the operations and financial management of the agency's real property inventory.

The central plant optimization technology improves cost management by (1) reducing cost with operational energy savings, and (2) minimizing energy cost by considering real-time prices of electricity.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY OVERVIEW

The CPOWER central plant optimization solution, illustrated in Figure 1, provides optimal chiller and boiler schedule and distribution temperature and flow rate setpoints. It relies on equipment performance models, forecasted load, a building model, and energy price information. The equipment and building models are set up based on historical data and updated as new data becomes available. The optimization is based on minimizing energy costs or maximizing efficiency and uses an evolutionary algorithm [6].

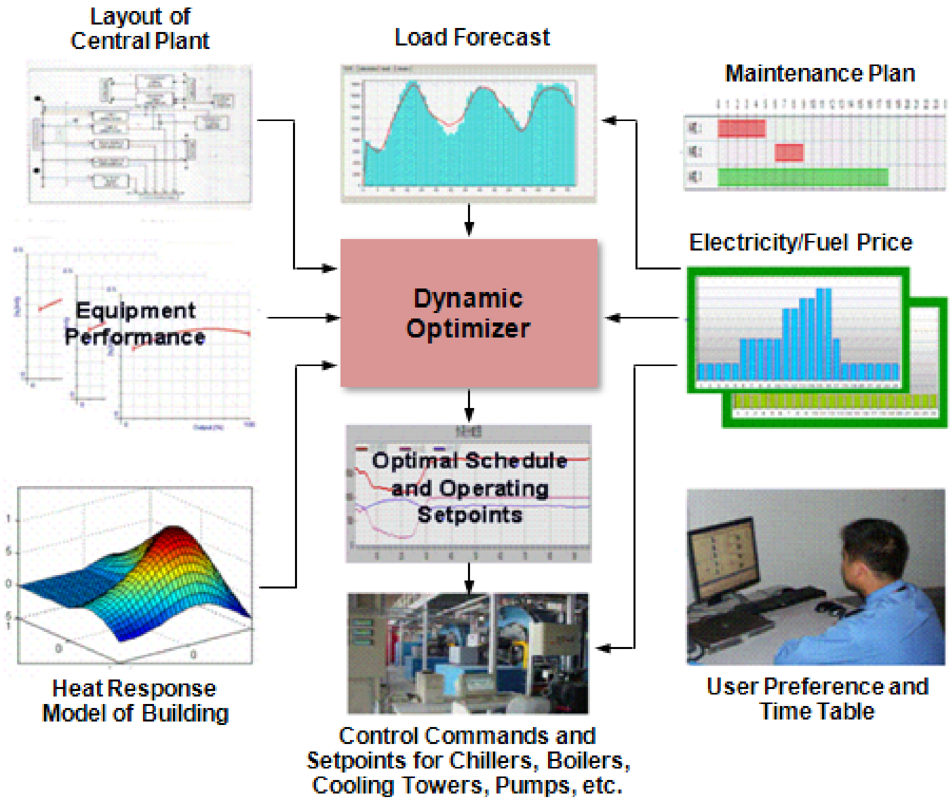


Figure 1: Technology Overview

2.1.1 Optimization Solution

The optimization solution in this project dynamically generates schedules and setpoints for plant equipment that minimize operating cost over a specific time period. The solution concept is illustrated in Figure 1. The dynamic optimizer block in the center interacts with the equipment performance models, the specific central plant layout, building model, forecasted load, and external inputs such as electricity pricing. The optimal schedule and setpoints are communicated to the controllers.

The online information flow is conceptualized in Figure 2. A demand forecaster predicts loads for the next 24- to 36-hr period of optimization based on the current weather, load history data, and occupancy criteria. The central plant model is configured from a library containing the models of chillers, boilers, cooling towers, pumps, and thermal storage system. A dynamic building model mathematically represents the changes in comfort conditions in the building in response to changes in energy supplied with the distributed chilled or hot water. Based on the inputs of upcoming demand loads, central plant performance, and building response, the optimizer solves the schedules and setpoints for the major equipment in the supply and distribution of chilled and hot water. The optimal schedules and setpoints are used by the plant controller to operate the central plant. Feedback from the buildings provides corrections to the long-term forecast load that are used to adjust energy supplied and the setpoints.

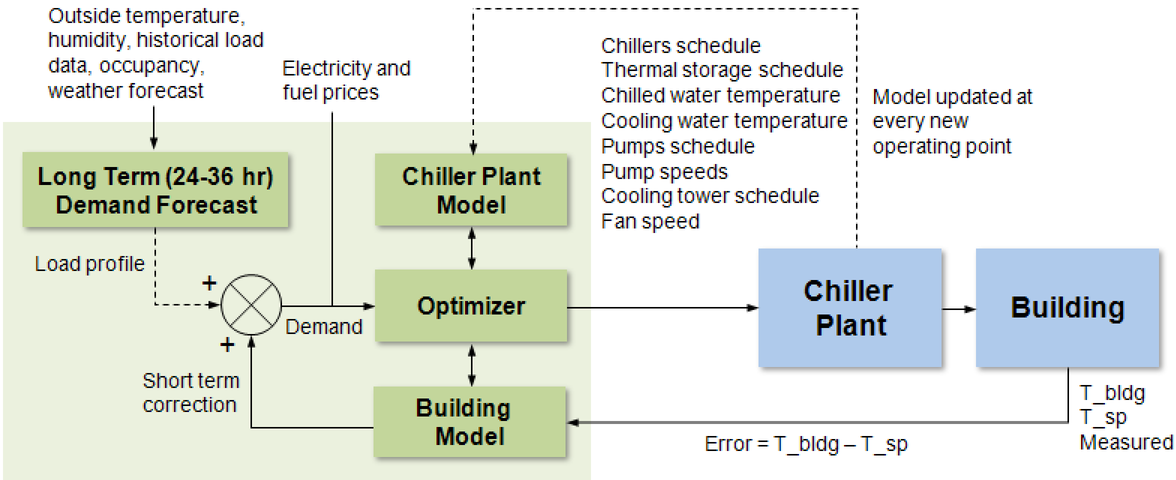


Figure 2: Optimization Implementation

2.1.2 Model Library

The model library is an integral part of the optimization solution that contains models to simulate the performance of the central plant and the building response under given conditions. These models are developed for a specific plant and building based on the data the optimizer collects when connected to the BMS. Most of the models are either regression trees or a collection of regression trees. They are learned using historical data and are periodically updated with newly arrived data. The solver can determine the optimal solution from various candidate solutions based on the plant performance. Since the optimizer models are based on data, they are continuously updated and therefore, do not lose their efficacy when the equipment deteriorates. They also provide the basis for performance monitoring of the plant. Separate models for each type of equipment are built based on regression tree principles and using several influencing factors as inputs, such as weather conditions, flow rates, and temperatures.

2.1.3 Problem Formulation and Solver

To search for the optimal schedule, the optimization problem is formulated with the following objective function and multiple constraints over an optimization horizon of h time steps:

$$Min\sum_{t=1}^{h}(Cost_t + \alpha Penalty_t)$$

subject to several constraints of equipment capacities, minimum outputs, ramp rates, interval between startup and shutdown, and others.

$Cost_t$ is the total energy cost of the central plant during the time interval t and is the sum of energy costs of all central plant equipment, determined from their models. $Penalty_t$ represents shortage of supply versus demand. α is a weight specified according to user preference for energy saving (α takes a bigger value) and comfort of occupants (α takes a smaller value).

The above optimization problem is further parametrized and solved to find an optimal solution for both discrete (i.e., ON/OFF) and continuous (i.e., setpoints) variables. This culmination of the modeling and optimization results in the entire system working in the most efficient manner.

2.1.4 Optimization hierarchy

The optimization problem is solved in two levels. The energy source dispatch between the thermal energy storage and the chillers occurs first; the run-time optimization of the chillers, associated pumps, and cooling towers occurs in the next level.

2.1.5 Solution Architecture

Figure 3 shows the system architecture, illustrating the interaction of the optimization layer with respect to the central plant control system. Sensors and controllers are usually linked to I/O modules to send and receive data in a uniform format through standard communication protocols such as LonWorks® or BACNet®. The data interface of the optimization module can communicate with these I/O modules, as well as controllers or building automation systems, using standard protocols. In the case of CPOWER at Ft. Bragg, the optimization software interfaces only with the existing building automation system for ease of implementation and to standardize on one type of interface. The optimization module directly controls plant equipment.

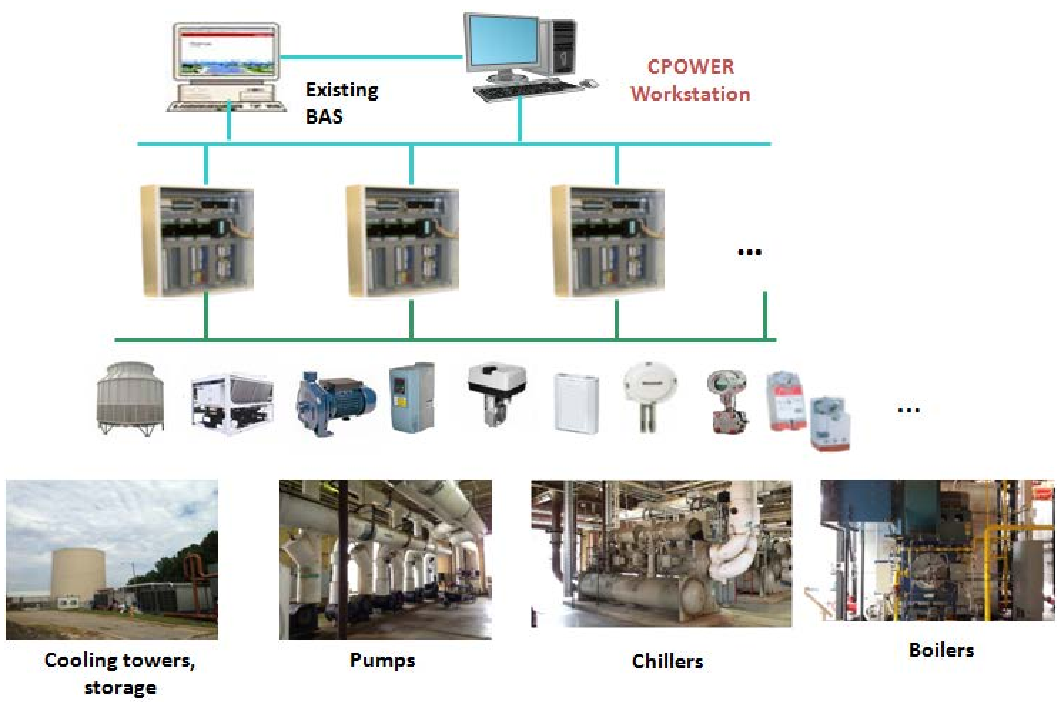


Figure 3: System Architecture

Figure 4 shows the software modules in CPOWER. The user interface accepts user inputs and displays relevant information. A data interface reads data (temperature, flow rate, power, etc.) and sends control commands and settings (ON/OFF, temperature setpoint, flowrate setpoint, etc.) to all relevant devices. A database saves data that needs to be archived and shared. The model library contains simulation models of plant, building, and load forecast. The solver module solves for the optimum schedules and setpoints based on the problem formulated. The fault detector monitors for alarms or availability of chiller plant devices.

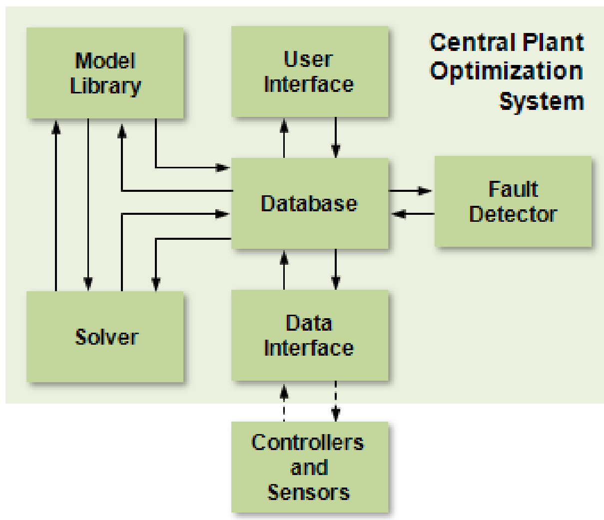


Figure 4: Central Plant Optimization Modules

2.1.6 Inputs and Outputs

System inputs can be categorized into five types: device information, connection information, ambient conditions, tariff model, and running settings. The outputs can be categorized as control commands, running settings, and supervisory information about the chiller plant. Major and typical items are described below.

Inputs

<u>Device Information</u>

The device information includes all basic properties of chiller plant devices (chiller, boiler, cooling tower, pump, etc.). Most of the design information is available from design documents or product specifications. Most of the running data can usually be read from sensors already installed to the chillers or the chiller plant.

<u>Connection Information</u>

The connection information describes how the water or piping system connects parts of a chiller plant together. Multiple connection matrices are employed to indicate which primary pumps can supply how much chilled water for a specified chiller and which cooling water pumps can supply how much cooling water for a specified chiller or cooling tower.

<u>Ambient Conditions</u>

The ambient conditions include representative indoor and outdoor air temperature and humidity, which are averaged or given weighted averages from multiple sensors.

Tariff Data

The tariff data contains time-dependent price of electricity or fuel.

Running Settings

The running settings of the system include maintenance schedule (when a specified chiller or pump will be offline in the near future for some maintenance work or overhaul), time settings of the chiller plant (e.g., when building working hours, which days are working days, etc.), temperature settings (the target indoor air temperature, allowed range of return/supply water temperature, etc.), and user's preference for energy saving or human comfort.

Outputs

The number of outputs is relatively small. For a chiller, the control commands are Open/Close chilled water valve and cooling water valve (if applicable), chiller On/Off, and sometimes, the chiller working mode (cooling or heating); the running settings may include chilled water temperature setpoint. For a boiler, the control commands are hot water valve Open/Close and boiler On/Off ; the running setting is the hot water temperature setpoint. For a pump, the control command is On/Off and its running setting is mainly the flow rate, or if it is a variable speed pump, the frequency. Although the intelligent control system will monitor running status of the whole chiller plant, it will send commands or settings only to devices that the user chooses for system control.

The inputs and outputs specific to the plants in our demonstration are shown in Table 8 and Table 9 in Section 5.3 (Design and Layout of Technology Components).

The supervisory information includes COP (Coefficient Of Performance) curves of chillers, COP curve of the whole system, cooling or heating supplied for previous hours, load demand for the following hours, running data of devices, and running schedule of all devices in the near future.

2.1.7 Chronological Summary

Honeywell has been developing a suite of optimization and control technologies that target the energy supply, distribution, and demand. The first prototype was implemented at a Honeywell office building in Shanghai, China in 2010. Several other prototypes of the solution were implemented in China between 2010 and 2013, including a hotel and office building (40,000 sq.m), NanJing subway station chiller plant, and a chiller plant at an electronics manufacturing plant. All basic technology development was completed over the past few years. Honeywell has begun the process of productizing the technology solution.

2.1.8 Expected Application

The proposed work is deployable at all central plants across DoD sites. As an example, there are 13 central plants in Ft. Bragg and 6 in Ft. Jackson, which indicate enormous energy and cost savings potential. Information from a CERL colleague indicates that there are 155 heating plants in the Army installations alone. The number of cooling plants, CHP, and heating plants at all DoD sites should run to several hundreds. The optimization technology has the potential to be applied to a majority of these central plants.

Although it was demonstrated at a central plant, the optimization technology is applicable to chiller and boiler plants in buildings as well, and is therefore applicable to decentralized cooling and heating plants at DoD sites.

2.2 TECHNOLOGY DEVELOPMENT

The optimizer implemented in this project is a result of several years of Honeywell investment. DoD funds were not used for the development of this software. However, as we encountered site specific layouts and conditions, especially for the thermal energy storage tank and the heat exchanger, we modified the software and configuration of these components.

2.2.1 Optimizer Software

Heat Exchanger

The full plant layout is shown in Figure 14 and Figure 15, later in the document. The heat exchanger connection is unique and the layout is shown below in Figure 5. The heat exchanger shares the cooling tower with chiller 4. The on/off 3-way valve is either open to the condenser side of chiller 4, or to the heat exchanger; therefore only chiller 4 or the heat exchanger may operate at any time. Our initial approach was to use the heat exchanger as another shared cooling source and the software was set up for this. After consulting with the site personnel and reviewing the interconnections for the heat exchanger, we decided to use the site protocol for starting a heat exchanger This approach provides easier decision making for the optimizer and a better certainty of a solution, since the heat exchanger is used in low load situations and is intimately connected to the operation of the other equipment in the chiller plant. Otherwise, a custom layer of software would have to be developed to account for chiller 4 being excluded or included in the optimization, with the added complexity of the operational sequence for the 3way valve and cooling towers. The heat exchanger is treated as a chiller, but with no power consumption of its own. It is configured to be run whenever the wet bulb temperature is below 48 degree F.

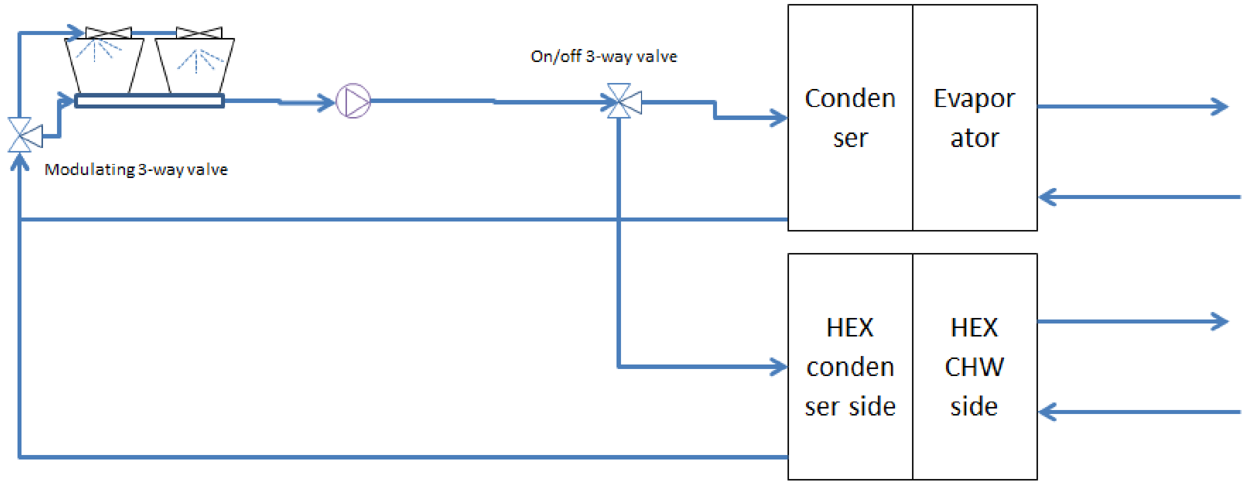


Figure 5: Interconnection of the Heat exchanger with Chiller 4

Thermal Energy Storage Tank

Energy storage technology is often used to reduce operating costs by shifting cooling production from higher cost periods to lower cost periods. Chillers produce and store chilled water in storage tanks at night during periods of off-peak electrical demand and use the chilled water during daytime peak demand hours for cooling. When cooling is required during daytime hours (when electric rates are higher), the stored chilled water is pumped through the cooling system's chilled water circuit to cool the buildings. With a properly sized storage tank, a facility's cooling needs can be met with minimal electrical usage during peak hours. Although the concept is very simple, the various operational modes, together with complicated layout and interconnections, increase the complexity of determining the optimal operating and implementation strategies. The implementation strategy includes determining the current status of the tank (charge, discharge or bypass) with the available measurements, and presenting the actions correctly on the UI screen when the optimizer is in control or otherwise. A screenshot of the UI is provided in Figure 6.

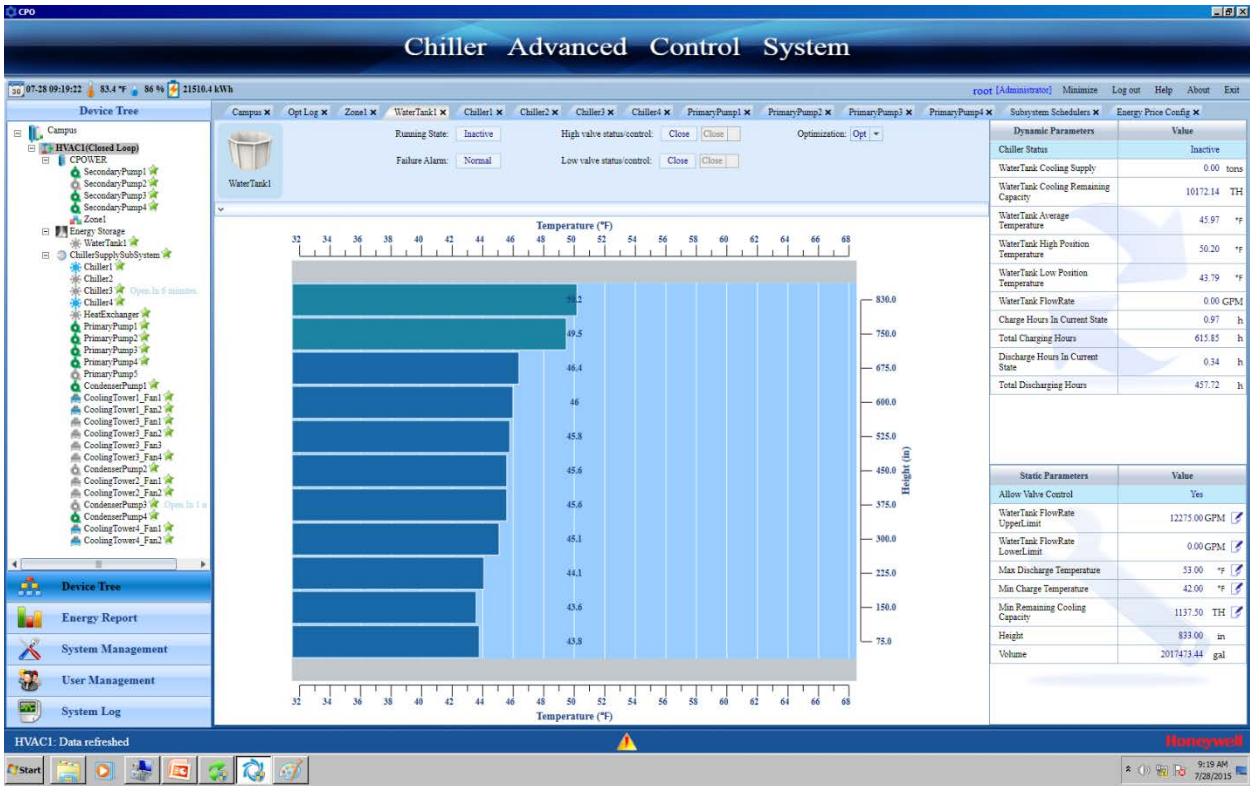


Figure 6: Thermal Energy Storage Tank Screen

On site, the storage tank is also used as the 'decoupler' or bypass between the secondary and primary water flow loops – see Figure 14. This means that when the storage tank valves are open they could appear to be in charge or discharge mode even when they are not in those modes. In addition to the valves on the top and bottom of the tank, 20 temperature sensors in the tank measure the chilled water temperature to determine the chilled water capacity. The tank also has a bi-directional flow meter that outputs the flow rate and the direction of flow. The model described next determines optimal operating strategies and estimates the start time based on limited information and a load forecast model.

The optimum cooling source allocation is first calculated by calculating the discharge time, by considering the remaining chilled water capacity of the water tank, electricity price in a 24 hour period, and the cost of energy. The energy cost is the total forecasted load, less the remaining capacity in the water tank, multiplied by the electricity price. The optimizer finds the optimal discharge time that minimizes the cost for the future 24 hour period. The remaining water tank capacity is calculated as follows:

$$\text{RemCapacity} = \text{TotalCapacity} * \sum_{k=0}^{n} (T_{\text{Maxdischarge}} - T_k)/n$$

T_k: is the temperature of water at different heights

n: is the number of temperature sensors in the water tank

$T_{\text{Maxdischarge}}$: is the upper limit of chilled water discharge

The tank charges based on the schedule set by the end users, and the remaining capacity in the water tank within that schedule.

2.2.2 Simulation Models for Testing

Simulation models of the central plants and building loads were developed as part of the project. The simulation models were used for testing the optimizer software prior to deployment to rectify operational issues, parameter configuration issues, and other unforeseen conditions. This approach was used because complex software working in a supervisory and local control capacity needs a large number of sensor and meter inputs, commands a large number of equipment settings, and requires many configuration parameters. The description of the simulation model is provided by our team member, University of California, Berkeley. It is attached in the appendix.

To integrate the simulation model (Figure 7) with the optimizer software, we created an OPC server with all I/O (input/output) points needed to be exchanged between the chiller plant optimizer and the model. The OPC server software was obtained from Honeywell MatrikonOPC.

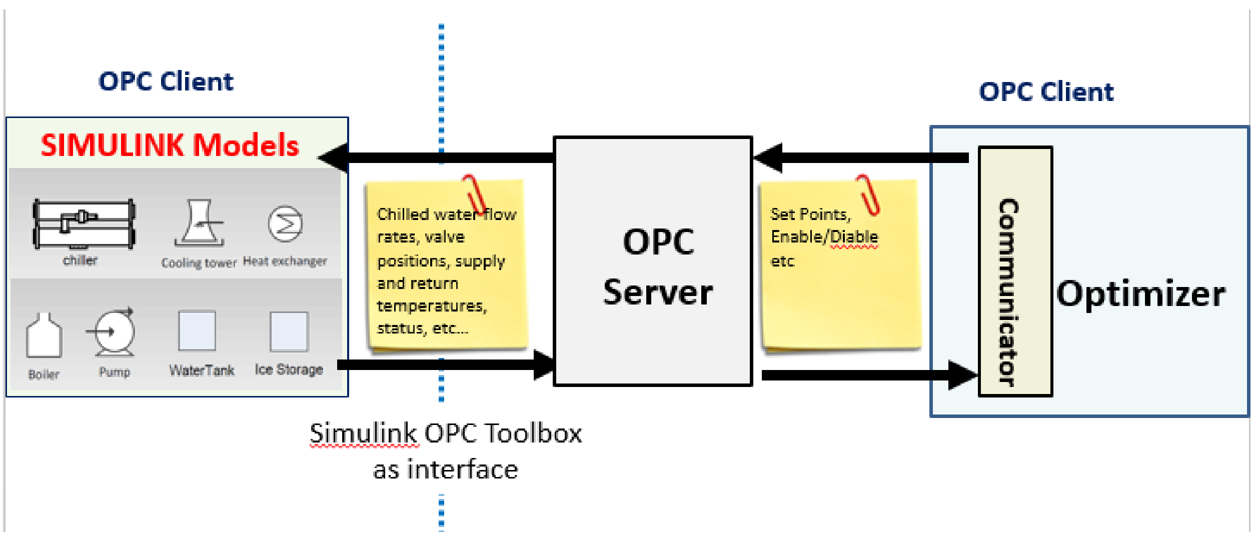


Figure 7: Simulation model and optimizer software integration

The I/O points are set up in Mathworks® Simulink®'s OPC toolbox read-write blocks, and mirrored in the server. On the optimizer side, the I/O points are configured in its communication interface, and mapped to the correct points on the model side. The OPC server serves a master set of I/O points that are read and written by the model and optimizer, enabling this exchange. The three components (model, OPC server, and optimizer) can be located anywhere on the same network, but for our convenience, the optimizer and OPC servers were installed on one virtual machine, and the simulation models were installed and run on a different workstation.

This simulation-based test platform lets us test the software before it is deployed on site, before controlling a real physical plant. It is especially important because DoD site restrictions don't allow remote access to the system.

2.2.3 Configuration Tasks

A configuration tool in the optimization software package, CPOBuilder, is used to configure the plant equipment and layout and to connect with the local control points. As shown in Figure 8, setting up the system configuration in CPOBuilder configures the operational UI of the optimization software, the database and supporting tools, and the communicator, which is the interface between the optimizer application and the plant control inputs and outputs.

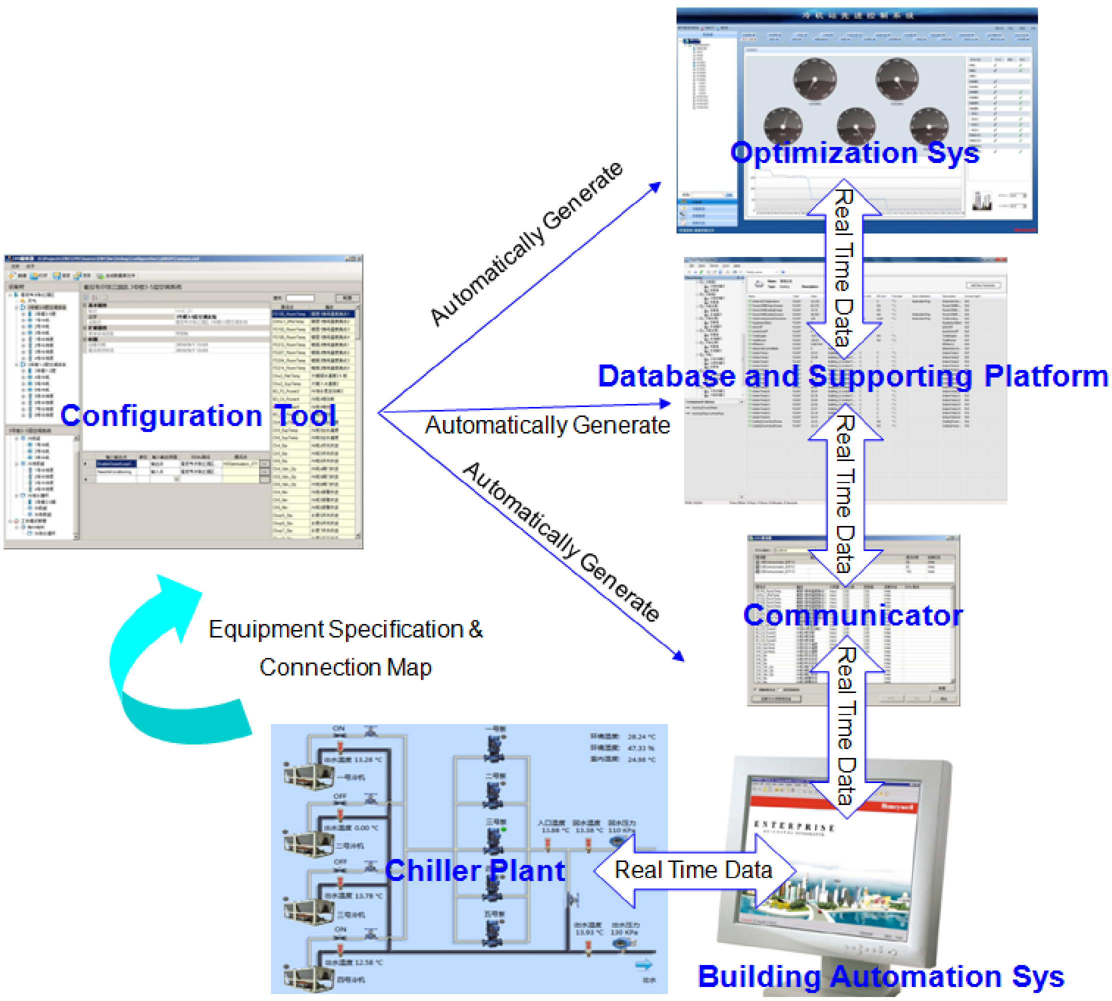


Figure 8: Configuration tool function and the software setup process

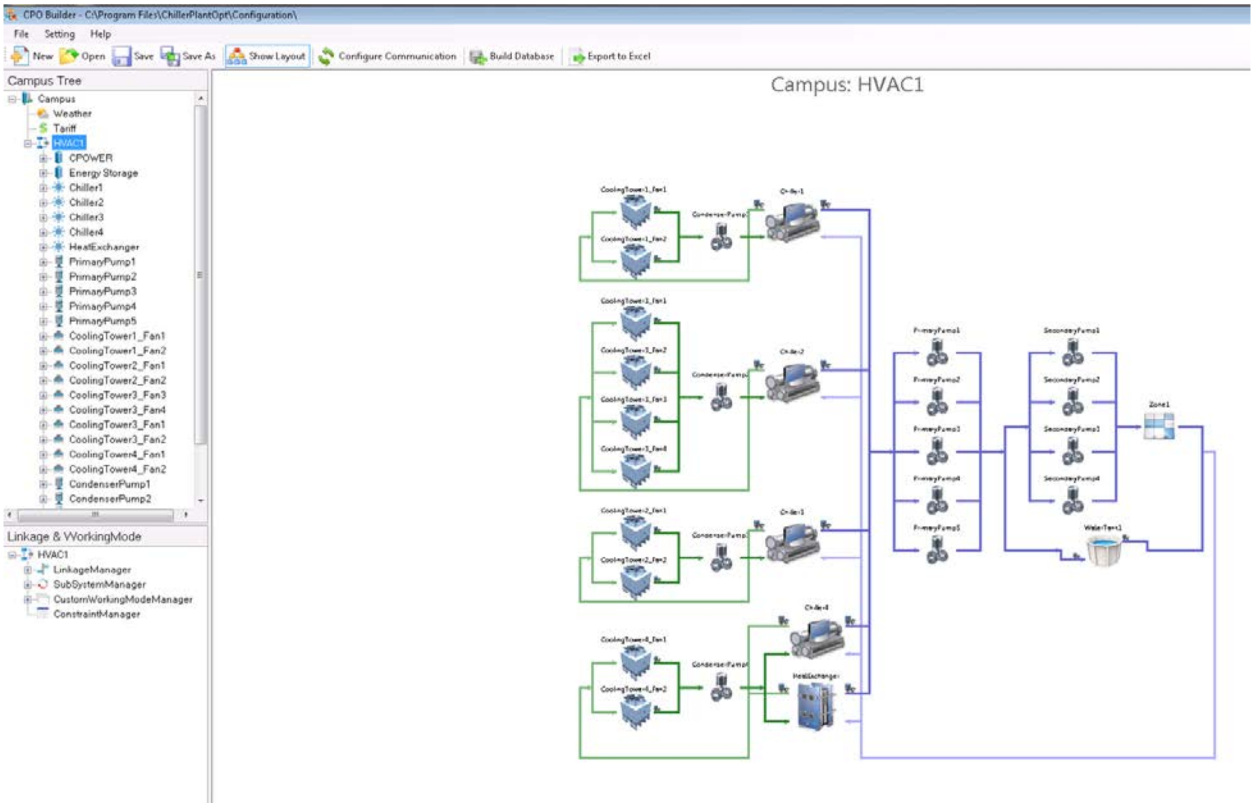


Figure 9: CPOBuilder configuration tool showing the plant layout

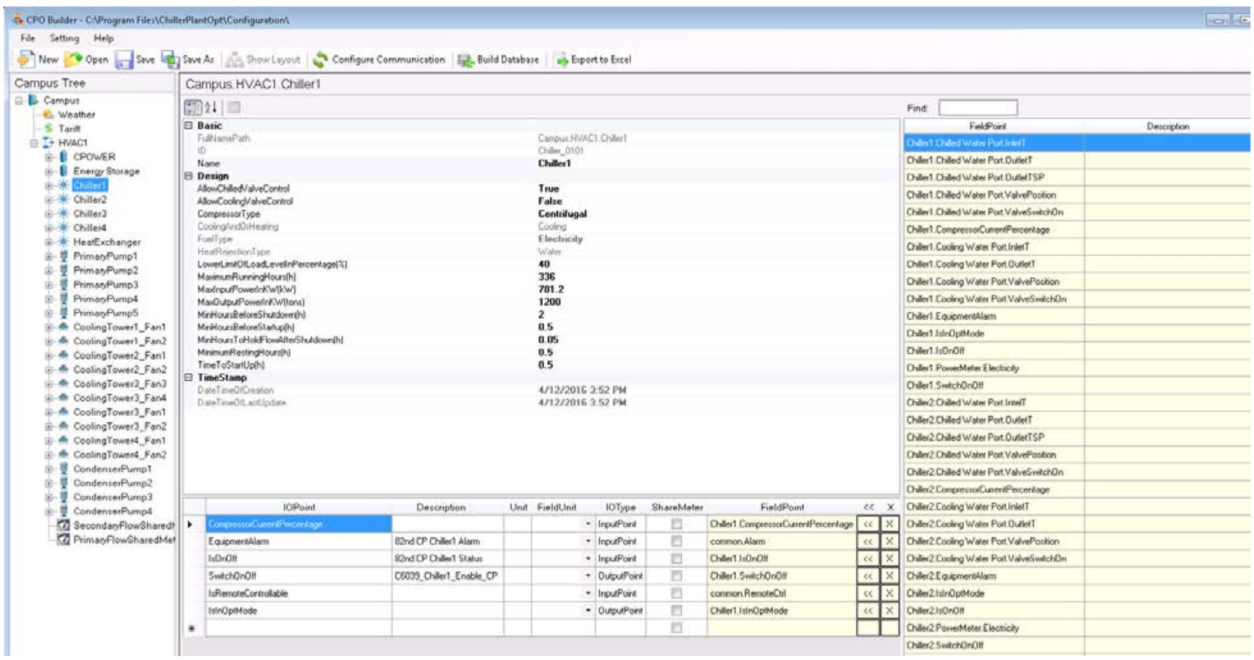


Figure 10: CPOBuilder tool showing points mapping functionality

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Performance Advantages and Limitations

CPOWER offers automated energy and cost savings without human intervention. It produces optimum operation outputs and directly supplies control commands to the plant operation, thus ensuring that optimum commands are followed. The performance advantages derive from:

1. Starting and stopping schedules of plant equipment based on accurate load forecasts, while considering efficiency curves at current ambient conditions.
2. Operating chillers and boilers at part loads and temperature setpoints that maximize system efficiency.
3. Changing pump and fan speeds in response to optimum flow rates computed by the optimizer.

Table 1compares advantages and disadvantages of CPOWER and current solutions.

Table 1. CPOWER vs. Custom Development Performance

Performance criteria	**CPOWER**	**Existing (custom solution development by experienced engineer)**
Advantages		
Plant operational parameters	Continuously measured values provide the most current plant parameters for operation.	Fixed manufacturer specifi-cations; may not be valid for current operation and are not updated as equipment deteriorate.
Control logic (ensures energy savings)	Dynamically generated by the solver for current conditions for optimization objectives; control logic based on general relationships (models) abstracted from data or knowledge of system.	Designed offline and based on fixed curves; specific rules are derived and applied based on experience and system physics knowledge; not updated with changing conditions.
Load prediction (ensures energy savings, reduces decision load on operator)	Long term forecasted load for optimi-zation over a horizon and short term corrections for deviations from forecast allow operation to take advantage of the thermal storage effect of buildings, and actual thermal storage systems.	No load prediction: cannot take advantage of inherent thermal storage of buildings; actual thermal storage system sche-duling is manual or programmed into control logic for pre-set conditions.
Real time prices (ensures cost savings, reduces decision load on operator)	Considers real time prices for optimum scheduling, taking advantage of thermal storage.	Real time prices must be input manually by operator.
Limitations		
Load forecasting	In a central plant, with several buildings, and with the chiller plant operating through the year (even in heating season) the original load forecasting model doesn't work well.	There is no load forecasting; instantaneous controls adjust supply to current conditions.

Performance criteria	CPOWER	Existing (custom solution development by experienced engineer)
Acceptance, complexity (operator needs to use the system for realizing the benefits)	Operational logic is not transparent to operator; and if it is not understood, there is a risk of not using the advanced optimization; the optimization was used infrequently.	Operator has long familiarity with the control logic and will likely keep it on; existing control probably simpler to understand.
Equipment switching (could result in reduced life of equipment)	If not properly configured, there is risk of equipment switching frequently to save energy. The software addressed this in a way that resulted in more equipment staying 'on,' reducing energy savings.	No frequent switching since set rules of operation precludes this.
A-priori energy savings estimation for commercial projects (affects widespread adoption in guaranteed energy savings programs)	Since energy savings are achieved in dynamic situations it is difficult to estimate savings a-priori unless a full plant and building model simulation is performed, with existing controls and advanced optimization.	Energy savings are estimated based on a-priori knowledge of chiller and other equipment sequencing, and the pre-set control strategy.
Local control integrated with optimization	In the current version of the software architecture, the optimizer also commands the sequence of local control, not just the supervisory commands. This could lead to time lag issues in control.	Automatic local control loops keep end equipment working stably.

Cost Advantages and Limitations

CPOWER is designed to enable cost savings from:

- Minimizing energy cost by considering real-time price signals for electricity
- Reduced cost from energy savings.
- Reduced cost of maintenance from maintenance scheduling decision aid.

GHG and other emissions reduction will be a direct result of reducing electricity and gas usage.

Table 2 compares cost advantages and disadvantages of CPOWER with current custom solutions.

Table 2. CPOWER vs. Custom Development Costs

Cost criteria	CPOWER	Existing (Custom solution development by experienced engineer)
Advantages		
Operations costs	Reduces cost of operations by saving electricity and fuel; from shifting energy use considering real time prices,	Current approaches do not automatically control for cost savings, and operators must

	and taking advantage of thermal storage in the system automatically for pre-cooling or pre-heating.	schedule for real time prices; thermal storage in the system is not considered for pre-cooling or heating.
Maintenance costs	Reduces cost of maintenance by displaying the most up-to-date performance of the plant and individual equipment that the operator can use for condition-based scheduling of maintenance, for any imminent failure or slow degradation of plant performance; alarming if commanded and feedback values don't match – indicating equipment problem.	Equipment performance is not provided — maintenance decisions are on-schedule, on breakage, or operator initiated.
Limitations		
Maintenance costs	If not properly configured, there is risk of equipment switching frequently to save energy thus increasing maintenance costs: this will be addressed in the software	No frequent switching since there are set rules of operation that precludes this.
Additional instrumentation (first costs)	If the plant is not well instrumented and automated, additional sensors and meters and communication must be added to the automation system.	Need for additional sensing and meters is lower, since current approaches do not consider current conditions in optimizing.

Social Acceptance

This optimization and automation technology faces some challenges to acceptance by central plant operators. Reliability is among the highest concerns for a plant operator and, thus, they can be understandably skeptical when presented with an unfamiliar control strategy. Plant operators used to running the plant with fixed control sequences may be uncomfortable with dynamically changing schedules and revert to older sequences.

Although we provide training to the plant operators, a new technology needs a long period of familiarization. The site staff decided the level of training needed for an advanced application should be longer and did not have the necessary means for providing it. The operators mainly monitored the equipment infrequently at the plant, but the optimized control itself was run by higher level technical staff.

3.0 PERFORMANCE OBJECTIVES

Table 3 describes the project's performance objectives and summarizes the results.

Table 3: Performance Objectives

Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
PO1: Simulated Optimizer software performance			
Optimizer output of plant operating schedules and setpoints (various units)	Simulated (not site data) optimizer outputs of eqpt schedules and setpoints	Optimizer outputs are within normal range of operation for equipment >95% of the time	The software performance met the objectives in simulation.
PO2: Optimizer software interconnection with control system			
Comparison of optimizer output and control system commands	Optimizer outputs and control commands for the same period	All required optimizer outputs are transmitted as control commands for plant operation.	The software interconnection objectives were met.
PO3: Energy savings			
Difference in plant energy consumption between baseline and demonstration periods in units of kWh (cooling plant) and MMBtu (heating plant)	Electricity and gas consumption at the central plants, prices, plant outputs, weather	>10% savings on weather normalized energy consumption data	The optimizer was commissioned successfully; however, post-data analysis revealed incorrect inputs into optimizer; a majority of the demonstration period was taken up with troubleshooting configuration and control interconnections; hence energy savings were not achieved during the demonstration period.
PO4: Comfort conditions in buildings			
Deviation from minimum comfort criteria in representative buildings (deg F)	Temperature and humidity data from representative buildings	Integral Average Error (IAE) from comfort conditions is within 10% of baseline period IAE	The comfort conditions in buildings was not adversely affected during optimized operation and the objective was met.
PO5: Economic performance			
Simple payback or life-cycle cost metrics produced by BLCC tool	Cost savings, initial investment cost, and annual maintenance cost of the technology	Net Present Value of >=0 for a 10 year project performance period	The main driver for cost savings is the energy savings (PO 3); energy savings could not be demonstrated for the reasons above; therefore the economic performance criteria were not met during the demonstration.

Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives continued			
PO6: Equipment short cycling			
Comparison of startup and shut-down frequency and duration between baseline and opti-mized operation for chillers and boilers	Equipment ON/OFF event data and times	ON/OFF frequency under optimized operation does not exceed manufacturer or operator specifi-cations	Based on the analysis provided in section 6.6, this performance objective has been met.
Qualitative Performance Objectives			
PO7: Effectiveness of user interface			
Ability and comfort of opera-tors to assess optimizer outputs for operating the plant to meet all loads	Feedback and questions from DPW staff about the logic behind optimizer outputs, and actions taken	A skilled DPW energy manager can effectively use the interface and is comfortable with the optimizer outputs	The site resource manager was able to effectively use the interface and was quite comfortable with the software, there were end –user concerns that we will consider in providing a better user experience in the future.

4.0 FACILITY/SITE DESCRIPTION

We selected Fort Bragg, NC as the demonstration site; within it, we used the 82nd central cooling plant and CMA heating plant as the demonstration plants.

4.1 FACILITY/SITE LOCATION AND OPERATIONS

Demonstration Site Description: Ft. Bragg, NC, is one of the largest U.S. Army installations, served by six large central energy plants and a number of smaller plants. A site visit and discussions with the DPW led to the selection of the 82nd Cooling Plant and the CMA Heating Plant for the demonstration. The 82nd Cooling Plant consists of four large chillers (1000, 1200, 2000, and 2200 tons), four cooling towers, associated pumps, and a chilled water storage tank of 2.5 million gallons capacity. This plant provides cooling to approximately 70 major buildings. The location of the plant is shown in Figure 11. The CMA Heating Plant contains three large natural-gas-fired hot water boilers, each having a heat input rating of 35 MMBH. Auxiliary equipment includes primary and secondary hot water pumps and air separation and water treatment equipment. This plant provides heating to approximately 100 major buildings.

Figure 11: 82nd Cooling Plant at Ft. Bragg

The complexity of these central plants is representative of other DoD plants, making the site desirable for studying transition to other installations. Both central plants have control and monitoring systems that either collect the needed data or can be easily modified for such data collection. The central chiller plant is monitored and controlled by Honeywell's Enterprise Building Integrator (EBI), and the heating plant is monitored by Honeywell EBI, but controlled manually at the plant.

Key Operations: Fort Bragg is the home of US Army Airborne and Special Operations Forces, and US Army Forces Command and US Army Reserve Command. Several units are stationed here most notably the 82nd Airborne Division and US Army Special Operations Command (USASOC).

Command Support: The Director of Public Works is Mr. Gregory Bean. This project has his support. Mr. Coby Jones, former DPW Energy Manager during project inception and implementation, provided direct support and advice. Mr. Coby Jones and the Energy Team at Ft. Bragg were briefed at the beginning of the project, and were briefed on progress. In addition to command support, we were supported locally by Honeywell staff under contract for services at the site.

Communications: Communication between the project team and DoD and civilian representatives of Fort Bragg were facilitated by Honeywell staff located on site at Fort Bragg.

All digital communication networks used in this program were already in place, approved, certified appropriately, and carry most of the needed plant telemetry data to/from the plants from/to plant monitoring center. Additional instrumentation needed for the program was put in place using the same networks and connected to the automation system that monitors all plants . The network architecture is shown in Section 5.3 under the sub-section System Integration and System Controls. The CPOWER software communicates with the certified EBI system via a private network and doesn't reach the site VLAN.

Location/Site Map

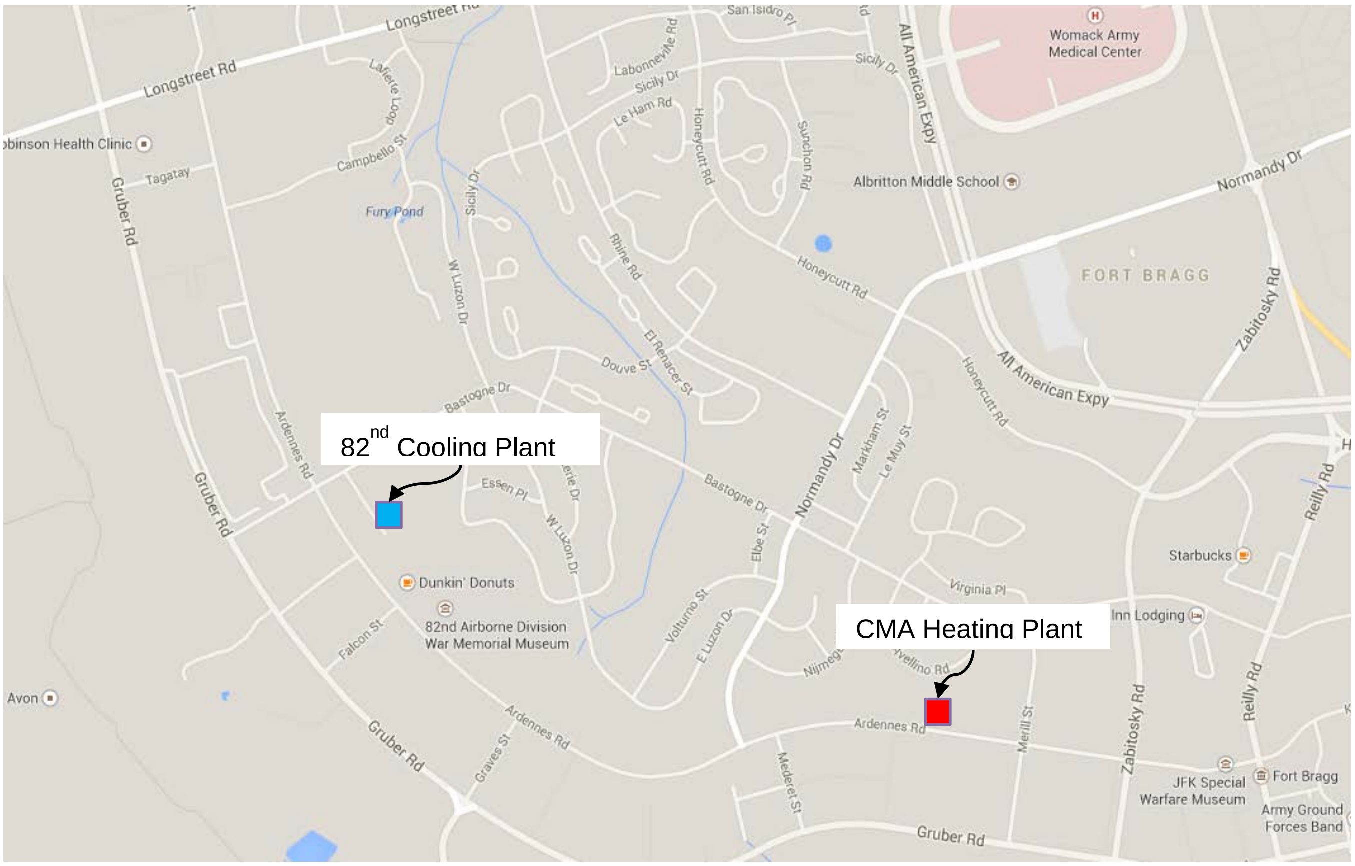


Figure 12: Location of Cooling and Heating Plants for the Demonstration

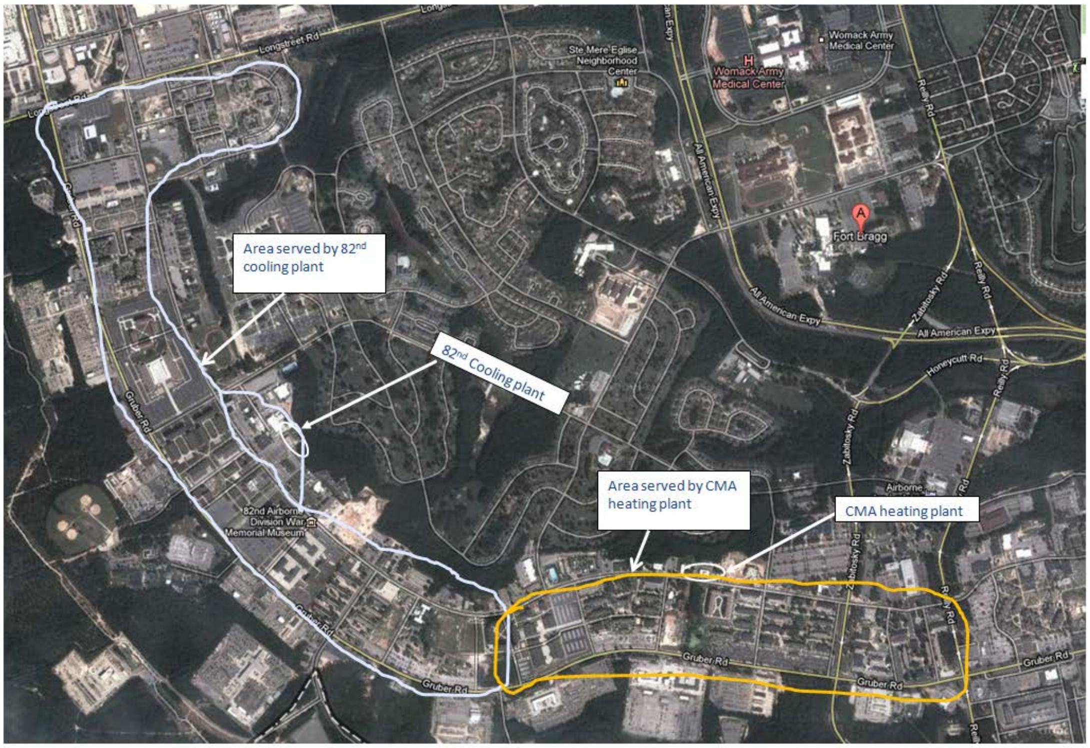


Figure 13: Location of Plants and Areas Served

4.2 FACILITY/SITE CONDITIONS

The 82nd chiller plant and CMA heating plant layouts are shown in schematic representations in Figure 14, Figure 15, and Figure 16. The specifications of major equipment are shown in Table 4 and Table 5.

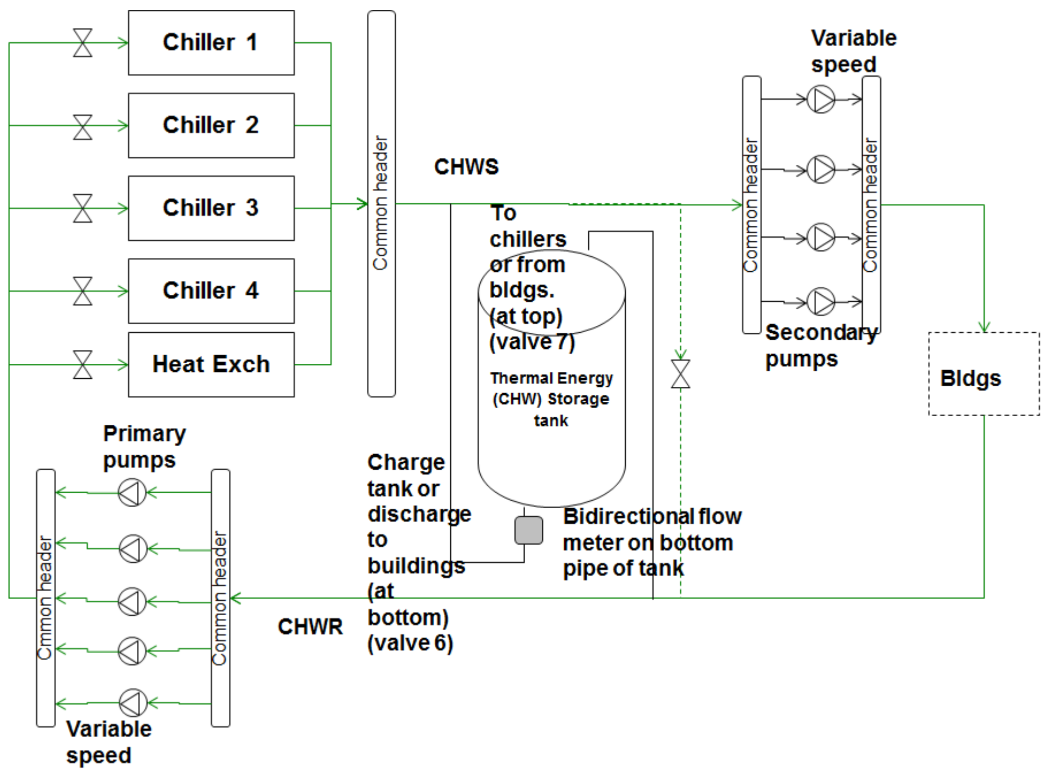


Figure 14: 82nd Chiller Plant Layout – Evaporator Side

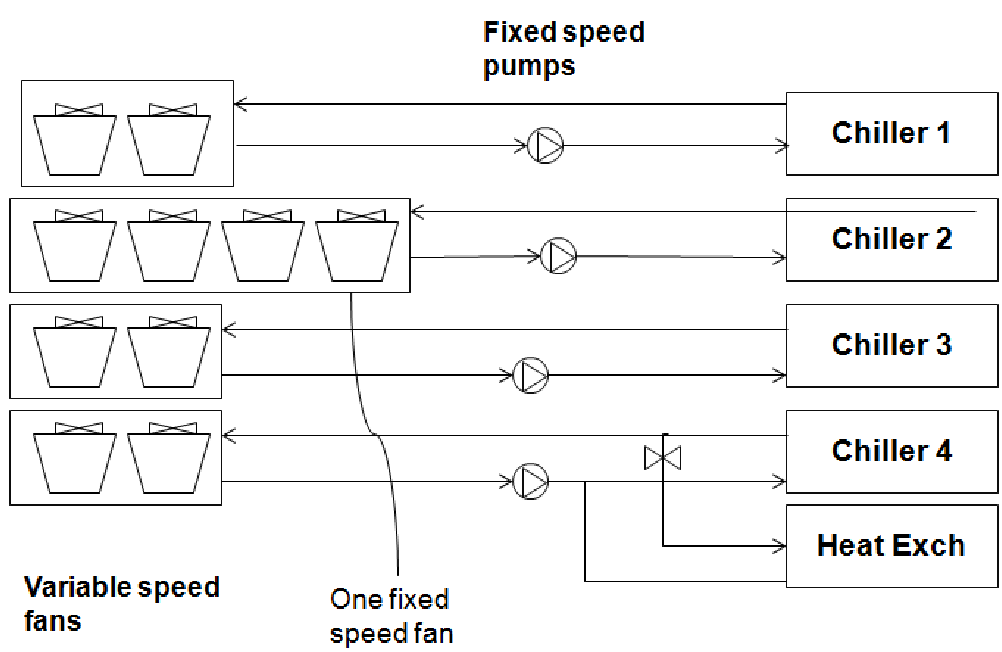


Figure 15: 82nd Chiller Plant Layout – Condenser side

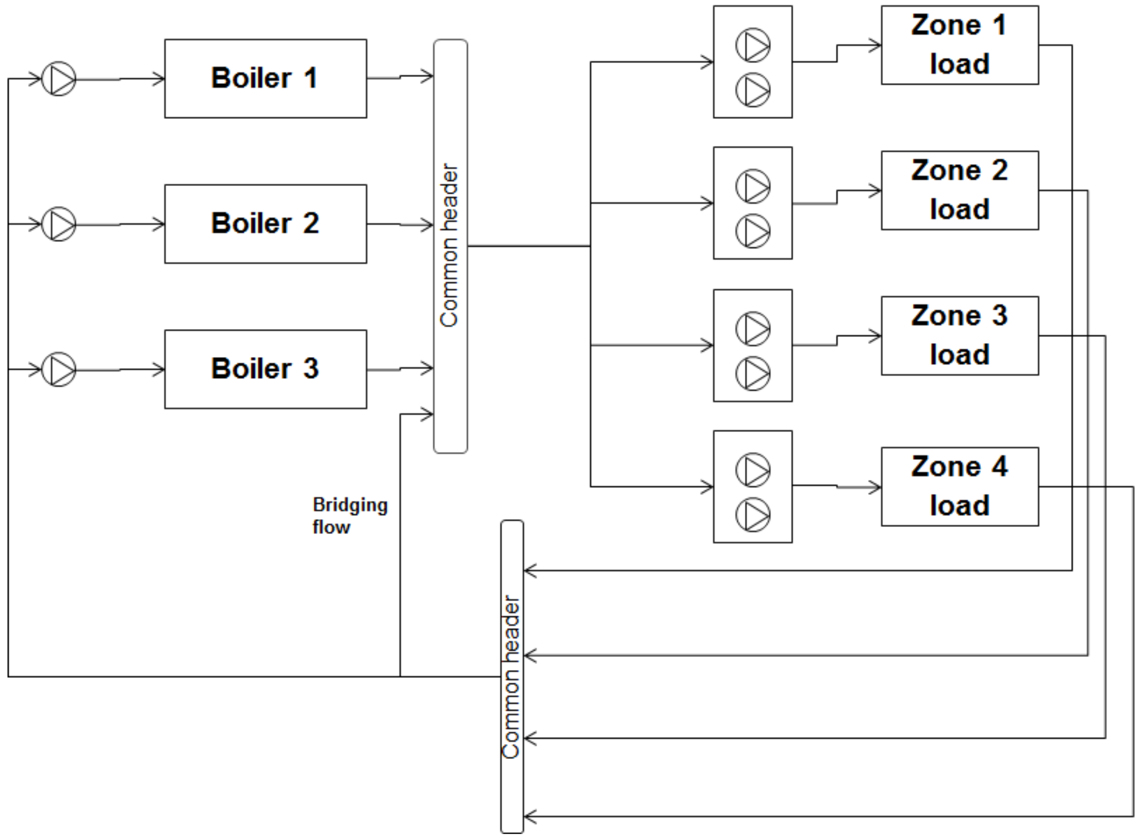


Figure 16: CMA Heating Plant Layout

Table 4: 82nd Chiller Plant Equipment Design Ratings

Equipment	Number				
Chillers	1	2	3	4	
Manufacturer	Mcquay	Mcquay	Trane	McQuay	
Design Capacity (refrigeration tons)	1200	2200	900	2000	
Primary chilled water pumps (VFD)	1	2	3	4	5
Manufacturer	Bell & Gossett	Bell & Gossett	Bell & Gossett	Bell & Gossett	Bell & Gossett
Power (HP)	60	60	60	60	60
Secondary chilled water pump (VFD)	1	2	3	4	
Power (HP)	250	250	250	250	
Condenser water pump (fixed speed)	1	2	3	4	
Manufacturer	Flowway	Flowway	Flowway	Bell and Gossett	
Power (HP)	100	100	200	150	
Cooling tower (10 VFD fans)	1	2	3	4	
Fan power (HP) (# of fans)	50(2)	50(2)		50(2)	
Heat exchanger	1				
Manufacturer	Bell and Gossett				
Design capacity (refrigeration tons)	1000				
Chilled water storage tank	1				
Capacity	2 milion gallons				

Table 5: CMA Heating Plant Equipment Design Ratings

Equipment	Number				
Boilers	1	2	3		
Manufacturer	English Boiler				
Design Capacity (MMBTU/hr)	35	35	35		
Primary hot water pumps (fixed speed)	1	2	3		
Manufacturer	Bell and Gossett	Bell and Gossett	Bell and Gossett		
Power (HP)	20	20	20		
Secondary chilled water pump (VFD) (redundant pump pairs)	1,2	3,4	5,6	7,8	
Power (HP)	25	40	40	150	

Plant Control System Architecture: The control and automation system architecture is shown in Figure 17.

