FINAL REPORT

Rapid Deployment of Optimal Control for Building HVAC Systems using Innovative Software Tools and a Hybrid Heuristic/Model-Based Control Approach

ESTCP Project EW-201409

MARCH 2017

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BrightBox Technologies

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ESTCP project EW-201409 aimed at demonstrating the benefits of innovative software technology for building HVAC systems. These benefits included reduced system energy use and cost as well as improved performance driven by autonomous commissioning and optimized system control. In the end, while many individual elements of the project were completed successfully, the project as a whole was not able to successfully demonstrate the technology.

Anecdotal evidence, academic studies, and system simulations demonstrate the importance and capacity for best-in-class control solutions to improve system performance and reduce energy use and cost. However, implementing these solutions into the extremely heterogeneous and often malfunctioning or misconfigured HVAC systems in real operating buildings poses a major challenge to reaping the benefits promised by advanced control.

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ACRONYMS AND ABBREVIATIONS

AC	Air Conditioning
AHU	Air Handling Unit: an HVAC system component that contains a fan and heating/cooling equipment
ALC	Automated Logic Controls Corporation (a division of United Technologies): a controls equipment manufacturer
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
BAS	Building Automation System
BLOM	Berkeley Library for Optimization Modeling: a general-purpose optimization modeling language
BOMP	BrightBox Optimization Modeling Platform: an HVAC control system modeling platform developed by BrightBox Technologies
C++	C plus plus: a modern, object-oriented computer programming language
CAV	Constant Air Volume
DDC	Direct Digital Controls: short-hand for computerized, networked building controls
DoD	Department of Defense
ESTCP	Environmental Security Technology Certification Program
FOH	First Order Hold: a category describing time-varying data used in solving control problems
HVAC	Heating, Ventilating, and Air-Conditioning
IBM	International Business Machines; a large computer hardware and software company
IPMVP	International Performance Monitoring and Verification Protocol
LCDR	Lieutenant Commander
ME	Mechanical Engineering
MPC	Model Predictive Control: a model-based system control approach
M&V	Monitoring and Verification
NPS	Naval Postgraduate School Monterey
NSAM	Naval Support Activity Monterey
NSA	Naval Support Activity
PE	Professional Engineer
PG&E	Pacific Gas & Electric: a California utility company
PI	Proportional + Integral: a common software element for system control

PID	Proportional + Integral + Derivative: a common software element for system control
PWA	Piecewise Affine
TOPP	Theoretical Optimum Plant Power
UC	University of California
UCB	University of California, Berkeley
VAV	Variable-Air Volume; also refers to a “VAV box,” which is a simple HVAC system component
VAVR	Variable-Air Volume Reheat; a type of VAV box that also contains a heating coil
VFD	Variable Frequency Drive
VP	Vice President
ZOH	Zero Order Hold: a category describing time-varying data used in solving control problems

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EXECUTIVE SUMMARY

ESTCP project EW-201409 aimed at demonstrating the benefits of innovative software technology for building HVAC systems. These benefits included reduced system energy use and cost, as well as improved performance driven by autonomous commissioning and optimized system control. In the end, while many individual elements of the project were completed successfully, the project as a whole was not able to successfully demonstrate the technology.

Two buildings at the Naval Support Activity Monterey (NSAM) facility were selected for this demonstration because they met the following criteria.

- Employed an Automated Logic Controls (ALC) building control system
- Contained HVAC central plants containing multiple chillers with the correct type of control points available and integrated into the ALC system
- Employed 'variable air volume reheat' (VAV-reheat) HVAC distribution systems
- Contained existing energy and flow meters to enable monitoring and verification

The first building selected was Building 245 (Watkins Hall). In the end we were not able to deploy the advanced control solution to this building because of chiller equipment failure. The Watkins plant consisted of three chillers, CH-1, CH-2, and CH-3. Despite being co-located, CH-1 served Building 246 next door, which contains critical security program spaces. During this project CH-1 became permanently disabled and CH-2 was repurposed to serve Building 246. This left only CH-3 to serve the subject Building 245, making the deployment infeasible.

The second building selected was Building 305 (Glasgow Hall). At this building we were not able to deploy the advanced control software because the chilled-water supply temperature setpoint control point was not properly configured at any of the three chillers serving this building. This control point is a key element in deploying the optimal control solution and it was not available.

To resolve the issue at Glasgow Hall, we formed a team consisting of BrightBox engineers, NSAM operations staff, two different NSAM support contractors, and equipment manufacturers to identify the source of the problem and develop a solution. After months of work, the team was able to identify the hidden cause of the problem as the undocumented replacement of a control board inside the chillers that was malfunctioning. It turns out this problem dates to the original system installation and was unknown to building operators over the past 10 years. We identified a solution and the ESTCP program made funds available to implement the repair.

In the end, project timing did not allow for this solution to be implemented because at roughly the same point in time BrightBox Technologies completely ceased operations in this market due to slow adoption of our software. The situation with the Glasgow chillers highlights the need for thorough documentation of system design intent coupled with commissioning activities to verify that systems are installed, configured, and operating properly.

Anecdotal evidence, academic studies, and system simulations clearly demonstrate the importance and capacity for best-in-class control solutions to improve system performance and reduce energy use and cost. However, implementing these solutions into the extremely heterogeneous and often malfunctioning or misconfigured HVAC systems in real operating buildings poses a major challenge to reaping the benefits promised by advanced control. For these reasons, BrightBox Technologies refocused our efforts away from optimal control toward autonomous commissioning with the goal of establishing a correctly-configured and properly-operating foundation onto which optimal control could eventually be deployed. Unfortunately, we were not yet able to successfully develop a market for autonomous commissioning products despite the clear need and benefits. BrightBox Technologies ceased operations in this market at the end of March 2016.

1.0 INTRODUCTION

The Department of Defense (DoD) spends approximately $4 billion per year on facility energy consumption to power and fuel over 500 military installations worldwide. These installations include over 500,000 buildings and structures. HVAC system energy use across this portfolio represents roughly 40 percent of these costs, which equates to $1.6 billion annually.

Despite the large number of DoD buildings, each is unique. No two buildings contain the same type or configuration of HVAC components and equipment. Contractors install custom HVAC controls in each facility to turn the individual components into functioning systems, and the quality of these control installations directly affects the efficiency and performance of the buildings they serve. Deploying highly optimized custom controls across a wide range of HVAC system types and uses is a challenging but important goal if DoD is to reduce energy costs.

BrightBox Technologies developed an innovative software solution to accomplish this goal while at the same time aiming to keep implementation costs low. The BrightBox controls optimization product worked with existing control systems in existing buildings to reduce HVAC energy use and operating costs between 20 to 40 percent. If successfully applied across the entire portfolio of DoD buildings with an average HVAC system performance increase of 25%, this would represent $400 million in annual savings for DoD.

1.1 BACKGROUND

Buildings waste energy today in part because their HVAC system controls are not optimized for energy efficiency. BrightBox Technologies developed an innovative approach to writing and deploying building control software that delivers optimized systems quickly and cost-effectively. The technology aimed to deliver 20% to 40% HVAC energy cost savings in existing buildings along with performance improvements and other benefits. This ESTCP demonstration project represented an excellent opportunity for BrightBox to extend product testing and development and demonstrate to The Department of Defense (DoD) a powerful approach that could potentially be implemented across a large portion of their existing facilities to reduce energy use, reduce utility costs, and improve energy security.

1.1.1 Current Technology State of the Art

Current product offerings from the major controls manufacturers – Johnson, Honeywell, Siemens, Automated Logic – define what is state-of-the-art in the building HVAC system controls industry. Because this industry has been hardware-focused for most of its history, those defining product offerings have also been hardware-centric, and in fact the current generation of HVAC controls hardware products are quite capable in keeping with the general advancement of the computer and IT industries. But while the hardware-side of HVAC controls has moved forward significantly, the software side has not kept up. It is only in the past 5-years or so that some of the major manufacturers have started to offer new software / user interface products, but in general across the industry the software tools and user interface do not reflect the significant advancements made in the wider software-industry.

The state of the art today with respect to commissioning is that despite a number of industry efforts to standardize the commissioning process and deliverables, it is still largely a manual ad-hoc process that varies considerably on a project-to-project and provider-to-provider basis. The benefits of commissioning are well recognized, but thorough and truly-effective commissioning is not yet applied to all projects to capture those benefits. Barriers to more widespread deployment of commissioning include high initial costs and perceived uncertainty about financial payback.

1.1.2 Current State of Technology in DoD

DoD buildings employ a wide variety of HVAC control products and systems based largely on the date of the building construction and/or most recent significant retrofit. There is no standard control approach or product across all of DoD, nor is there a policy or funding available to continually upgrade building controls to the latest version. The result is a heterogeneous mix of control products and generations across DoD facilities. A few ESTCP projects have been controls-focused and some have even explored the use of predictive-analytics to affect building operation. None to date has yet had a significant impact on the large DoD building portfolio. It is also the case that many older and/or smaller DoD buildings operate without a building operating system at all, or they use standalone or pneumatic controls do not offer as much potential for performance improvement.

1.1.3 Technology Opportunity

The goal of this project was to install the BrightBox software in DoD buildings to help advance the DoD mission by allowing resources currently allocated to building utility costs to be used elsewhere, specifically to spend less money on energy and on configuring BAS systems in existing buildings. This would allow for more buildings to become automated with the savings, or to allow the dollars that would have been spent on energy to be allocated elsewhere (like capital improvements, equipment replacement, or additional O&M staff).

The goal of the BrightBox software was that it would be able to work with multiple software manufacturers and software generations. At the time of this demonstration project, the BrightBox software only worked with Automated Logic Controls (ALC), but it was a future goal (outside of the scope of work for this project) to broaden the application to work with multiple control manufacturers. Through extensive data collection, it could also help unify the understanding and management of the DoD building energy performance portfolio.

The goal for the BrightBox AutoCx product was to deliver the benefits of commissioning at a much lower first cost than was previously possible. BrightBox AutoCx uses automation to reduce the amount of expensive field labor required to deploy commissioning. Following this approach, AutoCx addresses the key barriers to more widespread use of commissioning. The opportunity here was that commissioning could be deployed less expensively and more widely across DoD buildings.

1.2 DRIVERS

1.2.1 Executive Order 13693 (EO 13693)

Executive Order 13693 revoked Executive Order 13423 (EO 13423) from 2009, “Strengthening Federal Environmental, Energy, and Transportation Management” required federal agencies to lead by example in advancing the nation’s energy security and environmental performance in a wide variety of areas including building performance.

This executive order (13693) revoked EO 13423 on March 19, 2015, so 13423 is no longer a direct, forcing driver for this project. However, its existence does form some of the context for the ESTCP program.

EO 13693 also revoked Executive Order 13514 (EO 13514) from 2009 ,”Federal Leadership in Environmental, Energy, and Economic Performance,” which built on EO 13423 by adding specific target language. In the area of building performance, the goal was to “Ensure that all new construction and major renovations meet the Guiding Principles for High-Performance Sustainable Buildings, and that 15 percent of existing buildings meet them by FY 2015. Starting in FY 2020, the goal was to design federal buildings to achieve "zero net energy" by FY 2030.” The Guiding Principles for High-Performance Sustainable Buildings specifically refered to improving energy efficiency.

Like EO 13423 discussed above, EO 13514 was revoked on March 19, 2015, so it is no longer a direct, forcing driver for this project. However, its existence does form some of the context for the ESTCP program.

1.2.2 Federal Energy Independence and Security Act (Public Law 110-140)

The Energy Independence and Security Act (Public Law 110-140) from 2007 specifically aims to increase the efficiency of buildings among other things. This project will contribute to that goal.

1.2.3 Department of Defense Strategic Sustainability Performance Plan (SSPP)

The Department of Defense Strategic Sustainability Performance Plan (SSPP) from 2012, and updated in 2014, established the path by which DoD will improve practices that further the sustainability goals of the nation. In particular the DoD intends to integrate sustainability into the everyday course of DoD business. The plan requires an annual target reduction 3% in facility energy intensity across the DoD. This project will contribute to that goal.

1.2.4 Navy Service Policy UFC 1-200-02

Navy Service Policy UFC 1-200-02, last updated in August 2014 “High Performance and Sustainable Building Requirements” was specifically created to “drive transformation in the performance of the DOD facility inventory.” Areas of performance include: 1) energy efficiency, 2) optimized energy performance, and 3) measurement and verification. This project makes contributions in all three of these performance areas.

1.3 OBJECTIVE OF THE DEMONSTRATION

Our objective was to demonstrate how BrightBox software could be used to quickly and cost-effectively develop and deploy optimized controls across a wide array of existing buildings. Our approach was to deploy the BrightBox software at the Naval Support Activity Monterey (NSAM) in Monterey, California. This DoD site represents approximately 1.2 million square feet of space and contains more than 25 separate buildings. No two buildings at NSAM contain identical HVAC systems, and the systems were installed anywhere from 1930 to the present. The systems at NSAM represent a wide range from the simple (baseboard heaters coupled with operable windows) to the complex (multiple-chiller plant serving data centers operating 24x7, large central steam boiler plant). With the help of NSAM staff, we identified a subset of NSAM buildings to receive the BrightBox software that represent an interesting and relevant sample of the buildings on campus. The project objective was for software to be installed in these buildings and the impacts assessed to quantitatively and qualitatively judge the effectiveness of the installation.

1.3.1 Validate

The objective was for baseline performance data to be collected to form the basis for the validation. Validation was to occur via independent measurements of system performance after the BrightBox implementation and then compare new performance to the baseline.

The objective for AutoCx validation was to assess the current operational state of individual equipment components in the project sites to form the basis for the validation. AutoCx software would then be used to text equipment operation, and any deficiencies will be noted and referred to NSAM operations staff.

1.3.2 Findings and Guidelines

If the BrightBox demonstration met performance objectives, DoD might have wanted to implement general guidelines for building analytics technology using the BrightBox Technology as an example across a wider range of buildings. Guidelines could have been developed for evaluating the potential for building system optimization and AutoCx technology to save energy and money at other DoD sites.

1.3.3 Technology Transfer

A successful demonstration project would have resulted in data and supporting analysis that could have been used to launch successive projects at other DoD installations. In this case, BrightBox would have developed a case study document based on this ESTCP project that summarized goals, process, technology, and results. We understand that there are significant security-related issues to implementing BrightBox at other DoD facilities that have more rigorous security protocols than NSAM. One approach to addressing these security concerns would have been employing third-party secure hosting services such as the Amazon “secure cloud” service. It is possible that this new resource offers a valuable secure IT platform.

In addition, in the case of a successful demonstration, BrightBox would have developed recommended additions to the DoD whole building design guide Unified Facilities Criteria specifically in sections UFC 3-401-01 Mechanical Engineering and UFC 3-410-01 Heating, Ventilating, and Air Conditioning Systems. Finally, BrightBox would have produce a fact sheet for channel partners who have DoD accounts with specific information on how to implement the BrightBox technology in a DoD environment.

1.3.4 Acceptance

The objective for this project was that documented energy and demand savings at the NSAM site would have driven acceptance of the BrightBox approach for implementation at additional DoD facilities.

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2.0 TECHNOLOGY DESCRIPTION

BrightBox Technologies created software with the goal to make it possible to quickly and cost-effectively develop and deploy optimized controls software into existing buildings. We developed an innovative analytical framework in which complex building controls problems can be quickly described, solved, and optimized. The framework also allowed us to apply, test, and verify the resulting controls solutions. Further, it enabled new functionality (planned for future development) such as effective demand response and predictive information exchange with smart utility grids.

One reason that it has historically been difficult to achieve energy savings across large groups of existing buildings is that each building is unique. Equipment, components, systems, and configurations vary sometimes substantially from project to project based on the competitive nature of the market and the wide proliferation of available products as well as the one-off nature of the building design and construction process. The result is that energy efficiency measures that make sense in one building very likely may not in another. To correctly assess energy efficiency measures, each building needs to be considered independently.

BrightBox Technologies understood this need to create custom solutions for every project, and built a suite of software applications to attempt to effectively address this challenge. Our software allowed for buildings and systems to be quickly and correctly defined in a robust analytical modeling platform. Once these models were built, they were fed with current and historical data streams from the existing Building Management System (BMS), which were then used to calibrate the models for individual buildings based on real-world performance. These calibrated models then set the context in which optimization algorithms run and auto-generate new controls code. Finally, these optimized programs were executed and the resulting control parameters were delivered in real-time for use by existing building control components and embedded software.

Another barrier to energy efficiency that relates to the uniqueness of buildings is that it is difficult for operations staff to understand if each individual building control system is set up correctly and all equipment components are operating correctly at all times across the wide variety of deployed systems. Over the life of a building, equipment performance changes and components break, and it is possible that these changes can go unnoticed by operators. It is typically an indirect process by which problems are reported (often by occupants as ‘complaints’). The BrightBox system includes an ‘AutoCx’ product that systematically checks for correct system configuration and component operation, which directly, rather than indirectly, validates system setup and operation. Directly assessing and addressing setup and operation issues becomes the first phase of optimization, which reduces time to successful deployment and operation of model-based optimization.

DoD facility HVAC systems represent a wide range of applications from the simple to the complex. BrightBox development through 2013 has focused on HVAC systems such as ‘simpler’ system such as packaged rooftop direct-exchange (DX) cooling systems, hot-water boiler plants, and variable air volume reheat (VAVR) distribution systems.

More complex “built up” systems and chilled water plants are widely employed as the cooling source for large buildings and campuses. They often account for 20% to 30% of the total energy usage by these facilities [17]. Optimizing controls for chilled water plant systems alone can reduce their energy consumption up to 30% [15]. As stated above, the optimizations have to be performed for each individual system accounting for the project’s climate, cooling load, the characteristics of the plant equipment and system configuration. Consequently, most built-up systems and chilled water plants use standard control sequences that are not optimized for an individual application.

A few mechanical design firms have attempted to address this problem over the past decade. Alameda, California-based Taylor Engineering has been a leader in this effort, developing a set of software tools that can be used for determining the optimum control sequence for a water-cooled chiller plant. The approach uses a brute force optimization method that literally evaluates the full range of all control parameters then identifies the most efficient control scheme that will satisfy the load and equipment operating constraints. Taylor Engineering has validated the simulations using field measurements [16].

Unfortunately, these current chilled-water plant optimization tools are prohibitively slow to deploy and run because they do not employ a modular/flexible system modeling approach or modern optimization techniques to find the solution. BrightBox Technologies and Taylor Engineering collaborated on this project to incorporate the existing approach with research performed by BrightBox Technologies Chief Technology Officer Francesco Borrelli, PhD., to significantly reduce the system modeling effort and the computational time needed for this approach, and to further improve the results. Working together, BrightBox and Taylor Engineering extended the existing analytical tools to cover built-up systems.

The proven approach developed by Taylor Engineering was combined with the BrightBox software tools informed by Dr. Borrelli’s research to allow us to attempt to demonstrate to DoD a method to quickly and accurately generate and implement optimal controls for basic chilled water plants.

2.1 TECHNOLOGY OVERVIEW

The primary objective of the BrightBox software solution was to quickly and correctly develop and implement optimized controls for HVAC systems in existing non-residential buildings. Our approach to accomplish this goal consisted of the following elements.

- The BrightBox Optimization Platform. This is a computer modeling language and set of associated algorithms designed specifically for describing and solving complex building controls problems.
- A software platform that created a user interface for the BrightBox Optimization Language, designed with HVAC system templates and objects for quick and accurate modeling
- A communication and data-acquisition interface to existing building control system hardware and software platforms

- A real-time operating system that gathers HVAC system performance data and executed the optimization solver at regularly-scheduled intervals.
- AutoCx that validates basic equipment connectivity and functionality, and control system setup.

2.1.1 Description

The core of the BrightBox technology platform was the BrightBox Optimization Modeling Platform (BOMP). We developed this platform to allow for the complete description of HVAC controls problems in a manner that can be used to directly generate custom optimization solutions for any given building. This innovation allowed us to effectively capture the extremely heterogeneous world of existing HVAC systems and deal with them in a rational, systematic, and time-efficient manner. Behind the scenes, BOMP automatically generated powerful system descriptions using the Berkeley Library for Optimization Modeling (BLOM).

