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Advanced, Integrated Control for Building Operations to Achieve 40% Energy Saving

Final Report

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Executive Summary

Over the past decade, commercial buildings have experienced a substantial increase in energy-related costs and expenses, largely related to increased use of air conditioning, artificial lighting, and computing services. As of today, buildings are responsible for roughly 40% of the United State's primary energy consumption. To improve the management effectiveness and efficiency, a building automation system (BAS) is typically deployed in modern buildings to automate the various systems and devices. Today's BASs provides building customers with various control strategies to keep the building climate within a specified range, provide lighting based on an occupancy schedule, and monitor system performance and device failures. However, the state-of-art building automation and control systems are limited in the following perspectives, which lead to inefficient building energy usage:

- The heating, cooling, ventilation and lighting control systems are often operated in silos and the operation strategies are also running individually while in lack of coordination.
- The embodied energy within the buildings, natural heating cooling/heating and ventilation and day lighting are mostly wasted
- There is lack of model-based and data driven prediction tools on near-term weather forecasts, occupancy detection, and the existing buildings are incapable of intelligent and proactive decision making and control.
- Some of the strategies work well regarding energy efficiency, however not cost effectively, e.g., demand based ventilation requiring CO2 sensor installation and yearly maintenance.
- No smart load management capability for the consideration of demand response and energy price-sensitive operations
- No plug load control considered for energy efficiency

Through this ARRA/DOE project, we developed and demonstrated a software based integrated advanced building control platform called Smart Energy Box (SEB), which can coordinate building subsystem controls, integrate variety of energy optimization algorithms and provide proactive and collaborative energy management and control for building operations using weather and occupancy information. The integrated control system is a low cost solution and also features:

- Scalable component based architecture allows to build a solution for different building control system configurations with needed components;
- Open Architecture with a central data repository for data exchange among runtime components;
- Extendible to accommodate variety of communication protocols.
- Optimal building control for central loads, distributed loads and onsite energy resource
- Uses web server as a loosely coupled way to engage both building operators and building occupants in collaboration for energy conservation;

Based on the open platform of SEB, we have investigated and evaluated a variety of operation and energy saving control strategies on Carnegie Mellon University Intelligent Work place which is equipped with alternative cooling/heating/ventilation/lighting methods, including radiant mullions, radiant cooling/heating ceiling panels, cool waves, dedicated ventilation unit, motorized window and blinds, and external louvers. Specifically, the control strategies we studied include:

- Coordinated heating/cooling and ventilation control
- Control that selects among alternate actions the one most effective in achieving the desired space condition; for example, adjusting either the lights or the blinds to control the desired illumination in the room.
- Model based predictive control
- Hybrid ventilation using motorized windows
- Daylight utilization
- Measured occupancy based control of cooling/heating, ventilation, lights, and blinds
- Control that takes into account real time pricing and modern grid operations.
- Control that communicates effectively with both the building occupants and the building operators to satisfy the needs of both and to communicate pertinent information regarding energy use and the environmental impact, CO₂ emissions, associated with the building operation.
- Control that makes use of a multiplicity of various sensors

Based on the validation results of these control strategies, they were integrated in SEB in a collaborative and dynamic way. This advanced control system was programmed and computer tested with a model of the Intelligent Workplace's northern section (IW_n). The advanced control program was then installed in the IW_n control system; the performance were measured and compared with that of the state of the art control system to verify the overall energy savings great than 40%. In addition advanced human machine interfaces (HMI's) were developed to communicate both with building occupants and the building operator.

Lifecycle cost analyses of the advanced building control were performed, and a Building Control System Guide was prepared and published to inform owners, architects, and engineers dealing with new construction or renovation of buildings. The Guide will facilitate the design, installation, and integration of advanced control technologies to building controls systems. Siemens has developed the commercialization plan for the potential product Smart Energy box.

Chapter 1 Comparison of Project Accomplishment and Project Goals

The objective of this ARRA/DOE project is to develop an advanced, integrated control approach with an implementation at Carnegie Mellon University Intelligent Workplace to control its cooling/heating, lighting, ventilation, and window/blind operation to achieve 40% energy saving over standard while providing a healthy, productive, and comfortable environment for the building occupants with reduced operating and equipment costs for the building owners.

To achieve this goal, Siemens Corporate Research (SCR), Carnegie Mellon University (CMU), Siemens Building Technology (SBT) and OSRAM have successfully completed the following tasks:

[Task 2.0 Identify System Requirements and Develop System Architecture](#)

CMU has provided the requirements of the target environmental conditions (temperature, humidity, CO₂ level, air movement, ventilation, illumination) as well as suggested operational approaches to energy and cost reduction. Based on the inputs from CMU, SCR generated the system integration architecture which captures the overall integrated building control system functionality to meet comfort, visualization and energy saving goals.

[Task 3.0 Hardware Architecture, i.e. Specifications and Schematics](#)

SBT supplied the sensors, actuators, and automation hardware for cooling/heating, ventilation, and window control in the IW_n. SBT has designed the system architecture based on off-the-shelf Siemens Apogee solution. At the same time, CMU and OSRAM worked together and defined the hardware requirements for illumination control, including the lighting and the blinds.

[Task 4.0 Control System Hardware, Instrumentation and Control, Installation and Commissioning](#)

With the support from CMU and SCR, SBT and OSRAM deployed their hardware at CMU IW and completed the basic hardware system installation.

[Task 5.0 Basic Control System Development, implementation and Testing](#)

Based on a current state of the art control system for cooling/heating, ventilation, and lighting specified by SCR and CMU, SBT and OSRAM implemented basic control logic on SBT/OSRAM controllers. Traditional HMIs were created in Siemens APOGEE Building Management System and OSRAM Encelium system for the occupants to exercise manual control of their environment and for the operator to control and monitor the energy use and carbon footprint in the IW_n.

[Task 6.0 Modeling \(Thermal Load, Air Flow, Radiant Heat/Illumination\) in the IW_n](#)

CMU and SCR developed, programmed and validated a zoned, thermal performance model of the IW_n in TRNSYS/Comis and Energy Plus as well as a radiant heat transfer model and an illumination model. This model structure are composed of multiple modules: a building space model, the building space operating parameters, equipment models, control algorithm model and a model of the occupants. These models were then used in design, data analysis, and evaluation of the effectiveness of the advanced IW_n control system.

[Task 7.0 Advanced Control Algorithms Research and Development](#)

CMU and SCR have investigated and evaluated a variety of operation and energy saving control strategies on Carnegie Mellon University Intelligent Work place, for lighting system, heating system, cooling system and ventilation system respectively. With the inputs from field testing, SCR and CMU have developed an integrated optimal control architecture that minimizes total energy costs and CO₂ emissions without compromising comfort based on weather and occupancy forecast. .

[Task 9.0 Implementation of Advanced Control Strategies](#)

SCR successfully implemented the advanced control programs for the IW_n using Siemens Smart Energy Box, an open research platform for energy integration and optimization. The system was tested full functioning.

[Task 10.0 Development of Data Analysis and Human-Machine Interface \(HMI\)](#)

SCR has developed collaborative HMI based on latest visualization and social network technology which is able to engage occupants and building operators active participation in energy conservation collaboratively. The project team conducted building energy monitoring and carbon assessment during building operation. With the data collected from Siemens systems, three categories of data analysis studies were performed including study of the performance of the individual HVAC and lighting equipment in as installed conditions; study of the performance of the equipment in influencing conditions in the space; and study of the performance of the advanced control algorithms. Measurements from sensors in the space and in the HVAC and lighting equipment are used to determine the performance improvements brought by the use of the advanced control algorithm developed in this work to validate 40% energy saving.

[Task 11.0 Demonstration of the Overall Advanced Control system](#)

CMU operated the IW_n with its advanced control system with the support from Siemens. CMU also analyzed the operational data to validate the various models. The operation was closely followed to examine whether all scenarios for the system and its controls in the IW_n were properly played out. 40% of overall energy saving were validated for the advanced integrated control system.

[Task 12.0 Life Cycle Cost Analysis](#)

CMU had developed the overall cost benefit analysis methodology and used to provide an economic analysis of the advanced building control system. CMU used the models of the IW, equipment, and the basic and the advanced control systems to determine the annual effectiveness and energy consumption with the different control systems. CMU also assisted with equipment and installation costs required for cost analyses.

[Task 13.0 Commercialization Plan](#)

SCR has worked on customer value proposition and investigated the market potential of Smart Energy Box. We have analyzed the technical feasibility and specified the development process for future of commercialization of SEB

[Task 14.0 Dissemination of Findings through Publications](#)

SCR and CMU together have published more than 10 technical papers and made presentations on world class conferences. We have created documents fully describing and disclosing our work. The project participants successfully delivered all the quarterly reports and technical reports to DOE and made presentations to the NETL and Golden Office program managers during our milestone review meetings..

Task 1 and Task 8 are project management tasks.

Overall, during the two years of project period (July1, 2010 through June 30, 2012), the project team have successfully demonstrated the integrated advanced building control systems which enables 40% energy saving on building HVAC and light system operations at CMU Intelligent Workplace. The results are also applicable to regular commercial buildings, which was validated through simulations.

Chapter 2 Integrated Building Control Architecture for 40% Energy Saving

Today's building automation systems (BAS) provide building customers with various controls to meet building operation goal of maintaining thermal, lighting and ventilation comfort. However, state-of-art Building Management Systems (BMSs) failing to take advantage of coordinated control among different systems and the utilizations of advanced information technology (IT) poses challenges on the potential of energy savings. HVAC, lighting systems, and IT systems are operated in silos and the control strategies are also running individually while in lack of integration view. Most of the strategies are static programmed without considerations of weather and occupancy changes, not mention smart load management capability for the consideration of demand response and price-sensitive operations.

The integrated building energy management and control system developed by Siemens is a new approach and provides an innovative platform for advanced energy management implementation that is able to integrate a variety of technologies, including optimal combined HVAC and lighting control, model predictive control using weather forecast and building simulations, occupancy based collaboration energy management and collaborative control with advanced visualization and social network technology. The coordinated HVAC, lighting and plug load control and operation optimization on top of the existing building automation systems addresses both the reduction of the building total energy usage as well as the peak demand. The system has been demonstrated at Carnegie Mellon University (CMU) Intelligent Work Place (IW) to improve the building energy performance targeting at 40% savings.

This chapter covers the Project Task 2, 3, 4 and 5.

2.1 Advanced Integrated Building Control System Architecture

The main challenge for the integration of CMU building systems are from the fact that the previously existing IW HVAC and lighting systems of CMU IW building are from different vendors with limited technical supports. During the first phase of the project, the project team made thorough investigation on off-the-shelf Siemens Building Management System, and discovered that it is feasible to connect all of the existing HVAC and lighting devices through direct I/O connection and open industry communication protocols and all the controls can be conducted from single point of Siemens Apogee server. As shown in Figure 2.1, for the system integration work, all the ballast/plug load control points and occupancy/luminance sensor values from Encellium lighting control system are enabled as BACnet objects which can be commanded and read from Apogee. Part of the ventilation (SEMCO) control and observation points are also configured as BACnet objects by Automated Logic software and they are also accessible from Apogee. The Operable window control is integrated based on BACnet protocol as well, but in opposite way. Virtual window control commands were created in Apogee and enabled as BACnet objects. From Labview side, a BACnet client is implemented to poll the window operation commands and accordingly the commands are sent to the relays which actuate the windows.

However, to meet the requirements of a control framework for easy weather and occupancy forecast integration, Apogee is limited in being not open enough for the implementation of advanced control algorithms developed during our project. Instead, we utilized a separate research software platform called Siemens Smart Energy Box (SEB) and applied weather based advanced control and collaborative energy management to CMU IW building operation. As shown in Fig 2.1, SEB was developed with a BACnet interface as well as an interface for grid communication. This box can either be implemented in a standalone hardware platform or hosted by the same PC station with Apogee Insight.

Fig 2.1: Implementation view of integrated control for CMU IW North

2.2 SEB architecture

The key component for the integrated control is Siemens Smart Energy Box (SEB) which oversee all of the buildings subsystems, including HVAC control, lighting control, and local controllers for onsite energy resources and distributed loads. Specifically, as shown in Figure 2.2, SEB offers the following basic features and an extended API for additional function implementations:

- SEB acts as an integration platform allowing communication among buildings, building subsystems and building operators through stand protocols (BACnet, Modbus etc) in order to form coordinated demand side load and generation management.
- SEB implements both weather forecast adaptor for proactive energy management
- SEB implements an energy simulation engine for load forecasting and runtime assessment of energy efficiency strategy to minimize operational cost.
- SEB acts as a gateway to connect to grid based on open standards such as OpenADR, through which energy prices as well as demand response event can be delivered from utility to buildings.
- SEB provides a open data service for 3rd party function integration SEB implements an advanced human machine interface (HMI) for building operators based on the latest visualization technology, which provides the best transparency of how energy was, is and will be used, supporting the breakdowns among buildings, within buildings down to zone level.

SEB is a totally open logic box and is able to host variety of advanced control algorithms. For this project, we developed and tested weather based Energy Management and Control (EMC) strategies of which the energy saving potentials are presented in the following chapters. We also developed a Generic Energy Management and Control (GEMC) co-simulation platform based on this SEB to test the EMC strategies on the commercial benchmark buildings to explore the energy saving potentials. In addition, we also developed a collaborative energy management and control (cEMC) system which takes the advantage of latest information technology, visualization technology and social network technology to engage energy conservation from building occupants to the maximum. The details of cEMC will be illustrated in next section.

Fig 2.2 Architectural Overview of Siemens Smart Energy Box (SEB)

2.3 Collaborative Energy management and Control (cEMC)

cEMC is a special control component implemented in SEB which extends an existing BAS by means of

active occupant engagement in energy management and comfort control.

In today's commercial buildings, energy related control policies, such as HVAC set points and lighting schedule, are often defined and imposed by facility managers as shown in Figure 2.3 (a). Occupants have little control over the comfort settings and there is very limited means (phone calls and emails) for them to express their experience and comfort needs to facility managers. Meanwhile, existing building automation systems provide no feedback to the occupant about his energy use behavior and how he should behave to support facility managers to achieve energy saving goals.

The one way, top-down process of building control could lead to two opposite consequences. Under one circumstance, facility managers who implement aggressive energy policies often achieve energy saving goals with the sacrifice of occupants' comfort; under most of other circumstances, facility managers usually have to relax the energy policies to avoid occupant complains, and often miss the opportunity for energy saving. Figure 2.3 b shows the communication flow of our proposed collaborative energy management and control (cEMC) system, where occupants can submit their request to automation system directly. The requests from occupants and facility managers are merged automatically by a software arbitrator, which detects conflictive requirement and solve the confliction according to the rules established by the facility manager.

Figure 2.4 shows the system architecture of our innovative collaborative energy management and control system (cEMC), where occupants can directly submit their comfort needs to cEMC system while facility manager can configure energy policy as rules and send them to the cEMC controller. The cEMC controller detects and resolves conflicts to generate non-conflictive set points for building automation systems *automatically based on the building mode, energy efficiency or demand response*.

Figure 2.3 a Standard building automation system communication diagram.

Figure 2.3 b Collaborative Energy Management and Control.

Figure 2.4 cEMC system architecture.

As shown in Figure 2.4, cEMC has two major components: the front end HMI and the back end engine. The web-based platform, *collaborative HMI*, is utilized to facilitate the communication between facility manager and occupants, and among occupants themselves. Social networking between occupants and facility manager is adopted to enhance communication as well as to prompt energy responsive behaviors.

Collaborative HMI

The success of cEMC depends on the user interfaces provided to the building operators and building occupants. We designed and developed the Advanced HMI for building collaborative control that allows interactive communications and collaborations between occupants and facility managers to refine energy policies in ways that optimize energy saving and improve occupants' comfort. The Occupants' HMI, which is referred to as the "softThermostat", (see Figure 2.5 a & b for examples) allows occupants to change the zone set points and to input their activity and schedule information, as well as to define their preferences. The Facility Manager's HMI, referred to as "FM Dashboard" (see Figures 2.6 a & b examples), supports facility managers by enabling them to view current building energy performance and the aggregated information provided by all occupants.

Based on occupants' inputs of preference and schedule, both the Occupant's and the Facility Manager's HMI's can also visualize the energy efficiency information as calculated by the cEMC Controller and, in addition, the comfort information based on the match level between the current condition information and the occupants' preferences.

Figure 2.5 a Occupants' HMI

Figure 2.5 b Occupants can input their weekly schedule.

Figure 2.6 a Facility manager's HMI, also referred as FM Dashboard.

Figure 2.6 b Facility managers can view the aggregated preference information provided by occupants.

The HMIs also provide a social-networking mechanism for occupants and facility managers, which supports easy and efficient communications and collaborations as well as encourages energy saving behaviors (see Figure 2.7). One highlight feature of the Occupants' HMI is its comfort voting through which occupants can provide their immediate feedback for building conditions. Through this Advanced Collaborative HMI, facility managers can also easily create a Demand Response event and effectively

disseminate the information to all occupants.

Figure 2.7 HMI Social network view

Collaborative Engine

The heart of the *collaborative engine* is a rule engine that supports variations in control logic and conflict detection and resolution at run time. Therefore, requirements and control rules are captured by the HMI then loaded and executed by the rule engine directly. In previous systems, facility managers would have to hire professional software engineers to implement new requirements in software code. The process is costly in terms of time and labor.

The arbitration functions and energy saving rule sets are captured by XML-based rule files. It means the system is flexible to change its functionality without compilation, which requires non-trivial software development efforts. Equipped with the rule engine, facility manager can change their business rules and load to CEMC directly, without support from professional software engineers.

SCR developed a graphical tool for occupants and facility managers to type in the control logic in their mind. The prototype editor, named RuleMaker, is shown in Figure 2.8 and Figure 2.9. The RuleMaker has two level of presentation on the rules. On the high level, rules are captured as finite state machines (FSMs). Due to the nature of the HVAC hardware devices, the building can be considered a system that switches among a large number of states, i.e., an FSM. ASHRAE manual on recommended HVAC control sequences can be captured as FSMs. On the lower level, script language can be embedded inside the FSM to implement sophisticated logics. Currently, we support C# as the embedded script language in the FSM. Users can define full featured C# function in the “data model” section of each state as shown in Figure 2.9. Figure 2.10 shows an example of control rule set developed by for heating control.

Figure 2.8 User create, edit and visualize in rules using RuleMaker.

Figure 2.9 Script embedded in a rule file.

Figure 2.10 One example of control rule set developed by CMU

2.4 Conclusion on integrated control software architecture

Our integrated building control system is a software based solution, the cost is lower compared with hardware based energy efficiency strategies, e.g., occupancy detection sensor or CO₂ assisted demand based ventilation control. For example, the cost of cEMC mainly comes from engineering effort during the commissioning phase. After commissioning, no maintenance is needed for cEMC, in contrast with hardware based systems that use occupancy sensors requiring yearly calibration, e.g., CO₂ sensors. The return of investment on our integrated building energy management and control system based on SEB is expected to be within 3 years if the building already has a BAS system. If there is no automated control available for the demonstration building, our SEB can act as an advisory control to send suggestions to the user to turn off the heater, air conditioner or lights when not needed and to maximize the use of natural cooling and ventilation. The advisory version SEB will generate less energy savings; however, the return of investment can also be achieved within about 5 years. The benefits of an integrated control system using SEB would be clearly demonstrated and replicable on all commercial buildings.

Chapter 3 Modeling and Simulation

Building modeling and simulation are central to our project. We have spent intensive effort towards the development of first principle model, Trnsys, Comis, Daysim and Energy plus models which are used for evaluating and quantifying energy use and control strategies and models in predictive controls for energy optimization. This chapter covers Project Task 6 and highlights our effort on building modeling and calibration results for CMU IW.

3.1 First Principle Modeling and System Identification

During the project, we strived to build First-principle models (grey box models) for CMU Intelligent Workplace. Thermal modeling has been commonly achieved with the lumped capacitance or RC model, which draws parallels between circuit theory and thermodynamics to describe heat flow. Using this approach, circuit diagrams are used to depict heat dynamics of a building where voltage represents temperature, current represents heat flow, resistors represent material resistance to heat flow, and capacitors represent heat stored in materials. Fig. 3 illustrates this concept with an RC model depiction of a single wall that separates two building zones. In Fig. 3.1, nodes T_1 , T_2 , T_{w1} , and T_{w2} represent hourly mean zone and wall surface temperatures. The capacitors C_1 and C_2 represent the total heat capacitance of the zone air, and C_w represents the total heat capacitance in the wall. Current sources I_1 , I_2 and resistors R_1 , R_w , R_2 are used to represent conductive, convective, and radiative heat transfer in the two zones.

Figure 3.1 two-zone RC Model

Given the circuit diagram, a linear dynamic model parameterized can be constructed:

$$\begin{bmatrix} \dot{T}_1 \\ \dot{T}_w \\ \dot{T}_2 \end{bmatrix} = \begin{bmatrix} -\frac{1}{\tau_1} & \frac{1}{\tau_1} & 0 \\ \frac{1}{\tau_{w1}} & -\frac{1}{\tau_{w1}} - \frac{1}{\tau_{w2}} & \frac{1}{\tau_{w2}} \\ 0 & \frac{1}{\tau_2} & -\frac{1}{\tau_2} \end{bmatrix} \begin{bmatrix} T_1 \\ T_w \\ T_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{C_1} & 0 \\ 0 & 0 \\ 0 & \frac{1}{C_2} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix},$$

Where:

$$\tau_1 = (R_1 + .5R_w)C_1, \quad \tau_2 = (R_2 + .5R_w)C_2,$$

$$\tau_{w1} = (R_1 + .5R_w)C_w, \quad \tau_{w2} = (R_2 + .5R_w)C_w,$$

And

$$\theta = [R_1, R_2, R_w, C_1, C_2, C_w].$$

Multi-zone thermal models can be constructed similarly using this lumped parameter approach. The key step for this modeling approach is to calibrate the model with real data to identify the parameters in the equations above. Model calibration is important to ensure model match the physical systems. Model calibration is in fact a system-identification problem, and the challenge of parameter estimation for complex building models is a non-trivial one. The first principle model requires large number of parameters, 150 to 300 parameters for CMU IW north part. We experiences much difficulties following the current heuristic (manual) calibration approaches

1. The parameters of first-principle and software-based simulation models have physical meanings, therefore we know the rough range of valid parameters. This is an advantage: since we can eliminate fittings that infeasible for physical systems.
2. The number of parameters of data driven models are much less, which implies the dependence on high quality data is less. However, the disadvantage is the lack of physical meaning. We don't have guidance on appropriate range of the parameters. As every new set of data generate a new set of parameters, it is difficult to ensure when the model is accurate enough.

The difficult we experienced can be summarized as the following scenarios

1. Before the model calibration process, there is no guidance for us to design experiments for data collation, therefore the duration and result are not ensured.
2. During the calibration process, we are not sure when the model is good enough. Often, the model is seemed accurate enough for existing data, but when new data set arrives, the fitting is not accurate. We cannot predict the absolute minimal duration for the experiment design.
3. Typically data used for model calibration was collected during normal building operation, which means the temperature set points are designed for occupants' comfort, not optimized for model calibration. According the system identification theory, the desirable signal for model calibration is actually not comfortable, since the large variation and high frequency excitation signals leads to data with richer information, which is desirable for model calibration purposes.

Current system identification methods follow the architecture illustrated in Figure 3.2 a, where users define the excitation signal prior to the experiment. In the case of office buildings, these excitation signals can be square wave inputs corresponding to changing set point temperatures while disturbances represent uncontrollable heating or cooling such as solar radiation, infiltration, and thermal load of building occupants. We developed a closed-loop architecture for active system identification, as shown in Figure 3.2 b. The notion of sensors and actuators are the same as in Figure 3.2 a. This architecture is featured with a closed loop active system identification structure. The dashed lines are implemented as manual processes in this study as a proof of concept, but will be implemented as automatic functions. The grey arrows across the sensors and actuators indicate communication from the "active system ID" module which determines optimal sensor placements and sampling frequency before experiments. The key component of this architecture is a method to estimate and compare data quality.

Figure 3.2 a. Architecture of current open-loop system identification methods.

Figure 3.2 b. Architecture of proposed system identification process.

To quantify data quality, we use Fisher Information Matrix (FIM) as a metric. Assuming S_r is sensor reading, θ is parameter vector. FIM is defined as

$$M_r = \left(\frac{\partial S_r(\theta)}{\partial \theta} \right) \left(\frac{\partial S_r(\theta)}{\partial \theta} \right)^T \bigg|_{\theta=\theta_0}$$

For a given model, such as RC model, and a given set of data, we can calculate the FIM and quantify the estimation error of each parameter using singular value decomposition (SVD)

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where the smaller the singular values () the smaller the estimation error. Once we plot the singular values of each parameter, it is clear that some parameters may not be identified accurately for a given set of data. The result shown in Figure 3.3 and Figure 3.4 tells us about 2/3 of parameters in RC models are not identifiable numerically: although each data set generate one estimate of such parameter, the parameter is never accurate no matter how much more data we collect. To compensate this effect, we must improve data quality, such as install more sensors or change excitation signals.

Figure 3.3 Identification quality of step input excitation signal

Figure 3.4 Multi-sinusoidal waves with all parameters being estimated

3.2 Trnsys modeling/lighting modeling

The interrelationship of daylight and solar heat are critical factors for the control of internal and external blinds and louvers, whether the controls are manual or automatic. In this research effort, the CMU research team used Trnsys and Daysim to evaluate the impact of dynamically varying external louver positions on thermal and lighting energy demands.

DAYSIM is used as validated daylighting analysis software for IW daylight simulation and control based on the RADIANCE. As the first step, a 3D building model is created in ECOTECH and exported as RADIANCE file. Then the building definition is imported into DAYSIM and illuminance profiles are generated for different louver position and exported to TRNSYS, where thermal-daylighting co-simulation are made to generate energy effect control for IW louver systems.

Figure 3.5 Ecotect 3D model with louvers closed and louvers open

Experimental studies were conducted to characterize the impact of external glass louvers on indoor temperatures and light levels. These external louvers are composed of a series of 3 glass panels with a visible transmittance (VT) of 0.3. The panels can rotate to a 105° angle (fully open position) and be in fully closed position at 0° (see Figure 3.6)

Figure 3.6 External dynamic louvers for east and west facades can provide measurable cooling load reductions while sustaining daylight levels

CMU built an Ecotect-Daysim model of the IW that could be linked to the existing Trnsys model to explore model-predictive rule based control for six different louvers position (0° , 22.5° , 45° , 67.5° , 90° , and 105°). By integrating this model with a Trnsys-Daysim controller, illustrated in Figure 3.8, experimental measurements of the impact of various louver positions on Illuminance could be studied for different sensor locations.

Figure 3.7: Example comparison of Daysim results with experimental measurement (1 sensor position)

The development of model predictive controls for louver position (Figure 3.8) is then driven by running Daysim iteratively with Trnsys to balance thermal and lighting demands by orientation, season, and sky conditions using a predictable weather year for Pittsburgh (TMY2).

Trnsys-Ecotect-Daysim: Rule Based Model Control

Figure 3.8 Diagram of Rule Based Model for louver control

The result is a set of model predictive rules for controlling the best position of external louvers to ensure over effective internal illuminance for daylighting while providing the maximum shading in cooling seasons and the maximum passive solar contributions in heating seasons (Figure 3.9).

TRNSYS Format	Louvers 105° (Open)	Louvers 90°	Louvers 67.5°	Louvers 45°	Louvers 22.5°	Louvers 0° (Close)
t	550	500	450	350	250	250
t+1	600	555	500	400	300	300
t+2	750	700	650	550	450	450
t+3	900	850	800	700	600	550
t+4	950	900	850	750	650	600
t+5	950	900	850	750	650	600
t+6	900	850	800	700	600	550
t+7	800	750	700	600	500	425
t+8	750	700	700	600	500	400
t+9	750	700	650	550	425	350
t+10	650	600	550	450	350	250

Figure 3.9 external shading control while maintaining daylight levels for energy efficiency

Given the laboratory configuration and climate conditions of the Intelligent Workplace in Pittsburgh, the energy savings from dynamic louver control that maintains illuminance levels of 500 lux within 15 feet of building depth while minimizing heat gain in summer months is shown in Fig 3.15 for a three day period (no shading left, shading right).

Figure 3.10 Dynamic Louvers measurably reduce Solar Overheating

3.3 Energy Plus Modeling

The basic but very detailed IW north zone model has been established in E+. It can function for the whole year energy simulation. The set point can be specified to achieve optimal supervisory control for energy management.

The detailed building thermal model has been built in E+ using DesignBuilder as the interface. Building geometry and envelop were modeled (shown in Figure 3.11) with 13 zones defined to emphasize the effect of natural ventilation and keep the air conditioning components as they are for possible utilization from control point of view (shown in Figure 3.12).

Figure 3.11 The final IW geometry model with necessary simplifications

Figure 3.12 The IW North Bay zone names and coordinates

Since water mullions, cool waves and cool ceilings used in IW are not typical indoor components in most U.S. commercial buildings, only minimal support is provided in E+ to model these subsystems. As an alternative, radiant walls were created to simulate the water mullions. Similarly, the cool ceilings were modeled as internal source adiabatic ceilings. To simulate the cool waves, the chill beam (or fan coil without fan) like components--constant volume cooled beams are used to approximate the performance. Eight constant volume passive cooled beams were built for the cool waves.

DesignBuilder was also used to generate the natural ventilation linkage which is transferred into E+. The model for the natural ventilation geometry was based on Fig 3.11. The unconventional SEMCO and coupled natural ventilation make mechanical ventilation extremely difficult to model in Energy Plus. Currently it is approximated by adding vents into each individual zone.

Shading control is building in as a window property. The shading control can be specified as 21 different types, e.g. always on, always off, only schedule allows, only high solar on window, only high horizontal solar, only high outside air temperature, only high zone air temperature, only high glare, etc. To match the historical energy data, this item should be chosen as always on.

Daylighting control is used to dim overhead electric lighting when the interior illuminance calculated at one or two reference points satisfies the requirement. The devices currently supported in E+ include tubular, shelf and lightwell. The external louver of IW might be approximated by using the shelf type. The output from E+ can be the illuminance map. However, since this simulation is very time consuming, and the reference points need to be specified, the daylight control is currently unused in the E+ model.

Air and water loop in E+ is based on terminals, nodes, branches, splitters and mixers. Controllers and set point managers are additional to make the system function. Due to the constraints of Energy Plus, the branches for cool ceiling and cool wave cannot be set. Instead, they are set in parallel to all the other mullions with the branches and the pumps replaced by the pipes linking to individual water based terminals. As a whole building energy simulation engine, this change has minor influence on the thermal energy consumption. Further study on the improvement of the setting is needed if the dynamic performance of local control (for example, a valve) is desired.

The model, from the geometry, thermal system, natural ventilation, water loop to SEMCO, passed the integrity test and provides basic simulation for the IW North Bay. Figure 3.13 shows the some simulation result of zone mean air temperature.