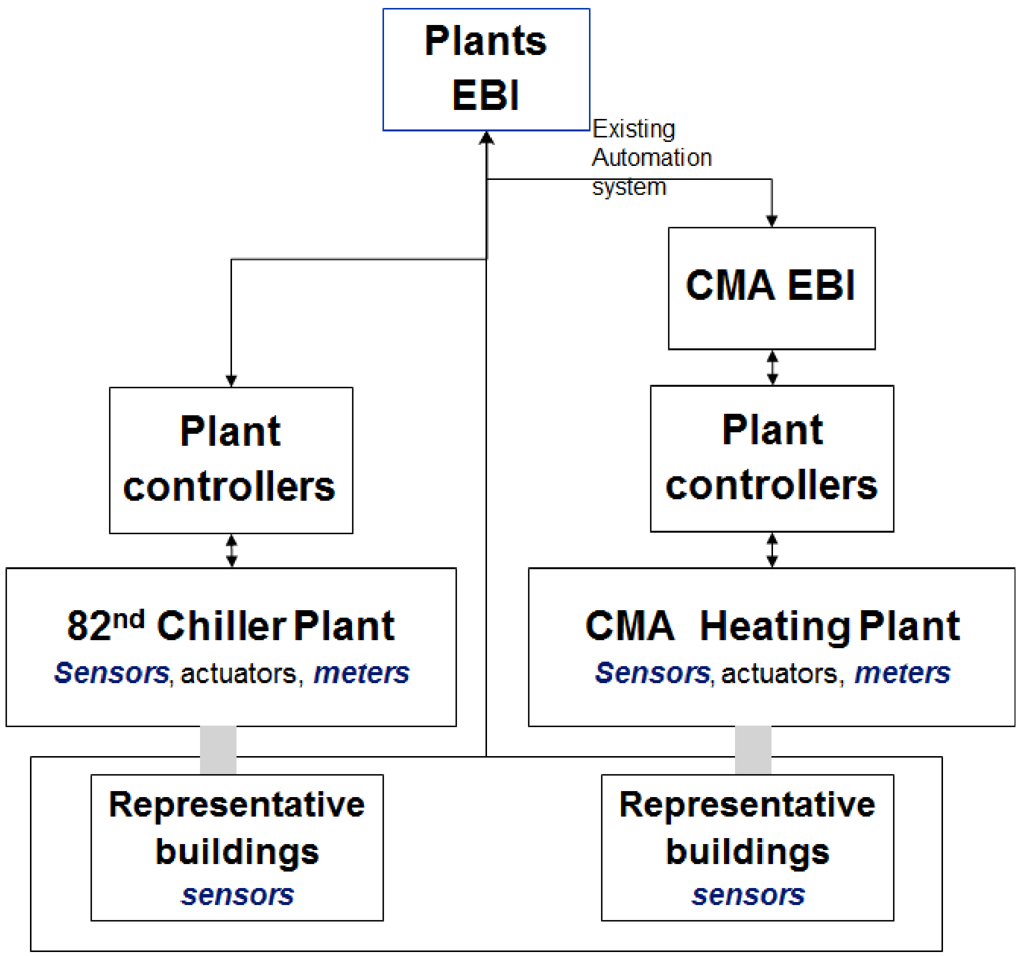


Figure 17: Plant Control and Monitoring System (existing)

Plant Condition: Both the chiller and heating plants are overseen 24/7 by roving operators who care for several plants on site. Honeywell's automation software EBI monitors both plants and has limited access to control the chiller plant. In the chiller plant, all control is automatic and has been programmed as different sequences by a skilled control technician. The operators have been trained to monitor the operator screens on EBI for this control. The control technician is also intimately involved with monitoring the plant or taking calls from the operators. The site was able to provide us access to all chiller plant controls including chiller starts and stops.

In the heating plant, the plant control – the start and stop of boilers, and temperature setpoints, are all manual. The boilers have Allen Bradley controllers.

The site could not provide us access to automated on/off or temperature control for the boilers because of warranty issues involving the boiler manufacturer (English Boiler) and the boiler control (Allen Bradley). This situation meant that we provided the optimizer outputs only as recommendations to the plant operators, who must then manually start or stop a boiler or change its supply temperature setpoint. We worked with the plant manager, operators, and control technician to develop a process so that the operators can follow the optimizer commands at the plant. Since there is a long start up and shutdown period (the boiler should be well warmed before turning on the gas, to avoid thermal stress problems), the local control starts the primary pumps when commanded by the optimizer. The operator sees the primary pump operation (from anywhere on site, not just the specific plant) and is aware that the boiler should be turned on about 30 minutes after the pumps are on. The supply temperature change is gradual enough for the operator to make the change periodically at the plant.

5.0 TEST DESIGN

Fundamental Problem: The fundamental problem addressed by the demonstration is the transformation from manual central plant operation to an automated, dynamically optimized operation that minimizes energy consumption and cost by considering load forecasts, real-time prices (forecast 24 hours in advance), equipment efficiency curves, and effect of various parameters on equipment usage and loads. The schedule of equipment operations is no longer fixed, but changes with changing conditions.

Demonstration Question: The demonstration attempted to answer two questions: What are the energy and cost savings achieved at a DoD central plant by using automated optimization? What is the economic and operational feasibility of implementing this technology?

Therefore, the test design involved: (1) measuring plant performance (consumption, loads, comfort), energy costs, and building comfort (a) while operating without optimization and (b) while operating with optimization; (2) calculating energy and cost savings; and (3) collecting feedback from operators about ease of operation.

5.1 CONCEPTUAL TEST DESIGN

Independent Variable	At the top level, the presence or absence of the CPOWER optimization software that operates the central plants
Dependent Variables	• Total electricity consumed by the selected central plants • Total gas consumed by the heating plant • Total cost of electricity for the selected central plants • Total cost of gas for the heating plant • Building temperature and humidity values (for occupant comfort) • Runtime of the central plant equipment
Controlled Variables	• Central plant heating/cooling equipment • Buildings being served by the central plant
Hypothesis	We tested the hypothesis that the optimized operation reduces wasted energy and energy costs by smart allocation of loads, by considering real-time price signals, and by operating at the temperatures, flows, and pump/fan speeds to achieve maximum efficiency of the central plant energy system.
Test Design	The baseline period ran concurrent with the demonstration period at times that were convenient for the site personnel to monitor the optimizer operation and when the plant equipment and control were not down. A software switch was incorporated in the optimizer software and building automation system that could switch the system between the original automatic controls and advanced optimization system. This switching could occur manually or at set intervals. Because of operator preference and constraints, the interval of optimized operation was for

	longer periods closer to a week. The original control was in control most of the time, interspersed with a few days of optimized operation. The data from the two operations was compared after applying weather normalization and day-of-week normalization for the operation with the existing control system (baseline) to enable fair comparison for dissimilar weather and occupancy schedules.
Test Phases	**Phase I: Control assessment, upgrades and data collection** This phase consisted of surveying the plants to assess the existing control and automation, upgrading the instrumentation and collecting plant specifications and data for the modeling task. Based on the assessment, the list of available points on the automation system is matched with the points needed for optimization. The instrumentation and communication is then upgraded to fill any unmet needs. **Phase II: Testing in simulation** The plant and load system are modeled in Simulink with given plant layout and specifications. The model is tuned with the data collected in Phase I. The optimizer software was integrated with the model and tested in the simulation environment. **Phase III: Installation and commissioning** The CPOWER software was installed onsite and connected to the plant automation system (Honeywell EBI) by mapping point in the appropriate protocol. Commissioning tests will be performed and system brought on line to control the plant. **Phase IV: Data collection and analysis** After commissioning, the software switch enabled the plants to run with optimized control and the existing control. Data was collected during this phase and analyzed.

5.2 BASELINE CHARACTERIZATION

The project test design enables a baseline characterization period that is concurrent with the demonstration period, because for the demonstration, only the central plants' operation changed and no permanent hardware device was installed. The change between optimized control and original control is accomplished with a software switch within the optimizer-BAS system.

5.2.1 Data Collection and Extraction for Baseline Characterization and Demonstration Data Analysis

Our initial plan was to obtain energy consumption (electricity, gas meters), building comfort (space temperature and humidity), and plant status (chillers and boilers on/off) data from Honeywell's EBI automation system that collects most of this data. However, the optimizer software system was already connected to all data sources and gathering the data in it database. Therefore, we obtained the demonstration data as zipped database files that contained all data from the start of the system. The input/output points needed by the optimizer are described in the next section (Table 8 and Table 9). All I/O points are recorded in the database every one minute. Once the database is downloaded, a software tool (CPOTools) along with the plant layout descriptor file campus.xml is used to extract and export the data to several Excel files. We imported the data into MATLAB® and then structured the data for ease of use for different analyses. Figure 18 illustrates this process.

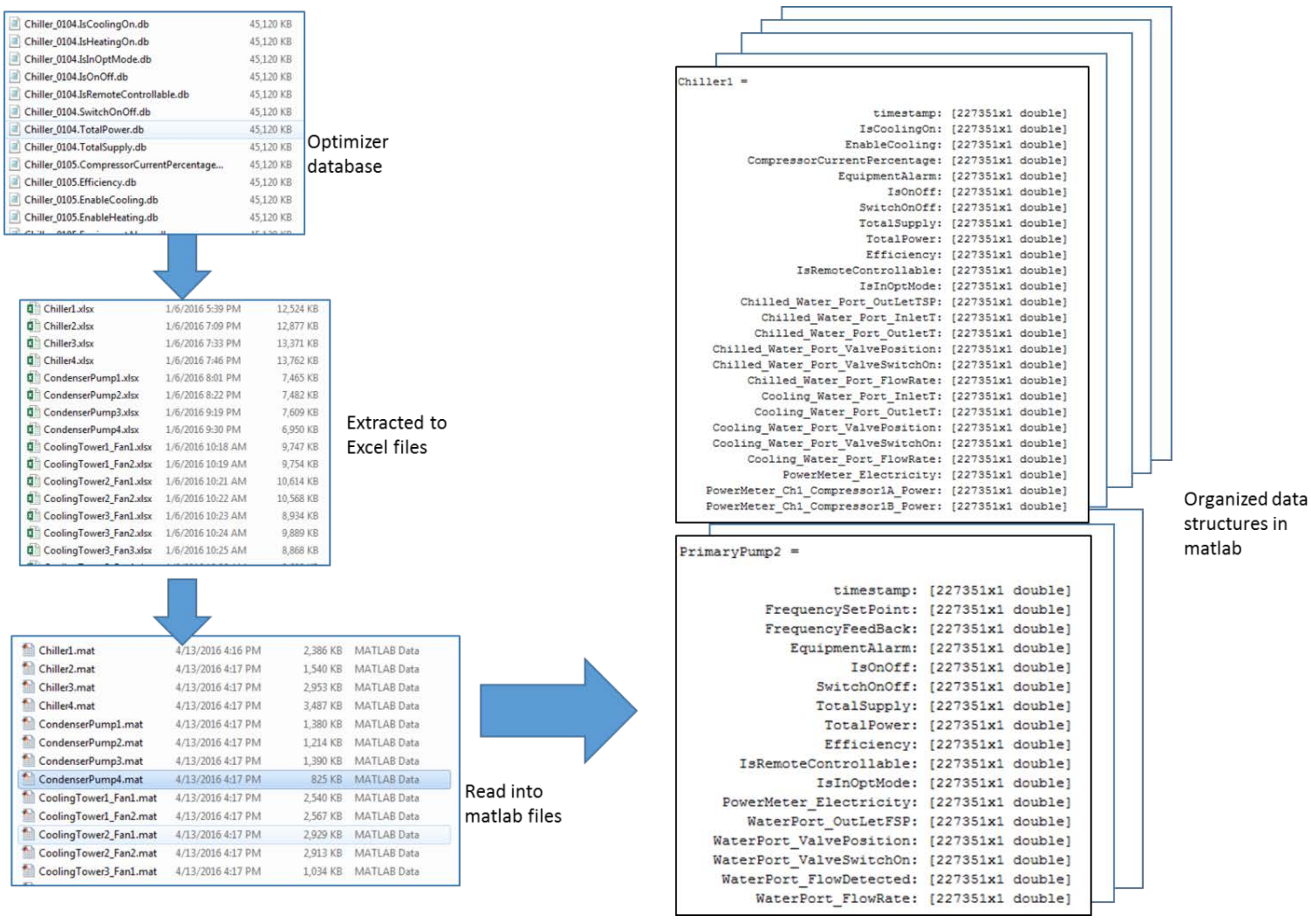


Figure 18: Data Extraction for Analysis

5.2.2 Baseline Characterization for the Chiller Plant

<u>Data:</u> The operational data between July and December 2015 was used to extract data that corresponded with original control operation. The optimizer was installed on site in April 2015, and a number of plant operational issues and optimizer software configuration issues kept us working to resolve them and perform operational testing on site until January 2016. However, the baseline original control operated as intended during the periods it was in control. We also used weather data from an outside source (Honeywell Novar weather data) for Fort Bragg during these periods, since not all weather data such as windspeed and solar radiation is recorded in CPOWER. For these periods, the following data fields from the CPOWER database and the weather database were used:

	Data	Frequency
CPOWER	Chillers' power consumption (KW)	Every 1 minute
	Primary, secondary and condenser pumps' power consumption (KW)	Every 1 minute
	Cooling tower fans' power consumption (KW)	Every 1 minute
	Plant total power consumption (KW)	Every 1 minute
	Outdoor air temperature	Every 1 minute
	Indoor air temperature (representative buildings)	Every 1 minute
Weather	Temperature (F)	Every 15 minutes
	Humidity (%)	Every 15 minutes
	Wet bulb temperature (F)	Every 15 minutes
	Wind speed	Every 15 minutes
Occupancy	Weekday or weekend	Calculated for day

Analysis: We summed the individual equipment power consumption data at each time period to arrive at the total power consumed at the plant. We also cross-checked this value with the total power recorded as a separate point in the database (see Figure 19).

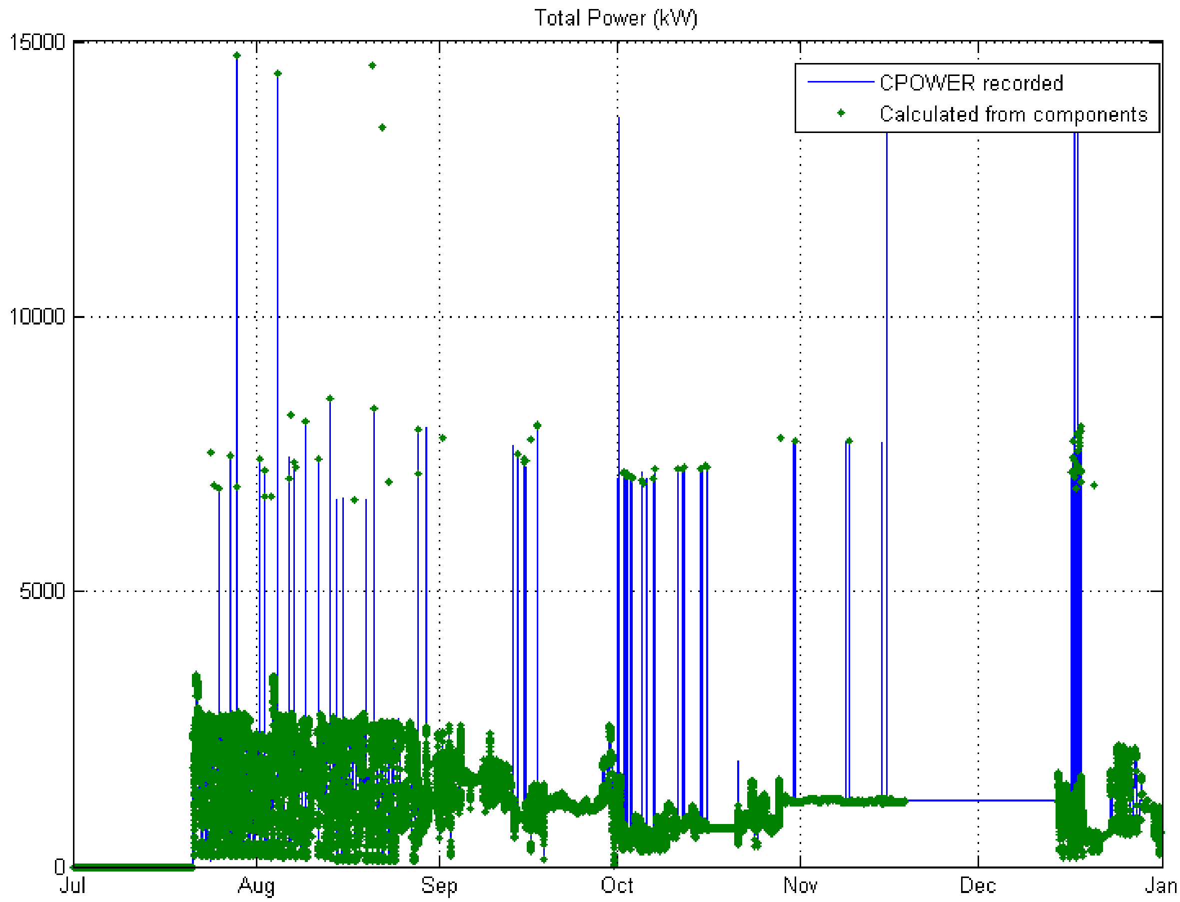


Figure 19: Total Power Consumption

As seen in Figure 19, the power data includes anomalous spikes; we were able to isolate these spikes to power data from Cooling Tower 4, Fans 1 and 2. Since all spikes were, at the most, 1-2 points at 1 minute frequency, we smoothed the anomalous power data from these two points by using previous values in the time series. The resulting cleaned power data is shown in Figure 20.

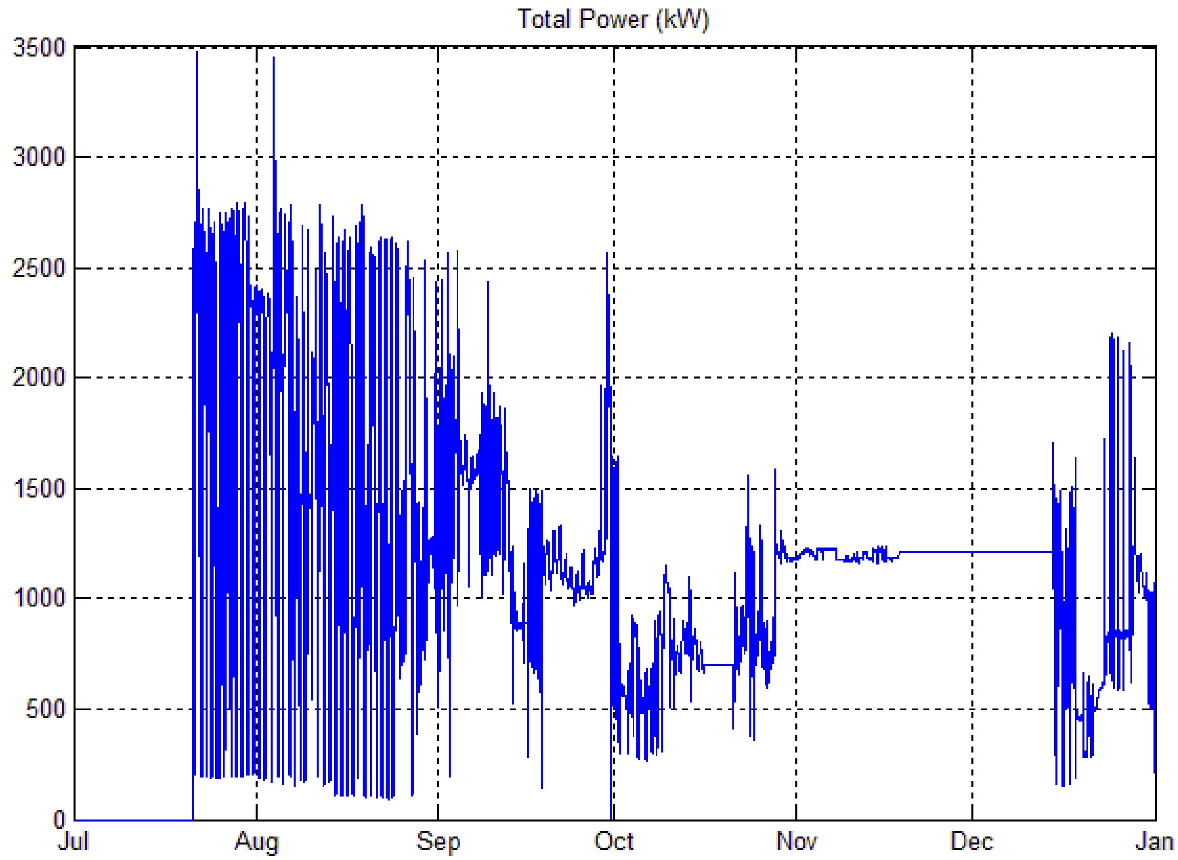


Figure 20: Total Power (anomalous spikes removed)

Anomalous constant values of power consumption also appear in October, November, and December. These values were removed from the dataset used for baseline characterization. The cause of these anomalies is not confirmed; however, the chiller plant had a number of communication issues during this period, which would account for the measured values not being transmitted.

We extracted data for the baseline original control days using the 'EnableClosedLoopControl' point, which indicates if the plant was in optimized (value of 1) or original control (value 0).

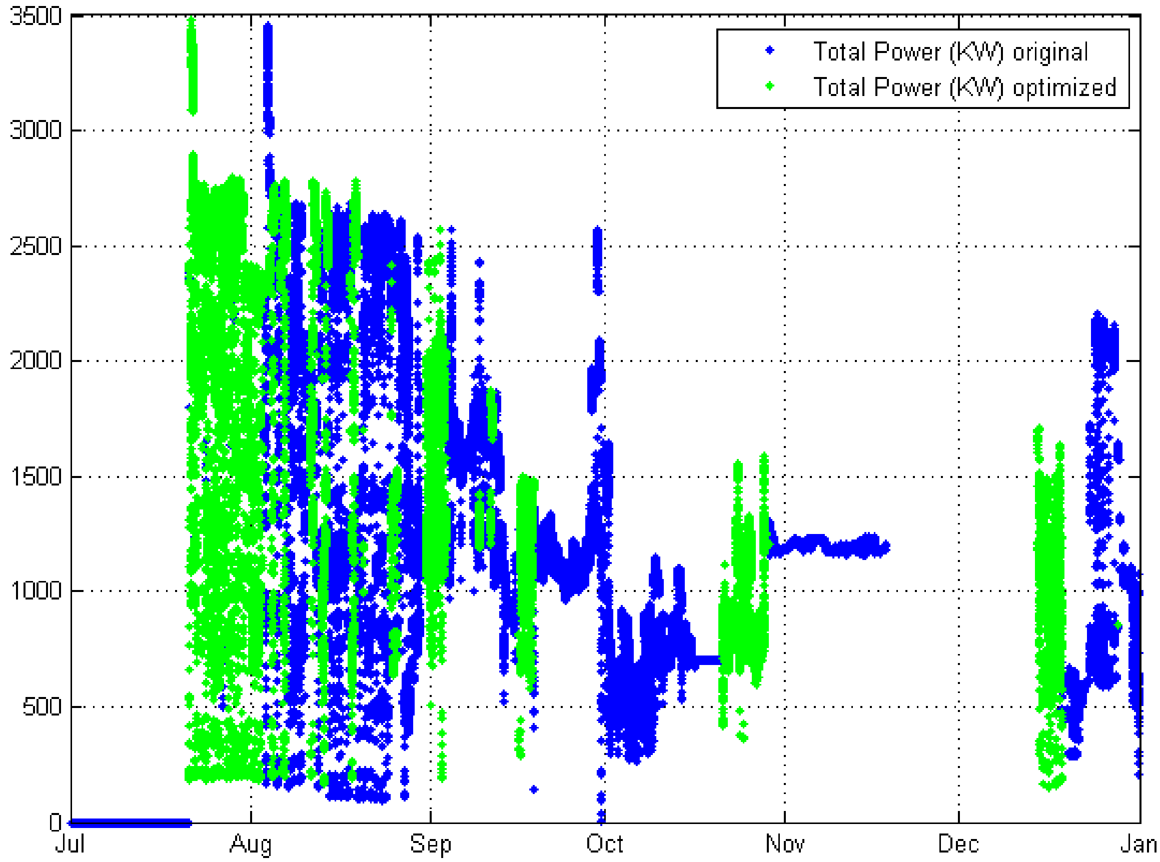


Figure 21: Power consumption - Optimized and Original Control

The dataset was divided into optimized and non-optimized periods; these periods were then sub-divided into 24-hour periods for energy analysis (after discarding any periods shorter than 24 hrs.). The total energy in KWh, average weather quantities, and indoor air temperatures for these 24 hour periods were calculated. The 24-hr period energy consumption is plotted against date in Figure 22. To provide a fair comparison, we need to normalize for factors that affect the energy consumed. Our approach developed a statistical model of the energy consumed during baseline operation, which can then be used to calculate predictions of energy usage for original operation at the conditions for optimized operation periods.

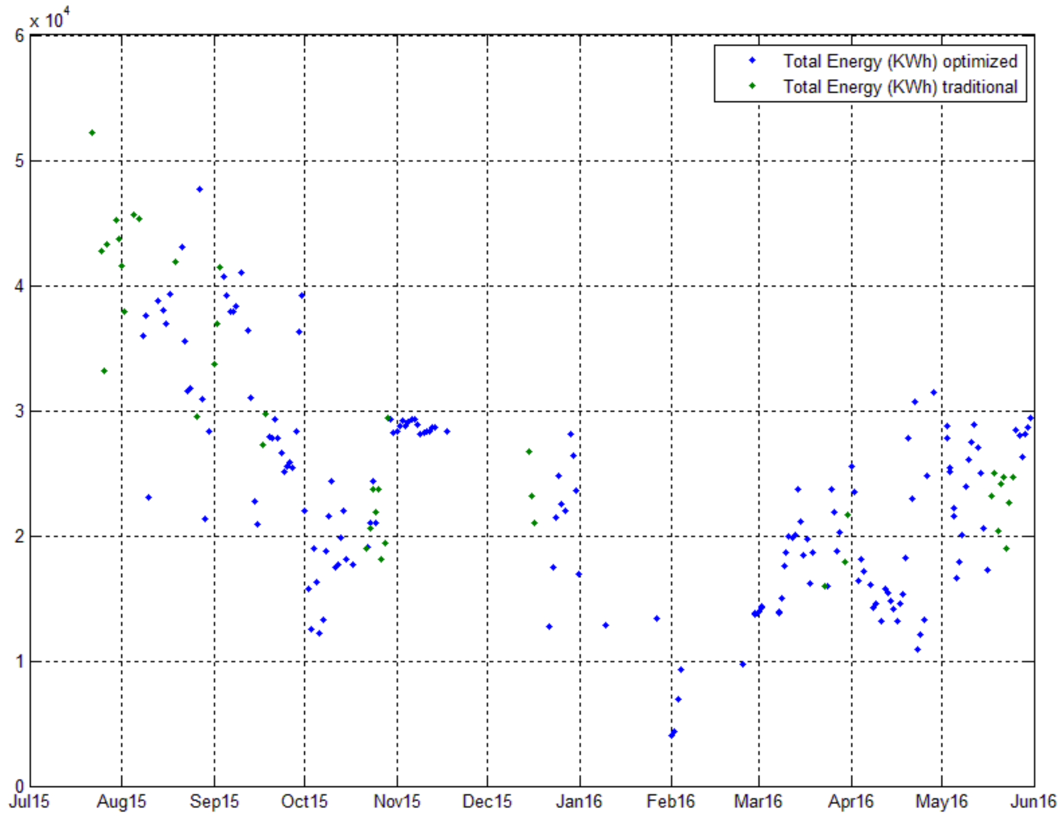


Figure 22: Energy Consumption (24-hr periods)

The main factors affecting energy consumption are weather, indoor air temperatures, and occupancy. We considered outdoor air temperature, humidity (and wet bulb temperature as another measure of humidity), wind speed, heat index, averaged indoor temperature, and day type of weekend or weekday (in lieu of actual occupancy), as factors in the regression models. The solar radiation data did not appear reliable in the weather dataset for the location, and hence we did not use this. The energy consumption data has a lot of variability, and to select a statistical model and regression variables that give the least prediction error, we decided to choose the model based on an evaluation of a combination of *regression model algorithm* and the *regression variables*. In addition, we performed baseline characterization twice, first with available data from July to December 2015; and later with all data from July 2015 through May 2016 when all such data became available. Table 6 and Table 7 show the regression variables and regression models that we evaluated with the 2015-only data, using a 'leave-one-out' approach (explained below). Each set of regression variables were evaluated with each model type, for a total of 28 in the first case and 24 in the second.

Table 6: Regression models and variables for 2015 data

	Model type			
Regression variables	Linear	Interactions	Purequadratic	Quadratic
Measured OAT	x	x	x	x
Novar OAT	x	x	x	x
Measured OAT + humidity	x	x	x	x
Measured OAT + humidity + windspeed	x	x	x	x
Novar OAT + humidity + windspeed	x	x	x	x
Novar OAT + humidity + windspeed + indoor temp	x	x	x	x
Heat Index	x	x	x	x

Table 7: Regression models and variables for all data (July 2015 – May 2016)

	Model type			
Regression variables	Linear	Interactions	Purequadratic	Quadratic
Novar OAT	x	x	x	x
Novar OAT + wetbulb	x	x	x	x
Novar OAT + humidity	x	x	x	x
Novar OAT + humidity + windspeed	x	x	x	x
Novar OAT + humidity + windspeed + weekday	x	x	x	x
Heat Index	x	x	x	x

KEY

Regression variables:

- Measured OAT: outdoor temperature measured on site
- Novar OAT: outdoor temperature from external weather source (Honeywell Novar)
- Humidity: Relative humidity from external weather source
- Windspeed: Wind speed from external weather source
- HeatIndex: HeatIndex from external weather source
- Indoortemp: Averaged (4 buildings) measured indoor temperature
- Weekday: Weekday or weekend day type

Regression models:

- Linear: model contains an intercept and linear terms for each predictor.
- Interactions: Model contains an intercept, linear terms, and all products of pairs of distinct predictors (no squared terms).
- Purequadratic: Model contains an intercept, linear terms, and squared terms.
- Quadratic: Model contains an intercept, linear terms, interactions, and squared terms.

When analyzing the data from 2016, we found that indoor temperature measurements and outdoor temperature and wet bulb temperature measurements from the site were flat-lined (constant values) in April and May 2016 (see Figure 55 and Figure 56). Therefore, for the baseline analysis for the full 2015-16 data, we used weather temperature and wet bulb data from the Novar data source, and we removed indoor temperature as a factor in the second analysis. As will be seen below, the 2015-only data confirms that indoor temperature is not a significant factor in the model accuracy.

Adding a weekday or weekend indicator or creating a separate weekday or weekend model did not increase the model accuracy in the 2015 data analysis, so this variable was left out of the evaluation. Two factors are probably responsible for this lack of change: several building types (office, barracks, warehouse, etc.) are served by the plant and the aggregate load does not have a distinct weekday or weekend characteristic. The effect of weekday is shown in the second analysis for all data; it does not improve the accuracy.

Leave-one-out approach: For each data set and each model type, leave one data row out of the training set, and calculate the prediction error; compute the root mean squared error (RMSE) from each prediction error by leaving one row out at a time.

The RMSEs computed with this approach for the 2015 data using the models in Table 6 are shown in a plot and a color map representation in Figure 22 and Figure 23. For this dataset and models, the quadratic or pure quadratic model with heat index as the only regression variable provides the least RMSE.

The RMSEs computed using the leave-one-out approach for *all data* using the models in Table 7 are shown in a plot and a color map representation in Figure 24 and Figure 25 For this dataset and models, the quadratic model with outdoor temperature, humidity and wind speed as the regression variables provides the least RMSE. We use this model as the baseline energy consumption model for the chiller plant. Figure 26 shows the comparison between the actual and expected energy consumption for this model. As we can see, even with the lowest RMSE model, the individual deviations are still significant.

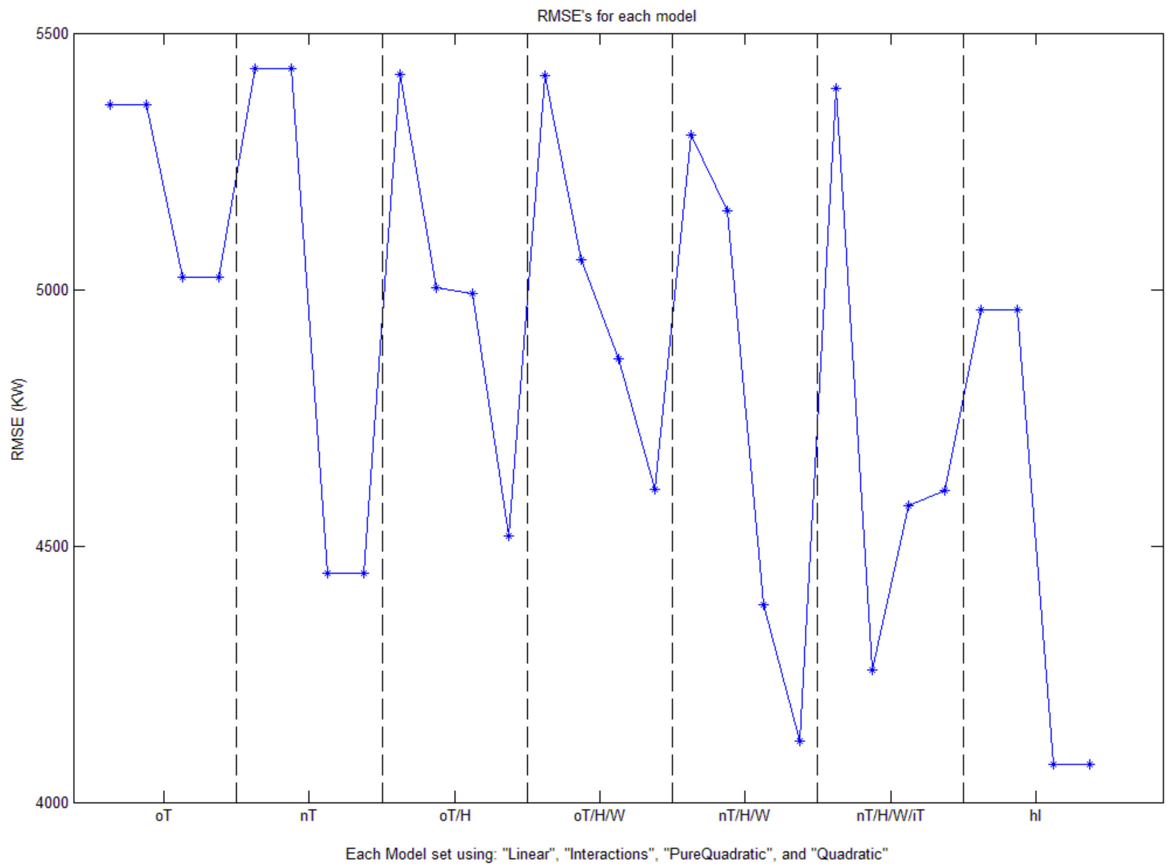


Figure 23: Evaluation of models and inputs (2015 data) – plot of root mean squared errors (RMSE)

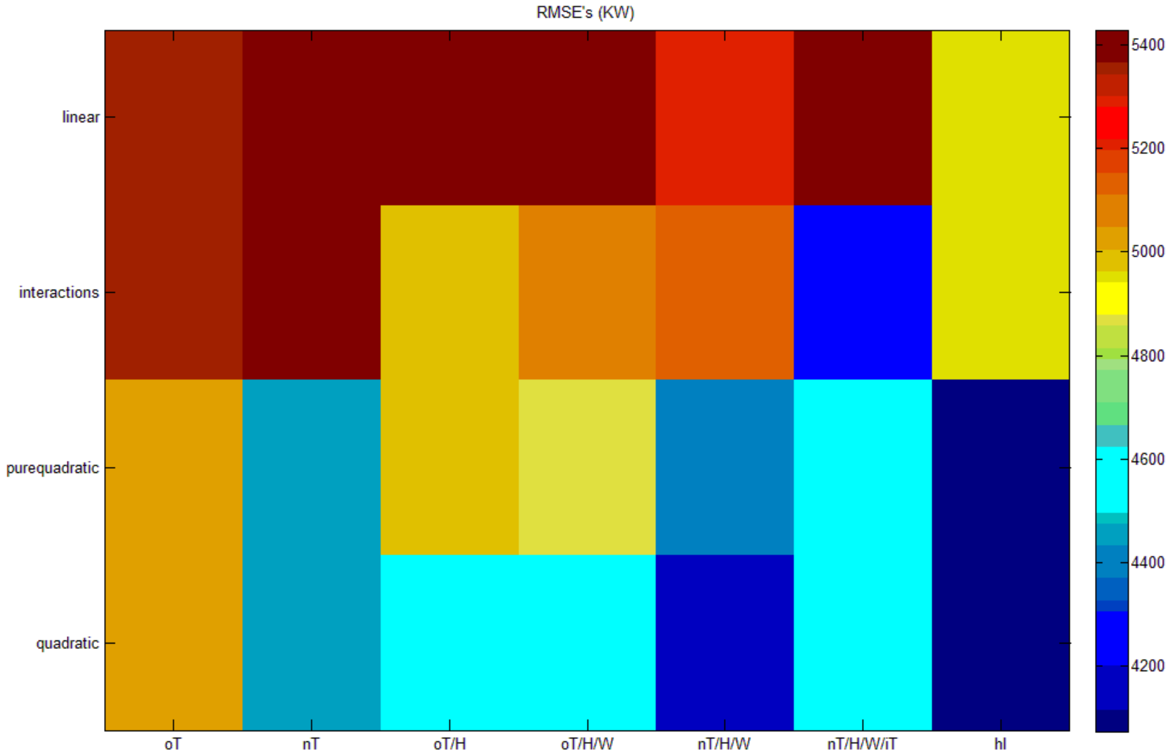


Figure 24: Evaluation of models and inputs (2015 data)– color map representation of RMSEs

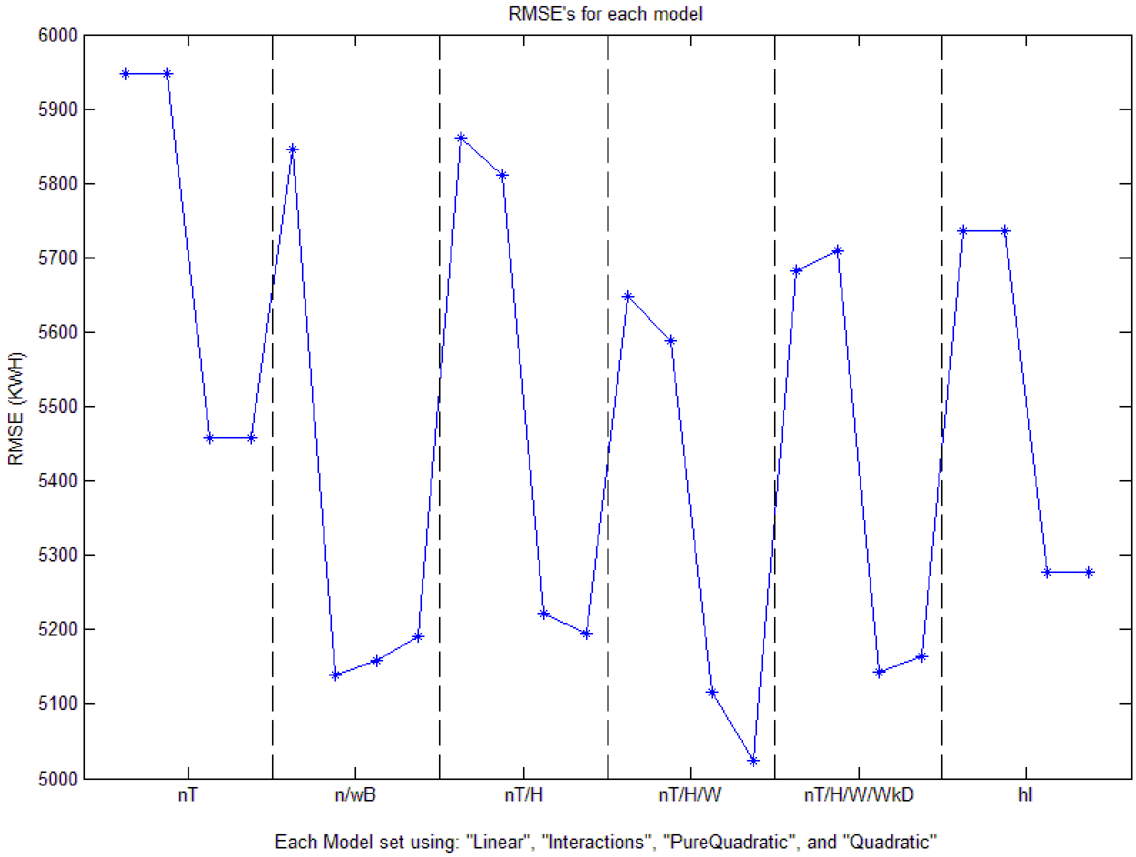


Figure 25: Evaluation of models and inputs (2015-16 data) – plot of root mean squared errors (RMSE)

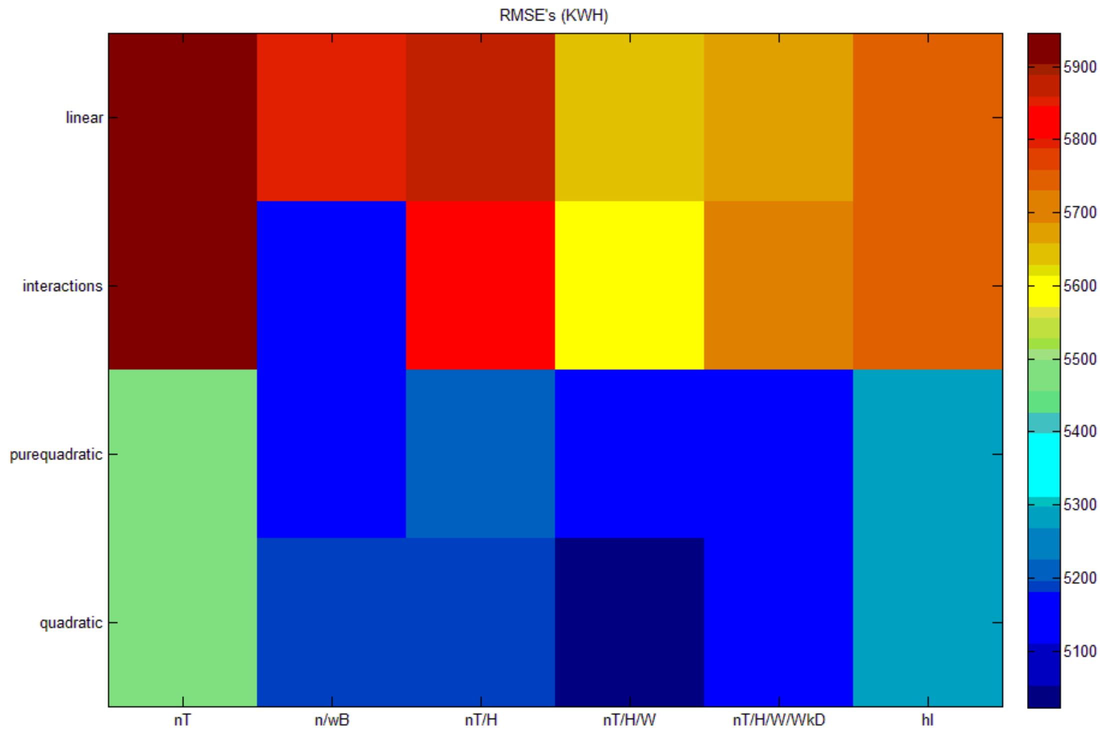


Figure 26: Evaluation of models and inputs (2015-16 data) – color map representation of RMSEs

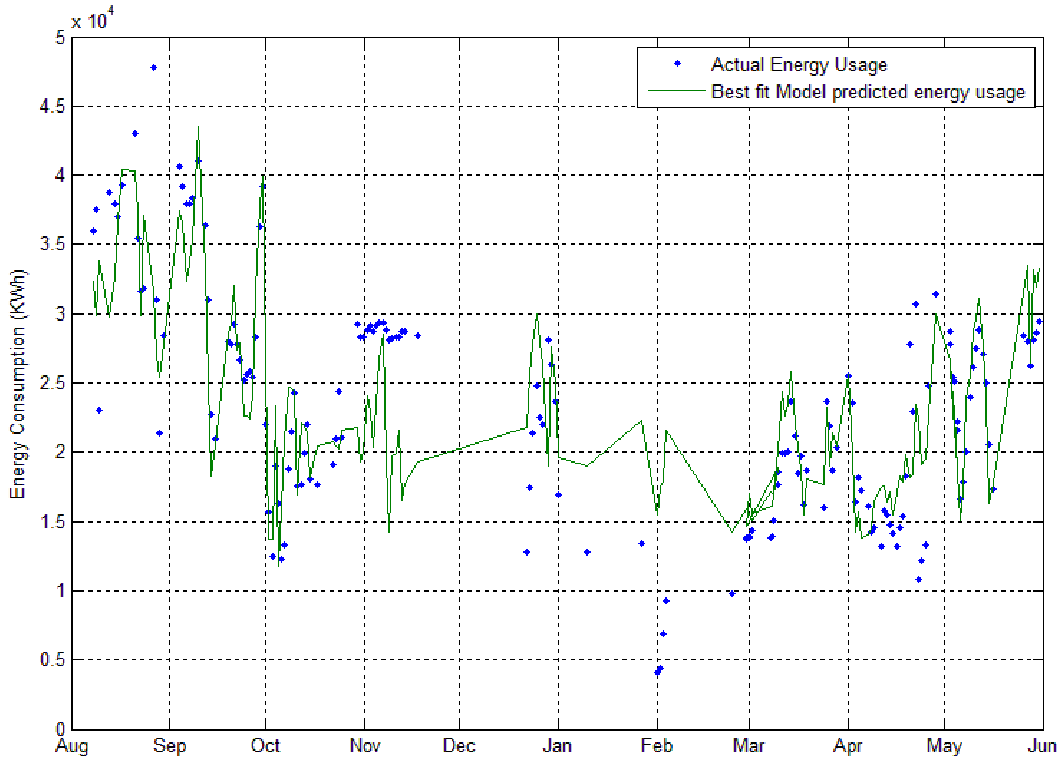


Figure 27: Actual and model comparison

5.2.3 Heating Plant

The operational data between January 2015 – April 2015 (the period of demonstration after commissioning) was extracted in the same manner as for the chiller plant data. In this dataset we found that the data for the original control (or non-optimized) period is not recorded (see section 5.6.1). In addition, the heating plant did not receive the command points needed to control the plant fully (see section 5.4.1), hence the baseline characterization was not performed for the heating plant.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

The central plant optimization solution provides optimal chiller and boiler schedule and distribution temperature and flow rate setpoints. The following subsection provides background information about central plants to clarify how an optimization system will improve the performance.

5.3.1 Central Plant Background

Central cooling and heating plants consist of chillers, boilers, cooling towers, pumps, and a piping system. They supply chilled or hot water to HVAC (heating, ventilation, and air conditioning) systems for several buildings to maintain building comfort conditions. Configuration of a central plant can vary in the number and type of devices, in their manner of connection to each other, and in the controllability of individual devices. Some plants employ a thermal storage system in the form of chilled water storage tanks that help shave peak power consumption.

Typically, in cooling mode, chilled water pumped by the primary or secondary pumps flows through air handling units of the HVAC system and absorbs heat from the air. A schematic in Figure 27 shows this arrangement and is representative of the arrangement of the 82nd Cooling Plant at Ft. Bragg. Similarly, in heating mode, hot water flows through air handling units of the HVAC system and supplies heat to the air.

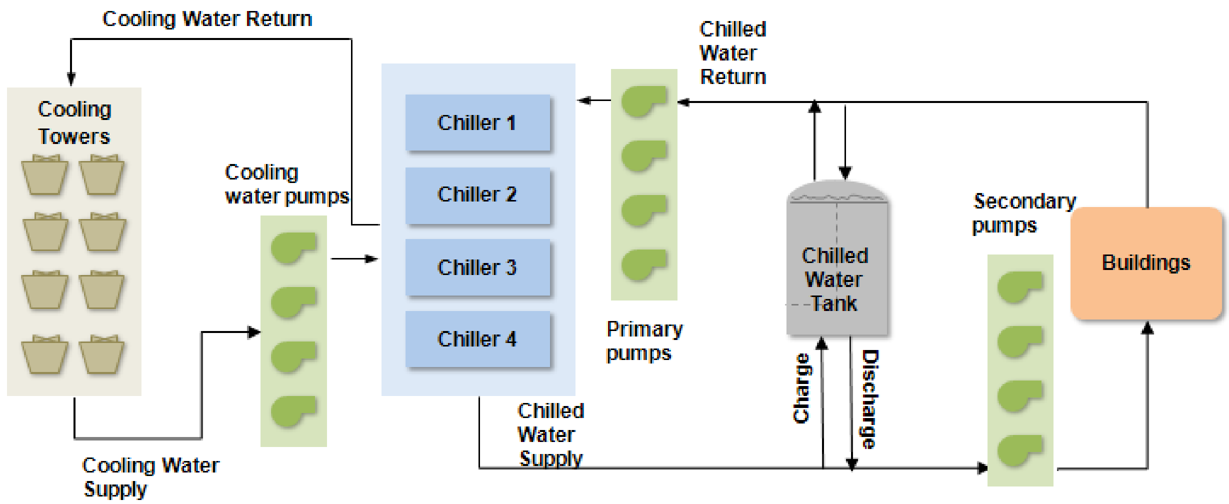


Figure 28: Chiller plant schematic

A control system is usually installed to facilitate and simplify automatic control of the plant so that chillers, pumps, cooling towers, and boilers can be started or shut down automatically in a proper order. When setting up the control logic for the control systems, a series of problems have to be solved such as: how to determine demand; how to decide when one component (chiller/cooling tower/ pump/ boiler) has to be started or shut down; how to assign setpoints (flow rate, water temperature, etc.) for that component; how to find an alternative component if the designated component is taken out of service for maintenance. Note that sequential control is involved here; for example, a series of devices will be activated in a certain order (shown in Figure 28) to get a chiller started properly. They are deactivated in the reverse order to get the chiller shut down. In addition, to prolong equipment life, frequent startup and shutdown of devices such as chillers and large pumps are avoided. Designing the control logic for such a system is complicated, especially when there are many devices or types of devices. In a typical operation, the control logic, once generated, is frozen in the controller until the next modification. Design and maintenance of the control logic relies heavily on the expertise, experience, and even design style of the engineer. Additional factors

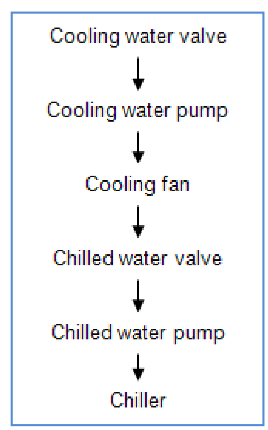


Figure 29: Chiller plant start sequence

complicating the control logic setup include lack of prior knowledge about future loads and their trends, ambient conditions, equipment performance, and building characteristics.

The 82nd chiller plant and CMA heating plant layouts are shown above in schematic representations in Figure 14, Figure 15, and Figure 16. The specifications of major equipment were also provided in Table 4 and Table 5.

System Design, Depiction and Components

The optimization solution dynamically generates optimal schedules and setpoints for plant equipment that will minimize overall operating cost over a specific time period. Figure 1, above, illustrates the functional components of the optimization system. The optimizer is first configured with the layout of the plants and additional plant information, including any maintenance plans, user preferences, and electricity and fuel prices. The configuration involves the input of several parameters for each piece of plant equipment, such as maximum and minimum capacity, maximum and minimum flowrates and temperature setpoints, minimum runtime, etc. The dynamic optimizer block in the center interacts with the equipment performance models, the specific central plant layout, building model, forecasted load, and external inputs such as electricity pricing. The optimal schedule and setpoints are communicated to the controllers via the site communication protocols. The software components of the solution are shown in Figure 4 (above). The user interface accepts user inputs and displays relevant information. A data interface reads data (temperature, flow rate, power, etc.) and sends control commands and settings (ON/OFF, temperature setpoint, flowrate setpoint, etc.) to all relevant devices. A database saves data that needs to be archived and shared. The model library contains simulation models of plant, building, and load forecast. The solver module solves for the optimum schedules and setpoints based on the problem formulated. The fault detector monitors for alarms or availability of chiller plant devices.

System Integration and System Controls

In the technology description section, Figure 3 showed the general system architecture. The plan for system integration layout at the Ft. Bragg site is shown in Figure 29. The CPOWER optimization software (in green outline) was installed on a workstation, and interacts only with the plant automation system - in this case, the Honeywell EBI system. The software was installed on two separate systems as shown, for the two plants. The workstations were

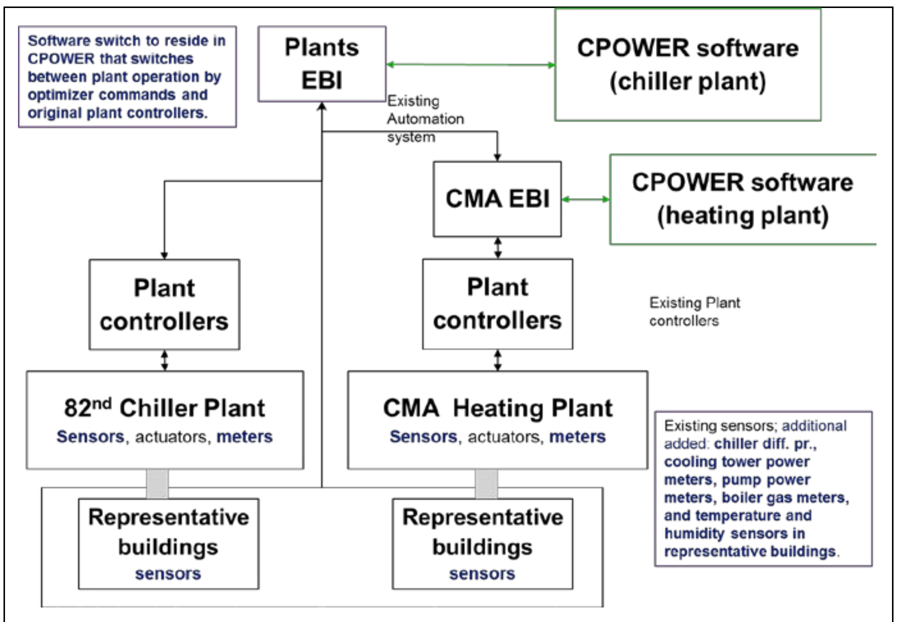


Figure 30: System Integration and Controls

prepared with the Army GoldMaster Operating System that is typical for systems at the site. The 82nd chiller plants' sensors, meters, controllers, actuators were all mapped to the central EBI system (shown as Plants EBI in Figure 29); the CMA heating plant is monitored by its own automation system, but also communicates with the central EBI system that monitors several plants. With the CPOWER optimization system installed, and the optimization system in control, all operational commands for the plant are routed as shown from the optimizer via the EBI system. In addition, we mapped temperature and humidity data from several representative buildings in the service area for each plant to its respective EBI system for providing feedback to the optimizer. We acquired weather and electricity rate data from an Internet Facing Server and created date/time stamped files. Those files were manually transferred to the CPOWER workstation on a periodic basis.

The network architecture for the optimization system with the existing BAS is shown in Figure 30 and Figure 31. After discussions with Honeywell site staff and DPW Energy manager, we connected the CPOWER workstation to the VLAN. The communication protocol between the CPOWER software and EBI was netAPI, which is an EBI-licensed feature for EBI version 410.2 (approved by DIACAP). The CPOWER software and workstation will need to be approved for a permanent installation as a product. We began the process to obtain the Certificate of Networthiness (CON) for the newly added functionality, working with Ft. Bragg DPW. However, for the purposes of this demonstration and in order to gather data for the CON, the DPW Energy Manager recommended that we keep to the project demonstration schedule for the demonstration period, since the CPOWER workstations need to interact only with the approved EBI system.