Now publicly available, BLOM was developed at UC Berkeley by Dr. Borrelli's research group specifically to describe and solve complex optimization problems. It enables automated C++ code generation and explicit evaluation of the Jacobian and Hessian matrix formulations of these control problems. BLOM was developed in part with funding from a past ESTCP project (Project: EW-201142, Energy Performance Monitoring and Optimization System for DoD Campuses).

BLOM consists of two main components: 1) a general-purpose collection of block diagram components for use in the Simulink/Matlab graphical modeling environment, and 2) a set of functions that run outside of Matlab that export system models to a variety of optimization solvers.

The visual block diagram representation of a system model intuitively captures the signal flow, connectivity, and hierarchy of a large-scale system. It supported the following operational phases:

1. System modeling by using intuitive component block diagrams
2. Forward simulation and validation of the model
3. Automatic export of the optimization problem to an efficient optimization solver
4. Solver finds optimal solution
5. Operational setpoints are extracted from the optimal solution and input to building control system
6. Repeat steps 2 through 5 every 5 minutes

BLOM is a powerful tool that has been developed to solve complex optimization problems. It allows automated C++ code generation and explicit evaluation of Jacobian and Hessian matrices, which are important and difficult-to-solve components used in determining optimal control solutions. A BLOM model could also use standard forward simulation features for verification and comparison with optimization results. Thus, the same model can be initially run in forward simulation mode, in order to compare it to reference data, and later can be automatically exported to an optimization solver.

There are two classes of input signals to a BLOM model: unknown signals that the optimization algorithm is free to adjust in order to minimize the cost function subject to constraints (sometimes also called degrees of freedom), and time-varying signals with a known trajectory of values over a future horizon. We will refer to the former as control inputs, and the latter as external inputs. In a model-based control problem, external inputs correspond to predicted future model parameters or disturbances. Both classes of inputs are parameterized as uniformly sampled time series. Time variation for each input signal within one time step is important for discretization accuracy. It can be either piecewise linear and continuous (first order hold (FOH)), or piecewise constant with discontinuities at the sample times (zero order hold (ZOH)).

While the BLOM package itself is a flexible and powerful language, it has some inherent limitations that make it difficult to use outside of a research environment. First, the native interface to BLOM is the Simulink graphic design/analysis tool that operates in the Matlab analytical platform. Simulink and Matlab are specialized, proprietary, research-oriented software packages that are expensive to operate and difficult to learn. Further, the Matlab environment is not suitable for real-time operation due to memory and license management issues. Matlab was simply not designed to be used in this mode.

BrightBox Technologies made the power of BLOM available for solving HVAC system controls problems by creating our own custom interface and extensions to the language, which we call the BrightBox Optimization Modeling Platform (BOMP). This approach allowed us to eliminate Simulink/Matlab from our software tool-chain and enabked us to present to users an interface that is purpose-built for solving HVAC controls problems.

Further, BOMP enhanced and extended the BLOM functionality. In BOMP, we merged a BLOM model with a database schema connected to historical and real-time data feeds. This unique, innovative approach allowed for parameter identification and curve-fitting based on historical data. Another benefit was that real-time optimal control based on current observed measurements are generated in a seamless fashion, implemented as a single query on a BrightBox BOMP model as outlined in steps 1-6 above.

2.1.1.1 AutoCX

One result of the BrighbBox market-explorations and product-development work from 2013 through early 2016 was that we clearly came to view optimization as the ‘top of the pyramid’ in that it relies on the physical components in the building to be working correctly before optimization can achieve its full benefit. If equipment is broken or misconfigured, the optimization will not succeed, or at least will not deliver its full potential.

To address this issue and to help create a solid foundation for optimization, BrightBox developed an “Autonomous Commissioning” product (called AutoCx) that performs point-to-point checkout of certain types of equipment to validate correct operation and pinpoint any installation or equipment failure issues. We used our AutoCx product at the demonstration site as part of this project. We now consider it a critical phase of diagnostics that runs in parallel with the model-based optimization control we are deploying.

The goal of AutoCx was to save time in the deployment of our optimization software. We directly identify configuration and operational issues rather than indirectly discover them through a mismatch between expected and observed system operation.

2.1.2 Visual Depiction

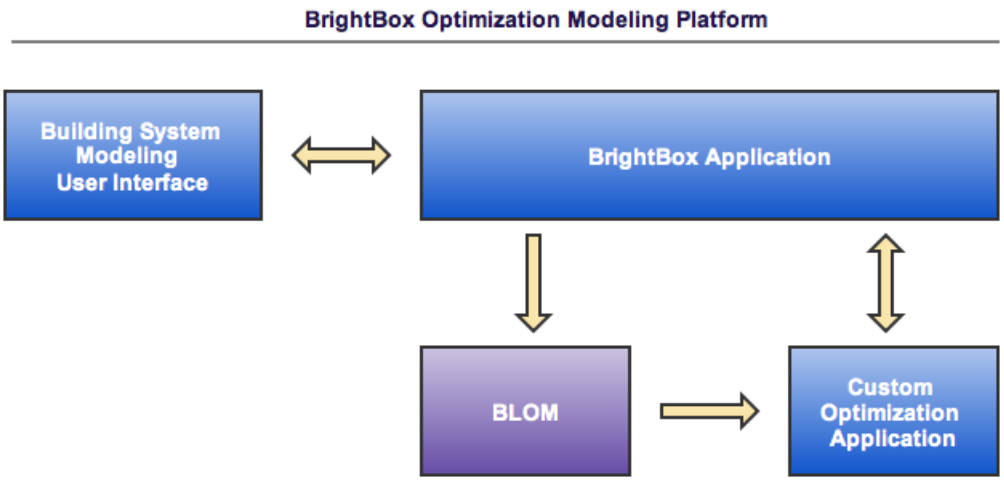

Figure 1. BrightBox Optimization Modeling Platform

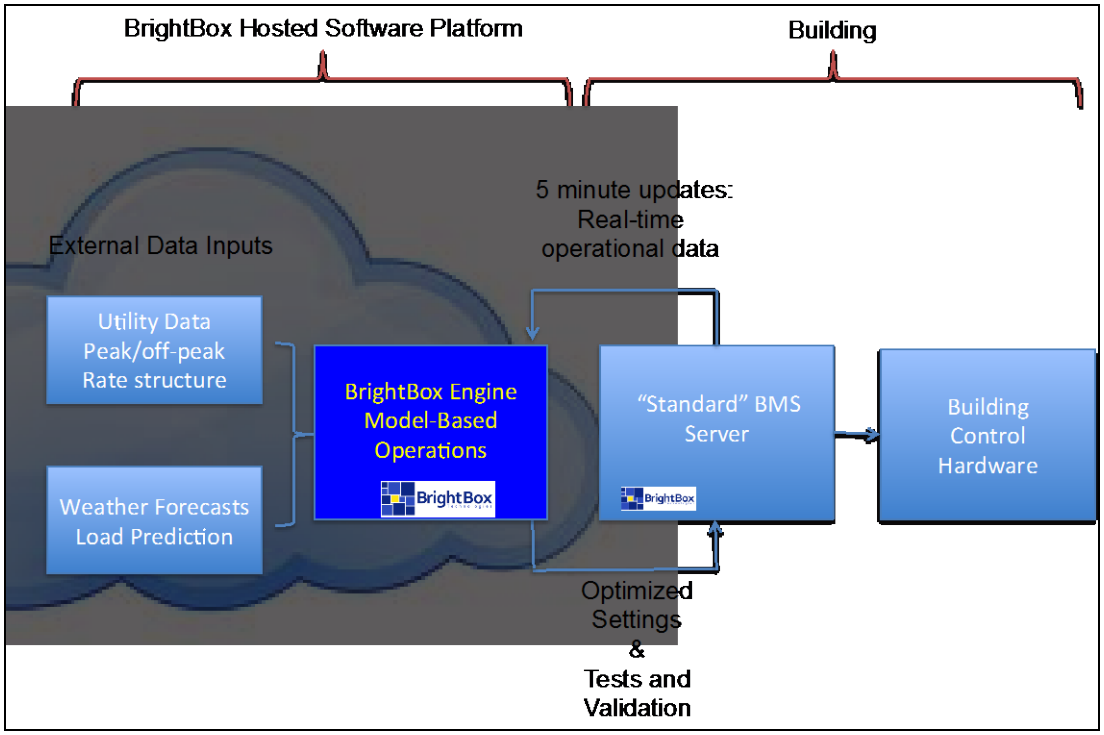

Figure 2. BrightBox Software Architecture and Interaction with Building

We recognized the need for a dashboard and real-time savings reports for building managers but those are future developments outside of the scope of this project. We do have some slides demonstrating energy savings that the system generates. See Figure 3 below.

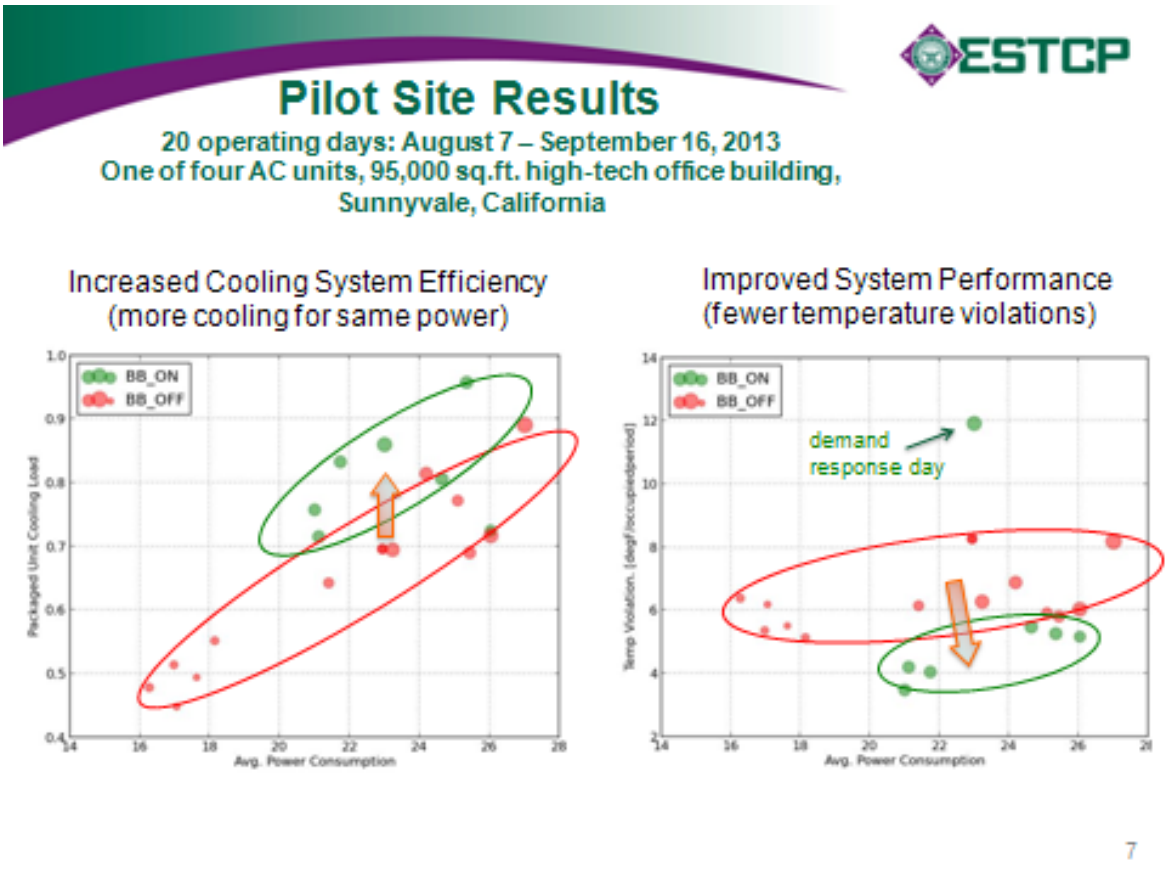

Figure 3. BrightBox Software Energy Savings Report

2.1.3 Chronological Summary

2.1.3.1 UC Berkeley Foundations

For the past seven years, BrightBox Technologies Chief Technology Officer Francesco Borrelli, PhD., has led the University of California, Berkeley (UCB) Mechanical Engineering research group that focuses on the theoretical and real-time implementation aspects of optimal model-based control design. He has extensive experience with linear, nonlinear, and hybrid systems in both small scale and complex large scale applications.

Dr. Borrelli and his UCB group have developed optimal control algorithms with experimental validation on a wide range of systems in the automotive field, in process industries, and in robotics, including several full-scale industrial problems [1-7].

2.1.3.2 Taylor Engineering Partnership

Taylor Engineering, an active consulting mechanical engineering firm and co-performer for this project, has already successfully collaborated with the UC Berkeley controls group on a project to optimize the control sequences for the central plant at the University of California, Merced. BrightBox Technologies Vice-President of Engineering Allan Daly is also a Principal at Taylor Engineering.

As part of this project, BrightBox Technologies software was extended to incorporate existing work developed by Taylor Engineering that makes use of the following elements:

- Performance data for chillers that use manufacturer data as well as real-world performance data determined by power meters installed in the field. Similar calibration techniques will be used for pumps, heat exchangers, chillers and cooling towers (as appropriate for the specific systems under study).
- Analytical models that account for equipment specifications, chilled water load and flow profile, and the coincident weather data. This program tests all of the possible operating modes for the plant against each hour of load, flow, and weather data. For each of the modes that meet the demands (load and flow) within the operating constraints of the equipment, the program calculates the plant energy and records the results. This step for a large plant can take up to 2-3 days running on 2-5 computers depending on the number of chillers, pumps, and towers.
- A database query used to identify the minimum plant energy (or plant energy cost) at each hour, summed up to provide the Theoretical Optimum Plant Power (TOPP). We then query the database to compare the proposed control scheme against the TOPP value.

BrightBox Technologies employed a systematic approach using system identification for hybrid systems. Hybrid systems are heterogeneous dynamic systems whose behavior is determined by interacting continuous and discrete dynamics. The continuous dynamics are described by variables taking values from a continuous set, while the discrete dynamics are described by variables taking values from a discrete, typically finite, set. We will extract Piecewise Affine (PWA) controllers which best fit the Taylor Engineering dataset. Note that here affine means "linear + constant term," for instance a lookup table of several PI controllers + feed-forward terms is a PWA controller. PWA control systems are obtained by partitioning the input domain into a finite number of non-overlapping convex polyhedral regions, and by considering linear controllers in each region.

Measurable success criteria for correct model development will be: (1) agreement in simulations between BOMP, TOPP, and real-world data, and (2) generation of the TOPP dataset using the BOMP approach with a factor 100x speed compared to the existing TOPP procedures.

BrightBox then determined near optimal sequences that can easily be implemented based on the Taylor Engineering TOPP results using the PWA technique. The resulting near-optimal sequences were compared with the BrightBox Optimal Control results. Criteria for success were: (1) automatic quantification of error between TOPP, PWA controller, and BrightBox Optimal control performance, (2) quantified reduction of the approximation error.

Identification of BrightBox PWA controllers from TOPP datasets required the estimation of both the control parameters and the coefficients of the hyper-planes defining the partition of the state-input domain where the controller is near-optimal. The identification problem included a classification problem where each data point must be associated to the most suitable partition. When such partition is fixed a priori the classification is very simple, and estimation of the controllers can be carried out by resorting to standard linear identification techniques. When the partition is estimated along with the sub-models the regions must be shaped to the clusters of data, and the strict relation among data classification, parameter estimation and partition estimation makes the identification problem challenging. We will exploit the particular structure of the TOPP dataset and employ an iterative algorithm that sequentially estimates the parameters of the model and classifies the data through the use of adapted weights by using support vector classifiers. The proposed approach has several advantages. In fact, in addition to be systematic, model based and computationally tractable, it also provides a sub-optimality metric of the resulting PWA controller

The project goal was to achieve a 100x speed improvement in computing the current Taylor Engineering chilled-water plant optimization approach by using the Berkeley Library for Optimization Modeling (BLOM). BLOM is a language for modeling and efficiently solving optimization problems for dynamic nonlinear systems.

2.1.4 AutoCx Development

Over the course of the first two years of BrightBox software development and deployments, we realized that we needed a robust, systematic method for validating individual component configuration and operational readiness. At first we discovered these issues in an ‘indirect’ manner, by debugging system deployments when observed performance did not match the expected. There are cases where we identified component mis-configuration or equipment that was broken – and these issues were the cause of reduced performance.

AutoCx was developed in part to actively seek and discover these issues, mimicking the approach used by an operator or technician who would review an installation using the building control system interface. The basic approach is to both passively and actively read/write data to the running systems and then analyze the collected data to see if it matches expectations. Where data does not match, it indicates a system configuration or performance problem with a very low rate of false-positives.

2.1.5 Commercialization

At the time of this project, BrightBox already had an entry level commercial product at the demonstration phase in approximately 6 facilities and in early 2015 acquired the first paying customer. The product was limited to interacting with controls systems manufactured by Automated Logic Controls (Atlanta, GA) and packaged rooftop direct-exchange (DX) cooling systems, hot-water boiler plants, and variable air volume reheat (VAVR) distribution systems. As part of this project, BrightBox expanded our component library to increase our ability to model ‘built-up’ system and more complex chiller plants greatly increasing the commercialization potential.

2.1.6 Future potential for DoD

The magnitude of the potential benefit we sought to demonstrate in this project for DoD was large. DoD spends approximately $4 billion per year on facility energy consumption to power and fuel over 500 military installations worldwide. These installations include over 500,000 buildings and structures. HVAC system energy use represents roughly 40 percent of this value, which equates to approximately $1.6 billion. A savings of 25% across this portfolio of existing buildings represents $400 million annually.

DoD has a large number of existing buildings with packaged equipment, built-up systems, and chilled water plants of various designs and sizes that could have benefited from the BrightBox controls approach if successful. DoD facility energy expenditures at the entire NSAM site are estimated to be in the range of $2 million per year. This approach aims to save approximately 25% of the HVAC energy used at the site in the subject buildings. We estimate the value of this savings to be approximately $150,000 per year. If this approach was scaled to apply to the entire NSAM site, we estimate savings of approximately $300,000 per year.

Similar savings could have been expected at other DoD installations, and for more complex buildings the values would increase. On a recent data center project with a chilled water plant of ~4,400 tons, Taylor Engineering reported that the life-cycle cost savings over 15 years were projected at $1,500,000 using a 4.9% real discount rate.

The NSAM site is relatively small compared to other large DoD sites. The NSAM provided an excellent demonstration opportunity because of the outstanding staff, wide mix of systems, and close proximity to the BrightBox main office, but the real value to DoD will be to scale this approach to other sites that are significantly more energy intensive.

At the time of the project, the BrightBox optimization software could have been used at any DoD site that employs Automated Logic Corporation (ALC) building controls. The BrightBox product development roadmap included extending the list of control systems with which we can interact and we anticipated that the number of DoD sites where this solution can be applied would have expanded rapidly in the next few years following the project.

AutoCx could be deployed widely at DoD sites – both in new construction projects and in existing buildings. The BrightBox AutoCx software product was designed to deploy simple tests in a broad, repeatable, ubiquitous fashion. Commissioning has been called the most cost-effective energy efficiency measure available today [30], with the potential to improve operational efficiency across many building types and deployments.

2.2 TECHNOLOGY DEVELOPMENT

The technology that is the subject of this project can be thought of in two parts: 1) the cloud-hosted software (the BrightBox software) that provides the advanced control and autonomous commissioning services, and 2) the building control system including the sensors and actuators that are integral to that system.

At NSAM, the building control systems in Watkins and Glasgow were augmented to provide data points required for monitoring and verification activities and calculations.