Figure 3.13 IW North East 1 zone temperature

In summary, although the model structure is created for the space and gives reasonable simulation, many parameters and controls are needed to be accurate in order to obtain a quality calibration. Since the model

is used for control purpose, this point is extremely important and challenging. Meanwhile, since IW has a small open space, the energy consumption simulation result is very sensitive to any change on the local equipment. A rough 20% RMSE match based calibration which is typically applied to whole building, where the discrepancy can be easily merged in the overall results, might not work for this space.

3.4 Co-simulation platform

We developed two co-simulation platforms to explore the energy saving potential of the proposed integrated and advanced energy management and control algorithms and strategies on commercial buildings. The first simulation platform is based on Matlab and Energyplus to simulate the closed-loop control of building automation and operation system. The second simulation platform is based on the real-implementation of SEB and HMI developed in this project. The energy saving simulation results are presented in the following later chapters.

3.4.1 Matlab and EnergyPlus co-simulation platform

A co-simulation platform as shown in Fig x connecting Matlab and EnergyPlus with MLE+ is developed to implement the model-based optimization control strategy. EnergyPlus is used as a virtual building for system identification and control test. By using MLE+, the EnergyPlus model of the building becomes an S-function block in the Matlab/Simulink. The main advantage of this co-simulation setup is that it takes full advantage of the Matlab/Simulink environment including interactive simulation, debugging, and all available Matlab toolboxes.

Figure 3.14 Closed-loop control using Matlab/Simulink and EnergyPlus

The detailed simulation architecture for the model-based optimization control strategy is shown in Figure 15. The model-based EMC using MPC technology is implemented in Matlab language and communicates to EnergyPlus via MLE+. The operation data from EnergyPlus provides building comfort information as well as the energy consumption profile as the feedback information for the EMC. The outputs from the EMC are supervisory control signals including set-points of zone temperature, humidity, and luminance and schedules of building control devices such as HVAC, Windows, and Lights.

Fig 3.15 Simulation Platform for Model-based Optimization Control Strategy

The Matlab/Simulink layout of the simulation is shown in Fig 3.16. The building EnergyPlus model is wrapped as a function block. The energy calculation and display block calculates and displays the energy consumption.

Fig 3.16 Matlab/Simulink Layout

3.4.2 Generic Energy Management Control (GEMC) simulation platform

The goal of this generic EMC development is to demonstrate that the EMC strategies developed in this project can be applied to the commercial benchmark buildings. The final demo is implemented in a hybrid platform which includes real implementation of HMI and SEB and simulation-based benchmark buildings models in EnergyPlus. Fig x shows the diagram of the generic EMC platform.

The customized SEB for Generic EMC does not use the BACnet to control the real building controller, so the BMS adapter module is disabled. Instead we developed a run-time component called Building Run-time Simulator to simulate the building dynamic behavior after run-time commands generated by EMC are applied to the building.

Fig 3.17 Generic Energy Management Control Simulation Platform with SEB

3.5 Conclusion

Generally, models serve as the base for the advanced integrated control in order to evaluate the evolution of the controlled system and determine the proper actions. The format and time scale of a model is determined by the purpose of the use. In a building thermal system, the building construction is usually of the longest time scale and the equipment has the shortest time scale. This information is very useful in the determination of the control system and its optimization. For the study of the dynamics of a given system, generally the parts with the relatively long time constant shall remain in dynamics, and the parts with the relatively short time constant can be simplified into quasi-steady-state. Model-predictive rule-based control (MPRC) is a very promising strategy for prioritizing energy savings opportunities in existing buildings, for establishing controlled field experiments and for estimating relative benefits for energy efficiency.

For the first principle modeling, the simulation and experimental data confirm that the experimental design is necessary for proper identification of models real systems, which might be achieved with closed-loop architecture for active system identification.

The models built in Energy Plus and Trnysys are huge, with thousands of specifications and assumptions based on the best available drawings and records for the building. The real building has had innumerable modifications, errors and omissions, and human overrides that make actual energy profiles far more erratic than the simulation would predict. Buildings are not like machines or process engineering, where exact system specifications and operational procedures can be set and where humans and weather are truly disturbances (rather than desirable contributions). In addition, the models are unwieldy for “on-the-fly” calculations of ideal set points and actions that are the hallmark of model predictive control strategies.

Simulation comparisons with short and long term energy profiles are very promising actions for indentifying energy savings opportunities in existing buildings. However, complete calibration of the energy model with measured energy use profiles is challenging. While the energy model must be calibrated against the energy use profile and control set points, the time step for calibration and percent of divergence remains a critical debate. A majority of large building simulations are calibrated against monthly averages, extremes, and patterns, modifying the simulation with iterative assumptions to come within 20% of accuracy. Hour-by-hour calibration of the model against hour-by-hour measured conditions, even for short periods, reveal significant variability. Despite over 30 years of development by hundreds of researchers these building energy simulation tools are still most effective for parametric analysis of alternative building systems *and* building control alternatives to assess their impact on average and peak loads. Matching hour-by-hour conditions may be possible for a single zone small test lab or house, but will be almost impossible for a commercial building with occupant and system operation & maintenance variations that cannot be completely identified.

Chapter 4 Electric Lighting and Daylighting Controls for 75% Energy Savings

Investment in existing US buildings has not kept pace with time or the changing nature of work. Lighting demands in buildings consume over 37% of US electricity use in buildings, predominantly during the daytime (CBEC 2003), 4-5 times that required given up-to-date technologies and controls.

Fig 4.1 While heating is the highest site energy load, lighting is the largest electrical and source energy load in commercial buildings.

The 70% energy savings that can be achieved through lighting system investments are related to:

- general ceiling based lighting typically designed to achieve both task and ambient light levels (T-A lighting) throughout the floor area and their reflectors, lamps, ballasts, diffusers and controls;
- task lights that have been acquired over the years and their controls;
- window layers, both external and internal and their controls.

Investments that can be considered for effective lighting and daylighting utilization range from simple sensor/relay and controls for groups of lights and manual control of blinds to the future of individually addressed and controllable fixtures and blinds. Through a partnership with OSRAM/Sylvania and Encelium, the DOE Siemens/CMU research effort tested a range of system upgrades and controls for their energy savings potential in the Intelligent Workplace test lab, described in the following sections.

4.1 Experimental Configuration: Lighting/Daylighting Intelligent Workplace

The Intelligent Workplace is a living and lived in laboratory for testing the performance and life cycle benefits of innovations in enclosure, mechanical, lighting, networking and interior systems. To support the lighting controls research, each of the existing infrastructures were mapped and evaluated relative to best of class technology that would be introduced today. For lighting, the 7000 square foot lab (see Fig 4.2) includes:

- 100 Zumtobel Latrave indirect direct task-ambient lights with 50 Sylvania addressable and continuously dimmable ballasts, T-5 lamps, with a “black box” control system that was no longer supported by the manufacturer (LuxMate). The high performance dimming ballasts installed in 1998 were 230 volt and relied on multiple step up transformers with a 0.1 watt/square foot parasitic load.

- Twenty 120 volt tracks for egress and security lighting with Zumtobel Spirit fixtures, combined with 23 halogen floor lights and 36 halogen façade lights, 8 fire alarm lights (redundant due to university rules) and 5 LED exit lights.
- External high reflectivity glass louvers on the East and West that can be electrically positioned from vertical for shading to perpendicular (0 degrees) to a 105 degree inward sloping position for light redirection.
- Innovative Retrosolar light and heat managing internal venetian blinds on the east and west that can be manually set in the full range of blind positions, with 50% motorized for potential on-line control, but as yet not electrified.

Fig 4.2 IW Lighting/Daylighting/Shading

The Siemens/CMU/Osram/Sylvania team assessed the lab conditions and made strategic decisions to introduce a number of improvements that would be recommended for most high performance office projects:

- For innovative control evaluation fixture by fixture, up to date high performance dimming ballasts were installed in each of Zumtobel ceiling luminaires with external relays. The new dimming ballasts operate on 110v eliminating the .1w/sqft parasitic load, consume only 10 watts per fixture in operational energy and have the best light to energy profile throughout the dimming range, of products on the market. This 100-1% dimming ballast is designed for T-5 lamps which provide 188% greater lighting output per lamp (high power factor) over the more conventional T-8 ballasts, eliminates flicker and provides a better light distribution (high luminous efficacy) as well as 12,000 hours of use.

- For the lowest energy demand and the highest level of automated control of egress and security lighting, the power supply to the 12 tracks and track lights was switched from 230V to 110V supply, and lamps were updated from 75 watt Halogen flood lights to 15 watt LED lamps.
- To evaluate the widest set of control options, an Encelium lighting control system was installed with fully integrated communication abilities to Sylvania dimming ballasts and LED track lights, a wide range of control options (Fig 4.2) and a critical Bacnet interface to the Apogee HVAC control system for comprehensive balancing of light and heat by season.

Fig 4.3 Encelium range of control options

The Encelium infrastructure includes an Energy Control Unit (ECU) that collects, processes and distributes lighting control information to I/O modules, zone controllers, and distributed scenes and lighting controllers (wireless switches) over a GreenBus™ network; and a System Support Unit (SSU) that serves as the database server for all data related to an Encelium system installed in a facility, although this could be integrated with the Apogee server.

- To support task light controls and their ambient lighting interfaces, a duplex Greenplug relay was installed in each of 46 power/data/voice floor boxes to control 2 power outlets per workstation based on occupancy, time scheduling, peak load shaving and other energy saving strategies.
- For evaluating the energy benefits of separating ambient and task lights, five LED 8W dimming, articulated arm Finelite task lights were gifted to the project.
- To evaluate the density of sensors that may be critical to effective control, 10 occupancy sensors and 6 daylight sensors were installed.
- To support advanced control of external dynamic louvers for shade, light and passive solar heating tradeoffs, 8 sets of external louver controls were connected to the Apogee control system with a two point control, fully closed (shading) and fully open (light redirection). Full angle control would have required additional investment beyond the budgets available.
- To support advanced venetian blind control, selected motorized blinds were connected to the Apogee control system with a two point control, fully open for views and light when neither glare or overheating is an issue, and down and closed when overheating and heat loss is managed in unoccupied periods. Full angle control would have required additional investment beyond the budgets available.

- Given the cost of wiring individual blinds with power, data, and adding relays, a second group of blinds have been fitted with photovoltaic wireless motor casings. These Blinds with PV driven motors allow accurately control of the tilt of the blades for lights redirection and glare control.

Table 4.1 summarizes the details of the lighting and power control system installations.

Table 4.1 : Advanced lighting sensing, actuating, and control technologies installed

Installation	Number	Description
Ceiling lighting: 55W, U-shape lamp 110V, 1%- 100% dimming ballast Encelium IO-module	200 100 100	All the existing Zumtobel ceiling luminaires in the IW were equipped with new lamps, ballasts and controllers.
Track lighting: Encelium IO-module	20	Each track light been equipped with one relay for 110V power supply
Plug load controller: Encelium IO-module	46	Each floor-based power box was equipped with 1 Encelium controller to control two power outlets
Dual technology occupancy sensor	10	installed in the ceiling space of the IW
Light sensor	6	installed in the ceiling spaces in the north zone of the IW
Wall mounted light switch	5	installed in the two conference spaces, kitchen area and two entrance of the IW
Encelium system SSU ECS	1 1	installed in the controller cabinets in the IW

4.2 Lighting Hypotheses

The research team developed a series of hypothesis for saving energy in existing office environments for field experimentation:

- Time of day** controls for existing lighting zones will eliminate x% electric lighting during unnecessary night and weekend hours.
- Daylight responsive** controls will eliminate x% electric light in perimeter zones (where existing zones include perimeter lights only) - adding new sensors and/or time of day control.
- Occupancy responsive** controls will eliminate x% electric light in any unoccupied space (where dedicated lighting zones exist, such as closed rooms) - adding new occupancy sensors.
- Vacancy responsive** controls, which require occupants to turn lights on but turn them off when they leave spaces, will eliminate x% electric light in both occupied and unoccupied space (where dedicated lighting zones exist, such as closed rooms) - adding new vacancy sensors.
- Shifting from task-ambient** ceiling light to high efficiency ambient only (300 lux) with low energy task lights will eliminate x% electric light – adding task light occupancy sensors or smart outlets.
- Individual control** of task-ambient lighting for paper and computer based tasks will eliminate x% electric light – adding individual dimming ballasts and occupant controls (with comfort zones).
- Automated control of individual task-ambient lighting with **compound controls** (daylight, time of day and occupancy) will eliminate x% electric light – adding individual dimming ballasts, daylight + occupancy sensors.
- Individual blind control** for daylighting (without glare) will extend daylight responsive lighting control to eliminate x% electric light in perimeter zones – adding daylight sensors and motorized control or knowledge based feedback.
- Individually ballasted ambient lighting, task lighting, automated blinds each with **occupancy controls combined with knowledge based feedback** will eliminate x% electric light (all additions).

- **Model predictive rule based control** linking daysim and thermal simulation with system expertise will eliminate x% electric light.
- Given the capabilities of the Osram/Sylvania/Encelium Control system and the density of sensor and control points, a number of lighting control strategies were evaluated for comparative energy impacts, contributing to the experimental findings that follow.
- All electric lights off until requested by occupants.
- 1st manual request at either door is for low level ambient with new LED track lights in the circulation area.
- Individual space lights to be turned on and dimmed by request at desk (PC or iphone interface); lowest setting becomes default.
- Occupancy sensor used as “vacancy” to turn off lights when no presence is detected (several extended timeout tested and then off).
- Timer will turn off lights in space without occupancy sensors (timer will turn lights off after a defined amount of time after the light was activated, flick warn will inform the users that the lights will soon turn Off, an action on the PCS software will re-launch the timer) .
- Meeting space lights (north and south) to be turned on at hard switch with dimming programmed as 1, 2, 3 scene control (lowest to highest).
- Task lights, where present, will be plugged into the Greenplug outlets.
- Task lights will be turned off when occupancy sensor reads vacant.
- Daylight sensor should be only to turn off lights (ambient and task) as daylight increases, with turning on lights requiring user requests.

4.3 Lighting Experimental Findings

4.3.1 User Control of Ambient, Task and Daylight

The first and most comprehensive lighting experimental study for this DOE project was completed by Yun Gu for her PhD dissertation entitled “*The Impacts of Real-time Knowledge Based Personal Lighting Control on Energy Consumption, User Satisfaction and Task Performance in Offices.*” This controlled human subject research involved the assessment of multiple lighting control options and user interfaces with expert feedback, incorporating energy monitoring, task performance testing, and user satisfaction surveys. A series of six hypothesis were developed:

Hypotheses 1-3:

Providing the occupant of an office with control of blinds, ambient light and task light will (H1) reduce lighting power demand, (H2) enhance office occupant satisfaction, and (H3) improve task performance - relative to no personal control.

Hypotheses 4-6

Providing the occupant of an office with control of blinds, ambient light and task light as well as real-time knowledge including suitability of light levels, related power consumption, equivalent CO₂ emission, and user “advisories”, will (H4) reduce lighting power demand, (H5) enhance office occupant satisfaction, and (H6) improve task performance relative to personalized control with no real-time knowledge as outlined above.

A user interface, shown in Fig 4.4, was developed to clearly link ambient and task lighting controls with daylighting controls through blinds, in the pursuit of the lowest energy use and carbon footprint with the highest user satisfaction, for two task types: computer and paper based tasks. This control dashboard is unique because it offers communication, control, recommendations and feedback:

Fig 4.4 Dashboard Interface for lighting control

The lower left allows users to control ceiling and desk light settings as well as blind positions for two sets of blinds. The upper left allows users to communicate what types of tasks they are pursuing to generate recommendations for controlling the four control choices lowest energy and highest user satisfaction, shown on the upper right. The lower right gives immediate feedback when lighting settings are changed as to the energy saved in daily kWh and the equivalent carbon benefits in numbers of trees shown. With over 60 subjects adjusting their lighting and daylighting conditions before completing paper and computer based tasks over a period of 6 months, the research revealed a number of substantial findings, shown in Fig 4.5.

Fig 4.5 Impact of control and feedback on lighting power density and illuminance

Even without expert recommendations, workstation occupants adjusted overhead lighting, task lighting and blinds to meet personal needs for paper and computer based tasks at substantially lower lighting power density with higher desk illuminance. The conventional ceiling based combined task-ambient lighting used 1.68 watts/sqft to create a uniform desk illuminance of 460 lux.

For computer based tasks, users manually reduced desk illuminance to 365 lux, on average, with measurable improvement in satisfaction. With expert recommendations, users manually reduced desk illuminance further to 222 lux with sustained improvements in satisfaction.

For paper based tasks, users manually reduced ceiling based task-ambient lighting levels but turned on task lights to raise task illuminance from 460 lux to 621 lux while substantially reducing lighting power density. With expert feedback, blinds were also adjusted to further reduce ceiling lighting demands, maintaining an average of 636 lux on the task at even lower lighting power densities.

Given a task mix of 2/3 computer work and 1/3 paper based tasks, overall lighting power densities dropped from 1.63 watts/sqft to .98 watts/sqft (Fig 4.6) with occupants manual adjustments to a low of .64 watts/sqft with expert recommendations, while increasing light levels on the task and increasing user satisfaction! While the research hoped to demonstrate productivity gains with lighting controls, the short time duration of the tasks and native language variabilities resulted in statistical significance for only the conclusion that productivity held constant with these shifts in light levels and controls.

Fig 4.6 Overall LPD dropped from 1.63 w/sqft average to a low of .64 with user control with higher satisfaction and light levels for paper based tasks

Critical finding #1: User controls of blinds, task lights and overhead lights offer 43% lighting energy saving + higher user satisfaction_+ no decrement in task performance; however knowledge-based user control of blinds, task lights and overhead lights offer 64% lighting energy saving + no decrement in user satisfaction and task performance.

The significance of this finding for lighting control is substantial, and has led to the following recommendations for as much as 70% lighting energy savings through controls:

- Lower task-ambient light levels and add high efficiency task lights for user control to save over 40% of lighting energy, improve light levels for task, and increase user satisfaction.
- Introduce user control interfaces to support the most energy efficient and satisfying management of ambient and task lights as well as blinds.

4.3.2 Linking Trnsys-Ecotect-Daysim for rule-based model predictive control of external louvers for effective shade with daylight

Critical finding #2: Controlling external dynamic louvers or internal blinds for both daylight and thermal optimums offer a reduction in lighting loads through effective daylighting, a reduction in heating loads through passive solar contributions, and a reduction in cooling loads through timely shading.

While few buildings have dynamic external louvers in the U.S., a majority of buildings have internal venetian blinds (CBECS data needed) that should be comparably controlled to balance daylight with solar heating and shading. The rule based model predictive control algorithms contributed to a future App for the Siemens Apogee system (Fig 4.7) that could be used on automated interior blinds as well as the external louvers and blinds that exist more prevalently in Europe.

Fig 4.7 XML rule for controlling external louvers and internal blinds to balance solar heat, shade and daylight

4.3.3. Maximizing lighting controls for individually addressable high performance fixtures in Conference Rooms and Closed Offices

Given the dynamic nature of office space planning and utilization, the next generation of office lighting will cost-effectively integrate individually addressable high performance fixtures with user friendly lighting control systems. Many office buildings have antiquated, energy consuming lighting that is mismatched with the present office layouts and work tasks. Circulation light levels often exceed workstation light levels, poorly shielded lamps cause direct and reflected glare, and lighting power densities are often over 2 watts/square foot. Given these pervasive conditions, lighting retrofits are very

energy effective actions and improve work conditions for both computer and paper based tasks. The Siemens/CMU/Osram/Sylvania/Encelium partnership led to the replacement of ballasts, lamps, and central lighting control system for the 7000 square foot Intelligent Workplace laboratory. This installation supported the rapid and ongoing ability to define control zones and to introduce at least 6 levels of control (Fig 4.8):

Zone variability in light levels (and rapid zone redefinition)

Occupancy/vacancy control

Daylight autonomy

Daylight harvesting

Output preference control

Integrated heating, cooling and lighting control (Encelium-Apogee interface)

Fig 4.8 Floor plan of the lighting installation

With the completion of the installation, the following strategies were implemented in the Encelium lighting control system:

- All electric lights off until requested by occupants.
- When dark, the 1st manual request at either door is for low level ambient from the new LED track lights in the circulation area; the 2nd manual request at the workstation is for individual office zones.
- Individual space lights are turned on and dimmed by request at the desk (PC or i-phone interface); lowest setting becomes default.
- Daylight sensors are used for dimming lights (ambient and task) as daylight increases, with dimming UP only with user request.
- Occupancy sensor are used as “vacancy sensor” to turn off lights when no presence is detected (different shut down profiles are currently tested to improve users satisfaction). No lights are automatically turned ON.
- Meeting space lights (north and south) are turned with the hard switches that have been programmed with buttons 1, 2, 3 with 1 at the top providing the lowest light output.
- In spaces with no occupancy sensors, time schedules are used to switch OFF the lights during anticipated unoccupied periods (requiring a request by the users to keep the lights ON).
- Task lights are plugged into the greenplug outlets for individual on/off.
- Task lights are turned off when occupancy sensor reads vacant.
-

The Intelligent Workplace laboratory automated lighting control experiments were running for more than a year (April 2011 – June 2012). They range from conference and closed office controls to open plan workstation controls to circulation and safety control strategies. The experiments discussed below are

accompanied by annual energy saving calculations to offer critical findings for building owners and tenants.

The DOE/ASHRAE AEDG guidelines identify an average of 29% of the floor area in medium sized offices is still dedicated to private offices, and 8% to conference and meeting rooms, with expected lighting power densities today of 1.1-1.3 watts per square foot before adjustments based on controls (Fig 4.9). Existing lighting power densities are substantially higher in medium sized offices in the US.

Table 3-3 Standard Percentage Assumptions by Space Type (Thornton et al. 2010)

Space Type	Percentage of Floor Area	Standard Baseline LPD, W/ft ²	Adjusted Baseline LPD, W/ft ²
Office—open plan	15%	1.1	0.68
Office—private	29%	1.1	0.8
Conference/meeting room	8%	1.3	0.77
Corridor/transition space	12%	0.5	0.5
Active storage area	14%	0.8	0.64
Restroom	4%	0.8	0.82
Lounge/recreation area	2%	1.2	0.73
Electrical/mechanical room	2%	1.5	1.24
Stairway	3%	0.6	0.6
Lobby	6%	1.3	1.09
Other	5%	1.0	0.82
Weighted LPD for the whole building	100%	1.0	0.75

Fig 4.9 Lighting power densities and adjustments based on controls

Conference spaces have typical rates of occupancy that range from an average of 30% to a high of 70%, leaving substantial time periods when lighting is not needed (Fig 4.10 from DEGW for GSA), and closed offices have typical rates of occupancy as low as 35% on average. The sporadic use of as much as 37% of the floor area for up to 70% of the time offers significant energy savings through advanced lighting controls.

Figure 2: Activities in workspaces

DEGW Research in multiple client sites across the globe has indicated that individual time spent at the desk, and time spent generally in the workplace is declining. Whereas once "office work" was predominantly process work undertaken at individual worksettings, the workplace today is as much mobile / collaborative working as it is individual, and this trend is predicted to increase.

Fig 4.10 DEGW tracks occupancy and activities in workspaces for GSA

The Siemens/CMU team completed a series of lighting control studies for conference spaces were completed over multiple days in April and September with impacts illustrated below.

Given ASHRAE/IES 2007 requirements, it is assumed that conference rooms would be lit at 1.2 watts/sqft throughout the work day (green line) as a baseline. While conference rooms with switches may be manually turned off 50% of the time, the installed lighting power density for conference rooms is often double the 1.2 watts/sqft, so this starting energy load is considered reasonable (Fig 4.11).

Fig 4.11 Conventional energy use profile for a conference room

For those conference rooms on the outside wall, including most executive conference rooms, arriving occupants often feel no need for artificial lighting for most of the day. In the IW testbed this was reflected in a 40% lighting energy savings by daylight “autonomy” from 8 am to 3 pm (Fig 4.12).

Fig 4.12 40% Energy saving by using daylight autonomy in conference rooms

In the dimmer light of early morning, and in overcast conditions in late afternoon, occupants felt the need for additional light, but only at 200-400 lux light levels given meeting and presentation activities. With

lower output requirements set by the occupants (selecting the lowest demand button 1 instead of 2 or 3), and additional 40% lighting energy savings was possible, for a cumulative 64% in savings (Fig 4.13).

Fig 4.13 64% Energy saving by daylight autonomy plus output control through scenes

Finally, daylight sensors combined with individually addressable dimming ballasts allowed lights to be dimmed to the desired light levels through daylight harvesting, saving an additional 20% of lighting energy for a total of 71% energy savings through controls with higher user satisfaction (Fig 4.14).

Fig 4.14 71% Energy savings with daylight access, output control and daylight harvesting

Clearly, these energy savings are dependent on a number of factors: lighting power density, daylight availability by season and day, sensors used to activate controls, user preferences by activity, and light fixture locations. Ideally, these studies would be repeated through a range of variations to solidify the energy savings possible. To this end, different control strategies were tested in the conference room on a series of days in September 2011 (Fig 4.15). Using baseline typical conference space lighting at 1.2 w/sqft average throughout the work day (green line), a different combination of four lighting control strategies were tested: daylight autonomy, vacancy sensors, occupancy light level preferences through scene control, and daylight harvesting.

Fig 4.15 Conference Room Energy Consumption profile over a Day

The Encelium/Apogee controls supported 60% savings by using the occupancy sensor as a vacancy sensor (does not turn on the lights, but will turn them off when no one is in the space) combined with daylighting sensor controls. 60% of the remainder was saved by the occupant selection of lower light levels (scene choices), and 40% of that remainder is saved by daylight harvesting (using electric lighting at lower levels to complement daylight availability), for a total of 89% lighting energy savings in conference rooms, on a sunny September study (Figs 4.16-4.17 and Table 4.2).

Fig 4.16 Occupancy and profile of use given daylight availability

Fig 4.17 Yearly energy savings for the conference space vs baseline offices

Table 4.2 Yearly Energy Saving for a large conference room

Control Strategies	Conventional Consumption	Daylight Access / Occupancy Control	Output Control / Scene Control	Daylight Harvesting	Measured Consumption (MC)
Consumption (kWh)	2541	560	308	278	278
Energy Saving (kWh)		-1880	-252	-30	/
Energy Saving (%)		78%	45%	9%	/
Total	89 % Total Energy Savings				

Critical Finding #3: In conference spaces and closed offices, individually addressable ballasts and a central lighting control system offers 30-60% energy savings through occupancy sensors, 40% energy savings through daylighting (when available), an additional 24% by user preferences (scene choices) with lower light levels (scene choices), and 9% more by daylight harvesting (adding appropriate electric light when daylight levels are diminishing), for a total of 70-90% lighting energy savings in conference rooms and closed offices.

4.3.4. Maximizing lighting controls for individually addressable high performance fixtures in Open Plan Offices

In US offices, open workstations are moving from a modest 15% of gross floor area to the predominant workstation type using up to 50% of the gross floor area, with the remainder taken by circulation, active storage, conference, lobby, rest rooms, stairways and support spaces. Lighting control in these workstations is confined to under-cabinet lights and task lights (often purchased by the occupants), and lighting power densities often exceed 2.5 watts/ square foot (GSA reference) with both ceiling task-ambient and task lights typically on throughout the work day and often through the night. Improved lighting controls of ceiling based task-ambient lighting offers substantial energy savings, beginning with the dimming of lights by 50% whenever occupants are away from their interior workstation during the day (over 50% of the time), and shutdown at night. The CMU/Siemens team completed studies on

lighting energy savings possible in open workstations, with a focus on workstations within 15 feet of the window wall. In one prototypical September 2011 study, over 85% of baseline workstation lighting of 1.2 watts per sqft could be saved throughout the work day. With no lights turned on automatically in office spaces, the Encelium/Apogee controls supported 75% savings by providing user control, since the occupant had easy controls and found daylight to be more than adequate. In addition, the occupant set desired light levels lower with ‘scene’ controls, offering 20% additional energy savings through output control. Finally, 20% of that remainder was saved by daylight harvesting, for a total of 85% lighting energy savings per workstation (Fig 4.18).

Fig 4.18 Single Office Energy Consumption profile over a Day

One condition that became evident during this study is that light levels often exceed 500 lux in the workstation through daylighting, more than might be needed for computer based tasks. Since daylighting levels can be modified through blind or shade control, the balance of heat and light for winter and summer is an important opportunity that can be met by linking lighting controls with thermal controls through BacNet interfaces to establish weather based optimums for blind positions. The energy benefits of these controls will be illustrated in Chapter 3: Cooling Controls. The lighting energy savings possible through individual control of combined task-ambient lighting through a combination of strategies is captured in Figs 4.19 and Table 4.3.

Fig 4.19 Yearly lighting energy savings for an open office with individual control

Table 4.3 Yearly lighting energy savings for an open office workstation

Control Strategies	Conventional Consumption	Daylight Access / Occupancy Control	Output Control / Scene Control	Daylight Harvesting	Measured Consumption (MC)
Consumption	930 kWh	261 kWh	197 kWh	181 kWh	181 kWh
Energy Saving (kWh)	/	-669	-64	-16	/
%	/	72%	25%	7.4%	/
Total	81% Total Energy Saving				

Critical Finding #4: In open plan workstations, individually addressable ballasts and a central lighting control system offers 72% energy savings through daylighting in perimeter workstations combined with occupancy sensors, 25% by user preferences for lower light levels to match task (scene choices), and an additional 7.5% by daylight harvesting (adding appropriate electric light when daylight levels are diminishing) for a total of over 81% lighting energy savings in perimeter open plan workstations (within 15 feet).

4.3.5 Lighting energy savings in Circulation Areas

Since the Intelligent workplace is a relatively small (7000 square foot) workgroup, the use of lighting controls to save energy in circulation and support spaces cannot be fully quantified (Fig 4.20).

Fig 4.20 IW floor plan and circulation area

Nonetheless, there is opportunity for modest savings through controls. Since the lab is a fully open plan office, the circulation is easily lit by daylight during the day and by indirect lights at night. Light in circulation area can be controlled with the two followings strategies:

- 2 hard-wired switches are located on each main entrance of the office (2 purple circle). Getting into the space people can turn ON the circulation lights the time they get to their office. This circulation will be then turned off according to a timer, personal control software or using the touchscreen.
- When office lights will be turned Off (by scheduling, occupancy sensor or manual command) at night (daylight level and time of day are checked), lights in the circulation will turn ON (This timer can be set ON) the time the users leave safely the place. This control algorithm was programmed into Apogee Insight software. The Bacnet Interface allowed a complete integration of the different control logic.

Given the ability of daylight to meet the modest light levels needed for safe circulation, the lighting energy use for circulation areas in the IW are limited to night-time hours. Responsive controls for occupants to safely circulate and meet workgroup demands without lighting up the whole facility has resulted in over 50% reduction in circulation light. These findings have not been generalized to larger and deeper office buildings.