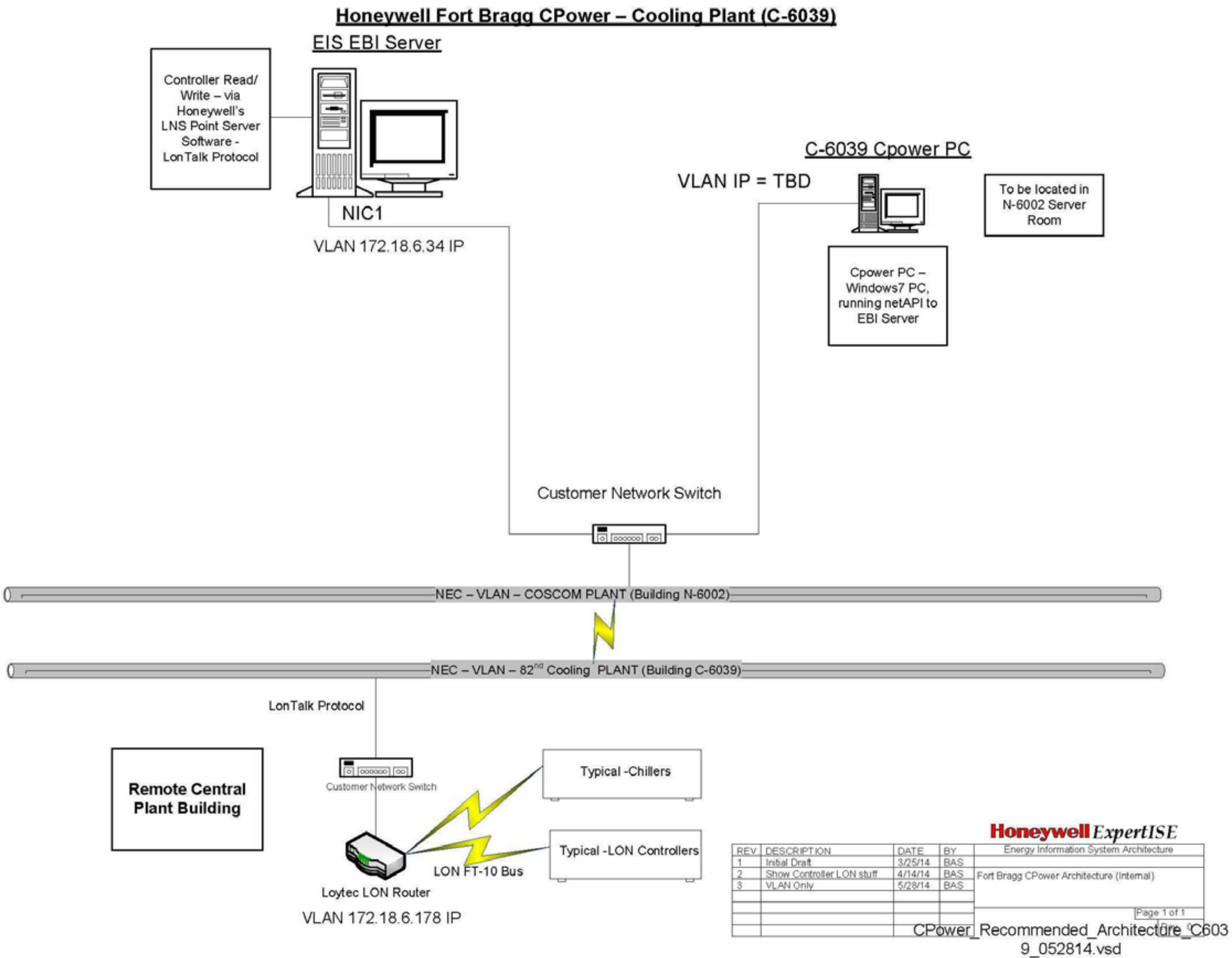


Figure 31: Network Architecture with CPOWER for the 82nd Cooling Plant

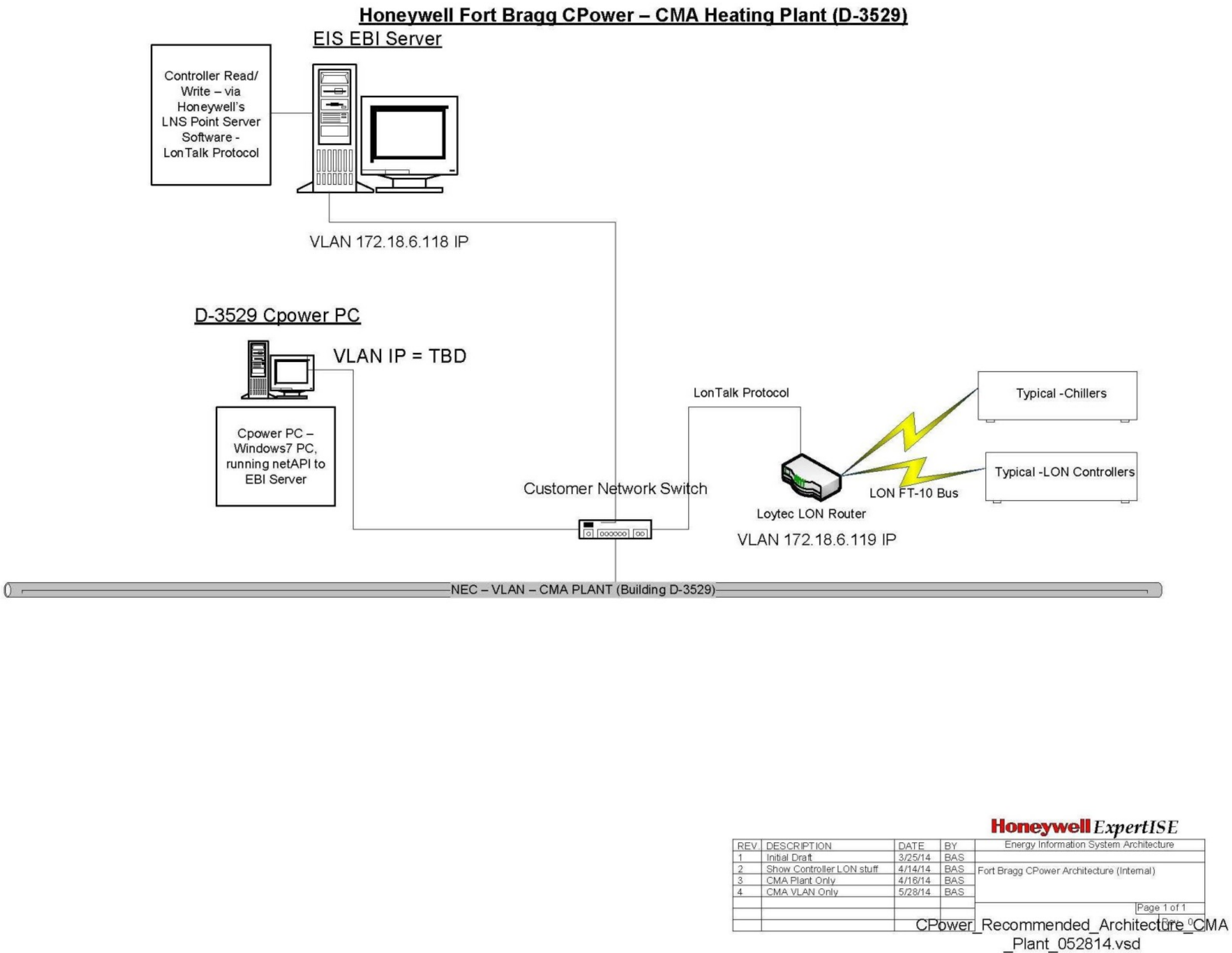


Figure 32: Network Architecture with CPOWER for the CMA Heating Plant

Changes to Existing System

All plant equipment, controllers and automation system remained the same. The new changes are highlighted in green (new system) or blue (partially new) in Figure 29. Some sensors and additional metering were added to the plant and representative buildings. The sensors, actuators and metering added at any site depends on the current plant layout and equipment, available instrumentation and automation and whether the instrumentation was mapped to the building automation system. The list of input and output points (I/O points) needed by the optimizer at the Ft. Bragg site are shown in Table 8 and Table 9. The input and output columns specify if a point was needed as input to the optimizer, or was an output (command) from the optimizer. The points in the shaded cells for the heating plant I/O table were not available for the optimizer to command, because of site restrictions.

The plant automation system was modified to add a software switching function that is triggered by an 'EnabledClosedLoop' command point from the optimizer. With the switch, the plant controller either (1) controls the plant, under the original control sequence, or (2) transmits the outputs from the optimizer to each piece of commanded equipment, under optimizer control. The switch is triggered manually from the optimizer UI by one of the site staff. The switch enabled alternate period testing between original and optimizer operation, as well as facilitated commissioning checks and tests, when several short duration testing was needed, while keeping central plants functional.

The site could not provide us access to automated on/off or temperature control for the boilers because of warranty issues involving the boiler manufacturer and the boiler control (Allen Bradley). The plants are managed by roving operators 24-7 who have several plants on site under their care. We worked with the plant manager, operators and control technician to develop a process so that the operators can follow the optimizer commands at the plant. Since there is a long start up and shutdown period (the boiler should be well warmed before turning on the gas, to avoid thermal stress problems), the local control starts the primary pumps when commanded by the optimizer. The operator sees the primary pump operation (from anywhere on site, not just the specific plant) and is aware that the boiler should be turned on about 30 minutes after the pumps are on. The supply temperature change is gradual enough for the operator to make the change periodically at the plant.

Table 8: I/O Points for Chiller Plant

Equipment	QTY	Point name	Input	Output
Chillers	4	Status (On/Off)	Y	
		Alarm	Y	
		Chilled water supply temperature	Y	
		Chilled water return temperature	Y	
		Condenser water entering temperature	Y	
		Condenser water leave temperature	Y	
		Compressor power	Y	
		Chilled water setpoint		Y
		Switch On/Off		Y
		Chilled water flow or differential pressure	Y	
		Chilled water valve status	Y	
		Chilled water valve Switch On/Off		Y
		Condenser water valve status	Y	
		Condenser water valve Switch On/Off		Y
Primary chilled water pumps (VFD)	5	Status (On/Off)	Y	
		Alarm	Y	
		Switch On/Off		Y
		Pump power	Y	
		Frequency feedback	Y	
		Frequency control		Y
Secondary chilled water pump (VFD)	4	Status (On/Off)	Y	
		Alarm	Y	
		Switch On/Off		Y
		Pump power	Y	
		Frequency feedback	Y	
		Frequency control		Y
Condenser water pump (fixed speed)	4	Status (On/Off)	Y	
		Alarm	Y	
		Switch On/Off		Y
		Current pump power	Y	
Cooling tower (10 VFD fans)	10	Status (On/Off)	Y	
		Alarm	Y	
		Switch On/Off		Y
		Frequency feedback	Y	
		Frequency control		Y
		Cooling tower power	Y	
Heat exchanger	1	Primary side valve status (CHW)	Y	
		Primary side valve Switch On/Off (CHW)		Y
		Secondary side valve status (CW)	Y	
		Secondary side valve Switch On/Off (CW)		Y
		Primary side inlet water temperature	Y	
		Primary side outlet water temperature	Y	
		Primary side water Flow rate	Y	
		Secondary side inlet water temperature	Y	
		Secondary side outlet water temperature	Y	
Chilled water storage tank	1	Tank water temperature at various heights	Y	
		Tank inlet water main pipe temperature	Y	
		Tank outlet water main pipe temperature	Y	
		Tank inlet water main pipe Flow rate	Y	
		High position valve status	Y	
		High position valve Switch On/Off		Y
		Low position valve status	Y	
		Low position valve Switch On/Off		Y
Chiller Plant	1	Main pipe chilled water supply temperature	Y	
		Main pipe chilled water return temperature	Y	
		Main pipe chilled water return flow	Y	
		Differential pressure	Y	
Ambient environment	1	Outside TEMP	Y	
		Outside HUM	Y	
Buildings	5	Representative Room temperatures	Y	

Table 9: I/O Points for Heating Plant

Equipment	QTY	Point name	Input	Output
Boiler	3	Status (On/Off)	Y	
		Alarm	Y	
		Manual or Remote	Y	
		Hot water supply temperature	Y	
		Hot water return temperature	Y	
		Hot water supply temperature setpoint		Y
		Switch On/Off		Y
Primary hot water pump (fixed speed)	3	Status (On/Off)	Y	
		Alarm	Y	
		Manual or Remote	Y	
		Switch On/Off		Y
		Current pump power	Y	
Secondary hot water pump (VFD)	8	Status (On/Off)	Y	
		Alarm	Y	
		Manual or Remote	Y	
		Switch On/Off		Y
		Current pump power	Y	
		Frequency feedback	Y	
		Frequency control		Y
Heating Plant	1	Hot water supply temperature	Y	
		Hot water return temperature	Y	
		Hot water flow	Y	
Zones	4	Hot water supply temperature	Y	
		Hot water return temperature	Y	
		Hot water flow	Y	
		Differential pressure	Y	
Ambient environment	1	Outside temperature	Y	
		Outside humidity	Y	
Building	5	Representative zone temperatures	Y	
		Representative zone humidity	Y	

Not available, apply workaround

The optimizer needs temperature feedback from zones that are representative of the area being served by the plant, so monitoring temperature in these locations provides us a good sense of the rest of the service area. The location of the representative buildings where temperature and humidity sensors were installed are shown in Figure 32 and Figure 33. These buildings were chosen because they are different distances from the plant (end, mid or beginning of line) and they provide diversity in their functions such as operations facility, barracks, administrative office, etc., that may have differing building occupancy schedules.

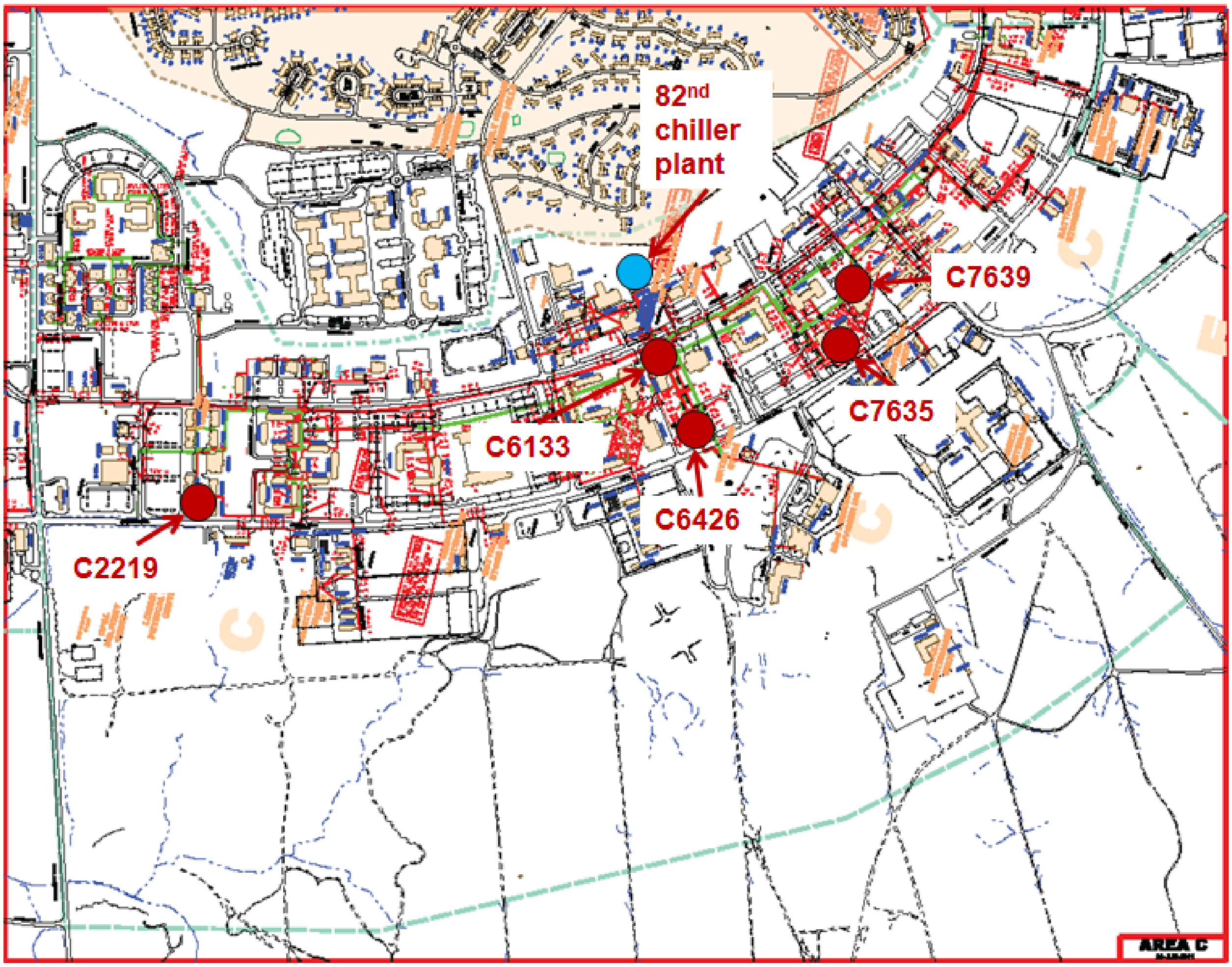


Figure 33: Location of Representative Buildings for Chiller Plant

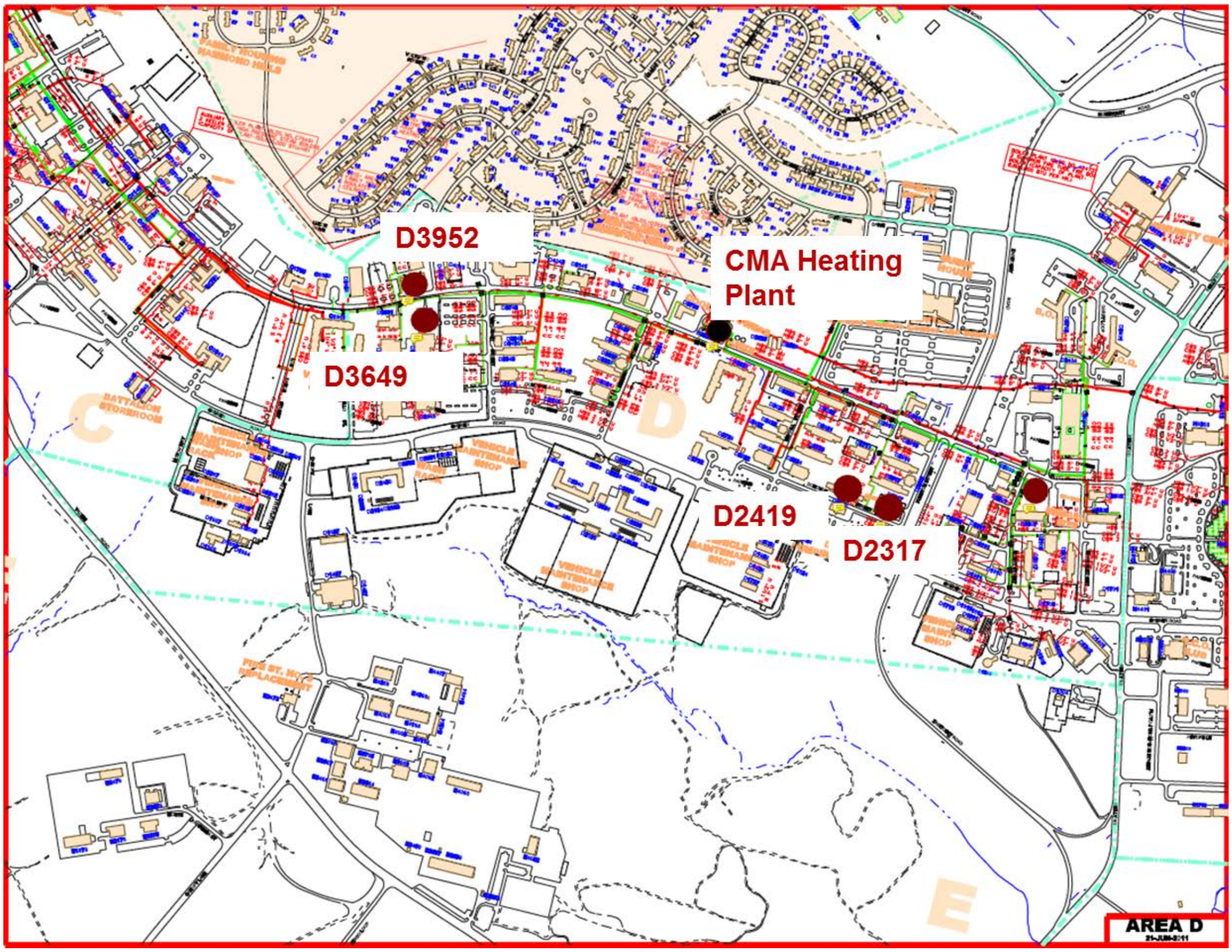


Figure 34: Location of Representative Buildings for Heating Plant

5.4 OPERATIONAL TESTING

5.4.1 Site Operational Testing

- Installation and configuration: The CPOWER optimization software was first installed on workstations for the heating and chiller plants in a phased manner. The optimizer's configuration tool was used to represent the two central plants in the software, with their layouts and other specifications. Next, all the inputs and outputs to and from the CPOWER Optimization system were configured. The field and controller points available were imported via the communication protocols and the optimizer software's CPOBuilder tool that provides the interface for these configuration steps. The CPOWER points created by the layout configuration were then mapped to the correct controller and field points available.
- Commissioning and Performance testing: After installation and configuration at both plants, we performed the steps described in Table 10.

Table 10: Execution of Commissioning and Performance Testing

SN	Item	Work Description	Success Criteria
Checkoff and Commissioning			
1	System communication	Connect all shared I/O points from BAS system via existing network protocol (netAPI in EBI)	Communication points were readable and writable
2	Point-to-point control testing	Control output points from CPO UI and watch input feedback, compare command with feedback	Each controllable point followed the control command. We confirmed result by monitoring the optimizer and BAS screens during optimizer commissioning.
3	Whole system commissioning	Switch all controllable equipment to "optimized" and adjust temperature setpoint in software to trigger increased load (e.g., Actual indoor temperature is 24℃, adjust setpoint to 16-18℃ , check response of optimizer)	1- Whole system ran well and safely for the systems that would normally be operational for that period. 2- Optimizer outputs reasonable commands. Extensive multi-day monitoring of the optimizer and BAS screens confirmed the commissioning success. Some systems could be tested only when they were likely to be used (e.g. heat exchanger in colder months) and we performed additional commissioning-type testing again.
Performance test			
4	Trial run	Adjust all parameters for normal operation, then do 72 hours continuous operation test	1- Energy forecast curve was reasonable. 2- Every control action followed safety rule and load requirements. 3- <20% optimization solver convergence problems in log. 4- Every control command responds on time. 5- 72 hours continuous running without any safety emergency. 6- Zone comfort was acceptable.
5	Energy and Cost Savings Test	Perform energy savings test by alternating optimizer and original control methodology, or by comparison with historical data	1- "Traditional/optimization" control strategy switched successfully. 2- Results show energy reduction.

We executed performance testing by running the optimizer for extended periods ranging from a day to a week. A chronology of all testing is shown in Figure 34. Our trial runs and performance tests overlap, since during most performance testing periods, we found configuration or software issues that needed to be corrected. Nevertheless, because of the project performance period ending, we are providing results based on the analysis of these testing periods.

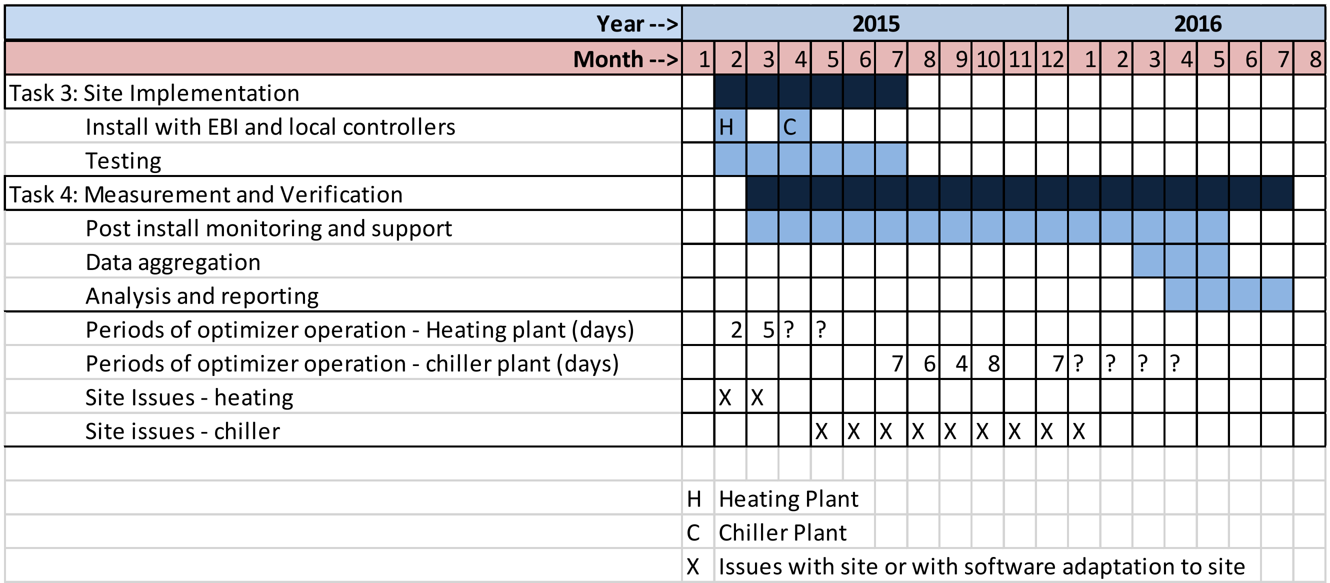


Figure 35: Testing Chronology

<u>Heating Plant</u>

As mentioned in the Facilities section, the optimizer was not able to fully command the plant. The optimizer could not automatically control the on/off or temperature control for the boilers because of warranty issues involving the boiler manufacturer (English Boiler) and the boiler control (Allen Bradley). This situation meant that we provided the optimizer outputs only as recommendations to the plant operators, who must then manually start or stop a boiler or change its supply temperature setpoint. It was decided that the optimizer outputs for the boiler will be displayed on the plant EBI screen. To avoid thermal stress related problems, the operators must follow a set sequence of operations to switch a boiler on or off. We worked with the plant manager, operators, and control technician to develop a process for the operators to follow, as well as a simpler CPOWER operator manual (see Appendices E and F). Since there is a long start up and shutdown period (the boiler should be well warmed before turning on the gas to avoid thermal stress problems), the local control starts the primary pumps when commanded by the optimizer. The operator sees the primary pump operation (from anywhere on site, not just the specific plant) and is aware that the boiler should be turned on about 30 minutes after the pumps are on. The supply temperature change is gradual enough for the operator to make the change periodically at the plant.

The optimizer had limited control of the secondary zone pumps that supply hot water to separate zones. The zone pumps are not common or shared for all buildings being supplied (see Figure 16); rather there are two zone pumps for each supply zone. The extent of control is even more limited because a site constraint dictates that one zone pump in each zone should always be on (the zone should not be starved). This situation meant that for testing we could control only the speeds and switching between the two pumps for the zone.

Another site constraint governs the minimum differential pressure that each zone pump should maintain. This constraint meant that the optimizer must not only control speeds for energy savings but also to keep within the acceptable differential pressure range for the site. The actual control for the differential pressure is best done at the local controller, since communication over several layers makes the cycle times for the optimizer longer and the optimization problem requires solving time. Therefore, the optimizer was modified to act in a supervisory capacity and to provide a pressure setpoint for the local controller used by each zone controller to control the pump speeds. The optimizer also provides the pump on/off command. The pressure setpoint is calculated from the optimizer output of a flow setpoint and the zone flow-pressure characteristics that were estimated based on historical data.

Chiller Plant

The optimizer at the chiller plant was fully automated and had access for full control of the plant, including on/off, temperature setpoint control and speed control, depending on the equipment. The process of configuration (setting correct capacities, high and low limits on temperature or flow setpoints, other plant parameters) was completed on site. Some parameters required by the optimizer are not available directly from site staff, so we estimated these by analyzing prior historical data. The system communication was set up using the available tools and tested, after which the full system was commissioned and handed over to the site staff. As reported in the progress reports, several issues were discovered involving software problems, configuration of parameters, communication and mapping of points, site communication network problems, unfamiliarity with software or site equipment shutdowns. We continued troubleshooting, updating the software and parameters, and testing on site, as site conditions permitted. The issues are more fully described in the Implementation Issues section of this report.

5.5 SAMPLING PROTOCOL

Data Description	All data and control points needed in the CPOWER optimization software are shown in Table 8Table 9. Once commissioned, the software is set up to collect all these data points, and additional derived quantities in its database at 1 minute interval, during optimized operation as well as during operation with the original control system. The data needed for energy savings calculations are part of this set. In addition, the Honeywell BAS also collects data from the plant at 15 min intervals that includes data needed for energy savings calculations: energy consumption at the chiller and boiler plants, cooling or heating outputs, and weather.
Data Collector(s)	Honeywell staff on site (Bruce Skubon, John Schlesinger)
Data Recording	Data recording will be automatic, by the existing BAS (Honeywell EBI) and DCS; the newly added optimizer workstation will connect to the BAS and record the data in its database.
Data Storage and Backup	The existing BAS and DCS have redundancy and data backup built into the system; we will look into the possibility of backing up the CPOWER optimizer database
Data Collection Diagram	List of Data and a system diagram provided in (Table 8, Table 9 and Figure 29)
Non-Standard Data	We obtained electricity price information separately for the demonstration period. This was input into the optimizer software, and recorded in the database.
Survey Questionnaires	No survey questionnaires were prepared or used.

5.6 SAMPLING RESULTS

Once the optimizer software is started, it begins recording all input and output data in its database. We used this database as the main data source for our analysis. Figure 18 shows our data extraction process and Section 5.2.1 describes the process. In Appendix B, the extracted data structures and fields for each structure in the chiller plant are shown. The size of the data is not final, as we gathered and extracted additional data after the example was inserted in the appendix. Similar structures were created for the heating plant after extracting data from the database (see Appendix C).

5.6.1 Heating Plant data:

Figure 35 is a summary plot of the raw heating plant data. It shows the supply, return temperatures, zone supply flow rate, total heating supply, and the gas used by the boilers. The 'Optimized' plot shows when the plant was under optimizer control using operational recommendations provided to the plant. However, it is clear from this plot that the data for the original control (or non-optimized) period is not recorded, as seen by the constant value lines that correspond to the value at the end of optimizer controlled operation. This situation may have occurred either because the workstation was switched off between optimized controlled operation or a duplicate set of points were created for the optimizer to read from and write to. The duplicate points were probably not written to the original local controller, which resulted in the optimizer not getting the correct I/O data. However, the varying supply temperature indicates that the optimizer is working to command the hot water temperature setpoints for the boilers. In the original control, these temperatures are seldom changed from a fixed setpoint of 220 deg F.

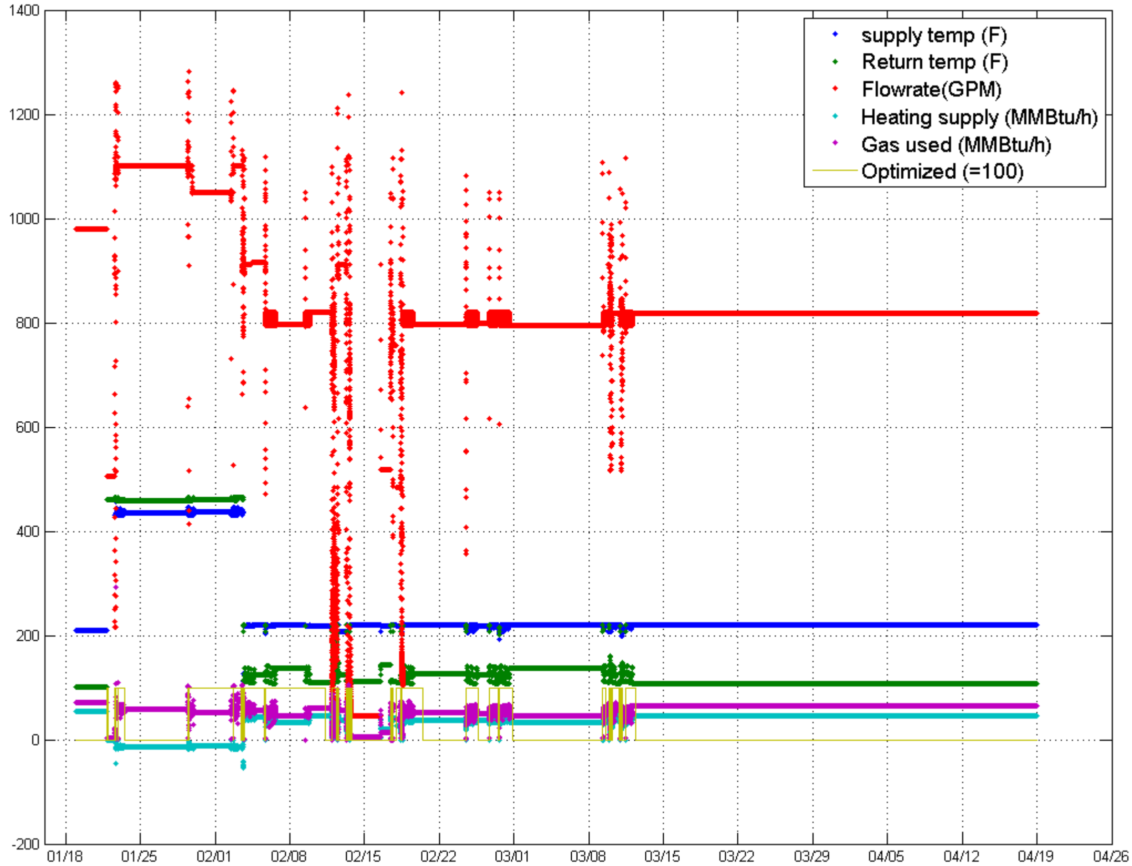


Figure 36: Heating Plant operational data

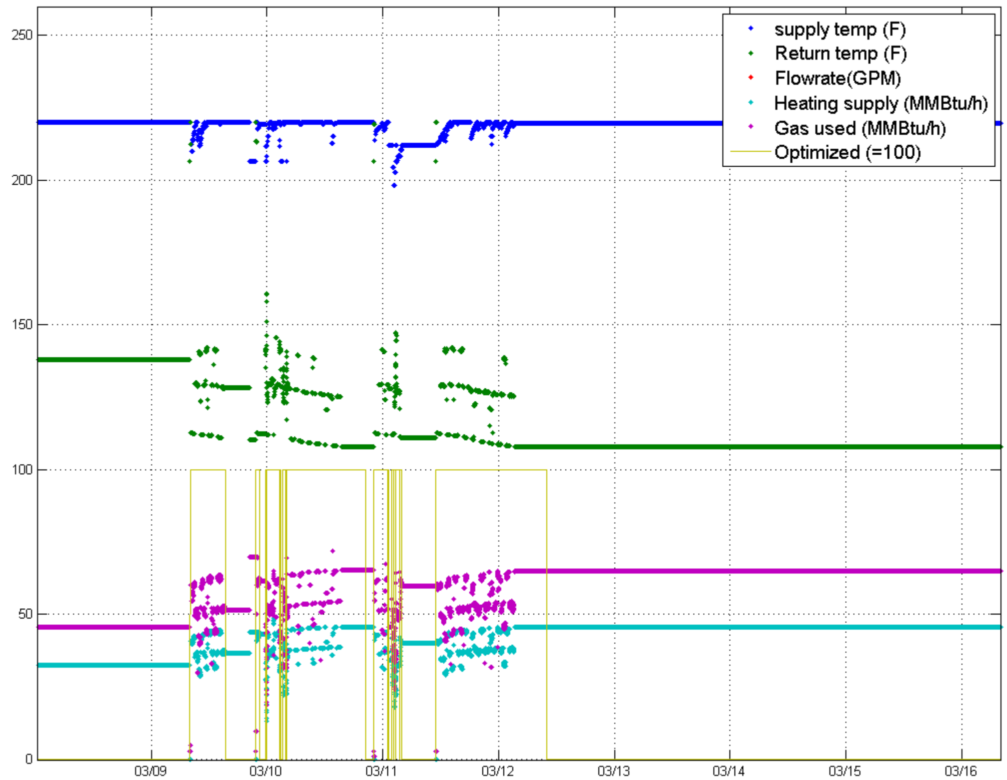


Figure 37: Supply temperature changing

5.6.2 Chiller Plant data:

The plots of optimized controlled periods, plant supply, and return temperatures and the total instantaneous power consumed during optimized and non-optimized periods are shown in Figure 37 - Figure 39.

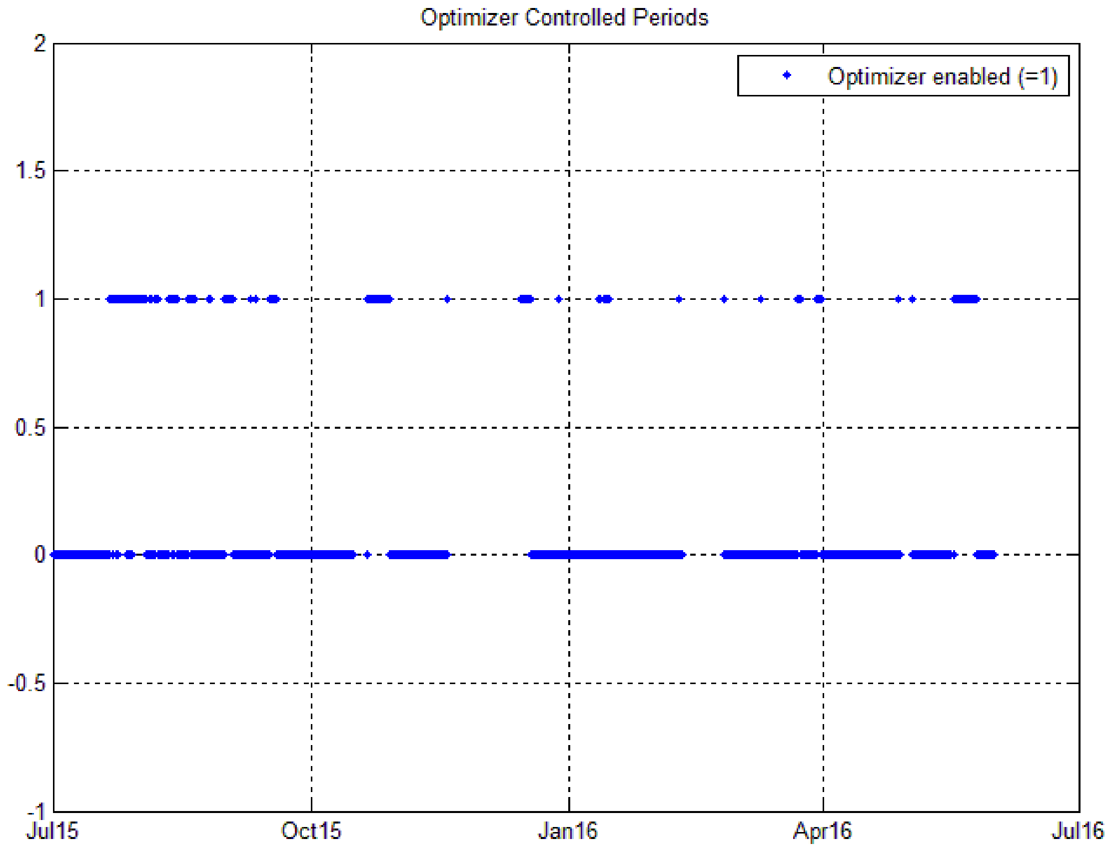


Figure 38. Chiller Plant optimizer enabled periods

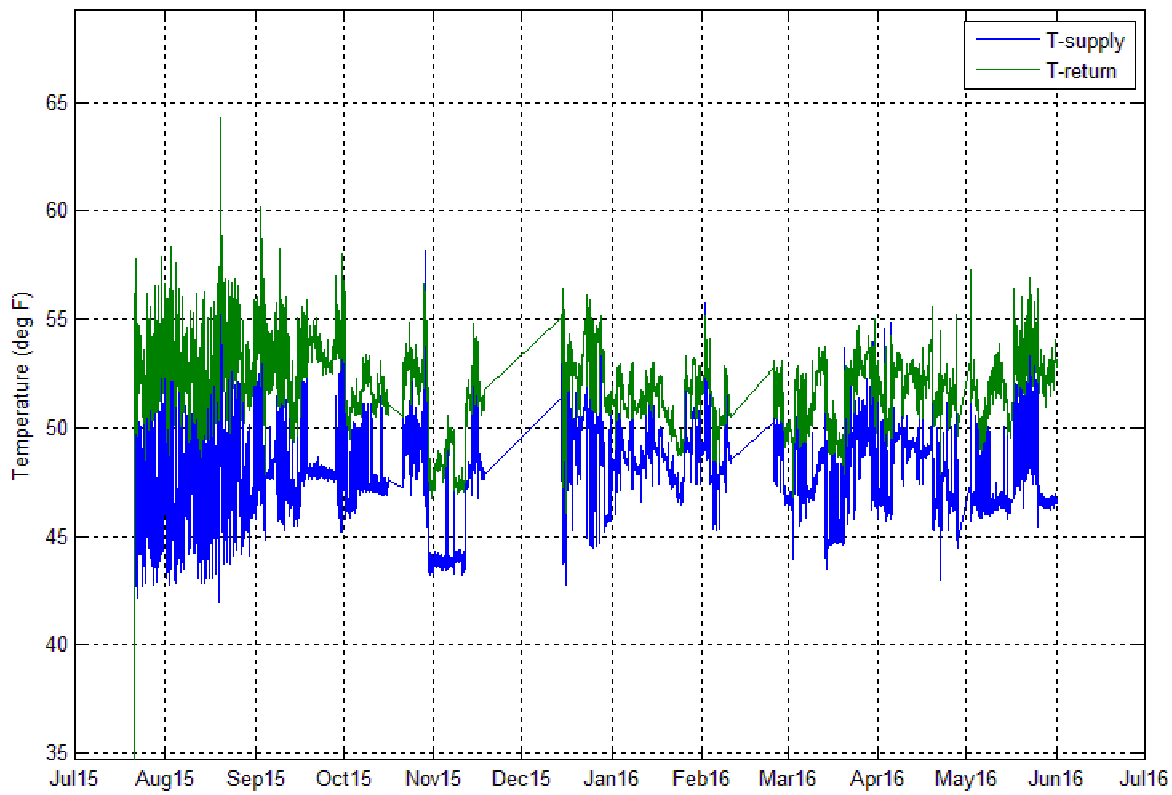


Figure 39: Chiller Plant supply and return temperatures

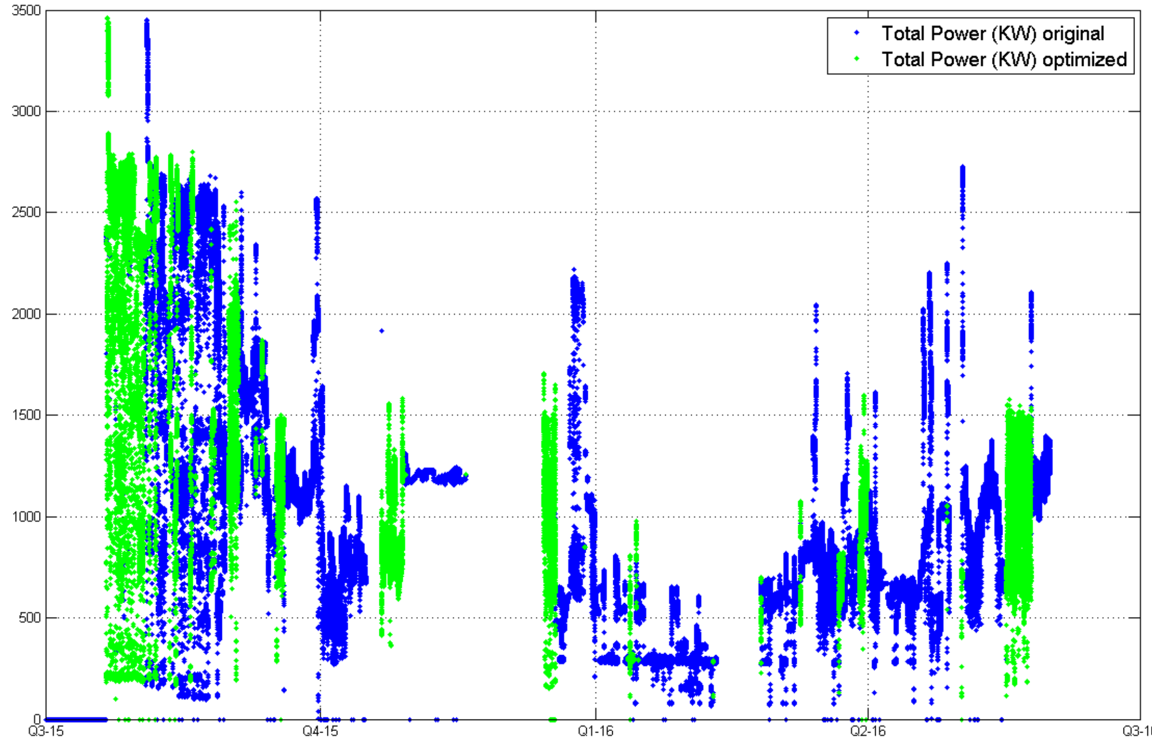


Figure 40: Total power consumed by the chiller plant

6.0 PERFORMANCE ASSESSMENT

6.1 PO1: SIMULATED OPTIMIZER SOFTWARE PERFORMANCE

The central plant optimizer works continuously and automatically to control the central plant. The core optimizer computes parameters such as demand, chiller or pump ON/OFF, flow rate, and temperature setpoints. The optimizer outputs are based on current and past measurements and the model of the plant that exists in the optimizer software. We ensured that the normal operating behavior and safe operating limits were captured correctly in the software by testing in a simulation environment.

Purpose: To show that the optimizer software can control the chiller and heating plants safely and within normal operating limits imposed by the manufacturer or required operating procedures.

Metric: Optimizer output of plant operating schedules and setpoints.

Data: The central plants and building loads were modeled in the Mathworks Simulink environment. The optimizer software for heating and chiller plants was interfaced with this model for testing. We performed several simulations of plant operation under different load and weather conditions; the optimizer provided the control commands for current conditions. We collected optimizer output data from the simulations for analysis. The data included: load, equipment schedule (ON/OFF), equipment setpoints, and simulated measurements.

Analytical Methodology: We simulated several combinations of activities covering the range of loads, weather and electricity prices, and their transitions in the simulation framework. The data collected (optimizer outputs) was compared against known normal operating ranges for the equipment. The number, level, and duration of deviations from normal were recorded for all deviations to arrive at a cumulative deviations time and the percent of time that the outputs were within normal range of operation. We illustrated the deviation distribution as histograms and other graphical representations.

We ran several simulations with the model-optimizer system to test for out-of-range outputs. Simulations also tested software changes to confirm that no unintended system consequences occurred because of the changes. Data was collected for several realistic simulations by providing a particular date and time of start, so that loads and plant response for particular weather conditions can be simulated. The weather simulation was performed with TMY (typical meteorological year) weather data for Fort Bragg, NC. Plots of data from several tests shown in Figure 40 through Figure 51 confirm that the optimizer did not output any out-of-bound commands and that it captured normal operating behavior and safe operating limits correctly.

Heating plant analysis:

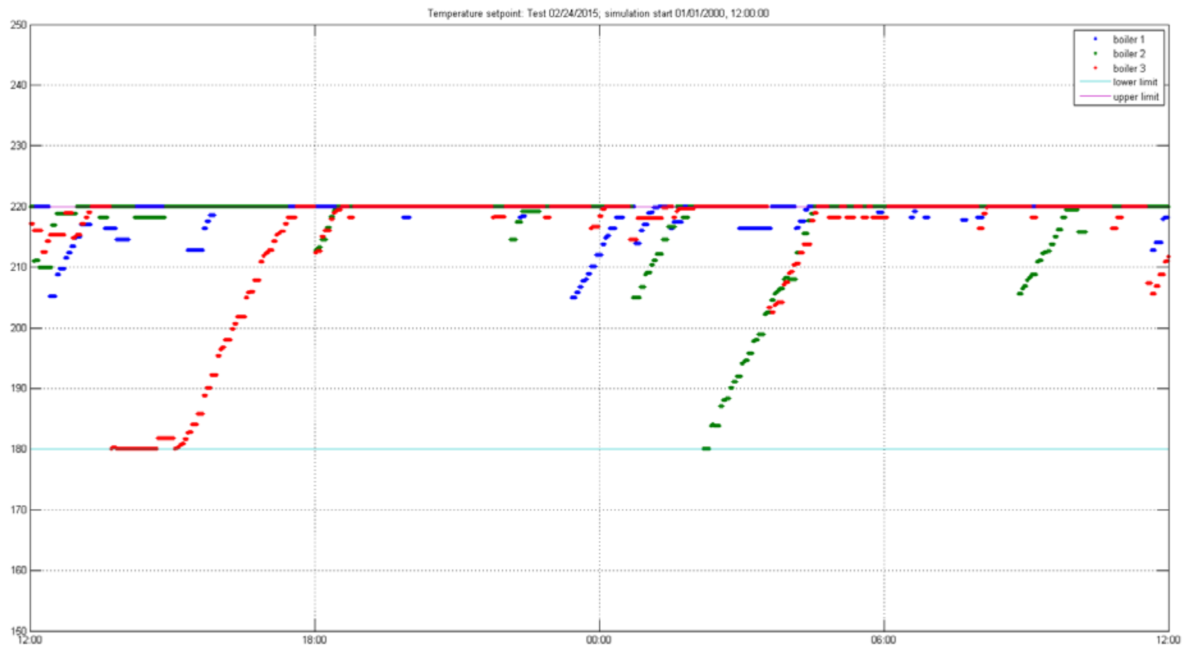


Figure 41: Supply temperature setpoint commands from the optimizer for the 3 boilers in the heating plant (all commands within limits)

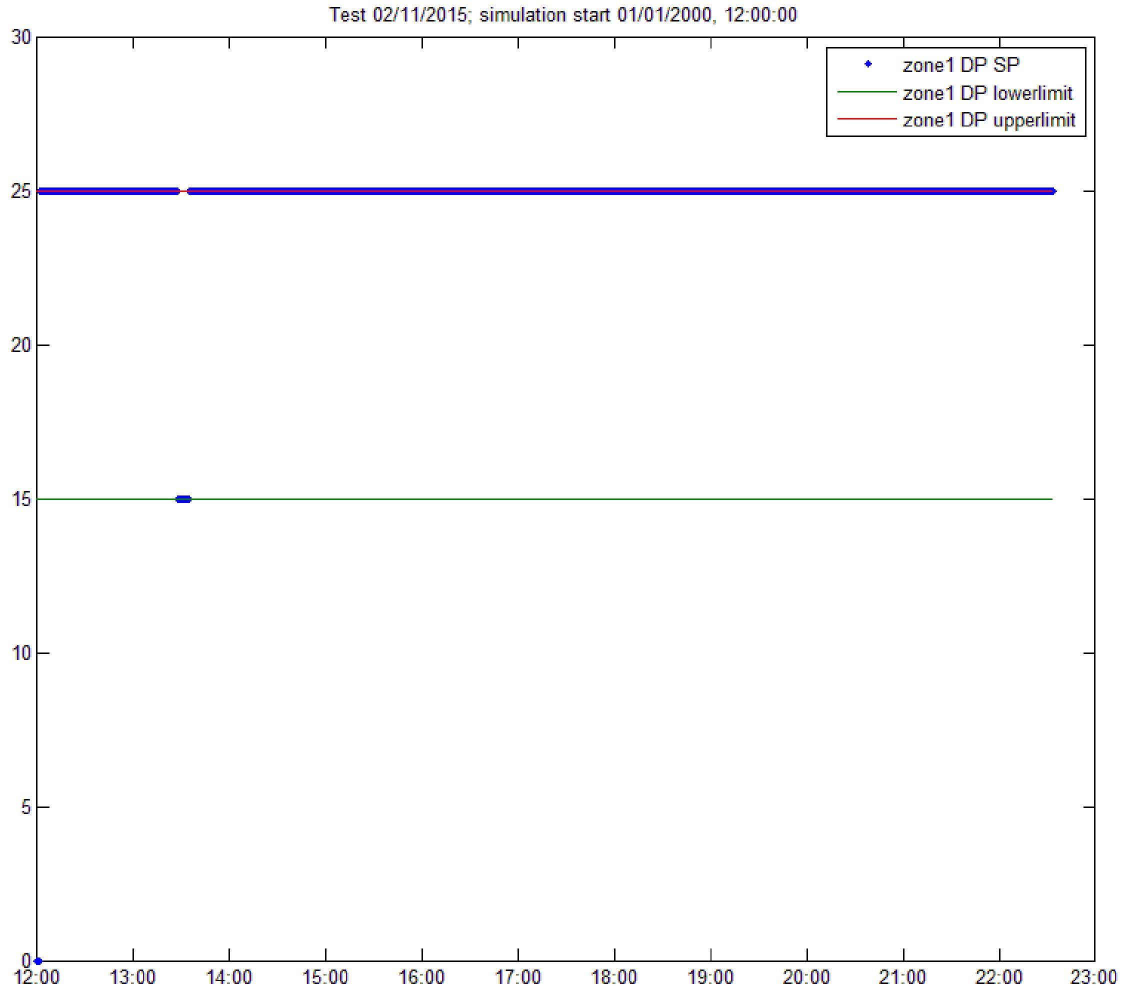


Figure 42: Zone 1 pumps differential pressure setpoint commands (all within limits)

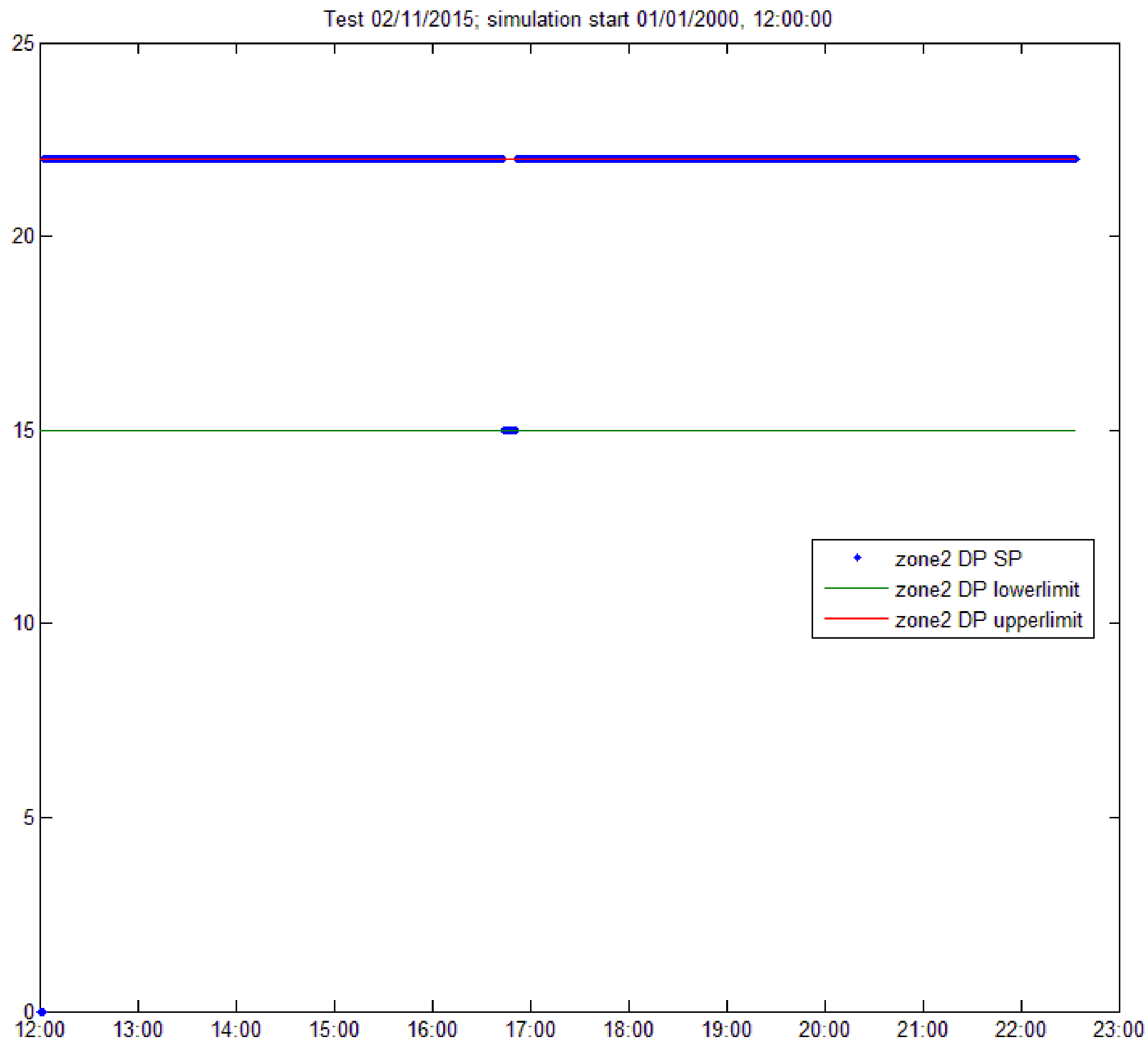


Figure 43: Zone 2 pumps differential pressure setpoint commands (all within limits)

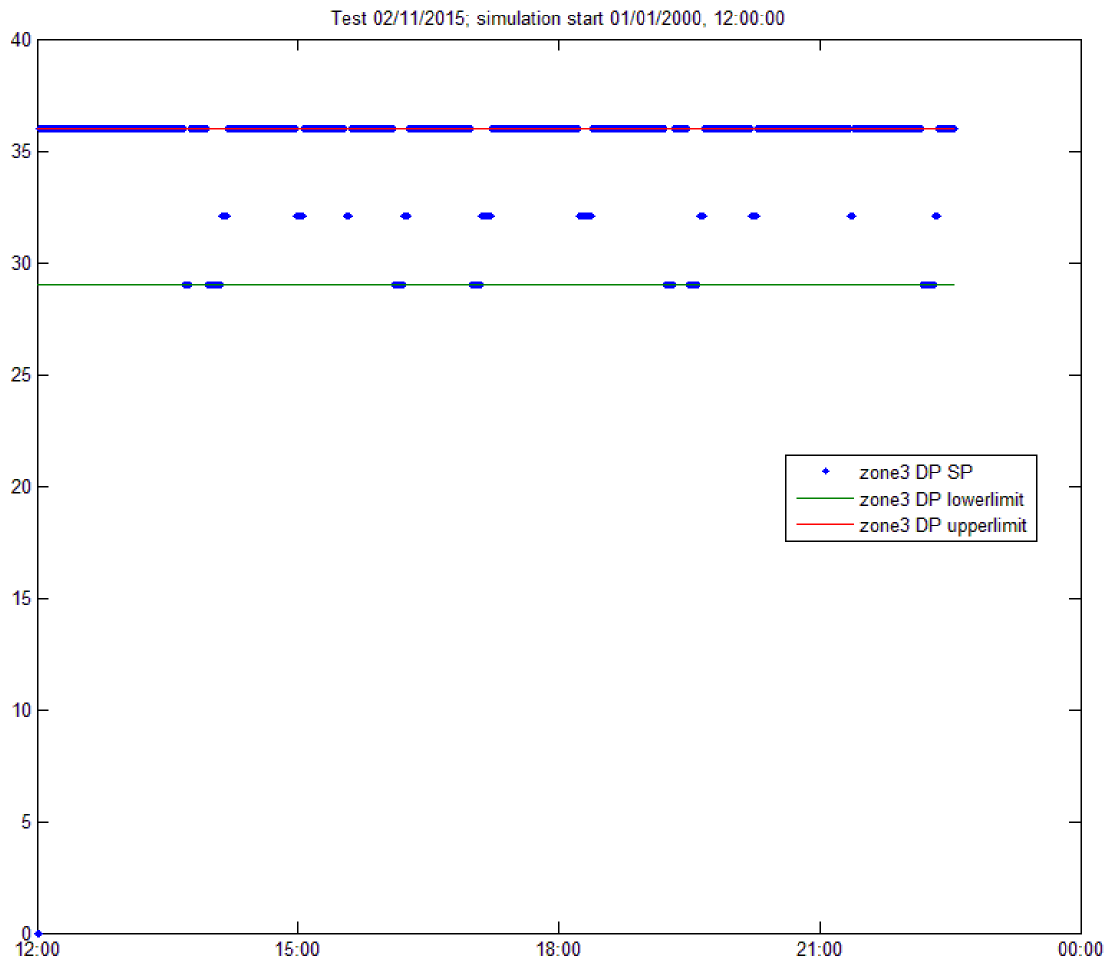


Figure 44: Zone 3 pumps differential pressure setpoint commands (all within limits)

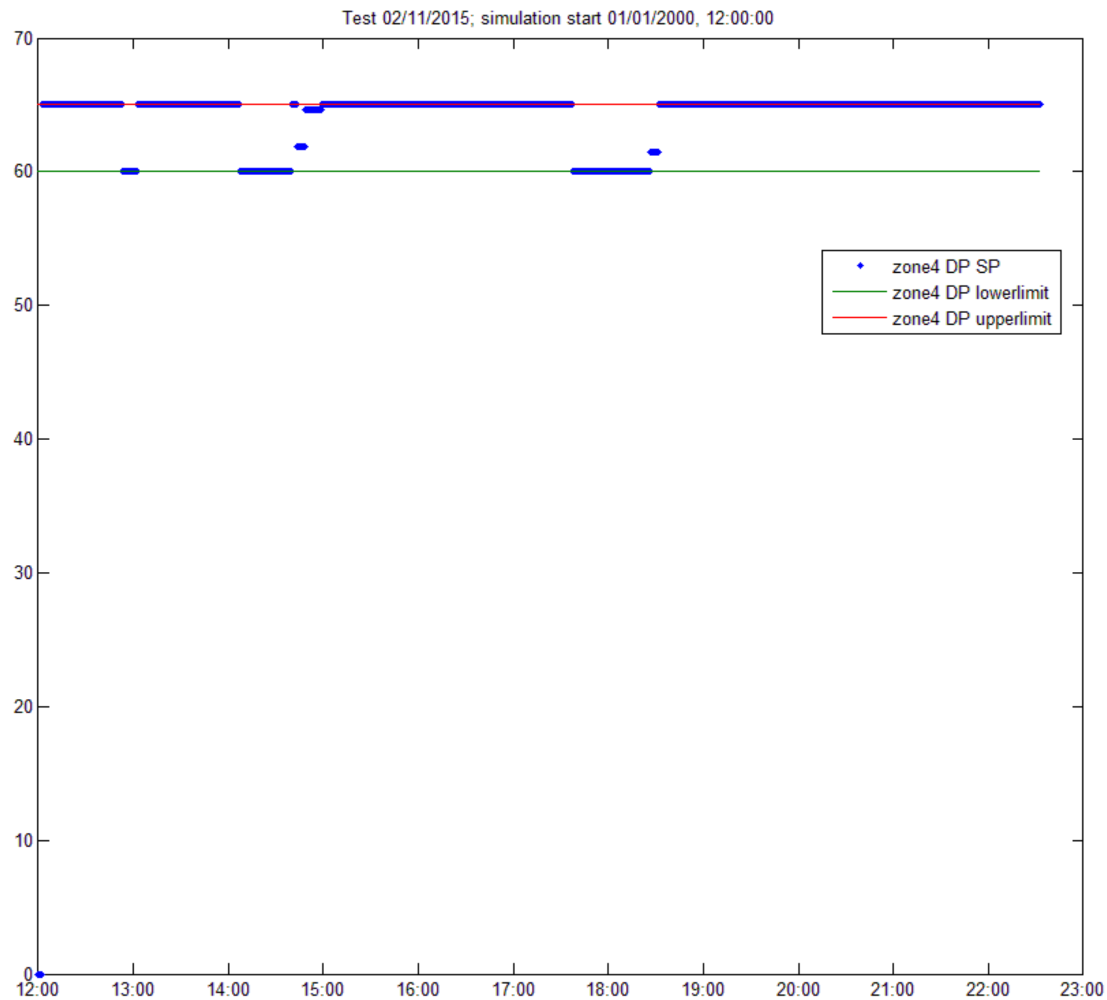


Figure 45: Zone 4 pumps differential pressure setpoint commands (all within limits)

Chiller plant analysis:

Chilled water supply temperatures: Figure 45 through Figure 48 show chilled water supply temperatures in simulation are within the upper and lower limits for the setpoints specified in the optimizer by the user. Chiller plant operators do not like the temperatures to be too high (to prevent high humidity) or too low (to prevent low temperature alarms in the chiller).