2.2.1 Software Technology Development

Before this project began, the BrightBox system was able to connect with, model, and provide real-time optimal control to one standard building HVAC system type: “packaged” rooftop air-conditioning units connected to a variable-air-volume reheat (VAVR) system. In order to deploy the technology at NSAM, and make it suitable eventually for other DoD sites, we needed to extend the library of components to include HVAC system types and components found at Glasgow and Watkins Hall, namely chilled-water cooling systems including air-cooled chillers and chilled-water pumps, which are components commonly found in medium to large size commercial and industrial buildings.

The BrightBox system software was successfully extended to include chilled water systems, air-cooled chillers, and chilled water pumps as part of this project. To validate that these new software components were implemented correctly, BrightBox software was tested against the Taylor Engineering TOPP Model Chilled-Water Plant modeling software.

The graphic below shows a performance ‘map’ for a chilled water pump software model component. Data shown in blue and black is manufacturer catalog data showing pump speed, pumping performance, and pump efficiency. The graphical data shown in red and green are two different formulations of pump efficiency models, with the difference between the two being that the red model uses pump speed as an independent variable, whereas the green model does not.

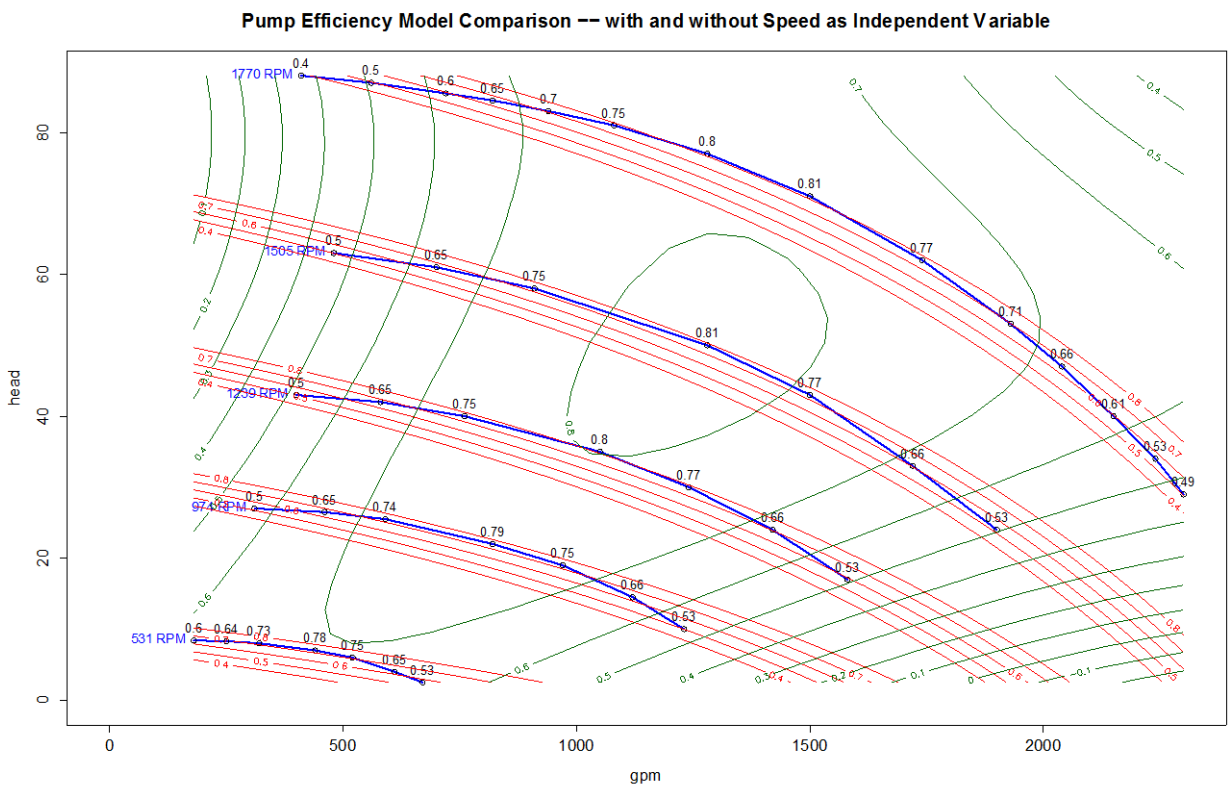

Figure 4. BrightBox Pump Model

The graphic below shows a comparison of the 'BrightBox' chilled-water plant modeling system results as compared to the Taylor Engineering 'TOPP Model' chilled-water plant modeling system results. Data here is broken down to show cooling tower performance, chilled-water pump performance, condenser water pump performance, and chiller performance each on separate graphs. Note that the performance is not identical in each case, but it is close enough to validate that the systems are working. The different performance is due to each modeling system arriving at optimal control decisions in a slightly different manner, with slightly different resulting final decisions.

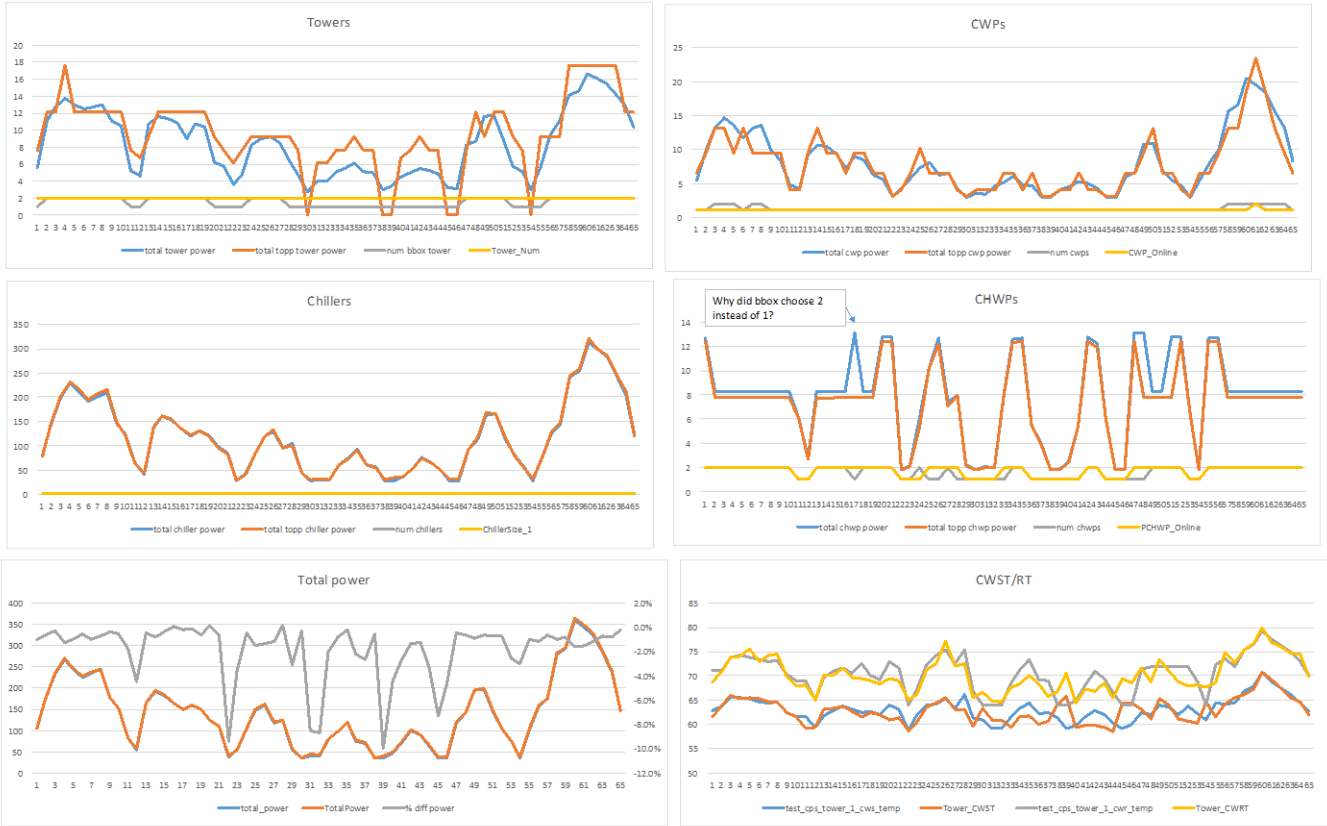

Figure 5. BrightBox Chilled Water Plant Modeling Comparison

The graphic below is a 'total plant power' comparison between the BrightBox system and the Taylor Engineering system. In the graphic the blue line represents the BrightBox result and the orange line represents the Taylor Engineering result. The blue line is hard to see because it is directly under the orange line. The gray line shows the percent different between the two and is read on the right-side axis. Note that the gray line is always at value 0% or below, indicating that the BrightBox optimal control decision-making is better than the Taylor Engineering result in that it delivers lower total plant power to deliver the same cooling result.

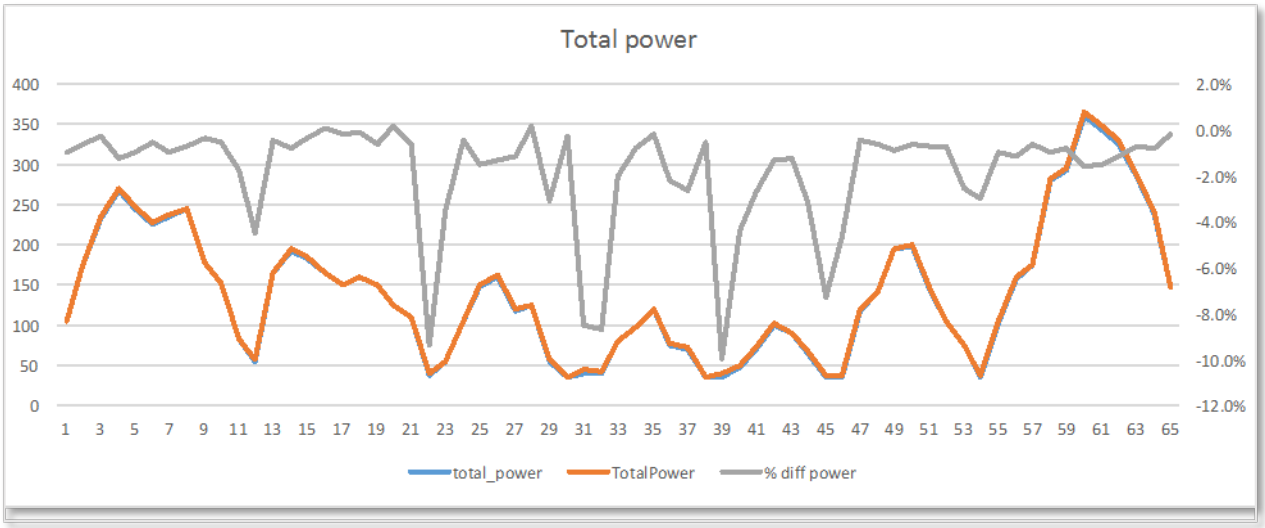

Figure 6. BrightBox Modeling Comparison Detail

We also extended the BrightBox system user interface in a rudimentary way to allow for the inclusion of chilled-water plant systems and components. The screen below shows one example from the revised UI.

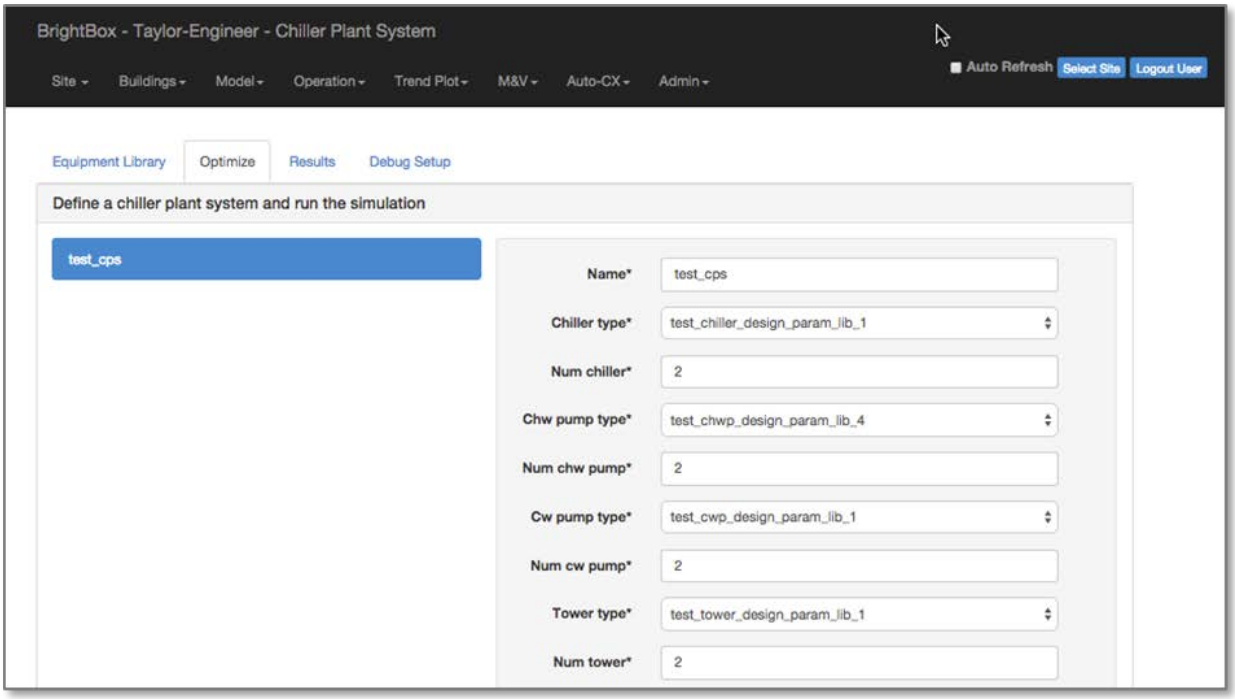

Figure 7. BrightBox Plant Modeling User Interface

2.2.2 Building Control Systems Technology Development

To support chilled-water system component model development and validation as well as monitoring and verification activities, the building control systems at Glasgow and Watkins were investigated and augmented as needed to provide required sensors and data streams.

The images below show the BrightBox team investigating the site as well as existing energy meters located at the site that were going to be used as part of the study.

These are existing BTU (energy) meters on the chilled water systems.

The buildings at NSAM have AMI (Advanced Metering Initiative) electrical meters at each building, but unfortunately the connective data-network to make that data available was not functioning, so this data was not available for the project.

The following matrix shows analysis and metering-data design performed for the subject buildings. This matrix formed the basis for a substantial sensor/meter installation project that was performed in each building. A larger version of this metering plan as well as the metering installation contract documents are provided as appendices.

NSAM / NSP Chilled Water Plant Metering Plan — January 17, 2015

Legend:	
	required meter and data already available, no change needed
	data not available, but not required for metering plan
	required data not available, need to install sensors / meters
	data sources uncertain, need to confirm this data in the field

	Building	Watkins (#245)				Ingersoll (#330)							Glasgow (#305)			
Chiller Info:	Tag:	CH 1	CH 2	CH 3	system	CH 1	CH 2	system	CH 3	system			CH 1	CH 2	CH 3	system
	Type:	air-cooled	air-cooled	air-cooled	primary only variable flow with bypass	air-cooled	air-cooled	primary only variable flow no bypass	water-cooled	primary only constant flow			air-cooled	air-cooled	air-cooled	primary only constant flow
	Manufacturer:	York	York	Trane		Carrier	?		Trane (?)				York	York	York	
	Model:	?	?	?	--	30HR080	?	--	--	--			YCAL ?	YCAL ?	YCAL ?	--
	Nominal Tons:	30	30	?	60	75	?	?	?	?			?	?	?	?
	Networked Controller:	yes	yes	no	--	yes	no	--	no	--			yes	yes	yes	--
	Serves:	B245	B245	B246	245+246	-->	-->	main building	--	data center			-->	-->	-->	3305
	Notes:	new	new	not sure this is operating	--	dates to 2008	older?	--	--	--			--	--	--	--
Cooling Tower / Dry-Cooler Info:	Tag:								CU 1							
	Type:	--	--	--	--	--	--	--	dry-cooler	primary only constant flow			--	--	--	--
	Manufacturer:								Colmac							
	Model:								ARV 90 16							
	Nominal Tons:	--	--	--	--	--	--	--	?	?			--	--	--	--
	Nominal Flow:	--	--	--	--	--	--	--	224 gpm	--			--	--	--	--
	Networked Controller:								no							
	Notes:															
CHW BTU meter:	[BTU] and [BTU/hr]	{@system}	{@system}	{@system}	yes	no	no	no	no	no			{@system}	{@system}	{@system}	yes
CHW flow:	[gpm]	{@system}	{@system}	{@system}	yes	{@system}	{@system}	yes	no	no			{@system}	{@system}	{@system}	yes
evaporator dp:	[ft] or [psi]	yes	yes	no	--	yes	yes	--	yes	--			no	no	no	--
CHWS temp:	[F]	yes	yes	yes	yes	yes	yes	yes	yes	yes			yes	yes	yes	yes
CHWR temp:	[F]	yes	yes	yes	yes	{@system}	{@system}	yes	yes	yes			yes	yes	yes	yes
Auto Isolat on Valve:		yes	yes	no		yes	yes		no				yes	yes	yes	
Bypass / Min Flow Valve:					yes	no	no	no								
CW BTU meter:	[BTU] and [BTU/hr]								no	no						
CW flow:	[gpm]	--	--	--	--	--	--	--	no	no	no	no	--	--	--	--
condenser dp:	[ft] or [psi]								yes	no						
CWS temp:	[F]	--	--	--	--	--	--	--	yes	yes			--	--	--	--
CWR temp:	[F]	--	--	--	--	--	--	--	yes	yes			--	--	--	--
Auto-Isolat on Valve:		--	--	--	--	--	--	--	no	--			--	--	--	--
Bypass / Min Flow Valve:		--	--	--	--	--	--	--	yes				--	--	--	--
Chiller Electrical Power:	[W]	no	no	no	--	no	no	--	no	--			no	no	no	--
Tower Electrical Power:	[W]								no							
	units	P 3	P 4	P 5		P 1	P 2		PCH 3	PCH 4			CHWP 1	CHWP 2		
Notes:		also CHP 1	also CHP 2	also CHP 3					CHW	CHW						
Nominal Flow:						180 gpm	180 gpm									
VFD:		yes	yes	yes		yes	yes		no	no			no	no		
networked:		yes	yes	yes	--	yes	yes	--	no	no			no	no	--	--
current:	[Amp]	yes	yes	yes	--	yes	yes	--	no	no			no	no	--	--
speed:	[Hz] or [%]	yes	yes	yes	--	yes	yes	--	no	no			no	no	--	--
power:	[kW]	yes	yes	yes	--	yes	yes	--	no	no			no	no	--	--
pump dp:	[ft] or [psi]	no	no	no	--	no	no	--	no	no			no	no	--	--
system dp:	[ft] or [psi]	--	--	--	yes	--	--	yes	--	--			--	--	--	--
	units								PCH-1	PCH-2	PAC-1	PAC-2				
Notes:		--	--	--	--	--	--	--	CW	CW	CW	CW	--	--	--	--
Nominal Flow:		--	--	--	--	--	--	--	80 gpm	80 gpm	150 gpm	150 gpm	--	--	--	--
VFD:		--	--	--	--	--	--	--	no	no	no	no	--	--	--	--
networked:									no	no	no	no				
current:	[Amp]								no	no	no	no				
speed:	[Hz] or [%]								no	no	no	no				
power:	[kW]								no	no	no	no				
pump dp:	[ft] or [psi]	--	--	--	--	--	--	--	no	no	no	no	--	--	--	--

This is a list of the points added to the subject systems:

Watkins Hall (Building 245)

- CH-1 (air cooled)
  - Power meter (Veris, Modbus)

- CH-2 (air cooled)
  - Power meter (Veris, Modbus)

- CH-3 (air cooled)
  - Power meter (Veris, Modbus)
  - Evaporator dp sensor
    (field verify if new pipe taps required)

- P-3 (CHW pump)
  - Inlet/outlet dp sensor
    (field verify if new pipe taps required)