4.3.6 User Interfaces for Controls

While the addition of lighting controls are key to the 70-85% lighting energy savings described, user interfaces play a significant role in delivering those savings. Encelium has excellent desktop or laptop control interfaces for individual space control of addressable fixtures in the workstation. Users can set a series of “scenes”, assigning the highest light levels to office cleaning, gentle lighting to the most typical computer and phone tasks (default), and plugged in task light controls for the more occasional paper based tasks (Fig 4.21).

Given that over 80% of a typical days tasks are on the computer or telephone today, the ability to set lower light levels at one’s workstation, without compromising general lighting conditions for safety, offers substantial energy savings and improved task conditions. In addition, there is the ability to rapidly lower or turn off lights when leaving the workstation through keystroke and mousing sensors available in the Encelium control suite. For the average workstation, these control interfaces ensure that significant percentages of ambient and task lighting energy is saved in a typical year through user controls,

occupancy controls, and general management controls that capture the assumptions of hours occupancy and activity identified in extensive field ‘shadowing’ studies by DEGW.

Fig 4.22: Encelium provides users with the easy ability to create ‘scenes’ for lighting controls

A second control interface study completed by the CMU/Siemens team with Encelium is the ability to customize programs for hardwired switches for conference rooms, stairs, kitchen and copy areas or rooms (see Fig 4.23). With individually addressable fixtures that can be bundled into zones as the space functions and layouts change, the introduction of hard switch controllers (wired or wireless) support measurable energy savings.

Fig 4.23 Zone control hard-wired switch and scene control hard-wired switch

As previously discussed programming lighting levels through switch position has measurable energy benefit. In conference spaces, users chose the lowest light level with high frequency when it is positioned as the top switch, and chose the highest level with almost equal frequency when it is the top switch, and only move to the second or third switch when they deem the lowest light level inadequate. The simple step of reversing the control choice positions, setting low as the first/top choice, saves as much as 30% of the lighting energy for what may be as much as 40% of the office space. Beyond the power of the Encelium control interfaces, the CMU/Siemens team partnered with the Technical University of Munich to develop another level of user interface for ensuring the highest level of energy savings. In his Masters thesis *“Intuitive access to environmental controls of the intelligent building with heterogeneous users”*, Sebastian Peters from TU Munich completed usability testing and programmed smart phone interfaces to the Encelium and Apogee control systems to intuitively control fixtures such as ceiling task-ambient lighting, task lights, external louvers, automated blinds, plugged in heaters or fans, and motorized windows by simply pointing at the target and completing simple gestures (Fig 4.24).

Fig 4.24. Iphone Control interface (Light, Louvers, Windows, Blinds Control)

The usability testing explored users understanding of “intuitive” and arrived at the conclusion that a point and gesture controller, possibly combined with voice, would provide the most universal functionality. In addition, the testing suggested that the almost universally owned smart phones might be the best interface since they are always with the occupant and eliminate the need for additional hardware and batteries. The TUM research team is a leader in smart phone utilization and identified the need for four critical capabilities to bring the gesture controller to a smart phone: wifi triangulation, accelerometer, compass and gyroscope (Fig 4.25).

WiFi Fingerprinting

The current room can be identified through different WIFI access points

Collaboration with TUM expert for indoor navigation

Gyroscope and compass

Modern smart phones like the iPhone 4 have a built-in compass and a gyroscope to detect the angle and direction of the device

Sensor fusion required

Fig 4.25 Today's smart phones support gesture controls for lights throughwifi, compass and gyroscope capability

This technically cutting-edge smart phone controller for lighting, louvers, operable windows, and plugged in task lights, fans and heaters was presented at the Onward Conference October 26, 2011 in Portland, Oregon with a paper and a film entitled “The intuitive control of smart home and office environments”. While not yet a commercially available product, the smart phone controller works seamlessly with the Encelium and Apogee Insight control systems and is in widespread use by the 25 occupants of the Intelligent Workplace laboratory for lighting, external louver, automated blind, coolwave (fan coils) and motorized window controls. The CMU team continues to develop the smart phone controller for several key functionalities: voice control; smart phone as occupancy sensor for vacancy controls; remote system management and calendaring. Additional descriptions can be found in Chapter 6: plug load management and control interfaces.

Critical Finding # 6: User Interfaces for Control play a significant role in achieving the 70-85% energy savings possible through individually addressed high performance lighting and central lighting control systems.

4.4 Retrofit Recommendations and Life Cycle Costing

These experiments reveal the substantial energy savings that can achieved through lighting controls, which must be balanced by retrofit costs, and reinforced by other benefits of the investments ranging from facility management to health and productivity savings. The Siemens/CMU team has selected five ‘tiered’ investment recommendations, from least cost to highest cost, to complete life cycle calculations.

Install vacancy sensors for closed spaces.

Install daylight harvesting for perimeter lights

Lower task-Ambient light and add task

Use blinds effectively

Install high performance fixtures w/automation

The costs of these five recommendations can vary significantly based on existing technology in the building, variations in the product and labor market, and intentions of the building owner to upgrading their building technologies already. The hardware and software components installed in the Intelligent Workplace living laboratory that yielded 70-85% energy savings over conventional systems were:

Electric Lighting Component/System Investments:

Relays, daylight sensors, control for bank of perimeter fixtures

Daylighting responsive on-off or dimming of bank of fixtures

Vacancy sensors for closed offices and occasional use spaces

No lights unless called for and automatic shut off when vacant
Lowering ambient lighting and providing task with occupancy sensors
Reduced ambient levels for computer work while meeting task when needed
Replacing ballasts with smart ballasts and integrated relays with control system
Daylight dimming in layers and by occupant request
Individual ambient levels - microzoning
Vacancy controls
Task light controls
Occupancy sensors/ keystroke controls
Modifying egress lighting controls
time of day and occupancy driven circulation space lighting (vacancy driven)

Daylighting Component/System Investments:

External louvers/light shelves fixed
Shading with effective daylight distribution
External louvers/light shelves automated with user access
Extended Passive solar, shading, daylight
Internal blinds manually controlled
 Shading with effective daylight distribution and view
Internal blinds automated with user access
 Extended Shading with effective daylight distribution and view

The industry-university team has collected average technology and labor costs for each of these retrofit recommendations given a medium size office of 50,000 square feet on three floors with 250 employees with 8.2 kWh/sqft of annual lighting energy use, 5.5 kWh/sqft of cooling energy, 6.1 kWh/sqft of heating and 1.3 kWh/sqft of ventilation energy, at an estimated cost of energy at \$0.10/kWh (CBPD, 2008). The life cycle benefits of each of these five recommendations have been calculated in three “return on investment” groups to offer a triple bottom line calculation: ‘hard’ economic cost benefits in the first bottom line; environmental cost-benefits that may be legislated or incentivized in the second bottom line; and the human cost-benefits that should drive standards and investments in buildings in the third bottom line. The economic benefits of each recommendation have been calculated or drawn from the literature. Environmental benefits have been assigned for CO₂, SO_x, NO_x, particulates and water use savings that accompany electricity energy savings, with values stated on the attached table. The human benefits associated with each recommendation have been drawn from the ongoing work of the Center for Building Performance and Diagnostics to aggregate research linking the quality of buildings to health and productivity outcomes in BIDS: the Building Investment Decision Support Tool (CBPD, 2008).

	US Average Emission Rate¹ (ton/kWh)	Emission Impact Value² (\$/ton)
CO ₂	8.20E-04	15
SO _x	4.29E-06	5,200
NO _x	1.50E-06	7,450
PM10	4.5E-08	4,850

4.4.1 Install vacancy sensors for closed spaces

Given that conference spaces have typical rates of occupancy that range from an average of 30% to a high of 70%, and closed offices have typical rates of occupancy as low as 35%, there are substantial time periods when lighting is not needed. The sporadic use of as much as 40% of the floor area for up to 70% of the time offers significant energy savings through occupancy controls, as shown in the experiments described. On the cost side of the equation, there are the material and labor costs for introducing switches

that incorporate occupancy sensors (set to vacancy operation) in each closed space – conference rooms, closed offices, storage rooms, kitchen and copy rooms, bathrooms, service rooms. The sensors themselves must be professionally installed to ensure they give appropriate coverage so that lights do not go off inappropriately. This is a quick and low cost lighting system retrofit for a majority of buildings.

	Per Sq ft	Per room
First cost	\$ 0.25	\$ 50
Installation labor cost	\$ 0.50	\$ 100
Initial investment costs	\$ 0.75	\$ 150

On the benefit side of the equation, the economic ROI includes the annual energy savings and could also include peak load shaving savings where utility incentives exist. The environmental savings are measurable for lighting controls, since lighting is entirely an electricity source with CO₂, SOX, NOX, particulates, and water impacts. Turning off lights in unoccupied spaces will not improve the health or productivity of the occupants in a building. As a result, the third ROI calculation of human benefits is not included.

Balancing the costs and the benefits, a triple bottom line calculation has been completed in the following table. With energy savings alone, the payback for this retrofit will be less than 2 years. With energy and environmental savings, the focus of any corporation and agency that has set carbon goals, the payback for this retrofit will be even sooner. In addition, the hardware and installation costs are falling for robust occupancy sensors, making their utilization in all closed offices and conference rooms a highest priority investment.

	Total Building investment costs	\$ 37,500	
		Per sq ft	Per employee
	Initial investment costs	\$ 0.75	\$ 150
First Tier Considerations	Energy savings	\$0.41	\$82.00
	O & M Savings (FM)	-	-
	Annual Baseline Savings	\$0.41	\$82.00
	ROI (Economic)	54.7%	
	15 year Net Present Value (Economic only)	\$ 155,923	
Second Tier Considerations	Energy savings	4.10 kWh	820 kWh
	First year Savings :		
	Air pollution emissions	\$ 0.20	\$ 40.98
	Cumulative ROI (Economic + Environment)	82%	
	Cumulative 15 year Net Present Value (Economic + Environment)	\$ 233,846	

Given that up to 50% of spaces may be closed in typical office buildings, this retrofit measure can save up to 30% of a medium size office buildings total lighting energy.

4.4.2 Install daylight harvesting for perimeter lights

The second retrofit action with rapid payback is the installation of on/off or dimming controls on the first and second row of lights on each building facade. This modest investment in new controls for groups of lights ensures 35% energy savings possible even in deeper buildings through ‘daylight harvesting’ (Verderber & Rubinstein, 1984). On the cost side of the equation, there are the material and labor costs for introducing new controllers to each row of perimeter lights that can be placed on independent switching. Encelium has developed a wireless control product that can be added to existing ballasts and a web based controller for calendar driven or daylight sensor driven switching of each row. This is a quick and low cost lighting system retrofit for a majority of buildings.

	Per Sq ft	Per employee
First cost	\$ 0.45	\$ 90
Installation + labor cost	\$ 0.50	\$ 100
Initial investment costs	\$ 0.95	\$ 190

On the benefit side of the equation, the economic ROI includes the annual energy savings and could also include peak load shaving savings where utility incentives exist. The environmental savings are measurable since lighting is entirely an electricity source with CO₂, SOX, NOX, particulates, and water impacts. Balancing the costs and the benefits, a triple bottom line calculation has been completed in the following table. With energy savings alone, the payback for this retrofit will be 10 Years. With energy and environmental savings, the focus of any corporation and agency that has set carbon goals, the payback for this retrofit will be 7 years. The human benefits, however, give this retrofit an immediate payback.

	Total Building investment costs	\$ 47,500	
		Per sq ft	Per employee
	Initial investment costs	\$ 0.95	\$ 190
First Tier Considerations	First year savings:		
	Energy savings	\$0.09	\$18.61
	O & M Savings (FM)	-	-
	Annual Baseline Savings	\$0.09	\$18.61
	ROI (Economic)	9.8%	
	15 year Net Present Value (Economic only)	\$ 35,395	
Second Tier Considerations	Energy savings	0.93 kWh	186 kWh
	First year Savings :		
	Air pollution emissions	\$ 0.05	\$ 9.30
	Cumulative ROI (Economic + Environment)	15%	
	Cumulative 15 year Net Present Value (Economic + Environment)	\$ 53,083	
Tier Consider	First year savings:		
	Health benefits	-	-

	Productivity increase	\$ 2.95	\$ 591
	Absenteeism	\$ 0.57	\$114.75
	Annual Baseline Savings	\$ 3.53	\$ 705
	Cumulative ROI (Economic + Environment + Equity)	386%	
	Cumulative 15 year Net Present Value (Economic + Environment + Equity)	\$ 1,394,354	

Given that up to 100% of spaces could be (and have been historically) daylit in many medium sized office buildings, this retrofit measure can save up to 70% of a medium size office buildings total lighting energy. Given deeper section buildings, daylighting harvesting can save an average of 11% of the lighting energy.

4.4.3 Lower task-ambient light and add task lights

As previously discussed, existing lighting power densities and light levels in US offices are excessively high given both today's available technologies and work tasks, averaging over 2 watts/sqft of lighting that is on throughout the work day. While replacing this lighting offers substantially higher energy savings, de-lamping or reducing ceiling lighting output and adding task lights has substantial cost benefit, especially given the 6-8 watt LED task lights available today. Using multiple 32 watt lamps in a ceiling light fixture to deliver 500 lux (or less) of 'task' lighting for paper based work consumes 64-138 watts of electricity as compared to the 6-8 watts in an LED task light that the user can position for 500 lux (or more) directly on the task. On the cost side of the equation, there is the labor cost for de-lamping fixtures - from 4 to 3 lamps, or from 3 to 2 lamps, throughout the workplace or delamping at least in fixtures not directly aligned without worksurfaces and tasks. If dimming ballasts already exist, there is the labor cost of resetting light level output to achieve 200-300 lux for computer based tasks rather than 500 lux or more for paper based tasks. In addition, under-cabinet lighting should be removed, since it is far more energy intensive than today's task lights and rarely puts the light on the most critical task surfaces. Finally, re-locatable, adjustable arm, 6-8W task lights will be purchased for each workstation (Fig 4.26).

Fig 4.26: LED Task Lamps use 6-8 watts for over 500 lux of light for paper based tasks

	Per Sq ft	Per employee
Cost for reducing ambient light levels	\$ 0.16	\$ 31

Cost for LED Desk Lamp	\$ 0.82	\$ 164
Initial investment costs	\$ 0.98	\$ 195

On the benefit side of the equation, the economic ROI includes the annual energy savings and could include the peak load savings given specific utility incentives. While not quantified here, there can be a spatial churn cost-benefit since task lighting can now move with the work-surface, eliminating the need to relocate or add ceiling fixtures with changing densities of workstations. The environmental savings are measurable since lighting is entirely an electricity source with CO₂, SOX, NOX, particulates, and water impacts. Balancing the costs and the benefits, a triple bottom line calculation has been completed in the following table. With energy savings alone, the payback for this retrofit will be a 2-3 Years. With energy and environmental savings, the focus of any corporation and agency that has set carbon goals, the payback for this retrofit will be less than 2 years. Adding productivity and health benefits, the payback is in months.

	Total Building investment costs	\$ 119,500	
		Per sq ft	Per employee
	Initial investment costs	\$ 0.98	\$ 195
First Tier Considerations	First year savings:		
	Energy savings	\$0.32	\$65.60
	O & M Savings (FM)	\$0.09	\$18.00
	Annual Baseline Savings	\$0.41	\$83.60
	ROI (Economic)	43%	
	15 year Net Present Value (Economic only)		
Second Tier Considerations	Energy savings	3.28 kWh	656 kWh
	First year Savings :		
	Air pollution emissions	\$ 0.16	\$ 32.78
	Cumulative ROI (Economic + Environment)	60%	
	Cumulative 15 year Net Present Value (Economic + Environment)		
Third Tier Considerations	First year savings:		
	Health benefits	\$ 0.07	\$13.87
	Productivity increase	\$ 0.89	\$ 178
	Absenteeism	\$ 0.04	\$ 7.65
	Annual Baseline Savings	\$ 1.00	\$ 200
	Cumulative ROI (Economic + Environment + Equity)	160%	

	Cumulative 15 year Net Present Value (Economic + Environment + Equity)	
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Given that only 50% of office floors are occupied by workstations that need higher light levels for paper tasks, and that we have shifted to predominantly computer-based tasks for which lower ambient lighting levels are preferred, this retrofit measure can save up to 40% of a medium size office buildings total lighting energy, with an ROI of 160%.

4.4.4 Use blinds effectively

The fourth lighting retrofit recommendation for which life cycle costing has been completed is to use venetian blinds more effectively for daylighting and thermal control. On the cost side of the equation, there are two different calculations needed, one for manual and one for automated control. Since a majority of office buildings have venetian blinds already installed, the least cost solution to increasing daylighting without excessive overheating is to set up schedules and train occupants as to effective blind management. The schedules will be dependent on the office building's climate, the orientation of the facades being controlled, and the activities in the adjacent spaces. The training could include an on-line video and facility management monthly oversight and communication. At the other end of the scale, the blinds could be placed on battery or PV powered automatic controllers, possibly designed to only manage the tilt of the blind to reduce the "heavy lifting" that would drain a battery. If new blinds need to be installed, the profiles should be inverted to reflect light up to the ceiling in the horizontal position, and selected for their reflectivity. An estimated first cost has been drawn from Means Cost Guides.

	Per Sq ft	Per employee
First cost	\$ 3.00	\$ 600

On the benefit side of the equation, the economic ROI includes the annual energy savings and could include the peak load shaving savings given specific utility incentives. The environmental savings are measurable since lighting is entirely an electricity source with CO₂, SOX, NOX, particulates, and water impacts. Balancing the costs and the benefits, a triple bottom line calculation has been completed in the following table to address manual blind control only.

	Total Building investment costs	\$ 150,000	
		Per sq ft	Per employee
	Initial investment costs	\$ 3.00	\$ 600
Tier First Considerations	First year savings:		
	Energy savings	\$0.41	\$52
	ROI (Economic)	9%	
	15 year Net Present Value (Economic only)	\$ 99,791	
Second Tier Considerations	Energy savings	2.62 kWh	525 kWh
	Air pollution emissions	\$ 0.13	\$ 26
	Cumulative ROI (Economic + Environment)	13%	
	Cumulative 15 year Net Present Value (Economic + Environment)	\$ 149.661	

	Productivity increase	\$ 2.36	\$ 473
	Absenteeism	\$ 0.57	\$ 114
	Annual Baseline Savings	\$ 2.94	\$ 587
	Cumulative ROI (Economic + Environment + Equity)	111%	
	Cumulative 15 year Net Present Value (Economic + Environment + Equity)	\$ 1,116,317	

Given that up to 100% of workstations may be within 15 feet of a window wall, this retrofit measure can save up to 35% of a medium size office buildings total lighting energy.

4.4.5 Install individually addressable fixtures with automation

The final lighting retrofit recommendation with life cycle costing is to invest in individually addressable dimming ballasts and central lighting control systems. While this is first cost intensive, there are multiple reasons why a significant number of existing offices should engage in comprehensive lighting retrofits, including:

- GSA field studies by the CMU team have identified over 20% of existing lighting in medium size offices still has T-12 lamps and magnetic ballasts that contain PCBs. In addition to unnecessary annual and peak energy loads, these fixtures are a health hazard, the noise they generate compromises productivity, and their flicker causes headaches. These offices should be undertaking comprehensive lighting retrofits.
- Even if offices that have upgraded to T-8 lamps and electronic ballasts, the poor ballast density and control zones are often so large that significant floor areas must be lit up if even a single worker is still in the office. Moreover, these fixtures often have flush lens covers that create direct and reflected glare sources, and create light levels that are excessive for the predominantly computer-based tasks.
- The mis-match between the uniform lighting grids of yesterday and today's workstation density and layouts is substantial. Worksurfaces are often cast in shadow while circulation aisles are overlit. A dissertation by Kung Jen Tu of a high rise office in Pittsburgh identified significant code violations that resulted from spatial variations floor by floor under a uniform ceiling lighting system, and the addition of under cabinet lighting by occupants to address these variations, with over 3 watts per square foot of demand as a result. Workstations at the window have poorly managed daylight and glare with artificial lighting on as well.

A comprehensive lighting retrofit offers the ability to:

- bring lighting power densities below 1 watt per square foot
- create ambient lighting levels appropriate to computer work
- offer task lighting exactly where it is needed at higher levels and significantly lower energy
- maximize daylighting (no lights) and daylight harvesting (filling the gap)
- maximize occupancy/vacancy control of unoccupied spaces
- maximize peak load shaving for DSM
- give controls back to occupants for output control and user satisfaction

A before and after study of the Chicago Federal Building illustrates the significant benefits of these investments for occupants (Fig 4.27). In addition to a reduction of connected lighting loads from 4 w/sft to 1.3 w/sqft, user satisfaction with the lighting quality increased by 20%. The spectacular views were no longer compromised by specular glare from electric lights at the perimeter, and users recorded their performance at task had increased.

Before – flush/ K-16 prismatic lens ceiling light fixture

After – medium-cell parabolic, semi-specular

Before – high partition, 2-3 underbin light as fixed task

After – low partition, no task light needed

Before – perimeter closed office, 1 x 4 with micro cell parabolic ceiling lights

After – closed offices moved to the core, same ceiling light system as the open area

Fig 4.27 The major lighting retrofit in the Chicago Federal Center reduced lighting loads

from 4 w/sqft to 1.3 w/sq ft and increased user satisfaction with lighting by 20%

On the cost side of the equation, there is the hardware, software and labor cost for installing individually addressable high performance fixtures and lighting automation systems. There are economies in these costs per square foot that are dependent on the quality of the existing lighting installation. If the fixture themselves are high performance with appropriate reflectors and lenses for ensuring good light distribution without glare, then only the ballasts and controllers may need to be replaced. Existing wiring to these fixtures may be adequate for both the power and data connections, and the ballasts can incorporate the relay/controllers (DALI) to simplify wiring costs. The purchase of the automation system will include installation, commissioning and training, as well as the facility manager and user control interfaces that are so valuable to optimizing energy savings. A study by Nancy Clanton a leading lighting designer in the U.S. (Fig 1.38) recommends that comprehensive lighting retrofits should move to fully addressable, dimming ballasts with wireless controllers for the most controlled first costs and the greatest energy benefits (Sanders & Chinnies., 2011).

Figure 11 – Capital Cost Breakdown for Boston

Fig 4.28 Cost Implications of Adding High Performance Controls in Lighting Retrofits
Equipment cost is highest for Wireless Scenario, but capital costs are the lowest

The research team identified that the best lighting savings occur with an investment in individually ballasted and addressable control systems with a lighting automation system. The cost assumptions for this system are:

	Per Sq ft	Per employee
First cost	\$ 1.75	\$ 350
Installation + labor cost	\$ 1.40	\$ 280
Initial investment costs	\$ 3.15	\$ 630

On the benefit side of the equation, the economic ROI includes the annual energy savings and could include peak load shaving savings in regions where there are specific utility incentives. While not quantified here, there can be a spatial churn cost-benefit since individually addressable light fixtures and

Advanced, Integrated Control for Building Operations to Achieve 40% Energy Saving

reconfigurable control zones eliminate the need for additional hardware or labor to support office layout changes or activity/task changes.

The environmental savings are measurable since lighting is entirely an electricity source with CO₂, SO_x, NO_x, particulates, and water impacts.

Balancing the costs and the benefits, a triple bottom line calculation has been completed in the following table. With energy savings alone, the payback for this retrofit will be 5 years. With energy and environmental savings, the focus of any corporation and agency that has set carbon goals, payback for this retrofit will be 3 years. Adding productivity and health benefits, the payback is in few months.

	Total Building investment costs	\$ 157,500	
		Per sq ft	Per employee
	Initial investment costs	\$ 3.15	\$ 630
First Tier Considerations	First year savings:		
	Energy savings	\$0.63	\$126.28
	O & M Savings (FM)	\$ 0.04	\$ 8.00
	Annual Baseline Savings	\$0.67	\$134.28
	ROI (Economic)	21%	
	15 year Net Present Value (Economic only)	\$ 255,333	
Second Tier Considerations	Energy savings	6.31 kWh	1263 kWh
	First year Savings :		
	Air pollution emissions	\$ 0.32	\$ 63.11
	Cumulative ROI (Economic + Environment)	31%	
	Cumulative 15 year Net Present Value (Economic + Environment)	\$ 375,335	
Third Tier Considerations	First year savings:		
	Health benefits	\$ 0.27	54.71
	Productivity increase	\$ 8.44	\$ 1,688
	Absenteeism	\$ 0.57	\$114.75
	Annual Baseline Savings	\$ 9.28	\$ 1,857
	Cumulative ROI (Economic + Environment + Equity)	326%	
	Cumulative 15 year Net Present Value (Economic + Environment + Equity)	\$ 3,906,344	

Given that up to 20% of office floors still have T-12 fixtures with magnetic ballasts, and over 50% of office floors exceed 2.5 watts/sq foot of lighting energy is use during the daytime, and that control zones

are often 25 fixtures or more, this retrofit measure can save up to 85% of a medium size office buildings total lighting energy.

4.5 Conclusions: Lighting Controls for up to 75% Lighting Energy Savings

Each of these lighting control strategies save substantial lighting energy, with measurable redundancy. Once lighting power density is reduced, or daylight is maximized, or occupancy sensors are deployed, the reductions in the remaining lighting energy use will be less. Independently, each of these lighting control solutions are extremely valuable for reducing annual and peak electric energy loads, for reducing the pollution and water costs of electricity generation, and for improving individual performance at task and human health.

- **Time of day controls** for existing lighting zones will eliminate 20% electric lighting during unnecessary night and weekend hours.
- **Daylight responsive controls** will eliminate 35% electric light in perimeter zones (where existing zones include perimeter lights only) - adding new sensors and/or time of day control.
- **Occupancy responsive controls** will eliminate 75% electric light demands due to unoccupied space (where dedicated lighting zones exist, such as closed rooms) – achieved by adding new occupancy sensors.
- **Vacancy responsive controls**, which require occupants to turn lights on but turn them off when they leave spaces, will eliminate 72% electric light in both occupied and unoccupied space (where dedicated lighting zones exist, such as closed rooms) - adding new vacancy sensors.
- **Shifting from task-ambient** ceiling light to high efficiency ambient only (300 lux) with low energy task lights will eliminate 40% electric light – adding task light occupancy sensors or smart outlets.
- **Individual control** of task-ambient lighting for paper and computer based tasks will eliminate 43% electric light – adding individual dimming ballasts and occupant controls (with comfort zones).
- Automated control of individual task-ambient lighting with **compound (daylight, time of day and occupancy) controls** will eliminate 87% electric light – adding individual dimming ballasts, daylight + occupancy sensors.
- **Individual blind control** for daylighting (without glare) will extend daylight responsive lighting control to eliminate 15% electric light in perimeter zones – adding daylight sensors and motorized control or knowledge based feedback.
- Individually ballasted ambient lighting, task lighting, automated blinds each with **occupancy controls combined with knowledge based feedback** will eliminate 64% electric light.
- **Knowledge based feedback** linking daysim and thermal simulation with system expertise will eliminate 20% electric light demands while also reducing cooling loads.

Chapter 5 Heating Controls for 40% Energy Savings

Investment in existing US buildings has not kept pace with time or the changing workplace. Heating demands continue to be the highest site energy load in US buildings, consuming over 12% of total U.S. energy use, and 30% of building site energy use (Fig. 5.1 CBEC 2003), substantially more than required given up-to-date technologies and controls.

Fig 5.1 Heating is the highest site energy load, predominantly from gas with electric assist

The 40% energy savings that can be achieved through investments in heating system controls are related to:

- Commissioning to ensure system performance as designed.
- Setback temperatures and dynamic setback temperatures dependent on next day predicted conditions.
- Micro-zoning of heating delivery, or separating ambient and task.
- User input into thermal setpoints.

With DOE ARRA funding, Siemens partnered with Carnegie Mellon University to complete a series of experiments in the Intelligent Workplace living laboratory to quantify the energy savings potential of each of these heating system control strategies, combined with Trnsys and EnergyPlus simulation for iterative exploration and annual quantification.

5.1 Experimental Configuration: Heating System Controls hardware and software in the Intelligent Workplace Testbed

To support the heating controls research, each of the existing infrastructures of the IW testbed were mapped and evaluated relative to best of class technology that would be introduced today (Fig 5.2). For heating, the 7000 square foot lab includes:

- A ‘radiant mullion’ heating system that utilizes campus steam to offset façade losses through 25 sets of 4 vertical mullions offset inside the windows throughout the facility.
- Eight radiant ceiling panels.
- Six electric resistance task heating panels, as needed, from the JC Personal Environmental Modules.
- Heating of ventilation air, as needed, through a SEMCO air handling desiccant unit; utilizing gas heating of outside air that has been preheated by heat recovery, with ducted distribution to

displacement ventilation and raised floor diffusers; the BacNet enabled automated Automated Logic Control System talks to the Siemens Apogee System.

Fig 5.2 Overview of Thermal Conditioning & Ventilation Systems in the IW Lab

The CMU team worked continuously with the SCR and SBT teams to support installation of sensors, actuators and field control panels for the laboratory configuration. Several reports were written on existing and needed components relative to the heating systems. The basic control definition and logic for

the four BAS panels was programmed by the SBT engineer, after analysis of the previous Metasys control algorithms. Table A summarizes the details of the thermal and ventilation systems that have been installed.

Table 5.1 Siemens Hardware Installations in the IW for Thermal Control

Siemens hardware	Number	Installation
½” 2 way, modulated valve and actuator	8	Replacing broken or mal-functioning mullion branch valves
½” 2 way, modulated valve and actuator	8	Controlling water flow rate supplied to cool ceilings
Surface temperature sensor	25	Being installed at the outlet of each branch of mullion water pipe
Surface temperature sensor	8	Being installed at the outlet of each branch of cooling ceiling water pipe
Space air temperature sensor	9	Been installed in the IW north zone as original proposed
Space humidity sensor	9	Been installed in the IW north zone as original proposed
Space CO ₂ sensor	9	Been installed in the IW north zone as original proposed
Ultra-sonic flow meter	4	Been installed to monitor hot water/chilled water flow to in the IW north zone, to cool wave, and to cool ceiling
PXCM field controller	4	Been installed to replace the four Johnson field panel in the underfloor space in the IW
PXCM field controller	1	Been installed to replace Johnson field panel in the Margaret Morison Basement
Apogee Insight work station	1	Been purchase and installed with the latest version of Apogee Insight system with BACnet function

Layered 3-D drawings with the location and status of each component in the thermal, and ventilation system were updated in Autocad to reflect the installations in as-builts for long term control operations. The first interface provides one layer per device – coolwave, radiant ceiling, mullion, operable window, louvers, etc. (Fig 5.3). A second interface illustrates the global Apogee installation, providing a layer for each EN panel from EN1-EN5 (thermal) plus Encellium (lights, plugs) and Labview (windows), with all devices assigned to their associated panel.