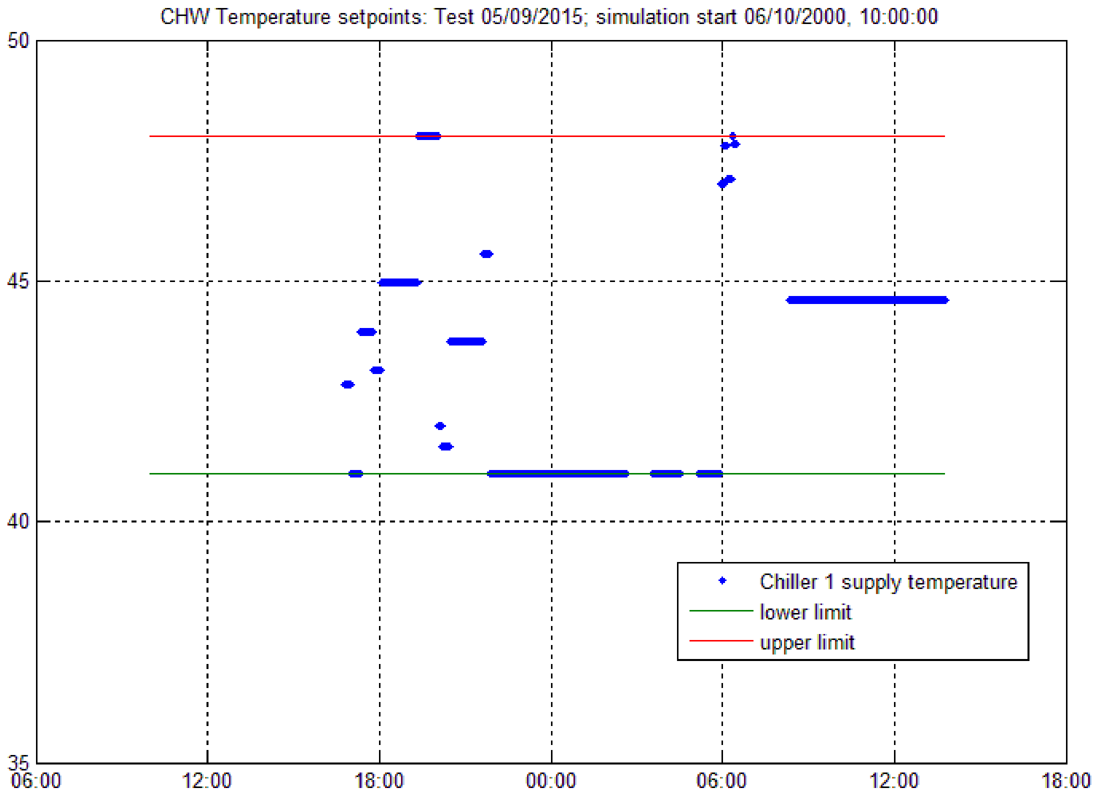


Figure 46: Chiller1 supply temperature

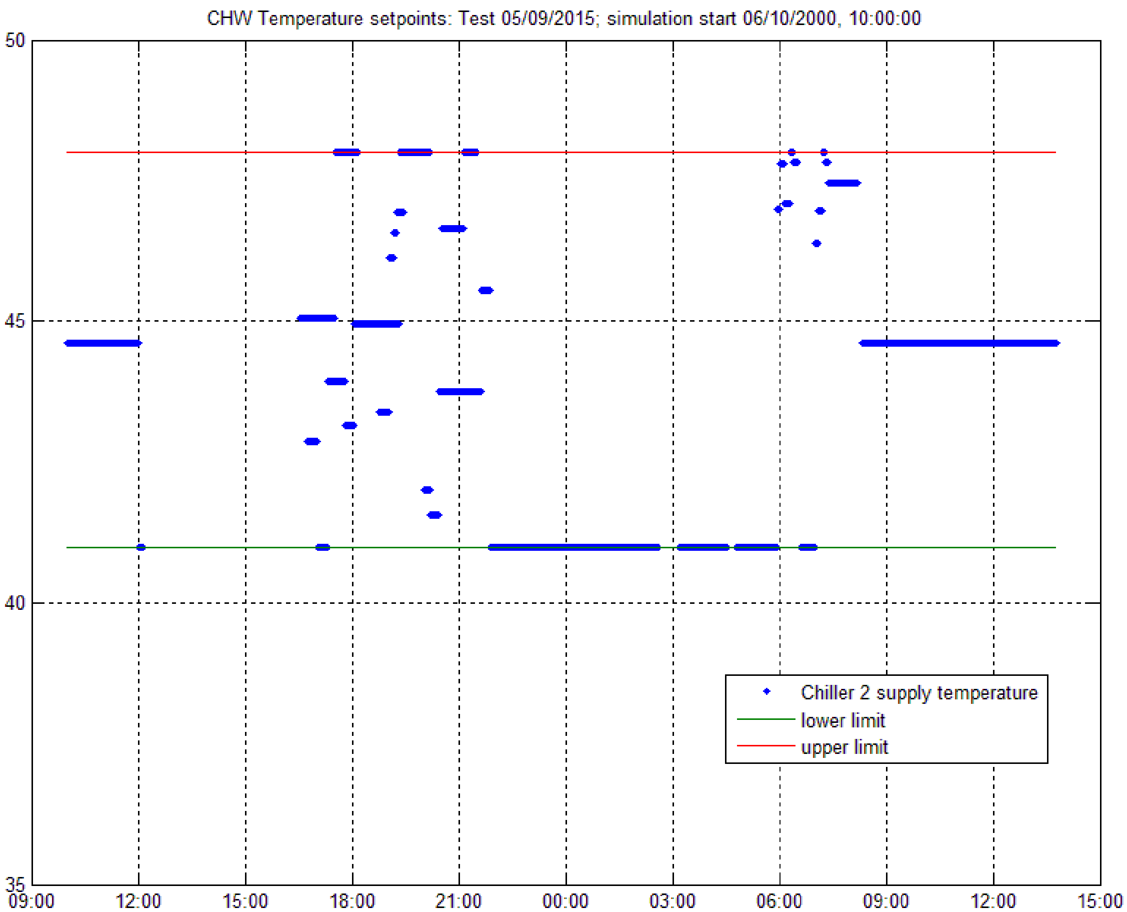


Figure 47: Chiller 2 supply temperature

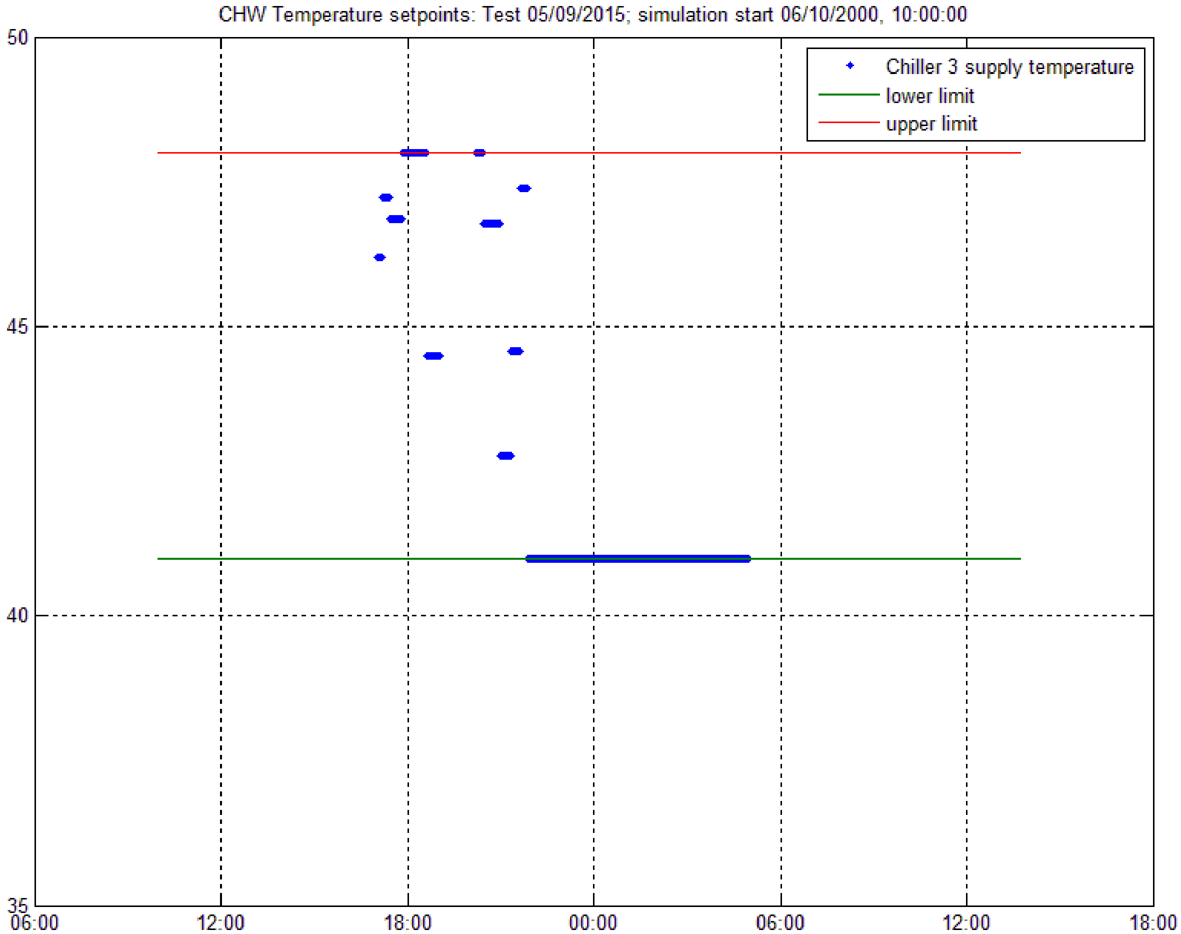


Figure 48: Chiller3 supply temperature

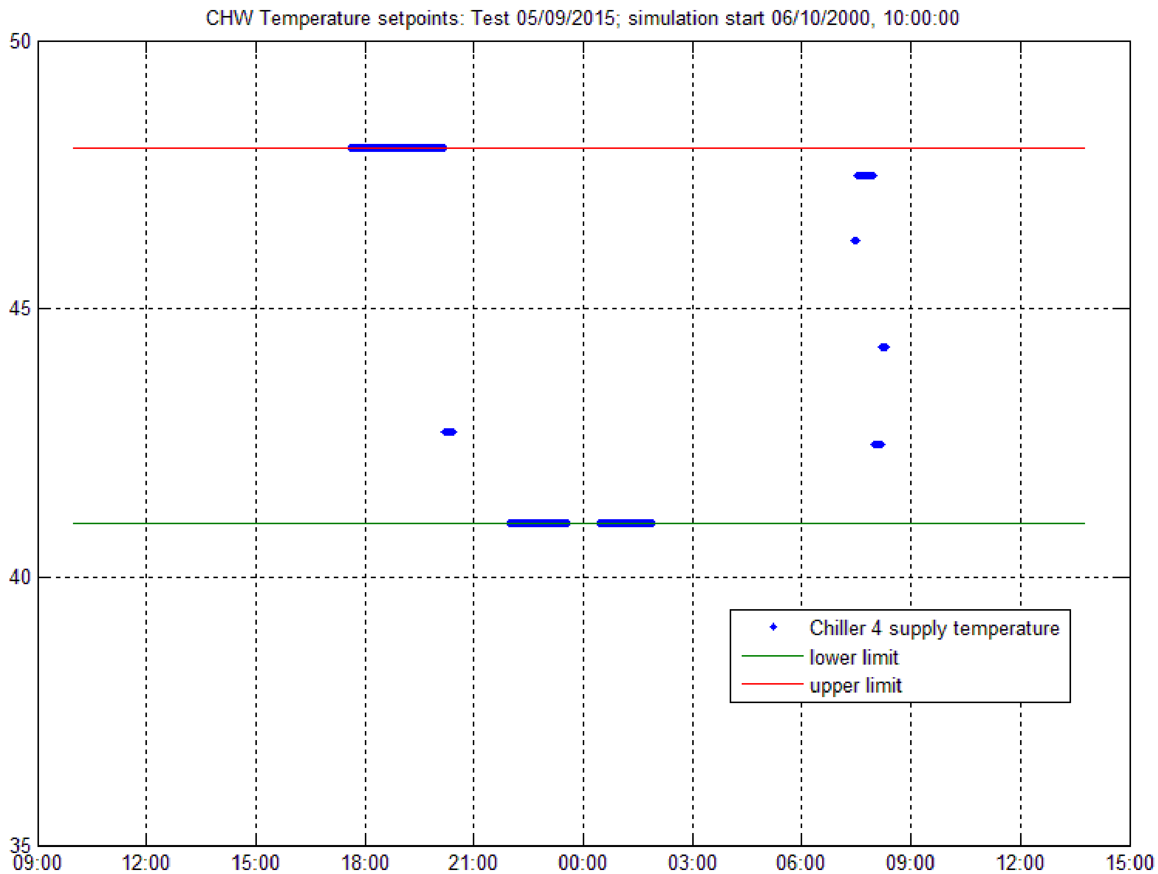


Figure 49: Chiller4 supply temperature

Condenser water return temperatures: Cooling water temperatures entering the condenser side of the chiller must be controlled within upper and lower limits to prevent damage to the compressor. We monitored and analyzed the cooling water temperature entering the chiller as illustrated in Figure 49. Because it was deemed unnecessary for testing, the simulation model did not model the thermal capacity of the cooling tower and chiller adequately, which resulted in the temperature rising high very quickly when a chiller changes load or is switched on. Apart from this anomaly, the cooling water temperatures are managed within the specified limits while the optimizer is in operation. The temperatures were out of bounds 0.76%, 1.93%, 0% and 0.009% of the time for chillers 1 through 4. We attribute these out-of-bounds percentages to the lack of proper equipment dynamics in the model.

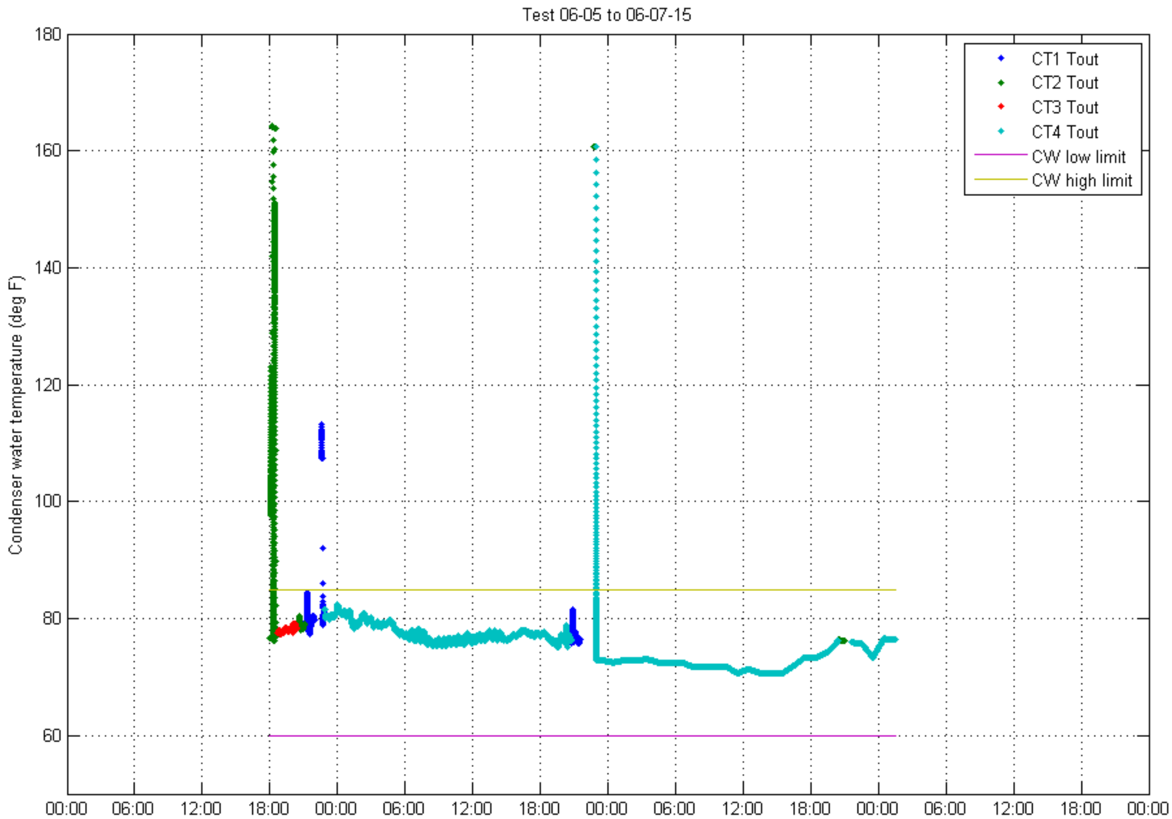


Figure 50: Cooling water return temperatures

Run times: One concern for plant managers and operators is excessive cycling of equipment. We analyzed the simulation data and calculated the chiller run times. Table 11 shows the run times for each chiller calculated with data from a simulation run on May 11, 2015. The run time columns represent the continuous periods in hours when a chiller was on. The run times in all except two cases meet the minimum run time parameter of 1 hour (1 hour was used for testing in simulation, not site test conditions). The two cases with runtimes shorter than the minimum, are at the start and end of simulation, which means that the chillers were already 'ON' before the start of simulation and at the end of simulation. The optimizer software, if not closed, continues 'running' a plant, whether a simulation is running or not, since it communicates only with the OPC server. Therefore, Chiller 2 would have been on before the start of simulation, and simulation would have stopped before Chiller 4 had a chance to fulfil its runtime obligation. This is confirmed in Figure 50, which shows the on times of each chiller and the heat exchanger.

Table 11: Chiller run times compared with minimum run times specified in simulation

	Chiller Run times (hours)			
	Chiller 1	**Chiller 2**	**Chiller 3**	**Chiller 4**
Date	**Test 5/11/2015, simulation start 7/17 18:00:00**			
Minimum run time specified (hours)	**1**	**1**	**1**	**1**
	5.8361	0.6216	7.5706	7.9122
	1.6678	5.5361	2.5678	1.3089
	3.6183	1.3928	1.3178	1.1006
		1.4422		1.4839
		1.0172		2.9267
		1.9761		0.2423
		3.7034		

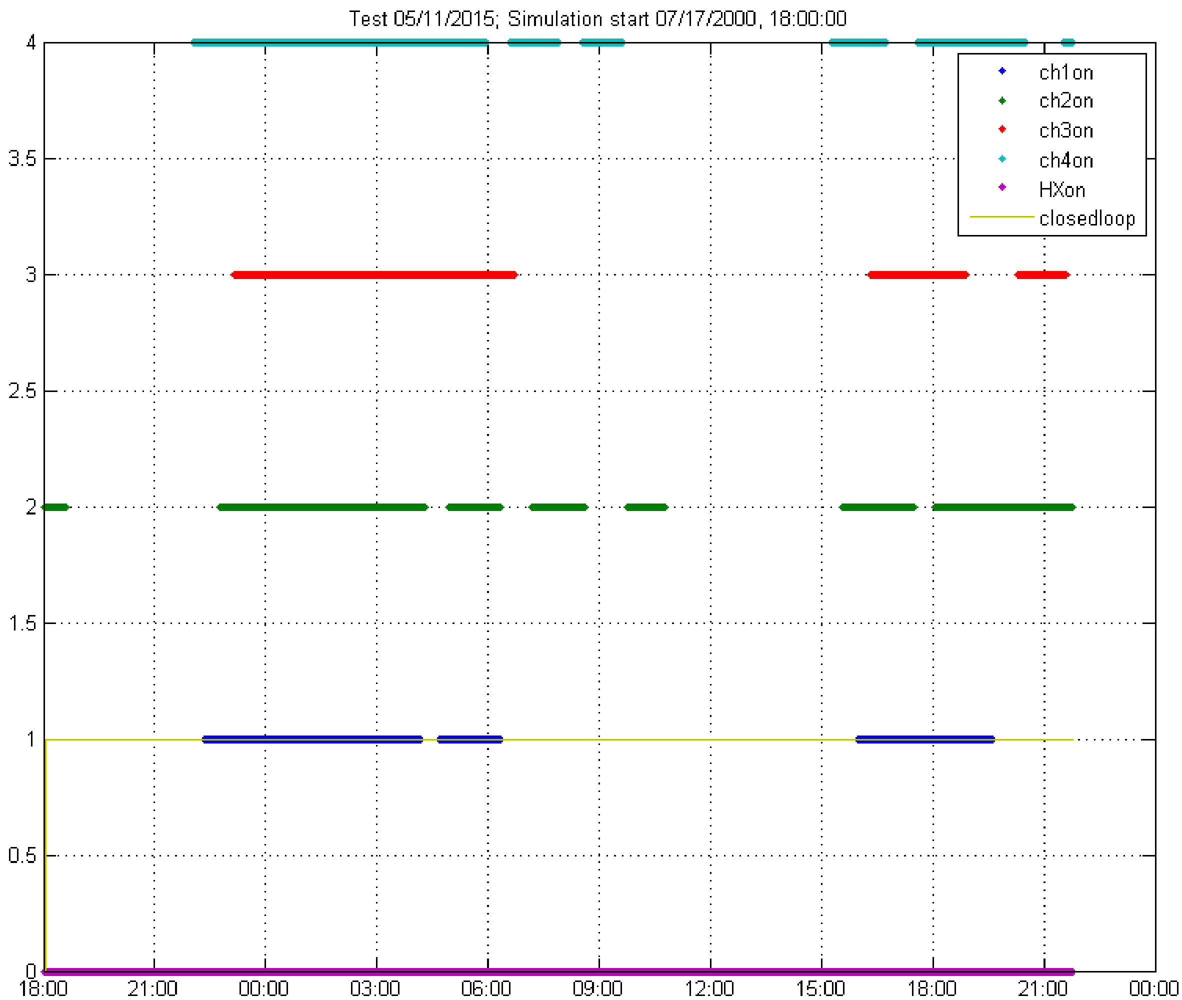


Figure 51: Chillers 'ON' in simulation

Zone supply and space temperatures: The plant staff is also concerned about the supply temperature at which the chilled water leaves the plant; this temperature depends on chiller supply temperatures, chiller flows, secondary loop flow and storage tank high level temperature. The plot in Figure 51 shows that the zone supply temperature is within the chilled water high and low limits. The optimizer monitors an average temperature representative of the building space temperatures. Although the chilled water plant cannot control the building temperatures directly, the space temperature is used as feedback for load calculation and adjusts the load being supplied. The plot in Figure 51 for one of the simulation tests shows that the space temperature is within the specified lower and upper limit parameters.

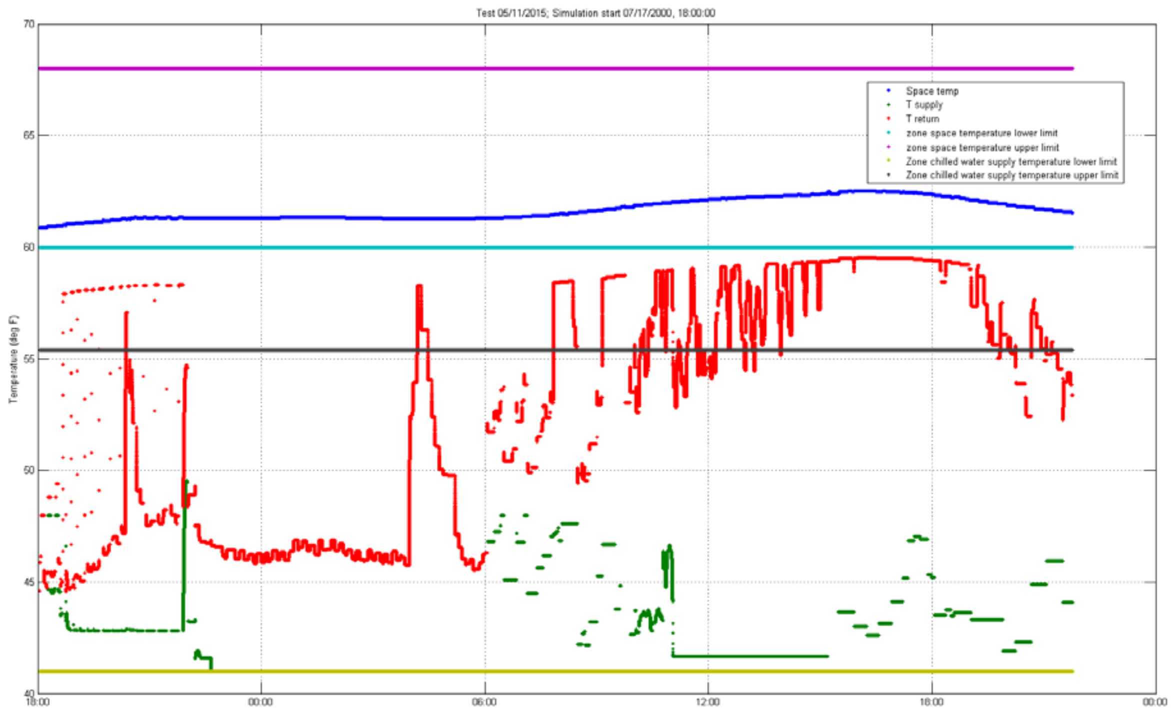


Figure 52: Zone supply and space temperatures

Success Criteria: Optimizer outputs are within normal range of operation for equipment >95% of the time.

Based on this criterion and the analyses presented above, we may conclude that the performance objective PO1 was successful.

6.2 PO2: OPTIMIZER SOFTWARE INTERCONNECTION WITH CONTROL SYSTEM

The core optimizer computes parameters such as demand, chiller or pump ON/OFF, flow rate or temperature setpoints. These values are then converted to control commands and provide the sequential automated control that ensures that a series of devices are activated in a certain order and that the right setpoints are applied. We need to ensure that the control commands provided to the chiller plant by the automation system are the same as the optimizer outputs, while accounting for control cycle lags. We also must ensure that no unaccounted-for legacy control loops might override the optimization commands.

Purpose: The purpose of this objective was to test that the optimizer interface to the automation and control system works correctly, the inputs and outputs have been mapped correctly, and an overlooked local control doesn't override the optimizer.

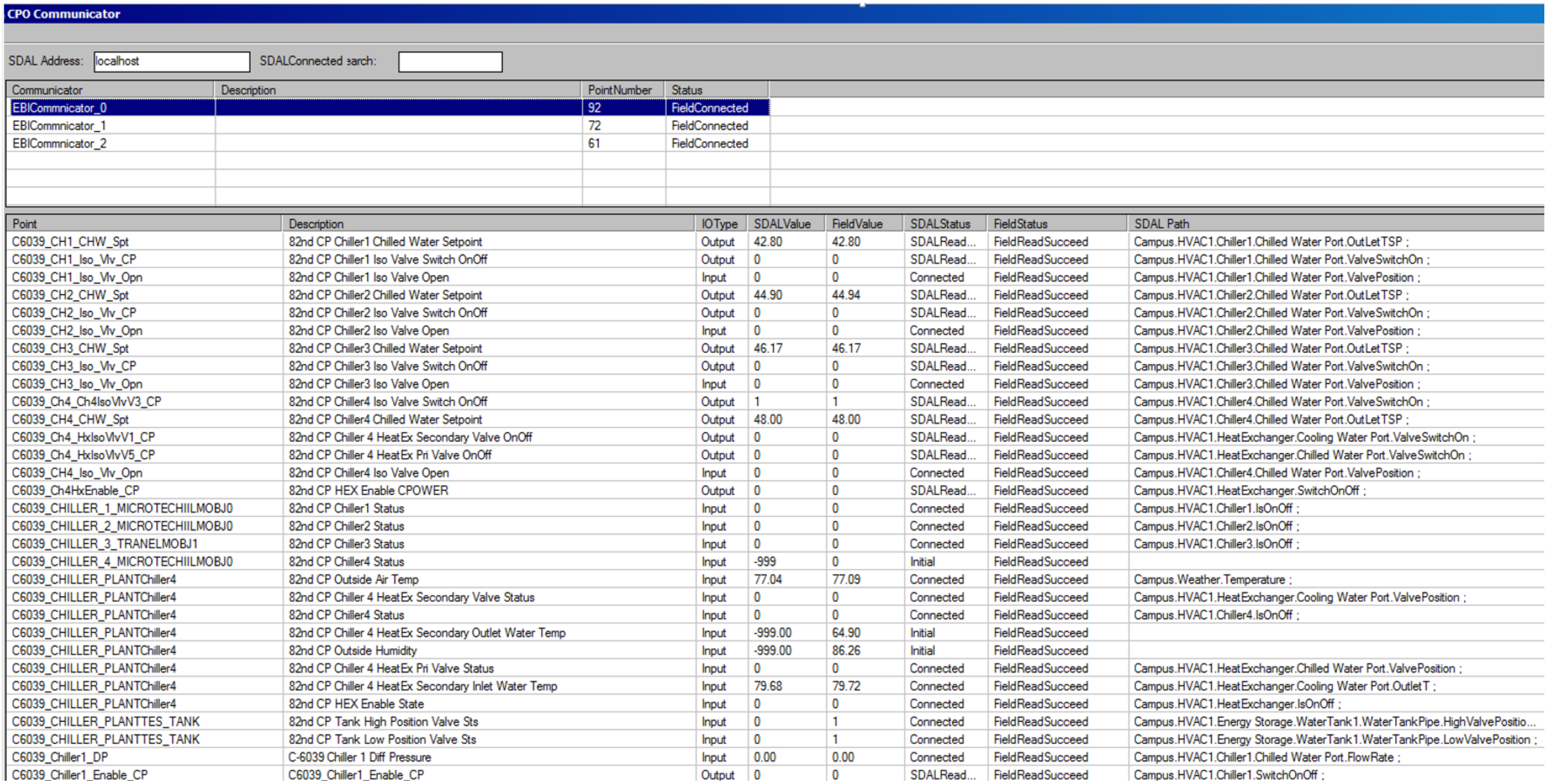
Metric: Comparison of optimizer output and control system commands and feedback. Values were given in various units depending on the output.

Data: As part of the installation and commissioning. we monitored optimizer outputs, control commands, and control feedback for several days to ensure that the system was working correctly.

Analytical Methodology: Two of the commissioning steps are points testing and phased testing by bringing equipment one-by-one into optimized operation. To test points, we ensured that all input points (measurements, equipment status) were read correctly in the optimizer's communicator module. Figure 52 shows a recent screenshot of the communicator, which is frequently monitored for communication and other issues. The SDAL value (value in the optimizer database) should match the field value (for most points), after accounting for system communication delays. Some values could display -999; these points are not mapped to actual measurements, but infer their values from other points that receive actual field measurements.

To test that the optimizer commanded points are reflected in the EBI equipment status screens, we brought each major piece of equipment into optimized operation one-by-one and enabled optimized operation,. Figure 53 shows an example of an equipment screen, in this case, Chiller 1. On the top pane, a dropdown to select whether the equipment will be in 'opt' or 'non-opt' mode represents the user's intention in including that equipment in the optimization system. If 'opt' is selected, the equipment is controlled by optimizer outputs; for 'non-opt', it can be controlled manually through the screen, such as turning it on or off, or adjusting its setpoint. (A star in the left hand pane tree indicates if the equipment is in 'opt' mode).

During commissioning, we put several pieces of equipment in 'non-opt' and just a few in 'opt' (for a smooth transition from original control, so the optimizer will continue running the same system until it has performed its first solver cycle), to test the commands to each chiller system. For example, Chiller 1 would be in 'opt,' along with several shared primary pumps, Condenser Pump 1 and Cooling Tower 1 fans. The secondary pumps also need to be controllable either manually or via the optimizer. Once the optimizer is enabled and takes over control, we can turn the chiller (for example) to 'non-opt' and test the setpoint output command by manually setting it in the optimizer screen and then checking the EBI screen to ensure Chiller 1 recognizes the same command. This process was repeated for switching equipment ON/OFF. Once all equipment was tested, we turned most pieces to 'opt,' and monitored that optimizer outputs (from optimization log – see Figure 54) were reflected in the EBI screens for the equipment and that the feedback response read by the optimizer input points and displayed on the equipment screen dynamic parameters pane. The optimizer raises a 'No Response' warning in the display if the command and feedback do not match within a certain time limit.


CPO Communicator

SDAL Address: localhost SDALConnected search:

Communicator	Description	PointNumber	Status
EBICommnicator_0		92	FieldConnected
EBICommnicator_1		72	FieldConnected
EBICommnicator_2		61	FieldConnected

Point	Description	IOType	SDALValue	FieldValue	SDALStatus	FieldStatus	SDAL Path
C6039_CH1_CHW_Spt	82nd CP Chiller1 Chilled Water Setpoint	Output	42.80	42.80	SDALRead...	FieldReadSucceed	Campus.HVAC1.Chiller1.Chilled Water Port.OutLetTSP ;
C6039_CH1_Iso_Vlv_CP	82nd CP Chiller1 Iso Valve Switch OnOff	Output	0	0	SDALRead...	FieldReadSucceed	Campus.HVAC1.Chiller1.Chilled Water Port.ValveSwitchOn ;
C6039_CH1_Iso_Vlv_Opn	82nd CP Chiller1 Iso Valve Open	Input	0	0	Connected	FieldReadSucceed	Campus.HVAC1.Chiller1.Chilled Water Port.ValvePosition ;
C6039_CH2_CHW_Spt	82nd CP Chiller2 Chilled Water Setpoint	Output	44.90	44.94	SDALRead...	FieldReadSucceed	Campus.HVAC1.Chiller2.Chilled Water Port.OutLetTSP ;
C6039_CH2_Iso_Vlv_CP	82nd CP Chiller2 Iso Valve Switch OnOff	Output	0	0	SDALRead...	FieldReadSucceed	Campus.HVAC1.Chiller2.Chilled Water Port.ValveSwitchOn ;
C6039_CH2_Iso_Vlv_Opn	82nd CP Chiller2 Iso Valve Open	Input	0	0	Connected	FieldReadSucceed	Campus.HVAC1.Chiller2.Chilled Water Port.ValvePosition ;
C6039_CH3_CHW_Spt	82nd CP Chiller3 Chilled Water Setpoint	Output	46.17	46.17	SDALRead...	FieldReadSucceed	Campus.HVAC1.Chiller3.Chilled Water Port.OutLetTSP ;
C6039_CH3_Iso_Vlv_CP	82nd CP Chiller3 Iso Valve Switch OnOff	Output	0	0	SDALRead...	FieldReadSucceed	Campus.HVAC1.Chiller3.Chilled Water Port.ValveSwitchOn ;
C6039_CH3_Iso_Vlv_Opn	82nd CP Chiller3 Iso Valve Open	Input	0	0	Connected	FieldReadSucceed	Campus.HVAC1.Chiller3.Chilled Water Port.ValvePosition ;
C6039_Ch4_Ch4IsoVlvV3_CP	82nd CP Chiller4 Iso Valve Switch OnOff	Output	1	1	SDALRead...	FieldReadSucceed	Campus.HVAC1.Chiller4.Chilled Water Port.ValveSwitchOn ;
C6039_CH4_CHW_Spt	82nd CP Chiller4 Chilled Water Setpoint	Output	48.00	48.00	SDALRead...	FieldReadSucceed	Campus.HVAC1.Chiller4.Chilled Water Port.OutLetTSP ;
C6039_Ch4_HxIsoVlvV1_CP	82nd CP Chiller 4 HeatEx Secondary Valve OnOff	Output	0	0	SDALRead...	FieldReadSucceed	Campus.HVAC1.HeatExchanger.Cooling Water Port.ValveSwitchOn ;
C6039_Ch4_HxIsoVlvV5_CP	82nd CP Chiller 4 HeatEx Pri Valve OnOff	Output	0	0	SDALRead...	FieldReadSucceed	Campus.HVAC1.HeatExchanger.Chilled Water Port.ValveSwitchOn ;
C6039_CH4_Iso_Vlv_Opn	82nd CP Chiller4 Iso Valve Open	Input	0	0	Connected	FieldReadSucceed	Campus.HVAC1.Chiller4.Chilled Water Port.ValvePosition ;
C6039_Ch4HxEnable_CP	82nd CP HEX Enable CPOWER	Output	0	0	SDALRead...	FieldReadSucceed	Campus.HVAC1.HeatExchanger.SwitchOnOff ;
C6039_CHILLER_1_MICROTECHIILMOBJ0	82nd CP Chiller1 Status	Input	0	0	Connected	FieldReadSucceed	Campus.HVAC1.Chiller1.IsOnOff ;
C6039_CHILLER_2_MICROTECHIILMOBJ0	82nd CP Chiller2 Status	Input	0	0	Connected	FieldReadSucceed	Campus.HVAC1.Chiller2.IsOnOff ;
C6039_CHILLER_3_TRANELMOBJ1	82nd CP Chiller3 Status	Input	0	0	Connected	FieldReadSucceed	Campus.HVAC1.Chiller3.IsOnOff ;
C6039_CHILLER_4_MICROTECHIILMOBJ0	82nd CP Chiller4 Status	Input	-999	0	Initial	FieldReadSucceed	
C6039_CHILLER_PLANTChiller4	82nd CP Outside Air Temp	Input	77.04	77.09	Connected	FieldReadSucceed	Campus.Weather.Temperature ;
C6039_CHILLER_PLANTChiller4	82nd CP Chiller 4 HeatEx Secondary Valve Status	Input	0	0	Connected	FieldReadSucceed	Campus.HVAC1.HeatExchanger.Cooling Water Port.ValvePosition ;
C6039_CHILLER_PLANTChiller4	82nd CP Chiller4 Status	Input	0	0	Connected	FieldReadSucceed	Campus.HVAC1.Chiller4.IsOnOff ;
C6039_CHILLER_PLANTChiller4	82nd CP Chiller 4 HeatEx Secondary Outlet Water Temp	Input	-999.00	64.90	Initial	FieldReadSucceed	
C6039_CHILLER_PLANTChiller4	82nd CP Outside Humidity	Input	-999.00	86.26	Initial	FieldReadSucceed	
C6039_CHILLER_PLANTChiller4	82nd CP Chiller 4 HeatEx Pri Valve Status	Input	0	0	Connected	FieldReadSucceed	Campus.HVAC1.HeatExchanger.Chilled Water Port.ValvePosition ;
C6039_CHILLER_PLANTChiller4	82nd CP Chiller 4 HeatEx Secondary Inlet Water Temp	Input	79.68	79.72	Connected	FieldReadSucceed	Campus.HVAC1.HeatExchanger.Cooling Water Port.OutletT ;
C6039_CHILLER_PLANTChiller4	82nd CP HEX Enable State	Input	0	0	Connected	FieldReadSucceed	Campus.HVAC1.HeatExchanger.IsOnOff ;
C6039_CHILLER_PLANTTES_TANK	82nd CP Tank High Position Valve Sts	Input	0	1	Connected	FieldReadSucceed	Campus.HVAC1.Energy Storage.WaterTank1.WaterTankPipe.HighValvePositio...
C6039_CHILLER_PLANTTES_TANK	82nd CP Tank Low Position Valve Sts	Input	0	1	Connected	FieldReadSucceed	Campus.HVAC1.Energy Storage.WaterTank1.WaterTankPipe.LowValvePosition ;
C6039_Chiller1_DP	C-6039 Chiller 1 Diff Pressure	Input	0.00	0.00	Connected	FieldReadSucceed	Campus.HVAC1.Chiller1.Chilled Water Port.FlowRate ;
C6039_Chiller1_Enable_CP	C6039_Chiller1_Enable_CP	Output	0	0	SDALRead...	FieldReadSucceed	Campus.HVAC1.Chiller1.SwitchOnOff ;

Figure 53: Communicator screen

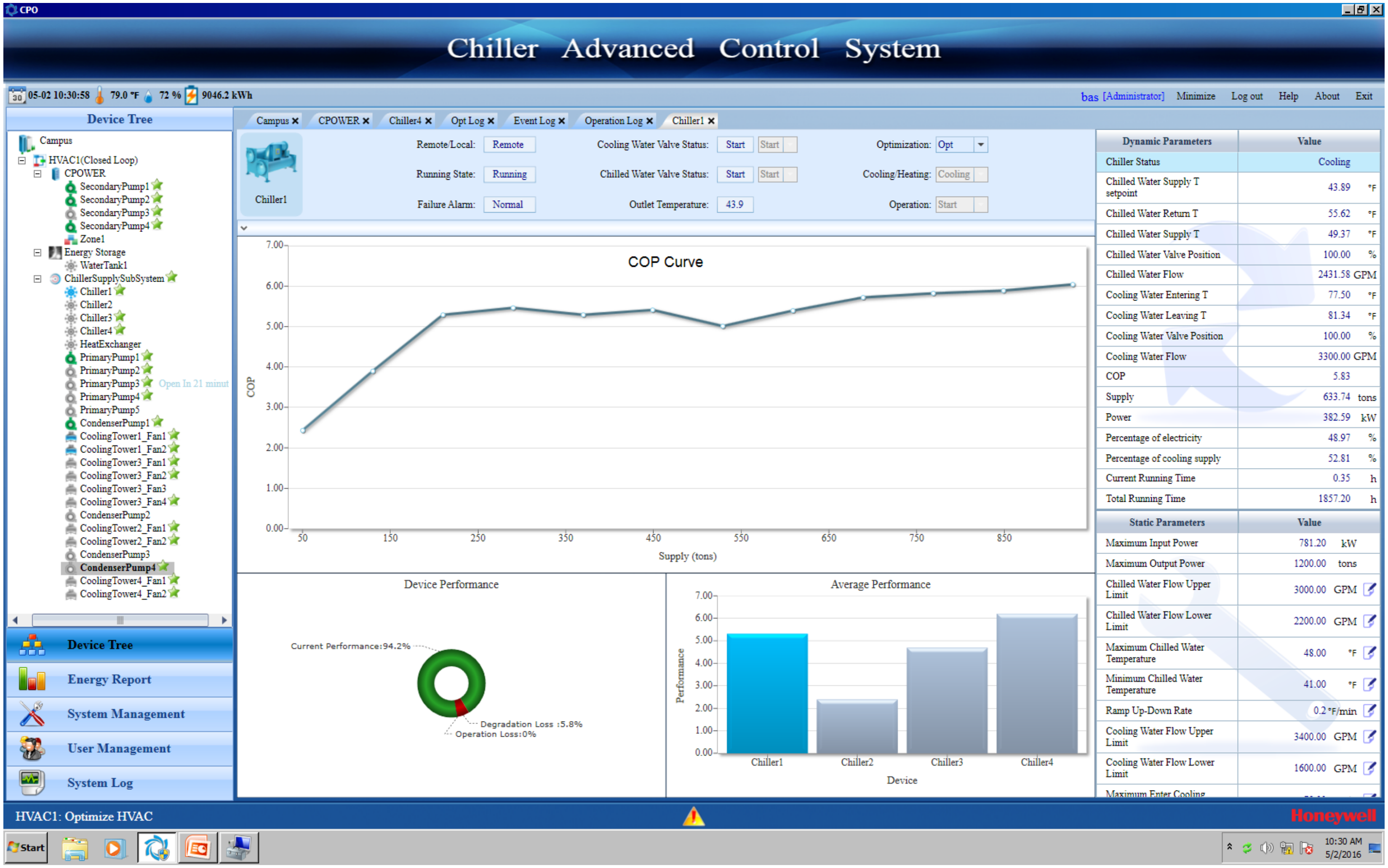


Figure 54: Optimizer's equipment screenshot (chiller example)

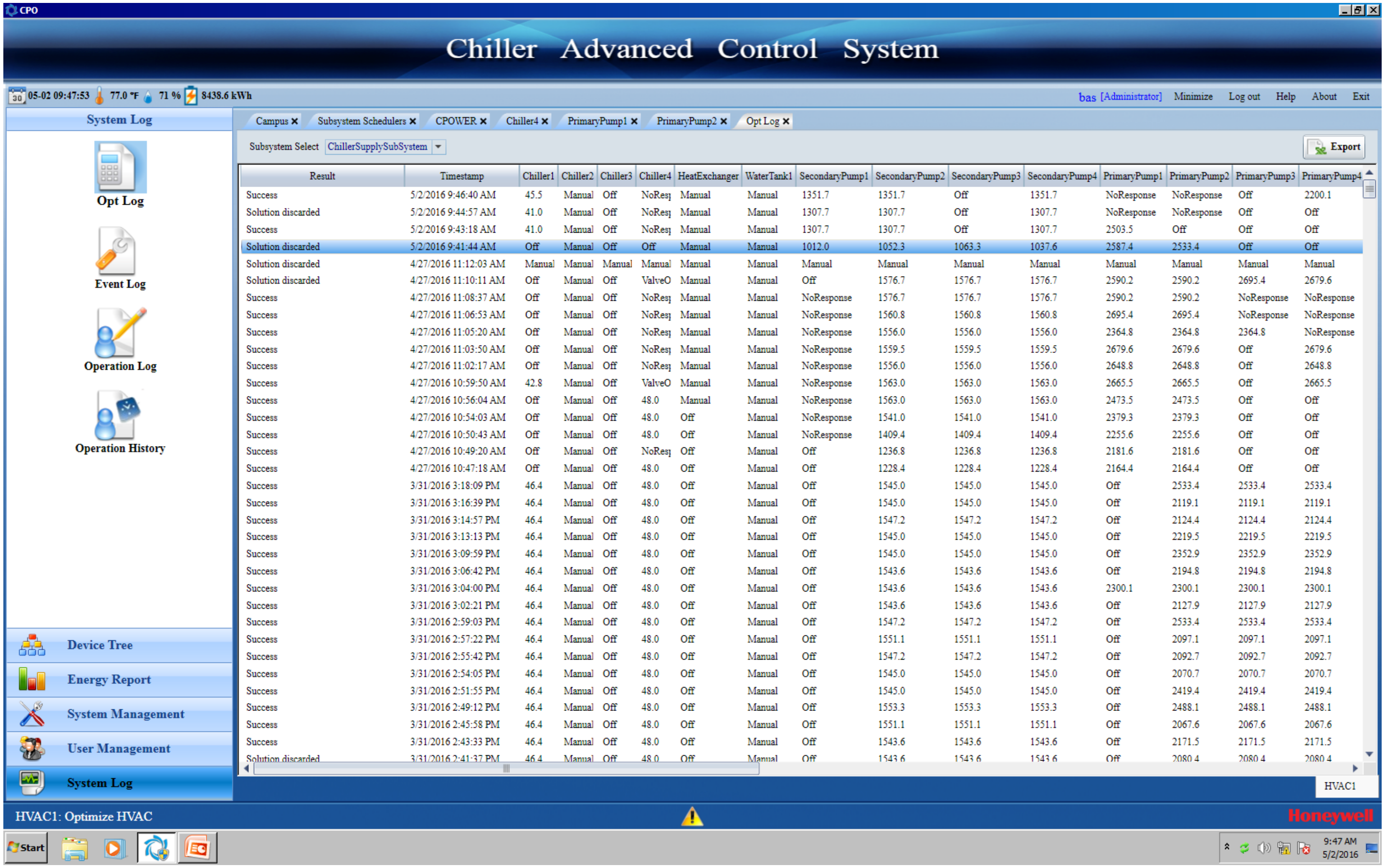


Figure 55: Optimization log showing outputs

Success Criteria: All required optimizer outputs are transmitted as autonomous control commands for plant operation.

Results: With the successful commissioning of the optimizer, when we monitored optimizer outputs and plant response and took corrective action when necessary, we may conclude that we have met this performance objective.

6.3 PO3: ENERGY SAVINGS

The main objective of the demonstration is to understand energy savings with optimized operation in central cooling and heating plants. Previous prototypes have yielded a wide range of savings, since this number is dependent on the plant layouts, current operations, and equipment. We gathered data to analyze the correct operation of the plant with the optimizer and to assess energy savings.

Purpose: To measure energy savings in cooling and heating plants by operating them with CPOWER's optimization solution.

Metric: Difference in plant energy consumption normalized for weather and other factors, between baseline and demonstration periods.

Data: All point data recorded in the CPOWER chiller plant databases were extracted and used; the BAS (Honeywell EBI) was also set up to record several sets of data. This data includes power consumption in the form of interval energy data or instantaneous power data. Please see Appendix B for the data fields in CPOWER.

No data from the heating plant was used, because the authority to command the heating plant by optimizer was not available, and because of the issues with baseline data discussed elsewhere (see 5.3).

Analytical Methodology: The central plants chosen for the demonstration serve several buildings (70-100) at Ft. Bragg. Some structural retrofits are underway for the chilled and heating water distribution to the buildings, and some buildings are being retrofitted to be served by different central plants. These changes made it difficult to get an accurate baseline prior to demonstration. Hence, the baseline period ran concurrently with the demonstration period. A software switch was incorporated in the Building Automation System to switch the system between the basic controls and advanced optimization system at pre-determined intervals, such as daily or weekly. This provided a more accurate comparison, because structural changes causing changes in before and after plant loads is less likely. Other factors, such as seasons and occupancy, are likely to stay more comparable.

After commissioning, we faced several issues with ensuring that the optimizer ran as intended, the plant was operated safely and reliably, and the plant personnel were comfortable with the operation. Our initial plan to switch the plant operation between the original control and optimizer control on alternate days or weeks was modified to operating with the optimizer for several days at a time, when site staff would be available to monitor, and no maintenance work was ongoing at the plant. All data for points that were mapped for CPOWER operation and other calculated data from the software were recorded in the CPOWER software database. It was deemed easiest on the site staff to have them zip this database and upload to a share drive on our request at periodic intervals. The data in this database was extracted to usable formats – see Figure 18. MATLAB scripts read Excel files exported from the database and organized them into user-friendly structures. Data extracts from different periods were merged to create .mat files with structures spanning the period from July 2015 through May 2016.

Most of the data analysis described below uses this data, except when other data sources were needed to corroborate or fill in gaps for periods of corrupted or unavailable data. Two other data sources were used for this: Weather data from an outside source (Honeywell Novar weather data) and the building automation system EBI's data. Honeywell's Novar weather data is currently accessible from a Hortonworks cluster; we query this dataset to obtain csv files for the periods and place of interest. The plant EBI data is shipped as Excel file reports for each week, for several equipment points. A separate set of MATLAB scripts were created to read these data into a streamlined usable format.

Data analysis: In comparing on-site energy performance for two different control methodologies, we should ideally consider how disturbances such as weather and occupancy affect performance, since both control strategies cannot be running at the same time. Occupancy is difficult to quantify, because of the large number of buildings with different functions involved, and since individual building energy use is not measured. The buildings also provide a diversity of operating schedules that might cancel the effect of occupancy. We considered a weekday or weekend classification as a surrogate for occupancy in our baseline modeling effort (see Section 5.2.2). However, the baseline model that considers day type (weekend or weekday) as a factor was not the best model, so occupancy or day type was not a factor in the final analysis. We considered outdoor temperature, outdoor wet bulb temperature, outdoor humidity, windspeed, heat index, and day type (weekend/weekday) as factors in each baseline model that we evaluated.

Data preprocessing: All data from non-optimized periods (and which were in non-optimized state for at least 24 hours) were used for baseline characterization (see Section 5.2.1). Data cleaning involved removing spikes and periods of constant power or other variable such as indoor space temperature, and substituting weather data from an outside source for the constant (flat-lined anomalous) value of temperature and wet bulb recorded in CPOWER (see Figure 55 and Figure 56). The reason for the flat-lined temperature measurements is not clear, and we suspect the communication interface between the optimizer workstation and BAS might have malfunctioned. For our analysis, we have substituted better data sources, or removed anomalous data from our analysis. However, the optimizer operates real time on the assumption that the input dataset is correct, and hence would not have the advantage of post-analysis.

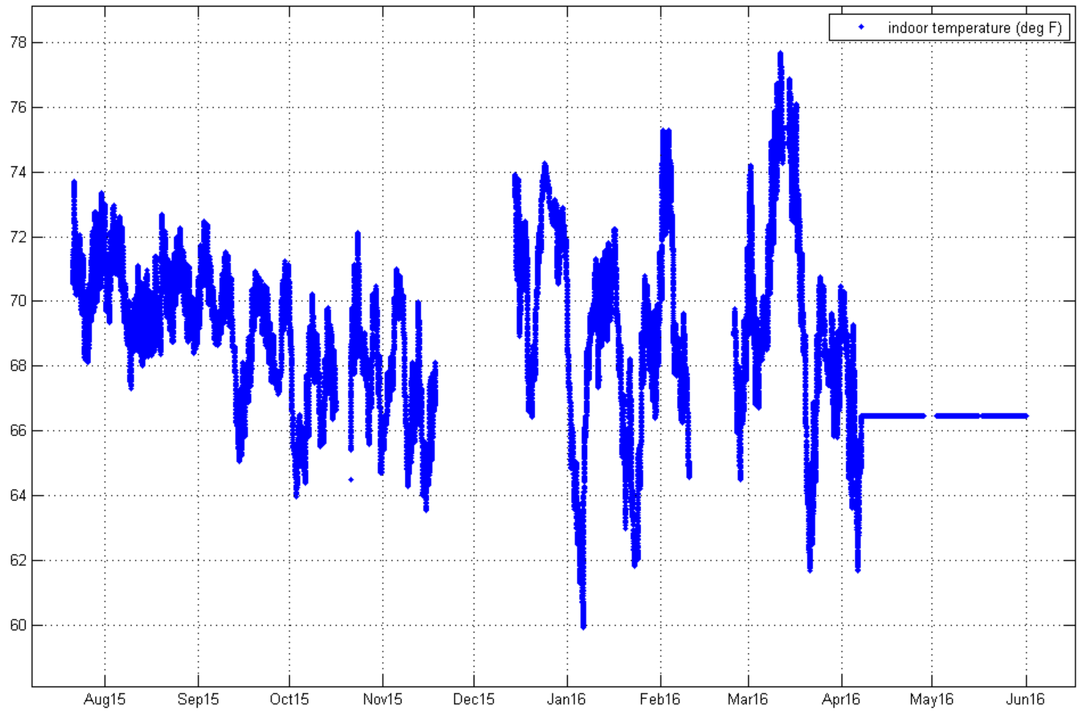


Figure 56: Indoor averaged temperature recorded in CPOWER software showing flat lined temperature in April and May2016

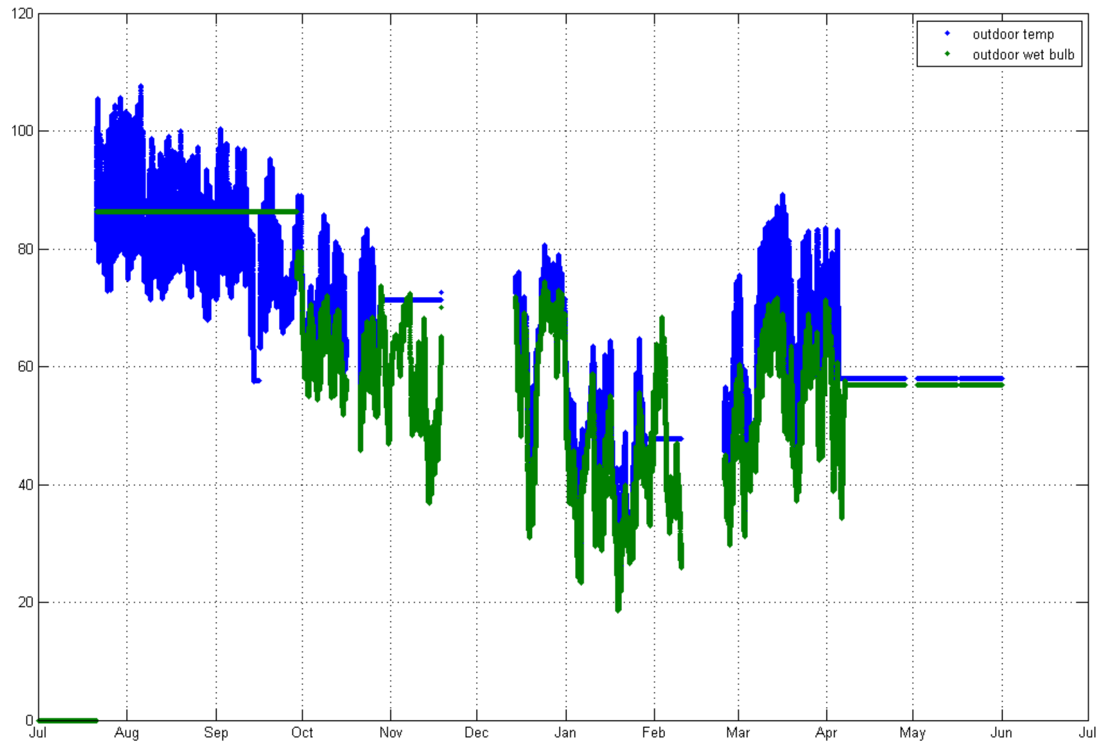


Figure 57: Outdoor weather temperature and wet bulb temperature recorded in database showing flat lined (anomalous) data

Our first set of analysis results show the overall energy consumption by the chiller plant as a whole. An earlier plot (Figure 21) showed the instantaneous power consumption for the chiller plant, when in optimized and non-optimized operation. We separated the data for the baseline original control days and the optimizer controlled days using the 'EnableClosedLoopControl' point, which indicates if the plant was in optimized (value of 1) or original control (value 0). The optimizer controlled periods are shown in Figure 58. The dataset was divided into optimized and non-optimized periods; these periods were then sub-divided into 24-hour periods for energy analysis (after discarding any periods shorter than 24 hrs.). The total energy in KWh, average weather quantities, and indoor air temperatures for these 24 hour periods were calculated. A plot of total energy consumed for these 24 hour periods is shown in Figure 58. It displays data for 164 periods of original control days and 39 periods of optimizer run control days.