- P-4 (CHW pump)
  - Inlet/outlet dp sensor
    (field verify if new pipe taps required)

- P-5 (CHW pump)
  - Inlet/outlet dp sensor
    (field verify if new pipe taps required)
- FC-2-E
  - CHW coil dp sensor
    (field verify if new pipe taps required)
  - CHWS temperature sensor
  - CHWR temperature sensor

- AH-3-2
  - CHW coil dp sensor
    (field verify if new pipe taps required)
  - CHWS temperature sensor
  - CHWR temperature sensor

Ingersoll Hall (Building 330) – Main Building System

- CH-1 (air cooled)
  - Power meter (Veris, Modbus)

- CH-2 (air cooled)

- Power meter (Veris, Modbus)

- P-1 (CHW pump)
  - Inlet/outlet dp sensor
    (field verify if new pipe taps required)

- P-2 (CHW pump)
  - Inlet/outlet dp sensor
    (field verify if new pipe taps required)

- SF-2 (CHW AHU with cooling)
  - Branch-1 HW coil
    - dp sensor
    - HWS temp sensor
    - HWR temp sensor
  - Branch-2 HW coil
    - dp sensor
    - HWS temp sensor
    - HWR temp sensor
  - Branch-3 HW coil
    - dp sensor
    - HWS temp sensor
    - HWR temp sensor

- SF-2 (CHW AHU with cooling)
  - CHW coil dp sensor
    (field verify if new pipe taps required)
  - CHWS temperature sensor
  - CHWR temperature sensor
  - SF-2 Power Meter (Veris, Modbus)
  - EF-3 Power Meter (Veris, Modbus)

<u>Ingersoll Hall (Building 330) – Data Center System</u>

- CH-3 (water cooled)
  - Power meter (Veris, Modbus)
  - CHW BTU meter
    - Flow meter (insertion-type, mag flow, Onicon)
    - New CHWS and CHWR sensors
- PCH-3 (CHW pump)
  - Power meter (Veris, Modbus)
  - Inlet/outlet dp sensor
    (field verify if new pipe taps required)

- PCH-4 (CHW pump)
  - Power meter (Veris, Modbus)
  - Inlet/outlet dp sensor
    (field verify if new pipe taps required)

- CU-1 (dry cooler)
  - Power meter (Veris, Modbus)
  - CW BTU meter (total CW flow = CH-3 branch + CRAC branch)
    - Flow meter (insertion-type, mag flow, Onicon)
    - New CWS and CWR sensors

- PCH-1 (CW pump – CH-3 branch)
  - Power meter (Veris, Modbus)
  - Inlet/outlet dp sensor
    (field verify if new pipe taps required)

- PCH-2 (CW pump – CH-3 branch)
  - Power meter (Veris, Modbus)
  - Inlet/outlet dp sensor
    (field verify if new pipe taps required)

- PAC-1 (CW pump – CRAC branch)
  - Power meter (Veris, Modbus)
  - Inlet/outlet dp sensor
    (field verify if new pipe taps required)

- PAC-2 (CW pump – CRAC branch)
  - Power meter (Veris, Modbus)
  - Inlet/outlet dp sensor
    (field verify if new pipe taps required)

- CW BTU meter (CRAC branch)
  - Flow meter (insertion-type, mag flow, Onicon)
  - New CWS and CWR sensors

<u>Glasgow Hall (Building 305)</u>

- CH-1 (air cooled)
  - Power meter (Veris, Modbus)
  - Evaporator dp sensor
    (field verify if new pipe taps required)

- CH-2 (air cooled)
  - Power meter (Veris, Modbus)

  - Evaporator dp sensor
    (field verify if new pipe taps required)

- CH-3 (air cooled)
  - Power meter (Veris, Modbus)
  - Evaporator dp sensor
    (field verify if new pipe taps required)

- CHWP-1 (CHW pump)
  - Power meter (Veris, Modbus)
  - Inlet/outlet dp sensor
    (field verify if new pipe taps required)

- CHWP-2 (CHW pump)
  - Power meter (Veris, Modbus)
  - Inlet/outlet dp sensor
    (field verify if new pipe taps required)

- FC-B-06
  - CHW coil dp sensor
    (field verify if new pipe taps required)
  - CHWS temperature sensor
  - CHWR temperature sensor

- FC-B-09
  - CHW coil dp sensor
    (field verify if new pipe taps required)
  - CHWS temperature sensor
  - CHWR temperature sensor

- FC-1-03
  - CHW coil dp sensor
    (field verify if new pipe taps required)
  - CHWS temperature sensor
  - CHWR temperature sensor

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

2.3.1 Performance Advantages

The goal for the BrightBox HVAC optimization technology was to increase energy efficiency by providing optimized control sequence of operation for existing controls infrastructures by updating optimized HVAC control algorithms quickly and on a regular basis (typically every 5 minutes).

2.3.2 Cost Advantages

As a software solution, BrightBox offers very low up first costs. Current typical sales cycles involve an offer of a no-cost demonstration to show what the BrightBox software can do and once energy savings have been quantified, the savings are shared between BrightBox and the customer so both parties share the savings.

AutoCx delivers the benefits of commissioning to new and existing buildings at a greater than 10x reduction in cost over traditional commissioning deployment methods.

2.3.3 Performance Limitations

BrightBox currently works only by optimizing the controls of existing HVAC equipment. Energy saving performance could be improved by expanding the BrightBox approach (for customers where it makes economic sense) to also retrofitting and changing installed HVAC equipment. Currently, BrightBox only works with HVAC control systems manufactured by Automated Logic Controls (A subsidiary of United Technologies). In its current form, an active internet connection is required to implement the BrightBox optimization. Future releases may include standalone or non-internet enabled solutions that may be applicable specifically in the highly secure DoD networks.

One significant limitation to deploying this technology became clear over the course of this project. The BrightBox optimization system requires the base building systems and components to be installed and working correctly in order for it to function properly. As we found out with the Glasgow chillers, if the equipment is not installed or operating correctly then those issues must be resolved first before any optimization can occur.

2.3.4 Cost Limitations

We don’t see any cost limitations with the BrightBox approach because we demonstrate cost savings first and then charge a portion of the savings for providing the service. Both the customer and BrightBox achieve a positive economic result using this approach.

2.3.5 Potential Barriers to Acceptance

Few barriers have arisen regarding the product and technology in the commercial sector. Every building operator we have encountered in the course of launching the BrightBox service embraces the idea that BrightBox can provide optimized HVAC controls algorithms. Early reports indicated that the building operators wanted a big button to turn BrightBox optimization off first if complaints or problems occur – so we now have a big “off” button integrated into the ALC interface for the BrightBox client software.

However, several barriers exist with respect to wide-spread DoD implementation of BrightBox HVAC optimization.

1. The recent hacking of Target Co. customer credit card information via a third-party HVAC contractor has raised concerns within all Federal agencies (not just DoD) regarding providing any outside contractor with direct access inside a secure network.

2. Although BrightBox is working to expand our product offering to additional controls platforms, currently the BrightBox optimization only works in buildings equipped with Automated Logic Controls (ALC)
3. Many DoD buildings would require extensive infrastructure upgrades to legacy/outdated/ or non-existent BAS in order for HVAC data analytics solutions such as BrightBox optimization to be deployed.

3.0 FACILITY/SITE DESCRIPTION

Home to over 15 tenant commands, NSAM Monterey (Monterey, CA) provides primary support to the Naval Postgraduate School (NPS), Navy Research Lab (NRL), and the Fleet Numerical Meteorology and Oceanography Center (FNMOC). NPS is the largest producer of advanced graduate degrees for the Department of Defense and proudly graduates thousands every year from all services and from over 50 countries. NRL provides all scientific and weather modeling as well as atmospheric and aerosol studies. FNMOC provides the highest quality, most relevant and timely worldwide Meteorology and Oceanography support to U.S. and coalition forces from FNMOC's 24x7 Operations Center in Monterey. NSA Monterey supports over 160 buildings which are located on more than 626 acres.

3.1 GENERAL FACILITY/SITE SELECTION CRITERIA

3.1.1 Geographic Criteria

There are no geographic criteria that impact whether or not this technology can be deployed. It can be applied to any HVAC system in any climate. At the same time, it likely makes more sense to deploy this type of energy efficiency technology in climates with high cooling and/or heating demands in order to maximize returns from the time and effort involved in deploying the system.

3.1.2 Facility Criteria

Because the current BrightBox technology addresses only packaged rooftop direct-exchange (DX) cooling systems, hot-water boiler plants, and variable air volume reheat (VAVR) distribution systems, we wanted to find a facility with a more 'built-up' chilled water plant. But it was also important that it not be too complicated. We wanted to find one or more buildings with relatively simple chilled water plants to extend the technology.

3.1.3 Facility Representativeness

Facility representativeness was not a factor. DoD has a large number of existing buildings with packaged equipment, built-up systems, and chilled water plants of various designs and sizes that can benefit from the BrightBox controls approach.

3.1.4 Other Selection Criteria

It was important to BrightBox to do the demonstration project in a relatively low security DoD environment both physically and electronically. Because BrightBox is a software solution, we need access to the HVAC controls via the internet through firewalls etc. A facility that was electronically isolated or 'locked-down' would not work at this stage. We are aware that most other DoD facilities are more secure and that we will need to develop a 'box on site' solution if we expect significant penetration into the DoD market.

During this project, the cyber-security awareness at NSAM was increased substantially and it moved from being a relatively 'open' system to one that implemented many standard DoD policies. As part of this escalation, a thorough cyber-security audit was performed and all of the operational BrightBox system components continued to function and passed the audit review.

Because the BrightBox system was not specifically evaluated during this review, it was not determined whether the system met the RMF requirements or if an Interim Authority To Test (IATT) was attained.

3.2 DEMONSTRATION FACILITY/SITE LOCATION AND OPERATIONS

The demonstration site was Naval Support Activity Monterey (NSAM). The largest tenant of NSAM is the Naval Post Graduate School (NPS). We chose two buildings assigned to the NPS for the demonstration project.

3.2.1 Demonstration Site description

NSAM is located relatively close (less than a 2-hour drive) to the BrightBox Technologies office in Berkeley, California, which will facilitate easy interaction with site staff and BrightBox presence on the campus as needed. Further, NSAM is served by Sunbelt Controls, a controls contractor partner of BrightBox Technologies and collaborator/channel-partner of our technology platform. Sunbelt Controls has been engaged as an active partner in the proposed ESTCP project, and they will be a valuable, knowledgeable, and capable partner in this effort.

The HVAC systems at NSAM are largely controlled with Automated Logic Corporation (ALC) control hardware and software. BrightBox Technologies has partnered with ALC to provide our software as an integrated "plug-in" to the ALC system.

BrightBox Technologies staff have corresponded with and visited NPS staff, including Public Works Officer LCDR Antillon, Deputy Public Works Officer Matthew Suess, Ken Jenvey APPS Support Contractor for NAVFAC SW (since replaced by Douglass Taber) and other key members of the operations staff. We have a good understanding of the systems in place and NSAM and, in collaboration with NSAM staff, have identified the following likely subject buildings for our demonstration. These buildings represent a wide range of systems, components, and HVAC design approaches onto which we can deploy the BrightBox optimal control approach to demonstrate the technology's broad range of applicability.

Name & Main Uses	Cooling Systems	Zonal Systems	Existing Metering
Glasgow Hall • Computer Science Department	System 1: 3 x 60-ton air-cooled chillers, 2 headered CHW pumps, constant-speed variable-flow primary-only configuration System 2: 2 x 50-ton air-cooled chillers with dedicated constant speed CHW pumps and CHW system bypass	2-pipe CHW fan coils, 4-pipe CHW & HW fan coils, CAV reheat, 2-stage packaged cooling-only AC unit with economizer, large built-up AHU with "fan wall," HW, CHW, and economizer	System 1 and System 2 CHW & HW system flow and BTU meters, building steam meter, building power meter
Watkins Hall • Building 245	System 1:single chilled water system, 3 air-cooled chillers @30 tons each. 3 headered chilled water pumps with variable flow. Primary only configuration	2-pipe and 4-pipe systems, a mixture of zonal fan coils with and without economizers and VAV 'cooling only' along with some reheat zones	Existing chilled water BTU meter, building power meter.

**In our original proposal, Ingersoll Hall was also included as a test site. However, as we initiated the demonstration, we found out that Ingersoll Hall is scheduled for a major physical retrofit that precludes the implementation of the BrightBox Optimization during the ESTCP project timeframe. Correspondence documenting electronic transmissions regarding the retrofit and subsequent acceptance by ESTCP management of a two building EW201409 demonstration project are attached as Appendix E.

3.2.2 Key Operations

NSAM supports the Naval Post Graduate School (NPS), Navy Research Lab (NRL), and the Fleet Numerical Meteorology and Oceanography Center (FNMOC).

3.2.3 Location/Site Map

3.2.3.1 General location in California.

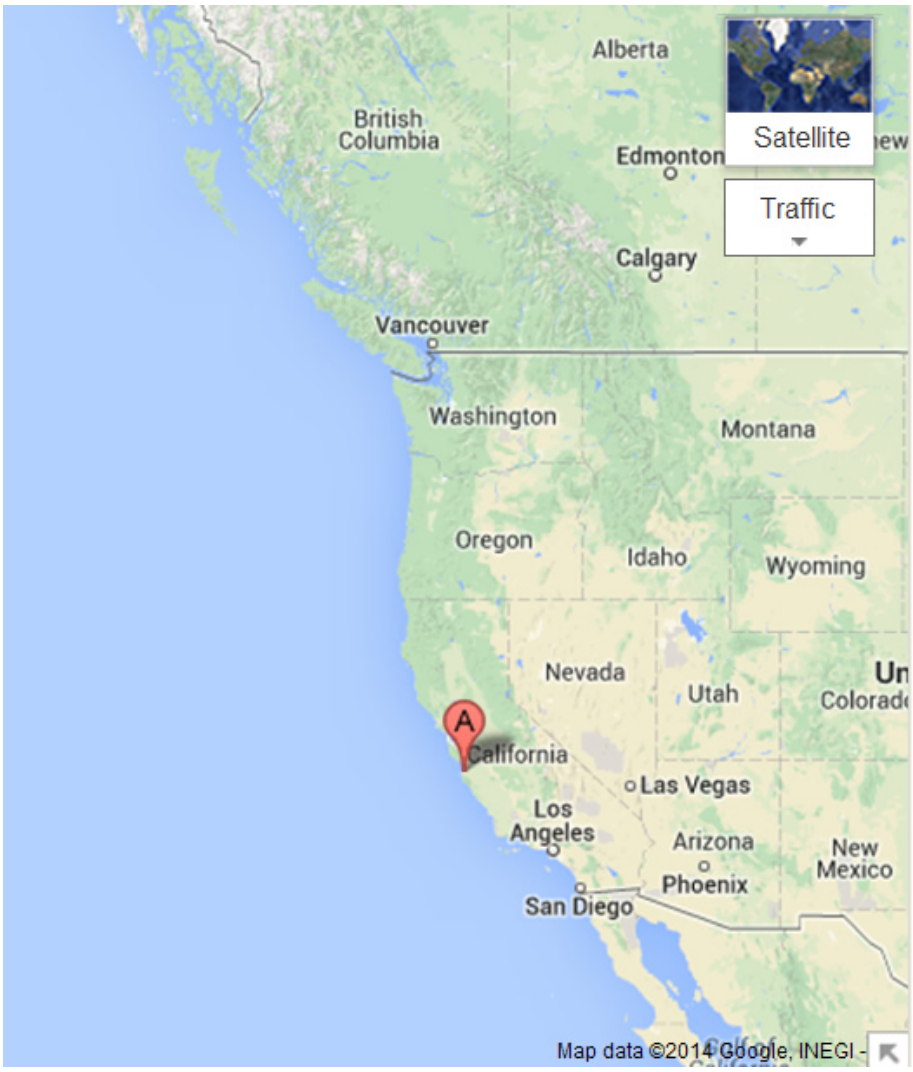

Figure 8. Location in California

3.2.3.2 Location in San Francisco Bay Area

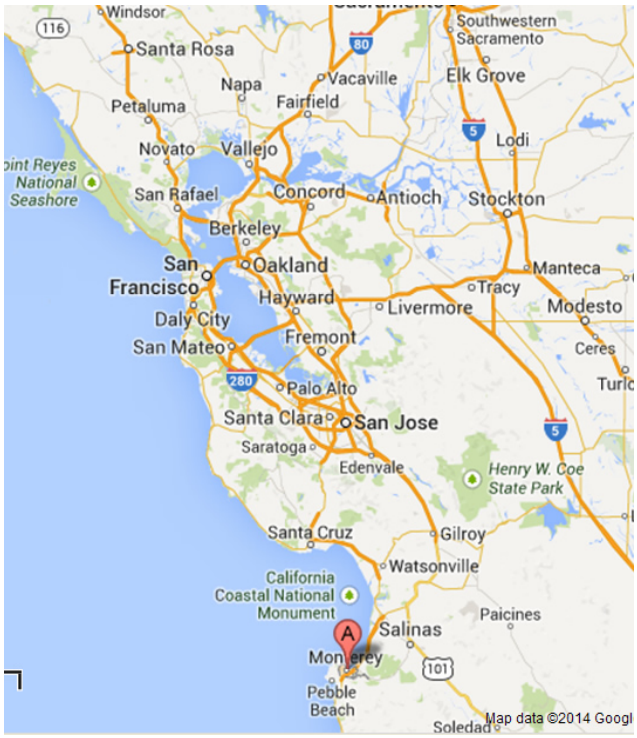

Figure 9. Location in San Francisco Bay Area

3.2.3.3 Location in Monterey

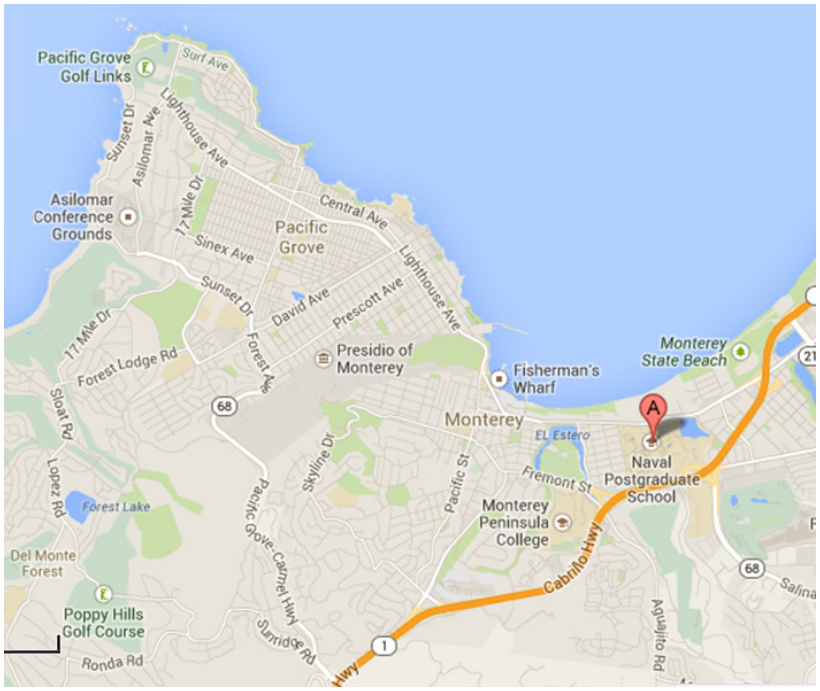

Figure 10. Location in Monterey

3.2.4 NSAM map

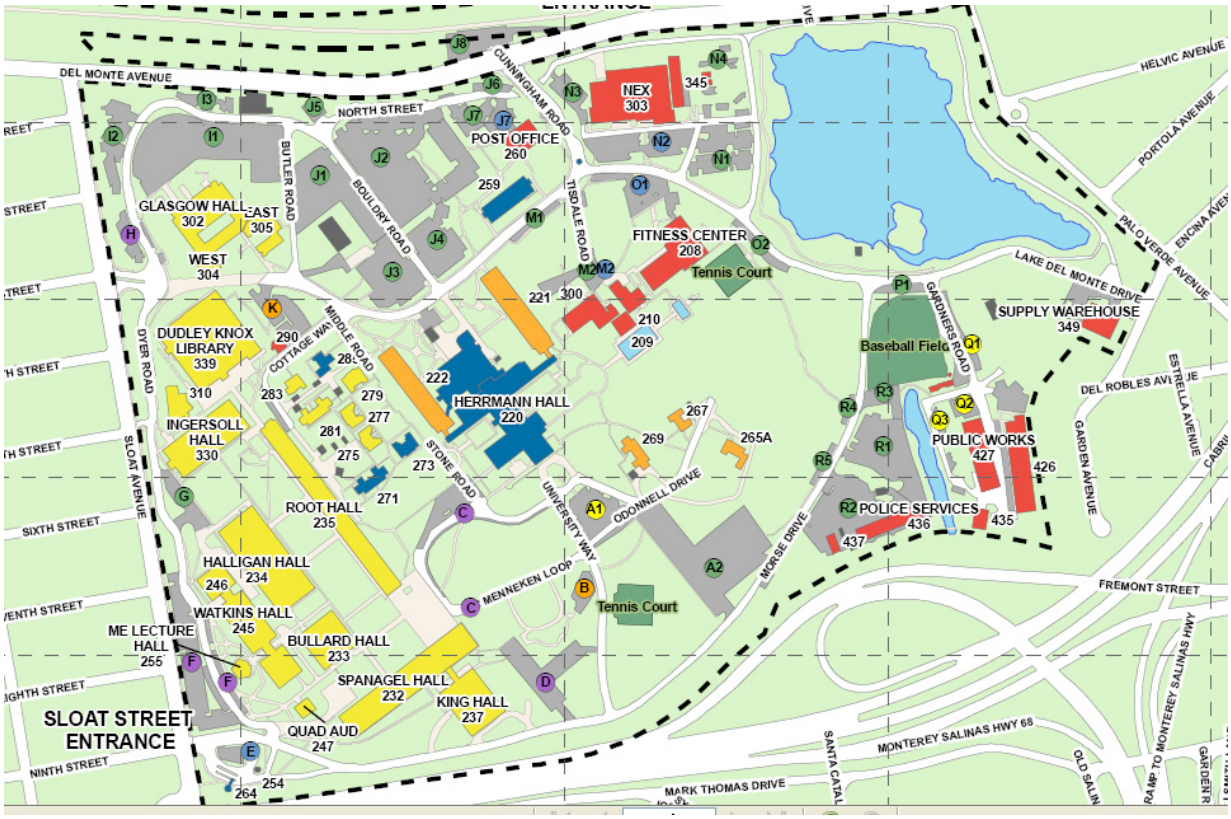

Figure 11. NSAM map

3.3 SITE-RELATED PERMITS AND REGULATIONS

Because BrightBox is a software solution, no site-related permits will be required during the course of this demonstration project.