Fig 5.3 Layered 3-D drawings with location & status of each thermal systems component

A facility manager interface (Fig 5.4) was developed to support research with the following attributes:

Fig 5.4 Facility manager interface for monitoring, control and maintenance

On the center panel top, all water systems can be monitored controlled, the most important ongoing task for the facility manager. On the center panel bottom, the experimental conditions and controls are revealed for the project team, factors that are constantly changing. On the left panel, informational interfaces can be accessed, with the potential for control of:

- All lighting/daylighting/shading systems (top three buttons)
- All mechanical and natural ventilation air systems (next three buttons)
- Room temperatures and humidity readings but not controls (next button)
- Piping flows and water temperatures but no controls (next two buttons)
- Comfort survey results but no controls

On the right panel, the immediate weather information, as well as links to historic and predicted weather data, can be accessed depending on control strategies being studied.

5.2 Hypotheses on Thermal Control for Energy Efficiency

The research team developed a series of hypothesis for saving energy in existing office environments for field experimentation:

- **Time of day controls** for existing thermal zones will eliminate c% cooling and h% heating energy during unnecessary night and weekend hours (setting broader bands of acceptable conditions).
- **Occupancy responsive controls** will eliminate c% cooling and h% heating in any unoccupied space (where dedicated thermal zones exist, such as closed rooms) - adding new occupancy sensors and a broader band of conditioning requirements for unoccupied periods.
- **Shifting to broad band of thermal comfort for all spaces with task heating and cooling** controls (individual radiant or mixing box/air controls) will eliminate h% heating and c% cooling.
- **Separating ventilation and thermal conditioning** with individual shut down of local thermal conditioning based on occupancy and preferences will eliminate h% heating and c% cooling – adding individual thermal zones.
- **Solar heat and shading responsive controls** in perimeter zones will eliminate c% cooling and h% heating– adding new sensors and/or weather and time of day control.
- **Night ventilation** will eliminate c% cooling and improve indoor air quality indices.
- **Tradeoffs between external and internal shading/light redirection** based on simulation balancing thermal and lighting energy use will eliminate c% cooling and x% lighting.
- **Knowledge based feedback** for maximizing passive conditioning, separate ambient and task requirements, or occupancy driven energy savings will eliminate h% heating, c% cooling and v% ventilation loads.
- Given the capabilities of the Siemens Apogee and heating infrastructure of the laboratory, a number of heating control strategies were evaluated for comparative energy impacts through two heating seasons, contributing to the experimental findings that follow.
- For passive solar heating, opening the louvers whenever outdoor temperatures <60F (16C).
- For passive solar heating, raising blinds, whenever outdoor temperatures <60F (16C) .
- During occupied hours, if outdoor temperatures are less than 55F (12C) automatically turning on water mullions to provide a minimum ambient temperatures of 65F (18C), enabling individual set points up to 72F in occupied areas (22C).
- During unoccupied hours, maintaining indoor temperatures at 55F (12C), allowing occupants to reset occupied and unoccupied hours easily.
- Turning off ventilation fans, desiccant wheel, heat recovery, and all cooling, relying on infiltration and natural ventilation for energy savings, while maintaining thermal comfort and air quality.
- If interior CO₂ > 800ppm turning on the SEMCO with 100% outside air and heat recovery, adding SEMCO heat to ensure supply air temperatures >65F (18C).
- Enabling occupants to turn on radiant panels whenever outdoor temperatures are less than 60F (16C), with occupancy sensors or keystroke monitoring to turn them off.
- Always allowing individual/ local overrides with a one-day time limit.

5.3 Experimental Approaches to Heating Controls for EE

CMU and SCR collaborated to create a full set of control options for field experimentation relative to heating. Recognizing the opportunities and limitations of the IW test bed, the control options included: Detailed Heating Control Rules; Detailed Cooling Control Rules; Mullion Control Strategies; Lighting/Daylighting Control Strategies; SEMCO/ Ventilation Control and Night Ventilation Strategies;

and the Deployment of Motes for microzone control. In the heating season, four control logics were established for experimentation

Detailed Heating Control Rules

Baseline: Fixed Set Points (Overall IW north)

- Fix Set Point (72°F)
- 24 hours – 5 Days Schedule from FM
- Logged data for demo

Rule 1: Calendar Control (Overall IW north)

- Fix Daytime Schedule (72°F 8am-6pm)
- Night Set Back (68°F During Night)
- Integration of inertia (x hours preheat - Set Back x hours before closing).
- Logged data for demo

Rule 2: Dynamic Control (3 offices/North Conference spaces)

- Dynamic Schedule Manual Change
- Dynamic Set Back
- Turn Off unoccupied space (even during work hours) with vacancy sensors
- No Motes
- Live DEMO or Logged data

Rule 3: Broad Band Temperature Control with Local Conditioning (3 offices)

- Dynamic Schedule through occupancy learning process (Occupancy Sensors)
- Learning process for dynamic schedule and better integration of inertia
- Reduced ambient temperature (ambient at 68°F= Broad Band Temperature)
- Micro zoning in occupied zone (72°F operative temperature with Radiant Panels)
- Task heating in occupied zones (72°F with plugged in Task Heaters)
- Motes integration for local comfort detection (Temperature and user satisfaction)
- Live DEMO, if time step possible, or logged data

Each of these control logics required detailed PPCL coding (power process control language) for the Apogee control system, or the introduction of “xml” control rules used by the SEB engine, to be discussed later.

5.3.1 Night and Weekend Setbacks

Due to variations in building insulation, internal heat gains, and thermal mass, each building will have different “balance point” temperatures at which heating and cooling needs to be turned on, and different lengths of time for re-heating after set-back in winter or re-cooling after set-up temperatures in summer. Establishing how low heating set-back and how high cooling set-up temperatures can be, over night and on long weekends, with assurance of achieving next day comfort at start of occupancy, is a critical energy savings action. Similar to many buildings, the BAS system in the IW lab was no longer operating strategically, with sporadic setback in winter (average low temperatures shown for blue heating months in Fig 5.5 below).

Fig 5.5 Average and Min/Max temperatures in the IW in 2010

The IW lab had not been running set-back strategically, and the spaces have been overheated and overcooled. The main mechanical flow meter used to measure the amount of water (chilled or hot) running in the IW and used for energy calculation was found to be drifting by almost 20%. With the installation of the Apogee BAS system and the upgrade of critical sensors, the first action undertaken was to re-establish modest night and weekend setback goals for a 7.7% energy savings (second bar, Fig 5.6). The ongoing monitoring of the Intelligent Workplace through winter/spring temperatures and sunny/cloudy day conditions has provided an excellent data base for the analysis of possible heating setback temperatures and shortened reheat times for energy conservation. Several factors contribute to the ability to take deeper setback temperatures: variations in occupancy patterns, internal or party wall heat gains, thermal mass, and outdoor conditions. The IW lab in specific had a measurable heat contribution from the historic masonry building below, accounting for at least a three hour lag in temperature response and a balance point temperature as high as 10F. In addition, actual hours of use were shifted from 8-6 to 9 am -8 pm and occupant densities were highly variable. Clearly reflected in metered conditions paired with climate data, Apogee night setbacks were deepened to 5F and weekend setbacks were deepened to 2F for predictably occupied periods and 7F for predictably vacant periods, with a 3-hour reheat period. With these variations in setback temperatures, a 15.5% heating energy savings could be achieved (third bar Fig 5.6).

Fig 5.6 Energy savings potential with greater heating setback temperatures

(baseline: few sensors, 7.7%: updated sensors and controls 24 hours, 15.5% night setback $\Delta 5F$ and weekend setback $\Delta 2-7F$; 36.1% for added lower ambient to 70F)

Critical heating control finding #1: Recommission the building automation system to realize night and weekend setback (winter) and setup (summer) temperatures for 7% energy savings, and use historic records to support deeper setback temperatures for up to 15% heating energy savings.

5.3.2 Dynamic night setbacks and reheat times based on radiant effect and predicted next day temperatures

The pursuit of lower set back temperatures and next day thermal comfort of the building occupants revealed that setback “reach” goals should incorporate predicted next day temperatures, due to the cold and hot wall “radiant effect” on comfort. The introduction of the thermal comfort voting interface, described in experiment 4, clearly revealed that too cold votes increased when outdoor temperatures were low, and too hot votes increased when outdoor temperatures were high, despite the same indoor conditions (Fig 5.7).

Fig 5.7 Radiant Impacts: the Cold and Hot Wall Effect on Comfort Voting

As a result, dynamic setback temperatures, varied by predictions of next day conditions, would save the most energy with the highest level of occupant comfort. This level of control would require an outer loop temperature regulator based on model predictive control algorithms. The research team used simulation to determine the energy savings possible with dynamic set back temperatures, with lower set-backs on nights where next day conditions were predicted to be warmer and/or sunnier. Two alternative control strategies were evaluated, one with dynamic mullion flow control based on indoor temperature and the second with constant flow but dynamic water temperature controls for meeting thermostatic demands. The use of dynamic water temperature controls was substantially better since it reduced the radiant temperature variations that caused discomfort. For the shorter simulation period studied, dynamic setback temperatures saved 7.7 % beyond more conservative setback temperatures, for a total of 36% energy savings over no setback at all (Fig 5.8).

Fig 5.8 Dynamic setback temperatures driven by next day temperatures and sunshine to manage radiant discomfort

Critical heating control finding #2: Use dynamic setback algorithms to support deeper night set back temperatures whenever next day temperatures are predicted to be warmer or sunnier, supporting up to 36% heating energy savings.

5.3.3 Microzoning of temperatures to match occupancy

As discussed in the chapter on lighting controls for energy savings, office workstations on average are only occupied 40-70% of the time (Fig 5.9). The need to condition every office to the same tight standard of comfort whether occupied or not can be reconsidered if the thermal conditioning system can be micro-zoned to deliver comfort where it is needed without compromising the comfort in adjacent spaces.

Fig 5.9 Occupancy of office workstations is typically less than 60% of the workday (DEGW)

Moreover, the spaces that need well controlled thermal conditions, such as closed offices, open workstations and conference spaces, are less than 60% of the total floor area in office buildings (Fig 5.10). Combined, this means that on average 36% of the spaces will need the highest level of thermal comfort at any point in time. A mechanical system that supports wider bands of comfort in circulation and support areas as well as unoccupied spaces could save substantial energy, a hypothesis that was tested by the Siemens/CMU team.

Fig 5.10 Occupancy of office workstations is typically less than 40% of the workday

A series of field experiments were undertaken in early November to identify the potential to turn off radiant conditioning in spaces that are unoccupied without compromising adjacent occupied spaces, and to determine the response time required when occupants arrived. These experiments required local valves to be opened and closed for both the mullions and radiant ceiling panels based on predicted occupancy. After installing a new differential pressure sensor and a new seasonal configuration of the supply water loop, heating micro-zone control experiments were conducted.

Two challenges were immediately apparent for microzoning the heating system.

1. Precise control of the flow rate in each mullion by controlling the actuators position was not achievable, and micro-zoning of a water based radiant heating system through precise flow control would not be possible (Fig 5.11).
2. In a water based conditioning system, the inter-dependency of the distributed units, in this case water mullions, and their relative position in the water loop also sets up differential flow rates between the spaces (Fig 5.12).

Fig 5.11 Comparison of 2 Valve behavior variations (Siemens-Johnson) for different valve opening requests.

Fig 5.12 Hot water flow rates vary depending on valve setting and relative position in the water loop, as well as variations in actuator authority between manufacturers.

As a result of the differences in valve positions and responses, there was variation in the actual flow rates through various mullions, as revealed in the thermographic image in Fig 5.13.

Fig 5.13 variations in heating valve position and response creates variable heat

Given these limitations, a level of microzoning could still be achieved, and two PID controllers were programmed and tuned, using a number of sensors and actuators:

- Radiant water-based heating and cooling system - 6 flow meters (mechanical and ultrasonic)
- Supply & return temperature sensors on each mullion (and on radiant ceilings)
- 9 ambient air temperature sensors in the North Zone
- All the data recorded at 1 minute time step in the Apogee System

Performance of each controller was tested independently and collectively with Apogee trending data collection. The experiments revealed that the dual PID response rates and accuracies were adequate for the control strategies that are being proposed. A new control logic was created for a better integration of these constraints: The mullions are now used as binary devices (fully open or fully closed) based on outdoor air temperatures and the need for radiant temperature management (Fig 5.14).

Fig 5.14 Water piping loop (supply in blue, return in red)

The baseline PPCL was updated with the integration of 2 closed PID loops (Fig 5.15):

Fig 5.15 IW's mullion control logic schematic chart

First PID loop controls the Supply Water Temperature Set Point (SSP) to maintain the North Zone Average Temperature ("IW.N.T.Ave") at Set Point ("IW.NZ.RSP").

Second PID loop (PID 2) maintains the Supply Water Temperature ("IW.MULL.SWT") around the Supply Water Temperature Set Point by controlling the 3-way mullion mixing valve ("IW.MULL.MVO") in the mechanical room. This valve controls the supply water temp by mixing hot water from the basement with return water temperature from the conditioned space.

The results with on-off controls are constrained yet significant. Setting an ambient low of 65 °F, individual mullions can raise the temp 2-3 °F within 2 hours and can maintain temperature differences as high as 4 °F between spaces (Fig 5.16).

Fig 5.16 Using a strategic set of zone controllers to create an average condition of 64F, opening valves in a specific office resulted in a 4F increase in air temperature.

Microzoning with radiant heating based on opening and closing of water valves may not be advisable. However, microzoning by modifying supply water temperatures to maintain lower ambient conditions and providing a secondary task system may be a very effective energy saving strategy for heating system, the subject of the next two experiments. However, an air based heating system designed for individual zone conditioning (after separating ventilation from thermal conditioning) would be capable of achieving these 2-4F differentials in 15-20 minutes, more appropriate to the dynamic occupancy conditions in offices. Fan-coils and heat pumps, a combination of water and air based conditioning, would also support microzoning for energy efficiency in the heating season.

Critical heating control finding #3: Provide local control to microzone heating (and cooling) delivery for 2-4F differentials between occupied and unoccupied workstations as well as support and circulation spaces, up to 10% of heating load (http://www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroup&pgw_code=TH).

5.3.4 Heating Experimental Findings #4: Separating ambient & task for the heating season – radiant ceilings

Microzoning of thermal conditioning is one vehicle for reducing energy use in unoccupied workspaces and in circulation and service spaces, but is dependent on individual zone control that may not be viable in all buildings. Another strategy for reducing heating energy use in unoccupied workspaces, and in circulation and service spaces, would be to lower ambient conditions throughout and provide a secondary task system for individual control of thermal comfort. The Siemens/CMU team pursued two task conditioning opportunities: water based radiant ceilings and electric resistance desk heaters for their delivery of thermal comfort with energy savings.

The first experiment was conducted to determine the energy savings potential of providing cooler ambient conditions as well as local control of 1.5 kW (5000 Btuh) radiant ceiling panels to provide task comfort between two adjacent semi enclosed offices. Two experiments were conducted during the heating season, at night to eliminate any solar radiation effects. Temperatures were measured by both mounted ceiling Siemens sensors linked to the Apogee Building Automated System (2.5 meters above the floor between spaces) and portable HOBO data loggers set at desk height (Fig 5.17). Individual control was through the Apogee control system, with a smart phone interface if needed, and ‘vacancy’ sensors would shut off the task heat when the space is unoccupied (The significance of a vacancy sensor is critical to energy effectiveness - an occupancy sensor instructed not to turn task system on when arriving but to turn the task system off when leaving).

Fig 5.17 Siemens and Hobo temperature sensors and Radiant Panels location

Two sets of experiments were undertaken, in December and March, to evaluate the differences in space temperature that could be achieved in adjacent spaces given variations in outdoor conditions.

The December two-day experiment revealed that local control of water based radiant ceilings could raise air temperatures 3°F over adjacent spaces in 45 minutes (Fig 5.18) for ‘task conditioning’.

Fig 5.18 Air temperatures can be lifted 3oF in 45 minutes using radiant ceilings

It is important to note, however, that air temperatures are not a true indicator of thermal comfort from radiant sources, so radiant temperatures were also monitored with a globe thermometer. While ambient temperature rose 3-4°F, radiant temperature rose 4-5°F (Fig 5.19). Given that human responses to each degree rise in radiant temperature conditions are the equivalent of 1.4°F in air temperature, these 4-5°F will create an operative temperature that is 5.6-7°F warmer than the ambient conditions for the occupant of the workstation.

Fig 5.19 The ambient and radiative effect of task heating with radiant ceilings.

These findings indicated that ambient office temperatures could be kept at the lower end of comfort in winter (68-71°F), especially in unoccupied and support spaces, with task heating in occupied spaces offering comfort at an effective 73-75°F.

To calculate the energy impact of this separation of ambient and task heating, the heat transfer to adjacent zones must be understood. Fig 5.20 reveals that heat migration from task heated areas (“Conf-Volker” series) to adjacent areas maintain at least a 2°F difference in air temperatures measured at the desktop (not the ceiling). This reveals the essential role of a well located temperature sensors for task heating control.

Fig 5.20 Heat dispersion in adjacent zones (purple two spaces away, green one space away)

Beyond the immediately adjacent spaces, further neighboring spaces were not influenced by the use of the task heating ceiling. A maximum air differential temperature between zones of approximately 2-3°F appears after a few hours.

An unexpected side finding emerged in the experimental study: with outdoor temperatures at 40°F, cracking an operable windows (shown in green in Fig 5.21) dropped temperatures 5°F in less than 15 minutes.

Fig 5.21 Cracking open a window on a 40°F day will drop indoor temps 5°F in 15 minutes

A March heating season experiment was undertaken to ascertain the maximum conditioning differentials possible by combining micro-zoning and task heating. The experiment supported the development of a new control logic with significant energy saving potential, using both the façade water mullions for micro-zoning and the ceiling radiant panels for task heating. “Hobo” temperature sensors were again installed at desk height in two adjacent spaces to be compared with the BAS ceiling level temperature readings.

Three experimental phases were established to determine the extent of temperature differences possible between two adjacent spaces: 1) all systems on in conventional conditioning mode; 2) a shift to microzoning of one space with mullion heat on and adjacent spaces off; and 3) the same space with radiant panels on in addition to local mullions. The results are evident in Fig 5.22.

- During phase 1, when only the Mullions were ON in both spaces the temperature between the 2 zones stayed close, with a maximum delta of 1°F at the desktop (Hobo sensors) and less than 0.5°F at the ceiling (Apogee sensors).
- During phase 2, the difference between the two zones between the conditioned (Mullion On) and unconditioned spaces (Mullion Off). This temperature difference reached 1°F at the ceiling (Apogee sensors) and 3°F at the desktop (Hobo sensors).
- During Phase 3, the radiant ceiling panel in the conditioned space was also turned ON. A quick increase of temperature occurred in less than 30 Minutes. This increase was measured to be about 2°F at the ceiling (green Apogee sensors) and 5°F at the desktop (brown Hobo sensors). The lack of heat in adjacent zones affected the temperature increase which stagnated after four hours.

Fig 5.22 Differential Temperature readings from ceiling Apogee sensors (lower curve) versus desktop Hobo sensors (upper curve).

In conclusion, a 1°F- 3°F microzoning heating potential is possible even in open plan offices, with the range dependent on the location of the temperature sensor. The addition of task heating in the form of radiant ceilings would support a 3-5°F temperature differential in two adjacent zones.

5.3.5 Separating ambient & task for the heating season - electric resistance heaters

A promising strategy for heating energy efficiencies, as well as increased occupant comfort, could be achieved by providing efficient and rapid task heaters triggered by occupancy or anticipated occupancy, while lowering the ambient overall temperature throughout the space. Preliminary experiments were conducted on the potential of separating ambient and task heating through the provision of simple electric heaters (Fig 5.23). Three Johnson Control electric resistance radiant panels at 170 Watts each were used for these experiments. Several orientations, positions, and combinations were tested using the Apogee sensor data and desktop Hobo sensors plus a mobile globe thermometer to evaluate thermal comfort. Occupancy sensors were used to turn the heaters off.

Fig 5.23 Schematic layout of the radiant heater test installation.

The experimental results on a cool day (45-55F) reveal that a single 170 watt radiant panel located directly under an office desk can increase ambient air temperature at a distance of 80 cm (30 inches, a standard seating position) by around 3F in less than 30 minutes. The radiant temperature increase is even greater. The Black Globe thermometer registered a 4F effective temperature rise in less than 30 minutes. Test incorporating multiples of two or three electric resistance radiant panels were also conducted to evaluate radiant asymmetry and power factor effects (Fig 5.24). The experiments results revealed measurable energy savings by lowering ambient temperatures throughout the space with small task heaters in occupant control. As previously cited, EPA has evaluated the impacts of setbacks on total energy use based on outside temperature conditions. Given that over 60% of spaces may not require narrow comfort conditions, the 4oF average differential that can be achieved could offer approximately 10% heating energy savings less the modest task heater loads for a heating energy savings of 8%.

Fig 5.24 Experiment reveals quick response times at 3-4°F rise for occupied spaces

5.3.6 Re-evaluating Ambient Choices with Thermal Comfort Voting

The energy saving potential of lowering ambient air temperatures in winter and providing low-energy task heaters must be balanced by an evaluation of acceptable ambient lows. The Siemens/CMU team initiated thermal comfort voting studies to establish the viable ambient temperatures.

The HMI interface under development for the SEB and Apogee (see chapter 5) will support occupant voting for iterative feedback to the facility manager as to lowest winter or highest summer acceptable ambient temperatures. In the meantime, the CMU team created an occupant thermal comfort voting interface using the Encellium web tool accessible to 17 occupants in the IW testbed. Using the ASHRAE 7-point comfort scale from too cold (-3) to neutral to too hot (+3), user satisfaction was collected continuously during a period of shifting temperatures from heating to swing seasons (ranges from 20-80°F) (Fig 5.25). The following voting instructions were given:

- *Vote in the morning when you arrive in your work space*
- *Vote each time your comfort changes throughout the day*
- *Vote in the middle of the afternoon.*

Fig 5.25 Encellium Interface used as thermal comfort voting interface

Preliminary results revealed that people tend to forget to sign in when they arrive, and only vote when they felt uncomfortable. If the occupant arrived chilled from outdoors they might vote with a -2 level of discomfort, but forget to change that vote as they warm up, leaving the system to believe they are still cold. To correct for this, the voting was set back to just right every 2 hours so that users only had to vote once in the morning and whenever they were uncomfortable (see Fig 5.26).

Fig 5.26 Timer reset to comfort to limit communication effort for occupants

The online voting was used experimentally to evaluate acceptable thermal comfort temperatures during the swing season when occupants are wearing a mix of winter and spring clothing, and temperatures are fluctuating daily (20-82F). Despite wide ranges of indoor temperatures from 68-82, over 80% of the occupants were satisfied, voting within the comfort zone range. 71°F seems to be the average threshold at which people express a mild discomfort level (-1), and 77 seems to be the average threshold at which people express a mild discomfort level (+1). Just right or neutral voting seems to be around 75°F. Too cold and cold thermal rates (-3 and -2) are linked to temperatures below 70°F, and too hot and hot thermal rates (+2 and +3) are linked to temperatures above 80°F. Given the density of temperature sensors, the votes and ambient air temperatures are matched by occupant in Fig 5.27.

Fig 5.27 Thermal Comfort responses linked to Indoor Ambient Air Temperatures

Important findings include: the variability in user definitions of comfort; variability of comfort temperatures with the same user (radiant environment, activity or clo driven); voting was more consistent early in the week; voting was more frequent when discomfort occurred. Given the limited sample size of 17 occupants, the results are only meaningful for the operation of this work environment:

- Over 80% of the occupants were satisfied in the ASHRAE winter and spring comfort range supporting votes from -1 to +1.
- 71°F is the beginning of a little too cold at -1.
- 77°F is the beginning of a little too hot at +1.
- Cold and too cold responses (-3 and -2) occurred for temperatures below 70°F.
- Hot and too hot responses (+2 and +3) occurred for temperatures above 80°F.

For heating energy savings, these results suggest that an ambient temperature of 70-71°F would be acceptable to a majority of occupants, especially if task heating sources were available. For cooling energy savings, these results suggest that ambient temperatures could be raised to 77°F, especially if task cooling sources (radiant or even mechanical fans) were available. Responding to occupant thermal preferences can have several energy saving benefits: fine tuning of low and high ambient set points for energy efficiency and maximum user comfort - in response to changes in outdoor temperatures, occupant density, or solar heat gain; broad band ambient conditioning in spaces where task heating and cooling have been provided; recognition of occupied and unoccupied spaces; changing preferences for temperature conditions based on summer or winter clothing.

Critical heating control finding #4: Lower ambient temperatures throughout the workplace and provide task heating (water based radiant or electric resistance heaters) to support up to 3-4°F of increased temperatures in occupied spaces as requested. As previously cited, EPA has evaluated the impacts of setbacks on total energy use based on outside temperature conditions. Given that over 60% of spaces may not require narrow comfort conditions, the 4°F average differential that can be achieved could offer approximately 8-10% heating energy savings.

5.3.7 Adding plug load control for ensured energy efficiency

The viability of energy savings by separating ambient temperatures from task, and separating ambient lighting from task, is dependent on turning off task heaters and task lights when the space is unoccupied. The least cost approach to this is reminders to occupants to turn off all items at their desk when leaving, either one by one, or through a master switch or occupancy sensor on a power strip. If individual workstation plugs have IP addresses and relays for on/off controls, however, task systems can be shut down by the building automation systems.

In the IW testbed, the Encellium lighting control system was upgraded to include relays on a set of two outlets per workstation for central BAS control and distributed control by the end user (Fig 5.28).

Fig 5.28 Encellium power relay/controllers allows occupants and BAS to shut off task systems during unoccupied hours.

This control upgrade enabled the project to achieve the highest energy savings by allowing Apogee central control and desktop individual switching for task lights, radiant heaters and other non-sensitive plugged in devices at the workstation. The benefits of workstation plug load control is a another important arena for ongoing controls research, and the CMU team has continued in the development of on-line and smart phone interfaces for energy efficiency. For smart phone interfaces, three generations of plug load and central system (BACnet) interfaces have been developed in collaboration with the Technical University of Munich and summarized in separate papers and videos (Fig 5.29).

Fig 5.29 Technical University of Munich smart phone user controls

For desk top interfaces, a new generation of dashboard is being developed at CMU that offers communication, consultation and control interfaces directly on each person's desktop (Fig 5.30). Effective communication is achieved through continuous plug load readings 'appliance by appliance' at the hourly, weekly and monthly intervals. Effective consultation is achieved by comparing these readings with historic data as well as best of class energy use for each appliance and generating prioritized energy saving actions. Effective control is achieved by easy interfaces for turning one or all appliances off, setting across the board calendars for automated control with specific exceptions as needed, and by prompters.

Fig 5.30 1st generation IW Dashboard for communication, expert consulting and control

The energy savings possible through the separation of ambient and task conditioning are at the highest level if the user is given comparative information, expert advice, and controls including calendar-based controls.

5.4 Retrofit Recommendations for Heating Controls

These experiments reveal the substantial energy savings that can achieve through heating controls, which must be evaluated against retrofit costs as well as other benefits ranging from spatial churn cost savings to health and productivity. The Siemens/CMU team has selected several ‘tiered’ investment recommendations, from least cost to highest cost, to outline the elements for life cycle calculations.

Commission BAS for setbacks

Update BAS for significant trending and control options

Lower ambient temperature and purchase efficient electric resistance heaters

Increase Zone Density with additional dampers/valves

Manually control blinds for shading and night sky cooling

Automate blinds for shading and night sky cooling

Install SEB and Apps

The costs of these recommendations can vary significantly based on existing technology in the building, variations in the product and labor market, and intentions of the building owner for upgrading their building technologies. Given the focus of this research on experimental studies for energy efficiency through controls, only one of these heating control strategies has been analyzed with a life cycle analysis using a triple bottom line calculation, including: ‘hard’ economic cost benefits in the first bottom line;

environmental cost-benefits that may be legislated or incentivized in the second bottom line; and the human cost-benefits that should drive standards and investments in buildings in the third bottom line.

The energy benefits for life cycle calculations need to be customized for:

- building specific setpoint ranges for different seasons, with predictive weather modifications to ensure maximum comfort (>80%) at the lowest energy use;
- dynamic setpoints through micro-zoning;
- defining the lowest ambient temperature at which task heating or task cooling can ensure local satisfaction; and
- façade management strategies for cooling load reduction.

The environmental benefits that accompany electricity energy savings have been quantified for CO₂, SOX, NOX, particulates and water use savings in the lighting life cycle calculations. The human benefits associated with each recommendation is the subject of ongoing work of the Center for Building Performance and Diagnostics, to aggregate research linking the quality of buildings to health and productivity outcomes in BIDS: the Building Investment Decision Support Tool. The factors that should be considered in triple bottom line calculations are discussed for each heating recommendations that follows, with a full calculation included for separating ambient and task heating.

5.4.1 'Commission' or replace building automation system for set-back energy savings

In buildings that do not have resident facilities managers, the set-points in the building automation systems are often not adequately updated for the changing densities, schedules and activities of the occupants. One of the most substantive energy saving strategies for existing buildings is to 're-commission' the building automation system (BAS or EMCS) to improve control set points and maximize night and weekend setback temperatures, as well as economizer cycles (outside air for cooling when the temperatures are right) to be discussed in the cooling chapter. The BAS expert can review historic records to determine the lowest night and weekend setback (winter) and highest setup (summer) temperatures from which the building can effectively recover for occupancy comfort, and the shortest hours necessary for preheating in winter and precooling in summer before the next occupied period. Historic records can also reveal the potential for dynamic setback or setup temperatures given predicted next day conditions for even further energy savings.

Recommission the building automation system to realize night and weekend setback (winter) and setup (summer) temperatures for 7% energy savings, and use historic records to support deeper setback temperatures for up to 15% heating energy savings.

On the cost side of the equation, there are two levels of investment, depending on the age of the BAS system. A system installed within the last ten years will need a few days of a BAS programmer with building system and thermal comfort expertise. A system that is over ten years old may require investment in updating the software and possibly the central and distributed control modules, as well as repairing or replacing sensors and controllers that may have aged over a decade.

On the benefit side of the equation, the economic ROI includes the annual energy savings based on the experimental findings in the 2nd and 3rd column below (Fig 5.31), first improving set points and then maximizing setbacks. These calculations are for heating energy savings only, so the ROIs would be higher if cooling energy savings were also calculated.

Fig 5.31 tighter temperature set points, setbacks and separating ambient and task have significant cost benefits.

The calculated annual heating energy savings, beginning from 24x7 operations, was found to be 7.7% through updated sensors that reduced overshooting and then compensating by undershooting (heating cycling) while maintaining a 24x7 operation; and 15.5% through night setback $\Delta 5^{\circ}\text{F}$ and weekend setback that ranged from $\Delta 2-7^{\circ}\text{F}$.

The environmental savings related to CO₂, SOX, NOX, particulates, and water impacts of energy use need to be calculated for a gas heating source. However, it is important to note that the Intelligent Workplace testbed is on a campus steam grid that was coal fired until 2010 with substantially higher environmental consequences.