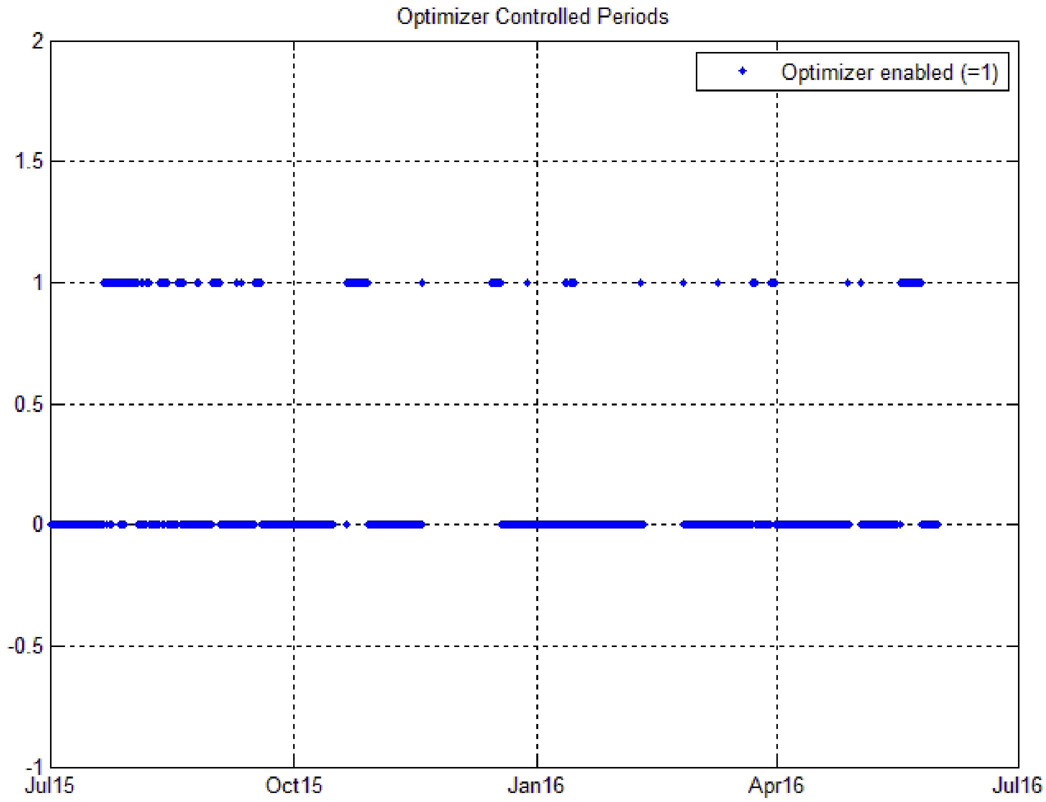


Figure 58: Optimizer controlled periods

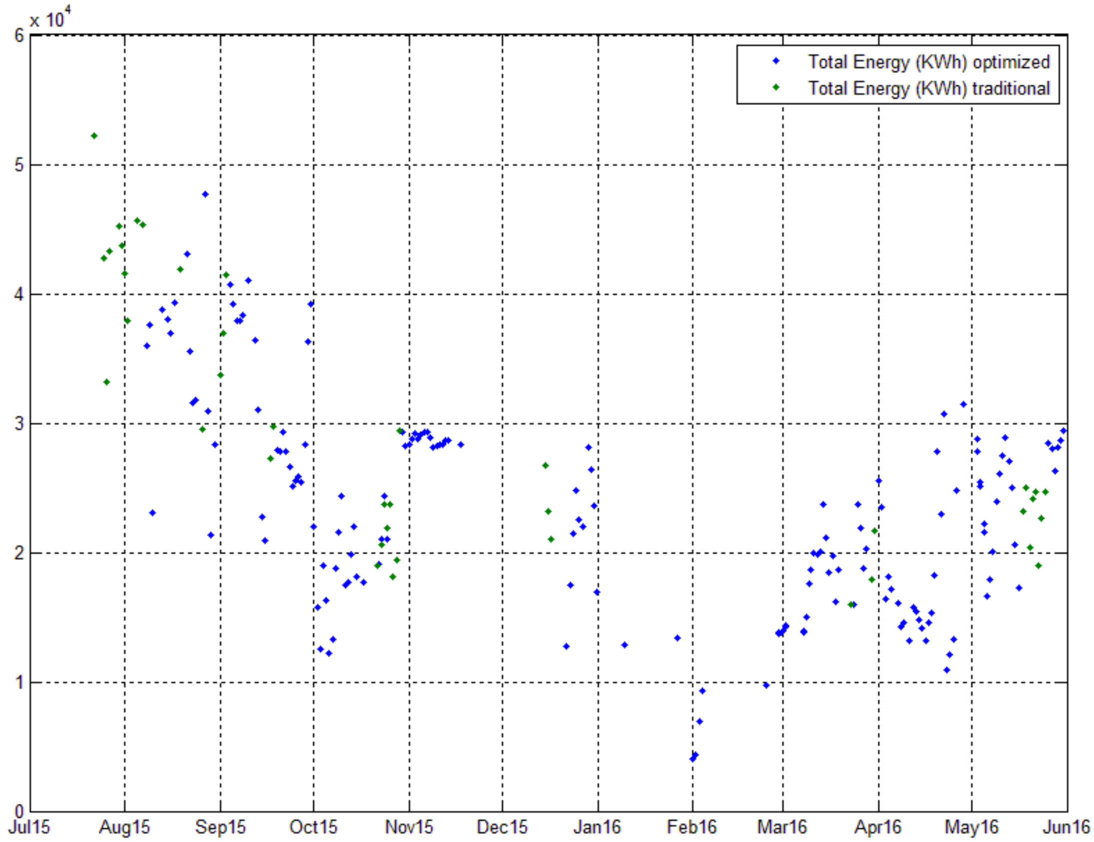


Figure 59: Total energy consumed in the chiller plant during 24 hour segments

We developed a statistical model of the energy consumed during baseline operation (see Section 5.2.2). For fair comparison, this model was used to calculate predictions of total energy usage for original operation at the conditions for optimized operation periods. The actual energy use during optimized periods and the expected energy use with original control are compared in Figure 59 and Figure 60. Both plots show one standard deviation error bar for the expected usage from the baseline model (the standard deviation is for the baseline model fit error). In most cases, the optimized actual consumption is within one standard deviation of the expected usage with original control. The unqualified overall usage however, does indicate that optimized operation did not improve the energy consumption and energy consumption increased by 5.84%.

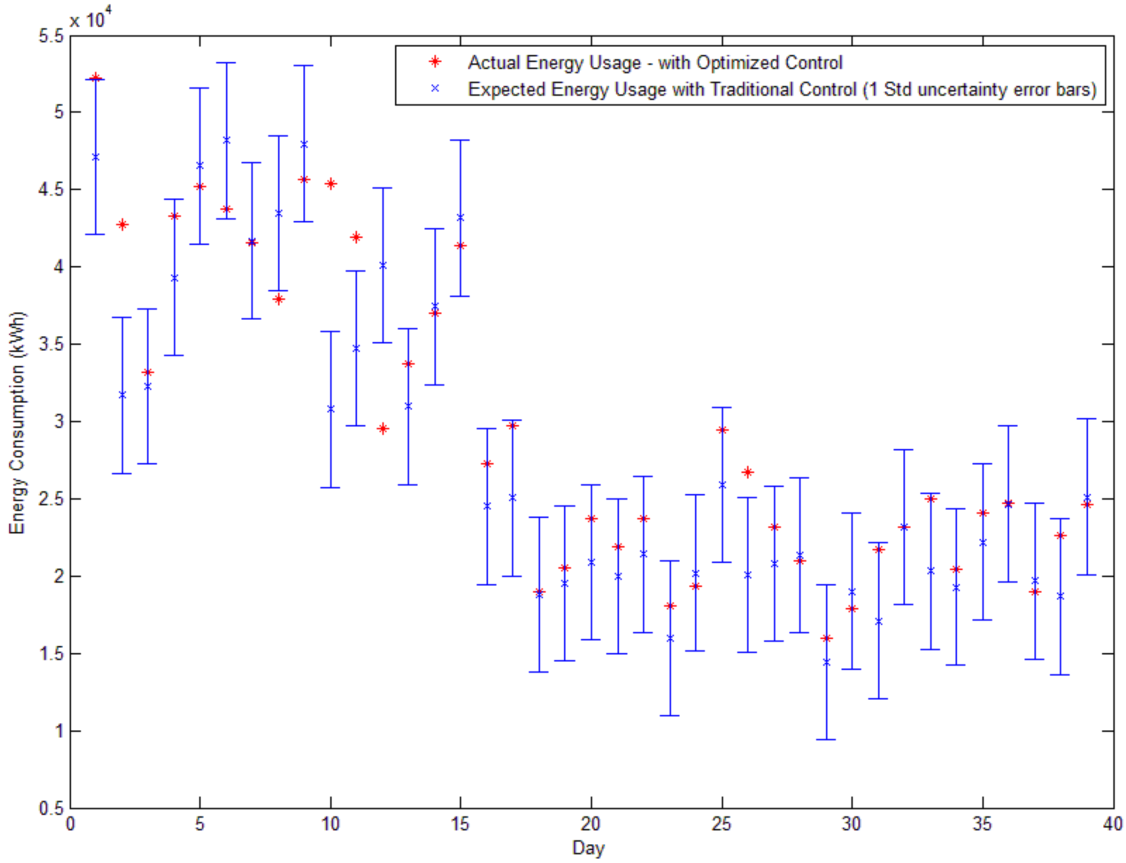


Figure 60: Comparison of actual energy used during optimized operation and expected energy usage with original control

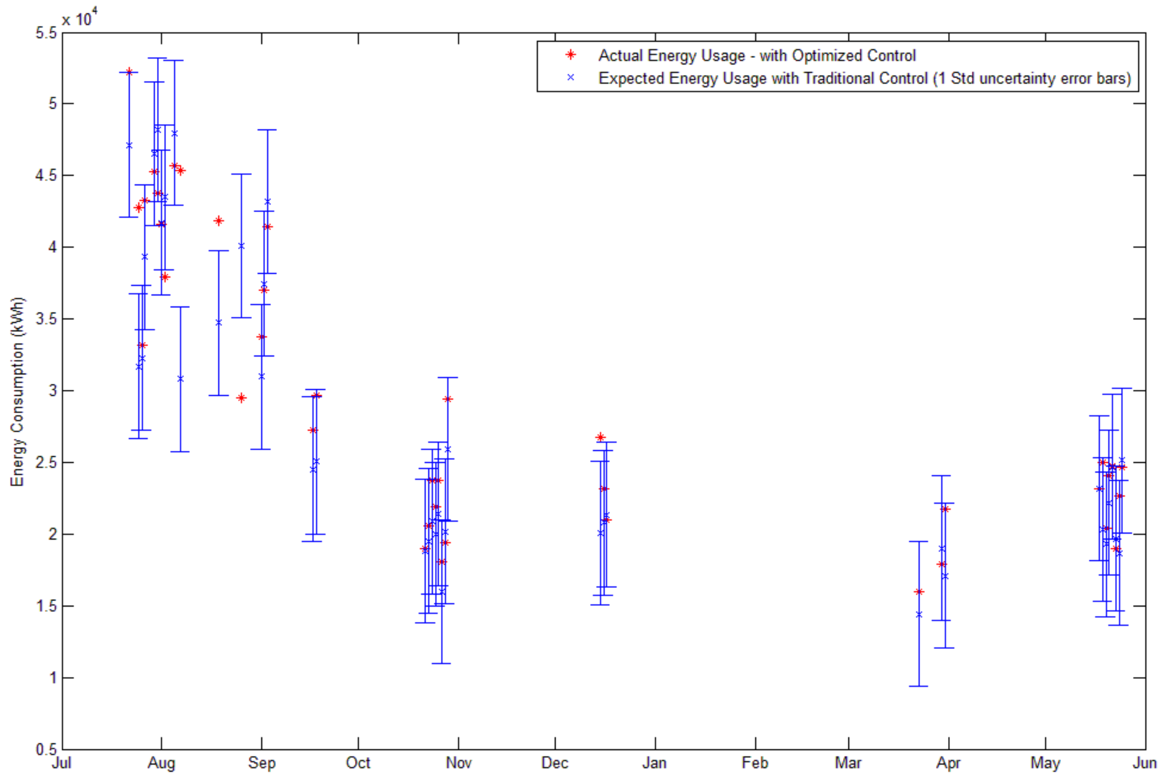


Figure 61: Actual energy used during optimized operation and expected energy usage with original control plotted against date

In depth analysis of optimized operation: Since the above results were fully unexpected, we analyzed the data to find out if the optimizer had been functioning correctly, if other factors were affecting optimized operation, and if input data into the optimizer during operation was correct.

1. Baseline model fit: Although we applied a rigorous method to model the baseline data, using several factors and model types, the best baseline model has significant deviations from the actual energy usage. Figure 21 (Section 5.2.2) showed the comparison of actual energy usage and that predicted by the model. Figure 61 shows the same data with 1 standard deviation error bars. It appears that several factors affect the total energy consumption of the chiller plant and additional data and additional factors (e.g., solar insolation) may be needed to obtain a better model.

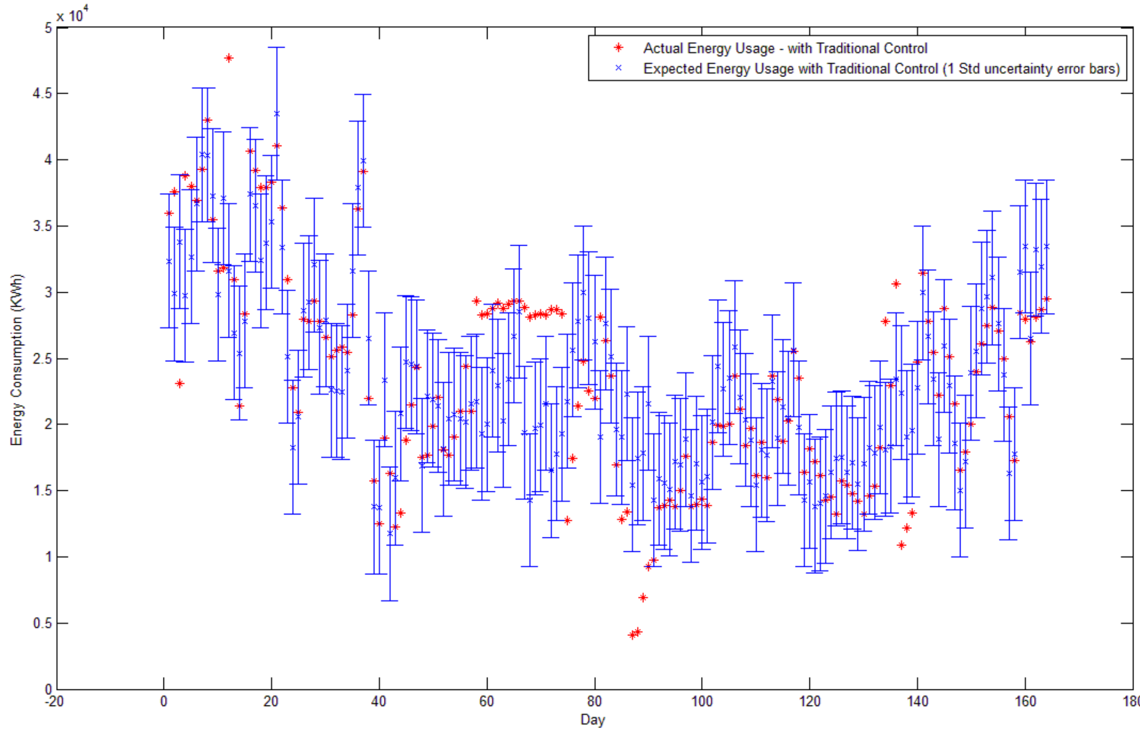


Figure 62: Actual and Model comparison for baseline periods, with error bars

2. Inputs to optimizer: Earlier, we showed some of the wrong data (Figure 55 and Figure 56). Although these may be cleaned or substituted for data analysis, the optimizer still receives the wrong measurements during real-time operation. Without a continuous presence on site or a remote connection, it is impossible to know if the user provided parameters and real time inputs are correct while the optimizer is in operation. The optimizer software is complex, and does not yet include standardized communication interfaces for controller or BAS integration, hence the application engineering skills to transfer the technology to the field have not been fully developed. The site staff includes mostly operations personnel. Software and communications must be monitored when in operation to ensure not just that the plant operates correctly (the site staff was qualified to do this), but the software is getting all its inputs and operating ideally (needed ACS Labs personnel or optimizer software experts for this). The indoor and outdoor temperature impacts how the optimizer forecasts load for starting and stopping chillers, and calculated correction to the supplied energy in the short term.

   One of the first anomalous data that we noticed with the new set of data in 2016, was the Total Power calculated from a summation of all equipment power data. Figure 62 shows the large spike in the total power calculated from summation of all equipment power. After further examination, we traced this to the power data for condenser pump #4. Figure 63 and Figure 64 plot condenser pump power data for all 4 pumps. Condenser Pump 4 has a large spike, and all other condenser pumps show a constant power value, from May 8 onwards. When zoomed in, the plot shows that Condenser Pump 4 has a flat power line from April 5 onwards.

   We have been interviewing the Honeywell site staff, exchanging plots and other data sources (EBI); however, the cause for this spike is not yet clear. For our energy analysis, we substituted the recorded total power for the chiller plant from a higher level record of summations in CPOWER software used for display from the data point Campus.HVAC1.-CPOWER.TotalPower in the database. However, the optimizer uses Condenser Pump 4 power in its models and solver, resulting in possibly erroneous optimum results. On being apprised of this power spike, the site staff lead immediately said that was probably why Chiller #4 was never being switched on, and would be switched off as soon as possible when optimizer was in control: 'the optimizer hated chiller #4.' Similarly, Figure 65 and Figure 66 show that the primary pumps and secondary pumps were similarly affected from April 5 onwards.

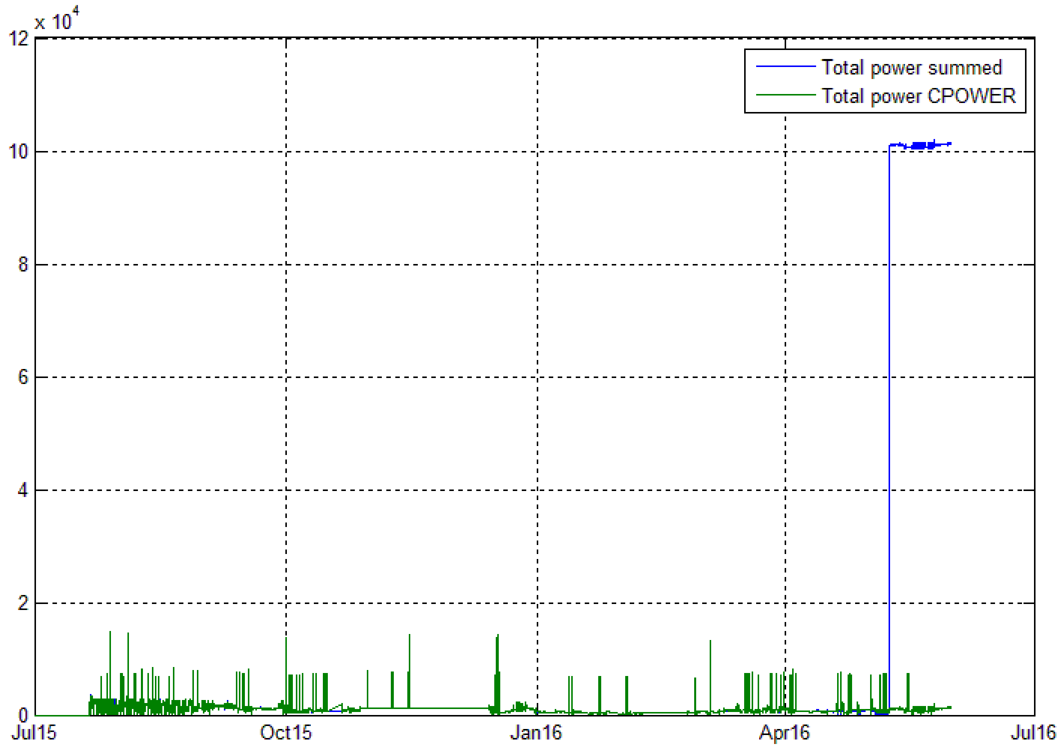


Figure 63: Total Power summed from individual equipment data and Total power as recorded

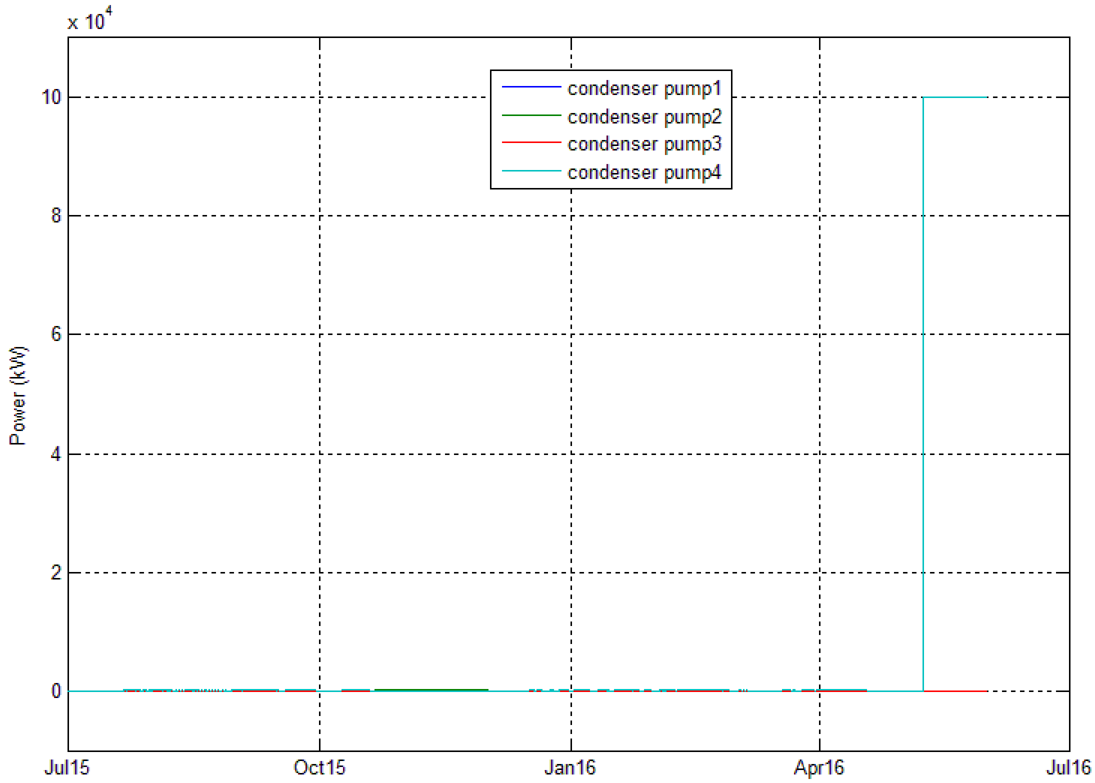


Figure 64: Condenser pumps power

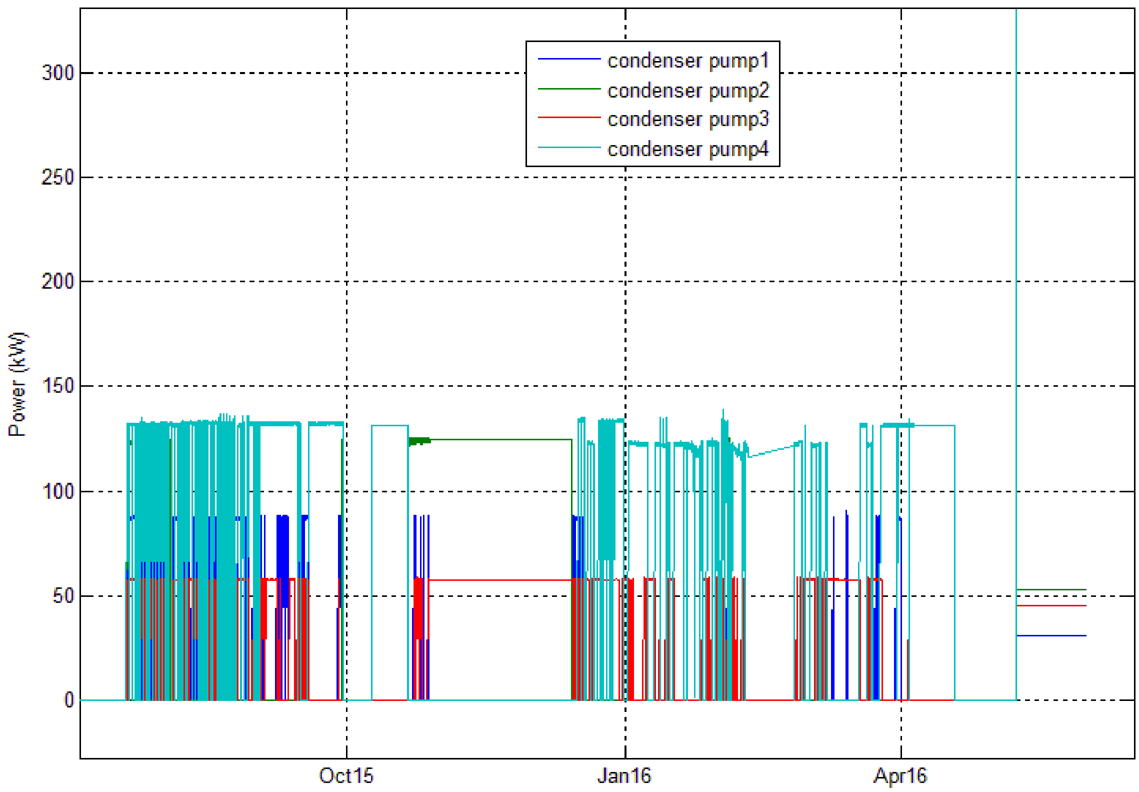


Figure 65: Condenser pumps power (zoomed in)

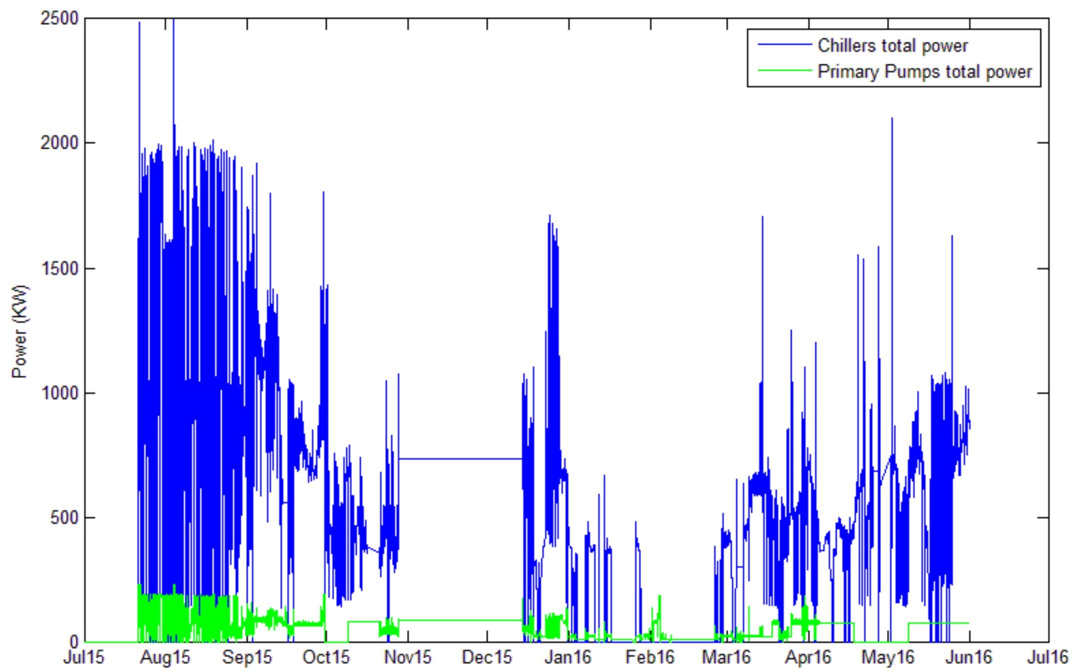


Figure 66:Chillers and primary pumps power

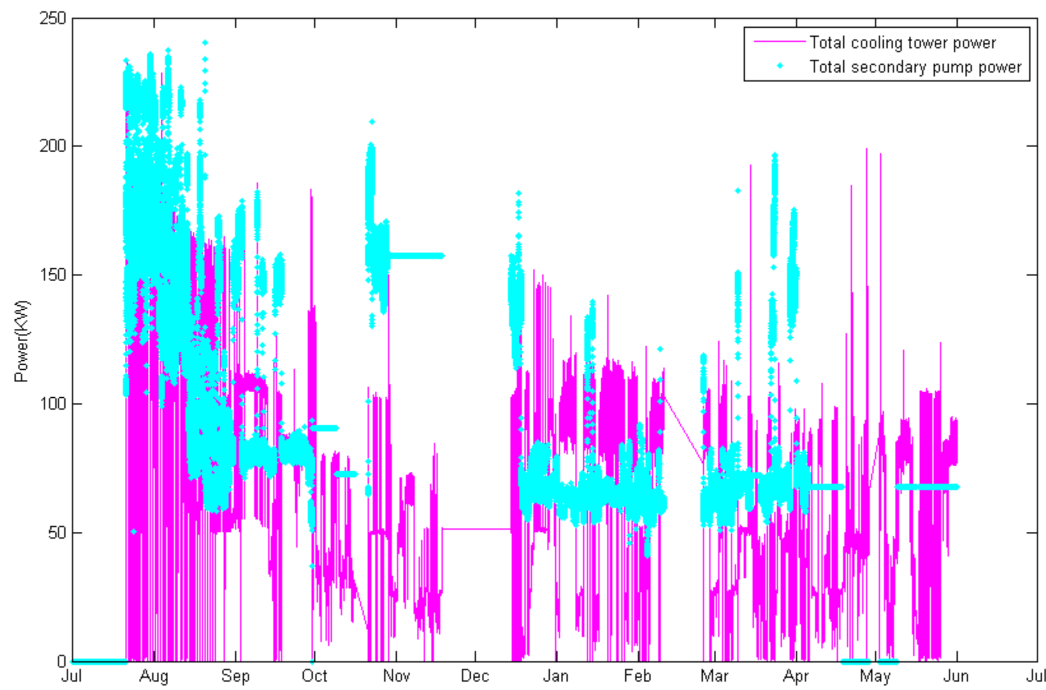


Figure 67: Cooling tower and secondary pumps power

Honeywell Minneapolis staff could not remotely monitor the optimizer. When we faced several issues after commissioning, they were difficult troubleshoot from afar because of the many control interface programming issues that we needed to deal with. From July 2015 until January 2016, we faced issues with the heat exchanger switching or storage tank operation at the site each time they would run for an extended period. (We traveled to the site twice after commissioning and training).

After January 2016, we asked the Honeywell site staff to run in optimized mode without either piece of equipment in the mix so we could collect additional data. However, from the data gathered it appears that although the site staff became more familiar with the optimizer, changes were made to get the optimizer to function in the short term. An example of this is that, when an equipment showed 'no response' (meaning that the commanded value and field value don't match) staff would make an equipment 'non-opt' (manual control) in the UI screen and change its status to that commanded by the optimizer. They informed us that there were periods of 'no response' when this was done. We have done some preliminary analysis of the data from the BAS (Honeywell EBI) system and the anomalous flat line does not appear there. We suspect the problem was the communication between the optimizer workstation and BAS, and the control interface programmed for switching between the optimized and non-optimized modes, during operation. We learned that the local controller was programmed with a duplicate set of points, so that when the 'Optimizer Enabled' was activated, the controller latched on to a set of points that the optimizer would write to and read from. When 'Optimizer Enabled' was de-activated, the controller latched on to a set of points that the local control logic would write to and read from. If a point server was re-configured for some site operation, or experienced other problems, the CPOWER optimizer's points may not have been written to.

3. Learning plant equipment models: The sequence of issues faced during the demonstration period meant that the optimizer software did not have long enough periods of stable operation for learning equipment models, and sometimes was not recording the correct inputs for the models.

As a final analysis point, we present the data from the last continuous run at the chiller plant in Figure 68. Without the rigorous comparison with the baseline model, it would appear that energy consumption for the optimized period was lower. However, energy comparison should be performed quantitatively (not visually) and for like conditions. Therefore, we cannot conclude energy savings based on this comparison.

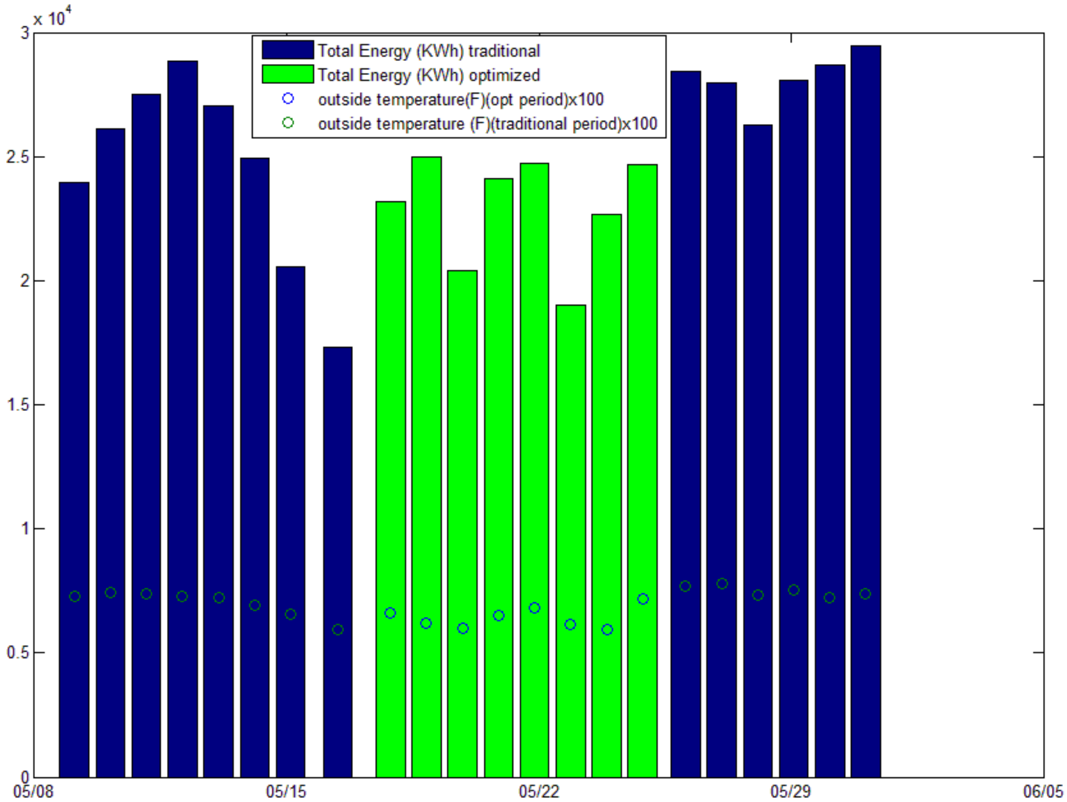


Figure 68: Total Energy Consumption for a few weeks of May 2016 (no weather normalization)

Success Criteria: The energy savings to be achieved depend on existing plant conditions, distribution network infrastructure. However, we anticipated a 10% energy savings on weather-normalized consumption data.

Results: From the above analysis, we conclude that the optimizer was not able to operate with correct data and parameter settings during the demonstration period. Additional work needs to be done to develop the site implementation strategy, so that several of the issues of connecting to the control system are made simpler and more robust. For this demonstration period, we conclude that the optimizer was not able to operate as intended and hence the energy savings could not be achieved.

6.4 PO4: COMFORT CONDITIONS IN BUILDINGS

The central plant optimization should not compromise comfort conditions in the buildings served by the plants. The central plant should supply cooling or heating to keep the temperature and humidity setpoints at the buildings being served. The goal of this objective was to monitor how closely the setpoints were maintained and whether the chilled water supply compromised the building temperatures. The central plants have little control of building temperature setpoints, which themselves have several zones with separate temperature setpoints. The buildings have independent control of their comfort through their air handling units, which is affected only by the chilled water flow and supply temperatures. If these values are within expected limits, the buildings should not show deviations in their space comfort conditions, assuming other factors and building controls function the same.

Some structural aspects of the cooling and heating distribution system are not under the control of the plant optimizer (such as building controls for airflow), which might cause indoor conditions to deviate from setpoints in certain buildings and zones. Therefore, we also measured how well the basic control system maintained the setpoints and compare with the deviations for the optimized operation.

Purpose: To ensure cooling and heating comfort is not adversely affected in the buildings during optimized operation.

Metric: Difference between indoor temperature (deg F) measurements of the baseline period and optimized operation.

Data: Temperature data from representative buildings during baseline and demonstration periods.

Analytical Methodology: Our initial plan was to analyze the actual temperature measurements from representative buildings with respect to the building controller temperature setpoint deadbands. We planned to ascertain that the building temperatures do not deviate significantly from their pervious operation, because of changes in chilled water supply temperatures and flows. We didn't have access to building controller configuration information, so our analytical approach (1) compared the indoor temperature measurements with respect to the temperature limits specified in the optimizer, and (2) used the data collected in 2014 as baseline for comparison with the indoor temperatures during the demonstration period.

We collected several batches of data from the Honeywell EBI system for simulation modeling purposes. The building space temperature data was available from May through August 2014. Figure 69 shows the 2014 raw temperature measurements from representative buildings (see Section 5.3, Figure 32), and Figure 70 shows the temperatures with the zero temperature outliers removed. Figure 69 shows the average of the five building measurements.

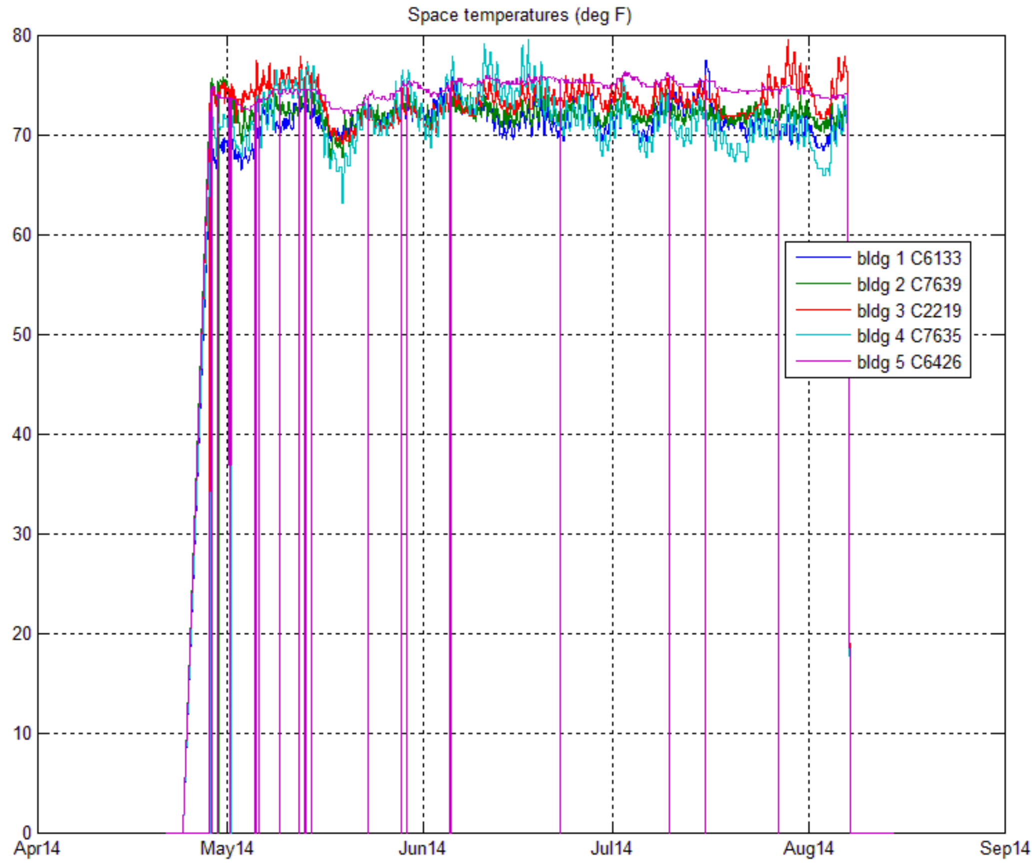


Figure 69: Indoor space temperature in representative buildings - 2014 baseline period (raw measurements)

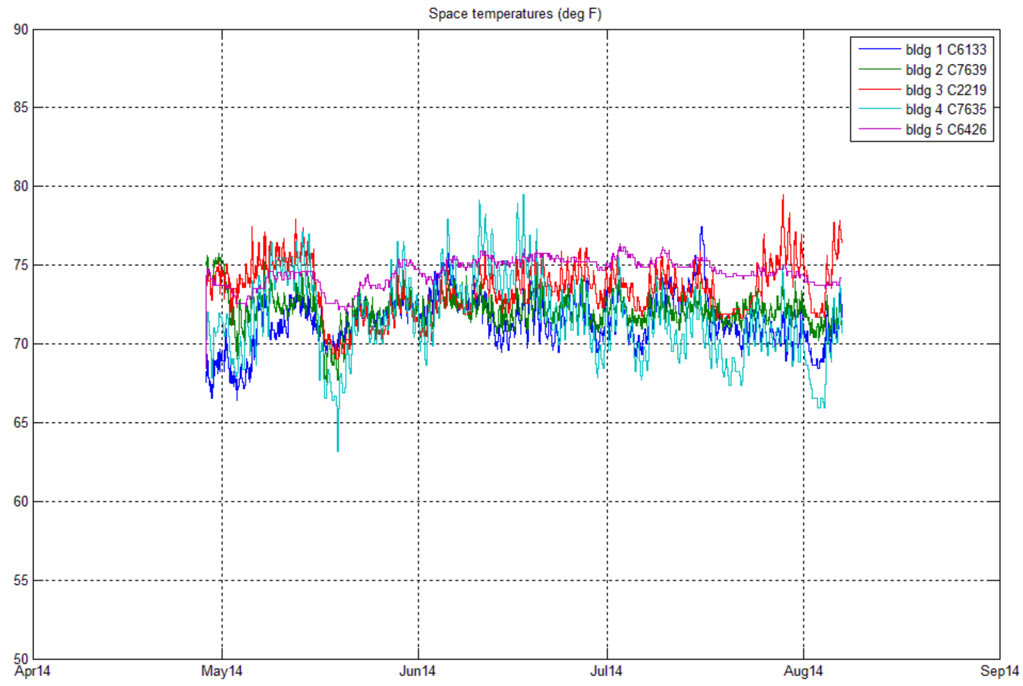


Figure 70: Indoor Space temperatures in representative buildings - 2014 baseline period (cleaned)

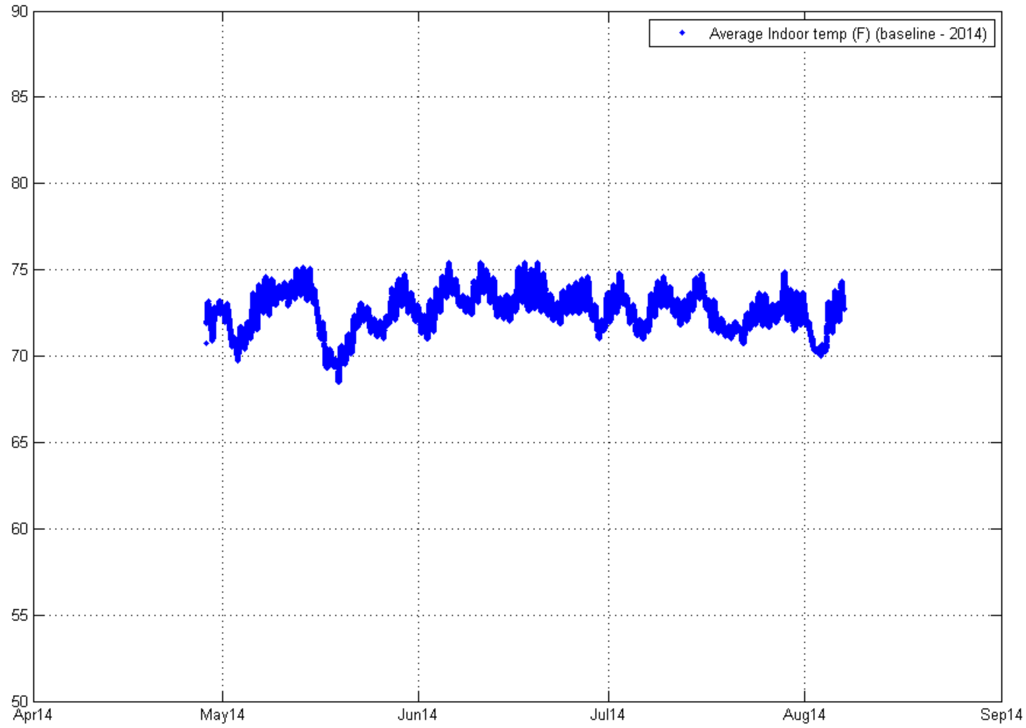


Figure 71: Averaged indoor temperature from all representative buildings (baseline period – 2014)

After installing and commissioning the optimization system for the chiller plant, we collected data in the optimizer's database at 1 minute frequency. We extracted data that included temperature measurements from the representative buildings; unfortunately, the humidity measurements were not mapped to the software, and hence these are not available. The database was also rebuilt towards the latter half of July 2015 for reconfiguring the models, and we have data from July 21, 2015 onwards.

Figure 70 shows the temperatures in each building. As noted in a previous section, no data was collected during parts of November and December 2015. Figure 71 and Figure 72 (zoomed to show details) show the averaged indoor temperatures for the five buildings. Colors distinguish temperatures during optimized (blue) and non-optimized operation (green). The plots also show the upper and lower limits for space temperature set by the user in the optimizer configuration. Note that the chiller plant controls cannot directly control the space temperatures, and the upper and lower limits provide the optimizer with setpoint flexibility, or range, to calculate the load and optimize a supply of chilled water to the buildings. We observed that the averaged temperature of the five buildings stayed within these upper and lower limits for the optimized periods, except for the initial period in July–August, 2015. The exception occurred because the building controllers were set to a higher temperature, and a lower setpoint in the optimizer will not control the building temperatures. It is important to note the visual comparison of the optimized and non-optimized operation and the temperatures indicate that the optimized operation has not had an adverse effect on the building space temperature.

Next, in Figure 73, we show the side-by-side comparison of the 2014 baseline data and the 2015 demonstration period data. The plots again demonstrate that indoor temperatures were not affected and in fact, the building temperatures were lower during the 2015 demonstration period for both optimized and non-optimized operation.

For a quantitative comparison, we compared the averaged value of available indoor temperature for July and August for 2014 with the averaged indoor temperature for July and August for optimized operation.

July and August 2014 indoor temperature average	**July and August 2015 indoor temperature average for optimized operation**
72.63 deg F	70.73 deg F

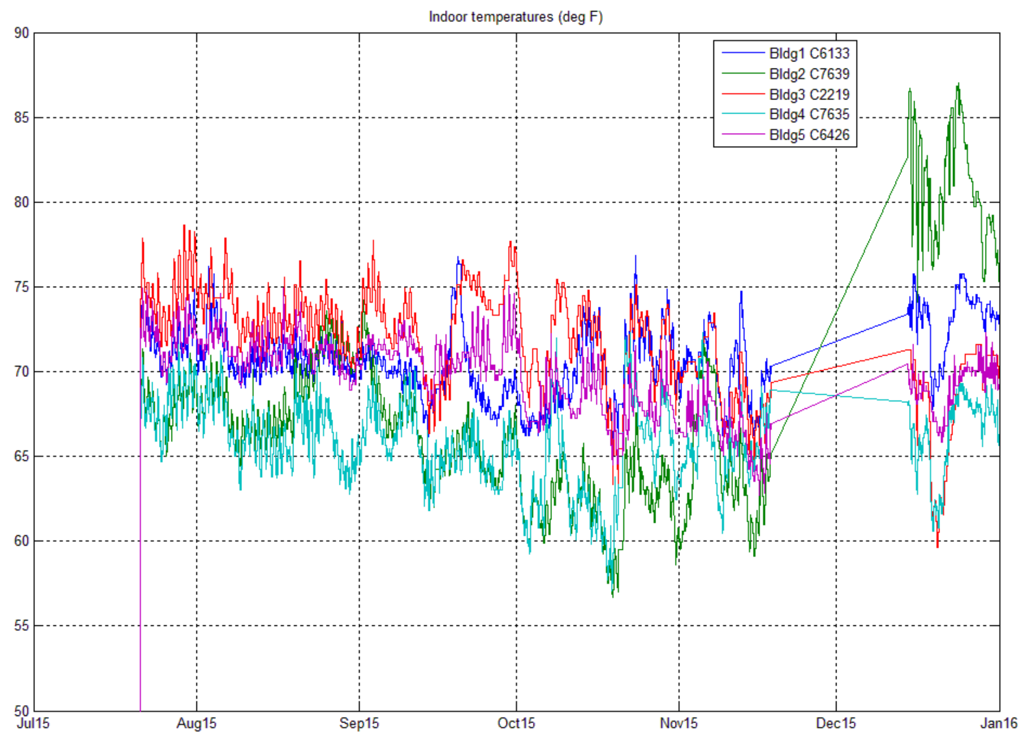


Figure 72 Indoor temperatures in representative buildings (demonstration period)

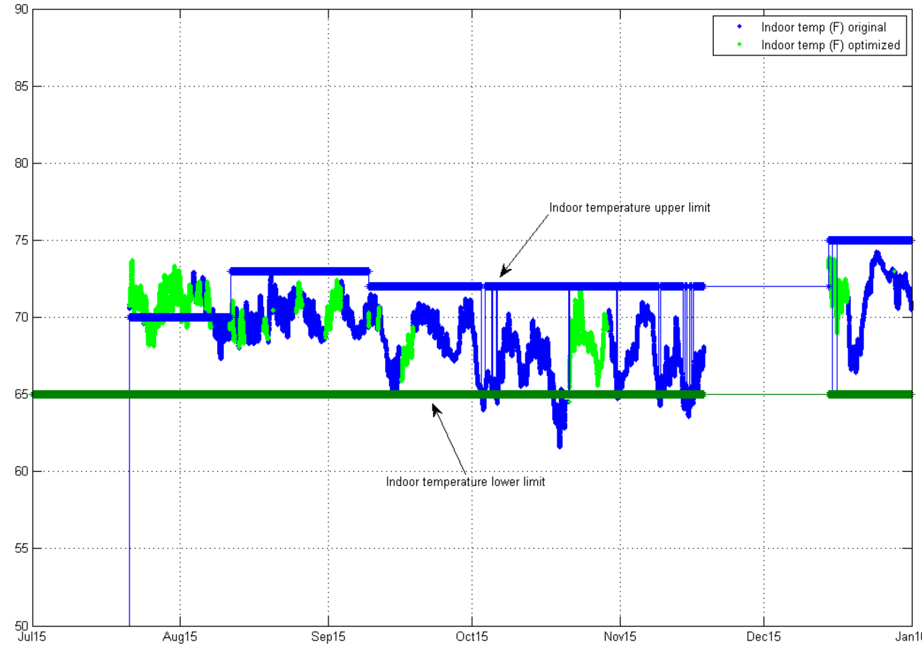


Figure 73: Averaged indoor temperature from all representative buildings

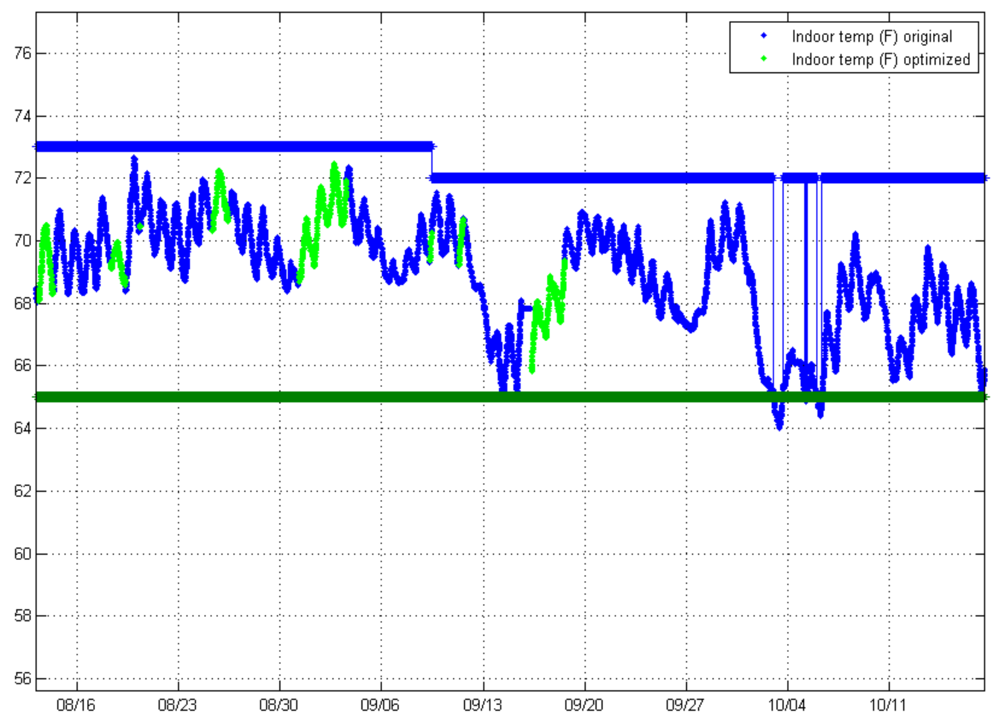


Figure 74: Averaged indoor temperature from all representative buildings (zoomed in example)

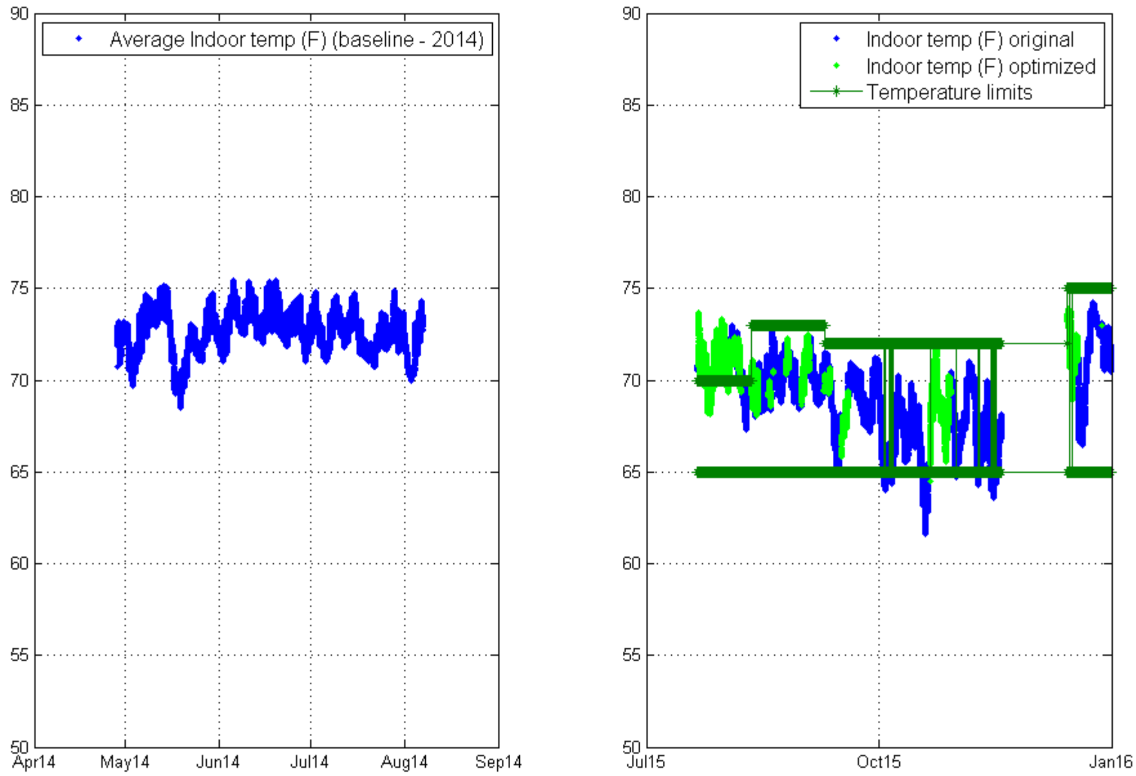


Figure 75: Comparison of indoor temperature averages from 2014 baseline and 2015 demonstration periods

Success Criteria: (We have altered the success criteria from the demonstration plan, since we also altered the analysis approach based on the data and information available.)

Visual comparison of baseline and optimized operation should show no significant adverse difference. Average value of indoor temperatures for comparable periods for baseline should not be more than 2 degrees lower than optimized operation.

Results: Based on the results of our analysis it is clear that this performance criteria has been met.

6.5 PO5: ECONOMIC PERFORMANCE

In order to be adopted across DoD and commercial sites, the technology being demonstrated should show good economic benefits over its lifecycle. Economic performance in the form of reduced energy costs, maintenance costs, and other benefits will be computed.

Energy projects undertaken by private industry as energy performance contracts on behalf of the government usually have a contract term of 10-30 years. The performance contractor and the government expect to have enough energy and other savings to recoup the expenditures within the terms of the contract. A project is successful if the Net Present Value is greater than 0.

Purpose: To quantify the life cycle cost benefit of the optimization technology being demonstrated.

Metric: NPV (Net Present Value) metric produced by BLCC tool.

Data: Cost savings, initial investment cost, and annual maintenance cost of the technology.

Analytical Methodology: The main driver for the cost savings comes from energy savings in this project. From the analysis provided for PO3 Energy Savings, we may conclude that cost savings arising from energy savings could not be achieved during the demonstration.

Savings could also accrue from shifting energy use to thermal energy storage and to pre-cooling appropriately during changing real time price conditions. However, during the demonstration period of summertime changing real-time price conditions, when the chilled water storage tank should have been in operation, we faced issues with the control interface, modifications made to the software to correct remaining capacity calculations, and the correct setting of charge and discharge operations. These problems were partly caused by the layout and operation of the plant: the storage tank is used as the bypass or bridge between the secondary and primary loops and is in operation all the time to balance the flows; when charging or discharging, the direction of the flow in and out of the tank changes. We applied a number of workarounds in the software to correctly input the mode of operation and commands so that the software would not infer the wrong mode of operation from measured flows.