3.4 REGULATIONS

No regulations that we are aware of.

3.4.1 Environmental Permits

No environmental permits required that we are aware of.

3.4.2 Agreements

No agreements were required to perform the technology deployment at NSAM. The key point of contact was the NSAM Public Works Officer who is LCDR Oscar Antillion. LCDR Oscar Antillion participated in the site visit meeting that occurred between BrightBox Technologies, Taylor Engineering, Sunbelt Controls, and NSAM personnel at NSAM on July 18th, 2014. LCDR Oscar Antillion was very encouraging and specifically expressed the sentiment that NSAM would be supportive of the project and that they were excited to be testing the latest technology at their facility and welcomed the opportunity to lead the Navy.

3.4.3 Military Requirements

Information assurance has been identified as serious obstacle to rolling out BrightBox Technologies product in its current form to other DoD facilities. In fact, NSAM personnel during the first site visit suggested that if the team could design a solution to successfully overcome the information assurance obstacles as part of this project, that would be a very welcome outcome.

However, information assurance is not a problem at the NSAM site. We have already been granted remote access to the NSAM building control systems that we need for the project.

As mentioned above, the cyber-security concerns at NSAM escalated during the course of the project. The BrightBox encrypted data connection (outbound-only using HTTPS) passed the security review, which was a very positive result.

3.5 Property Transfer

As part of this demonstration project, we installed end-use power/fuel meters at key pieces of equipment in the buildings and integrate these new meters into the existing control system. Now that the project is complete, these meters will remain in place and operational and will become DoD property.

NSAM expressed their desire to leave all meters in place. We intentionally installed them in an integrated manner with the existing building control systems so they could be left in place and continue to operate with no disruption to the buildings.

4.0 PERFORMANCE OBJECTIVES

We set performance objectives for this project based on our experience to date in commercial buildings. The BrightBox software solution has been deployed in roughly a dozen commercial buildings and we have achieved savings of 20% to 35% of HVAC energy. This experience is restricted to packaged HVAC units, not chiller plants. An objective of the current project was to extend the BrightBox system to include built-up chiller plants so naturally we do not have any existing data. Therefore, it makes sense to set the energy objective at the low end of the range – 20% of HVAC energy.

The site has a number of meters in place in each building so we won't be increasing the number of metered buildings. However, we plan to add specific meters according to the following plan:

Glasgow Hall:

- Three (3) Veris Modbus Power Meters, One (1) for each Chiller
- Three (3) Chiller Evaporator DP Sensors, One (1) for each Chiller
- Two (2) Veris Modbus Power Meters, One (1) for each Chilled Water Pump
- Two (2) Chilled Water Pump DP Sensors, One (1) for each Pump

Watkins Hall:

- Three (3) Veris Modbus Power Meters, One (1) for each Chiller
- One (1) Chiller Evaporator DP Sensor for Chiller #3
- Three (3) Chilled Water Pump DP Sensors, One (1) for each Pump
- One (1) FC-2-E Chilled Water DP Sensor
- Two (2) FC-2-E Chilled Water Temperature Sensors (strap-on sensors)
- One (1) AH-3-2 Chilled Water DP Sensor
- Two (2) AH-3-2 Chilled Water Temperature Sensors (strap-on sensors)
- Two (2) Chilled Water Strap-on Sensors located next to two (2) existing well sensors for lag comparison. Location to be determined (B233 Chiller is the first choice)

We don't currently have any sub-metering information available to make a system economic analysis of the potential economic savings at the start of the project. We only have electric bill information for the one meter that serves the entire NSAM site. We have no information on energy consumption or costs available for any of the individual buildings. As we get into the project, monitor the buildings and apply the BrightBox technology, we will begin to be able to provide estimates of the system economics. However, we project that a 20% reduction in energy use should lead to a reduction in energy costs of a similar amount – 20%.

We are fortunate that we can turn the BrightBox software on and off remotely whenever we want. This allows us to continuously collect baseline data. Baseline data is whatever the system is doing when the BrightBox software is turned off.

The goal was for the BrightBox system to increase energy security at NSAM (and potentially other military installations in the future) by reducing energy density. BrightBox will contribute to cost avoidance reducing energy usage. The goal was for the BrightBox system to contribute to reducing GHG emission by reducing energy usage.

4.1 "TABLE 1" SUMMARY OF PERFORMANCE OBJECTIVES

4.1.1 Table 1. BrightBox Performance Objectives – ESTCP 201409

Table 1. Performance Objectives

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives				
Facility Energy Usage	Energy Intensity (kWh/ft^2)	Meter readings of energy used by installation; square footage of buildings using energy; sub-metered HVAC system data	20% Reduction in HVAC system energy use compared to baseline, 7.5% reduction in overall energy use.	No data collected. Demonstration not performed.
System Economics*	Savings to investment ratio (SIR)	Measured reduction in HVAC system energy costs	SIR >= 1.67**	No calculation performed.
BOMP Library Expansion	Number of BOMP Library Components	Number of BOMP Library Components	Expand the BOMP component library to include 13 new components	Only hydronic components completed (5 of 13)
BrightBox Control Software Generation	Models Generated	Models Generated	The BrightBox software will be able to successfully generate new control software automatically for each of the two buildings.	Completed in simulation, not deployed.
TOPP model dataset generation speed	Time to generate TOPP model data	Time to generate TOPP model data using BrightBox platform and Taylor platform	100x improvement in the time to generate TOPP model data using the BrightBox platform versus the Taylor platform.	TOPP data set generation and BrightBox solution generation rougly same time to complete. No improvement.
AutoCx number of objects tested and number of issues found	Number of objects tested and number of issues found	Number of objects tested and number of issues found	All testable objects at the demonstration site have been tested and number of issues found has been field verified.	Half of testable objects tested.
Qualitative Performance Objectives				
Satisfaction with BrightBox Control Software	Facility Surveys (a sample survey is provided in Appendix C)	Positive Responses on User Surveys	Based on survey responses, the facilities staff at NSAM indicate that they feel the new control sequences generated by the BrightBox software are adequate/functional and will remain in use.	No surveys issued.

*For "System Economics" - Refer to the NIST Building Life Cycle Cost program, available on the DOE website: http://www1.eere.energy.gov/femp/information/download_blcc.html#blcc

** We don't currently have any sub-metering information to use to make a system economic analysis of the potential economic savings at the start of the project. We only have electric bill information for the one meter that serves the entire NSAM site. We have no information available for any of the individual buildings. As we get into the project, monitor the buildings and apply the BrightBox technology, we will begin to be able to provide estimates of the system economics.

4.2 PERFORMANCE OBJECTIVES DESCRIPTIONS

4.2.1 Facility Energy Usage

4.2.1.1 Purpose

Reduce facility energy usage via the BrightBox HVAC control optimization application.

4.2.1.2 Metric

Measured facility energy usages (kWh) with the BrightBox application running compared to the with the BrightBox application not running (kWh).

4.2.1.3 Data

Data collected using the BrightBox system from the HVAC controls systems at the NSAM site. Data from energy and power meters installed on HVAC equipment at the NSAM site.

4.2.1.4 Analytical methods

Graphs and tabulations comparing baseline HVAC system performance compared to HVAC system performance with the BrightBox application in operation. These data will be adjusted for load and weather differences.

4.2.1.5 Success Criteria

If the HVAC energy savings meet or exceed 20% of the baseline, we have succeeded.

4.2.2 System Economics

4.2.2.1 Purpose

To reduce facility energy costs.

4.2.2.2 Metric

The metric will be Savings to Investment Ratio (SIR)

4.2.2.3 Data

The data will be the computed savings in dollars while the investment is the cost that NSAM would pay for the BrightBox service if it were being purchased commercially.

4.2.2.4 Analytical methods

SIR is a simple ratio.

4.2.2.5 Success Criteria

We will have been successful if we produce a SIR in excess of 1.67.

4.2.3 BOMP Library Expansion

4.2.3.1 Purpose

To add library components to BOMP that allow the modeling of HVAC system components.

4.2.3.2 Metric

Number of components

4.2.3.3 Data

Number of components

4.2.3.4 Analytical methods

Not applicable

4.2.3.5 Success Criteria

We will be successful if we add the following 13 BOMP components.

- "Built Up" Air-Handling Units, including the following components
  - Economizers
  - Chilled Water Coils
  - Supply Fans
  - Return Fans
  - Relief Fans
  - Variable-Frequency Drives serving any of the fans listed above
- "Built Up" Hydronic Systems, including the following components
  - Air-Cooled Chillers
  - Single-Speed Pumps
  - Variable-Speed Pumps, served by a variable-frequency drive

  - Primary / Secondary Pumping Configurations
  - Primary-Only Pumping Configurations
- Zone HVAC Systems, including the following
  - 2-Pipe Fan Coil Units (cooling only)
  - 4-Pipe Fan Coil Units (both heating and cooling)

4.2.4 BrightBox Control Software Generation

One key to wide deployment is not just the ability to generate models but to generate them quickly and easily. We do keep track of time to deploy broken down by hours and tasks. BrightBox has a library of components that can be assigned to a model. A software wizard searches the library to find the best component matches to the model and builds the model. Then we use field data to calibrate the model.

4.2.4.1 Purpose

To evaluate overall operation of the BrightBox software

4.2.4.2 Metric

Is the BrightBox software operating properly?

4.2.4.3 Data

Are HVAC system control setpoints and reset signals being generated and pushed into the HVAC control system at the two NSAM buildings?

4.2.4.4 Analytical methods

Not applicable.

4.2.4.5 Success Criteria

We will be successful if HVAC system control sequences are being generated and pushed into the HVAC control system at the two NSAM buildings.

4.2.5 TOPP Model Dataset Generation Speed

4.2.5.1 Purpose

To evaluate whether the BrightBox model development approach is faster than the Taylor TOPP model approach.

4.2.5.2 Metric

Is the BrightBox software model development approach faster than the Taylor TOPP model approach?

4.2.5.3 Data

Hours spent by programmer/analysts to develop models.

4.2.5.4 Analytical methods

Not applicable.

4.2.5.5 Success Criteria

We will be successful if the BrightBox models are developed faster than the Taylor TOPP models.

4.2.6 AutoCx

4.2.6.1 Purpose

To evaluate the success of AutoCx as a diagnostic tool for this demonstration project

4.2.6.2 Metric

Did AutoCx test all testable objects at the buildings included in the demonstration project?

Were all issues found by AutoCx field verifiable on the actual equipment?

4.2.6.3 Data

Counts of testable equipment and tested equipment. Counts of issues reported by AutoCx and field verified issues.

4.2.6.4 Analytical methods

Not applicable

4.2.6.5 Success Criteria

We will be successful if all testable objects at the demonstration site are tested by AutoCx and all issues reported by AutoCx are verified by field inspection.

4.2.7 Satisfaction with BrightBox Control Software

4.2.7.1 Purpose

To evaluate whether the facility staff are satisfied with the installation and operation of the BrightBox software.

4.2.7.2 Metric

Are the facility staff satisfied with the BrightBox software as expressed in responses to a series of survey questions?

4.2.7.3 Data

Answers to survey questions (a sample survey is provided as Appendix C)

4.2.7.4 Analytical methods

Not applicable.

4.2.7.5 Success Criteria

We will be successful if a majority of the answers to the survey questions are positive in nature.

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5.0 TEST DESIGN

The test design is as follows. Currently HVAC systems in two buildings at NSAM are operating with traditional controls systems. Such systems are reactive in the sense that components react to "state" signals from other components in a control sequence. BrightBox will implement a different control approach based on predictive control. The test design centers around comparing energy consumed by the HVAC systems when the traditional reactive control sequences are operating to energy consumed when the new predictive control sequences are operating.

- Fundamental Problem: The fundamental problem is that traditional HVAC system controls are reactive and do not use models of equipment performance when controlling building systems. BrightBox software optimization based on model predictive control is a new approach to HVAC control that will replace older traditional methods of HVAC control. Also fundamental is creating a software model within which this optimization of HVAC system controls can exist and evolve.
- Demonstration Question: The demonstration question is: "Can BrightBox software optimization using model-based predictive control be extended to 'built-up' chiller plants in an HVAC system and also save 20% of HVAC energy consumption in two buildings at NSAM?"

5.1 CONCEPTUAL TEST DESIGN

Conceptually, the test design is that we will measure the energy consumed by HVAC equipment in two buildings at NSAM with the BrightBox software optimization running and also not running. Power consumption, supply and return air and water temperatures, flow rates, fan speeds will also be measured and used in the model.

5.1.1 Hypothesis

BrightBox software optimization can save 20% of HVAC energy consumption in two buildings at NSAM.

5.1.2 Independent Variable

The independent variable is: The state of the BrightBox optimization software (on or off).

5.1.3 Dependent Variable

The dependent variable is: The amount of energy consumed by the HVAC equipment.

5.1.4 Controlled Variables

There are several controlled variables in the test design:

The first controlled variable is the size of the buildings. During the course of the project we will not make any physical modifications to the buildings.

The second controlled variable is the NSAM installed HVAC equipment. BrightBox is a software-only solution so the mechanical equipment will not be modified or changed in any way. Any modifications or significant maintenance (filter changes, coil replacements/flushing etc.) that could alter system performance will be documented and incorporated into our final report analysis.

The third controlled variable is the internal setpoints for temperature and humidity in the NSAM buildings.

Building occupancy is an important variable that we cannot control. However a primary input to the model is thermal load which is a proxy for building occupancy. We use thermal load to learn the historical behavior of each zone. In fact, in our approach, thermal load is a more fundamental component in the model than occupancy data could be.

A final controlled variable is the state of the components in the HVAC system. AutoCx will be used to validate the configuration and operational readiness of a number of HVAC system components. If AutoCx identifies any issues that require remediation, those issues will be assessed to determine the cost to remedy. Where costs are reasonable (no-cost or low-cost) the issues identified by AutoCx will be addressed.

5.1.5 Test Design

The test design is a standard baseline/intervention test design. How much energy do the HVAC systems in these two buildings at NSAM consume without the BrightBox software optimization running versus how much energy do the HVAC systems in these two buildings at NSAM consume with the BrightBox software optimization running?

It has been noted that equipment cycling and runtime can have a significant impact on energy performance. BrightBox will maintain trend data to track compressor cycling and create tracking metrics for how the HVAC system operates with BrightBox on versus BrightBox off. These data will be available for networked chillers only: including Watkin Hall chillers 1 and 2 and Glasgow Hall chillers 1,2 and 3. Watkins Hall chiller #3 does not have a network controller.

5.1.6 Test Phases

The first phase is to collect some baseline data using metering equipment that is already installed. At the time of this writing, the ALC Webcntrl platform at NSAM has been upgraded but there is still an HTTPS certificate problem that prevents remote data collection. The problem is that HTTPS communication can only occur between servers with authenticated certificates and the NSAM server lacks the authenticated certificate. NSAM is working on this problem.

When the HTTPS certificate problem has been fixed, we will remotely monitor all data available in the ALC system for regular operation of the HVAC system including zone temperatures, existing power meters and chilled water flow.

Please see Appendix D for the NSAM/NPS Chilled Water Plant metering plan and associated metering installation request document provided to our subcontractor Sunbelt Controls.

After the new models of the chiller plants have been developed by the BrightBox engineering team, the next phase is to roll-out the software and verify that the optimization is functioning correctly. The next phase is to collect data with the BrightBox optimization software operating and not operating to compare the two conditions. The last phase is to analyze this data.

5.2 BASELINE CHARACTERIZATION

The baseline characterization will constitute periods of time when the BrightBox optimization software is not operating compared to periods of time when the BrightBox software is operating. We anticipate that several days to a week in each mode will provide good baseline-to-test mode ratio data.

5.2.1 Reference Conditions

Reference conditions are designated to be conditions when the BrightBox optimization software is not operating. Retrospectively, reference conditions will be designated as periods of time when the BrightBox optimization software is not operating where similar weather and loads occurred compared to a period when the BrightBox optimization software was operating

5.2.2 Baseline Collection Period

Baseline data collection has already begun to understand how these buildings operate. Baseline data for quantitative calculations to support the objectives of the project will be collected concurrently with the test data by turning the BrightBox optimization software on and off and observing HVAC system energy consumption in similar weather conditions.

5.2.3 Existing Baseline Data

No existing baseline data exists. We only have some recent utility data for one meter that serves the entire NSAM site of roughly 30 buildings. We have no existing data specifically for the two buildings we intend to focus on for this project.

5.2.4 Baseline Estimation

We don’t have a reliable baseline estimation that we can provide in advance. However, during the course of the project we will be collecting baseline data continuously during the course of the project during periods when the BrightBox software optimization is turned off.

5.2.5 Data Collection Equipment

The buildings at NSAM have some metering equipment installed. We intend to install additional meters to measure power and energy consumption, supply and return air and water temperatures, and flow rates. The facility already has HVAC controls provided by Automated Logic Controls (ALC) and we intend to upgrade the ALC controls to the latest version and connect any new metering equipment to the upgraded ALC system.