The human benefits of optimized heating controls include the reduction in facility management complaints of too cold and too hot workplaces, the benefits of thermal comfort for task performance, and the health benefits of managing cold radiant conditions with timely and effective heating.

Even without triple bottom line accounting, recommissioning the building automation system to realize night and weekend setback (winter) and setup (summer) temperatures will support at least 7% energy savings, and using historic records to support deeper setback temperatures and appropriate setback times for up to 15% heating energy savings, for paybacks as low as 1-2 years (<http://cbpd.arc.cmu.edu/ebids>).

5.4.2 Support micro-zone control of heating set points to reduce over conditioning of unoccupied and support spaces

Given the meeting and travel schedules of today's workforce, office workstations on average are only occupied 40-70% of the time. The need to condition every office to the same tight standard of comfort whether occupied or not can be reconsidered if the thermal conditioning system can be micro-zoned to deliver comfort where it is needed without compromising the comfort in adjacent spaces. Moreover, the spaces that need well controlled thermal conditions, such as closed offices, open workstations and conference spaces, are typically less than 60% of the total floor area in office buildings. Combined, this means that on average 40% of the spaces will need the highest level of thermal comfort. A mechanical system that supports wider bands of comfort in circulation and support areas as well as unoccupied spaces could save substantial energy. Two types of mechanical systems can effectively support micro-zoning: an

air system with damper/ zone control at every workstation, and a water based heating system with local fan or water flow controls.

To provide local control to micro-zone heating (and cooling) delivery for 2-4F differentials between occupied and unoccupied workstations, as well as support and circulation spaces, the mechanical system must be updated to support workstation based controls. One example of workstation based control is the SARI AMEX offices in Paris in which each office has a dedicated fan-coil unit with occupant control of fan speed and temperature $\pm 2^{\circ}\text{C}$ (Fig 5.32). In this high rise office, thermal conditioning is maintained at a broader band of comfort throughout the building (2°C cooler in winter and 2°C warmer in summer) until the occupant arrives and individually calls for tighter temperature conditions. At the end of the workday, systems automatically revert to the broader band unless the occupants call for two hours of additional conditioning. The individual comfort and energy impact of this “micro-zoned” conditioning system has made the SARI office developments the lowest energy and highest satisfaction “Class A” buildings in Paris.

Fig 5.32 SARI/ AMEX HVAC system managed by Carrier France has a fan-coil for every office; Tate Task Air Modules provide local control of air velocity

The Siemens/CMU research team was able to demonstrate the potential for at least 2°F differentials between adjacent spaces through “micro-zoning” controls, offering 5-10% annual heating and cooling energy benefits based on EPA findings.

On the cost side of the equation, their need to be two types of investments, one for air based systems and a second for fan-coil or heat pump systems. For an air based system, there is a need to make every diffuser a VAV control zone, maintaining minimum settings for ventilation. This can be achieved through addressable dampers or mixing boxes at each diffuser. In floor or furniture based HVAC buildings, a desk based mixing box, such as Johnson Controls Personal Environment Module™ could be installed (Fig 5.33). With the increased density of controls, on-line or smart phone based interfaces need to be added to enable individual occupants to call for the finer thermal conditions when they arrive. The BAS priorities need to be reset to support individual controls of $\pm 2^{\circ}\text{F}$, with broader thermal set points for all unoccupied spaces and periods.

Fig 5.33 Johnson Control PEMs provide mixing boxes at every desk to provide a high level of occupant control over air temperature, speed and direction (Milwaukee HQ).

For a water-based heating and cooling system with existing fan coils or heat pumps, the costs of setting ambient thermal conditions until the space is occupied may be more modest since the density of controls is already at an individual office basis. In this case, only the on-line or smart phone based interfaces need to be added to enable individual occupants to call for the finer thermal conditions when they arrive (or before, if a smart phone app such as the Nest thermostat). Again, the BAS priorities need to be reset to support individual controls of $\pm 2^{\circ}\text{F}$ or more, with broader thermal set points for all unoccupied spaces and periods.

On the benefit side of the equation, the economic ROI includes the annual energy savings based on the experimental findings given a water based system and open plan offices that could support only a 2°F maximum differential.

The environmental savings related to CO_2 , SOX, NOX, particulates, and water impacts of energy use would be calculated for a gas heating source and an electric cooling source. .

The human benefits of optimized heating and cooling controls include the reduction in facility management complaints of too cold and too hot workplaces, the benefits of **individual control** for task performance and health.

Even without triple bottom line accounting, providing local control to micro-zone heating and cooling delivery for $2\text{-}4^{\circ}\text{F}$ differentials between occupied and unoccupied workstations offers 10% heating and cooling energy savings.

5.4.3 Lower ambient temperatures and provide task heating systems to maximize comfort at the lowest energy

An alternative approach to introducing individual control zones for every workstation, at least for the heating season, is to lower ambient temperatures throughout the workplace and provide task heating (water based radiant or electric resistance heaters) to support up to 4°F of increased temperatures in occupied spaces when requested. Similar to separating task and ambient lighting with the ceiling providing lower ambient light requirements and an efficient desk lamp or two providing higher task lighting, separating ambient from task heating conditions can also save energy and increase occupant comfort and performance.

Task heaters are pervasive in today's workplace to compensate for cold conductive floors, cold and drafty facades, variations in occupant clothing and health, and poorly balanced HVAC systems. These components are consistently seen as energy and safety hazards and often confiscated by management.

Just like the new generation of task lights, however, task heater can be a major benefit to building energy efficiency. Given the variations in occupant density and thermal comfort demands, electric resistance heaters can be significantly more efficient than blanket heating of all spaces to precise temperatures.

On the cost side of the equation, there are a number of high efficiency electric resistance heaters for consideration (Fig 5.34), though the furniture and HVAC industries could substantially improve on these choices and costs. Our research studies were based on the most affordable 170 watt electric resistance panels.

Fig 5.34 Electric heaters vary in cost and efficiency, and include electric resistance, ceramic cores and convection

	Per Sq ft	Per employee
First cost for electric resistance panels	\$ 0.19	\$ 38

On the benefit side of the equation in the first bottom line (traditional NPV), the Siemens/CMU research team was able to demonstrate the potential for 2- 4oF differentials between adjacent spaces through task heating based on introducing 1-3 panels per workstation, with a rapid rise in conditions to meet occupant demands. The annual heating energy benefit has been calculated based on maximum expected workstation occupancies of 70% during the work day and the net area that needs well controlled thermal conditions, such as closed offices, open workstations and conference spaces, of less than 60% of the gross floor area in office buildings. This establishes the 2-4 F higher task conditioning demand in less than 50% of the floor area, with an annual heating energy savings of 36% (see Fig 5.35 below).

Fig 5.35 Heating energy savings (before and after)

In the second NPV calculation, the environmental savings related to CO₂, SOX, NOX, particulates, and water impacts of energy use are calculated for a gas heating source and an electric task heater (net benefits).

Finally, the third NPV calculation incorporates the human benefits of optimized heating controls, include the reduction in facility management complaints of too cold and too hot workplaces, and the benefits of **individual control** for task performance and health. A weighted average of the following studies has been incorporated in the calculation.

Temperature Control = Individual Productivity

In a 2006 meta-analysis of 24 lab and field office building studies, utilizing metrics such as text typing, simple calculations, and length of telephone customer service time, Seppanen et al. identify 10% higher performance when the temperature is increased from 15°C to 21°C, 8.9% higher performance when the temperature is reduced from 30°C to 21°C, and a temperature band of 21°C to 24°C for optimum productivity.

Seppanen, O.; Fisk, W.; Lei, Q. (2006): Effect of temperature on task performance in office environment: Proceedings of the 5th International Conference on Cold Climate Heating, Ventilating, and Air Conditioning; Paper S3-16: May 21-24, 2006; Moscow: LBNL-60946.

Individual temperature control = Individual productivity

In a 1996 controlled experiment / meta-analysis study, Wyon identifies that providing individual temperature control over a range of 6°K (10.8°F) results in performance improvements of 2.7% on thinking and decision-making tasks, 7% on typing tasks, and 3.4% on skilled manual tasks.

Wyon, D.P. (1996) Individual microclimate control: required range, probable benefits, and current feasibility. In Proceedings of Indoor Air '96: 7th International Conference of Indoor Air Quality and Climate, Nagoya, Vol. 1, pp.1067-1072.

Individual temperature/air control = Individual productivity

In a 2001 controlled experiment in Japan, Hayashi et al identified an average 1.5% improvement in performance on typing tasks for subjects with individual control of task air systems (including temperature and velocity of air and temperature of a radiant heat panel beneath the desk), as compared to fixed temperature and airflow conditions (disabled task air systems).

Hayashi, J., T. Akimoto, S. Lee, N. Iesaki, T. Yokota, S. Tanabe. (2003) Thermal preference of the task environment and its influence on productivity. In Proceedings of Healthy Buildings 2003, December 7-11, 2003, Singapore.

Individual temperature control = Health

In a 1998 controlled experiment, Witterseh identifies a 67% reduction in headache symptoms in noisy office conditions (55dBA) and a 42% reduction in headache symptoms in quiet office conditions (35 dBA) when subjects are exposed to 22°C workplace temperatures, as compared to 30°C temperatures, revealing the importance of temperature control in different noise conditions.

Witterseh, T. (2001) Environmental Perception, SBS Symptoms and the Performance of Office Work under Combined Exposures to Temperature, Noise and Air Pollution. Ph.D. Thesis, Technical University of Denmark, Denmark.

Balancing the costs and the benefits, a triple bottom line calculation has been completed in the following table 2. With energy savings alone, the payback for this retrofit will be one year. With energy and environmental savings, the focus of any corporation and agency that has set carbon goals, the payback for this retrofit will be less than 1 year. Adding productivity and health benefits, the payback is in less than one season.

Table 5.2 Triple Bottom Line calculation for Separate Ambient and Task Heating

	Total Building investment costs	\$ 9,500	
		Per sq ft	Per employee
	Initial investment costs	\$ 0.19	\$ 38
Tier First Considerations	First year savings:		
	Energy savings	\$0.20	\$40
	Annual Baseline Savings	\$0.20	\$40
	ROI (Economic)	104%	
	15 year Net Present Value (Economic only)	\$ 74,889	
Tier Second Considerations	Energy savings	1.97 kWh	394 kWh
	First year Savings :		
	Air pollution emissions	\$ 0.10	\$ 20
	Cumulative ROI (Economic + Environment)	155%	
	Cumulative 15 year Net Present Value (Economic + Environment)	\$ 112,314	
Tier Third Considerations	First year savings:		
	Health benefits	\$ 0.24	\$ 49
	Productivity increase	\$ 5.18	\$ 1,035
	Annual Baseline Savings	\$ 5.42	\$ 1,084
	Cumulative ROI (Economic + Environment + Equity)	3008%	
	Cumulative 15 year Net Present Value (Economic + Environment + Equity)	\$ 2,173,369	

It is possible that the existing building infrastructure already includes a local heating source – a radiant ceiling panel, a fan-coil or heat pump unit at the window wall – in a building that is perimeter conditioning based. In this case, the cost of the retrofit action will be reduced to programming for lowering the ambient set points by 2 F, providing training for the occupants and repairing individual controls at each local heating source.

Lowering ambient temperatures throughout the workplace and providing user controllable task heating (water based heating or electric resistance heaters) will support up to 3-4F of increased temperatures to meet occupancy demands, providing 36% heating energy savings at a ROI of 104-3008%.

5.4.4 Use SEB innovations for dynamic setback energy savings

Programming of setback temperatures in the heating season, in addition to the hours of preheat for next day occupancy, are typically set by average building lessons learned, and not linked to next day or predictive temperature and sun conditions. Innovative building control system interfaces have the potential, however, to establish dynamic algorithms to support deeper night set back temperatures or shorter pre-heat periods whenever next day temperatures are predicted to be warmer or sunnier.

Siemens Corporate Research team has developed a Smart Energy Box (SEB) to support model predictive control and innovative control set points based on historic and external data sets. This system can review historic records to determine the lowest night and weekend setback (winter) and highest setup (summer) temperatures from which the building can effectively recover for occupancy and the shortest hours necessary for preheating in winter and precooling in summer before the next occupied period. Historic records combined with live weather feeds can also reveal the potential for dynamic setback or setup temperatures given predicted next day conditions for even further energy savings.

The Smart Energy Box is an innovative software development of SCR that is BACnet enabled for communication with a wide range of building automation systems. The costs for the software and hardware have been estimated based on a typical mid-sized office building of 50,000 square feet with an up to date BAS system.

On the benefit side of the equation, it is important to point out that the Smart Energy Box provides capabilities far beyond dynamic setback and setup temperatures with predictive weather input. It is the interface that supports the development of a wide range of apps for individual control; negotiated group control; model predictive control of individual HVACs components; micro-zoning; and more. For this reason, the cost-benefit analysis will incorporate the combined heating and cooling energy savings of all the experiments discussed in this and the next chapter.

For dynamic setbacks, the annual energy savings is based on the experimental findings of 7.7 % energy savings beyond more conservative setback temperatures, and a total of 36% heating energy savings over no setback at all.

The environmental savings related to CO₂, SOX, NOX, particulates, and water impacts of energy use can be calculated for a gas heating and electric cooling sources.

Given the breadth of actions possible through the SEB, the human benefits of optimized heating and cooling controls might be illustrated by the reduction in facility management complaints of too cold and too hot workplaces and the benefits of thermal comfort for task performance, as previously discussed.

Even without triple bottom line accounting, introducing the Smart Energy Box interface with dynamic setback algorithms will support deeper night set back temperatures whenever next day temperatures are predicted to be warmer or sunnier for 36% heating energy savings, as well as supporting a broad range of cooling, ventilation and lighting control efficiencies.

5.5 Conclusions: Controls for 40% Heating Energy Savings

Of the hypotheses generated at the beginning of the project, the Siemens/CMU team was able to confirm a range of heating energy savings, with overlaps between four major strategies, which are estimated to aggregate to 40% heating energy savings.

- **Setback controls** for existing thermal conditioning systems to set lower temperatures in unoccupied periods will eliminate 15.5% heating energy during unnecessary night and weekend hours.
- **Microzoning** to provide user control of finer thermal conditions only in occupied spaces, with vacancy sensors for automated management, will eliminate 10% heating in unoccupied spaces.
- **Shifting to broad band of thermal comfort for all spaces with task heating** controls (individual radiant or mixing box/air controls) will eliminate 8-10% heating.
- **Dynamic setback controls** to set even lower temperatures during unoccupied hours if next day predicted temperatures will be warm will eliminate up to 36% heating energy during unnecessary night and weekend hours .

Chapter 6 Cooling Controls for 25% Energy Savings

While heating and lighting demands are the greatest site and source energy loads, respectively, cooling and ventilation loads are the fastest growing loads in US office buildings (see Fig 6.1 Annual Energy Outlook 2011 with projections to 2035). This is due in part to climate change, to increased occupant and equipment densities in buildings, inadequate solar shading, and increased building tightness that reduces heat dissipation through infiltration and exfiltration.

Fig 6.1 Annual Energy Projection (DOE/EIA, 2011)

With DOE ARRA funding, Siemens partnered with Carnegie Mellon University to complete a series of experiments in the Intelligent Workplace living laboratory to quantify the energy savings potential of a number of cooling system control strategies:

- Separating Ventilation and Thermal conditioning to Support Natural Ventilation
- Daytime Cooling with Economizer
- Separating Task & Ambient Cooling
- Night Ventilation Pre-Cooling (setpoints, aperture, PCM)
- Controlling Heat Gain while Optimizing Daylight with Venetian Blinds

The field experiments, undertaken for periods of weeks in summer and swing seasons, are then combined with Trnsys and EnergyPlus simulations to provide annual quantification of energy savings possible through this set of cooling systems controls.

6.1 Experimental Configuration: Cooling system controls hardware and software in the Intelligent Workplace Testbed

The Intelligent Workplace is a living and lived in laboratory for testing the performance and life cycle benefits of innovations in enclosure, mechanical, lighting, networking and interior systems. The air based and water based cooling systems overlap considerably with the heating infrastructures described in the previous chapter:

- A ‘radiant mullion’ cooling system that utilizes campus chilled water to offset façade gains through 25 sets of 4 vertical mullions offset inside the windows throughout the facility.
- Eight radiant ceiling panels.
- Cooling of ventilation air, as needed, through an electric heat pump in the SEMCO air handling unit that has been precooled by the enthalpy recovery wheel, with ducted distribution to displacement ventilation and raised floor diffusers.
- Several additional components are critical to the cooling of the Intelligent Workplace test bed, also shown in Figs 6.2 and 6.3 repeated from the heating chapter.
- 10 LTG coolwaves in the north zone, that integrate dual chilled water coils and a paddle for inducing and then spinning cool air to occupied areas directly below (a form of chilled beams);
- A desiccant wheel in the SEMCO air handling/ enthalpy recovery unit to ensure that air is kept adequately dry for water based cooling, with a BacNet enabled automated Automated Logic Control System that talks to Apogee.
- 4 LTG underfloor fan coil units in the south zone.
- 10 Johnson Controls Personal Environmental Modules, desk mounted mixing boxes that draw conditioned ventilation air from the SEMCO and allow local mixing, air speed and directional control by the occupants.
- For both the heating and cooling controls research, the existing system was updated with:
 - an updated Apogee Building Automation System with Insight software on a PC server, BacNet enabled, and four underfloor PXC controller boxes plus one in the basement, all native BacNet. The Apogee BAS is one of the most advanced control systems and with BacNet interfaces it can operate as the central controller for heating, cooling, ventilation, lighting, and even blind and dynamic shading control as well as submetering analysis and control.
 - An increase in sensor density: 9 additional air temperature, humidity, and CO2 sensors; 42 surface temperature sensors on return water piping from mullions, radiant panels and coolwaves (used for cooling).
 - Replacement of eight water mullion valves and installation of four ultrasonic flow meters to add to two mechanical flow meters that were recalibrated.
 - Three differential pressure sensors, on each in the mullion loop, the radiant panel loop, and the coolwave loop.
- Specifically for the cooling system operation, the existing systems were updated with:
 - Cleaning of the desiccant wheel in the SEMCO;
 - Updating the automated Logic software and replacing the manual outdoor damper control in the SEMCO with an automated controller;
 - Setting up the 9 additional humidity sensors as redundant wet bulb temperature controllers
 - Adding automated control valves for each of the 4 pairs of radiant ceilings.

Fig 6.2 Thermal Water systems layout of the IW

Fig 6.3 Ventilation systems layout of the IW

6.2 Hypotheses for Cooling Control for Energy Efficiency

The research team developed a series of hypotheses for saving cooling energy in existing office environments to develop field experimentation in the IW test bed.

- **Time of day controls** for existing thermal zones will eliminate c% cooling and h% heating energy during unnecessary night and weekend hours (setting broader bands of acceptable conditions).
- **Occupancy responsive controls** will eliminate c% cooling and h% heating in any unoccupied space (where dedicated thermal zones exist, such as closed rooms) - adding new occupancy sensors and a broader band of conditioning requirements for unoccupied periods.
- **Shifting to broad band of thermal comfort for all spaces with task heating and cooling controls** (individual radiant or mixing box/air controls) will eliminate h% heating and c% cooling.
- **Separating ventilation and thermal conditioning** with individual shut down of local thermal conditioning based on occupancy and preferences will eliminate h% heating and c% cooling – adding individual thermal zones.
- **Solar heat and shading responsive controls** in perimeter zones will eliminate c% cooling and h% heating– adding new sensors and/or weather and time of day control.
- **Night ventilation** will eliminate c% cooling and improve indoor air quality indices.
- **Tradeoffs between external and internal shading/light redirection** based on simulation balancing thermal and lighting energy use will eliminate c% cooling and x% lighting.
- **Knowledge based feedback** for maximizing passive conditioning, separate ambient and task requirements, or occupancy driven energy savings will eliminate h% heating, c% cooling and v% ventilation loads.

However, the cooling capacity of the existing water based infrastructure and air handling unit were not adequate to pursue a number of these tradeoffs. Raising night-time temperatures in the unoccupied space could not be pursued if next day comfort conditions were to be achieved. Natural ventilation and night ventilation had to be constrained by acceptable wet bulb temperatures for water based cooling. External louvers were set in a full shade mode as soon as temperatures rose above 75F and left in that position.

6.3 Experimental Approaches to Cooling Controls for EE

Despite limitations in cooling capacitance available, the capabilities of the Siemens Apogee and the cooling infrastructure of the laboratory supported the evaluation of a number of cooling control strategies through two cooling seasons, contributing to the experimental findings that follow.

- Close the **louvers**, whenever outdoor temperatures >75F (25C)
- Lower **blinds** but leave in an open position, whenever outdoor temperatures >75F (25C).
- During the daytime, open motorized and **operable windows** if indoor air >75F (25C) and outdoor air < 65F (18C) and rain is not too strong (0.5 in/hr).
- At **nighttime for precooling** with projected next day temperatures >75F (25C), open motorized and operable windows if indoor air > 70F (10C) and outdoor air < indoor Air or not lower than 55F(12.8C), rain is not too strong (0.5 in/hr), and wind < 6 mph.
- If less than 65F (18.3C) outside, turn off **SEMCO** fans, desiccant wheel, heat recovery, and all cooling, unless predicted weather anticipates >85F (29C), or unless CO₂ > 800ppm
- If greater than 70F (22C) turn on SEMCO fans, desiccant wheel, but no cooling, unless predicted weather anticipates >85F (29C), or unless CO₂ > 800ppm
- If greater than 80F (27C) leave on SEMCO fans, desiccant wheel, and add heat recovery wheel and SEMCO cooling and all water mullions during occupied hours + 2 hours.
- If outdoor temperatures are greater than 85F (29C) automatically turn on **water mullions**, with water temperatures 2F above dew point temperatures.

- Enable occupants to turn on water mullions whenever outdoor temperatures are greater than 75F, with water temperatures 2F above dew point temperatures.
- Enable occupants to turn on **cool waves and radiant panels** whenever outdoor temperatures are greater than 75F, with water temperatures 2F above dew point temperatures.
- Turn on cool waves and radiant panels whenever outdoor temperatures exceed 90F (32C), with water temperatures 2F above dew point temperatures.

6.3.1 Separating ambient & task conditioning with local cooling

Microzoning controls for cooling control, room by room, is one vehicle for reducing energy use in unoccupied workspaces and in circulation and service spaces. In an air based system, especially one with dedicated ventilation air delivery (DOAS), microzoning could be achieved through individual damper control in each diffuser. In a water based cooling system, microzoning might be achieved by local fan-coil or heat pump controllers for water flow or fan speed.

A second strategy for reducing cooling energy use in unoccupied workspaces, and in circulation and service spaces, would be to raise ambient conditions throughout and provide a local task system for individual control of thermal comfort. The Siemens/CMU team pursued two task cooling conditioning opportunities in the IW testbed: water based radiant ceilings and water based “coolwaves” for their delivery of thermal comfort with energy savings. In our climate, these water-based local cooling systems are only possible due to the use of a desiccant air handler that ensures that no local condensation occurs.

The LTG Coolwave™ is a paddle coil system in which two chilled water coils are set in a V-pattern, and a paddle pulls air across the coils and spins it back out to the occupied space. These local cooling devices do not have drip pans and rely on supply water temperatures that are always above dewpoint. Even with the benefit of a desiccant air handler, these individual cooling devices use supply water temperatures that are 10F warmer than conventional air conditioning, which supports the use of return water from the primary cooling (an energy cascade). Ten Coolwaves exist in the conference area and in several offices in the north of the IW testbed, individually controllable to meet the needs of the space (Fig 6.4). If ambient temperatures are kept at the high end of satisfaction, previously determined to be 77F, or allowed to float even higher in unoccupied times, the research question is how quickly the task cooling system can lower local temperatures to satisfy users.

Fig 6.1 Coolwaves in the IW testbed

A number of experimental tests were run, with one shown in Fig 6.5 below. These studies reveal that two adjacent ‘coolwaves’ can yield 4-5 °F of local cooling in 30 minutes or less, dropping the temperature from 81F to an average of 76-77 depending on the distance from the sensor to one or both Coolwaves™.

These findings indicated that ambient office temperatures could be kept at the higher end of comfort in summer (77-80°F), especially in unoccupied and support spaces, with task cooling in occupied spaces offering comfort at an effective 74-76°F.

Fig 6.2 LTG Coolwaves can rapidly lower individual (work area) temperatures 2-5F below ambient conditions to provide local comfort while allowing unoccupied spaces and circulation to be warmer (note average space temperature is dropping because outdoor conditions are reaching night temperatures; even so, the delta is significant).

Additional studies evaluated the impact of a single coolwave in a warmer room, revealing at least 1F of rapid reductions in air temperatures (Fig 6.6). The effective cooling, however is closer to 2F due to the benefits of convective cooling from the Coolwave spinning air (ASHRAE standard 55P).

Fig 6.3 A single task cooling Coolwave™(paddle coil with water always above dew point) can rapidly provide 2F of effective cooling when including convection.

Critical cooling control finding #2: Raise ambient temperatures throughout the workplace and provide task cooling - local damper controllers for air conditioning (where DOAS provide ventilation) or water based radiant or chilled beams - to support 2-5F of decreased temperatures in occupied spaces as requested.

6.3.2 Daytime Cooling with Economizer

The use of natural cooling with direct outside air for swing seasons ensures

affordable high levels of fresh air with the greatest energy efficiency. International studies consistently link increases in outdoor air supply to both productivity and health gains in the workplace (Fisk, Mirer, & Mendell, 2009). In addition, the substantial opportunity for “free cooling” through the use of outside air is vastly underestimated by calculations focused on only ideal outdoor conditions. Natural cooling is possible whenever outside conditions are within or below the comfort zone both day and night. The use of both passive (open windows) and active economizer cycles can save over 50% of the cooling demand in various regions of the U.S.

A simple analysis of coincident temperature and humidity conditions in our climate region reveal that 9.4% of the year is in the ASHRAE comfort zone, 13.3% is in the adaptive comfort zone (with natural ventilation), 11% of free cooling hours when outdoors temperatures are below indoor set points (given the IW testbed 76 F summer Set Point) that would support natural ventilation for 25% of hours including economizer controls to mix cooler outside air with return air to meet set point (Fig 6.4).

Fig 6.4 Psychrometric for Pittsburgh Region shows layers of free cooling opportunity

Because the SEMCO unit has a manual outside air damper instead of an automated damper, the field experimentation focused on the ventilation energy savings by turning the unit off during all periods below the comfort zone and relying on infiltration and natural ventilation for achieving air quality and thermal comfort. These studies will be discussed more fully below. Simulation was used to determine the energy benefits of economizer controls. Preliminary Energy Plus simulation revealed that using outside air cooling as an alternative to mechanical cooling whenever outside air is less than 70F WBT will eliminate 1% of the ventilation loads on the fan and 17% of the annual cooling loads (Fig 6.8).

Fig 6.8 Energy Plus Simulated Monthly total energy savings with hybrid ventilation

The ASHRAE *AEDG Guide for Small and Medium Office Buildings* also identify the benefits of air side economizers to eliminate mechanical cooling, if the system is sized to deliver enough air flow and adequately controlled and maintained. Portland Energy Conservation Inc (PECI) reported a national average of 12% cooling energy savings through economizers in a 2009 report entitled *A Study on Energy Savings and Measure Cost Effectiveness of Existing Building Commissioning (annex report)*.

6.3.3 Daytime Cooling with Natural Ventilation

Design for effective natural ventilation and natural cooling requires multi-disciplinary expertise to ensure that building shape, orientation, atria/courtyards, chimneys, as well as window types, sizes and locations ensure effective cross and stack ventilation. In many climates, ‘mixed-mode’ HVAC systems will also have to be designed to provide air conditioning for thermal comfort and ventilation for air quality when and where natural ventilation is inadequate. There are three types of mixed mode HVAC systems:

- Concurrent systems, which use natural ventilation and mechanical HVAC simultaneously. Occupants are free to open windows and the HVAC system provides supplemental ventilation, dehumidification, and cooling, while an advanced control system coordinates zone air supply rates with window positions;
- Changeover systems or hybrid conditioning, where the building alternates between natural and mechanical mode on a seasonal or daily basis;
- Zoned systems, in which different conditioning strategies are used simultaneously in different zones of a building.

The Siemens/CMU team conducted several sets of experiments on the use of operable windows for “free cooling” and ventilation. The first 12 week study during spring and summer periods in 2011 was based on the opening of a modest aperture area offered by eight Traco windows automated with Somfy Motors, with BacNet/ Apogee controls for temperature, humidity, wind speed and rain (Fig 6.9). The study measured the impact of opening windows on ambient temperatures and CO₂ levels and led to calculated impacts on cooling energy demands.

Limitations on the use of operable windows were critical. Rain could not exceed 0.5 inch/hour, wind could not exceed 6 mph, and if cooling was on, outdoor dewpoint had to be less than indoor dewpoint, and relative humidity had to be less than 80%. The dewpoint and humidity limitations on operable windows are necessary because water based cooling is subject to condensation that must be avoided. These limitations would be less constrained in an air based cooling system.

Fig 6.9 Traco awning windows automated with Somfy Motors were controlled by Lab View linked to Apogee through Bacnet.

The studies were undertaken with the 8 windows in the north zone, linking the control logic in LabView (Fig 6.10) through BacNet to the Apogee Control System. The Apogee Control system is critical for continuous retrieval of the environmental conditions that constrain the use of natural ventilation.

Fig 6.10 Hybrid Ventilation & Cooling: Labview Experimental Control Interface

Given the 2011 findings, a Trnsys/Comis integrated simulation of the potential cooling season from April 15th to October 15th was completed using TMY2 weather data. The study found that windows opened 9% of the time for a 7.2% cooling energy savings during the year. Field experimentation identified that simulation underestimate the hours and that from April-October windows could be opened 15% of the time for cooling energy savings up to 10%.

The second set of hybrid ventilation and cooling studies was conducted during the summer of 2012 for a full four months from May through August. Table 1 captures the percent of time that windows were opened given the indoor and outdoor environmental constraints on the use of natural ventilation. It is clear from these studies in Pittsburgh that May and June months can take greatest advantage of hybrid conditioning. However, 8% of the of the time in the month of July and 16% of the month of august can also benefit from hybrid conditioning. The percent of hours are further divided into nighttime hours open which benefits cooling energy savings (with expanded comfort zones), and daytime hours open which benefits both ventilation and cooling energy savings.

Table 6.2: The percentage of open windows during the months of May- August

	% open	% open	
May	22%	9%	Day time
		13%	Night time
June	25%	5%	Day time
		20%	Night time
July	8%	2.4%	Day time
		5.6%	Night time
August	16%	8%	Day time
		8%	Night time

The following Figs 6.11-14 illustrate the times when windows are open or closed (0 = closed position and 1 = open position) and the occupancy profile (grey areas on the upper area of the chart represent no occupancy).