After the software corrections and settings were applied, the summertime real-time significant price changes were no longer in effect, and the site did not want to run in charge or discharge modes until the next summer. Therefore, we are unable to provide an analysis of the cost savings from shifting of energy use.

Success Criteria: Net Present Value of >=0 for a 10 year project performance period.

Results: Cost savings were not achieved during the demonstration period.

6.6 PO6: EQUIPMENT SHORT CYCLING

One of the concerns about advanced optimization solutions that minimize energy costs is that they may turn major equipment ON and OFF (short-cycling) more frequently than is considered normal by operators, as this may increase degradation and repair costs. However, equipment switching is one of the ways energy savings is achieved. Therefore, we monitored equipment ON/OFF events for this performance objective.

Purpose: To quantify the short cycling of chillers and boilers.

Metric: Chillers time in OFF position before turning ON, and time in ON position before turning OFF.

Data: The optimizer database gathered data from the chiller plant at 1 minute intervals. Each chiller’s ON/OFF status and other measurements were recorded. The database also recorded the optimizer ‘enabled’ status along with the timestamp.

Analytical Methodology: Using ON/OFF data, we computed ON and OFF time intervals for each chiller and boiler . The time intervals were compared with minimum ON and OFF times for such equipment, as gathered from manufacturer specifications and operator interviews.

The optimizer software allows the user to set up minimum and maximum run and rest times for chillers and other equipment. These parameters are soft constraints, since they may be overridden by other concerns such as safety or comfort. For example, the optimizer will respect a minimum run time setting of 2 hours, unless a safety concern such as exceeding maximum compressor current occurs, and then the chiller would be commanded OFF. Similarly, if the load suddenly increases and the chiller is needed to meet comfort constraints, it may be started up even if it has not reached its minimum rest time. A screenshot of the software showing the parameters is in Figure 74.

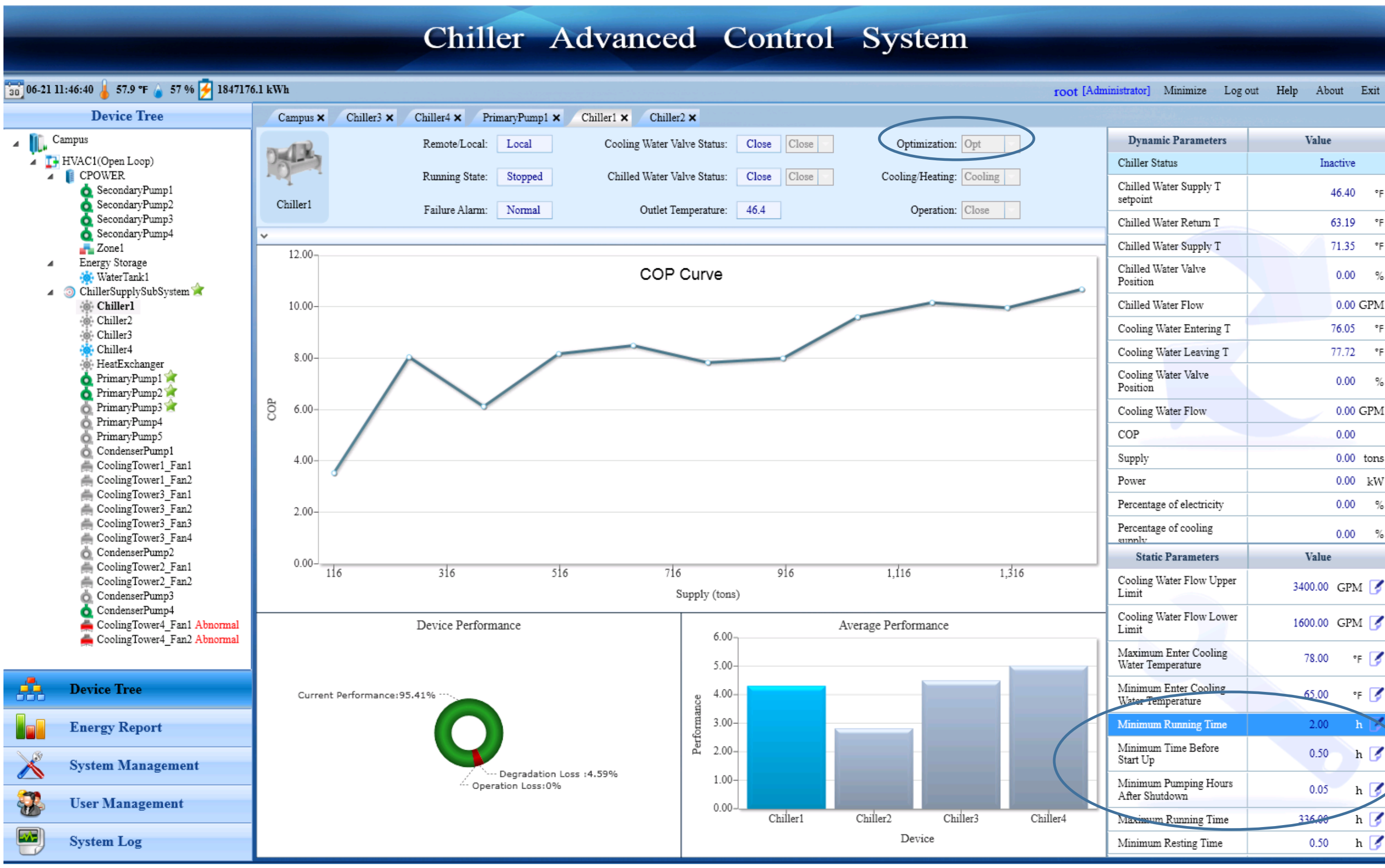


Figure 76: Chiller screen with user set parameters of minimum run time etc.

Two other parameters of concern in this analysis are: optimizer 'enabled' condition (when the optimizer controls the chiller plant) and whether a chiller is in optimization mode. The former parameter is self-explanatory. The latter parameter (e.g., Chiller1.IsInOptMode in our dataset) is provided so a user can remove specific equipment from the optimizer's control, e.g. when a chiller is under maintenance and shouldn't be used. Chiller usage is actively optimized only when the optimizer is enabled for the plant and the chiller is in 'optimized' mode. Figure 75 through Figure 78 show each chiller's on/off operation during its optimized and original or manual control states.

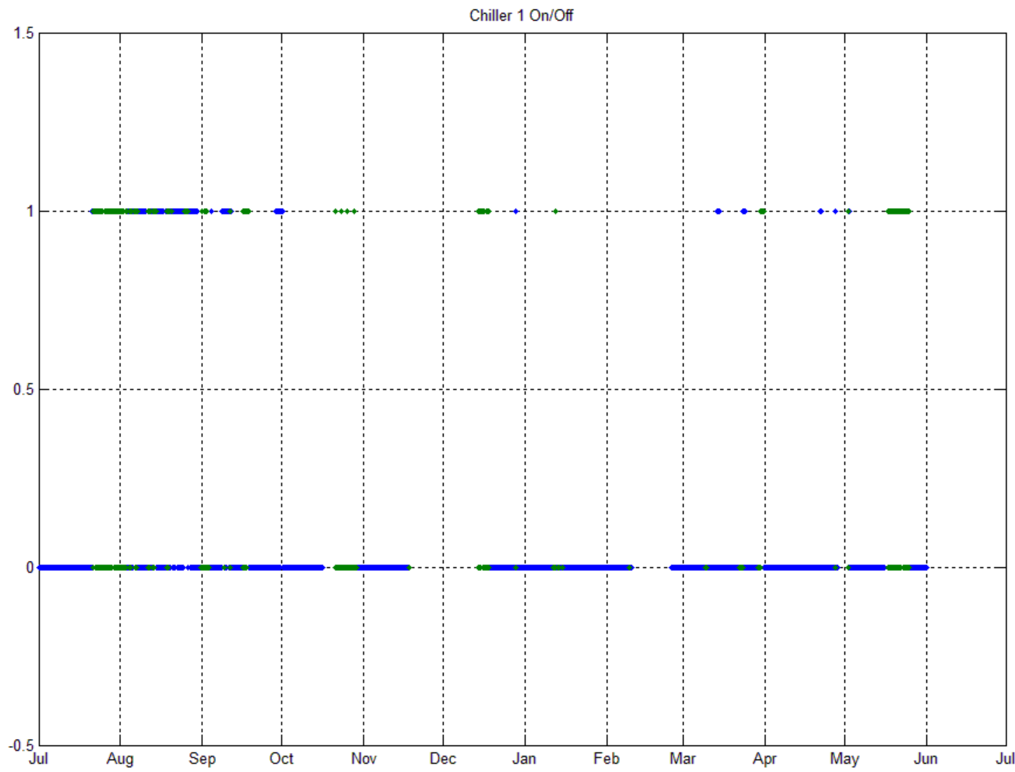


Figure 77: Chiller 1 ON (=1) during optimized and original control operations

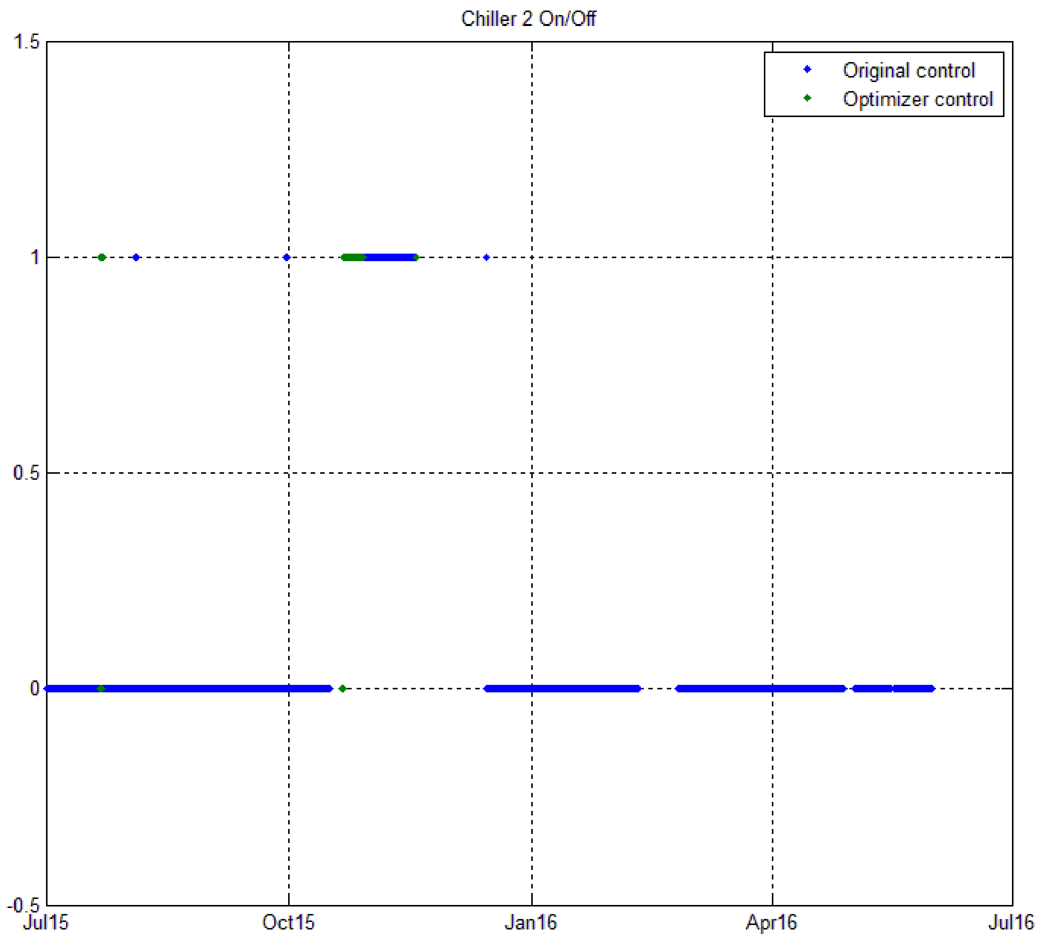


Figure 78: Chiller 2 ON (=1) during optimized and original control operations

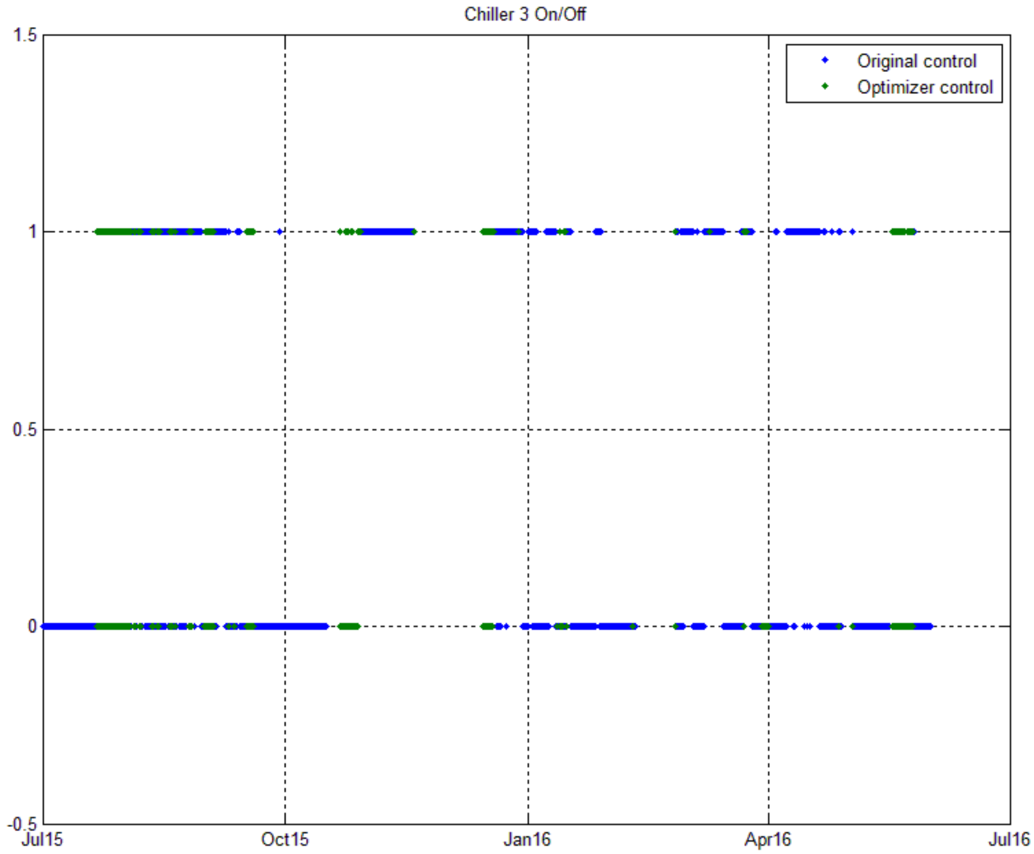


Figure 79: Chiller 3 ON (=1) during optimized and original control operations

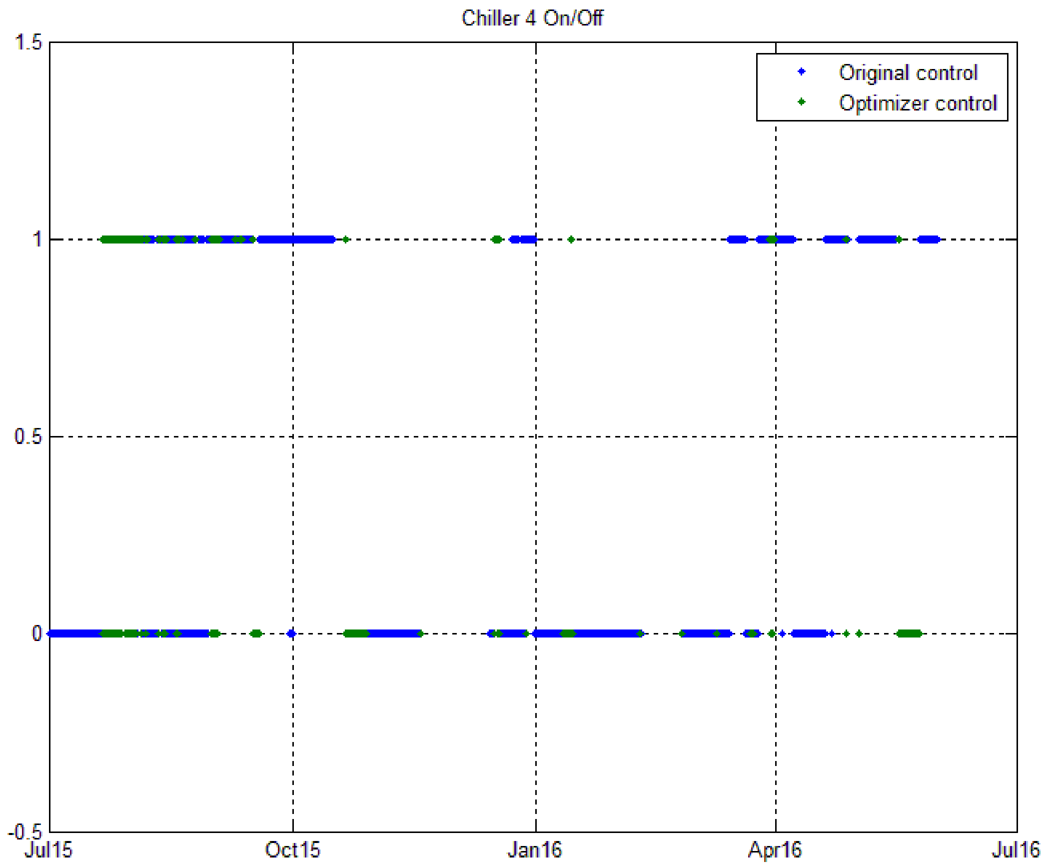


Figure 80: Chiller 4 ON (=1) during optimized and original control operations

Chiller ON durations: Since the visualizations in Figure 75 through Figure 78 are difficult to interpret quantitatively, even if zoomed in (see Figure 79), we need to compare actual ON time durations. To calculate the lengths of time when a chiller was on, we extracted all chiller on indices and extracted the lengths of sequential indices. Each 1 minute timestamp is one index. In Figure 80, the Chiller 1 ON duration is plotted against the mean timestamp for that duration along with the plot of optimizer enabled and the minimum runtime set by the site user. The minimum runtime is the minimum duration that the operator wants the chiller to be continuously in the ON state. The Chiller 1 minimum runtime was initially set to 2 hours. Subsequently, the software and parameter settings were modified when site complaints were received about the chillers not shutting off sooner when load was low. The minimum runtime was set to 0 after this period. Although it is difficult to separate out or estimate the on times during optimized and non-optimized periods, we can infer that the optimizer commanded the chiller on mostly for durations greater than 2 hours, although there were some shorter periods. Note, this analysis includes all data, including some testing and troubleshooting periods, which may overstate the number of shorter durations.

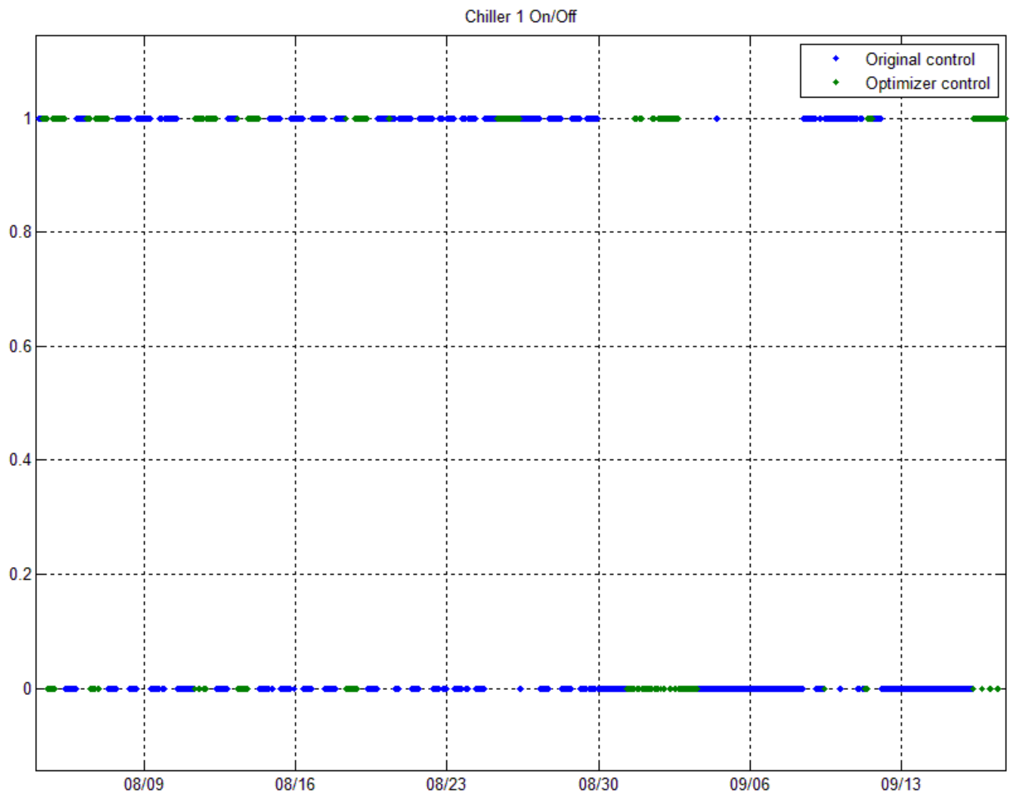


Figure 81: Chiller 1 ON zoomed in

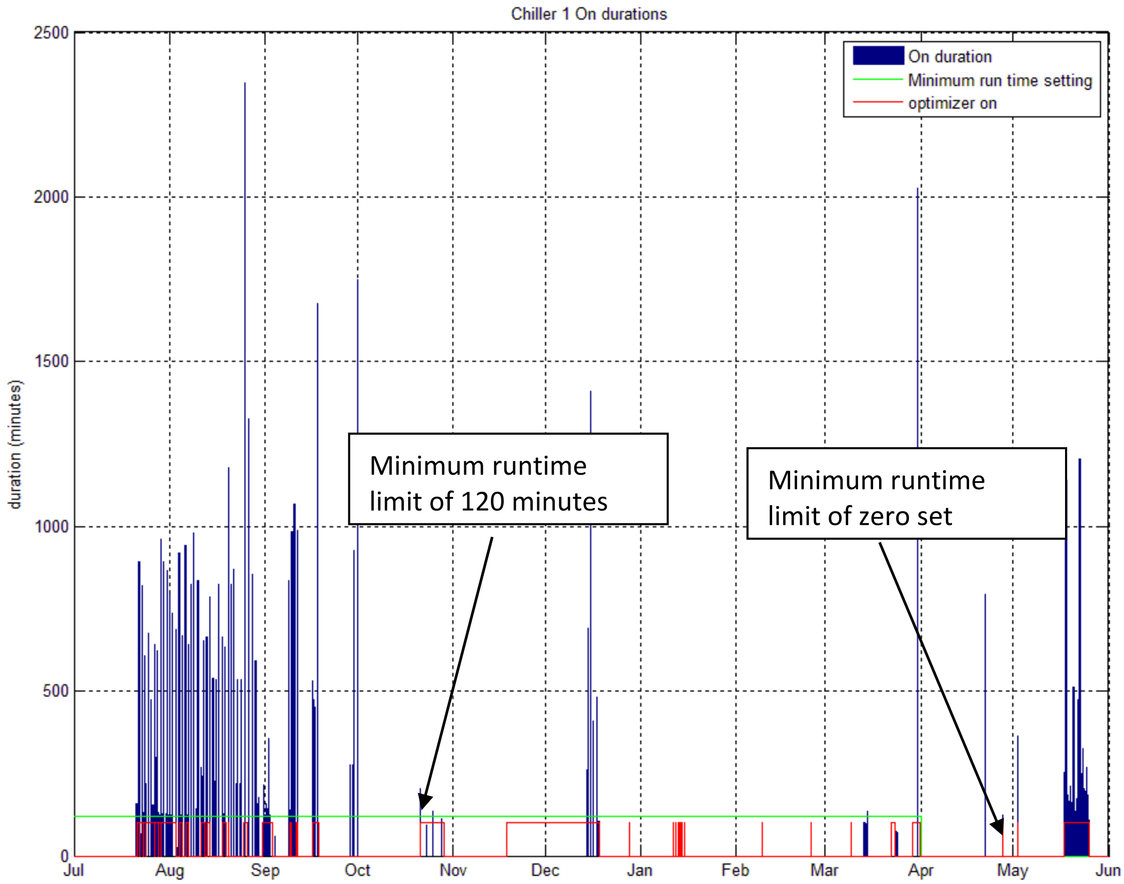


Figure 82: Chiller 1 ON durations

For a more quantitative comparison, a distribution of the duration of ON times for Chiller 1 during the demonstration period is plotted as a histogram in Figure 81. We can see that the original control operation has more long duration ON periods, and the optimized control has a more short duration ON periods. This is not unexpected, since the optimizer will always look for ways to reduce energy usage, sometimes shutting down the chiller oftener than is current practice. We were unable to find a manufacturer-provided maximum cycling frequency that the site follows. The current practice is to operate based on current loads. The site provided us the number for the minimum runtime of 2 hours, so we use this as a benchmark.

The two duration plots above are repeated for Chillers 2, 3 and 4 below in Figure 82 through Figure 87. Note that Chiller 2 had not been taken out of operation for most of the demonstration period because of problems (unrelated to the optimizer operation).

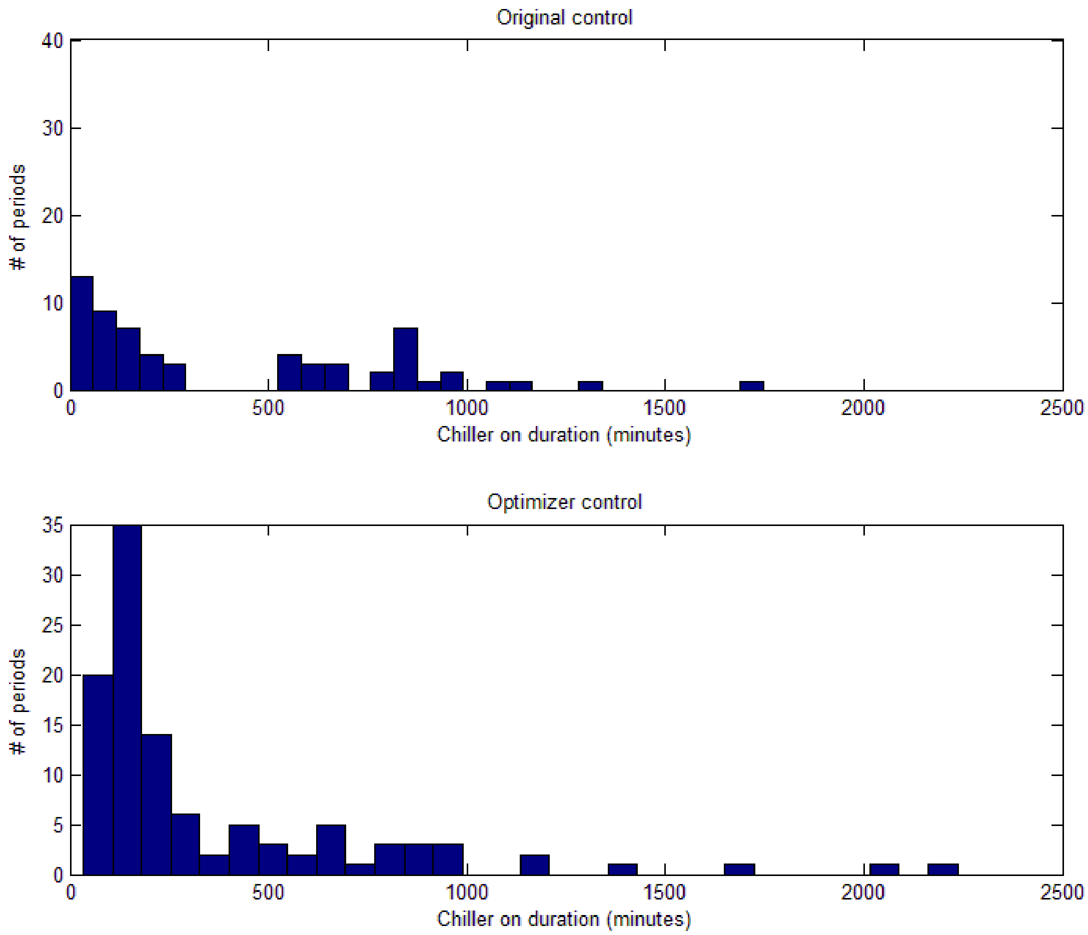


Figure 83: Chiller 1 ON duration frequency distribution

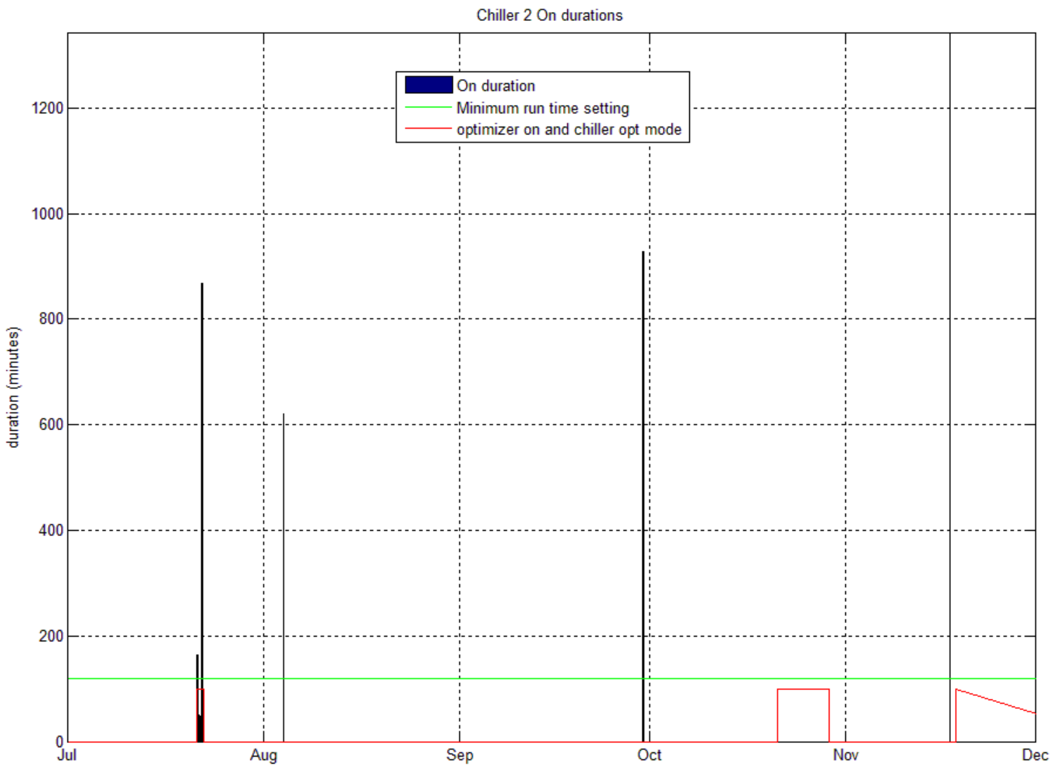


Figure 84: Chiller2 ON durations

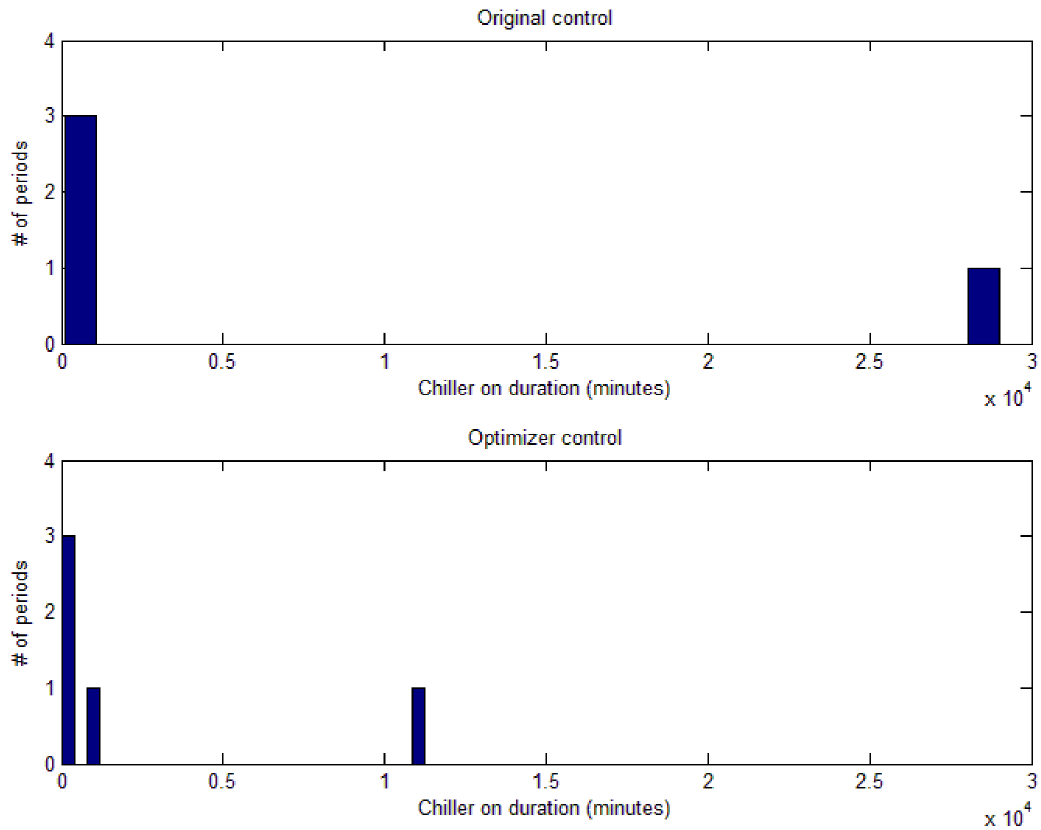


Figure 85: Chiller 2 ON duration frequency distribution

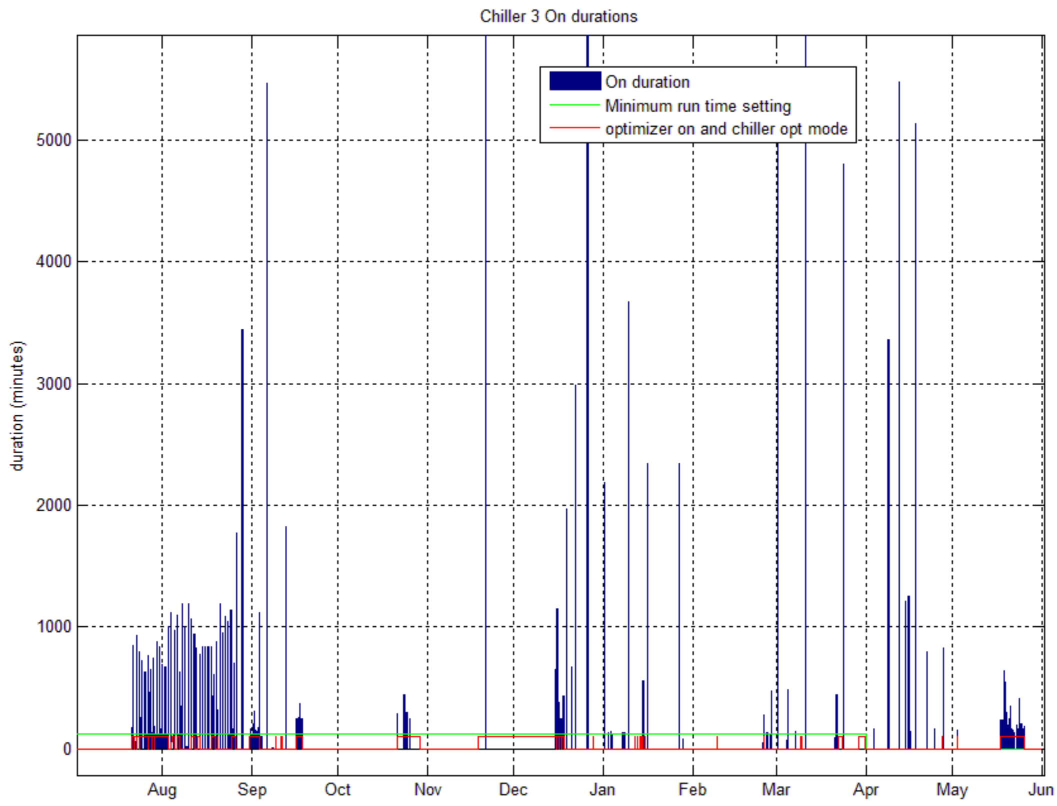


Figure 86: Chiller 3 ON duration

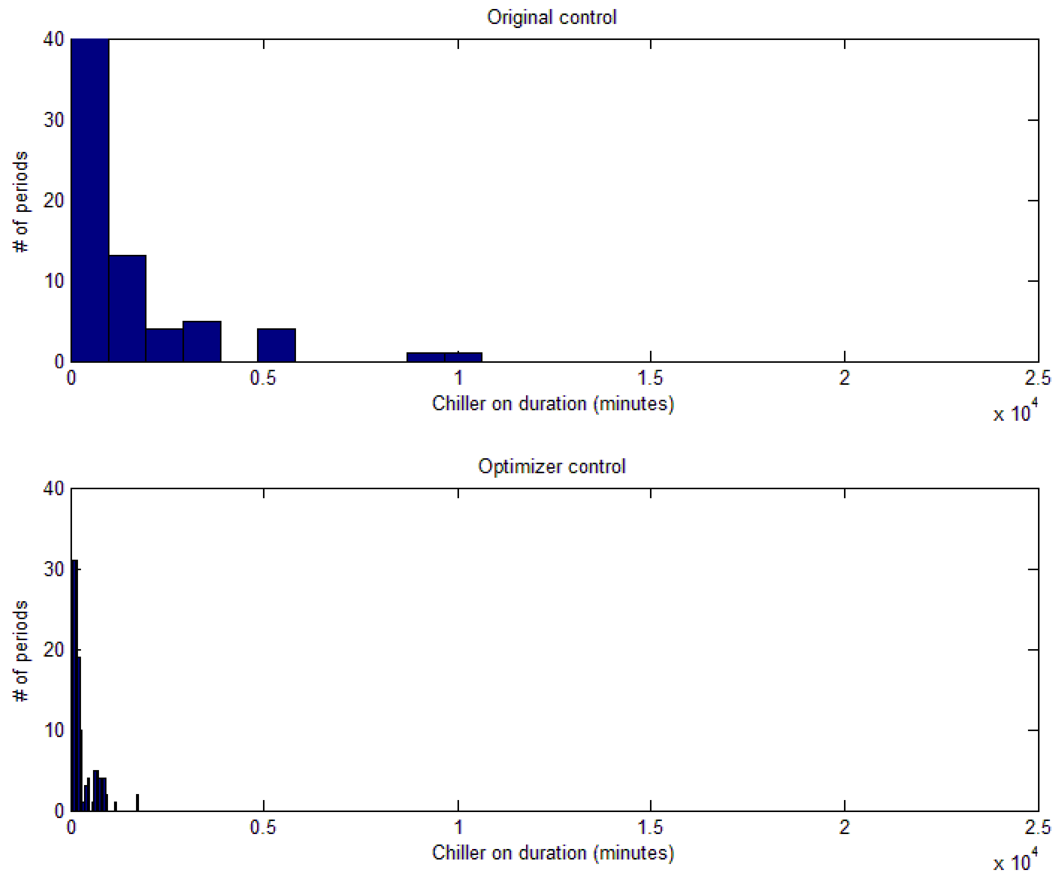


Figure 87: Chiller 3 ON duration frequency distribution

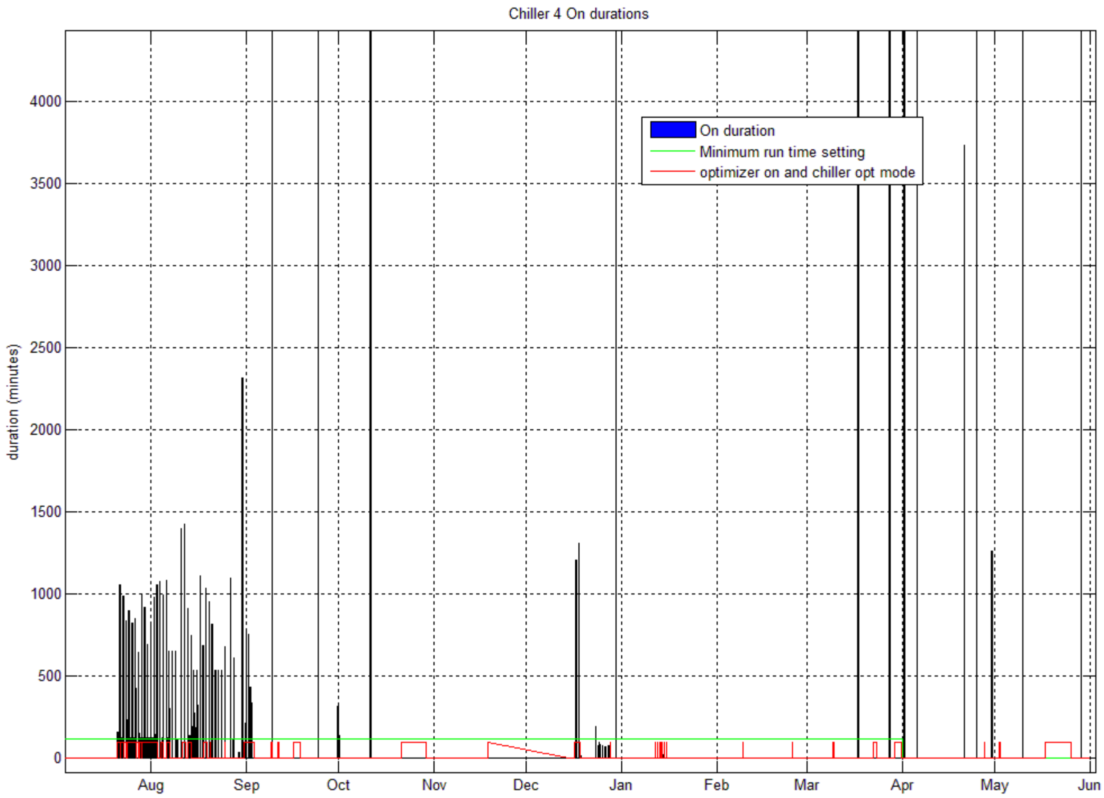


Figure 88: Chiller 4 ON durations

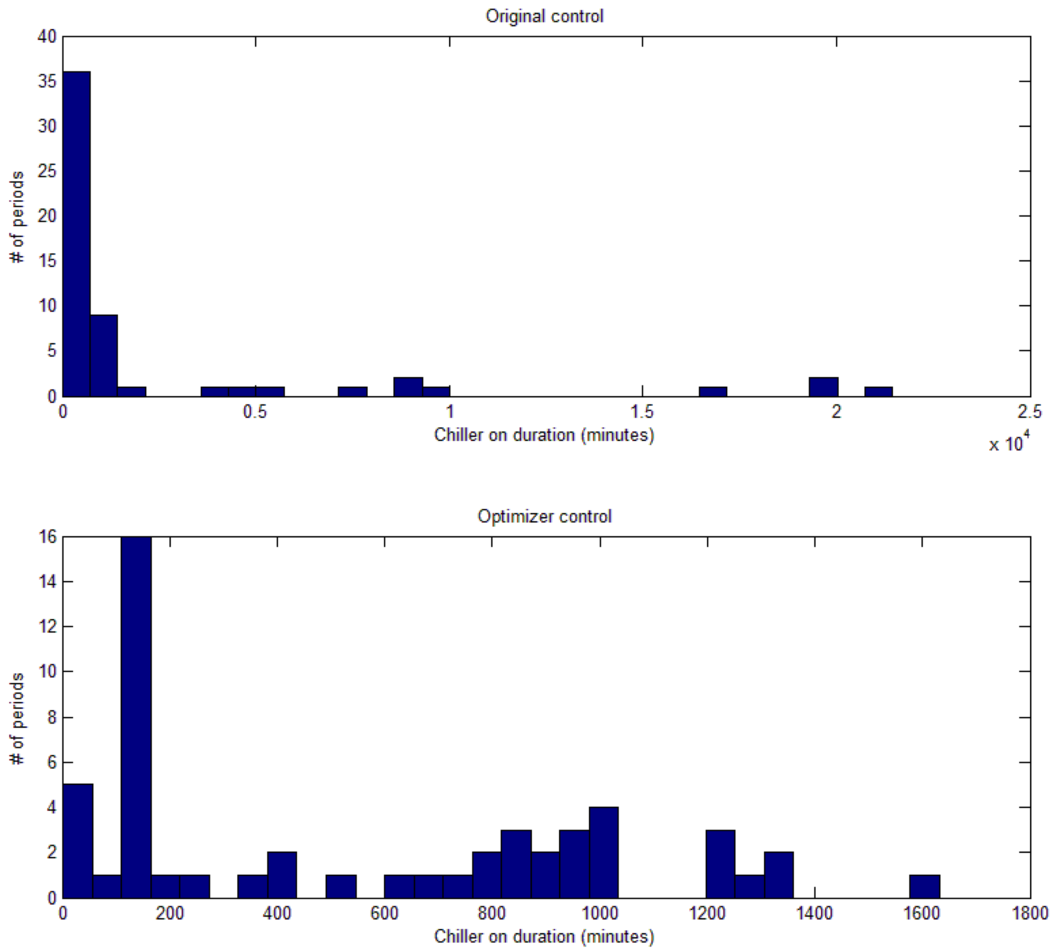


Figure 89: Chiller 4 ON duration frequency distribution

Similar analysis was performed for OFF duration. We are not presenting the plots for these since they are similar to the above plots.

Quantitative information about the ON and OFF times for the four chillers are presented in Table 12 and Table 13. Columns 2 and 3 present the median duration of ON or OFF periods for optimizer and original control periods. The last two columns present the number of periods when the durations were shorter than the benchmark 2 hours (for ON), or 30 minutes (for OFF), versus the total number of periods in the demonstration period.

Table 12: ON duration statistics

Chiller	Median ON duration – optimization (minutes)	Median ON duration - original (minutes)	# Shorter than 2 hours /total # durations-optimization	# Shorter than 2 hours/total # durations - original
# 1	169.5	217.5	22/108	11/62

# 2*	50	773.5	2/5	0/4
# 3	164	484	6/136	15/81
# 4	428.5	536	3/52	12/57

* Chiller # 2 had problems and was not run much during the demonstration period.

Table 13: OFF duration statistics

Chiller	Median OFF duration – optimization (minutes)	Median OFF duration - original (minutes)	# Shorter than 30 min/total # durations-optimization	# Shorter than 30 min/total # durations - original
# 1	73	565	0/107	1/63
# 2*	228.5	29245	1/4	0/5
# 3	45	376.5	14/135	5/82
# 4	141	401	1/52	1/57

* Chiller # 2 had problems and was not run much during the demonstration period.

Success Criteria: Our stated criterion was that ON/OFF frequency under optimized operation does not exceed the manufacturer or operator provided specifications. However, as we reported in the analysis section, the site did not provide specifications, nor were we able to find a manufacturer's recommendation on what would be considered short-cycling. We use 2 hours minimum ON time and 30 minutes minimum OFF time as parameters in the software, which could be considered benchmarks.

Results: As seen in the analysis section, the chiller ON/OFF durations are shorter for the optimized than for original operation. However, that condition was expected, given the optimizer's objectives. During the demonstration period, we analyzed the on and off times for both optimized and original control. Apart from the larger number of shorter cycles, it is not clear that the optimizer is exceeding a threshold very frequently, even compared with the original control. The last two columns in Table 12 show that the original control also had several instances of cycle durations shorter than our benchmark above. Therefore, given that the optimizer software provides the flexibility to adjust the cycle times, we consider this performance objective has been met.

6.7 PO7: EFFECTIVENESS OF USER INTERFACE (QUALITATIVE)

Advanced optimization solutions are sometimes considered 'black boxes' by field personnel or central plant managers and operators because the computationally intensive software may not readily explain its control outputs. Operators routinely monitor certain plant parameters and make adjustments. For the optimization system to be well-adopted, operators and others who interact must be comfortable with the displayed parameters and their ability to understand current plant operation.

Purpose: To evaluate need for improving operator UI for future widespread adoption.

Metric: Ability and comfort of operators to assess optimizer outputs for operating the plant to meet all loads.

Data: Feedback and questions from DPW staff about the logic behind optimizer outputs, and actions taken.

Analytical Methodology: We interacted extensively with the site control technician, the BAS programmer, and the site technical resource manager who oversaw site operations. Most of our initial interactions were for site instrumentation, optimizer implementation, local control modifications, and training. We worked side-by-side during the commissioning phase and later troubleshooting visits. We met with the site technical resource manager as part of the project meetings every two weeks for the duration of the project. The results of these interactions and their impressions of the optimizer are described below.

Success Criteria: A skilled DPW energy manager can effectively use the interface and is comfortable with the optimizer outputs.

Results:

1. With frequent use, the site lead became familiar with the optimizer software and functionality compared to initial impressions. He was very comfortable putting the optimizer in control and letting it operate without supervision overnight and several days continuously.
2. The site lead liked the optimizer changing the chilled water and hot water supply setpoints continuously, within specified limits, because the current control system is set up to operate at fixed setpoints. This feature is not confusing and the users see the benefit of changing the load on a chiller proactively by changing setpoints, before switching them on or off.
3. The site personnel did not like the cycling of the equipment. The optimizer software was set up so that chillers, which are large equipment, did not switch frequently; however the pumps and fans were set up to give them flexibility in switching, within limits. Each of the optimizer screens lets users set minimum run times and rest times. However, once the minima are satisfied, the optimizer may switch from one piece of equipment to the next. Our recommendation to improve the solver is for the equipment switching to have a cost associated with it.
4. The optimizer software is complex and provides many parameters for each piece of equipment that the user can modify. This design provides flexibility for a plant manager who is familiar with the software; however, it can be overwhelming to learn all the different choices. The plant personnel also did not know why the optimizer would make a particular choice, when they would have intuitively made a different choice. Our recommendation is to improve the software by providing a concise quantitative reason that shows the comparison of energy cost between a previous setting and current setting.

7.0 COST ASSESSMENT

7.1 COST MODEL

Table 14: Cost Model

Cost Element	Data Tracked During the Demonstration	Estimated costs
Software License cost	Software license	$60,000 - $150,000
Software Installation costs	Estimate of labor required to install and configure software	$11,000
Training	Software Training to operators and technicians	$6,800
Hardware and installation costs	Extra instrumentation on site – cost of hardware and installation labor	$10,000
Cost of PC workstation	Cost of PC to host software	$2,500
Maintenance	Software maintenance updates and customizations	$15,200 (recurring)

The costs given in Table 14 reflect an estimate based on our experience on site and our vision for scaling the demonstration for commercial use. The estimate reflects considerations of software improvements to reduce site troubleshooting, changes in the software architecture, streamlined interface for optimizer with local controller or automation system, training of application engineers for installation.

Software license fees: This is the estimated cost of the software license for small- to large- sized complex chiller plants, ranging from 2 chillers and 1200 tons to 5 chillers and 6500 tons.

Software installation cost: This cost includes labor to install and configure the software for a specific site by connecting to the input and output points. It includes the labor for installing appropriate compliant software on the workstation such as Army Gold Master OS and connecting to the automation system.

Operator training: This cost includes the labor cost for an application engineer to train the operators and facility manager.

Hardware and installation costs: We assume that a well-instrumented central plant will have automation, but that not all required measurements and actuation for optimizer software will be available. Typically, flow or BTU meters and power meters for pumps and cooling towers may not be available. In addition, it is possible that an existing sensor, actuator, or controller may have the requisite measurement but is not connected to the automation or control system. Communication cards may be needed to bring in all the points needed for the optimizer. The installation costs include labor for installation of additional sensors, meter, communication cards, and the labor to map these measurement points to the automation system.

Cost of PC workstation: Cost of the computer to host the software on site. This estimate may change in the future as we address enhancements in the software architecture and automation system architecture, such as Cloud hosted services.

Maintenance: This estimate provides the labor cost of software upgrades and customizations for the site (after commissioning).

7.2 COST DRIVERS

Cost drivers that can impact the cost of implementing the technology include:

- Status of instrumentation and automation at the site: Several sensors and meters are needed to gather all data inputs for the optimizer. If a site is already well-instrumented and automated, the cost of upgrading to a supervisory level optimizer will be lower.
- Availability of skilled control technicians on site: The cost of implementation will decrease as more support and knowledge from the site becomes available on mapping and contextualizing control points.

7.3 COST ANALYSIS AND COMPARISON

The realistic cost estimates for the technology when implemented operationally are provided in the previous section (Table 14) and described further in the same section. Table 15 illustrates a cost analysis is for a central chiller plant. The full comparative life cycle analysis and inputs are in Appendix F.

Assumptions:

1. For the cost analysis, we assume a site with a large plant, but without the complexity of storage tank or free cooling that we encountered at the Ft. Bragg, NC site.
2. The site is well instrumented and the site has control technicians able to provide support for integrating the software at the plant.
3. The plant is maintained well with minimum downtime of plant equipment.
4. The site has modern communication and automation infrastructure that is maintained well.
5. The optimization software has been productized with a robust architecture and other improvements, and standardized support from application engineers and technicians trained in installation and commissioning.

Table 15: Summary cost analysis for a chiller plant

Inputs		Outputs	
Project Name:	CPOWER	**Results**	**15-yr**
Project Location:	North Carolina	Energy Consumption Cost Savings	$ 443,698.00
Analysis Type:	FEMP	PV of total savings	$ 215,698.00
Base Date:	April 1 2015	Net savings	$ 85,398.00
Beneficial Occupancy Date:	April 1 2015	Savings-to-investment ratio	1.66
Study Period (years):	15	Adjusted Internal Rate of Return	6.52%
Discount Rate:	3% (default	Payback period (simple and discour	7 years
Discounting Convention:	End-of-year	Electricity savings (kWh)	8,245,290.00
Electricity Savings Per Year (kWh)	549,761.29		
		Emissions reduction	
		CO2 reduction (kg)	9,761,923.21
Optimization Package Capital	$130,300	SO2 reduction (kg)	32,358.95
Annual Maintenance, Updates	$15,200	Nox reduction (kg)	14,606.06

8.0 IMPLEMENTATION ISSUES

We encountered three types of issues during the demonstration period:

1. **Technical and personnel resource issues:** The optimizer is complex software with advanced algorithms. In addition, it performs the actions of a simple controller, commanding equipment in real time. The transition from R&D to production prototype functions proved to be difficult, exacerbated by geographically spread out team members. The advanced nature of the underlying algorithms and the prototype state of the software means that experienced application engineers and software and algorithm developers need to work smoothly on site to install and commission. The site implementation also involves site personnel such as control programmers, BAS programmers, and operators and managers. The optimizer needs to be integrated well with the existing automation, which requires experience and skill in a succession of staff in the project sequence—algorithm developer, software architect and developer, application engineer, control engineer and technician, BAS programmer, plant supervisor, plant operator, and site technical manager. A number of the issues occurred because the prototype software hadn't yet been architected for easy deployment, with appropriate tools, and this succession of staff weren't always available. A productized version of the software will not face the same issues and the mobilization of staff would be automatic: software that is a current business offering has the backing of trained staff to support the releases which is their job priority; a prototype version is still in the proof of concept phase and staff has to be mobilized on a case-by-case basis.

2. **End User concerns:** The end users were not always comfortable with the software. We have documented some of the concerns in the performance objectives section. In summary, the main points of user concern are:

    a. Operating the plant with the optimizer is a very different from current practice. In current practice, the controller operates the chillers in different fixed modes; in each mode, the chiller supply and condenser return are set to a fixed temperature. The chillers are switched on or off based on load and flows in the system. Under the optimizer operation, when the site staff see supply temperatures, flows, and switch on/off of any equipment changing, they cannot understand the operation and motivation until they become more familiar with the software. To improve and speed up site staff familiarity with the software, one recommendation is to develop an improved human interface that can explain automated system changes and the benefits to the user, real-time.

    b. The users felt that the optimizer cycled the equipment too much compared to the current practice. This concern was handled to some extent by configuring user parameters in the optimizer software as well as making changes in the backend of the software; however, this concern will remain at new implementations with the current software. This concern will have to be addressed through software improvements that can assign a cost to cycling, training of personnel, and data-driven explanations on the software front end to the user.

3. **Site issues:**

a. Data quality: A lesson learned during this demonstration is that the data quality needs continuous monitoring. Although we had tested rigorously during commissioning, and at other visits, two of our assumptions were wrong, because our focus was on correctly operating the optimizer: (1) that the data continues to be good if the optimizer can operate reasonably within limits, and (2) the data recorded by the optimizer is the same as that used by the local original control. From an operational perspective, we find that despite bad data, the optimizer continued to function reasonably smoothly, however, it did not control optimally. We discovered that a duplicate set of points were created for the interface to the optimizer, which meant that the optimizer did not see all the same states and commanded points that the original control used unless they were written to the duplicate points by the original control.
b. Remote monitoring and troubleshooting: Because of DoD site restrictions, no remote access to the optimizer workstation was permissible. This severely restricted the speed and quality of troubleshooting that we could provide without being on site. As stated previously, the software is complex and in a prototype state; therefore, it is difficult to manage and monitor continuously without the experts, since it works real-time. The software should ideally be provided as a cloud service and, at a minimum, with expert remote support. Providing a process for secure remote access would have greatly increased our effectiveness and the value of the project.
c. Information assurance: A DoD-wide smooth information assurance process would have saved time and effort in this project. We started the information assurance pre-work in early 2014. We understood from the DPW Energy Manager that the CoN (Certificate of Networthiness) and later, the Interim Authority to Test (IATT) were the approval process for implementing a software on site. We created the network architecture and attempted gathering information on the process and information to be provided from the NEC as well as NETCOM through the DPW Energy Manager. We enlisted the help of our CERL colleagues as well, as we could not access the sites without a CAC card. This formal process was finally not required, since the software was implemented on a test basis, on a VLAN that is isolated from other site networks.

Procurement issues: All hardware required for implementation is standard commercial off-the-shelf [COTS] and not expected to be a concern in the future.

The effectiveness of the program is in the successful commissioning of a very complex supervisory level optimization software that continuously receives real time sensor data, computes optimal operating points and commands plant equipment in real time. The testing provided valuable lessons for improvement of the software, user experience and transitioning to DoD sites. Below are some recommendations for improvement of the specific technology process, as well as the project process.

(1) Re-architect the software to separate the supervisory and local control layers; the supervisory layer providing high-level operating schedules and setpoints which are then

managed and controlled by the local control layer. This will not only improve the software ease of implementation and performance, but eliminate safety concerns due to network communication issues, and also vastly improve the operational staff's comfort with the software.

(2) Phase in the commercial transition with less complex plants, e.g. chillers only without additional energy sources
(3) Develop standard implementation tools to quickly and reliably configure the software and connect it to the local control on site.
(4) Improve user experience by providing explanations of major actions by the optimizer
(5) Improve cycling frequency by considering equipment cycling as a cost in the optimization objective function.

(6) Data quality check process: Data quality checks were done at several points in the project, which led us to successful commissioning. However, for any control, software or data-intensive applications that require continuous data streams, the data quality check and cleaning should be inserted as an automated data anomaly detection software. This would alert the field engineers if the data coming into the application is correct.
(7) For complex software that needs advanced development skills, it is usually difficult to have the software developed that is simple for field engineers to understand or one that has no field engineer concerns. Securing remote access to the system would have provided off-site expert engineers access to monitor the in-operation performance and would have flagged issues early. Another approach may be to partner with advanced solution providers near the DoD site (e.g. Universities, national Labs or industry partners), who could be embedded on-site for closer monitoring of the system operation.

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10.0 APPENDICES

APPENDIX A: POINTS OF CONTACT

Point of Contact	Organization	Phone & E-mail	Role in Project
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APPENDIX B CHILLER PLANT DATA STRUCTURES AND FIELDS

The structures and fields depicted in the following figures represent the data collected for each piece of equipment. Only one example field list is shown for each type of equipment such as a chiller – all other chillers would have the same fields.