5.3 DESIGN AND LAYOUT OF SYSTEM COMPONENTS

5.3.1 System Design

The system design centers around remotely administered model-based HVAC controls optimization. The system replaces reactive HVAC controls (controls that react to various inputs) with a predictive model that anticipates how the HVAC system will need to operate based on various data inputs – weather, indoor temperature setpoints, HVAC system component capabilities, cost of energy etc. Setting an optimization parameter, perhaps lowest possible energy use, or lowest possible energy cost, the system then constructs the optimal control sequence for that HVAC system for the immediate future. A new control sequence is optimized and uploaded via the internet to the building every 5 minutes. In the BrightBox initial commercial deployments, 20%-30% HVAC energy savings have been typical with this approach.

5.3.2 Components of the system

The components of the system include an engineering team in Berkeley, CA that quickly builds a model of the parts and pieces and interactions of the HVAC system in a specific building, algorithms that produce optimized control sequences for that HVAC system that live in servers in the cloud, and then access and updates to the HVAC system in a specific building via an ALC WebCTRL interface.

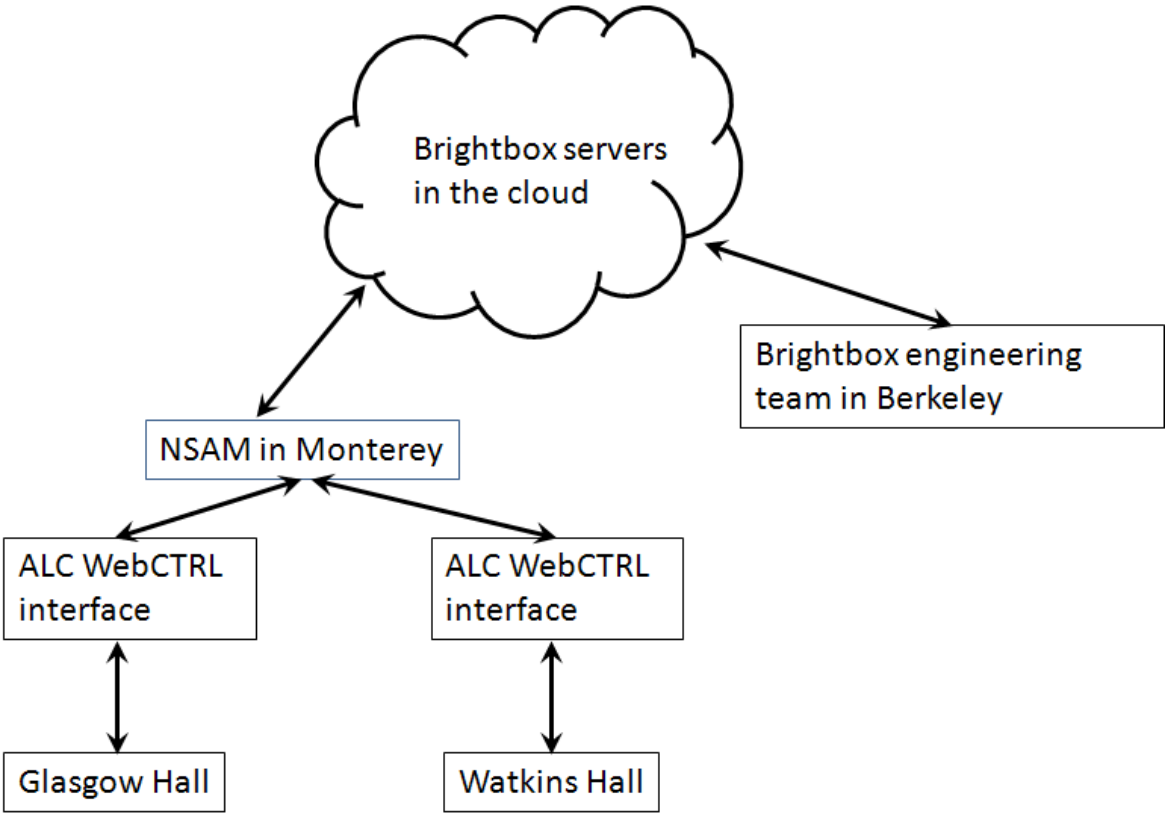

Figure 12. System design

5.3.3 System Integration

The existing HVAC systems in Glasgow Hall and Watkins Hall are not optimized for the lowest energy consumption or cost performance. BrightBox will demonstrate better HVAC system performance.

The existing ALC controls had older versions of the operating system software and have been upgraded to the latest version. However, no hardware changes will be required. Rather, BrightBox will update the HVAC system control sequences with optimized versions remotely over the internet every 5 minutes.

5.3.4 System Controls

BrightBox does have an “off” button. If at any time, an onsite facilities manager believes that the BrightBox HVAC optimization software isn’t working properly, there is a big “off” button available so that person can turn the BrightBox optimization software off. This button is available in the ALC WebCTRL interface.

5.4 OPERATIONAL TESTING

5.4.1 Operational Testing of Cost and Performance

Operational testing of cost and performance is ongoing and continuous. Once the BrightBox models of the HVAC systems are built and operational they operate continuously unless turned off.

5.4.2 Modeling and Simulation

The BrightBox model-predictive control solution is central and critical to the success of the project. Below is a task list showing the work breakdown for extending the BrightBox BOMP model to HVAC systems including built-up chiller plants and air-handling units.

Task

1. Build Chiller Schema
    a. Develop chiller model
    b. Develop pump model
    c. Develop load model
    d. Assemble chiller plant model
    e. Develop coil model to decouple water and air systems
2. Build Air-side schema
    a. Develop AHU model
    b. Assemble air-side model
3. Build Identification Routines
    a. Chiller plant

   b. Air-side
   c. Load aggregator

4. Chiller Control Architecture
   a. Control variables definition and sampling time
   b. Interaction with the air side

5. TOPP Model Simulation
   a. Run optimization of MPC problem with Hp=2 as simulator
   b. Get simulation results from trend sets

6. Finite State Machine Design and Integration (AutoCx infrastructure)
   a. Requirement review
   b. Choose packages or libraries
   c. Develop modularized approach

7. TOPP Model Optimization
   a. Enumerate all possible feasible combinations of logic variables
   b. Dispatch TOPP workers to simulate system
   c. Reduce the set of simulation results to a single optimum

8. Extend to real-time implementation
   a. review operational constraints

9. System Monitoring
   a. Chiller running status
   b. Chiller plant savings visualization
   c. AHU running status

10. User Interface Design and Implementation
    a. Chiller plant configuration pages
    b. TOPP model optimization pages
    c. Chiller plant monitoring pages
    d. AHU monitoring pages
    e. Chiller plant reporting page

5.4.3 Timeline

Below is a list of milestones and the expected month and year of completion.

Table 2. Milestones and Date of Completion

Milestone	Completion (Month/Year)
Confirm demonstration site	07/2014
Kickoff Call	07/2014
Project Plan Approved	07/2014
Submit Draft Execution Plan for Year 1 Funding Increment	07/2014
Submit Draft Table 1 Performance Objectives and Test Design	07/2014
Submit Draft Submit Draft Demonstration Plan	09/2014
Baseline performance	11/2014
Initiate requests for Permits, Approvals, Agreements	11/2014
Required Permits, Approvals and/or Agreements received/completed	12/2014
Demonstration Preparation/Mobilization	01/2015
Complete Software Development Part 1	02/2015
First IPR	02/2015
Initiate Demonstration	03/2015
Complete Software Development Part 2	06/2015
Demonstration 25% complete	06/2015
Submit Draft Execution Plan for Year 2 Increment	09/2015
Demonstration 50% complete	10/2015
Demonstration 75% complete	01/2016
Submit Draft Outbrief	02/2016
Second IPR	02/2016
Collect Data	03/2016
Conduct Data Analysis	06/2016
Decommissioning	06/2016
Submit Draft Final Report	06/2016
Property Transfer	07/2016
Submit Final Final Report	07/2016
Submit Draft C&P Report	07/2016
Demonstration Complete	07/2016

5.5 SAMPLING PROTOCOL

Table 3. Sampling Protocol

Item	Data
Data collector	BrightBox Technologies remotely over the internet
Data Recording	BrightBox Technologies remotely over the internet. If the network goes down, any trend data that is required for the operation of the control system is cached locally and can be recovered. Any additional data that BrightBox Technologies might be collecting in realtime would be lost for the period of the network outage.
Data description	Power and energy consumption, supply and return air and water temperatures, flow rates, thermostat values, and fan speeds etc. Minimum sampling rate of 5 minutes.
Data storage and backup	BrightBox utilizes cloud services so data backup is continuous and automatic.
Data collection diagram	The data collection for this project is very complex. A diagram would not be practical or useful.
Non-standard data	No non-standard data will be collected
Survey Questionnaires	A user satisfaction survey will be part of this project

5.6 EQUIPMENT CALIBRATION AND DATA QUALITY ISSUES

5.6.1 Equipment Calibration

Where equipment calibration is required, subcontractor Sunbelt controls will perform the calibration. We do not anticipate calibration will be required; however, based on the system design and operation, we establish a reasonable range for each parameter. We monitor the parameter continuously relative to the reasonable range so we can quickly identify equipment that may require calibration.

5.6.2 Quality Assurance Sampling

We have found that our data collection through the ALC controls infrastructure is very reliable.

5.6.3 Post-Processing statistical analysis

Real time statistical analysis of energy savings is built in to the BrightBox software optimization platform. Incorrect readings or faulty measurement equipment will be easy to identify.

6.0 PERFORMANCE ASSESSMENT

6.1 PERFORMANCE OBJECTIVE ANALYSIS OVERVIEW

ESTCP project EW-201409 aimed at demonstrating the benefits of innovative software technology for building HVAC systems. These benefits included reduced system energy use and cost as well as improved performance driven by autonomous commissioning and optimized system control. In the end, while many individual elements of the project were completed successfully, the project as a whole was not able to successfully demonstrate the technology.

The following items were successfully completed as part of this demonstration project.

- Technology development related to incorporating chilled-water plant elements into the BrightBox system
- Air-cooled chiller plant models
- Chilled-water (and condenser water) pump models
- Cooling tower models (for the sake of validation against the Taylor Engineering software)
- Primary-only variable-flow chilled-water system operation (for validation)
- Building controls system expansion to include new sensors, meters, and graphic screens at Glasgow and Watkins
- Establishment of secure bi-directional data connection between BrightBox remote secure data-center and the NSAM WebCTRL system.
- Deployment of AutoCx at Watkins Hall.

The following items were not successfully demonstrated.

- Testing of ‘air-side’ BrightBox system components
- Operation of the BrightBox chilled-water-system controls optimization.

The two buildings at the Naval Support Activity Monterey (NSAM) facility that were selected for this demonstration met the following criteria.

- Employed an Automated Logic Controls (ALC) building control system
- Contained HVAC central plants containing multiple chillers with the correct type of control points available and integrated into the ALC system
- Employed ‘variable air volume reheat’ (VAV-reheat) HVAC distribution systems
- Contained existing energy and flow meters to enable monitoring and verification

The first building selected was Building 245 (Watkins Hall). In the end we were not able to deploy the advanced control solution to this building because of chiller equipment failure. The Watkins plant consisted of three chillers, CH-1, CH-2, and CH-3. Despite being co-located, CH-1 served Building 246 next door, which contains critical security program spaces.

During this project CH-1 became permanently disabled and CH-2 was repurposed to serve Building 246. This left only CH-3 to serve the subject Building 245, making the deployment infeasible.

The second building selected was Building 305 (Glasgow Hall). At this building we were not able to deploy the advanced control software because the chilled-water supply temperature setpoint control point was not properly configured at any of the three chillers serving this building. This control point is a key element in deploying the optimal control solution and it was not available.

At Glasgow, NSAM staff, NSAM service contractors, and BrightBox staff were eventually able to diagnose the cause of the malfunctioning control point and we did identify measures to repair the equipment. The ESTCP program agreed to make extra funds available to fix the equipment, but another project roadblock appeared. BrightBox Technologies went out of business at this time due to slow market adoption of our software.

Anecdotal evidence, academic studies, and system simulations clearly demonstrate the importance and capacity for best-in-class control solutions to improve system performance and reduce energy use and cost. However, implementing these solutions into the extremely heterogeneous and often malfunctioning or misconfigured HVAC systems in real operating buildings poses a major challenge to reaping the benefits promised by advanced control. For these reasons, BrightBox Technologies refocused our efforts away from optimal control toward autonomous commissioning with the goal of establishing a correctly-configured and properly-operating foundation onto which optimal control could eventually be deployed. Unfortunately, we were not yet able to successfully develop a market for autonomous commissioning products despite the clear need and benefits. BrightBox Technologies ceased operations in this market at the end of March 2016.

6.2 STATISTICAL METHODOLOGIES

We had originally planned to use comparisons of energy use with the BrightBox software optimization program either on or off integrated over time to show energy savings. We were never able to deploy the software, so we were not able to perform this statistical analysis for the deployment at NSAM.

6.3 GRAPHICAL METHODOLOGIES

We had originally planned to use visual comparisons of energy use with the BrightBox software optimization program either on or off, integrated over time to show energy savings. As described in section 6.2 above, the optimization software was not deployed so there are no graphic analyses of the data to present.

We were able to partially deploy the “AutoCx” autonomous commissioning software in Watkins hall where some VAVR zone equipment was installed. The images below show the Watkins Hall AutoCx software results.

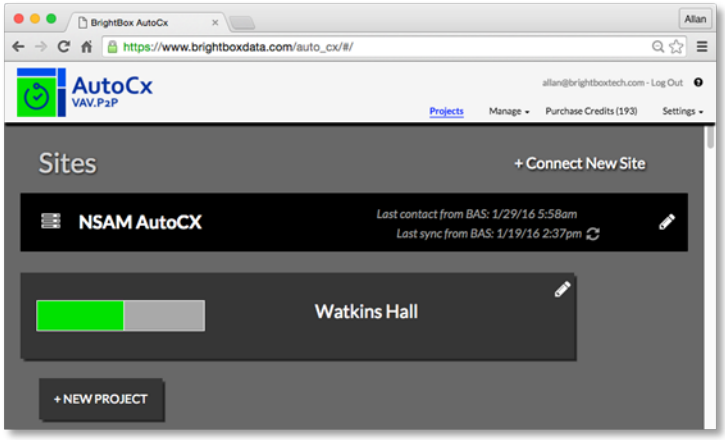

Figure 13. AutoCx User Interface

This image shows a screen capture of the AutoCx web-application with the NSAM Watkins Hall project indicated. The green progress bar indicates that roughly half of the available tests were able to be performed at Watkins Hall.

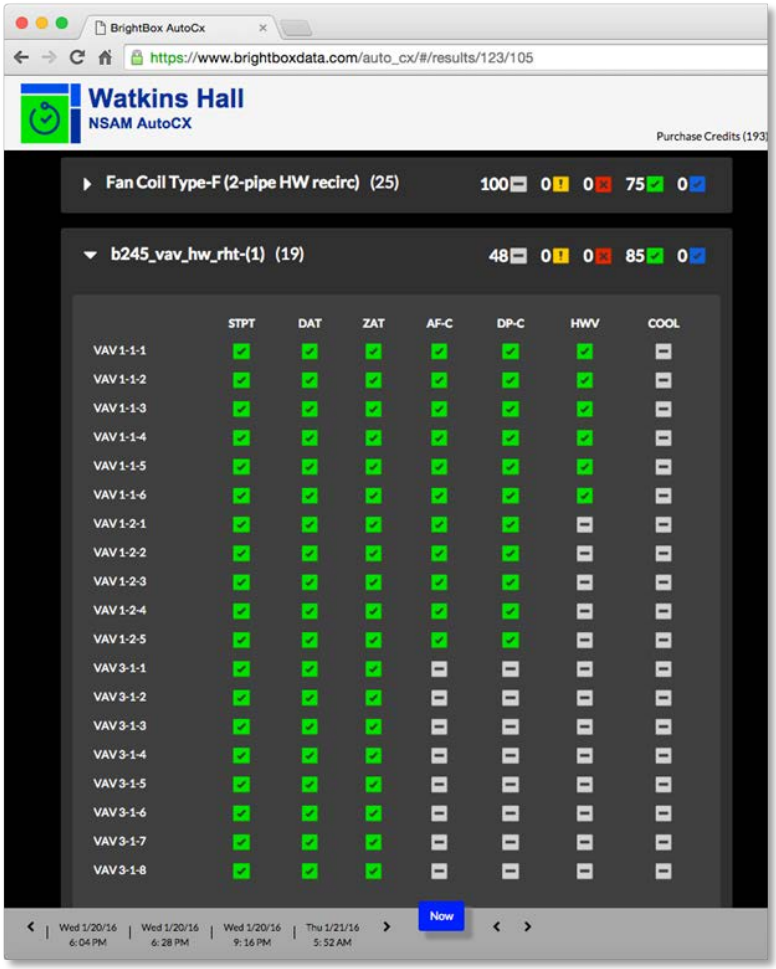

Figure 14. AutoCx User Interface

The figure above shows the 'test results' view of the Watkins Hall AutoCx deployment. Green checkmarks indicate that tests were run and passed. Gray boxes indicate that tests were not run. In most cases tests were not run because they would have affected space conditions (heating up or cooling down the space) and it was known that these spaces contained laboratory program and users would need to be notified about the performance of the tests. This coordination did not occur before work on the project ceased.

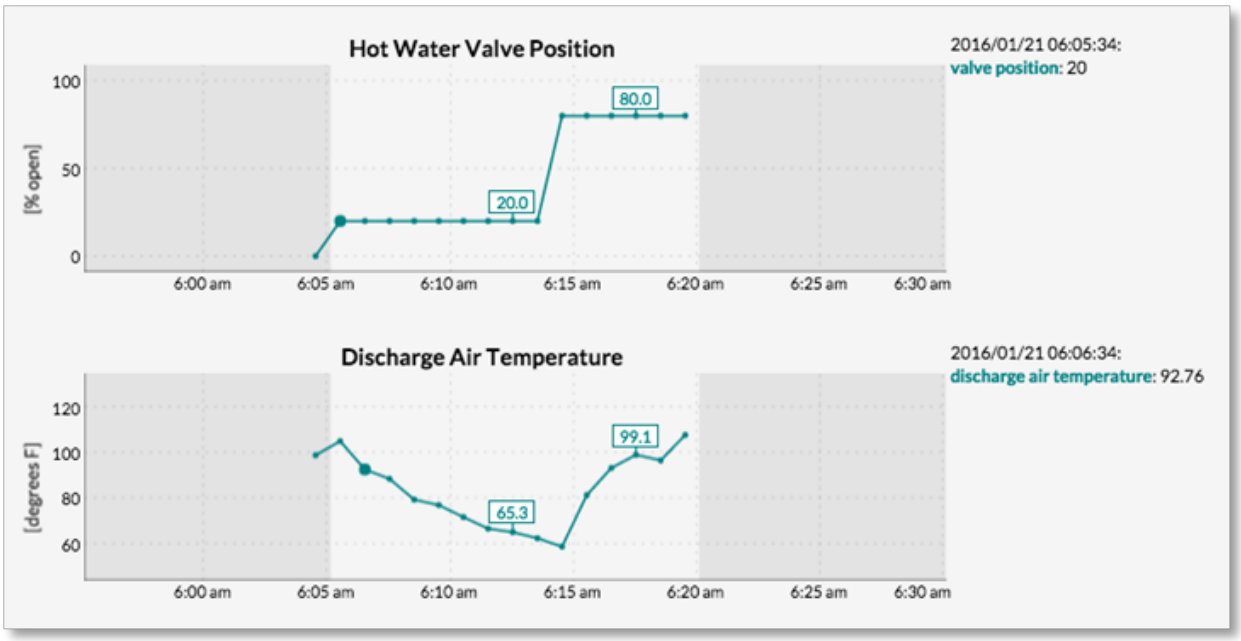

Figure 15. AutoCx Results View

This figure shows how data signals are used to assess correct operation. Systems are actively manipulated by the BrightBox AutoCx software as can be seen in the top graph – the hot water valve is driven to 20% open then to 80% open, then returned to automatic operation. The lower graph shows that the discharge air temperature increased, indicating that the hot water valve is operating correctly.