Fig 6.11 During May 2012, the windows opened 22% of the time (9% of the daytime, 13% of the night time).

Fig 6.12 During June 2012, the windows opened 25% of the time (5% during daytime, 20% during night time).

Note: BAS control failed to respond for almost 2 weeks during June and prevented the windows from being opened.

Fig 6.13 During July 2012, the windows opened 8% of the time (2.4% during daytime, 5.6% during night time).

The higher outdoor temperature and humidity during July reduced the amount of time when the windows can be opened. The water based cooling system requires precise control of humidity to avoid condensation, provided by the desiccant ventilation unit.

Fig 6.14 During August 2012, the windows opened 16% of the time (50% during daytime, 50% during Nighttime).

The mild August of 2012 allowed a longer usage of natural ventilation.

Given the recent collection of data, precise calculations of energy savings for office buildings in the Pittsburgh region have not been completed. Simulation will be completed that take field data into a TMY analysis of:

- Chilled water energy saving from daytime and nighttime free cooling.
- Electrical energy saving from daytime and nighttime free ventilation
- Gas energy saving from turning off the ventilation desiccant unit.

Given the displaced cooling loads and hours of operation during the summer of 2012, it is estimated that up to 10% of the cooling energy required can be displaced by natural ventilation during occupied hours.

Critical cooling control finding #2: Use outside air for 17% cooling energy savings with economizer cycles and up to 10% cooling energy savings through operable windows during the occupied hours.

6.3.4 Night Ventilation Pre-Cooling (varying setpoints, aperture, mass through PCM)

The use of operable windows for cooling during the *unoccupied* hours can be even more substantial since it will not be limited by thermal comfort constraints, other than the ability to achieve next day temperature and humidity control by the time of occupancy. The Siemens/CMU team pursued a number of night ventilation studies for precooling the building for next day cooling energy savings. These studies ranged from colder acceptable set points to greater percent of openings (Fig 6.15), to the addition of phase change materials to increase thermal mass for night cooling retention.

Fig 6.15 Awning windows were opened manually to add to the automated clerestory windows for increased night ventilation cooling

While these studies are ongoing, the one significant finding is the impact of dramatically increased aperture area to 10% of opening versus 3% with transoms alone on a June summer night that dropped from almost 80F to a low of 55F. The indoor temperatures could be lowered 15F and offered sustained comfortable conditions for up to 6 hours the following day (Fig 6.16). Outdoor temperatures were similar for these 3 days.

Fig 6.16 Indoor temperatures with no windows opened (Green curve: 13th -14th June), transom alone (Red curve: 6th -7th June), and full aperture (Purple curve : 25th -26th).

Critical cooling control finding #3: in buildings with substantial operable windows, open all windows wide on evenings expected to be below 65 F and next day temperatures are expected to exceed 75F, unless outdoor dewpoint is higher than indoors or relative humidity exceeds 80%.

6.3.5 Controlling Heat Gain while Optimizing Daylight with Venetian Blinds

The fourth cooling control strategy researched by the CMU team was the use of internal blinds for daytime cooling energy savings while sustaining adequate daylight levels. The Intelligent Workplace testbed has inverted aluminum venetian blinds from RetroSolar™ in Germany. As with any venetian blind, these can be positioned up and open, down and closed, down at a 90 horizontal position, and down at a 45° greater shading angle. The use of internal blinds for shading requires climate and orientation specific quantification of their respective impacts on air temperature, radiant temperature, and light levels at the worksurface.

Several bays in the IW testbed have been configured for sequential testing of blinds in the closed, open, 45° and 90° tilt positions in rapidly varying spring and summer climate conditions. Measurements have included: radiant (globe thermometer) temperatures, surface air temperatures, ceiling air temperatures, and surface light measurements.

During the spring months, while maintaining interior ambient temperatures between 68-74°F and light levels of 100-150 lux minimum, the following findings are significant for energy savings in existing buildings: Closing blinds on a day with outdoor temperatures rising from 40-65°F (8 am-6 pm), will maintain 2°F cooler indoor ambient air temperatures, and 8°F cooler peak radiant temperature conditions during the morning hours (Fig 6.17). Surprisingly, opening blinds at night allowed 3°F of free cooling through radiation to the night sky.

Fig 6.17 Closing S and E blinds in the morning and opening at night reduces indoor temperatures 2-3oF

To sustain higher daylighting levels, the field experiments revealed that setting south and east blinds to a 45° tilt will reduce air temperatures by 1-2°F, as compared to blinds set horizontally, while maintaining daylight levels above 200 lux for effective ambient lighting. Radiant temperature differences were again more substantial, which will also have energy and comfort impacts.

Given the external building shading of the IW test bed for western sun, field studies reveal that setting south and west blinds to a better shading position at a 45° tilt will also reduce air temperatures, but not as significantly as in the South and East, with .5-1°F reductions as compared to blinds set horizontally. On the other hand, daylight levels were sustained at 400-600 lux for effective task lighting (Fig 6.18).

Fig 6.18 Given building shading from the West, closing S and W blinds in the afternoon reduces indoor temperatures .5 to 1oF

On additional finding from the experimental setup is the significant variation in measured ambient temperatures given sensor locations. With over a 5°F differential in sensor reading at the desk versus the ceiling location, overcooling could be reduced if deskbased sensors became the norm (Fig 6.19). Given

the innovations in “motes” or micro-sensors that could be integral with the computer or even an iphone, the opportunity for more refined set points in occupied spaces is a major area for future research.

Fig 6.19: Desktop sensors could reduce overcooling by eliminating the thermal stratification effect on ceiling sensors

Critical cooling control finding #4: Lower blinds into horizontal or 45 positions throughout the summer season to reduce cooling loads and reopen them on cool nights to lower next day start up temperatures.

6.3.6 Two additional cooling control strategies: Night Set-up and Enthalpy (Coolth) Recovery

There are two additional cooling control strategies that were the subject of experimentation in the Intelligent Workplace testbed. Just as setback and dynamic setback temperatures are effective energy saving heating control strategies, it was expected that set-up controls to set higher temperatures in unoccupied summer periods would reduce cooling loads. The cooling capacitance of the IW testbed, however, is not large enough to support re-cooling due to a limitation in the chilled water capacity delivered to the space and the limitation in acceptable supply water temperature in a water based cooling system to avoid system condensation. The chilled water capacitance is now being increased to the lab and future experiments will include set-up temperatures for energy savings during unoccupied periods in the evening and on weekends.

Another experiment to reduce cooling energy demands is the use of an Enthalpy recovery wheel to recover “coolth” from the exhaust air to precool the ventilation air. In measured studies over a full year, the enthalpy recovery wheel saves 78.5% of the cooling demands for ventilation air, that itself represents approximately 10% of the total cooling load, which will be further discussed in the ventilation chapter.

6.5 Retrofit Recommendations for Cooling Controls and Life Cycle Costing

These experiments reveal the substantial energy savings that can be achieved through cooling controls, which must be evaluated against retrofit costs as well as other benefits ranging from spatial churn cost savings to health and productivity. The Siemens/CMU team has selected several ‘tiered’ investment recommendations, from least cost to highest cost, to complete life cycle calculations.

- Task cooling controls
- (individual water based or mixing box/damper air based controls)
- Economizer controls

- Operable window controls for natural ventilation cooling and precooling
- Internal Shading/ Light redirecting blind controls

The costs of these recommendations can vary significantly based on existing technology in the building, variations in the product and labor market, and intentions of the building owner to upgrading their building technologies already. The industry-university team has collected average technology and labor costs for each of these retrofit recommendations given a medium size office of 50,000 square feet on three floors with 250 employees and 5.47 kWh/sf cooling energy use annually.

The life cycle benefits of each of these recommendations have been calculated in three “return on investment” groups to offer a triple bottom line calculation: ‘hard’ economic cost benefits in the first bottom line; environmental cost-benefits that may be legislated or incentivized in the second bottom line; and the human cost-benefits that should drive standards and investments in buildings in the third bottom line.

The economic benefits of each recommendation have been calculated or drawn from the literature. Environmental benefits have been assigned for CO₂, SOX, NOX, particulates and water use savings that accompany electricity energy savings, with values stated on the attached table. The human benefits associated with each recommendation have been drawn from the ongoing work of the Center for Building Performance and Diagnostics to aggregate research linking the quality of buildings to health and productivity outcomes in BIDS: the Building Investment Decision Support Tool.

The energy benefits have been calculated based on:

- defining the lowest ambient temperature at which task heating or task cooling can ensure local satisfaction;
- defining the temperature, humidity and other climate conditions under which daytime natural ventilation cooling can be supported,
- defining the temperature, humidity and other climate conditions under which night time ventilation precooling can be supported.
- façade management strategies for cooling load reduction.

6.5.1 Shift to a broad band of temperatures for all spaces and allow individual control of task cooling

Similar to separating task and ambient lighting delivery with the ceiling providing lower ambient light requirements and an efficient desk lamp or two providing higher task lighting, separating ambient from task cooling conditions can also save energy and increase occupant comfort and performance. This is especially important given the 30-40% of today’s workspaces that are empty at any particular point of the work day, and that 50% of the workplace that is dedicated to support spaces and circulation that could have a less restrictive comfort band.

Raising summer indoor set points by 1 or 2F and providing task cooling for those locations where comfort is critical and occupants are working offers significant opportunity for increasing comfort and reducing energy. Beyond desk fans which do provide a level of convective cooling, task cooling is not a typical technology today. The Intelligent Workplace testbed has two water based task cooling systems – individually valved radiant ceiling panels and individually addressable “paddle coils” or Coolwaves™ a form of chilled beams. The testbed also has one air based task cooling system - desk based mixing boxes from Johnson Control (see Fig 3.20 Personal Environmental Modules™). Similarly, the Canadian Government developed a ceiling based mixing box (Task Air Module) for individual temperature control without compromising ventilation. If an office has a dedicated outside air system (DOAS) with a VAV system dedicated to thermal conditioning alone, individually addressable damper controllers could be introduced at each diffuser for local control of temperature with improved air quality.

Fig 6.20: Johnson Control Personal Environmental Module delivers air conditioning to the individual with mixing box controls for temperature modification

Because there is still no marketplace for task cooling, the cost of PEMS, TAMS and radiant ceilings range from \$600-1000 a workstation. However, individual controls in an automobile (his, hers and the kids in the back) place a \$200 premium per seat on the cost of the car which could be the future for office buildings as well. We could not live without personal control for an hour of commute in the car, yet we continue to have no control for eight hours of concentrated performance in the office.

First Cost	Per sq ft	Per employee
PEM	\$ 4.00	\$ 800
Task Air System	\$ 2.88	\$ 576

The economic benefits include the energy saved by separating ambient and task conditions through the cooling season. This is accomplished by increasing the ambient temperatures 1 and 2F throughout the workplace, minus the energy used by the local cooling devices to lower temperatures in the 70% occupied workstations, that fill 50% of the office (35% total demand for the task cooling). Since hot and cold complaints translate into facility management costs, the second benefit of task cooling is the elimination of these costs calculated at 10% of total FM costs/year.

The environmental savings related to CO₂, SOX, NOX, particulates, and water impacts of energy use are calculated for an electric cooling source.

The human benefits of individual cooling controls include the benefits of thermal comfort for task performance and the benefits of individual control over temperature conditions for both task performance and human health.

Task Ambient Conditioning = Individual Productivity + Energy Savings

A 2009 field experiment conducted at the University of California at Berkley, Zhang et al. identify a 7.4% improvement in logical thinking and a 13.6% improvement in mental performance due to the use of task ambient conditioning systems. Additionally, TAC assisted HVAC systems were found to save 40% energy for wider (18C-30C) dead band and 30% energy for narrower (20C-28C) dead band than the

conventional dead band (21.5C-24C).

Individual temperature control = Individual productivity

In a 1992 multiple building field study of 42 workstations in three Bank of America office buildings in San Francisco, Bauman et al estimate an average 2.8% increase in employee productivity following the installation of Johnson Controls Personal Environmental Modules with individual temperature, air speed, and air direction control, in place of conventional overhead distribution systems.

Individual Temperature Control = Health + Individual Productivity

In a 2002 building case study at a government office building in the Midwestern U.S., Mendell et al identify an average 15.3% decrease in sick building syndrome (SBS) symptoms and an average 4.1% improvement in self-reported productivity for every 1°C decrease in summer indoor temperature from 25.6° to 22.2°C, supporting the need for improved temperature control.

Thermal Comfort = Health + Individual Productivity

In a 2000 field experiment of 30 subjects clothed for thermal neutrality at 22°C in an office laboratory at the Technical University of Denmark, Witterseh et al identify an average 32.7% decrease in eye irritation, 37.0% decrease in nose irritation, 30.6% decrease in throat irritation, 44.9% decrease in headache intensity, and a 7.5% increase in self-estimated productivity among subjects in work environments with thermal acceptability (22°C), as compared to those in warm thermal work environments (26°C).

Individual temperature control = Individual productivity

In a 1996 controlled experiment / meta-analysis study, Wyon identifies that providing individual temperature control over a range of 6°K (10.8°F) results in performance improvements of 2.7% on thinking and decision-making tasks, 7% on typing tasks, and 3.4% on skilled manual tasks.

Balancing the costs and the benefits, a triple bottom line calculation has been completed in the following table. With energy savings alone, the payback for this significant investment in individual control (\$800 for a retrofit) will be 10 years. With energy and environmental savings, the focus of any corporation and agency that has set carbon goals, the payback for this retrofit will be reduced to 9 years . Adding productivity and health benefits, however, shifts the payback to less than one year.

	Total Building investment costs	\$ 200,000	
		Per sq ft	Per employee
	Initial investment costs	\$ 4.00	\$ 800
First Tier Considerations	First year savings:		
	Energy savings	\$0.08	\$15.75
	O & M Savings (FM)	\$.32	\$64.35
	Annual Baseline Savings	\$.40	\$80.10
	ROI (Economic)	10%	
	15 year Net Present Value (Economic only)	\$152,317	
Second Tier Considerations	Annual Energy savings	0.79 kWh	158 kWh
	Associated Air pollution emissions savings	\$0.04	\$7.24
	Associated Water Savings	\$0.003	\$0.63

Third Tier Considerations	Cumulative ROI (Economic + Environment)	11%	
	Cumulative 15 year Net Present Value (Economic + Environment)	\$167,287	
	Annual Health benefits	\$0.92	\$184
	Annual Productivity benefits	\$6.08	\$1,215
	Annual Absenteeism benefits	\$0.57	\$115
	Annual Human Savings	\$7.57	\$1,514
	Cumulative ROI (Economic + Environment + Equity)	200%	
	Cumulative 15 year Net Present Value (Economic + Environment + Equity)	\$3,045,817	

Shifting to a broad band of summer indoor temperatures and providing task cooling will support at least 14.4% energy savings, reduced facility management costs, and improved worker health and productivity, with a ROI of 200%.

6.5.2 Automate an Economizer Cycle and enable Natural Ventilation Cooling

The Energy Information Agency has identified that less than 30% of the US floor area is supported by economizer systems which deliver free cooling and improved air quality through the delivery of higher quantities of outside air in swing seasons (DOE/EIA, 2011). More troubling is the fact that a substantial number of economizers that are installed are not appropriately controlled or maintained for long term performance (Pacific Energy Center, 2000). Yet economizers can deliver substantial free cooling ranging from 5-50% of the cooling load depending on climate and building type, with data centers benefitting the most.

Fig 6.21 Free cooling obtained through Economizer (Pacific Energy Center, 2000)

Every building must have an outside air intake with a damper to ensure code compliance in the delivery of breathing air. However, the use of this damper to deliver higher quantities of outside air for natural

cooling when the outside weather conditions are appropriate (typically ranging from 50° to 75° F with outdoor dew point temperatures below indoor dew point temperatures), requires additional investment. Similar to many ventilation systems, the Intelligent Workplace testbed's outside air damper was manual and set at a 30% fixed air intake rate.

The environmental savings related to CO₂, SOX, NOX, particulates, and water impacts of energy use are calculated for an electric cooling source.

Due to the increased ventilation rates delivered, the human benefits of economizer cooling or natural ventilation cooling are significant. A doubling or tripling of code requirements for outside air measurably reduces headaches, colds, flus, nasal symptoms, coughs, and SBS symptoms (Fisk, Mirer, & Mendell, 2009). In a meta-analysis of 20 ventilation rate studies, Seppanen, Fisk and Lei found that the relative risks of respiratory illnesses were 1.5–2 for higher in low ventilation rate buildings (below 10 L/sec) as compared to high ventilation rate buildings (up to 20 L/sec), alongside a 1.1–6 higher risk of sick building syndrome symptoms in low ventilation rate buildings (Seppanen, Fisk, & Lei, 2006). A number of research findings linking increased ventilation rates with health and productivity outcomes have been used to complete the third bottom line calculation.

Increased outside air / Economizer = Individual productivity (absenteeism savings)

In a 2004 simulation study, Fisk et al identify that implementation of an economizer cycle enables a doubling of outside air ventilation rate with no energy penalty, while also reducing absenteeism by 33%.

Higher Ventilation Rate and Economizer = Health, Productivity, Reduced Absenteeism

In a 2011 simulation and equation based meta-study of office buildings, Fisk et al. identify 15% less SBS symptoms, 0.91% higher work performance, and 2% less absenteeism with increased minimum ventilation rate from 8 to 15 L/s per person. Fisk et al. also identify 25% less SBS symptoms, 1.6% higher work performance, and 14.1% less absenteeism, due to the installation of economizers in the ventilation systems.

Increased outside air = Individual Productivity

In a 2006 meta-analysis of ten previous studies, Seppanen et al identify a 2-3.5 % increase in productivity per 10 l/s-person (20 cfm) increase in outside air ventilation rate, up to 40 L/s-person.

Increased Ventilation Rate = Individual Productivity + Health

In a 1997 meta-analysis study, Fisk and Rosenfeld identify a 10 to 30% reduction in the incidence of respiratory disease, asthma, and allergies and a corresponding reduction in associated health and productivity costs, as a result of improved delivery of outside air through an increased ventilation rate, reduced air recirculation, and improved filtration.

Increased Ventilation Rate = Individual Productivity

In a 2000 controlled experiment, Wargocki et al identify an average 1.7% productivity increase for each two-fold increase in ventilation rate between 3 L/s per person and 30 L/s per person (corresponding to air change rates of 0.6 to 6 per hour) given conventional office pollutant sources.

Increased ventilation rates = decreased SBS symptoms + increased performance

In a 2005 lab experiment at the International Center for Indoor Environment and Energy, Denmark, Seduikyte et al identified a 65% increase in perceived perception of air quality, a reduction in SBS symptoms (eyes irritation 11%, difficulty to think 12%) and a measured 11.5% work productivity increase when increasing the ventilation rate of 3 L/s/p with a pollution source in the room to 20 L/s/p with no pollution source.

Balancing the costs and the benefits, a triple bottom line calculation has been completed in the following table. On the benefit side of the equation, the economic ROI includes the simulated annual energy savings

Advanced, Integrated Control for Building Operations to Achieve 40% Energy Saving

of 17% with economizer cooling. With energy savings alone, the payback for this retrofit will be 6 years. With energy and environmental savings, the focus of any corporation and agency that has set carbon goals, the payback for this retrofit will be 4 years. Adding productivity and health benefits, the payback is in one month.

	Total Building investment costs	\$ 22,500	
		Per sq ft	Per employee
	Initial investment costs	\$ 0.45	\$ 90
Tier First Considerations	First year savings:		
	Energy savings	\$0.08	\$16.41
	ROI (Economic)	18%	
	15 year Net Present Value (Economic only)	\$31,204	
Second Tier Considerations	Energy savings	0.8 kWh	164 kWh
	Air pollution emissions	\$0.04	\$7.54
	Water Savings	\$0. 003	\$0. 66
	Cumulative ROI (Economic + Environment)	27%	
	Cumulative 15 year Net Present Value (Economic + Environment)	\$46,798	
	First year savings:		
Third Tier Considerations	Health benefits	\$0.23	\$45.50
	Productivity increase	\$3.60	\$720.00
	Absenteeism	\$0.54	\$107.87
	Annual Baseline Savings	\$4.37	\$873
	Cumulative ROI (Economic + Environment + Equity)	998%	
	Cumulative 15 year Net Present Value (Economic + Environment + Equity)	\$1,707,501	

Automating the outside air damper to support economizer cooling, or enabling natural ventilation cooling during the swing season can support at least 17% cooling energy savings, and improve indoor air quality for worker health and productivity, with a ROI of 998%.

6.5.3 Introduce Deep Temperature Night Ventilation Pre-cooling

The outdoor air delivery system for meeting ventilation requirements in offices, in addition to operable windows, can also be used at night to pre-cool the building, offering several hours of free cooling the next day. Indeed, allowable outside air temperatures at night could be much cooler than economizer cooling would allow, as long as next day comfort conditions are still met. During the cooling season, night ventilation cooling should be pursued every night that is expected to be cooler than 70F, with outdoor dew point temperatures below indoor dewpoint, outdoor RH <80%, rain less than 0.5 inch/hour, and winds < 6mph. The facility manager and the occupants should pursue the highest air change rate possible, with outdoor air dampers wide open or all windows opened (assuming insect and rain protection are a given).

The cost of deep temperature night cooling is in programming the correct control strategies for the air handlers, and/or automating and controlling windows. The building automation system needs to be able to access predictive weather conditions to anticipate a next day cooling load after a cool evening, but limited to a 65F indoor temperatures. In the Intelligent Workplace testbed, transom windows from Traco were automated by Somfy motors and linked to the Apogee control system, at a cost of \$8/sqft. Additional windows in the IW are manually operable and occupants in the lab collaborated on the implementation of deep temperature night ventilation pre-cooling experiments by opening all windows at night and closing them when returning the next day. One additional investment that the research team is exploring is the introduction of phase change materials in the ceiling tiles to see if longer periods of natural comfort can be achieved the next day.

On the benefit side of the equation, the economic ROI includes the simulated annual energy savings of 10% deep temperature night ventilation pre-cooling. This energy savings is based on scheduling for use on every night below 70F, when next day temperatures will demand cooling, but limited by rain and high winds, as well as minimum set point temperatures by the start of the work day.

The environmental savings related to CO₂, SOX, NOX, particulates, and water impacts of energy use are calculated for an electric cooling source.

Since this is a night-time energy saving strategy, there are no human benefits. As a result, balancing the costs and the benefits yields only a double bottom line calculation shown in the following table.

	Total Building investment costs	\$ 841,477	
		Per sq. ft	Per employee
	Initial investment costs (automated)	\$ 8.14	\$ 1,629
Tier First Considerations	Energy savings	\$0.24	\$48
	ROI (Economic)	3%	
	15 year Net Present Value (Economic only)	\$ 91,531	
	Energy savings	2.41 kWh	481kWh
Second Tier Considerations	Air pollution emissions	\$0.11	\$22
	Water Savings	\$0.001	\$2
	Cumulative ROI	4.4%	

	(Economic + Environment)		
	Cumulative 15 year Net Present Value (Economic + Environment)	\$ 137,273	

Deep Temperature Night Ventilation Pre-cooling will eliminate 23% cooling, based on predictable building flywheel as well as night-time and next day temperatures. If the use of operable windows are to be automated, the combined energy and environmental ROI is 4.4%. If windows are to be opened manually with prompts for the building occupants when nighttime conditions are ideal for night ventilation, the payback for setting up the BAS prompter message will be less than one cooling season.

6.5.4 Control internal blinds to maximize shading while maintaining appropriate daylight levels

Most offices in the US have horizontal venetian blinds which can be manually or electrically controlled to maximize summer shading for cooling energy savings while maintaining appropriate daylight levels for perimeter offices. If new blinds are to be purchased, the ideal blinds would be highly reflective in color and inverted to redistribute daylight to the ceiling plane. The inverted blinds could even have a seasonally “smart” profile that reflects high sun angles back outdoors to reduce solar gain in the cooling season and reflects low sun angles into the space to increase solar gain in the heating season (see Retrosolar™ profile Fig 6.22). Even better are exterior blinds that can be raised, lowered and tilted, though these are rare in the US.

Fig 6.22: Retrosolar Blinds: Retrolux O

The costs of managing blinds for cooling energy savings can vary substantially. Building occupants can be empowered with daily email alerts to lower the blinds and position them at a 90 or 45 degree tilt for shading on warm days. They can be engaged to open them again before cool nights to increase radiant and conductive exchange to the night sky. This has a modest manpower cost of five minutes per person per day, or even less if they are positioned once for the cooling season. On the other hand, existing blinds can be automated with distributed motors linked to building automation systems (wired or wirelessly). While this has a substantial cost of over \$100 per blind, a new generation of motors driven by photovoltaic cells on the surface of the blinds may make this significantly cheaper in the future.

On the benefit side of the equation, the measured data from field experiments of installing blinds on west bay of building has supported simulations of 2.2% annual cooling energy savings possible through blind management. While most offices do not very effectively use daylight as the dominant light source even at

the perimeter, this recommendation is based on algorithms for managing blinds to ensure no less than 200 lux of daylight in the adjacent spaces while maximizing shading.

The environmental savings related to CO₂, SOX, NOX, particulates, and water impacts of energy use are calculated for an electric cooling source.

The human benefits of managing blinds to control solar heat gain are based on two aspects of solar heat – thermal discomfort and glare. Several research studies have shown that productivity goes down when individuals are overheated, and air conditioning often cannot compensate for direct solar gain on the occupant. In addition, glare compromises visual acuity affecting performance and task, and glare contributes to headaches.

Lighting Control = Health

In a 1998 controlled experiment, Aaras et al identify a 27% reduction in the frequency of headaches in computer work when conventional downlighting is replaced by user-controlled suspended indirect-direct lighting (75/25) and venetian blinds are added.

Glare Control = Individual Productivity

In a 2006 two building case study conducted in Sheffield, U.K., Zhang and Altan, identified that occupants were dissatisfied with the environment in a conventional high-rise office block compared to a building designed with natural ventilation and passive strategies. 65.3% of the occupants had glare discomfort in the former building and 57.5% found it difficult to use shading devices. In a separate 1992 lab experiment conducted using 6 female and 20 male subjects, Osterhaus and Bailey found a 3% productivity increase in visual task efficiency by reducing glare discomfort.

Balancing the costs and the benefits, a triple bottom line calculation has been completed in the following table, given the investments for adding manual blinds in a building that has none. Unless there are existing blinds to manage, energy savings will not justify the purchase price, and energy and environmental benefits of electricity reductions will only marginally improve the ROI. However, adding the productivity and health benefits of controlling direct solar gain and glare, the payback is 1-2 years .

	Total Building investment costs	\$ 147,500	
		Per sq ft	Per employee
	Initial investment costs	\$ 2.95	\$ 590
First Tier Considerations	First year savings:		
	Energy savings	\$0.01	\$2.45
	ROI (Economic)	0.42%	
	15 year Net Present Value (Economic only)	\$4,660	
Second Tier Considerations	Energy savings	0.12 kWh	25 kWh
	First year Savings :		
	Air pollution emissions	\$0.01	\$1.13
	Water Savings	\$0.0005	\$0.10
	Cumulative ROI(Economic + Environment)	0.62%	

	Cumulative 15 year Net Present Value (Economic + Environment)	\$6,988	
Third Tier Considerations	First year savings:		
	Health Savings (27% x 73)	\$0.10	\$19.71
	Productivity increase (3% x 35% x 45,000)	\$2.36	\$472.50
	Absenteeism (1% x 1.7% x 45,000)	\$0.04	\$7.65
	Annual Baseline Savings	\$2.50	\$500
	Cumulative ROI (Economic + Environment + Equity)	85%	
	Cumulative 15 year Net Present Value (Economic + Environment + Equity)	\$957,472	

Controlling internal blinds to maximize shading in the cooling season, while maintaining appropriate daylight levels, will eliminate 2.2% cooling and improve health and productivity.

6.6 Conclusions: Controls for 25% Cooling Energy Savings

Of the hypotheses generated at the beginning of the project, the Siemens/CMU team was able to confirm that up to 25% cooling energy savings can be achieved through four major strategies, accounting for redundancies in benefits:

- **Shifting to broad band of thermal comfort for all spaces with task cooling** controls (individual radiant or mixing box/air controls) will eliminate 20% cooling.
- **Economizer and Natural Ventilation Cooling** will eliminate 17% cooling and improve indoor air quality indices.
- **Deep Night ventilation pre-cooling** will eliminate 10% cooling, based on predictable building flywheel as well as night-time and next day temperatures.
- **external and internal shading/light redirection** based on simulation balancing thermal and lighting energy use will eliminate 2 to 5% cooling and 10% lighting.
- **Enthalpy recovery of exhaust air** can eliminate up to 70% cooling energy for the delivery of conditioned ventilation air in the summer (a 10% or less subset of all cooling energy) with the use of an enthalpy recovery wheel (see ventilation chapter).

Chapter 7 Ventilation Controls for 75% Energy Savings

Alongside cooling, ventilation loads in US commercial buildings are growing in response to increased density in the workplace and the elimination of natural ventilation as an alternative. Ventilation loads are 5-8% of the total site energy demand in offices and schools, substantially higher in hospitals where 100% of return air must be exhausted. In addition to the heating and cooling of outside air, dehumidification and fans define ventilation energy demands for meeting the outside air requirements (for breathing air) in buildings.

With DOE ARRA funding, Siemens partnered with Carnegie Mellon University to complete a series of experiments in the Intelligent Workplace living laboratory to quantify the energy savings potential of a number of ventilation system control strategies, combined with Trnsys and Energy Plus simulation for iterative exploration and annual quantification:

1. Enthalpy recovery ventilation
2. Desiccant ventilation
3. Demand controlled ventilation
4. Natural ventilation
5. Integrated air handling units
6. Model predictive controlled ventilation

7.1 Experimental Configuration: Ventilation System Controls hardware and software in the Intelligent Workplace Testbed

The Intelligent Workplace living laboratory for testing the performance and life cycle benefits of innovations in enclosure, mechanical, lighting, networking and interior systems has two ventilation systems, for mechanical and natural ventilation (Fig 7.1):

- A SEMCO air handling unit with a manually controlled outside air intake, an enthalpy recovery wheel, a gas fired desiccant wheel, and an electric heat pump for cooling and heating outside air, with ducted distribution to displacement ventilation and raised floor diffusers; and
- Natural ventilation through manual and automated windows.
- The laboratory also has an Aircuity Optinet™ air quality monitoring system that utilizes nano-tubing to continuously sample air in 15 locations throughout the 7000 square foot facility. By drawing air samples to a central sensor suite, the Optima system supports much higher sensor quality, with annual maintenance, than is affordable or maintainable with multiple distributed sensors (Fig 7.2).