Name	Value
CPOWER	1x1 struct
Chiller1	1x1 struct
Chiller2	1x1 struct
Chiller3	1x1 struct
Chiller4	1x1 struct
CondenserPump1	1x1 struct
CondenserPump2	1x1 struct
CondenserPump3	1x1 struct
CondenserPump4	1x1 struct
CoolingTower1_Fan1	1x1 struct
CoolingTower1_Fan2	1x1 struct
CoolingTower2_Fan1	1x1 struct
CoolingTower2_Fan2	1x1 struct
CoolingTower3_Fan1	1x1 struct
CoolingTower3_Fan2	1x1 struct
CoolingTower3_Fan3	1x1 struct
CoolingTower3_Fan4	1x1 struct
CoolingTower4_Fan1	1x1 struct
CoolingTower4_Fan2	1x1 struct
EnergyStorage	1x1 struct
HEX	1x1 struct
HEX_Waterports	1x1 struct
PrimaryPump1	1x1 struct
PrimaryPump2	1x1 struct
PrimaryPump3	1x1 struct
PrimaryPump4	1x1 struct
PrimaryPump5	1x1 struct
SecondaryPump1	1x1 struct
SecondaryPump2	1x1 struct
SecondaryPump3	1x1 struct
SecondaryPump4	1x1 struct
WaterTank1	1x1 struct
WaterTankPipe	1x1 struct
Zone1_1	1x1 struct
Zone1_2	1x1 struct
weather_tariff_closedloop_meters_flow	1x1 struct

Figure 90: Data structures

```
CPOWER =

                                           timestamp: [227351x1 double]
                          CPOWER_IndoorAirTemperature: [227351x1 double]
                        CPOWER_IndoorAirTemperatureSP: [227351x1 double]
                             CPOWER_IndoorAirHumidity: [227351x1 double]
                           CPOWER_IndoorAirHumiditySP: [227351x1 double]
                         CPOWER_AverageAirTemperature: [227351x1 double]
                                CPOWER_EquipmentAlarm: [227351x1 double]
                                       CPOWER_IsOnOff: [227351x1 double]
                                   CPOWER_SwitchOnOff: [227351x1 double]
                                   CPOWER_TotalSupply: [227351x1 double]
                                    CPOWER_TotalPower: [227351x1 double]
                                    CPOWER_Efficiency: [227351x1 double]
                          CPOWER_IsRemoteControllable: [227351x1 double]
                                   CPOWER_IsInOptMode: [227351x1 double]
                  CPOWER_TemperatureSwitchToExchanger: [227351x1 double]
             CPOWER_Chilled_and_Hot_Water_Port_InletT: [227351x1 double]
            CPOWER_Chilled_and_Hot_Water_Port_OutletT: [227351x1 double]
      CPOWER_Chilled_and_Hot_Water_Port_ValvePosition: [227351x1 double]
      CPOWER_Chilled_and_Hot_Water_Port_ValveSwitchOn: [227351x1 double]
       CPOWER_Chilled_and_Hot_Water_Port_FlowDetected: [227351x1 double]
           CPOWER_Chilled_and_Hot_Water_Port_FlowRate: [227351x1 double]
                  CPOWER_PassiveFlowPipe_PressureDiff: [227351x1 double]
                 CPOWER_PassiveFlowPipe_ValvePosition: [227351x1 double]
                 CPOWER_PassiveFlowPipe_ValveSwitchOn: [227351x1 double]
                  CPOWER_PassiveFlowPipe_FlowDetected: [227351x1 double]
                      CPOWER_PassiveFlowPipe_FlowRate: [227351x1 double]
                        CPOWER_PowerMeter_Electricity: [227351x1 double]
                                CPOWER_PowerMeter_Oil: [227351x1 double]
```

Figure 91: Data fields in the CPOWER structure

```
Chiller1 =

                          timestamp: [227351x1 double]
                        IsCoolingOn: [227351x1 double]
                      EnableCooling: [227351x1 double]
        CompressorCurrentPercentage: [227351x1 double]
                     EquipmentAlarm: [227351x1 double]
                            IsOnOff: [227351x1 double]
                        SwitchOnOff: [227351x1 double]
                        TotalSupply: [227351x1 double]
                         TotalPower: [227351x1 double]
                         Efficiency: [227351x1 double]
               IsRemoteControllable: [227351x1 double]
                        IsInOptMode: [227351x1 double]
         Chilled_Water_Port_OutLetTSP: [227351x1 double]
            Chilled_Water_Port_InletT: [227351x1 double]
           Chilled_Water_Port_OutletT: [227351x1 double]
     Chilled_Water_Port_ValvePosition: [227351x1 double]
     Chilled_Water_Port_ValveSwitchOn: [227351x1 double]
          Chilled_Water_Port_FlowRate: [227351x1 double]
            Cooling_Water_Port_InletT: [227351x1 double]
           Cooling_Water_Port_OutletT: [227351x1 double]
     Cooling_Water_Port_ValvePosition: [227351x1 double]
     Cooling_Water_Port_ValveSwitchOn: [227351x1 double]
          Cooling_Water_Port_FlowRate: [227351x1 double]
               PowerMeter_Electricity: [227351x1 double]
    PowerMeter_Ch1_Compressor1A_Power: [227351x1 double]
    PowerMeter_Ch1_Compressor1B_Power: [227351x1 double]
```

Figure 92: Chiller data fields

```
CondenserPump1 =

                  timestamp: [227351x1 double]
          FrequencySetPoint: [227351x1 double]
          FrequencyFeedBack: [227351x1 double]
             EquipmentAlarm: [227351x1 double]
                    IsOnOff: [227351x1 double]
                SwitchOnOff: [227351x1 double]
                TotalSupply: [227351x1 double]
                 TotalPower: [227351x1 double]
                 Efficiency: [227351x1 double]
       IsRemoteControllable: [227351x1 double]
                IsInOptMode: [227351x1 double]
     PowerMeter_Electricity: [227351x1 double]
        WaterPort_OutLetFSP: [227351x1 double]
    WaterPort_ValvePosition: [227351x1 double]
    WaterPort_ValveSwitchOn: [227351x1 double]
         WaterPort_FlowRate: [227351x1 double]
```

```
CoolingTower3_Fan2 =

                           timestamp: [227351x1 double]
                FanFrequencyFeedBack: [227351x1 double]
                FanFrequencySetpoint: [227351x1 double]
                      EquipmentAlarm: [227351x1 double]
                             IsOnOff: [227351x1 double]
                         SwitchOnOff: [227351x1 double]
                         TotalSupply: [227351x1 double]
                          TotalPower: [227351x1 double]
                          Efficiency: [227351x1 double]
                IsRemoteControllable: [227351x1 double]
                         IsInOptMode: [227351x1 double]
        ChilledWaterPort_OutLetTSP: [227351x1 double]
           ChilledWaterPort_InletT: [227351x1 double]
          ChilledWaterPort_OutletT: [227351x1 double]
    ChilledWaterPort_ValvePosition: [227351x1 double]
    ChilledWaterPort_ValveSwitchOn: [227351x1 double]
         ChilledWaterPort_FlowRate: [227351x1 double]
            PowerMeter_Electricity: [227351x1 double]
```

```
EnergyStorage =

                          timestamp: [227351x1 double]
                 AverageTemperature: [227351x1 double]
                     EquipmentAlarm: [227351x1 double]
                            IsOnOff: [227351x1 double]
                        SwitchOnOff: [227351x1 double]
                        TotalSupply: [227351x1 double]
                         TotalPower: [227351x1 double]
                         Efficiency: [227351x1 double]
               IsRemoteControllable: [227351x1 double]
                        IsInOptMode: [227351x1 double]
   EnergyStoragePipe_CoolingPositionT: [227351x1 double]
   EnergyStoragePipe_HeatingPositionT: [227351x1 double]
             EnergyStoragePipe_InletT: [227351x1 double]
            EnergyStoragePipe_OutletT: [227351x1 double]
      EnergyStoragePipe_ValvePosition: [227351x1 double]
      EnergyStoragePipe_ValveSwitchOn: [227351x1 double]
       EnergyStoragePipe_FlowDetected: [227351x1 double]
           EnergyStoragePipe_FlowRate: [227351x1 double]
```

```
HEX =

                  timestamp: [227351x1 double]
                IsCoolingOn: [227351x1 double]
                IsHeatingOn: [227351x1 double]
              EnableCooling: [227351x1 double]
              EnableHeating: [227351x1 double]
   CompressorCurrentPercentage: [227351x1 double]
             EquipmentAlarm: [227351x1 double]
                    IsOnOff: [227351x1 double]
                SwitchOnOff: [227351x1 double]
                TotalSupply: [227351x1 double]
                 TotalPower: [227351x1 double]
                 Efficiency: [227351x1 double]
       IsRemoteControllable: [227351x1 double]
                IsInOptMode: [227351x1 double]
     PowerMeter_Electricity: [227351x1 double]
```

```
HEX_Waterports =

                              timestamp: [227351x1 double]
             ChilledWaterPort_OutLetTSP: [227351x1 double]
    ChilledWaterPort_MinBodyTemperature: [227351x1 double]
    ChilledWaterPort_MaxBodyTemperature: [227351x1 double]
    ChilledWaterPort_AvgBodyTemperature: [227351x1 double]
                ChilledWaterPort_InletT: [227351x1 double]
               ChilledWaterPort_OutletT: [227351x1 double]
         ChilledWaterPort_ValvePosition: [227351x1 double]
         ChilledWaterPort_ValveSwitchOn: [227351x1 double]
          ChilledWaterPort_FlowDetected: [227351x1 double]
              ChilledWaterPort_FlowRate: [227351x1 double]
                CoolingWaterPort_InletT: [227351x1 double]
               CoolingWaterPort_OutletT: [227351x1 double]
         CoolingWaterPort_ValvePosition: [227351x1 double]
         CoolingWaterPort_ValveSwitchOn: [227351x1 double]
          CoolingWaterPort_FlowDetected: [227351x1 double]
              CoolingWaterPort_FlowRate: [227351x1 double]

PrimaryPump2 =

                  timestamp: [227351x1 double]
          FrequencySetPoint: [227351x1 double]
          FrequencyFeedBack: [227351x1 double]
             EquipmentAlarm: [227351x1 double]
                    IsOnOff: [227351x1 double]
                SwitchOnOff: [227351x1 double]
                TotalSupply: [227351x1 double]
                 TotalPower: [227351x1 double]
                 Efficiency: [227351x1 double]
       IsRemoteControllable: [227351x1 double]
                IsInOptMode: [227351x1 double]
     PowerMeter_Electricity: [227351x1 double]
        WaterPort_OutLetFSP: [227351x1 double]
    WaterPort_ValvePosition: [227351x1 double]
    WaterPort_ValveSwitchOn: [227351x1 double]
     WaterPort_FlowDetected: [227351x1 double]
         WaterPort_FlowRate: [227351x1 double]
```

```
WaterTank1 =

                  timestamp: [227351x1 double]
             DischargeState: [227351x1 double]
                ChargeState: [227351x1 double]
          ChargingPumpState: [227351x1 double]
       DischargingPumpState: [227351x1 double]
           ChargingFlowRate: [227351x1 double]
        DischargingFlowRate: [227351x1 double]
             EquipmentAlarm: [227351x1 double]
                    IsOnOff: [227351x1 double]
                SwitchOnOff: [227351x1 double]
                TotalSupply: [227351x1 double]
                 TotalPower: [227351x1 double]
                 Efficiency: [227351x1 double]
       IsRemoteControllable: [227351x1 double]
                IsInOptMode: [227351x1 double]
     PowerMeter_Electricity: [227351x1 double]
```

```
WaterTankPipe =

              timestamp: [227351x1 double]
      HighValvePosition: [227351x1 double]
      HighValveSwitchOn: [227351x1 double]
       LowValvePosition: [227351x1 double]
       LowValveSwitchOn: [227351x1 double]
          HighPositionT: [227351x1 double]
           LowPositionT: [227351x1 double]
              OutLetTSP: [227351x1 double]
     MinBodyTemperature: [227351x1 double]
     MaxBodyTemperature: [227351x1 double]
     AvgBodyTemperature: [227351x1 double]
                 InletT: [227351x1 double]
                OutletT: [227351x1 double]
          ValvePosition: [227351x1 double]
          ValveSwitchOn: [227351x1 double]
           FlowDetected: [227351x1 double]
               FlowRate: [227351x1 double]
                      a: [227351x1 double]
                      b: [227351x1 double]
                      c: [227351x1 double]
                      d: [227351x1 double]
                      e: [227351x1 double]
                      f: [227351x1 double]
                      g: [227351x1 double]
                      h: [227351x1 double]
                      i: [227351x1 double]
                      j: [227351x1 double]
                      k: [227351x1 double]
```

```
Zone1_1 =

                   timestamp: [227351x1 double]
      IndoorAirTemperature: [227351x1 double]
    IndoorAirTemperatureSP: [227351x1 double]
         IndoorAirHumidity: [227351x1 double]
       IndoorAirHumiditySP: [227351x1 double]
             WaterPressure: [227351x1 double]
           WaterPressureSP: [227351x1 double]
            EquipmentAlarm: [227351x1 double]
                   IsOnOff: [227351x1 double]
               SwitchOnOff: [227351x1 double]
               TotalSupply: [227351x1 double]
                TotalPower: [227351x1 double]
                Efficiency: [227351x1 double]
      IsRemoteControllable: [227351x1 double]
               IsInOptMode: [227351x1 double]
         WaterPressureSPFB: [227351x1 double]
               WaterFlowSP: [227351x1 double]
    C6133_IndoorAirTempAvg: [227351x1 double]
    C6426_IndoorAirTempAvg: [227351x1 double]
    C7635_IndoorAirTempAvg: [227351x1 double]
    C7639_IndoorAirTempAvg: [227351x1 double]
    C2219_IndoorAirTempAvg: [227351x1 double]

Zone1_2 =

                               timestamp: [227351x1 double]
          ChilledandHotWaterPort_InletT: [227351x1 double]
         ChilledandHotWaterPort_OutletT: [227351x1 double]
    ChilledandHotWaterPort_ValvePosition: [227351x1 double]
    ChilledandHotWaterPort_ValveSwitchOn: [227351x1 double]
     ChilledandHotWaterPort_FlowDetected: [227351x1 double]
         ChilledandHotWaterPort_FlowRate: [227351x1 double]
            PassiveFlowPipe_PressureDiff: [227351x1 double]
           PassiveFlowPipe_ValvePosition: [227351x1 double]
           PassiveFlowPipe_ValveSwitchOn: [227351x1 double]
            PassiveFlowPipe_FlowDetected: [227351x1 double]
                PassiveFlowPipe_FlowRate: [227351x1 double]
              PowerMeter_Electricity: [227351x1 double]
                      PowerMeter_Oil: [227351x1 double]
```

APPENDIX C HEATING PLANT DATA STRUCTURES

Name	Value
Boiler1	*1x1 struct*
Boiler2	*1x1 struct*
Boiler3	*1x1 struct*
Building	*1x1 struct*
PrimaryPump1	*1x1 struct*
PrimaryPump2	*1x1 struct*
PrimaryPump3	*1x1 struct*
SecondaryPump1	*1x1 struct*
SecondaryPump2	*1x1 struct*
SecondaryPump3	*1x1 struct*
SecondaryPump4	*1x1 struct*
SecondaryPump5	*1x1 struct*
SecondaryPump6	*1x1 struct*
SecondaryPump7	*1x1 struct*
SecondaryPump8	*1x1 struct*
Zone1	*1x1 struct*
Zone2	*1x1 struct*
Zone3	*1x1 struct*
Zone4	*1x1 struct*

APPENDIX D: MODEL OF COOLING AND HEATING PLANT

Sergey Vichik, Jason Kong, Saman Fahandezhsaadi

Wed Apr 15 08:06:17 2015

Prepared for :	Honeywell Automation and Control Solutions

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1 Introduction

This document describes the simulation prepared for CPOWER Project (ESTCP) of a cooling and a heating plants. The goal of CPOWER project is to demonstrate campus level energy savings by applying an optimal controller of cooling and heating plants.

The simulation is built using MATLAB® and Simulink®. The simulation is required to reliably represent thermodynamical properties of the modeled system and its input and output interface to support development and testing of the optimal controller.

The documents describes the model of cooling plant in Section 2 and heating plant in Section 3. We describe the governing equations, model architecture, model identification procedure and identification results.

2 Cooling Plant

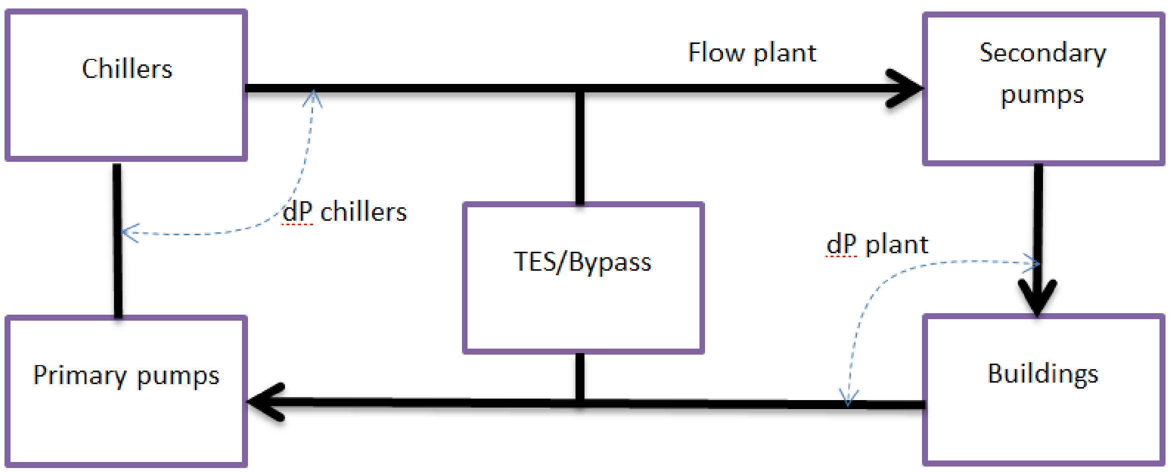


Figure 1: Cooling Plant Construction

The cooling plant model captures the behaviour of campus cooling plant and buildings that consume the cooling energy. The model architecture that is shown in Fig. 1 contains the following main components:

1. Chillers
2. Heat Exchanger
3. Cooling towers
4. Buildings
5. Pumps

6. Thermal energy storage (TES)) tank
7. Pipe flow model
8. Energy control loops
9. Flow control loops

The next sections describe each component in details.

2.1 Flow modeling

The static solution for flow in system of pipes might be non trivial to find in a simulation, since it requires to solve a non linear system of equations in every iteration. Therefore, in this simulation we chose to perform dynamical simulation of flow. When the dynamics of flow is considered, on each time step the flow is updated according to a dynamical model that presented in Section 2.1.1. The static solution is achieved after a transient phase. Using this approach, almost arbitrary complicated flow network can be solved and the dynamical properties of a real system are naturally included in the model.

2.1.1 Flow equation

The flow model in pipes is based on the following dynamic equation:

$$Kv^2 + \dot{v} \cdot I_f = H_{pump} \tag{1}$$

Where K is pipe friction coefficient, v is the flow, I_f is the inertia of the fluid and H_{pump} is the differential pressure generated by the pumps.

In steady state, the equation is reduced to

$$Kv^2 = H_{pump}. \tag{2}$$

Therefore, using static flow and pressure measurements, the coefficient K is immediately available. Using time series data, the inertia can be estimated.

2.1.2 Flow Loops

The flow in the system is modeled as two loops: the primary loop and the secondary loop. The flow in each loop is described by:

$$\dot{v} = \frac{H_{pump} - Kv^2}{I_f} \tag{3}$$

As can be seen in top part of Figure 2, the primary loop is driven by difference in pressure drop between the primary pumps and chillers, the secondary flow is driven by the pressure drop difference between the buildings and the secondary pumps.

The two flows are not necessary the same. Any mismatch in the flows is redirected through a bypass system. The bypass flow goes either through the TES tank or through a bypass connection. The selection between the two is done according to a global variable "TankValvePos".

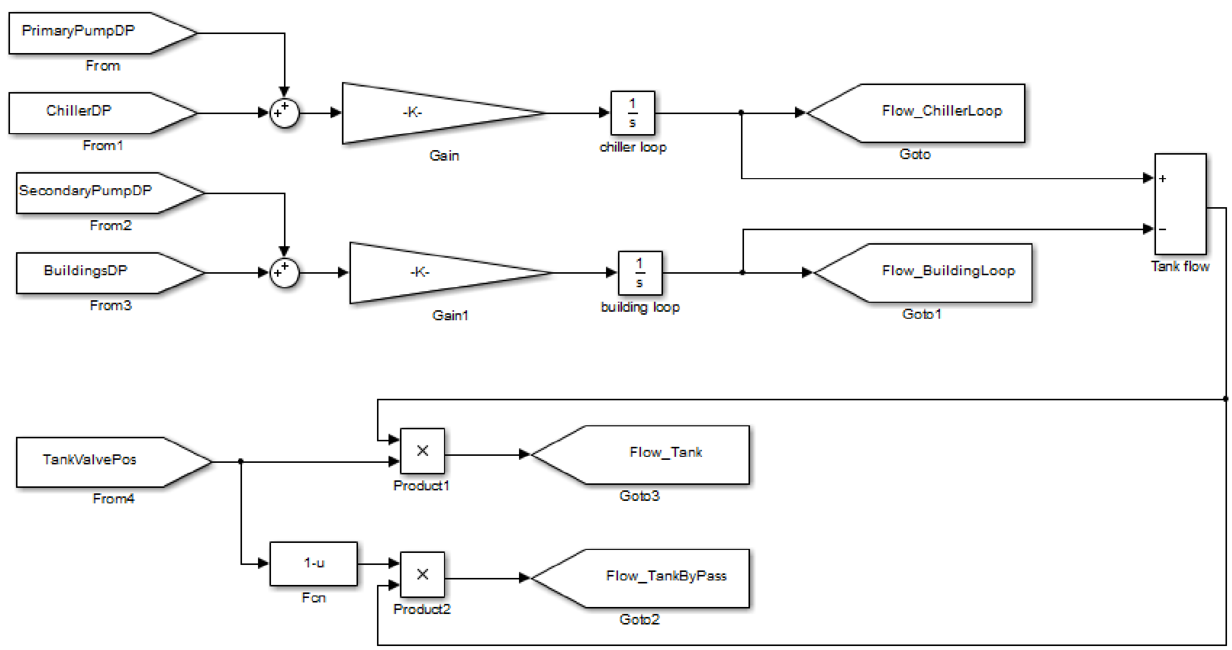


Figure 2: .

2.1.3 Flow distribution between parallel systems.

Multiple systems, such as chillers, that are connected in parallel to the same headers require special treatment to find the flow through it. It is not efficient to dynamically model the flow through it, because this dynamics is faster than the rest of the system and dynamical modelling will require to significantly reduce time step. Therefore, for those cases a static solution is computed for each time step.

When given the total flow through all the sub systems, we need to find the pressure drop and the flow through each of the sub systems. The pressure drop is the same for all sub systems, and the total flow v is the sum of subflows v_i.

$$v_i^2 K_i = \Delta P \tag{4}$$

$$\sum_i v_i = v \tag{5}$$

where v_i is the flow via subsystem i, ΔP is the pressure drop, K_i is the i-th pipe friction coefficient.

$$v_i = \sqrt{\frac{\Delta P}{K_i}} \tag{6}$$

$$v = \sum_i v_i = \sum_i \sqrt{\frac{\Delta P}{K_i}} \tag{7}$$

$$v = \sqrt{\Delta P} \sum_i \frac{1}{\sqrt{K_i}} \tag{8}$$

$$\Delta P = \frac{v^2}{\left(\sum_i \frac{1}{\sqrt{K_i}} \right)^2} \tag{9}$$

The equation (9) yields the total pressure drop as function of the total flow and individual friction coefficients. The flow for each sub system is found using (6). Figure 3 shows Simulink implementation of the solver to get chiller plant flow.

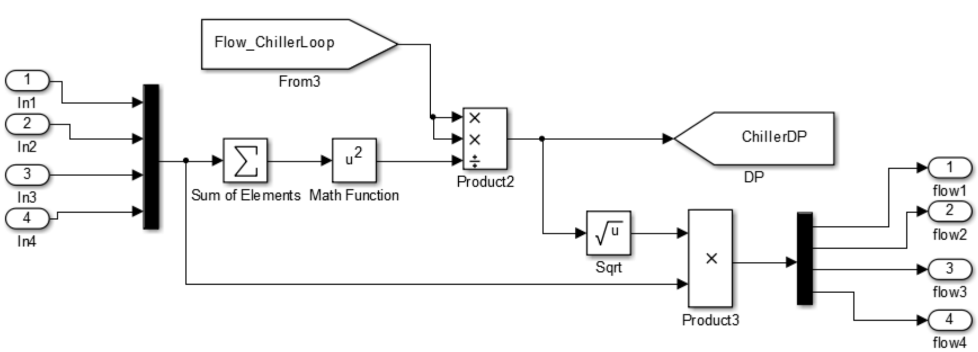


Figure 3: Parallel flow solver for the chiller plant.

2.1.4 Flow Control

The flow is controlled by PID controllers that imitate the real low level control of the system. The controller architecture is shown in Figure 4. As can be seen, the secondary loop is set to maintain pressure drop of 34.9 PSI in buildings. The primary loop controlling maintains a goal for flow through chillers - "ChillerReqFlow". The require flow is determined by the number of operating chillers and their flow requirements. All the pumps are assumed to be on and the command is common to all pumps.

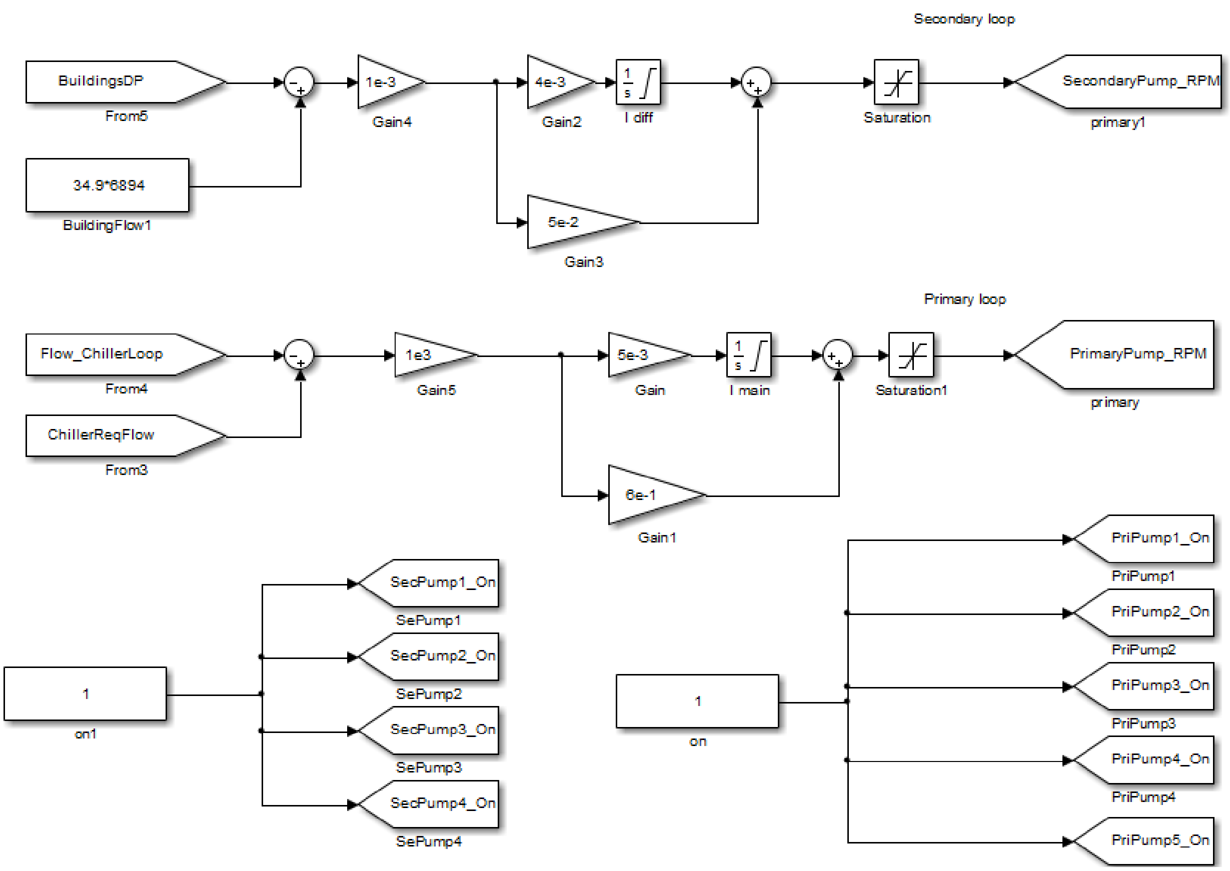


Figure 4: .

2.2 Chiller plant model

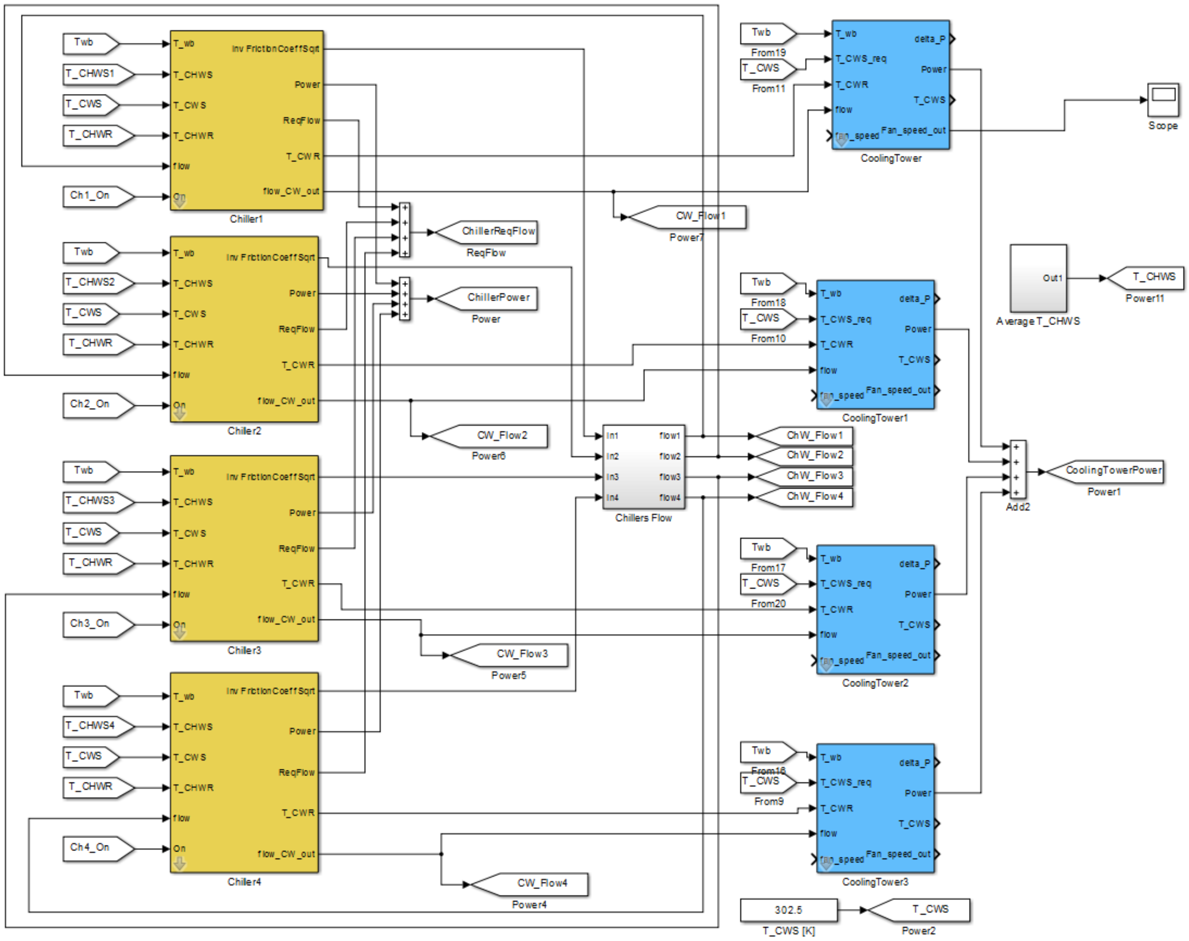


Figure 5: Chiller plant.

Figure 5 shows the organization of chiller plant model. The model includes 4 chillers and 4 cooling towers. Each chiller reports its power consumption, required flow and the return temperature of condenser. The required flow is an input to flow control PID loop, that adjusts the flow rate to number of operating chillers.

2.2.1 Single chiller model

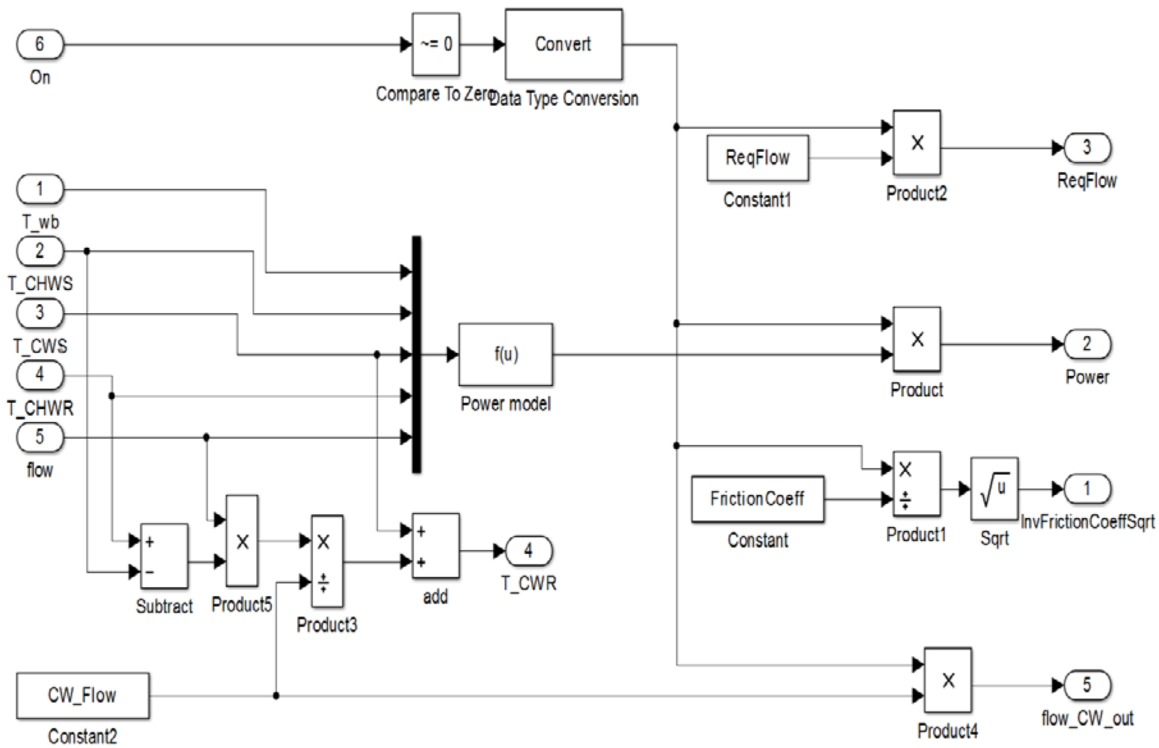


Figure 6: Chiller model

The chiller model is show in in Figure 6. The model treats two aspects of chiller operation: thermodynamic aspect (detailed in section 2.2.2) and flow aspect. The flow is computed outside of the chiller model, as described in section 2.1.3. The chiller model outputs inverse of friction coefficient and its flow is computed in a centralized manner for the whole chiller plant. The power consumption model and the return condenser temperature are described in the following section.

2.2.2 Chiller performance

For this project, we will use a second order polynomial model for the power. Let us first define a few terms that will be used for the system identification:

Table 1: Chiller model ID parameters

	Name	Description
	T_{chws}	chilled water supply temperature
	T_{cws}	condenser water supply temperature
	Q_{nom}	normalized heat by ref. chiller heat capacity

Using the data for the chiller, we fit the power using the following equation

$$P = a_0 + a_1 Q_{nom} + a_2 Q_{nom}^2 + a_3 (T_{chws} - T_{cws}) +$$

$$a_4 (T_{chws} - T_{cws})^2 + a_5 Q_{nom} (T_{chws} - T_{cws}) \quad (10)$$

It is possible to find the coefficients of Equation 10 using a least squares approach and most of the data points. The data points not used for fitting was used to validate the model. Three out of four chillers in this project have two condensers. For the chillers with two condensers, the power of the two condensers were lumped together for the fit and model simplicity.

2.2.3 Chiller Fitting

Using the model described in § 2.2, we performed a least squares fit on the available data for the chillers. After fitting, we found the following coefficients for the chiller model:

Table 2: Chiller identification coefficients

Coefficients	**Chiller no.1** $*10^5$	**Chiller no.2** $*10^6$	**Chiller no.3** $*10^5$	**Chiller no.4** $*10^6$
a_0	2.4747	1.6088	6.1856	−7.1944
a_1	9.9409	−2.8059	6.8927	1.2098
a_2	−2.5854	1.9305	4.3155	0.5184
a_3	0.4629	0.0870	0.6812	−0.7273
a_4	0.0208	0.0011	0.0246	−0.0180
a_5	0.2381	−0.1472	0.3049	0.0416

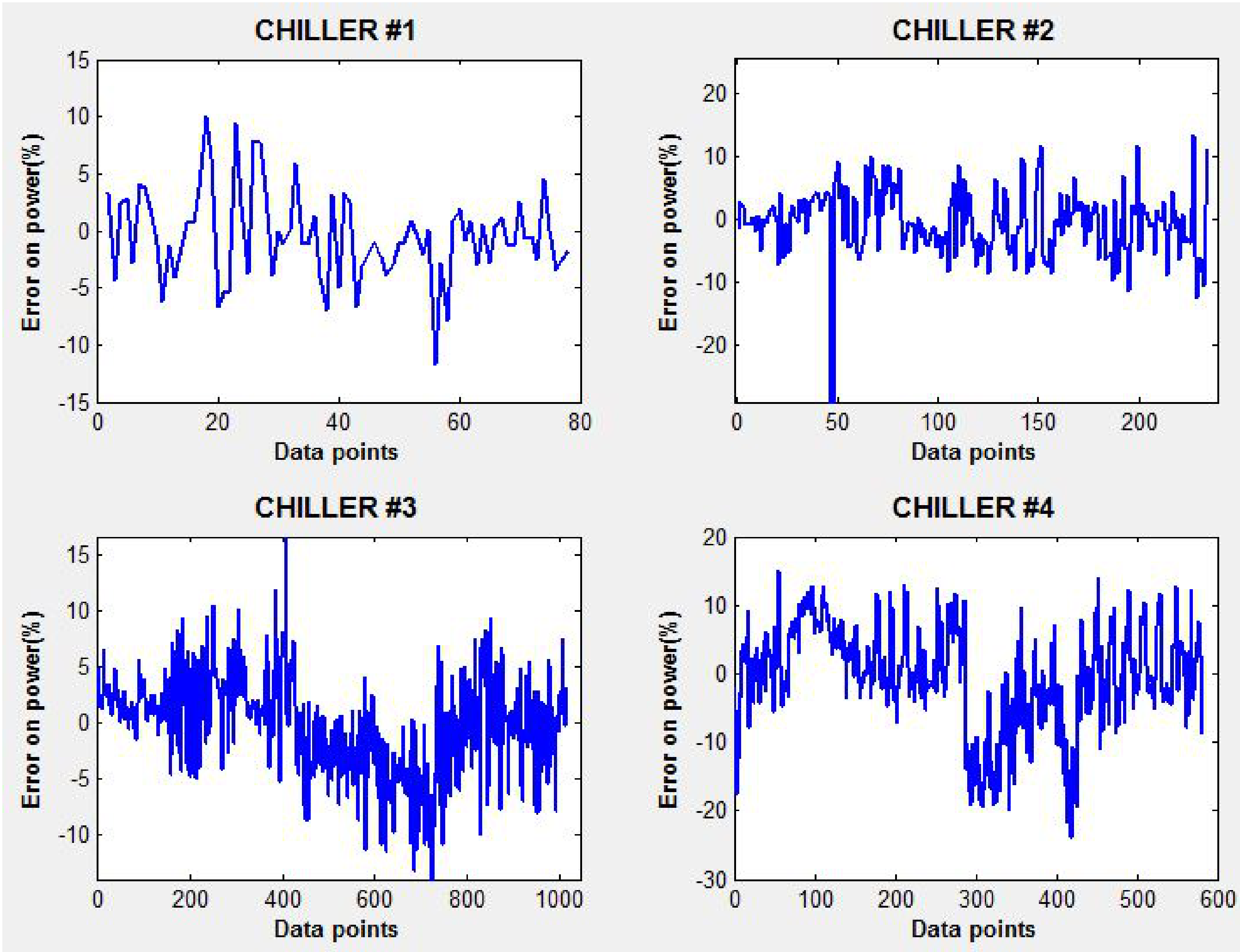


Figure 7: Chillers Validation

2.3 Heat Exchanger

Heat exchanger model is based on [1]. In the case of free cooling, chiller 4 works as a heat exchanger in the system. Model identification for heat exchanger is based on the chilled water supply, chilled water return, condenser water supply, and condenser water return as listed in the following table:

Table 3: Heat Exchanger model ID parameters

Name	Description
T_{chws}	chilled water supply
T_{chwr}	chilled water return
T_{cws}	condenser water supply
T_{cwr}	condenser water return
V_{chw}	volume flow rate, evaporator side
V_{cw}	volume flow rate, condenser side(fixed)

Defining two new terms (heat capacity flow ratio and static heat exchanger effectiveness) with the following equations help us to model the heat exchanger: [1]

$$R = \frac{V_{cw}}{V_{chw}} \tag{11}$$

$$P = \frac{T_{cwr} - T_{cws}}{T_{chwr} - T_{cws}} \tag{12}$$

Using the data for the heat exchanger, we fit the outputs using the following equations:

$$\begin{pmatrix} T_{chws} \\ T_{cwr} \end{pmatrix} = \begin{pmatrix} 1-RP & RP \\ P & 1-P \end{pmatrix} \begin{pmatrix} T_{chwr} \\ T_{cws} \end{pmatrix} \tag{13}$$

When the P for identification is:

$$P = a_0 + a_1 R \tag{14}$$

2.3.1 Heat Exchanger Fitting

Using the model described in § 2.3, we can perform a linear least square fit on the data P and R for the heat exchanger. After fitting, we found the following coefficients for the heat exchanger model:

Table 4: Heat exchanger model ID coefficients

Coefficients	**Heat Exchanger**
a_0	0.3825
a_1	-0.0554

The plots in Figure 8 show the validation of the model using the data, which are not used for identification.

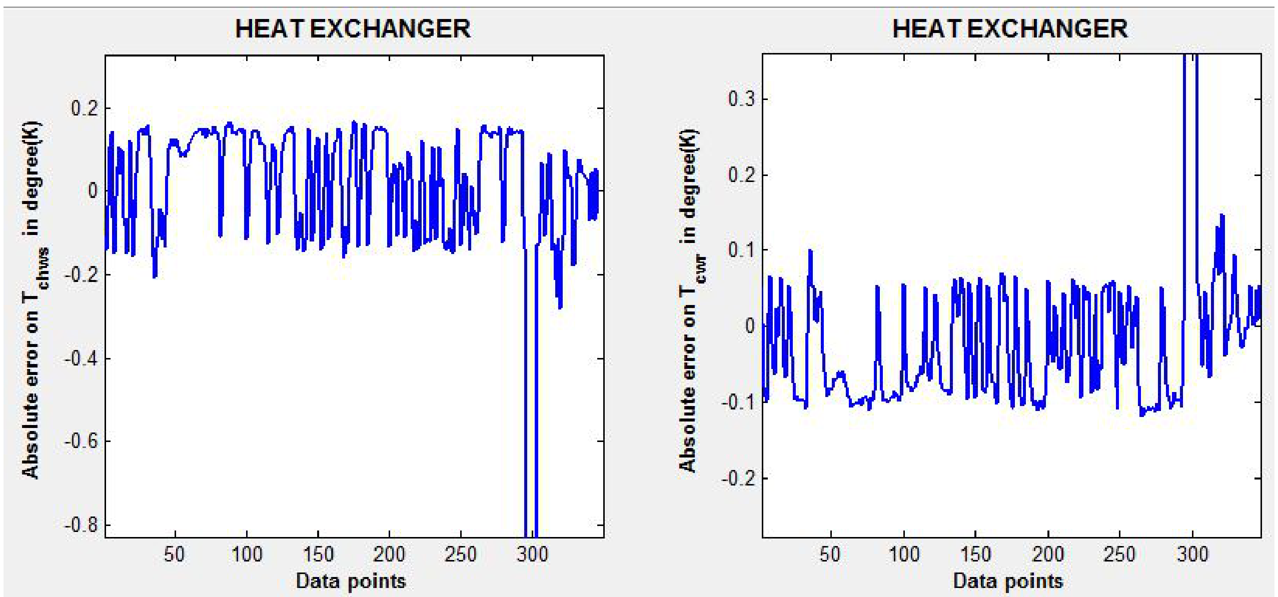


Figure 8: Heat Exchanger Validation

2.4 Pump model

Pump model is based on [2]. As shown in Fig. 9, input to the model is flow and pump speed. Output is is differential pressure and consumed power.

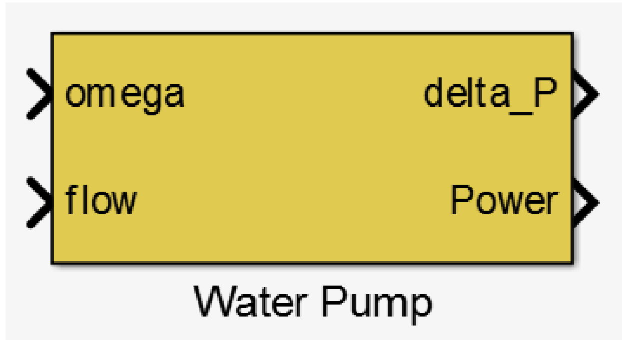


Figure 9: Pump model

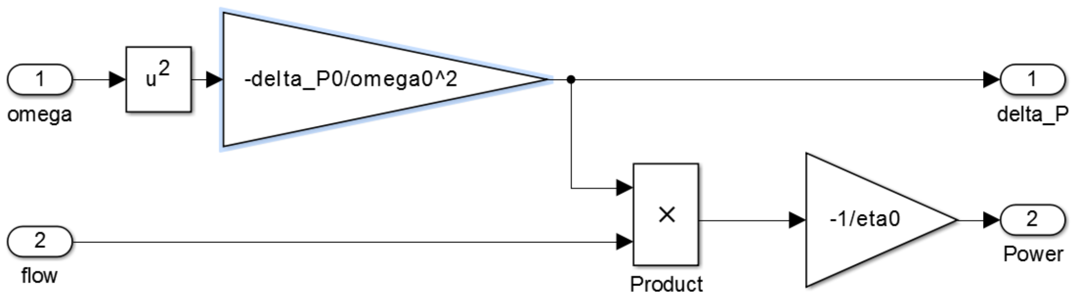


Figure 10: Pump model

Computation of delta pressure and power is shown in Fig. 10 and summarized here

$$\frac{\Delta p}{\Delta p_0} = \left(\frac{\omega_{pump}}{\omega_{pump,0}} \right)^2 \tag{15}$$

$$P_{pump} = \frac{\Delta p q}{\eta} \tag{16}$$

where η is the efficiency of a pump and is computed from known nominal power P_0, nominal delta pressure Δp_0 and nominal flow q_0 as

$$\eta = \frac{P_0}{q_0 \Delta p_0}. \tag{17}$$

2.5 Cooling Tower model

Four cooling towers(CT) work with the chillers in the condenser side. Each cooling tower has two fans, except CT3 which works with four fans. The model for cooling tower is based on the average fan speed ratio, wet bulb temperature, and condenser water return temperature(output of cooling tower) as inputs to the system and approach temperature as an output of the model. Table 5 shows the terms that are used for the modeling of the cooling tower.

Table 5: Cooling tower model parameters

Name	Description
T_{wb}	wet bulb temperature
T_{cwr}	condenser water return
T_{cws}	condenser water supply
R	average fan speed ratio
T_{app}	$T_{cws} - T_{wb}$
ΔT	$T_{cwr} - T_{wb}$

The approach temperature is modeled as following:

$$T_{app} = p_1 \Delta T + p_2 \Delta T R + p_3 \Delta T R^2 + p_4 \Delta T R^3 + p_5 \Delta T T_{wb} R^3 \quad (18)$$

where the coefficients $p_1, \ldots, p_6$ are identified using time series and other symbols are defined in Table 5.

Cooling tower fan power is computed using a cubic model:

$$P_{fan} = R^3 P_{nom} \quad (19)$$

where P_{nom} is the nominal fan power.

2.5.1 Cooling Tower Fitting

Using the model described in § 2.5, we performed a least square fit on the available data to find $T_a pp$ as an output of the model. After fitting, we found the following coefficients for the cooling towers model ID:

Table 6: Cooling Tower model ID coefficients

Coefficients	CT no.1	CT no.2	CT no.3	CT no.4
p_1	0.974983	0.958882	0.979979	0.969947
p_2	0.424135	0.28624	-0.023763	0.521003
p_3	-0.0438994	-0.0276032	-0.0086269	-0.0570555
p_4	-2.56898	-1.96074	-0.716373	-2.57844
p_5	14.5716	9.26565	2.93721	18.3859

Figure 11 shows the validation of model based on the output of the model, which is T_{app}. Time series data for validation are not used for the case of identification.

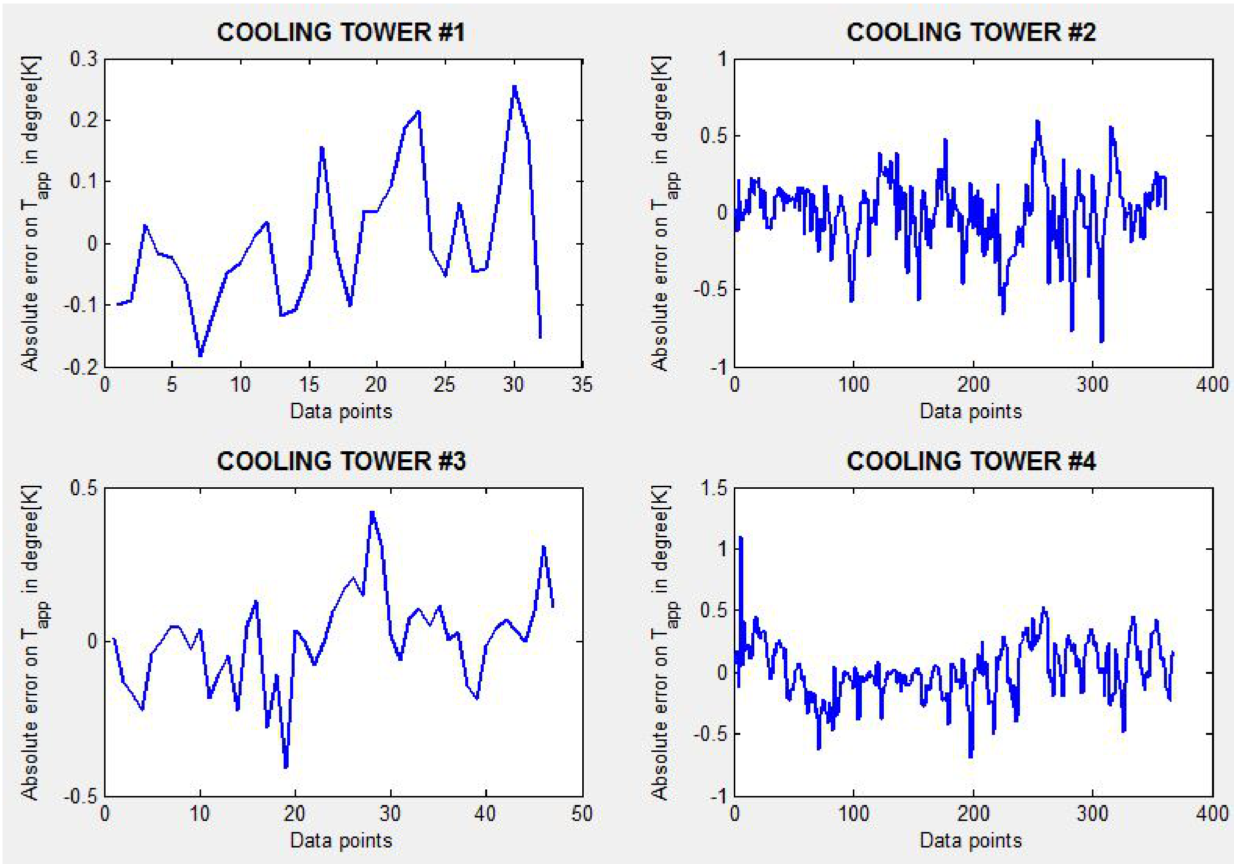


Figure 11: Cooling Tower Validation

Since all available data for the speed ratio R are in the range of 50% to 100%, the model has been adjusted such that can also handle the model of the system when the fan speed is zero.The graph in Figure 12 shows this relationship between fan speed ratio and the T_{app}, which has been considered in the modeling of cooling towers. The plot is drawn for constant parameters $T_d = 3.45$ and $T_{wb} = 294K$.

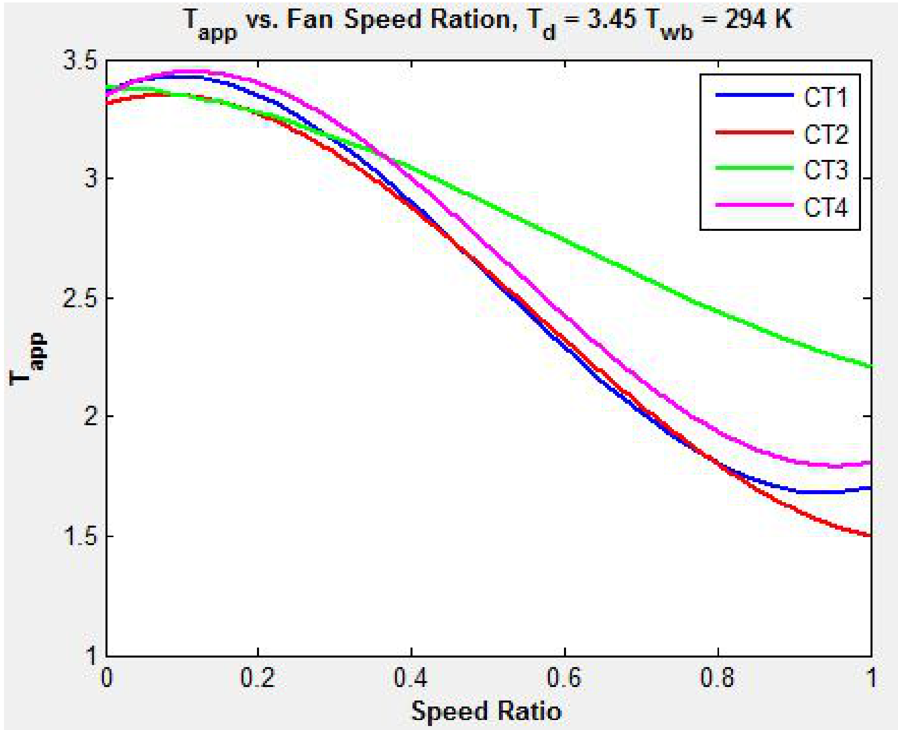


Figure 12: Model adjustment for zero fan speed

2.6 Buildings model(cooling plant)

The buildings are modeled as a lumped capacity thermal model. The model is driven by the weather conditions, thermal load that is function of time of day and day of week, sun irradiation, and a cooling control that tracks set point and is limited by the cooling energy supplied by the plant. Time series data from representative zones will be used to identify the model parameters.

The model is detailed in the following equations.

$$T_z(k+1) - T_z(k) = p_1(T_a - T_z(k)) + p_2(T_a - T_z(k-1)) + p_3(T_a - T_z(k-2)) + p_4 I_{sun}$$

$$+ L(TOD, DOW) + p_5 Q \tag{20}$$

$$Q = \text{Saturate}\left(\left\lfloor K_p(T_s(TOD, DOW) - T_z(k)) - K_I \int (T_s(TOD, DOW) - T_z(k)) \right\rfloor, Q_{plant}^{\max}\right)$$
(21)

$$Q_{plant}^{\max} = q_{\text{secondary}}(T_z(k) - T_{chws}) \tag{22}$$

$$L(TOD, DOW) = \begin{cases} c_1 + c_2 TOD + c_3 TOD^2 + c_4 TOD^3 + c_5 TOD^4 & @DOW \text{isworkday} \\ d_1 + d_2 TOD + d_3 TOD^2 + d_4 TOD^3 + d_5 TOD^4 & @DOW \text{isweekend} \end{cases} \tag{23}$$

Where Q is the buildings load in watts, T_a is the ambient temperature, I_{sun} is sun irradiation, TOD is the time of day, DOW is the day of week, L is the thermal load, T_z is the lumped zone temperature, T_s is the set point temperature, $Q_{plant}^{\max}$ is the maximum cooling power available, and $q_{\text{secondary}}$ is the flow in the buildings loop. The variable $Month$ is reserved for future use, if enough data is available to differentiate between seasons.

The equation (27) describe third order auto-regressive thermal model. The PI controller (21) tracks the set point T_s and is saturated by the available cooling power $Q_{plant}^{\max}$. The available cooling power is approximated using the flow $q_{\text{secondary}}$ and the temperature drop between zone temperature and the supply water temperature T_{chws} as in (22). The set point temperature T_s and the thermal load L are functions of time of day and day of week.

2.6.1 Model identification of buildings load

The identification is carried in stages:

1. The profile of T_s as function of TOD and day of week is approximated using historical data of the zone temperatures.

2. System identification is performed using (27), where the expression for L is substituted and c and d parameters are identified together with p parameters. For the identification, the value of Q is computed from the difference between supply and return chilled water temperatures.

3. The coefficients of PI controller are tuned to achieve reasonable performance, compatible to time series data.

2.6.2 Building model(cooling plant) Fitting

Using the model described in § 2.6, we can perform a least square fit which is dependent to the available data T_z, T_a, $I_s un$, TOD, DOW, and Q. After fitting, we found the following coefficients for the model of buildings:

Table 7: Cooling Tower model ID coefficients

Coefficients		DOW(work day)		DOW(weekend)	
p_1	0.0665991	c_1	0.0141195	d_1	0.013092
p_2	-0.0786302	c_2	-0.371464	d_2	-0.26912
p_3	0.014104	c_3	2.26781	d_3	1.65634
p_4	$9.336948*10^{-6}$	c_4	-3.76646	d_4	-2.7765
p_5	$-4.71464*10^{-9}$	c_5	1.86097	d_5	1.3861

Figure 13 shows the validation of building model when the ΔT_z is the output of the model.