6.4 MODELING AND SIMULATION

We used the TOPP model (Theoretical Optimum Plant Performance model) to establish the theoretical optimum and calculate plant power demands. We modeled the same plant in the BrightBox simulation and optimal control platform to validate the BrightBox software performance against a well-known and validated source. The graphic below show TOPP results compared to BrightBox results – a very good match is indicated.

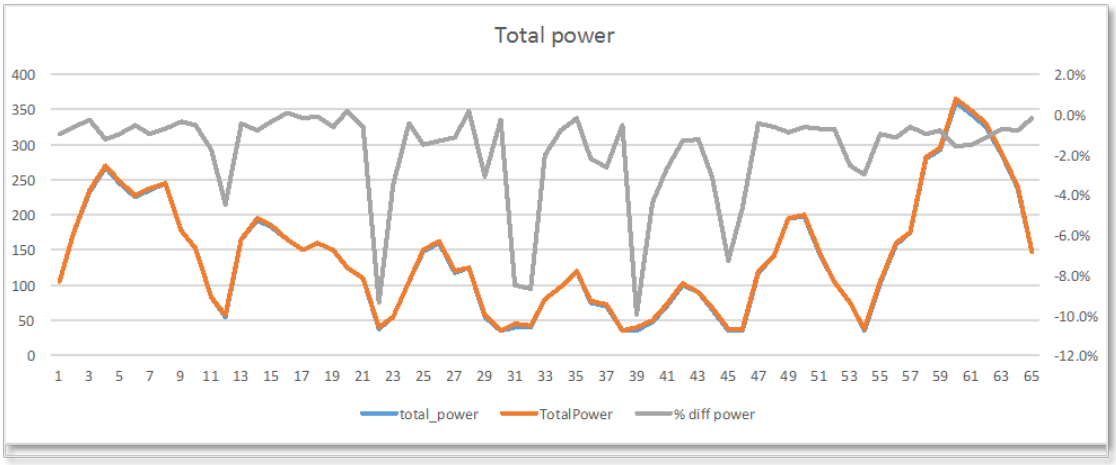

Figure 16. Modeling Comparison Detail

This figure show TOPP total power predictions in orange and BrightBox total power predictions in blue for an example chilled-water plant. The two match up well and in all cases the BrightBox optimal control approach results in slightly lower power use. The gray line shows a percentage difference between the TOPP results and the BrightBox results and values are read on the right-hand Y-axis scale. Please note that the wide variation in percent difference is due to the significant variation in the magnitude of the power use values. When the magnitude of the power-use is small, then even small differences between the TOPP values and the BrightBox values end up looking like large percentage differences.

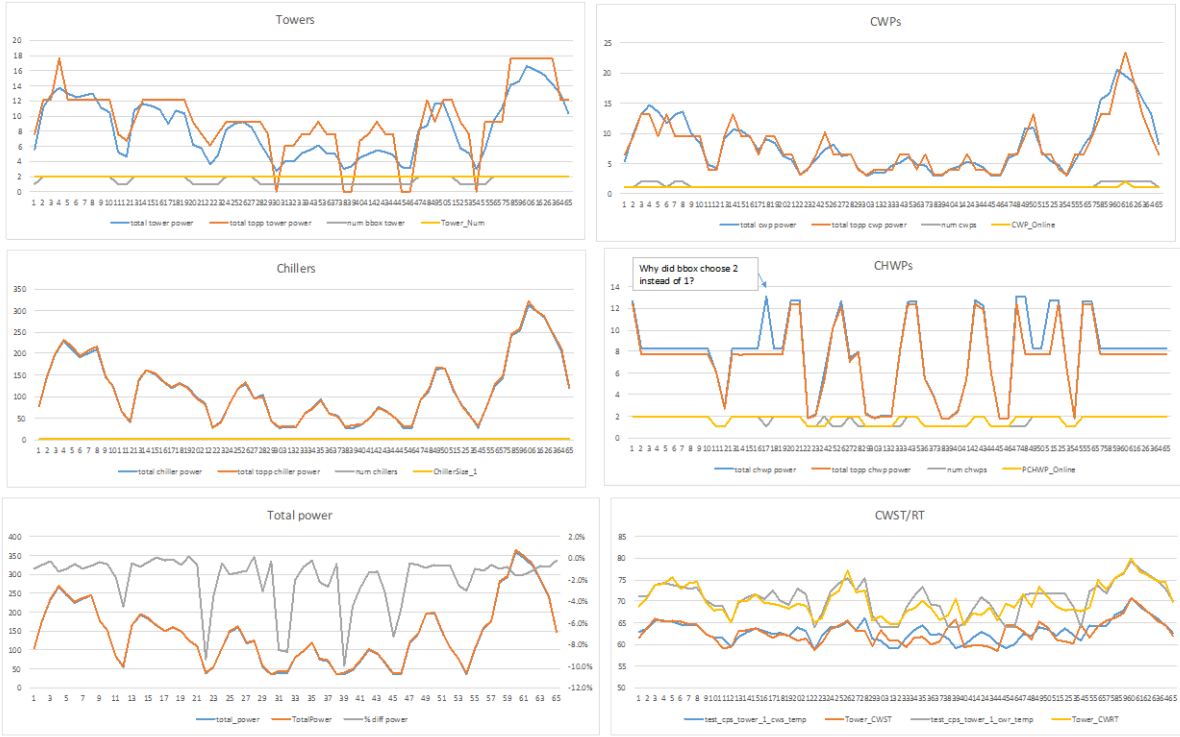

Figure 17. Modeling Comparison Overview

This figure shows simulated optimal control key variables such as cooling tower power, chiller power, condenser water pump power, chilled water power, and condenser water supply and return temperature. It is interesting to see that the TOPP methodology and the BrightBox methodology determine similar-but-different control approaches, resulting in slightly lower power use in the BrightBox simulated case.

6.5 SENSITIVITY ANALYSIS

Not applicable.

6.6 ANECDOTAL PERSPECTIVES

Although the BrightBox team is coordinating with leadership including the Public Works Officer in charge (LCDR Oscar Antillion), NSAM representative Doug Taber, our primary technical work will be with Facilities Manager Michael Fitzgerald and HVAC technician Erik Abbot. We propose to have a formal exit interview with Michael and Erik at the end of the project. We will administer the survey (Appendix C) and ask for any additional comments or ways we could have improved the project.

6.7 INDUSTRY STANDARDS

ASHRAE has formed a committee to develop standard control sequences for HVAC systems but this effort is in its' infancy. There are no industry standards for model-based predictive control systems applied to HVAC equipment that we are aware of.

6.8 INTERNAL VALIDITY

No internal validity tests are planned at this time.

6.9 EXTERNAL VALIDITY

Not applicable

7.0 COST ASSESSMENT

The BrightBox solution is more similar to the ESSCO model than a traditional life-cycle cost model. The BrightBox technology costs a customer nothing up front. Once the BrightBox technology has been installed and proven, BrightBox retains a portion of the cost savings.

A typical contract would be issued and renewed on an annual basis. If an on-site server had to be installed because of security concerns, responsibility for upfront and maintenance costs would fall to the customer.

After this project is over, NSAM will be offered a contract to continue the BrightBox service. No setup fee will be charged. However, for the purposes of performing the economic analysis, we will assume a $10,000 setup fee.

BrightBox target cost numbers assume typical baseline HVAC energy cost is $2 per square foot per year. Assuming BrightBox can save 10% of HVAC energy costs on average, that would be $0.2 per square foot per year. A setup fee of $10,000 per project, $1,000 for operator training, and split of 75% of the savings to BrightBox and 25% to NSAM. The total square footage for Glasgow and Watkins hall is roughly 225,000. This implies annual energy costs of $450,000 and associated savings of $45,000. NSAM keeps $11,250 for a simple payback time of just under one year.

- Building Life-Cycle Cost Program:

  The data from Table 4 along with the assumptions above, a 3% discount rate, and a 10 year lifetime were entered into BLCC5 for analysis. The detailed life-cycle cost report is attached as Appendix F. In summary, over a ten-year lifetime, the base case total life-cycle cost is $4,748,295 or $513,263 per year. The alternate BrightBox case total life-cycle cost is $4,036,210 or $436,291 per year.

- Life-Cycle Cost Table: See Table 4

- Life-Cycle Cost Elements:

  The main cost to achieve the savings is the $10,000 installation cost.

- Life-Cycle Cost Timeframe:

  The timeframe for the life-cycle cost estimate is the DOE default of 10 years. While the software itself doesn't wear out per se, it is anticipated that after a 10 year lifetime, a better solution may be available.

Table 4. Cost Model

Cost Element	Data Tracked During the Demonstration
Hardware capital costs	$0
Installation costs	$10,000
Consumables	$0
Facility operational costs	10% reduction in HVAC energy costs used for this plan, actual energy reduction will be used for final report
Maintenance	$0.10 per square foot per year. For Watkins and Glasgow Halls at 226,111 square feet this is $22,611 per year.
Hardware lifetime	10 years
Operator training	Included in maintenance fee
Salvage Value	$0

8.0 TECHNOLOGY TRANSFER

Due to the unsuccessful nature of this demonstration project, no technology transfer activities are planned. This final report serves as the documentation of the project successes and failures. In fact BrightBox as a company has completely ceased operations in this market due in part to wider-market barriers that we encountered that were similar to those we found at NSAM.

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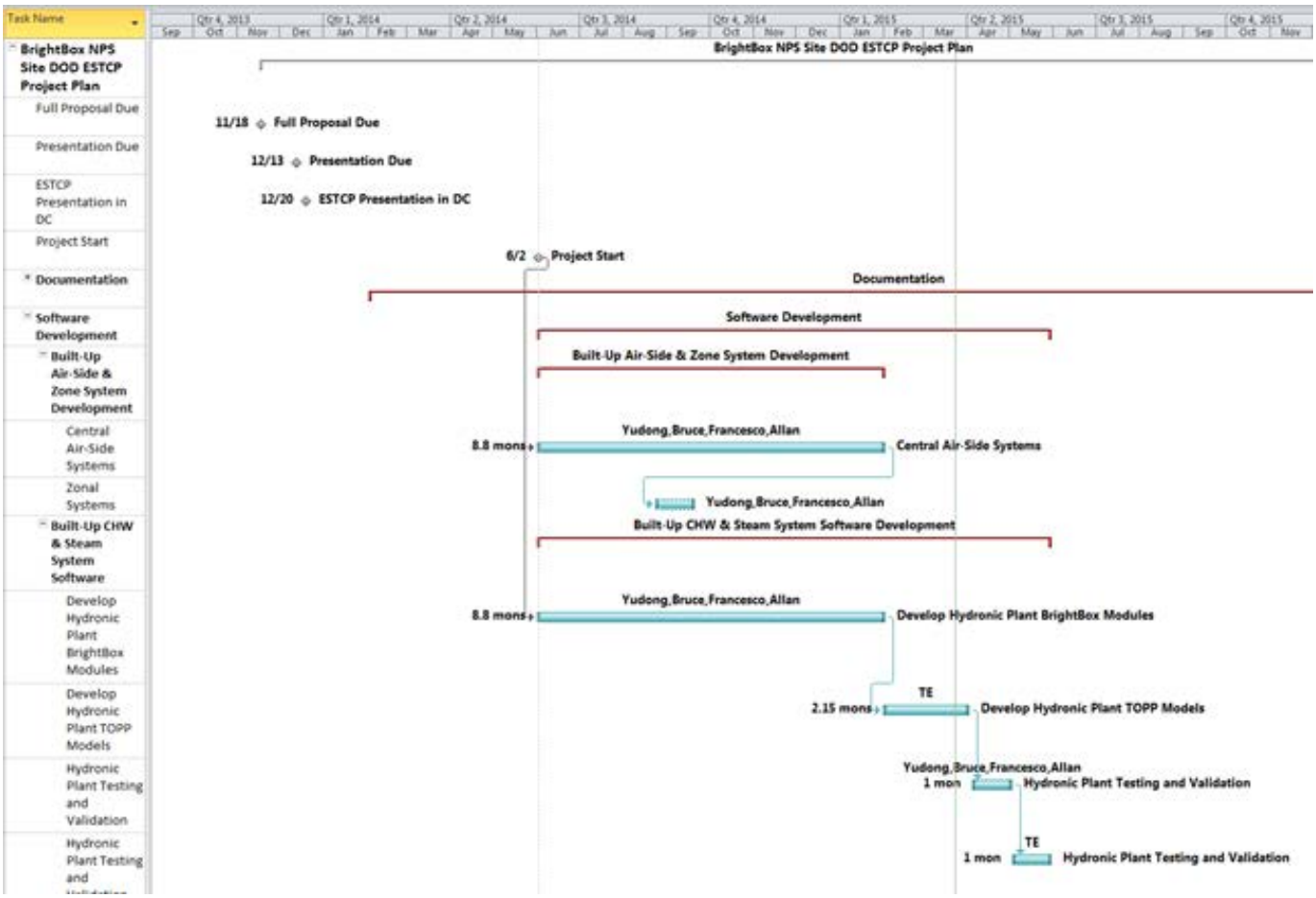
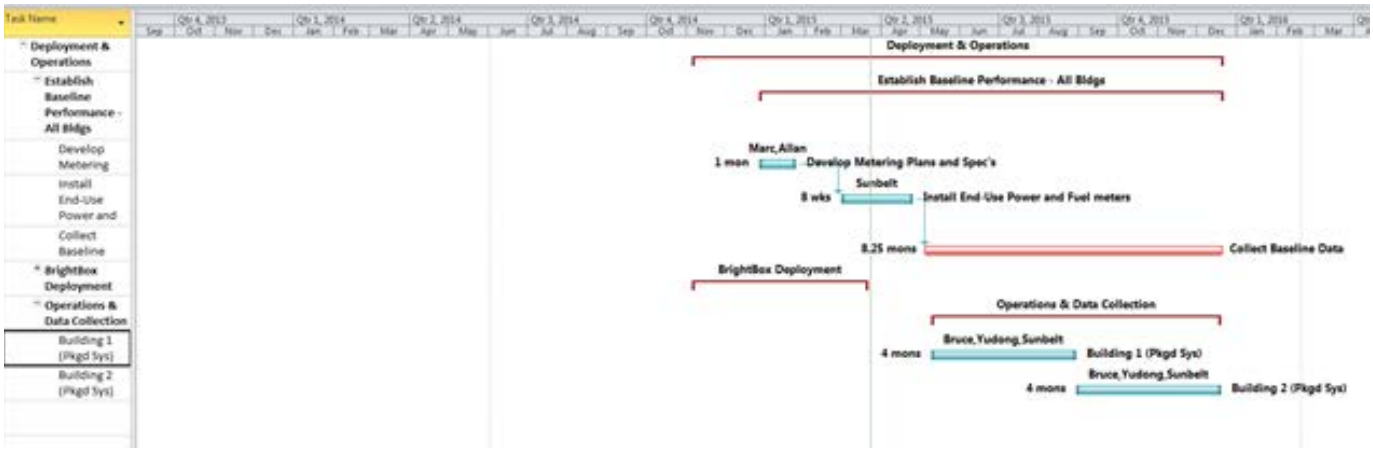
9.0 SCHEDULE OF ACTIVITIES





Note that the two sections of the Gantt chart are offset.

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10.0 MANAGEMENT AND STAFFING

Allan Daly, the BrightBox Principal Investigator managed the software development and engineering effort on a day-to-day basis. Marc Fountain managed all coordination, planning, reporting, communication, invoicing etc., with the DoD. Mark Hydeman led the Taylor Engineering sub-contractor effort and Rich Phifer the Sunbelt Controls sub-contractor effort. However, Allan was also a principal at Taylor Engineering and worked with Mark to coordinate and execute the Taylor Engineering scope of work.

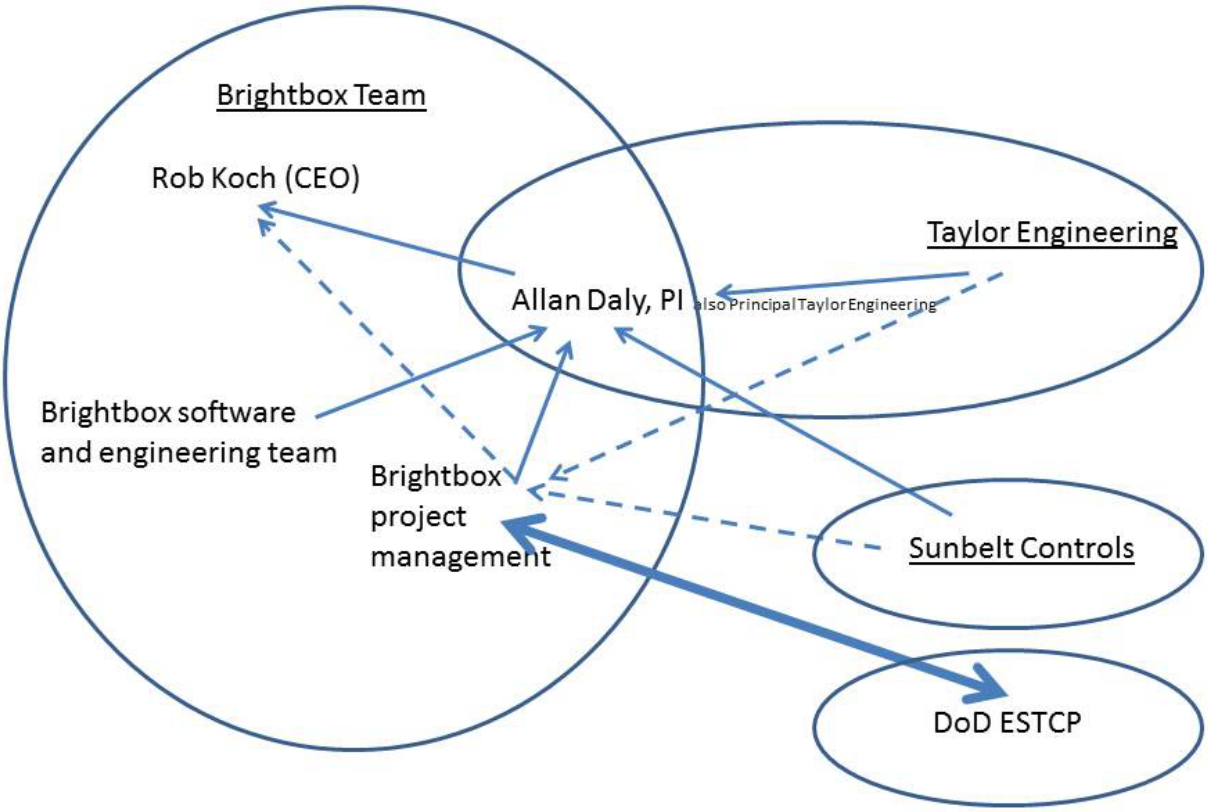

Figure 18. Management and Staffing

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APPENDIX A HEALTH AND SAFETY PLAN (HASP)

BrightBox is a software solution that should not have any physical health and safety impacts. We will not be engaging in construction or any activities that could impact Health and Safety. Therefore, a Health and Safety Plan is not included.

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APPENDIX B POINTS OF CONTACT

Point of Contact Name	Organization Name Address	Phone Email	Role in Project
Allan Daly	BrightBox Technologies	510-220-0500 allan@brightboxtech.com	Principal Investigator
Rob Koch	BrightBox Technologies	650-743-2082 rob@brightboxtech.com	Chief Executive Officer
Marc Fountain	BrightBox Technologies	510-681-4778 marc@brightboxtech.com	Project Manager
Mark Hydeman	Taylor Engineering	(510) 263-1543 mhydeman@taylor-engineering.com	Sub-contractor lead
Rich Phifer	Sunbelt Controls	650-333-8685 rphifer@sunbeltcontrols.com	Sub-contractor lead
LCDR Oscar Antillion	NSAM	oscar.antillon@navy.mil	Public Works Officer (lead for NSAM)
Matt Seuss	NSAM	matthew.suess@navy.mil	Deputy Public Works Officer
Michael Fitzgerald	NSAM		Facilities Manager
Erik Abbot	NSAM	erik.abbott@navy.mil	HVAC technician
Douglass Taber, RA, CEM	NSAM	831-656-3653 douglass.c.taber@navy.mil	Demonstration site representative

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APPENDIX C SAMPLE SURVEY

Dear NSAM Facilities Management Staff:

BrightBox Technologies has now completed our ESTCP demonstration project at your facility. As part of our agreement with the Department of Defense, we are required to ask for your feedback to help evaluate the success of the project. Please take a moment to complete the brief survey below and return to Marc Fountain, BrightBox Technologies 2040 Bancroft Way Suite 302, Berkeley, CA 94704 or marcfountain@comcast.net

1) Did you find the BrightBox software easy to work with?