Fig 7.1 IW Mechanical and Natural Ventilation systems layout

Fig 7.2 Aircuity optinet system for continuous air sampling

For the ARRA/ DOE research effort, the existing system was updated with a number of components that are shared with heating and cooling control updates:

- An Apogee Building Automation System was installed with Insight software on a PC server, BacNet enabled, and four underfloor PXC controller boxes plus one in the basement, all native BacNet.
- An increase in sensor density: 9 additional air temperature, humidity, and CO₂ sensors; 42 surface temperature sensors on return water piping from mullions, radiant panels and coolwaves (used for cooling).
- A re-commissioning of the ten-year old SEMCO unit to replace filters, correct enthalpy wheel controls, and clean the desiccant wheel.
- An update of the SEMCO Automated Logic controller to make additional control points available to Apogee through BacNet, including control of the enthalpy and desiccant wheels.
- The CMU team worked continuously with the SCR and SBT teams to support installation of the sensors, actuators and field control panels for the laboratory configuration. The basic control

definition and logic for the four panels was programmed by the SBT engineer, after analysis of the previous Metasys control algorithms

7.2 Hypotheses on Ventilation Controls for Energy Efficiency

The research team developed a series of hypothesis for saving energy in existing office environments for field experimentation:

- **Heat recovery ventilation** will eliminate hh% heating and cc% cooling of ventilation air.
- **Desiccant ventilation for latent load management** and expanded thermal comfort zones at higher temperatures will eliminate vv% ventilation loads, albeit with hh/cc% heating/drying energy costs, and improve IAQ.
- **Occupancy responsive or demand controlled ventilation (DCV)** for targeting ventilation rates to occupied spaces will eliminate vv% ventilation loads and improve IAQ.
- **Natural ventilation** as an alternative to mechanical ventilation whenever outside air is less than 70F WBT will eliminate vv% ventilation loads and cc% cooling loads, with temperature, humidity, rain and wind limiting controls.
- **Integrated air handling unit control** to eliminate vv% ventilation loads
- **Model predictive control to optimize ventilation and thermal conditioning tradeoffs** will eliminate hh/cc% thermal energy.
- Given the capabilities of the Siemens Apogee, SEMCO and natural ventilation infrastructure in the laboratory, a number of ventilation control strategies were evaluated for comparative energy impacts, contributing to the experimental findings that follow.
- Turn on the SEMCO ventilation system whenever indoor CO₂>800 ppm, using 100% outside air.
- Turn on the SEMCO gas fired desiccant wheel whenever indoor humidity >70% and indoor CO₂>800 ppm.
- Turn on the SEMCO heat pump and heat recovery wheel whenever the SEMCO is on and indoor-outdoor temperature differences exceed 25F.
- Turn off all SEMCO components when outside air temperatures <65F (18C) and indoor CO₂<1000 ppm.

7.3 Experimental Approaches to Ventilation Controls for EE

CMU and SCR collaborated to create a full set of control options for field experimentation relative to heating. Recognizing the opportunities and limitations of the IW test bed, the control options included: Ventilation system re-commissioning; Enthalpy recovery ventilation; Desiccant ventilation; Demand controlled ventilation; Natural ventilation; Multiple air handler optimization; and Model predictive controlled ventilation.

Ventilation system re-commissioning was a critical first step to saving ventilation energy. Service was undertaken on the SEMCO air handling unit to resolve inadequate flow rates. Filters were replaced, the desiccant wheel cleaned, the heat recovery wheel cleaned and re-booted, and the BACNET interface re-evaluated. Historic energy use records revealed periods of high gas usage for the desiccant wheel, an indication that the enthalpy wheel was not running. Connecting the Automated Logic through BacNet to Apogee insight allowed for ongoing monitoring of supply and return air flows; of temperatures, gas consumption, and electric consumption for the DX coils (Fig 7.).

Fig 7.3 Apogee control interface for the Semco system

Field measurements of inlet and outlet pressure differentials revealed that filters needed to be changed and the desiccant wheel needed to be cleaned. When compressor outlet pressure was too high it led to shut downs, calling for the development of new set points (Fig 7.4).

Fig 7.4 Fan consumption for different supply flow rates and filter cleanliness

In addition to re-commissioning the unit to perform as built, several improvements were critical. The enthalpy and desiccant on/off switches were not connected to Bacnet, so they needed to be updated. With these changes, the field experiments for ventilation energy savings continued across four seasons in the Intelligent Workplace laboratory.

7.3.1 Enthalpy recovery ventilation

Since the dominant energy costs for ventilation is heating and cooling of outside air to meet indoor comfort standards, investments in heat recovery or enthalpy recovery wheels are economically beneficial (Fig 7.). Heat recovery wheels capture the sensible energy from exhaust air (warm or cool air) to preheat or precool the outside air, minimizing the need for auxiliary heating or cooling of the ventilation air

stream. Enthalpy recovery wheels, as installed in the IW test bed, capture both the sensible and the latent energy (energy trapped in the moisture) for even greater heating and cooling energy savings.

Fig 7.5 Enthalpy Recovery Wheel: Sensible Heat Recovery

The SEMCO unit in the Intelligent Workplace has an integral enthalpy recovery wheel that was the subject of two PhD dissertations (see references). These efforts have been able to definitively demonstrate that simulated energy savings accurately reflect field measured energy savings, at close to 78% total energy savings for heating and cooling of ventilation air (Fig 7.).

Fig 7.6 Enthalpy Recovery Wheel: Measurements compared to Simulation

Using trended hourly operational data from 2006, the performance of an enthalpy recovery wheel can be projected to medium size office buildings through Energy Plus simulation. As illustrated in blue in Fig 7., without the enthalpy recovery wheel, ventilation air needs to be fully conditioned to comfortable temperatures in both winter and summer, at significant energy expense. On the other hand, if thermal energy can be captured from the exhaust air by using an enthalpy recovery wheel, at considerable energy savings, as shown in red.

Fig 7.7 Heating/cooling energy consumption for ventilation air with and without an Enthalpy Recovery Wheel in the Intelligent Workplace in Pittsburgh

Using Energy Plus simulation, the trended hourly data is further summarized into months, with any missing data made up with the average of the data in the same month.

Fig 7.8 Monthly ventilation energy use with and without enthalpy wheel, Pittsburgh

Critical ventilation control finding #1: Enthalpy Recovery Ventilation can eliminate 76.5% of the heating energy and 78.5% of the cooling energy for ventilation air.

7.3.2 Desiccant ventilation

In environments with heat and high humidity, ventilation systems must not reduce the temperature of the air in summer months, it must reduce the humidity or moisture content significantly. Most ventilation systems reduce the moisture content by over cooling the air to reach dew-point so that the humidity “rains” out of the air, and then reheat the air to acceptable delivery temperatures. An active desiccant wheel dries the air through absorption and then dries the wet wheel by rotating it into an exhaust air stream with some heat added (Fig 7.9 Illustration of desiccant ventilation unit). The energy savings through desiccant air handlers is determined by the depth of the dehumidification needed by the space and the final supply air temperatures needed for cooling.

Fig 7.9 Illustration of desiccant ventilation unit

In the Intelligent Workplace laboratory, the CMU team has undertaken long term data gathering on the performance of the desiccant air handler (Fig 7.). Measured data has supported the development of performance algorithms that can now be used in an Energy Plus simulation of a more typical 50,000 square foot office building in our climate region.

Fig 7.10 Simulated and tested energy efficiency of an active desiccant unit

The trended data of the desiccant wheel unit performance in 2006 is applied in comparing a conventional DX plus reheat unit for ventilation delivery to an active desiccant ventilation system. The comparison is made for the months from June to September when cooling and dehumidification of ventilation air are both necessary.

In the simulation, the following assumptions were made regarding the conventional cooling-only system:

- The primary air is cooled well below the desired supply air temperature to deliver the same supply air humidity as a desiccant wheel system (12.7°C).
- The dry, cold air is reheated to acceptable supply air temperatures for avoiding drafts and thermal discomfort (16.8°C).

Simulations for both the Conventional DX + Reheat System and the Active Desiccant Wheel System were based on 2006 trended summer data from May to September. The conventional system simulation, Fig 7., reveals that the reheat penalty for super cooling outside air as an approach to humidification costs a constant 5-10kW of reheat to deliver acceptable supply air temperatures.

Fig 7.11 Additional cooling and reheat energy consumption for dehumidification with a conventional DX ventilation unit, Pittsburgh

At the same time, there is also a penalty with a desiccant unit since dehumidification raises the outside air temperature further and recooling is needed. The desiccant system simulation, Fig 7.12 , reveals that the additional cooling penalty for outside air is a variable from 0 -10kW.

Fig 7.12 Cooling and recooling energy consumption with a desiccant unit

The cumulative energy costs of the two systems in Pittsburgh, however, reveal that the additional cooling penalty of the desiccant wheel (first red bar) is substantially less than the electric reheat penalty of the conventional DX ventilation system (second red bar). For DOE Climate Region 4, the field experimental data and annual simulation show a 7% reduction in ventilation loads due to the use of a desiccant wheel. These energy savings will grow wherever there are greater ventilation demands or higher humidity conditions.

Fig 7.13 Total energy consumption comparison in 2006, Pittsburgh

In addition to the direct energy savings when using an active desiccant wheel for dehumidification, there is the major advantage of enabling water based cooling without condensation. The dry air provided by the SEMCO unit is critical for the use of radiant ceilings, coolwaves™, and façade cooling with water mullions. Water is a significantly more efficient medium for thermal conditioning, with thermal energy

savings typically between 15 to 20% (John Dieckmann, Kurt W. Roth, and James Brodrick, Radiant Ceiling Cooling, ASHRAE Journal. 2004, pp: 42-43).

Critical ventilation control finding #2: In hot humid climates, control the desiccant air handler for a minimum of 7% savings on ventilation energy.

7.3.3 Demand controlled ventilation

With the use of CO₂ sensors to evaluate ventilation demands, demand controlled ventilation reduces outdoor air delivery in spaces that are unoccupied, but supports increased ventilation in response to local demand. By predominantly relying on natural ventilation and infiltration during the swing and cold seasons, the Intelligent Workplace laboratory uses CO₂ sensors to trigger demand controlled ventilation shifting from natural to mechanical ventilation. The energy benefits of natural ventilation for a majority of months will be discussed in the next section. However, for deeper buildings that cannot rely on infiltration and natural ventilation, demand controlled ventilation (DCV) offers measurable energy savings at modest first cost.

To provide a quantitative analysis of the energy saving potential of demand controlled ventilation, EnergyPlus simulations were used with DOE baseline medium sized office buildings (http://www1.eere.energy.gov/buildings/commercial_initiative/after_1980.html). This baseline building has a VAV system fed by a gas furnace as well as electric reheat, a packaged air conditioner and variable fan controls. While all simulation assumptions are held constant (Table 7.1), the occupant density and hours with consequent ventilation requirements are variable.

Table 7.1 The zone summary

Zone Name	Area (m ²)	Volume (m ³)	Floor-to-Ceiling Height (m)	Gross Wall Area (m ²)	Window Glass Area (m ²)	People (m ² /per)	People	Lights (W/m ²)	and Process (W/m ²)	SWH (L/h)	(L/s/Person)	Ventilation Total (L/s)	Infiltration (ACH)
Perimeter_bot_ZN_3	207	569	2.74	137	65	18.58	11.16	10.76	10.76		10.00	111.59	0.26
Perimeter_bot_ZN_2	131	360	2.74	91	44	18.58	7.06	10.76	10.76		10.00	70.64	0.28
Perimeter_bot_ZN_1	207	569	2.74	137	65	18.58	11.16	10.76	10.76		10.00	111.59	0.26
Perimeter_bot_ZN_4	131	360	2.74	91	44	18.58	7.06	10.76	10.76		10.00	70.64	0.28
Core_bottom	984	2,698	2.74	0	0	18.58	52.93	10.76	10.76	37.5	10.00	529.34	0.00
Perimeter_mid_ZN_3	207	569	2.74	137	65	18.58	11.16	10.76	10.76		10.00	111.59	0.26
Perimeter_mid_ZN_2	131	360	2.74	91	44	18.58	7.06	10.76	10.76		10.00	70.64	0.28
Perimeter_mid_ZN_1	207	569	2.74	137	65	18.58	11.16	10.76	10.76		10.00	111.59	0.26
Perimeter_mid_ZN_4	131	360	2.74	91	44	18.58	7.06	10.76	10.76		10.00	70.64	0.28

Core_mid	984	2,698	2.74	0	0	18.58	52.93	10.76	10.76	37.5	10.00	529.34	0.00
Perimeter_top_ZN_3	207	569	2.74	137	65	18.58	11.16	10.76	10.76		10.00	111.59	0.26
Perimeter_top_ZN_2	131	360	2.74	91	44	18.58	7.06	10.76	10.76		10.00	70.64	0.28
Perimeter_top_ZN_1	207	569	2.74	137	65	18.58	11.16	10.76	10.76		10.00	111.59	0.26
Perimeter_top_ZN_4	131	360	2.74	91	44	18.58	7.06	10.76	10.76		10.00	70.64	0.28
Core_top	984	2,698	2.74	0	0	18.58	52.93	10.76	10.76	37.5	10.00	529.34	0.00
Firstfloor_plenum	1661	2,025	1.22	203									0.11
Midfloor_plenum	1661	2,025	1.22	203									0.11
Topfloor_plenum	1661	2,025	1.22	203									1.00
Total Conditioned Zones	4,982	19,741		1,978	653		268						
Data Source						1		2	4	4	3	3	4
Sources													

A two week simulation with these assumptions reveal 18% less electricity for cooling (105 kWh) and 150% less gas for heating (1.8 kWh) of cumulative ventilation energy consumption given 15 minute intervals (Fig 7.14).

Fig 7.14 Energy consumption comparison with different OA intake control

Compared to conventional ventilation systems, the full annual simulation reveals that demand control ventilation generates the most energy savings in the heating season (Fig 7.15), moderate savings in the cooling season (Fig 7.16), and occasional savings in swing seasons.

Fig 7.15 33% Monthly heating energy savings through DCV

Fig 7.16 5.7% Monthly cooling energy savings through DCV

While energy savings help to justify the investment in sensors and controllers for demand controlled ventilation, indoor air quality gains are even more compelling. In many office buildings, fresh air delivery does not always meet code, as indicated by the measured CO₂ levels that the CBPD team has found in federal workplaces across the US (reference NEAT).

DOE has identified that CO₂ is an effective indicator of poor and good air quality (), and thereby can be an effective driver for increased ventilation.

Fig 7.17 Relationship between CO2 and ventilation rates (From DOE Demand-Controlled Ventilation Using CO2 Sensors)

Demand Controlled Ventilation increases ventilation rates in those spaces at those times when CO2 exceeds thresholds of 800-1200 ppm. This helps to ensure that ventilation air delivery meets or exceeds code. The value of increased ventilation air for human health and productivity will be further discussed in the cost-benefit section of this chapter.

Critical ventilation control finding #3: Introduce local ventilation sensors and controls to support occupancy responsive demand controlled ventilation for 33% heating and 5.7% cooling energy savings (11% total) while improving indoor air quality in occupied spaces.

7.3.4 Natural ventilation

While most new offices do not have operable windows, almost all building built before 1950 had windows that open to provide all or most of the ventilation requirements in offices, classrooms, hotels, etc. In winter periods, the windows could remain closed while still delivering adequate ventilation through infiltration, with temperature differentials driving higher infiltration rates. In swing and summer periods, the windows were often open as the only cooling system thus ensuring adequate ventilation rates even without the thermal differentials. Unless it is a very deep building, a very tight building, or a windowless building, there is no reason the modern commercial building cannot utilize natural ventilation and infiltration as the dominant ventilation source during the cool and cold months.

The IW has been operated on full mechanical conditioning with 30% fixed outside air rates, and on full natural ventilation with the air handlers turned off while water based heating is available. Aircurity sensors reveal the variability in CO2 during these periods without forced ventilation, as occupancy loads in offices and conference rooms fluctuate. In general CO2 levels are less than 100 ppm above outdoor conditions (450-550 ppm outdoors) and only with high density does CO2 approach the recommended highs of 1100 ppm (which would be used to drive demand controlled ventilation).

Fig 7.18 Passive Ventilation through infiltration alone in winter in an office and in the large conference room

Combining measured data with simulation, the reduction in ventilation energy use would reach 70% if every day that temperatures are below 60F would be ventilated by infiltration with the air handling unit turned off. This could be stretched to 70F if humidity is below 60% and occupants are prompted to open windows to ensure adequate air exchange without the thermo-siphoning driver of indoor-outdoor temperature differences.

Critical ventilation control finding #4: In narrower buildings designed at one time for natural ventilation, shut off air handlers whenever temperatures drop below 60F and rely on infiltration for meeting ventilation demands. If windows are still operable, rely on opening windows for ventilation up to 70F as long as outdoor dewpoint is below indoor or humidity is below 80%.

7.3.5 Integrated Air Handling Units

Most commercial office buildings run multiple air handlers often divided between perimeter and core occupied areas. The core open spaces may be high density, high equipment and lighting heat gain with no enclosure losses, while the perimeter zones may have low occupancy densities and substantial enclosure heat loss. Control innovations that integrate the operation of air handling units can both utilize internal heat gain as a free perimeter heat source in winter, and minimize sensible and latent load coupling during partial load conditions.

While the Intelligent Workplace does not have multiple air handlers, Yuebin Yu et al. (2012a, 2012b) developed and tested the synergization of multiple air handling units in an office building in Nebraska, with multiple publications to capture the methodology and findings.

Fig 7.19 Case building information for IAHU operation

The only investment for integrated air handling unit controls (IAHU) is the building automation system. The building automation system negotiates between the two or more air handlers to reallocate the outdoor air intake and redistribute the ventilation air based on shared thermal and ventilation loads. It solves two challenges in conventional AHU operation:

- The utilization of internal heat gain in winter is no longer limited. Compared to those of earlier times, modern office buildings have higher internal heat gains since more electricity-powered equipment is employed, such as computers, copy machines, printers, and even small data servers. By analyzing a hypothetical multistory office building, it is found that, if the internal heat gain can be fully transferred and utilized, no external heat source is needed for this virtual building during the occupied periods when the outside air temperature is at or above -5°C (23°F).
- The sensible and latent coil load no longer need to adversely couple in some partial load conditions. Moisture load in office buildings mainly comes from the outside air intake, either the mechanical ventilation or unorganized outside air infiltration. To maintain indoor thermal comfort, the working condition of the cooling coil needs to satisfy the bigger one of the sensible load and the latent load. In transition seasons, when the space has low sensible cooling load, the conventional cooling and dehumidification operation could cause huge terminal reheat and waste energy.

Fig 7.20 Integrated Air Handling Units Simulation Parameters

Fig 7.21 Integrated Air Handling Units Control Logic

Based on mass conservation, the operational strategy will improve the energy performance while maintaining the air quality in both zones. The simulation results based on all outdoor air temperature variations are included in Fig 7..

Fig 7.22 Comparison of energy consumption and savings against the outside air temperature

The thermal energy consumption of normal AHU and IAHU, and the energy savings are plot against the OA temperature for this given building. As shown in the Fig, when the OA temperature is below 10°C (50°F) degree, the IAHU energy saving capability gradually increases first and then decreases as the temperature drops. This is because the OA intake gradually decreases when the interior region slides in free cooling mode. The amount of OA intake from VAHU_i satisfies both the interior region thermal load and the building overall ventilation requirement at high and free cooling temperature. When the OA temperature keeps dropping until below a turning point, i.e., roughly -5°C (23°F) degree, a supplementary OA intake from the exterior region VAHU_e is needed, and gradually increases in quantity to satisfy the overall building IAQ. The energy savings still exist but decrease along with the OA temperature thereafter.

Another temperature band with great energy savings is between 12.7°C (55°F) and 25°C (77°F) when the partial load is most likely to happen. The savings are mainly from the coil load decoupling operation. The stream of dehumidified cold air from the AHUs in normal operation has to be reheated up before it is distributed into the space when the partial load mode drops below the threshold of the system. A great amount of energy is saved by converting the normal operation AHUs into IAHU.

The impact on month by month thermal loads for ventilation are shown in the following Fig 7.23 and Fig 7. and summarized for the variety of climate conditions in Fig 7..

Fig 7.23 23.4% heating energy savings through IAHU operation

Fig 7.24 5.4% cooling energy savings through IAHU operation

Fig 7.25 Thermal energy performance comparison in different scenarios

The dynamic operation strategy is categorized based on the relationship of the indoor and outdoor air temperature, and indoor and outdoor enthalpy as listed in Fig. 7.21. The simulation results in Fig 7. show that, while the operations consume most energy in scenario A and D/E, the opportunity of improving energy efficiency for the scenarios is also obvious. The normal operation in scenario A consumes about 25% more thermal energy than that of IAHU. About 110,000kWh (375MMBTU) thermal heating could be saved in this scenario, as plot in Fig 7.. While the accumulative energy savings in scenario B is small due to the short duration, it has high hourly energy savings (92 kWh/hr). The energy savings of applying IAHU can be much higher in a climate where B has longer duration. The savings in scenario D/E come from the coil latent and sensible load decoupling operation. IAHU consumes about 50,000kWh (171MMBTU) less thermal energy than the normal operation by decoupling the sensible and latent load.

Fig 7.26 Thermal energy savings in scenarios

In the four scenarios shown in Fig 7., condition B has the highest hourly saving potential, followed by condition A and then D/E. Since condition C has identical operation as normal AHUs, it does not yield any energy savings. By utilizing IAHU, the total thermal energy savings in this case building is 176,000kWh (600MMBTU), accounting for about 10% of the total thermal energy consumption. The hourly thermal savings reach 55kWh (187MBTU). The savings equal to around 11kWh/m² year (3.5MBTU/ft² year) on the annual energy use intensity. Among the total annual savings in all the scenarios, roughly 80% are saved as thermal energy for heating (or reheating) purpose. While heating in many office buildings is directly provided by steam, gas combustion or electricity, the energy saving effect of using IAHU on heating is conspicuous. As an advance control on the secondary system, IAHU can be implemented during energy conservation optimization process to improve the energy efficiency higher than the designed. In addition to the simulation-based validation, a further evaluation through real implementation in office buildings is valuable. Moreover, the performance of IAHU, including the energy savings, indoor air distribution, and so forth, in various climates and with different space layouts deserves more investigation. The research is ongoing and the results will be reported in the near future.

Critical ventilation control finding #5: In conventional office buildings with separate perimeter and core air handlers, introduce Integrated Air Handling Unit (IAHU) control to eliminate 10% of the ventilation air thermal loads.

7.3.6 Ongoing research: Model Predictive Controllers for Integrated Energy Recovery Desiccant Ventilation and Thermal Conditioning Systems

Research continues on the development of a model predictive controller for the optimization of the SEMCO system which balances ventilation, heat recovery, desiccant and thermal conditioning. Several scenarios have been developed to investigate the performance of classical MPC for the three components in the hybrid ventilation unit. The nonlinear models are linearized around the operating points to form the internal linear model for future dynamic prediction. The following points are identified in the study:

- The MPC controllers on the enthalpy recovery unit and vapor compression unit have good disturbance rejection capability. The system response to the step changes on the inputs and the set points with acceptable stability.
- The MPC controller on the enthalpy recovery wheel can integrate the algorithm to maximize the use of free cooling air when the outdoor air is favorable and minimize the outdoor air intake for ventilation only when the its adverse to the air-conditioning mode.
- The MPC controller on the vapor compression unit can effectively coordinate the multiple inputs and multiple outputs for a given set point. A tuning on the weights can guide the unit toward a higher energy efficiency for a given load.
- The MPC controller on the active desiccant wheel can manipulate the heat input and regeneration air flow to follow the humidity set point for most of the time and avoid large penalty on the unwanted heat.

The simulation results have been analyzed in terms of the energy consumption, thermal comfort, and simulation duration for each of the scenarios. With the proposed Wiener and Hammerstein-Wiener nonlinear MPC, the space thermal conditioning system can be controlled toward minimum energy consumption, track a desired thermal comfort condition, and handle the nonlinearity involved in the system. The rejection capability on the unmeasured disturbances from the infiltration, internal heat gains, etc., is acceptable. The controller can proactively guide the system transit from unoccupied condition to occupied condition in an energy conservative manner. The computational cost of the simplified approach is low which makes it suitable for online implementation in conventional building systems for space thermal conditioning. This effort has been further discussed in detail in Yuebin Yu's PhD thesis.

Fig 7. illustrates the base structure of the hybrid ventilation unit. There are five variable speed drives (VFDs) installed, four of them modulate fans' speed and one modulates the compressor speed. The enthalpy recovery wheel and the active desiccant wheel are equipped with speed-adjustable motors. A gas burner is fed with natural gas through a modulating valve to control the regeneration air temperature. The binary points provided by the manufacturer include: system on/off, supply fan on/off, compressor on/off, compressor VFD status, condenser fan status, condenser fan VFD status, regeneration fan on/off, and burner power on/off. The airflow, temperature, dew point, relative humidity and enthalpy of the outdoor air, return air, air entering the coil, air leaving the coil, etc., are monitored through the manufacturer control panel.

Fig 7.27 Illustration of the hybrid ventilation unit

The decentralized structure has better reliability since the computational load is divided into three. Another approach can be one MPC for the whole unit as shown in Fig 7.. The computation load is higher with more manipulated variables and constraints. The tuning effort for the centralized MPC control is also higher. The benefit of using a distributed MPC structure is more obvious when the equipment complexity grows.

Fig 7.28 MPC architecture- example 1

Fig 7.29 MPC architecture- example 2

Evaluation of MPC control over the hybrid ventilation unit is based on the weather data trended in 2006. Fig 7.30 plots the weather data by minutes. The unit was newly installed in 2006. The space air temperature and supply air temperature are plot in Fig 7.. Part of the trended data is used as the default set points in the study of MPC control. To increase the variation of disturbances and investigate the performance of the MPCs, the trended data are mapped from seconds to minutes. More fluctuation of the external and internal air conditions present in the study.

Fig 7.30 Trended outdoor air temperature in 2006

Fig 7.31 Room air and supply air temperature

Take the enthalpy recovery wheel (ERV) as an example for the performance comparison. It is desired that control of the outdoor air processing unit can bring in more outdoor air when the space is in cooling mode, and modulate properly the intake when the outdoor air condition is favorable to maximize the free cooling benefit. When the outdoor air is warm, the outdoor air intake should be reduced to the minimum. To investigate the control of MPC, a time slot is picked with large variation. As shown in Fig 7., the outdoor air temperature fluctuates between 284 K to 302 K and the outdoor air humidity is around 5 g/kg for most of the time. A dynamic linearization or weighting adjustment is needed to ensure the linear model represents the original nonlinear model well and the MPC functions properly, due to the following three different modes in the time period as marked in Fig 7.:

- For the initial time period, condition "a" in Fig. 7.22, the outdoor air temperature and the return air temperature are close to each other and also the set point;
- For condition "b", the outdoor air temperature is lower than the set point while the return air temperature is higher than the supply air temperature set point;
- For condition "c", both the return air and the outdoor air temperature are higher than the supply air temperature set point.

For condition "a" and with space in cooling mode, maximum outdoor air intake shall be encouraged since the outdoor air is favorable. For condition "b", a modulation is probably needed to maintain the supply air temperature set point. For condition "c", a minimum outdoor air intake is considered to avoid penalty since the outdoor air temperature is higher than the return air temperature.

Fig 7.32 Disturbance conditions

Fig 7.33 ERV manipulated variables in swing season

Fig 7.34 ERV air temperature control in swing season

Fig 7.35 ERV air temperature tracking zoom in, ERV- 4

Fig 7.36 ERV air humidity control in swing season, ERV- 4

With the MPC, a conditionally consecutive linearization and dynamic weighting are used to accommodate the large switches. When the outdoor air temperature is lower than the return air temperature, the system is linearized around the operation point. The supply air temperature gets a weight as 1. To prevent the unit from over-tuning, a weight of 0.5 is imposed on the outdoor air intake modulation rate. When the outdoor air temperature changes to be higher than the room air temperature and the supply air temperature set point, a weight as 1 is added to the outdoor air intake and the supply air temperature output. The simulation results are plotted in Fig 7. to Fig 7..

It is shown in Fig 7. that the outdoor air intake is kept to maximum when the outdoor air temperature is lower than the return air temperature and close to the supply air temperature. An economizer with maximum outdoor air intake is achieved. When the outdoor air temperature drops to be lower than the supply air temperature, a modulation action is taken by the MPC. From Fig 7. and Fig 7., it can be seen that the supply air temperature is controlled to 290 K as the set point. This strategy is similar to free cooling operation as in rule-based control. 290 K is selected to prevent over-cooling of the space and it is adjustable if more free-cooling is desired. When the outdoor air rises to be higher than the return air temperature, it is a typical cooling season and a minimum outdoor air intake is desired. As illustrated in Fig 7., MPC reduces the outdoor air intake to the minimum and turns the ERV rotation speed to full to recycle the heat. The warm outdoor air intake is cooled down to close to the return air temperature. The outdoor humidity set point is not weighed since the outdoor air in the season is mild or dry. Dehumidification is not a concern with temperature control dominating.

For space thermal conditioning, to gain the maximum benefit of using MPC and reduce the modeling and model maintenance efforts, a linear approach has been pursued, using the Wiener-Hammerstein structure. The conceptual structure is given in Fig 7. and Fig 7..

Fig 7.37 Illustration of Hammerstein-Wiener nonlinear model

Fig 7.38 Pure linear classical MPC for building systems

As shown in Fig 7.59, two heat fluxes from the terminals are the direct inputs to the air nodes. The outdoor air temperature, boundary surface temperature, and solar radiation heat flux are the external inputs that affect the space temperature through the construction surfaces. In addition, the sensible heat gain, latent heat gain, infiltration air flow rates, etc., are the disturbances to the system. The indoor air temperature and average air humidity are the direct outputs from the LTI space system.

Fig 7.5 : Illustration of the variables in HW nonlinear MPC

Fig 7.40 Outdoor air condition and solar radiation

Fig 7.40 plots the outdoor air temperature, relative humidity, solar radiation to the two rooms. The outdoor air fluctuates between 2°C to 18°C during the simulation period, which represents a typical winter.

In the nonlinear HW-MPC, water flow rates to the space terminals are considered as the manipulated variables for the space thermal conditioning. Instead, the supply water temperature may be regarded as one manipulated variable if the whole space is treated as one zone. With the two-zone space layout, the total number of manipulated variables is two for each control time interval. In the prediction horizon, e.g. 100 minutes, twenty variables in total needs to be determined by the MPC controller. The input constraints are the minimum and maximum water flow rates. With 10 to 20 minutes as one control horizon, which is long enough to achieve a stable water distribution among the terminals, the water flow changing rates are not constrained.

The following scenarios in Table 7.2 are considered in this study to evaluate the performance of classical MPC and proposed HW nonlinear MPC for the hydronic system. The MPC objectives are selected as the room air temperature, thermal comfort, and energy consumption respectively. The simulations are conducted for five days in the heating season. The control horizon for the study of the space is 1 and the prediction horizon is 10 unless otherwise declared. Results are plotted and analyzed in next section. Both Scenarios SC-1 and SC-1' are temperature set point oriented control.