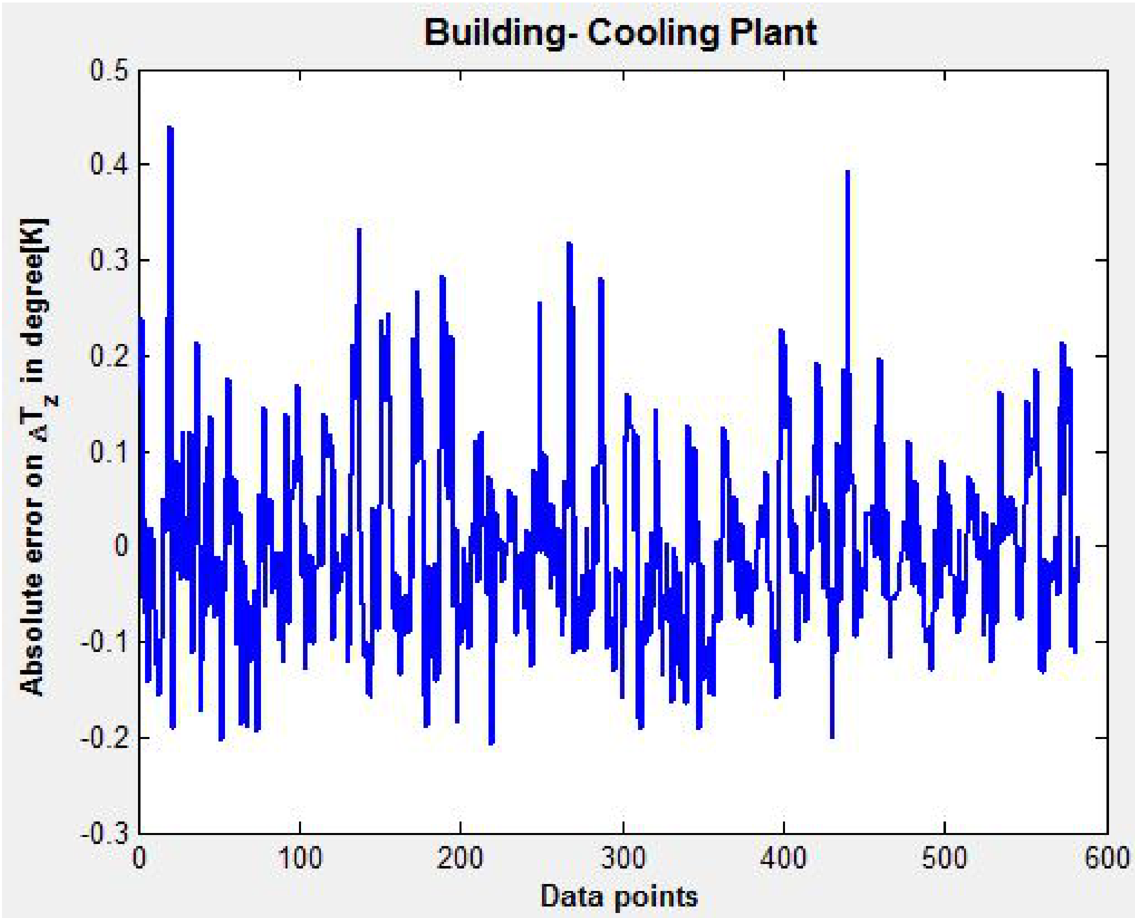


Figure 13: Building model ID Validation

3 Heating Plant

The heating plant architecutre is depicted in Fig. 14. It includes buildings, boilers, primary and secondary pumps. There are three boilers, and four zones. The following sections discuss how the flow, boilers and zones are modeled. The pump model is the same as used in chilling plant an described in Section 2.4.

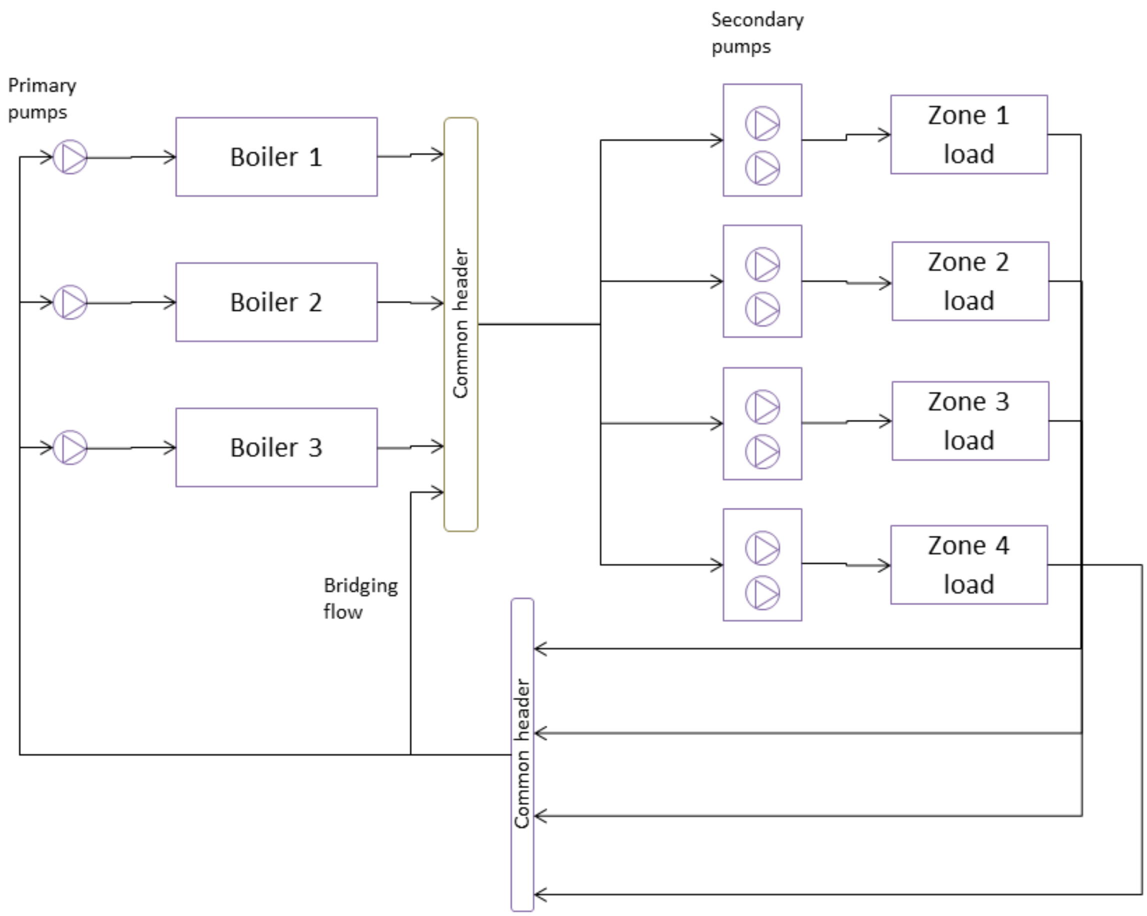


Figure 14: Heating plant block diagram

3.1 Flow

Similar to the cooling plant, the flow is modeled as a dynamical system driven by pressure differences that is generated by the pumps. Primary pumps are exception, since in the heating plant they have fixed RPM and generate constant flow. Therefore, for simplicity and robustness we do not model the dynamical behaviour of the prime loop, rather set the flow to the design value if the corresponding pump is on.

3.1.1 Flow mixing model

The three primary and four secondary loops have a common point where the pressure is equal, since it passes through common header and via a bridging connection that equalizes the supply and return pressures.

The four secondary flows are modeled as in (3). Each loop is computed independently and a mixing model is applied to determine the supply and the return temperatures.

The system has two distinct modes that are set by direction of flow in the bridging pipe. First mode associated with direction of the flow is according to the arrow in Fig. 14. In this mode zones flow is larger and some of the return water is mixed with boiler supply water and supplied to the zones. Other mode associated with a reverse bridging flow. In this mode the flow via the boilers is bigger than zones flow and some of the hot water supplied by the boilers is mixed with zones return water is returned to the boilers for reheating. Implementation of this logic is shown in Fig. 15.

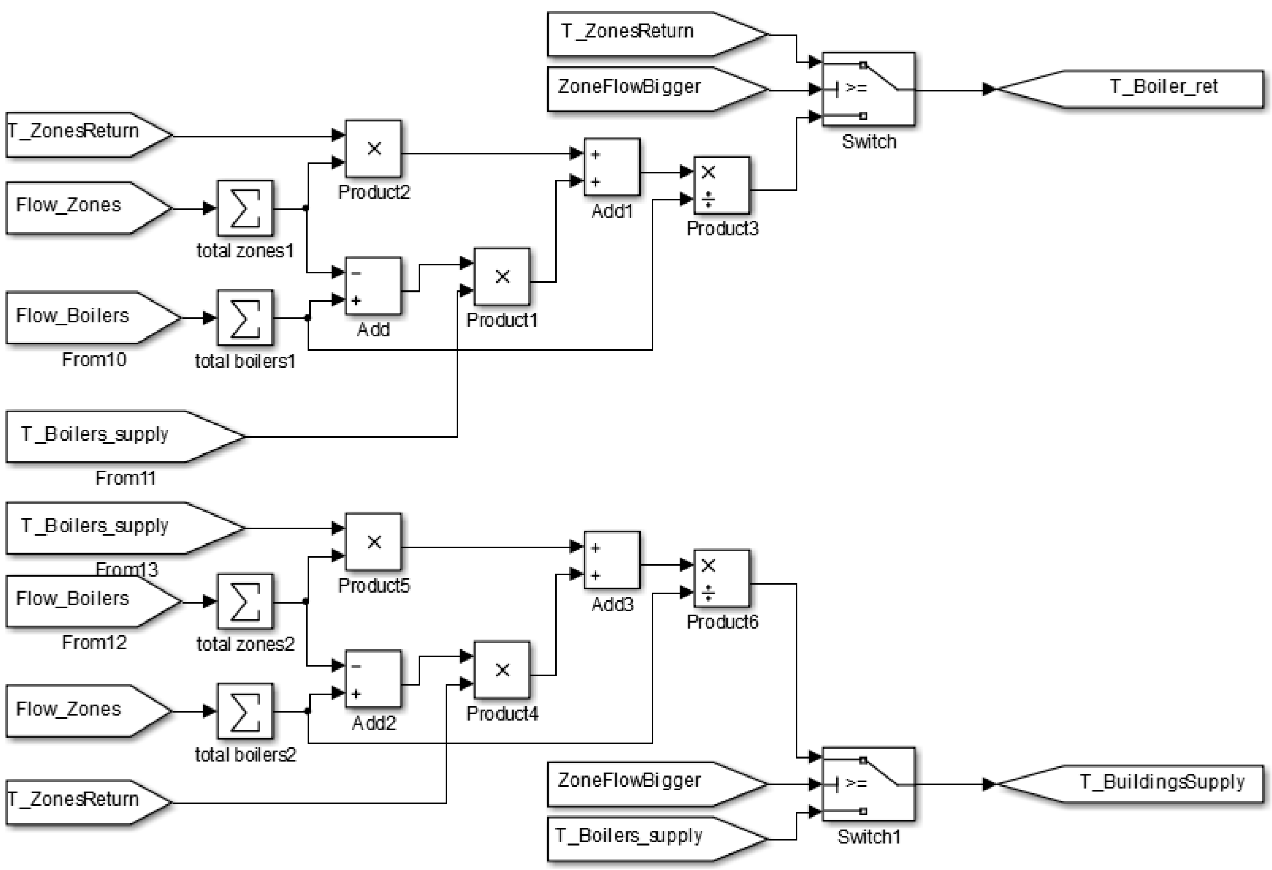


Figure 15: Flow mixing model for heating plant.

3.1.2 Flow control

Similar to the cooling plant, the flow of secondary loop (zones) is controlled using a PID controller that keeps the delta pressure [24.8,33,34,86.9] ft for zones $1-4$. The PID contoller is shown in Fig. 16.

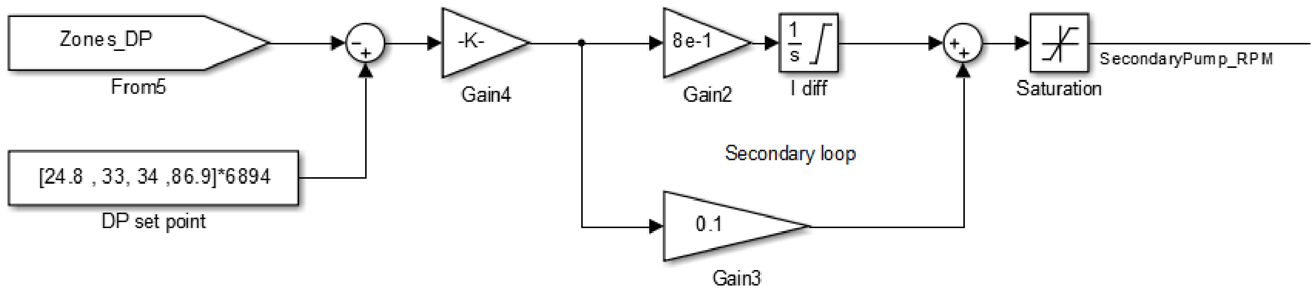


Figure 16: PID controller for zone flows of the heating plant. All wires are 4-dimensional signals.

3.2 Boilers Model

Boilers are modeled in a simple way. Boilers burn natural gas and produce heat, so efficiency of a boiler is the only term which remains for estimation. Since the efficiency is related to the amount of load which will be applied on the boiler, the efficiency is modeled as a quadratic polynomial of heat produced by the boiler. The terms used for the model are listed in Table 8:

Table 8: Boiler model parameters

Name	Description
Q_b	heat
V_b	boiler volume flow rate
$T_{b,s}$	supply temperature (boiler)
$T_{b,r}$	return temperature (boiler)
NG	natural gas consumption
ρ	NG energy density

The model is detailed with the following equations. Q_b is the produced heat by the boilers, and $(NG)\rho$ is the amount of energy content of natural gas.

$$Q_b = C_p V_b (T_{b,r} - T_{b,s}) \tag{24}$$

$$(NG)\rho = a_0 + a_1 Q_b + a_2 Q_b^2 \tag{25}$$

For boiler no.1, time series data collected for volume flow rate V_v are incorrect. So because of these defective data, the model for boiler no.1 is adopted form boiler no.2. Since both boilers(no. 1 and 2) have the same general capacities and other same features, in the absence of data, using the same model for both boilers seems reasonable.

3.2.1 Boiler model Fitting

Using the model described in § 3.2, we can perform a least square fit which is dependent to the available data listed in table 8. After fitting, we found the following coefficients for the boilers:

Table 9: Boiler model ID coefficients

Coefficients	Boiler no.1	Boiler no.2	Boiler no.3
a_0	0.0114	0.0114	0.0390
a_1	-0.0792	-0.0792	-0.0541
a_2	0.0003	0.0003	0.0086

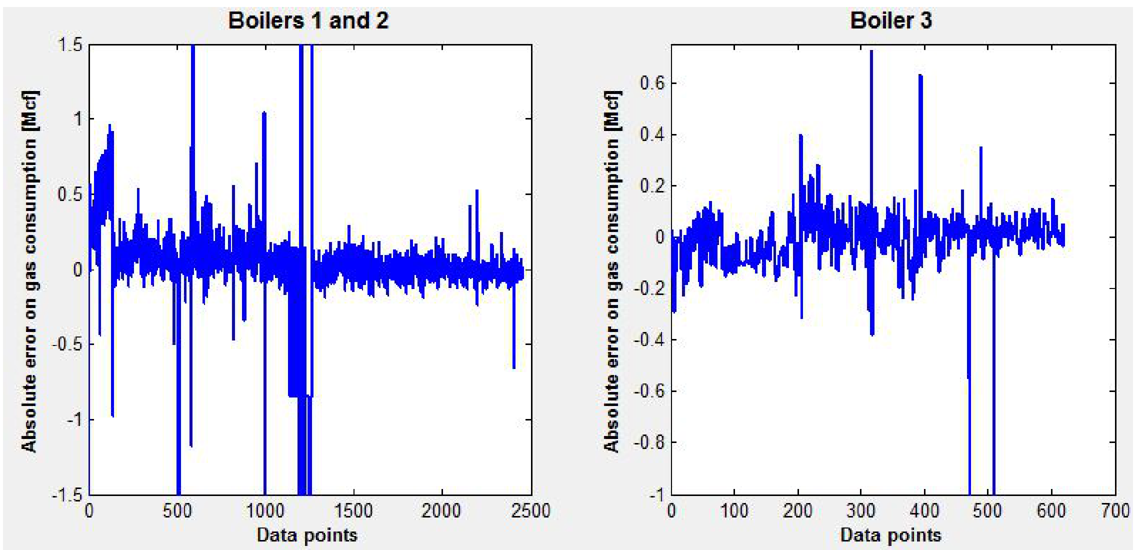


Figure 17: Boiler model ID Validation

Since there are no available data for the boiler no.1, the model for this boiler is adapted from boiler no.2

3.3 Buildings Model(Heating plant)

For the modeling of buildings the thermodynamic aspect will be considered. In the case of supplied heat to each building, flow of each zone and difference between return and supply temperature are considered. The terms are listed as below:

Table 10: Building model parameters (Heating plant)

Name	Description
T_s	building supply temperature
T_r	building return temperature
V_z	volume flow rate

Using the time series data of zones, it can be found the heat supplied to each zones:

$$Q_z = C_p V_z (T_r - T_s) \tag{26}$$

Since different buildings are part of a zone, each zone will be modeled as lumped capacity load as a whole. The model is based on ambient temperature, zone temperature, thermal load, time of day, day of week, sun irradiation, and average supplied load for each zone Q_z.

$$T_z(k+1) - T_z(k) = p_1(T_z(k) - T_a) + p_2(T_z(k-1) - T_a) + p_3(T_z(k-2) - T_a) + p_4 I_{sun}$$
$$+ L(TOD, DOW) + p_5 Q_z \tag{27}$$

$$L(TOD, DOW) = \begin{cases} c_1 + c_2 TOD + c_3 TOD^2 + c_4 TOD^3 + c_5 TOD^4 & @DOW \text{isworkday} \\ d_1 + d_2 TOD + d_3 TOD^2 + d_4 TOD^3 + d_5 TOD^4 & @DOW \text{isweekend} \end{cases} \tag{28}$$

As seen above, the model needs the zone temperature to be defined. Since, the correlation between building zone temperatures and zones no. 2 and 4 is not determined, the model for these two zones are adopted from model ID from zone no. 3 by adding a weighting factor to make this adaptation more precise and acceptable. The factor is obtained by dividing supplied heat to each zone Q_z to the supplied heat of zone no. 3 as following:

$$Weightingfactor = \frac{Q_{z,1}}{Q_{z,3}} \tag{29}$$

References

[1] K. Mathison, M. Morari, and S. Skogestad. Dynamic moldes for heat exchanger and heat exchanger networkers. *Computers chem. Engng*, 18(1):S459–S463, 1994.

[2] Yudong Ma, A. Kelman, A. Daly, and F. Borrelli. Predictive control for energy efficient buildings with thermal storage: Modeling, stimulation, and experiments. *Control Systems, IEEE*, 32(1):44–64, Feb 2012.

APPENDIX E: OPTIMIZATION MODE PROCEDURE FOR BOILERS AT THE CMA PLANT

The following procedure is to be followed by the operator when the Local/CPOWER control is in 'Optimizer'.

1. Optimizer recommends boiler to turn on.
2. EBI displays text 'Optimizer recommends turn on boiler # ..'.
3. Local controller turns on primary pump automatically.
4. After the boiler is warmed up the operator should turn on (Enable) 'boiler# Operator Enable' point at the EBI display on the Systems Details page.
5. Operator will perform actions needed to bring boiler up to operating temperature.
6. Optimizer will start providing recommended boiler supply temperatures. Operator should follow these recommendations when possible. This will be done on the Allen Bradley control display.
7. During these operator actions, the boiler switch stays on 'Auto'.
8. Boiler stays on for at least required number of hours set in optimizer.
9. Optimizer recommends boiler to turn off.
10. EBI displays text 'Optimizer recommends turn off boiler # ..'.
11. Operator turns off (Disable) 'boiler# Operator Enable' point on EBI display point on the Systems Details page.
12. There will be a 30 minute OFF delay on the primary pump. Local controller switches off primary pump automatically.

APPENDIX F: SIMPLIFIED OPERATOR MANUAL FOR HEATING PLANT

Login procedure:

Follow local procedures to log on locally or remotely to the Heating Plant Optimization PC.

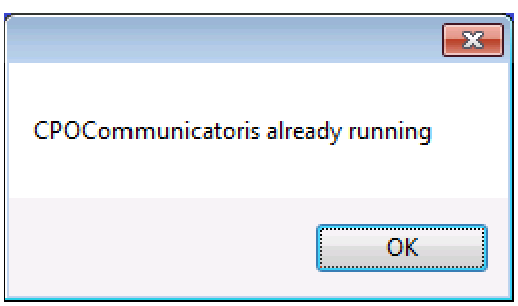
Startup procedure:

CPO should already be running, if so, you can skip to step 5, if not:

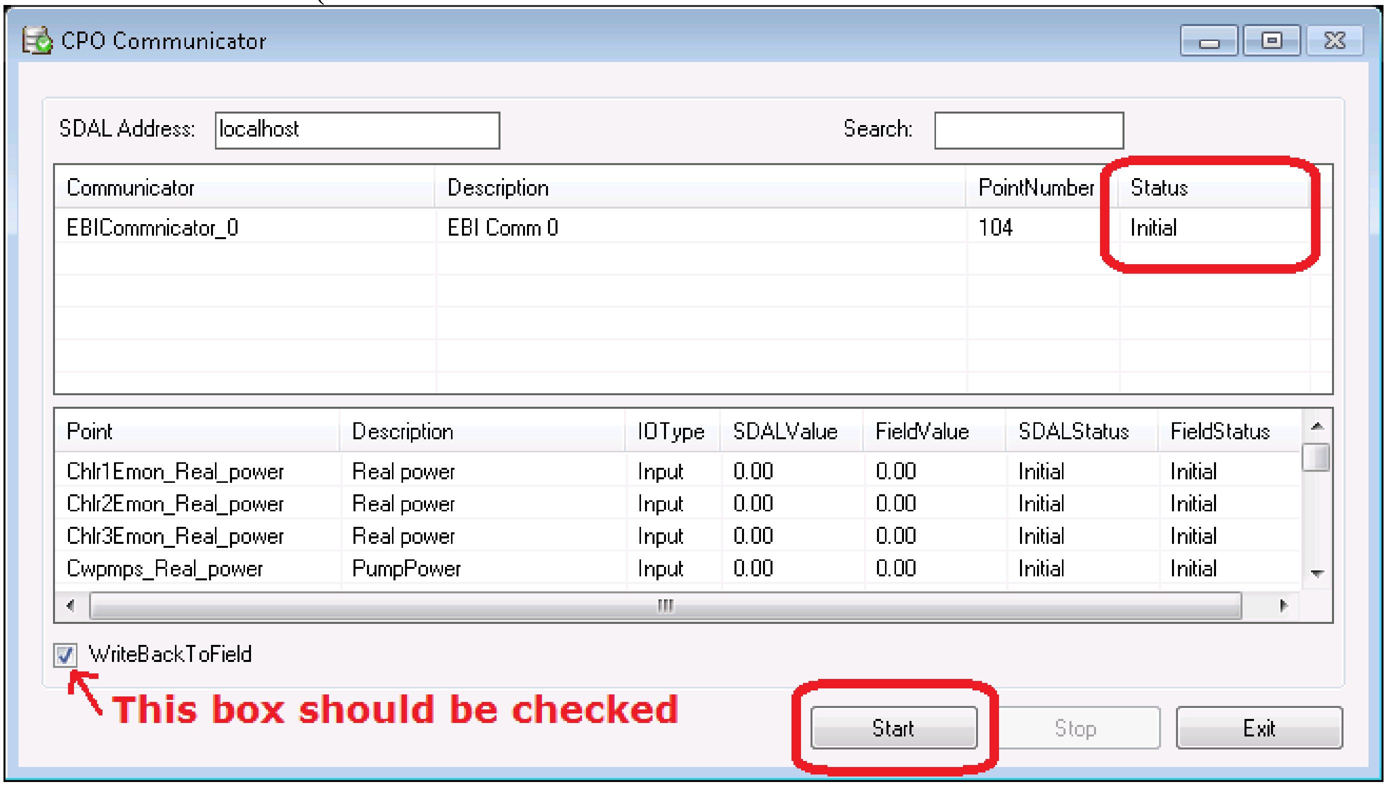
1. First, ensure CPO Communicator is running by double-clicking on the desktop icon.

Note: All CPO related applications should be 'Run As Administrator'.

2. If CPO Communicator is already running, you will see the following dialog. You can click [OK] and go to step 3.



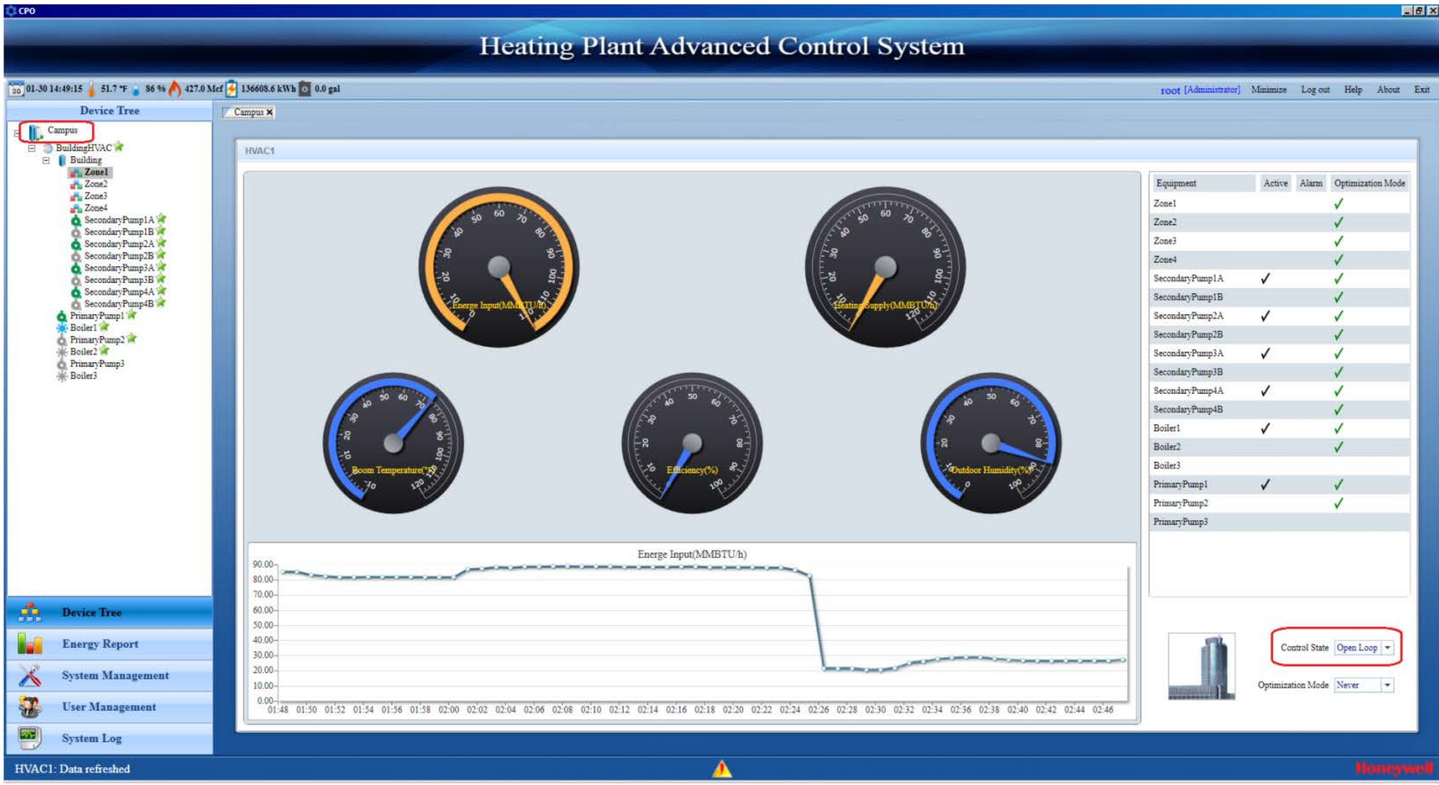
If CPO Communicator is not running, then the main window will open (shown below). Ensure that the box (lower-left) is checked to enable 'WriteBackToField'. Click on the [Start] button, and ensure the 'Status' changes to 'FieldConnected', which means you have a good connection to EBI. You should see point data values updating in the FieldValue and SDALValue columns. The CPO Communicator window is discussed in detail in the last section of this document (



3. Start CPO by double-clicking on its desktop icon.

4. At the login screen of CPO, use: root / root as the username / password.

5. CPO will start in 'Open Loop', which means it is **<u>not</u>** in control of the heating plant. To enable control of the heating plant with CPO, ensure the 'Campus' node is selected in the Device Tree on the left-side of the screen, and select the drop-down box of 'Control State' (bottom-right corner of screen) and select 'Closed Loop'. The figure below shows the location of the drop-down box highlighted by a red border.



Shutdown Procedure:

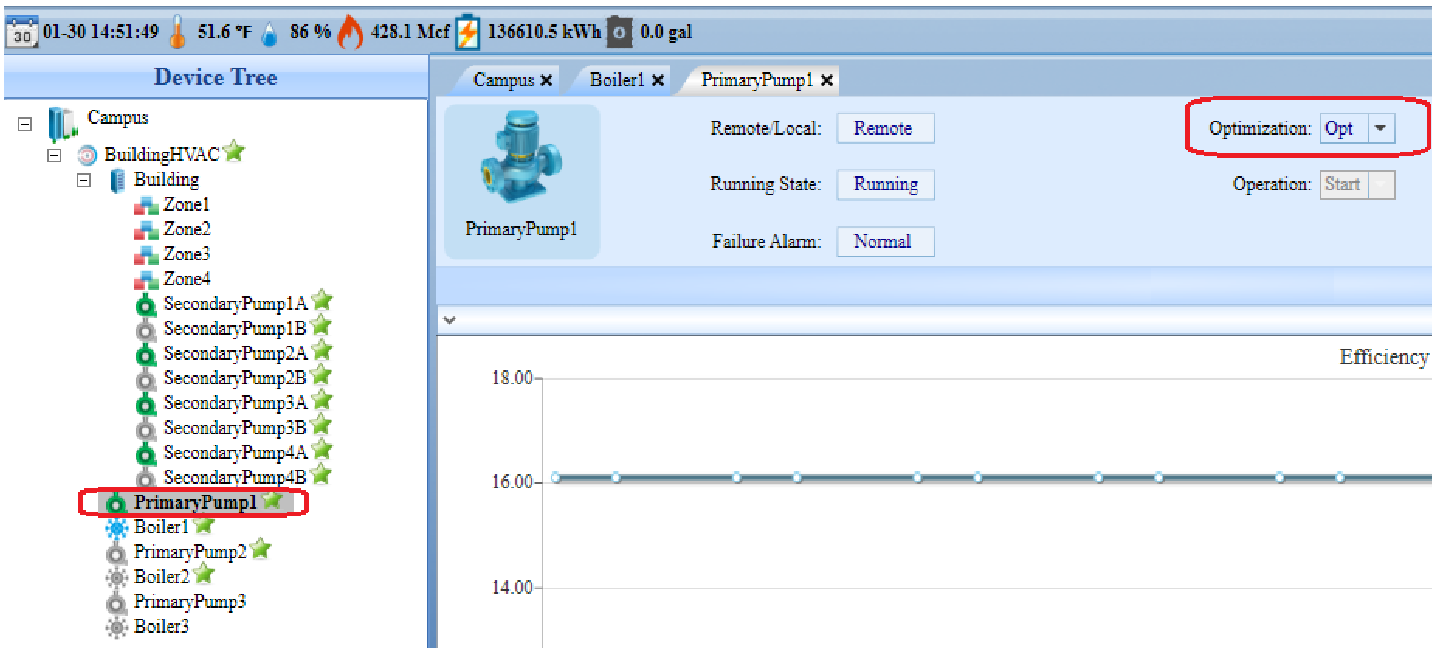
To return the heating plant control to EBI, go to the ‘Campus’ node display screen (shown above), and select the drop-down box for ‘Control State’ and select ‘Open Loop’. Note that you do **not** need to Exit CPO, nor should CPO Communicator be ‘Stopped’ or closed. EBI will regain control of the plant; it should be confirmed by looking at the Heating Plant summary display page in Station.

Operational Equipment Procedures:

Individual equipment can be controlled by selecting them in the Device Tree. Across the top of the equipment’s status screen, you can choose to include the equipment in Optimization, or remove it and manually control it.

Note: A green-star to the right of the equipment name in the Device Tree means the equipment is included in the optimization.

For example, in the screenshot below, PrimaryPump1 is running and Optimized. To remove it from optimization and stop it, select ‘Non-Opt’ from the Optimization drop-down, then select ‘Stop’ from the ‘Operation’ drop-down, and/or set it’s ‘Frequency Set Point’ parameter to 0 (zero). This same procedure to remove equipment from optimization can be followed even if the equipment is not running.

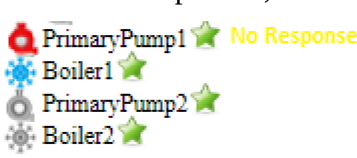


Equipment Status:

 = Pump is OFF  = Pump is ON

 = Boiler is OFF  = Boiler is ON

Note that although the Primary Pumps and Boilers are included in Optimization mode, they are not directly controlled by CPO. This may cause CPO to highlight the equipment red and labeled with “No Response”, but this warning can be safely ignored.



Optimization Status and Results:

The user can view a summary of optimization and event logs by selecting ‘System Log’ (last category button in the left menu), and choosing either ‘Opt Log’ or ‘Event Log’.

The Opt Log (first of 2 figures below) will provide a history of optimization attempts by the CPO solver software and what each equipment’s setting should be, given a successful result. This view is useful to get a quick snapshot of all the equipment’s expected state (on/off, speed, temperature, etc), and see if previous optimization attempts were successful or not.

The Event Log (second of 2 figures below) provides a rolling history of events encountered during CPO control, to include warning messages, when the last optimization occurred, and more. This view is useful to review past error / warning messages, when the last refresh of data was completed, and when optimization was last run.

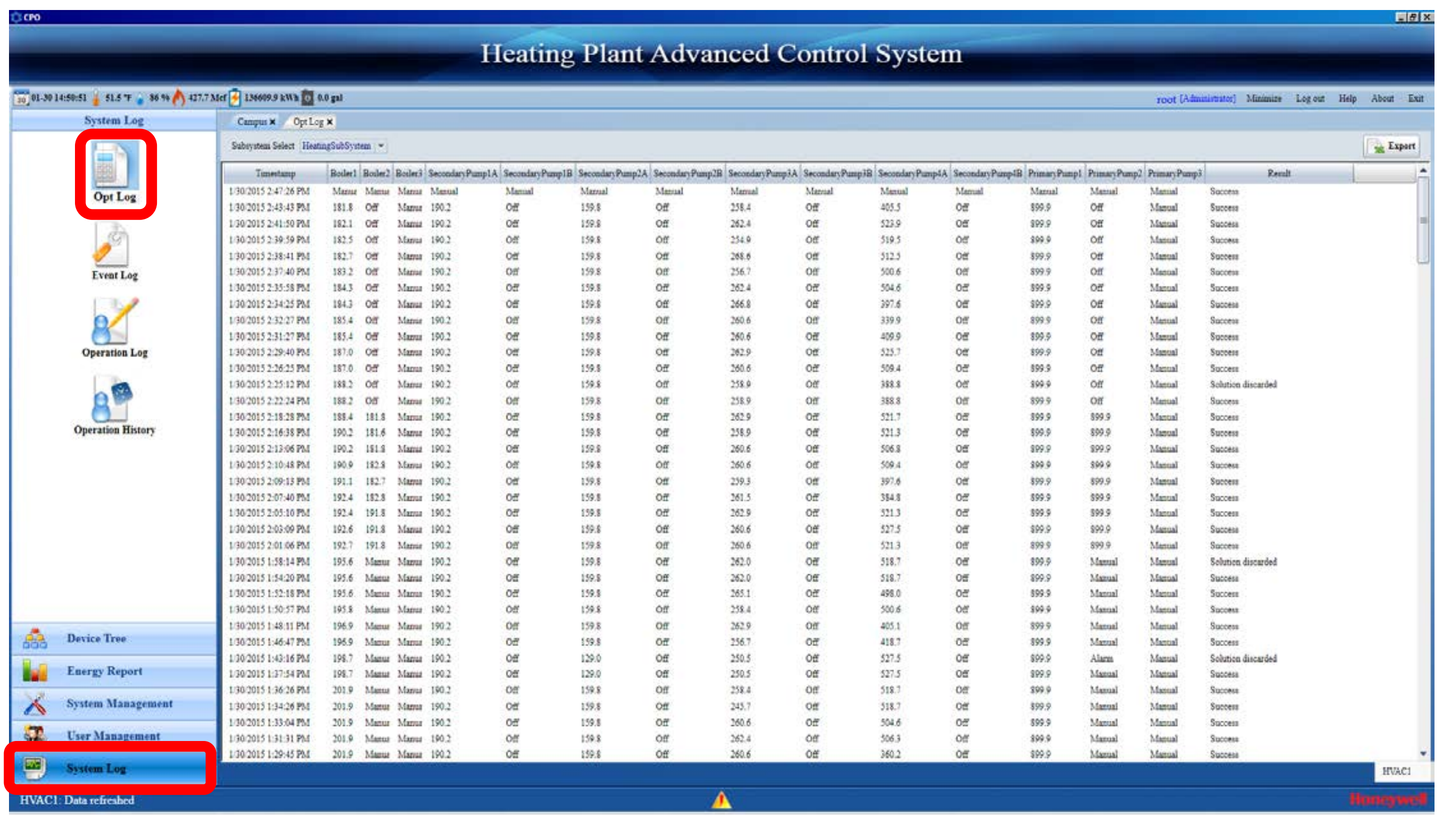


Figure 93: Opt Log

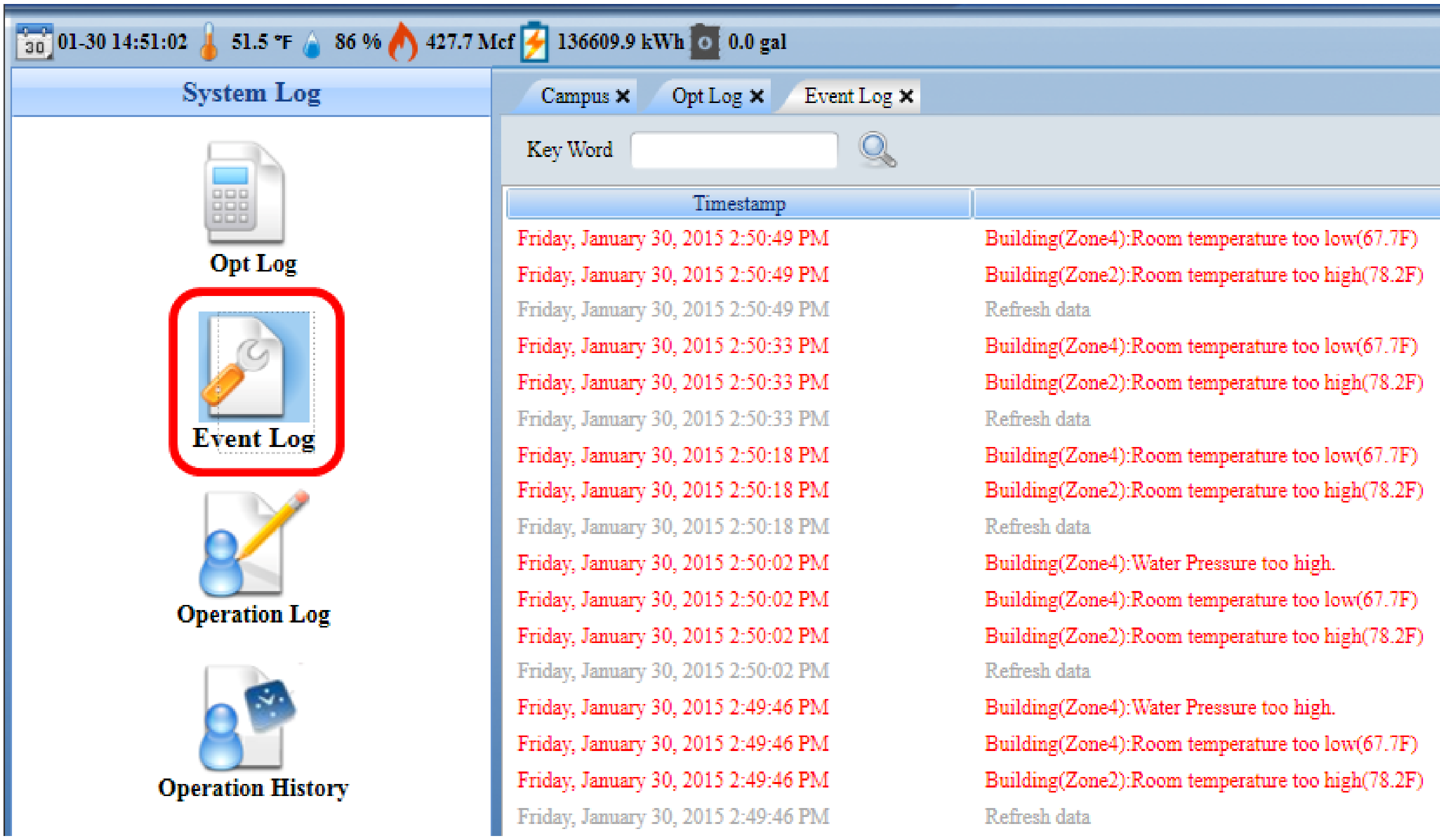


Figure 94: Event Log

CPO Communicator:

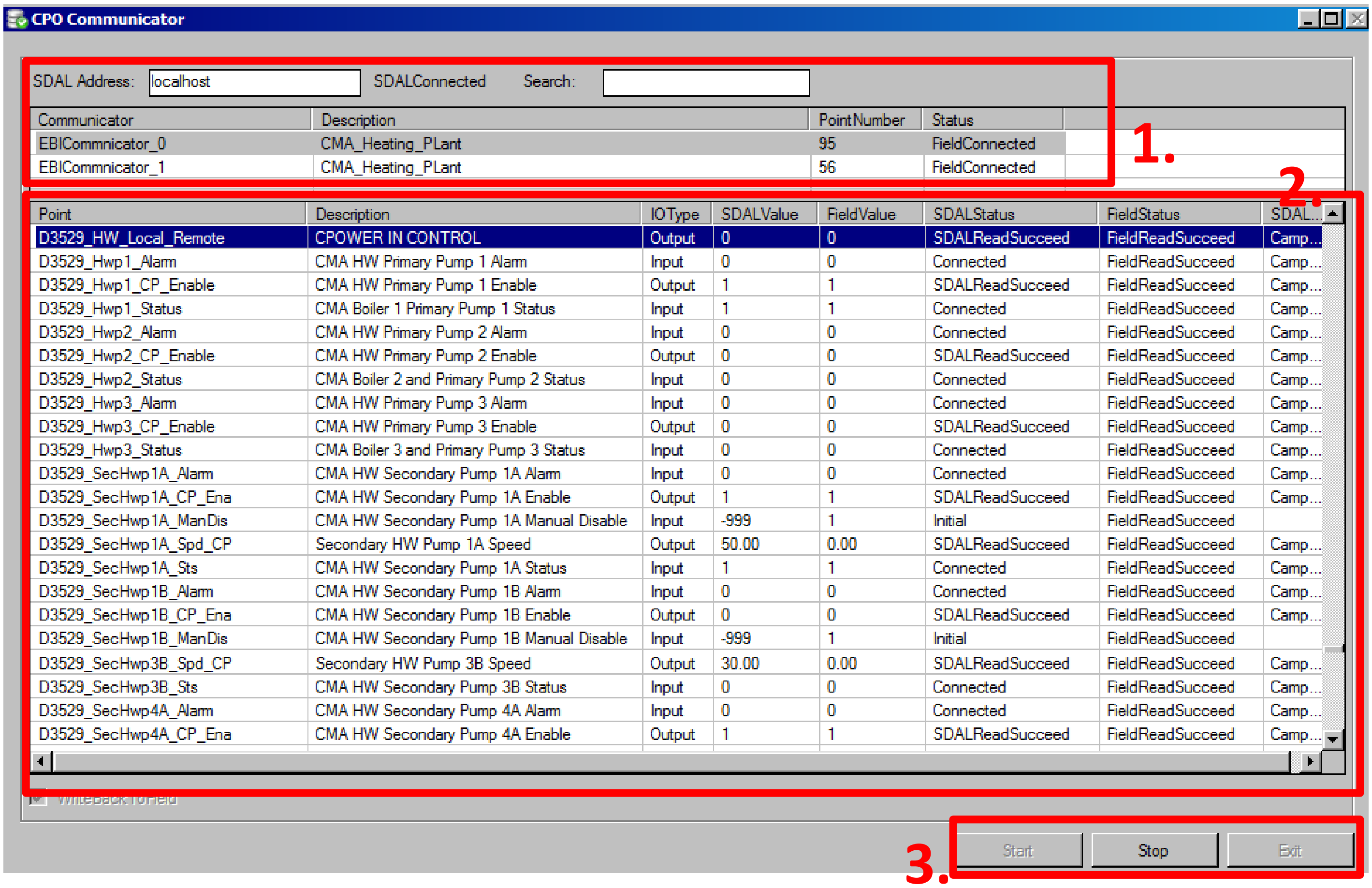
The CPO Communicator window provides some useful information about the current state of all point-parameters and their values. Reference the figure below for the following points:

1. The top section lists all configured Communicators (Created in CPO Builder), here there are 2:
    a. EBICommunicator_0: 96 points configured, mostly tied to pumps
    b. EBICommunicator_1: 56 points configured, mostly for Boiler
2. The bottom section contains the list of points configured for the selected Communicator. The following columns are defined as follows:

Point	Name of point
IOType	Input: point data is read from field device Output: command point that is written to a field device
SDAL Value	Last good value, either read from field and stored in local database flat-file, or generated by optimizer and sent as a command value
Field Value	Last read value from field device
SDAL Status	Connected: Input point has successfully been read SDAL Read Succeed: Local database point was read successfully

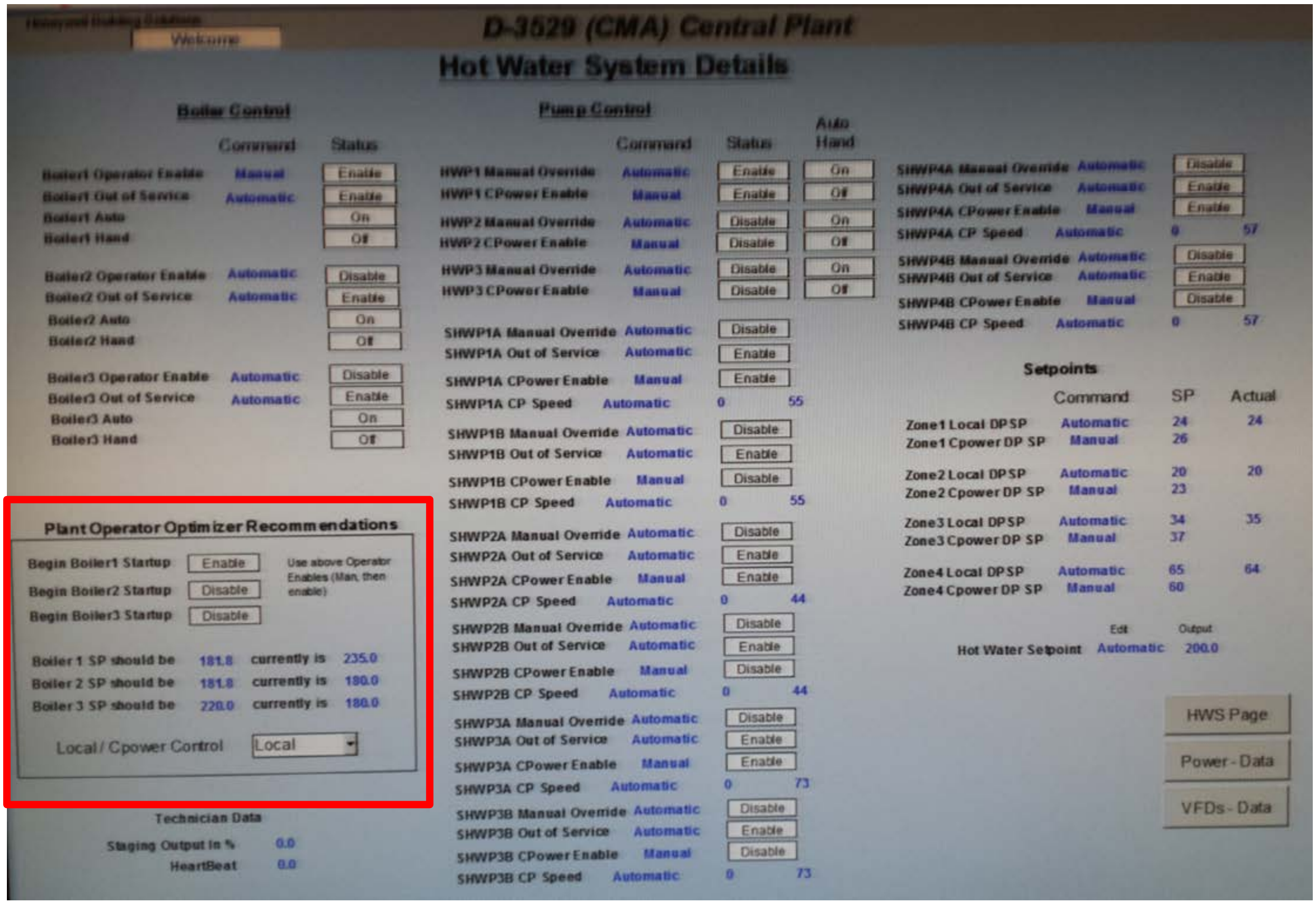
	Initial: initial read from field succeeded, but point is not mapped to a device, so it is not written to database flat-file.
FieldStatus	FieldReadSucceed: point data successfully read from field device.

3. Start/Stop/Exit: Starts communication with EBI if not already running; Stop communication with EBI; Exit (close) CPO Communicator (required if user needs to run CPO Builder).



CPO Status on EBI:

The D-3529 (CMA) Central Plant screen contains information about the current control state of the CPO software. The lower-left of the screen contains a control-toggle drop-down selector for changing from CPO to/from EBI control of the plant. This area of the screen (highlighted by red box in figure below) also contains recommended states of the boilers when CPO is in control. The plant operator should regularly check the status of the boilers when CPO is in control. The rest of the screen contains information about pump control, zone differential pressures and temperatures. If the plant operator is unable to access the host CPO environment (remote desktop), this EBI screen can be utilized instead.


D-3529 (CMA) Central Plant
Welcome
Hot Water System Details
Boiler Control
Command
Status
Boiler1 Operator Enable
Boiler1 Out of Service
Boiler1 Auto
Boiler1 Hand
Boiler2 Operator Enable
Boiler2 Out of Service
Boiler2 Auto
Boiler2 Hand
Boiler3 Operator Enable
Boiler3 Out of Service
Boiler3 Auto
Boiler3 Hand
Pump Control
Auto
Hand
HWP1 Manual Override
HWP1 CPower Enable
HWP2 Manual Override
HWP2 CPower Enable
HWP3 Manual Override
HWP3 CPower Enable
SHWP1A Manual Override
SHWP1A Out of Service
SHWP1A CPower Enable
SHWP1A CP Speed
SHWP1B Manual Override
SHWP1B Out of Service
SHWP1B CPower Enable
SHWP1B CP Speed
SHWP2A Manual Override
SHWP2A Out of Service
SHWP2A CPower Enable
SHWP2A CP Speed
SHWP2B Manual Override
SHWP2B Out of Service
SHWP2B CPower Enable
SHWP2B CP Speed
SHWP3A Manual Override
SHWP3A Out of Service
SHWP3A CPower Enable
SHWP3A CP Speed
SHWP3B Manual Override
SHWP3B Out of Service
SHWP3B CPower Enable
SHWP3B CP Speed
SHWP4A Manual Override
SHWP4A Out of Service
SHWP4A CPower Enable
SHWP4A CP Speed
SHWP4B Manual Override
SHWP4B Out of Service
SHWP4B CPower Enable
SHWP4B CP Speed
Setpoints
Command
SP
Actual
Zone1 Local DP SP
Zone1 Cpower DP SP
Zone2 Local DP SP
Zone2 Cpower DP SP
Zone3 Local DP SP
Zone3 Cpower DP SP
Zone4 Local DP SP
Zone4 Cpower DP SP
Hot Water Setpoint
Automatic
200.0
Plant Operator Optimizer Recommendations
Begin Boiler1 Startup
Begin Boiler2 Startup
Begin Boiler3 Startup
Use above Operator Enables (Man, then enable)
Boiler 1 SP should be 181.8 currently is 235.0
Boiler 2 SP should be 181.8 currently is 180.0
Boiler 3 SP should be 220.0 currently is 180.0
Local / Cpower Control
Local
Technician Data
Staging Output in %
HeartBeat
HWS Page
Power - Data
VFDs - Data

APPENDIX G: NIST BLCC 5.3-15: INPUT DATA LISTING

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

General Information

File Name: C:\Program Files\BLCC5\projects\CPOWER_final.xml

Date of Study: Thu Jun 23 14:19:32 CDT 2016

Analysis Type: FEMP Analysis, Energy Project

Project Name: Chiller Plant Optimization

Project Location: North Carolina

Analyst:

Base Date: April 1, 2015

Service Date: April 1, 2015

Study Period: 15 years 0 months (April 1, 2015 through March 31, 2030)

Discount Rate: 3%

Discounting Convention: End-of-Year

Discount and Escalation Rates are REAL (exclusive of general inflation)

ALTERNATIVE: ORIGINAL CONTROL

Energy: Electricity

Annual Consumption: 5,497,613.0 kWh

Price per Unit: $0.06500

Demand Charge: $0

Utility Rebate: $0

Location: District of Columbia

Rate Schedule: Commercial

State: District of Columbia

USAGE INDICES

From Date	Duration	Usage Index
April 1, 2015	Remaining	100%

Escalation Rates

From Date	Duration	Escalation
April 1, 2014	1 year 0 months	1.38%
April 1, 2015	1 year 0 months	0.45%
April 1, 2016	1 year 0 months	-0.76%
April 1, 2017	1 year 0 months	0.1%
April 1, 2018	1 year 0 months	1.47%
April 1, 2019	1 year 0 months	1.75%
April 1, 2020	1 year 0 months	0.88%
April 1, 2021	1 year 0 months	0.94%
April 1, 2022	1 year 0 months	0.2%
April 1, 2023	1 year 0 months	0.73%
April 1, 2024	1 year 0 months	0.46%
April 1, 2025	1 year 0 months	0.49%
April 1, 2026	1 year 0 months	0.23%
April 1, 2027	1 year 0 months	-0.26%
April 1, 2028	1 year 0 months	-0.16%
April 1, 2029	1 year 0 months	0.2%
April 1, 2030	1 year 0 months	0.49%
April 1, 2031	1 year 0 months	0.68%
April 1, 2032	1 year 0 months	0.55%
April 1, 2033	1 year 0 months	0.54%
April 1, 2034	1 year 0 months	0.48%
April 1, 2035	1 year 0 months	0.6%
April 1, 2036	1 year 0 months	1.01%
April 1, 2037	1 year 0 months	1.25%
April 1, 2038	1 year 0 months	1.54%
April 1, 2039	1 year 0 months	0.88%
April 1, 2040	1 year 0 months	0.6%
April 1, 2041	1 year 0 months	0.6%
April 1, 2042	1 year 0 months	0.62%
April 1, 2043	1 year 0 months	0.59%
April 1, 2044	Remaining	0.66%

ALTERNATIVE: OPTIMIZED CONTROL

Energy: Electricity

Annual Consumption: 4,947,851.7 kWh

Price per Unit: $0.06500

Demand Charge: $0

Utility Rebate: $0

Location: District of Columbia

Rate Schedule: Commercial

State: District of Columbia

Usage Indices

From Date	Duration	Usage Index
April 1, 2015	Remaining	100%

Escalation Rates

From Date	Duration	Escalation
April 1, 2014	1 year 0 months	1.38%
April 1, 2015	1 year 0 months	0.45%
April 1, 2016	1 year 0 months	-0.76%
April 1, 2017	1 year 0 months	0.1%
April 1, 2018	1 year 0 months	1.47%
April 1, 2019	1 year 0 months	1.75%
April 1, 2020	1 year 0 months	0.88%
April 1, 2021	1 year 0 months	0.94%
April 1, 2022	1 year 0 months	0.2%
April 1, 2023	1 year 0 months	0.73%
April 1, 2024	1 year 0 months	0.46%
April 1, 2025	1 year 0 months	0.49%
April 1, 2026	1 year 0 months	0.23%
April 1, 2027	1 year 0 months	-0.26%
April 1, 2028	1 year 0 months	-0.16%
April 1, 2029	1 year 0 months	0.2%
April 1, 2030	1 year 0 months	0.49%
April 1, 2031	1 year 0 months	0.68%
April 1, 2032	1 year 0 months	0.55%
April 1, 2033	1 year 0 months	0.54%
April 1, 2034	1 year 0 months	0.48%
April 1, 2035	1 year 0 months	0.6%
April 1, 2036	1 year 0 months	1.01%
April 1, 2037	1 year 0 months	1.25%
April 1, 2038	1 year 0 months	1.54%
April 1, 2039	1 year 0 months	0.88%
April 1, 2040	1 year 0 months	0.6%
April 1, 2041	1 year 0 months	0.6%
April 1, 2042	1 year 0 months	0.62%
April 1, 2043	1 year 0 months	0.59%

April 1, 2044	Remaining	0.66%

COMPONENT: SOFTWARE AND INSTALLATION COSTS

Initial Investment

Initial Cost (base-year $): $130,300

Annual Rate of Increase: 0%

Expected Asset Life: 15 years 0 months

Residual Value Factor: 0%

Cost-Phasing

Cost Adjustment Factor: 0%

Years/Months (from Date) Date Portion

0 years 0 months April 1, 2015 100%

Recurring OM&R: Maintenance support

Amount: $15,200

Annual Rate of Increase: 0%

Usage Indices

From Date	**Duration**	**Factor**
April 1, 2015	Remaining	100%

APPENDIX H: NIST BLCC 5.3-15: COMPARATIVE ANALYSIS

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Original control

Alternative: Optimized control

GENERAL INFORMATION

File Name: C:\Program Files\BLCC5\projects\CPOWER_final.xml
Date of Study: Thu Jun 23 14:09:19 CDT 2016
Project Name: Chiller Plant Optimization
Project Location: North Carolina
Analysis Type: FEMP Analysis, Energy Project
Analyst:
Base Date: April 1, 2015
Service Date: April 1, 2015
Study Period: 15 years 0 months(April 1, 2015 through March 31, 2030)
Discount Rate: 3%
Discounting Convention: End-of-Year

COMPARISON OF PRESENT-VALUE COSTS PV LIFE-CYCLE COST

Initial Investment Costs:	Base Case	Alternative	Savings from Alternative
Capital Requirements as of Base Date	$0	$130,300	-$130,300
Future Costs:			
Energy Consumption Costs	$4,436,981	$3,993,283	$443,698
Energy Demand Charges	$0	$0	$0
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$181,466	-$181,466
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	$0	$0
Subtotal (for Future Cost Items)	$4,436,981	$4,174,749	$262,232
Total PV Life-Cycle Cost	$4,436,981	$4,305,049	$131,932

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings $262,232

Increased Total Investment $130,300

Net Savings $131,932

Savings-to-Investment Ratio (SIR)

SIR = 2.01

Adjusted Internal Rate of Return (AIRR)

AIRR = 7.92%

PAYBACK PERIOD

Estimated Years to Payback (from beginning of Service Period)

Simple Payback occurs in year 7

Discounted Payback occurs in year 7

ENERGY SAVINGS SUMMARY

Energy Savings Summary (in stated units)

Energy Type	Average Base Case	Annual Alternative	Consumption Savings	Life-Cycle Savings
Electricity	5,497,613.0 kWh	4,947,851.7 kWh	549,761.3 kWh	8,245,290.5 kWh

Energy Savings Summary (in MBtu)

Energy Type	**Average Base Case**	**Annual Alternative**	**Consumption Savings**	**Life-Cycle Savings**
Electricity	18,758.6 MBtu h	16,882.8 MBtu	1,875.9 MBtu	28,134.1 MBtu

Emissions Reduction Summary

Energy Type Emission	**Average Base Case**	**Annual Alternative**	**Emissions Reduction**	**Life-Cycle Reduction**
Electricity				
CO2	6,508,839.88 kg	5,857,955.89 kg	650,883.98 kg	9,761,923.21 kg
SO2	21,575.59 kg	19,418.03 kg	2,157.56 kg	32,358.95 kg
NOx	9,738.71 kg	8,764.83 kg	973.87 kg	14,606.06 kg
Total:				
CO2	6,508,839.88 kg	5,857,955.89 kg	650,883.98 kg	9,761,923.21 kg
SO2	21,575.59 kg	19,418.03 kg	2,157.56 kg	32,358.95 kg
NOx	9,738.71 kg	8,764.83 kg	973.87 kg	14,606.06 kg