1	2	3	4	5
Difficult	Somewhat difficult	Neither difficult nor easy	Somewhat easy	Extremely easy

2) Did any issues come up with the software that were difficult to resolve?

1	2	3	4	5
Difficult	Somewhat difficult	Neither difficult nor easy	Somewhat easy	Extremely easy

(please elaborate)

3) Were the promised energy savings realized or exceeded?

1	2	3	4	5
Not realized	Somewhat realized	Realized	Somewhat exceeded	Extremely exceeded

4) Were the promised cost savings realized or exceeded?

1	2	3	4	5
Not realized	Somewhat realized	Realized	Somewhat exceeded	Extremely exceeded

5) Would you recommend BrightBox to a colleague?

1	2	3	4	5
Definitely not	Probably not	Undecided	Probably	Definitely

6) Any other comments for the BrightBox team?

Thank you for your feedback!

APPENDIX D NSAM/NPS CHILLED WATER PLANT METERING PLAN

The goal of the attached metering plan is to provide adequate data to be able to characterize and validate the performance of the following BrightBox model components that will be deployed at this site. All meters will be connected to the existing WebCTRL building controls system and will remain in place after the project is complete.

- Chillers
- Cooling Towers
- Pumps
- Coils (CHW)

The metering plan is a comprehensive list of all the metering points.

NSAM/NPS BRIGHTBOX PROJECT -- METER INSTALLATION PLAN

<u>Watkins Hall (Building 245)</u>

- CH-1 (air cooled)
  - Power meter (Veris, Modbus)

- CH-2 (air cooled)
  - Power meter (Veris, Modbus)

- CH-3 (air cooled)
  - Power meter (Veris, Modbus)
  - Evaporator dp sensor

- P-3 (CHW pump)
  - Inlet/outlet dp sensor

- P-4 (CHW pump)
  - Inlet/outlet dp sensor

- P-5 (CHW pump)
  - Inlet/outlet dp sensor

- FC-2-E
  - CHW coil dp sensor
    CHWS temperature sensor
  - CHWR temperature sensor

- AH-3-2
  - CHW coil dp sensor
    CHWS temperature sensor

- CHWR temperature sensor

Glasgow Hall (Building 305)

- CH-1 (air cooled)
  - Power meter (Veris, Modbus)
  - Evaporator dp sensor

- CH-2 (air cooled)
  - Power meter (Veris, Modbus)
  - Evaporator dp sensor

- CH-3 (air cooled)
  - Power meter (Veris, Modbus)
  - Evaporator dp sensor

- CHWP-1 (CHW pump)
  - Power meter (Veris, Modbus)
  - Inlet/outlet dp sensor

- CHWP-2 (CHW pump)
  - Power meter (Veris, Modbus)
  - Inlet/outlet dp sensor

- FC-B-06
  - CHW coil dp sensor
    CHWS temperature sensor
  - CHWR temperature sensor

- FC-B-09
  - CHW coil dp sensor
    CHWS temperature sensor
  - CHWR temperature sensor

- FC-1-03
  - CHW coil dp sensor
    CHWS temperature sensor
  - CHWR temperature sensor

APPENDIX E DOCUMENTATION SUPPORTING REDUCING THE NUMBER OF BUILDINGS IN THE DEMONSTRATION TO TWO.

Winter 2015 ESTCP In-Progress Review Project Number: EW-201409

Principal Investigator: Mr. Allan Daly (BrightBox Technologies)

Project Title: Rapid Deployment of Optimal Control for Building

HVAC Systems using Innovative Software Tools and a Hybrid Heuristic/Model-Based Control Approach

Action Items

1. In your next Quarterly Progress Report (QPR) due **15 April 2015**, briefly discuss the feasibility of hosting DoD domains through Amazon Web Services for future application of the BrightBox technology. Determine if DoD accredits the Amazon Web Services for Industrial Control System applications.

2. In the Final Report discuss the potential impact of time of use (TOU) pricing on the long term application of the technology.

Comments

1. Limiting the demonstration to two buildings with high fidelity metering is acceptable to ESTCP.

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APPENDIX F BLCC5 LIFE CYCLE COST ANALYSIS

12.0 NIST BLCC 5.3-13: DETAILED LCC ANALYSIS

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

12.1 GENERAL INFORMATION

File Name:	C:\Program Files\BLCC5\projects\NSAM.xml
Date of Study:	Tue Apr 14 11:12:41 PDT 2015
Analysis Type:	FEMP Analysis, Energy Project
Project Name:	NSAM
Project Location:	California
Analyst:	Marc
Base Date:	January 1, 2015
Service Date:	January 1, 2016
Study Period:	11 years 0 months (January 1, 2015 through December 31, 2025)
Discount Rate:	3%
Discounting Convention:	End-of-Year

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

13.0 ALTERNATIVE: BASE CASE

13.1 INITIAL COST DATA (NOT DISCOUNTED)

13.1.1 Initial Capital Costs

13.1.1.1.1 (adjusted for price escalation)

Initial Capital Costs for All Components: $0

13.1.1.2 Component:

13.1.1.2.1. Cost-Phasing

Date	Portion	Yearly Cost
January 1, 2015	100%	$0
	---	---

Total (for Component) $0

13.1.2. Energy Costs: Electricity

13.1.2.1.1 (base-year dollars)

Average Annual Usage	Average Price/Unit	Average Annual Cost	Average Annual Demand	Average Annual Rebate
5,625,000.0 kWh	$0.08000	$450,000	$120,000	$0

13.2 LIFE-CYCLE COST ANALYSIS

	Present Value	Annual Value
Initial Capital Costs	$0	$0
Energy Costs		
Energy Consumption Costs	$3,748,654	$405,208
Energy Demand Charges	$999,641	$108,055
Energy Utility Rebates	$0	$0
	---	---
Subtotal (for Energy):	$4,748,295	$513,263
Water Usage Costs	$0	$0
Water Disposal Costs	$0	$0
Operating, Maintenance & Repair Costs		
Component:		
Annually Recurring Costs	$0	$0
Non-Annually Recurring Costs	$0	$0
	---	---
Subtotal (for OM&R):	$0	$0
Replacements to Capital Components		
Component:	$0	$0
	---	---
Subtotal (for Replacements):	$0	$0
Residual Value of Original Capital Components		
Component:	$0	$0

	---	---
Subtotal (for Residual Value):	$0	$0
Residual Value of Capital Replacements Component:	$0	$0
	---	---
Subtotal (for Residual Value):	$0	$0
Total Life-Cycle Cost	$4,748,295	$513,263

13.2.1 Emissions Summary

Energy Name	Annual	Life-Cycle
Electricity:		
CO2	1,479,019.47 kg	14,788,170.00 kg
SO2	364.55 kg	3,645.00 kg
NOx	607.58 kg	6,075.00 kg
Total:		
CO2	1,479,019.47 kg	14,788,170.00 kg
SO2	364.55 kg	3,645.00 kg
NOx	607.58 kg	6,075.00 kg

14.0 ALTERNATIVE: BRIGHTBOX

14.1 INITIAL COST DATA (NOT DISCOUNTED)

14.1.1 Initial Capital Costs

14.1.1.1.1 (adjusted for price escalation)

Initial Capital Costs for All Components: $10,000

14.1.1.2 Component:

14.1.1.2.1 Cost-Phasing

Date	Portion	Yearly Cost
January 1, 2015	100%	$10,000
	---	---

Total (for Component)	$10,000

14.1.2 Energy Costs: Electricity

14.1.2.1.1 (base-year dollars)

Average Annual Usage	Average Price/Unit	Average Annual Cost	Average Annual Demand	Average Annual Rebate
5,062,500.0 kWh	$0.08000	$405,000	$60,000	$0

14.2 LIFE-CYCLE COST ANALYSIS

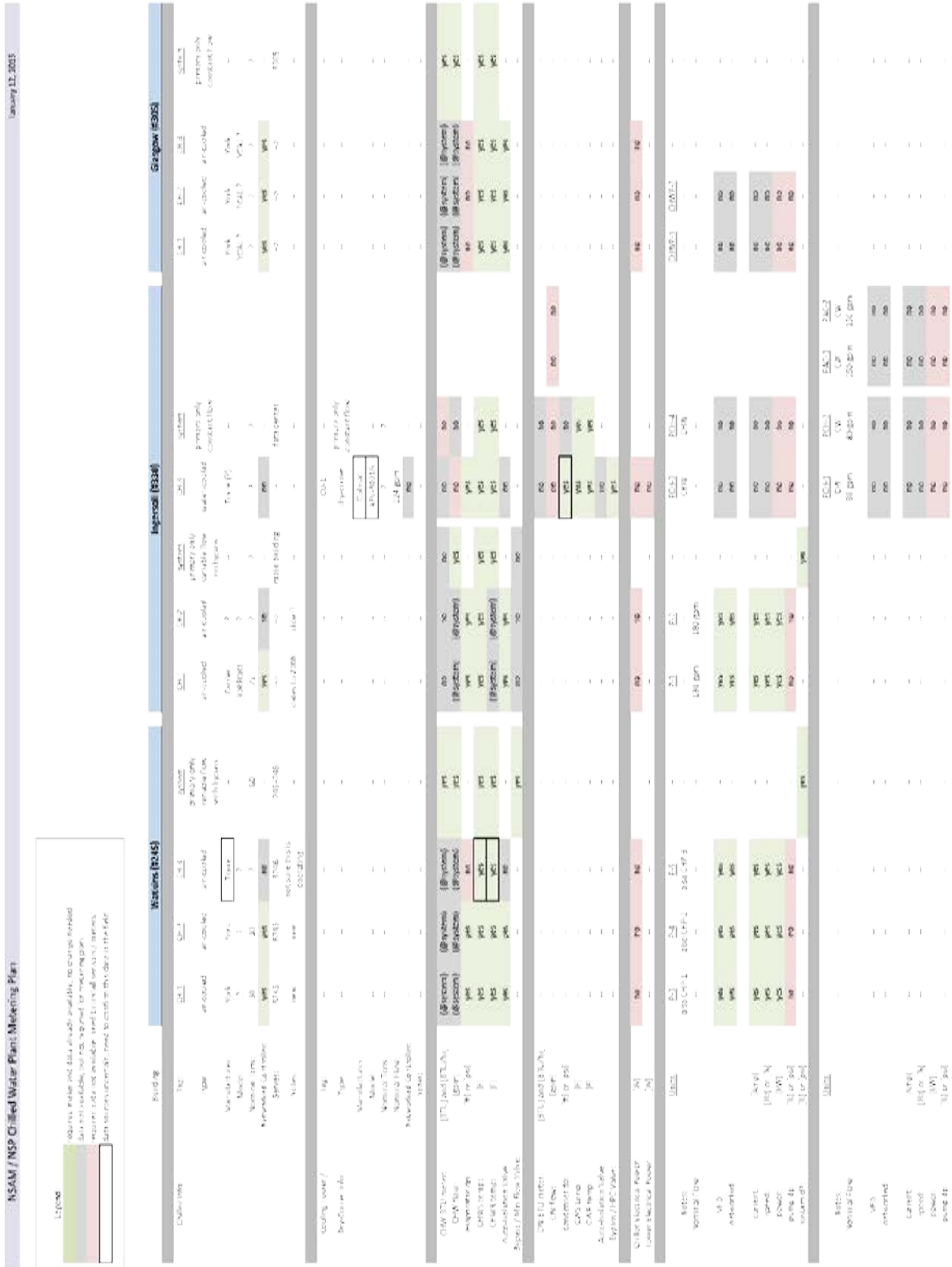
	Present Value	Annual Value
Initial Capital Costs	$10,000	$1,081
Energy Costs		
Energy Consumption Costs	$3,343,591	$361,423
Energy Demand Charges	$495,347	$53,544
Energy Utility Rebates	$0	$0
	---	---
Subtotal (for Energy):	$3,838,938	$414,967
Water Usage Costs	$0	$0
Water Disposal Costs	$0	$0
Operating, Maintenance & Repair Costs		
Component:		
Annually Recurring Costs	$187,272	$20,243
Non-Annually Recurring Costs	$0	$0
	---	---
Subtotal (for OM&R):	$187,272	$20,243
Replacements to Capital Components		
Component:	$0	$0
	---	---
Subtotal (for Replacements):	$0	$0
Residual Value of Original Capital Components		

Component:	$0	$0
	---	---
Subtotal (for Residual Value):	$0	$0
Residual Value of Capital Replacements		
Component:	$0	$0
	---	---
Subtotal (for Residual Value):	$0	$0
Total Life-Cycle Cost	$4,036,210	$436,291

14.2.1 Emissions Summary

Energy Name	**Annual**	**Life-Cycle**
Electricity:		
CO2	1,331,117.52 kg	13,309,353.00 kg
SO2	328.09 kg	3,280.50 kg
NOx	546.82 kg	5,467.50 kg
Total:		
CO2	1,331,117.52 kg	13,309,353.00 kg
SO2	328.09 kg	3,280.50 kg
NOx	546.82 kg	5,467.50 kg

APPENDIX G NSAM BUILDING METERING MATRIX AND CONTROLS I/O POINT INSTALLATION CONTRACTS



BID CONTRACT

Principal Office: 4511 Willow Road, Suite 4, Pleasanton, CA 94588
Telephone: (925) 660-3900 Fax: (925) 660-3933
Corporate Office: Glendale, CA
Principal Offices: Sacramento Orange County Santa Clara San Diego Seattle, WA

JOB #

QUOTATION TO:
Mr. Allan Daly
Brightbox Technologies
2040 Bancroft Way Suite 302
Berkeley, CA 94704

JOB NAME/ADDRESS:
NSAM Monterey
Glasgow Hall

THE CONDITIONS PRINTED EITHER ON THE REVERSE SIDE OR ATTACHED ARE PART HEREOF.
This work or price quotation does not include detection, abatement, encapsulation or removal of asbestos or products, materials, or equipment containing asbestos.

SCOPE OF WORK:
Please accept the following proposal to provide labor, material, equipment and engineering required, as outlined below, for the installation of DDC Controls at Glasgow Hall in Monterey. Controls will be installed as follows:

Item-1: Provide Project Management labor to attend meetings, manage project schedule, manage project safety requirements, and manage overall project execution.
Item-2: Provide Engineering labor to develop and generate construction drawings and as-builts.
Item-3: Provide and install the following equipment:
- Three (3) Veris Modbus Power Meters, One (1) for each Chiller
- Three (3) Chiller Evaporator DP Sensors, One (1) for each Chiller
- Two (2) Veris Modbus Power Meters, One (1) for each Chilled Water Pump
- Two (2) Chilled Water Pump DP Sensors, One (1) for each Pump

Item-4: Provide and Install ALC Control Panels as required to support new monitoring points.
Item-5: Provide 120VAC electrical work as required.
Item-6: Provide piping work and pipe insulation work as required.
Item-7: Provide programming, graphics and DDC system start-up.
Item-8: Provide Three (3) hours of system Training.
Item-9: Provide One (1) Laptop and One (1) Tablet.

Proposal Clarifications and Exclusions:
- All drawings to be provided in Adobe Acrobat PDF format.
- All work to be performed during normal working hours, swing shift and overtime are not included.
- All wire to be exposed plenum rated cable in the ceiling and walls. Conduit is included in Mechanical Rooms and on the roof.
- Repairs to existing systems are not included.

"Contractors are required by law to be licensed and regulated by the Contractors' State License Board which has jurisdiction to investigate complaints against contractors if a complaint is filed within three years of the date of the alleged violation. Any questions concerning a contractor may be referred to the Registrar, Contractors' State License Board, P. O. Box 26000, Sacramento, CA 95826."
California State License No. 800423

The total price of this work is **$47,508.00**, including all taxes. Terms of payment, unless modified above, are: **0** down payment and the balance due upon the receipt of invoice.

Your signed acceptance of this Bid Contract within 30 days from February 23, 2015 shall, upon the acceptance of the Seller, constitute a contract to perform the work described above, including all Terms and Conditions contained herein.
Seller shall be defined to mean SUNBELT CONTROLS or its assigns.
Buyer shall be defined to mean the Owner, Owners/Agent, Builder, Architect, lessees, or any person acting on behalf of any of the foregoing.

Proposal # Glasgow-1 **SEE TERMS AND CONDITIONS TO BID CONTRACT** **02-23-15**

BID CONTRACT

Principal Office: 4511 Willow Road, Suite 4, Pleasanton, CA 94588
Telephone: (925) 660-3900 Fax: (925) 660-3933
Corporate Office: Glendale, CA
Principal Offices: Sacramento Orange County Santa Clara San Diego Seattle, WA

JOB #

QUOTATION TO:
Mr. Allan Daly
Brightbox Technologies
2040 Bancroft Way Suite 302
Berkeley, CA 94704

JOB NAME/ADDRESS:
NSAM Monterey
Watkins Hall

THE CONDITIONS PRINTED EITHER ON THE REVERSE SIDE OR ATTACHED ARE PART HEREOF.
This work or price quotation does not include detection, abatement, encapsulation or removal of asbestos or products, materials, or equipment containing asbestos.

SCOPE OF WORK:
Please accept the following proposal to provide labor, material, equipment and engineering required, as outlined below, for the installation of DDC Controls at Watkins Hall in Monterey. Controls will be installed as follows:

Item-1: Provide Project Management labor to attend meetings, manage project schedule, manage project safety requirements, and manage overall project execution.
Item-2: Provide Engineering labor to develop and generate construction drawings and as-builts.
Item-3: Provide and install the following equipment:
- Three (3) Veris Modbus Power Meters, One (1) for each Chiller
- One (1) Chiller Evaporator DP Sensor for Chiller #3
- Three (3) Chilled Water Pump DP Sensors, One (1) for each Pump
- One (1) FC-2-E Chilled Water DP Sensor
- Two (2) FC-2-E Chilled Water Temperature Sensors (strap-on sensors)
- One (1) AH-3-2 Chilled Water DP Sensor
- Two (2) AH-3-2 Chilled Water Temperature Sensors (strap-on sensors)
- Two (2) Chilled Water Strap-on Sensors located next to Two (2) Existing Well Sensors for lag comparison. Location to be determined, we suggest B233 Chiller.

Item-4: Provide and Install ALC Control Panels as required to support new monitoring points.
Item-5: Provide 120VAC electrical work as required.
Item-6: Provide piping work and pipe insulation work as required.
Item-7: Provide programming, graphics and DDC system start-up.
Item-8: Provide Three (3) hours of system Training.
Item-9: Provide One (1) Laptop and One (1) Tablet.

Proposal Clarifications and Exclusions:
- All drawings to be provided in Adobe Acrobat PDF format.
- All work to be performed during normal working hours, swing shift and overtime are not included.
- All wire to be exposed plenum rated cable in the ceiling and walls. Conduit is included in Mechanical Rooms and on the roof.
- Repairs to existing systems are not included.

"Contractors are required by law to be licensed and regulated by the Contractors' State License Board which has jurisdiction to investigate complaints against contractors if a complaint is filed within three years of the date of the alleged violation. Any questions concerning a contractor may be referred to the Registrar, Contractors' State License Board, P. O. Box 26000, Sacramento, CA 95826."
California State License No. 800423

The total price of this work is **$54,220.00**, including all taxes. Terms of payment, unless modified above, are: **0** down payment and the balance due upon the receipt of invoice.

Proposal # Watkins-1 **SEE TERMS AND CONDITIONS TO BID CONTRACT** **02-23-15**