Table 7.2 Control scenarios for classical MPC and HW nonlinear MPC

Scenario	Problem description
SC-1	Classical MPC, direct heat flux inputs, temperature oriented control. 24/7 schedule.
SC-1'	Classical MPC, direct heat flux inputs, temperature oriented control. Office

	schedule.
SC-2	Wiener nonlinear MPC, thermal comfort oriented control.
SC-3	Wiener nonlinear MPC, energy consumption and thermal comfort oriented control. Thermal comfort serves as constraints, $PMV = [-0.5, 0.5]$.
SC-4	HW nonlinear MPC, thermal comfort oriented control.
SC-5	HW nonlinear MPC, energy consumption and thermal comfort oriented control. Thermal comfort serves as constraints, $PMV = [-0.5, 0.5]$.
SC-6-1	As case 5, with variable occupancy schedule. When unoccupied, $PMV = [-3, 3]$; when occupied, $PMV = [-0.5, 0.5]$. Band control.
SC-6-2	As case 6-1, dynamic constraints based on outdoor air temperature.
SC-7	As case 4, with variable occupancy schedule and full look-ahead ability. When unoccupied, $PMV = [-3, 3]$; when occupied, $PMV = 0$.

The simulation results in terms of the energy consumption, thermal comfort, and simulation duration for the scenarios are collected in Table 7.3. In addition to the simulation duration and energy savings, an additional index based on PMV value in the occupied hours is also included. We assume -0.5 should be adopted in winter, the results show that the higher the mean PMV value, the lower the energy savings. Scenario SC-6-1 stands out since cool morning hours happen which is not acceptable. With a 24/7 schedule, comfort oriented MPC control in the test bed can bring in from 6 to 36 percent energy savings. With an office schedule, comfort oriented MPC control can offer from 7 to 41.6 percent energy savings.

Table 7.3 Comparison of energy consumption, thermal comfort, and simulation duration

Case number	Heating Energy Consumption (kWh)	Mean (PMV+0.5) in Occupied Hours	Energy Savings (%)	Simulation Duration (s)
SC-1	3091.7	0.72	0	36.1
SC-2, 4	2895	0.56	6	76.9 - 78.1
SC-3, 5	1977	0	36.1	175.8 - 198.1
SC-1'	1941	0.69	0	40.6
SC-6-1	840.8	-0.25	56.7	187.4
SC-6-2	1134	0.01	41.6	205.3
SC-7	1800	0.51	7	460

With the study, the following points can be concluded about the proposed MPC:

- The space thermal conditioning system can be controlled toward a minimum energy consumption condition, tracking a desired thermal comfort condition, and handling the nonlinearity involved in the system. Thermal comfort in a band offers more energy savings than a fixed thermal comfort reference approach;

- The rejection capability on the unmeasured disturbances from the infiltration, internal heat gains, etc., is acceptable. The controller can proactively guide the system transit from unoccupied condition to occupied condition in an energy conservative manner;
- Dynamic look-ahead on both the set points and the weights improves the overall performance since the future information is utilized for the preparation of a building system where the time scale is of hours level;
- The computational cost of the simplified approach with linear MPC as the core is low which makes it suitable for online implementation in conventional building systems for space thermal conditioning. All the scenarios for one week control can be accomplished in less than eight minutes;
- By applying thermal comfort oriented control, in a 24/7 schedule condition, an MPC helps acquire about six to thirty six percent of energy savings. In an office schedule condition, about seven to forty two percent of energy may be saved by using MPC empowered thermal comfort control.

Critical ventilation control finding #6: Building systems are naturally multiple-input and multiple-output system. Energy savings and thermal comfort are the two reasons for deploying a control system. Model based predictive control can offer the benefits of utilizing system models and future information into the control. The life span might also be included in the local equipment control with MPC. With an office schedule, comfort oriented MPC control can offer from 7 to 41.6 percent energy savings.

7.4 Conclusions

The Siemens/CMU team was able to confirm the following hypothesis for saving ventilation energy in existing office environments through field experimentation. The impacts are calculated independently and would not be directly additive.

- **Heat recovery ventilation** will eliminate 76.5% heating and 78.5% cooling of ventilation air.
- **Desiccant ventilation for latent load management** and expanded thermal comfort zones at higher temperatures will eliminate 7% ventilation loads, albeit with 15%-20% heating/drying energy costs, and improve IAQ.
- **Occupancy responsive or demand controlled ventilation (DCV)** for targeting ventilation rates to occupied spaces will eliminate 11% ventilation loads and improve IAQ.
- **Natural ventilation** as an alternative to mechanical ventilation whenever outside air is less than 70F WBT will eliminate 70% ventilation loads and 15% cooling loads, with temperature, humidity, rain and wind limiting controls.
- **Integrated air handling unit control** to eliminate 10% ventilation loads
- **Model predictive control to optimize ventilation and thermal conditioning tradeoffs** will eliminate 7-42% thermal energy.

Chapter 8 Software Products Commercialization Plan and Technology Transfer

The major product concept has been identified from this research project is Smart Energy Box. The Smart Energy Box (SEB) is a product concept for an integrated platform for commercial building automation dealing with advanced energy aspects of a building. It intelligently integrates with building management system and takes collective decisions of load management continuously without losing occupancy comfort.

The key aspects of SEB product concept are as follows

- Supporting of industry standard protocols to communicate with building devices
- Real-time Weather forecast
- Central Load Control
- Embedded simulation engine based on Energy Plus
- Advanced visualization for both occupants and building operators
- Collaborative energy management and control

8.1 Key features

The following key features have been demonstrated as part of the Smart Energy Box.

Intelligent integration with Building Management System

SEB can integrate smartly with any building management systems that support industry standard protocols such as i.e. BACnet, Modbus. It also supports SOAP based access for Siemens Apogee system. However the system is designed in such a way that it can adapt any other standard protocols easily. This adaptation can be done either by the Siemens or by the user with developing new SEB pluggable component dealing with that protocol.

Weather Forecast

SEB brings real-time weather forecast from weather data providers such as NOAA, which is used for load forecast based on Energy Simulation.

Control Strategy Evaluation

SEB evaluates building energy strategies using energy simulation. Energy simulation is performed by EnergyPlus. EnergyPlus is an energy analysis and thermal load simulation program. Based on a user's description of a building from the perspective of the building's physical make-up and associated mechanical and other systems, EnergyPlus calculates heating and cooling loads necessary to maintain thermal control setpoints, conditions throughout a secondary HVAC system and coil loads, and the energy consumption of primary plant equipment. Simultaneous integration of these—and many other—details verify that the EnergyPlus simulation performs as would the real building.¹

¹ Energy Plus Energy Simulation Software,
http://apps1.eere.energy.gov/buildings/energyplus/energyplus_about.cfm

Grid Gateway

SEB acts as building to grid gateway. On receiving real time price signal from utility provider, it starts planning load shaping. If there is enough time to evaluate building thermal situation with real-time weather forecast, then it performs energy simulation and selects best strategy suitable for the given weather forecast. Otherwise it starts planning all non thermal intensive loads shedding such as lighting, plug loads. SEB supports Open ADR protocol for demand response communication.

Central Load Control

Central load control is being taken care centrally by the SEB, which especially controlling HVAC, Central lighting or any other equipment that can access centrally using standard building device protocols

Configuration and Maintenance

Building owner can monitor and configure settings using a rich user interface that accesses the SEB data using a SEB web service.

Collaborative Energy Management and Control

A special SEB control module that allows interactive communications among occupants, facility managers and building control systems with advanced human machine interfaces (HMI) based on the latest visualization and social network technology.

8.2 Market Requirements

Based on the above design concepts, an initial set of marketing requirements for the Smart Energy Box could be established as shown in the table below.

<i>Title</i>	<i>Description</i>
SEB network and communication connection to be IT friendly	SEB connection to be "IT friendly". It is acceptable to have dedicated connection to be established and secured by client IT department if they agree. Preferably connection can be normal IT connection where client IT department does not have to create and secure a dedicated port.
SEB Application Guides	Site enablement guide to be developed for enabling Siemens and third party sites for developing and implementing advanced building control strategy. The guide can be released in stages to support incremental SEB Box features.
SEB to incorporate runtime energy strategy engine for various building systems, including but not limited to HVAC system	SEB to incorporate on site intelligence to execute energy saving actions by commanding control points through the BAS system.
SEB to incorporate ability to specify command priority level when commanding control points for load reduction	SEB to allow operator to specify the command priority level when commanding control points for load reduction control actions.

Advanced, Integrated Control for Building Operations to Achieve 40% Energy Saving

control actions.	
SEB to incorporate runtime energy strategy engine for collaborative energy management and control	SEB to incorporate on site intelligence to conduct collaborative energy management and control and to provide easy configuration to reduce site enablement cost.
SEB to incorporate weather forecasting capability for determining model predictive energy management and control	To further optimize DR strategy, SEB could use forecasted weather to drive the simulation to determine the optimal proactive energy efficiency strategy for natural heating, cooling and ventilation utilization.
SEB to optionally support different building to grid protocols	In addition to the OpenADR communication protocol and the protocol used internally by the Siemens Building Technologies, SEB should be designed in such a way that different DR protocols can be added to the SEB without affecting other DR features (such as on-site DR strategy engine). This requirement is particularly important when these gateways are to be adapted for future Smart Grid Standards such as OpenADR 2.0 and other standards that are emerging in the international markets.
SEB to provide local event view	SEB must provide ability for local personnel to visualize the DR event and status of load reduction control actions.
SEB to be aligned with Siemens Building Technologies Building Automation System Product portfolio	The final form factor shall be aligned with Siemens BAS product portfolio.
SEB to support BACnet and MODbus and APOGEE SOAP services	SEB is to minimally support BACnet or MODbus or APOGEE SOAP service communication protocols.
SEB to have same quality requirements as other Siemens Building Technologies Building Automation System Products	SEB shall have the same environmental, agency and quality requirements as the existing Siemens Building Automation System products.
SEB to have Local Opt Out functionality for energy saving mode	SEB must provide feature to allow an operator to opt-out of the DR event. Opt out mechanism should be assessable from the BAS.
SEB to be remotely upgradable	SEB must include feature to allow the software remotely upgraded.
Sales and Marketing material	Sales and Marketing material and branch training to be developed to target building owners and tenants.
The SEB licensing scheme is	The SEB is to be compatible with current Siemens product licensing scheme.

to be compatible with Siemens products licensing scheme.

8.3 Technical Feasibility

Based on what we have learned from this research project, specific areas that would require further technical feasibility and alternate technical solution evaluation have been identified. Those specific technical feasibility areas are described below.

The above figure shows the major components of the Smart Energy Box. The components that could use further technical evaluation are Simulation; EMC/cEMC (Optimization); BMS adapter (command and control through BAS); and advanced energy efficiency strategies.

SEB simulation: Setup Time

The setup of simulation model for evaluating energy efficiency strategies is a major component of the Smart Energy Box. The time and effort to set up and verify the accuracy of the simulation model was recorded for this research project as shown in the table below. As shown in the table, the time and effort

is significant. The setup time is translated into installed costs. High installed costs could prohibit the successful launching of SEB as a commercial product.

<i>Line #</i>	<i>Description</i>	<i>Time in man-hours</i>
1	Creating and validating the Energy Plus model (For this research project, Notepad++ and Energy Plus IDF editor have been used for creating and editing the Energy Plus model.)	640
2	Acquisition of historical weather data in the right format for Energy Plus simulation	(part of line 1)
3	Creating new equipment module and/or updating performance curves	(part of line 1)
4	Tie the Energy Plus model to the SEB and map the control points	16
5	Training on Energy Plus	(part of line 1)
	Total	656

Such an effort to set up the Energy Plus simulation model for the IW has resulted in the prediction of electrical demand and consumption (using 15 minutes time step) in the neighborhood of plus or minus 15 percents from the actual measured demand and consumption. The accuracy of the simulation model is well within the acceptable range. However, the effort required for setting up the simulation model is too high and will not be practical for field deployment.

SEB Simulation: Alternate Technology Evaluation

In practical, the effort for setting up the simulation model has to be substantially reduced to make the deployment of SEB economically feasible. For the building about mid size (50,000-200,000 square feet), in the author's opinion the time required to set up the simulation model should be reduced to around 40 - 80 man-hours. (There is at least one commercial company that the author is aware of that has claimed that setting up the Energy Plus simulation model with considerable accuracy for energy efficiency evaluation purpose can be done within that amount of time.) Alternate technologies and approaches to set up the simulation model must be explored to reduce the installed cost of setting up the simulation model. Potential alternate technologies to further evaluate are as follows:

<i>Line #</i>	<i>Description</i>
1	Automated technology to take information from as-built drawings and create Energy Plus model; Need to substantially reduce the time to set up the simulation model or even automate the process.

2	Templates of typical building types that can be used in most cases (The template can be used as a starting point to reduce the simulation model setup time.)
3	Alternate simulation model tool that could require less set up time than Energy Plus and still achieve acceptable prediction accuracy
4	Alternate technologies and methods to reduce the time to carry out simulation model measurement and verification task
5	Alternate approach for predicting demand and consumption instead of using full blown simulation model such as Energy Plus
6	Trade off between setup time, simulation time step, and simulation accuracy; For line items 3, 4, 5, further analyses are required to understand the trade off in particular the set up effort and the accuracy.
7	Sub-metering and alternate technologies to obtain sub-metering data for verifying predicted demand and energy at equipment level and/or at the circuit level
8	Alternate approach to measure load when sensors such as air flow meters or water flow meters are not available.
9	Sensitivity analysis of simulation results in relationship to the accuracy of forecasted weather data; For the PeakDay Pricing Mode, the simulation model relies on the accuracy of the forecasted weather and the forecasted peak temperature for the day. The impacts of the accuracy of forecasted peak temperature on the optimal DR strategies need to be studied. Adjusting factors and correction factors to lessen the impact of accuracy could be identified as part of the study.
10	Identify typical equipment models that could be used for most HVAC system simulation; Various HVAC equipment models (performance curves) used in the set up of Sudarja Hall Energy Plus simulation model have been tweaked to increase predicted accuracy (i.e., ahu fan, VAV box, cooling tower fan, and chiller). Such an effort to tweak the equipment model for every commercial building that we need to set up the SEB Energy Plus Simulation model would not be possible in the real world due to the effect on installed costs.

SEB Optimization: Execution Time and Setup

Time required to complete the optimization run depends on the type of optimization run and the computing power. During the research phase of this project, the following data have been collected:

<i>Line #</i>	<i>Description</i>	<i>Time in man-hours</i>
1	On-line optimization run	0.3
2	Off-line optimization run (genetic algorithm – 370 evaluations)	12

3	Configuring all APOGEE control points needed for the optimization run	80-120
4	The cost of Optimization run time engine such as Math Lab platform	
	Total	93 – 120

SEB Optimization: Alternate Technology Evaluation

Computing equipment installed at the customers' sites might not have enough CPU power and memory to handle such intensive computation required by the optimization run. Alternate technologies should be investigated to make the optimization run practical in the field. Examples of such technology evaluations could be as follows:

<i>Line #</i>	<i>Description</i>
1	Evaluate alternate optimization run time engine; The Math Lab platform is very powerful and contains lots of features. However, only a handful of such Math Lab features are needed for solving the SEB optimization problem. Alternate platform with features needed for SEB that are cheaper to license and deploy should be investigated and evaluated.
2	Simplify/reduce the number of evaluations; Reducing the number of evaluations could reduce the execution time and could make the techniques suitable for instantaneous determination of DR strategies.

SEB Command and Control: BMS Adapter

The SEB platform developed for this research project implements two BMS communication protocols: APOGEE SOAP and BACnet. In the future, there could be a need to support other communication protocols such as MODbus communication protocol. The underlying framework of the BMS adapter must be evaluated for its ability to support other communication protocols. If the current BMS adapter is unable to effectively support additional protocols, evaluation of alternate technology/method to enhance or replace BMS adapter must be carried out as part of the technical evaluation phase.

SEB Command and Control: Energy Efficiency (EE) Strategies Evaluation

The project identifies the followings as key EE strategies for load reduction control actions at CMU IW including:

1. Time of day control
 - Business hour based schedule
 - Fixed set-points during the day
2. Occupancy based schedule
 - Input: Occupancy schedule and preference
 - Different set-points for occupied and unoccupied

3. Knowledge (occupancy task) based
 - Input: Occupancy schedule and task (computer, read, lab)
 - For lighting only
4. Natural Ventilation (weather based)
 - Includes all above strategies
 - Additional Input: Weather broadcasting
 - Free cooling
5. Load Shifting for Peak Load Limiting
 - Pre-cooling or Pre-heating before Peak Load Time
 - Optimize pre-cooling or pre-heating start time and duration
6. Total Cost Optimization
 - Includes all above EMC strategies
 - Additional Input: Weather broadcasting
 - Free cooling

Some of the load control strategies require that the sequences of commands sent from the SEB to the BAS have to be strictly followed to ensure that proper load reduction control actions take place. This is particularly important when the commands are intended for application specific controller (ASC) devices since those ASC devices have their own internal logic to carry out certain control actions when certain commands are received. The SEB Strategy Executor logic might need to be enhanced to allow commands to be issued in a specific order to ensure the desired load reductions.

The EE strategies, if not yet included in the internal SEB application guide for advanced integrated energy saving application will be evaluated and added to the guide.

8.4 Development Decision

Before concepts like SEB can be further developed into products, the product marketing manager of the demand response family of product has to present a business case to justify the investment (including money, time, and human resource). Fundamental data required to create the business case include the following data:

- market size and potential product sales,
- development costs,
- sales and marketing expenses,
- other non-monetary factors including required profit margin and internal rate of return

Market size and potential product sales

Substantial market studies that will be needed to estimate the market size of SEB, in particular the market studies to identify market size for advanced integration platform for energy efficient control strategy implementation. Once the market size is estimated, potential income from Siemens product sales can be estimated by multiplying the market size with an estimated potential Siemens market share. Since the market for such advanced integration platform as SEB does not yet exist, estimating the market size will pose the most challenge to the product marketing team.

Product development costs

Siemens divides product development project into the following phases: Pre-development, Concept, and Development. Each phase will have cost associated with them. Most of the technical feasibility and technical evaluation tasks as described in Section 8.3 will be done in the pre-development phase. Prioritized initial marketing requirements (of which samples are described in Section 8.2) dictate the areas of technical feasibility to pursue. The technical feasibility and technical evaluations constitute major costs of the pre-development phase. Results from the technical feasibility and marketing requirements will dictate the scope and effort needed for the development. The final marketing requirements and selected technical approaches are then used for estimating the cost of product development.

Sales and marketing costs

The sales and marketing costs cover the cost marketing and promotional materials. The costs include, but not limit to, salaries, product printed material, advertising, and travel and expense to promote products internally and externally. The sales and marketing costs are heavily incurred during the first two years of the product introduction. After the first two years, the sustaining marketing costs become minimal.

Other non-monetary factors

In addition to the above product development costs, other factors that will affect the decision to develop the products are:

- alignment with existing product portfolio,
- affect on existing product line,
- potential market leadership,
- required product profit margin
- required internal rate of return and
- number of years to reach break-even point

8.5 Development Process

Once the product is justified for the development, Siemens has a rigid product development process to ensure that the product is developed with the highest quality and craftsmanship. Due to the proprietary nature of the Siemens development process, details of the product development can not be disclosed here

in this report. The high level overview of the product development process however can be described as follows:

Development Phases and Milestones

Siemens development process divides the project into phases to allow for multiple points to check for completeness and quality. Milestones for each development phase are pre-defined and meetings are scheduled regularly to ensure that the project is still on track and still meets the delivery schedule. At each milestone, there are specific sets of reporting requirements (i.e., published documents, progress reports, etc) that the development team must meet. Each member of the development team will also have specified tasks and responsibilities to fulfill at each milestone. These development phases and milestones enable Siemens to closely track the progress of development, ensure that required features are properly implemented, and development costs are still within planned.

Testing and Quality Assurance

Every product that is developed at Siemens must go through rigorous testing processes to ensure the product achieves highest quality. Each product (and all the features) must at least go through three major test processes: unit testing, system testing, and field-testing. Developers are responsible for unit testing. For example, as the software code is being developed, a software developer carries out unit testing to make sure that each software module is functioning to meet the marketing requirements. Test records are kept. Deviation of implementation from the requirements must be approved and signed off by the product owner.

A separate System Test group then takes the product and installs it in a system test environment. For example, the potential product such as SEB will be installed in an actual building automation system control networks. The system test control networks will consist of several field panel controllers at the automation level network level and several application specific controllers at the field level network level. The System Test group will test all possible required system interaction features between the SEB and the controllers on the control network. Defects will be recorded and corrections will be made by the developer. Corrected product is then sent back to the System Test group to repeat the tests.

When the product development reaches the final stage and passes system test, the product will go through the field testing phase. During the field testing phase, the product will be installed at the customer site. Field testing will be conducted to ensure that all the features and functions of the product work in the real world. In addition, the product will be left running at the customer site for at least 2-3 weeks to ensure that there will be no problem related to the longevity of the product running at the customer site.

Commercial Product Release

Once the product completes the field testing phase and all issues have been identified and resolved, the product is released to manufacturing for production. In addition, a field support team for the product will be formed. Support team member will be trained on all aspects of product features and functions.

8.6 Product Launch and Promotion of the Use of Technology

When the product is released for manufacturing, the marketing team will kick off several product launching activities. Possible activities during the product launching phase include:

- Basic planning of product launch activities (a product launch checklist is used)
- Sales channel analysis: if a standard sales channel does not exist for the product, alternative sales channels will be established.
- Budget planning for product launch (e.g., advertising materials, pilot/sample devices)
- Creation of a marketing and communication concept (concepts will also be adapted to individual customer groups/sales channels)

Several communication channels will be used to promote and educate users on the benefits and usages of the product. Some of key channels frequently used by Siemens are as follows:

Conferences and Tradeshows

Conferences and tradeshows are good places for Siemens to introduce new products. Potential product such as SEB is likely to be introduced at the following building and HVAC industry key conferences:

- ASHRAE (Association Of Heating, Refrigeration, Air Conditioning Engineer)
- BOMA (Building Owners and Managers Association International)
- NAESCO (National Association of Energy Services Companies)
- Connectivity Week
- Grid Week
- WEEC (World Energy Engineering Congress)
- Engineered System High Performance Building Conference

Webinar and Web Video

Periodically Siemens in association with trade organizations such as McGraw Hill, Engineered System Magazine, Automated Building.COM and several other organizations organize webinars that are opened to everyone to attend. Such a webinar is used to educate audience on the basic concept of technologies and introduce the Siemens products that have successfully implemented such technologies. In addition, Siemens also posts the introduction of the technology in the form of user generated story web video at the Siemens Internet web site. Video introduction of new technologies are sometime posted on Youtube.com.

Internal Webinar

For new technology such as SEB, Siemens typically organizes several internal webinars to introduce the technologies before the products are officially released. Internal seminars are made available to everyone at the home office and at the branch locations. Depending on the topic and the complexity of the topic, one or more seminars will be set up. At the end of the seminar, ample time is allocated for the audiences to ask questions and discuss the implementation. Internal SharePoint sites are also setup to provide additional material and recordings of the seminars.

Product Announcement, Advertising and Marketing Brochure

The product marketing team is responsible for developing the product launch concept and all marketing related activities. Marketing brochure will be developed. All channels for launching the products will be identified and launching strategy for each channel will be established. Advertising and product announcements will be made to industry trade magazines and web sites. Specific sales promotion programs could be created to generate fast sales during the product introduction. Consulting and engineering firms will also be informed of the new products.

Rollout Training

Depend on the complexity of the product, in person training will be organized to get the installation personnel up-to-speed on the technology as soon as possible. When the product incorporates technology such as on-line simulation model and optimization engine, it could be necessary for certain key personnel to attend the training offered by outside vendors. For training purpose, a live demonstration system will also be set up and used during the rollout training to demonstrate the inner working operation.

Chapter 9 Conclusion

Buildings account for about 40% of the total energy consumption in the U.S. and most of the energy is used to heat, ventilate, and air-conditioning the space. To improve the management effectiveness and efficiency, a building automation system (BAS) is typically deployed in modern buildings to automate the various systems and devices. Today's BASs provides building customers with various control strategies to satisfy energy demand and consumption targets and meet building operation goals while maintaining comfort, life safety, security and productivity of the building occupants, including economizer, scheduling, night setback, peak demand limiting, supply air/chilled water reset and demand based ventilation etc. However, the state-of-art building energy management strategies are limited in the following perspectives:

1. The buildings are operated in silos and the strategies listed above are also running individually while in lack of integration view.
2. Most of the strategies are static programmed without considerations of weather and occupancy changes.
3. Some of the strategies work well regarding energy efficiency, however not cost effectively, e.g, demand based ventilation requiring CO2 sensor installation and yearly maintenance.
4. No smart load management capability for the consideration of demand response and price-sensitive operations
5. No plug load control considered for energy efficiency

As studied through this ARRA/DOE project, our integrated advanced building control technology main advantages compared with existing technologies are integrated denenergy management optimization algorithms based on weather and occupancy forecast for buildings and low cost software solution. In addition the integrated system based on SEB is:

- Scalable component based architecture allows to build a SEB with only the needed components;
- Open Architecture with a central data repository for data exchange among runtime components;
- Extendible to accommodate variety of communication protocols.
- Optimal building control for central loads, distributed loads and onsite energy resource
- Uses web server as a loosely coupled way to utilize SEB;
- Supports multiple communication protocols including BACnet and Modbus.

Based on the open platform of SEB, we have investigated and evaluated a variety of operation and energy saving control strategies on a building equipped with alternative cooling/heating methods, including fan coil units, radiant mullions and motorized window and blinds. Specifically, the control strategies to be studied include:

- integrated control of all building systems based on modeling and information provided by weather and occupancy forecasts.
- control that selects among alternate actions the one most effective in achieving the desired space condition; for example, adjusting either the lights or the blinds to control the desired illumination in the room.
- measured occupancy based control of cooling/heating, ventilation, lights, and blinds
- control that takes into account real time pricing and modern grid operations.
- control that communicates effectively with both the building occupants and the building operators to satisfy the needs of both and to communicate pertinent information regarding energy use and the environmental impact, CO2 emissions, associated with the building operation.

- control that makes use of a multiplicity of various sensors
- control that incorporates that incorporates wireless sensors and actuators

Based on the validation results of these control strategies, a collaborated integrated control approach was developed to integrate the existing and advanced control strategies. This advanced control system was programmed and computer tested with a model of the Intelligent Workplace's northern section (IW_n). The advanced control program was then installed in the IW_n control system; the performance were measured and compared with that of the state of the art control system to verify the predicted, target energy savings of 40% overall. In addition advanced human machine interfaces (HMI's) were developed to communicate both with building occupants and the building operator.

Lifecycle cost analyses of the advanced building control were performed, and a Building Control System Guide was prepared and published to inform owners, architects, and engineers dealing with new construction or renovation of buildings. The Guide will facilitate the design, installation, and integration of advanced control technologies to building controls systems. Siemens has developed the commercialization plan for the potential product Smart Energy box.

Appendix A: Publications

1. Zhen Song, Xianjun Zheng, Kun Ji and Yan Lu, “Collaborative Building Control to Optimize Energy Saving and Improve Occupants’ Experience,” ASHRAE winter conference, January 26-30, 2013, Dallas, Texas.
2. Zhen Song, Lingyun Wang, Yan Lu, “Demo Abstract: Social Learning SoftThermostat for Commercial Buildings,” ACM BuildSys (a workshop of ACM SenseSys,) 2012.
3. Clarence Abgi, Zhen Song, and Bruce Krogh, “Parameter Identifiability for Multi-Zone Building Models,” paper submitted to Conference of Decision and Control.
4. Zhen Song, Yan Lu, Kun Ji, Flore Marion, Yuebin Yu, Marion Kerl, Linxia Liao, and Dong Wei, “Experimental Study on Control-oriented Simulation Models for Building Control and Energy Management”, Building Simulation 2011, Nov. 2012, Sydney
5. Kun Ji, Yan Lu, Zhen Song, and Yuebin Yu, “Management Control Framework of Optimization Control and Operation for Energy Efficient Buildings”, accepted and presented in the ACEEE 2012 Summer Study on Energy Efficiency in Buildings
6. Kun Ji, Yan Lu, Linxia Liao, Zhen Song, and Dong Wei, “Prognostics Enabled Resilient Control for Model-based Building Automation Systems”, Building Simulation 2011, Nov. 2012, Sydney
7. Yuebin Yu and Vivian Loftness, “A Study of Rule and Model Cascaded Predictive Control for an Office Building” accepted and published in the Proceedings of the 6th International Conference on Energy Sustainability and Fuel Cell July 23-26, 2012
8. Yuebin Yu, Vivian Loftness, Daihong Yu, Volker Hartkopf. 2012. Development and evaluation of a simplified modeling approach for hydraulic system. 2nd International conference on High Performance Buildings, Purdue University.
9. Yuebin Yu, Mingsheng Liu, Haorong Li, Daihong Yu, Vivian Loftness. 2012. Synergization of air handling units for high energy efficiency in office buildings: implementation methodology and performance evaluation. Energy and Building, 2012.
10. Yuebin Yu, Vivian Loftness, Daihong Yu, Yan Lu, Zhen Song. 2012. Investigation of an innovative energy system and its advanced control in Energyplus. Proceedings of eSim 2012, Canada.
11. Sebastian Peters, Vivian Loftness and Volker Hartkopf, The Intuitive Control of Smart Home and Office Environments, Onward! 2011, Oct. 22-27, Portland, Or, USA
12. Yun Gu, The Impacts of Real-time Knowledge Based Personal Lighting Control on Energy Consumption, User Satisfaction and Task Performance in Offices, PhD Thesis, Carnegie Mellon University, 2011.
13. Yuebin Yu, MODEL-BASED MULTIVARIATE CONTROL OF CONDITIONING SYSTEMS FOR OFFICE BUILDINGS, PhD Thesis, Carnegie Mellon University, 2012.

Appendix B Networks or collaborations fostered

Based on the project results, SCR has established the collaboration with United States Air Force Academy (USAFA), KEMA, Boeing and UCB and won a Department of Defense ESTCP installation award to demonstrate the advanced and integrated building energy management and control on USAFA campus at Colorado Springs CO.

CMU is a member of the EEBHub, a DOE funded initiative, and is involved in 3 different projects that are directly related to this project, including “Portable Building Evaluation Toolkit” for energy audit, occupant comfort and satisfaction survey, and the IEQ assessment; “Building Investment Decision Support”, to develop a life-cycle decision framework for capturing research and building studies that demonstrate the cost-benefits of energy efficient building components and systems and develop the framework for future incorporation into a multi-media decision support tool; and “Empowering Occupants to Achieve Energy Efficiency” which is directly related to this proposal as another platform to refine the control algorithms and understand occupant behavior in relation to energy conserving strategies.

Appendix C Inventions/Patent Applications

1. Kun Ji and Yan Lu “Optimal building energy management using intelligent optimization” 61/657,996
2. Kun Ji, Yan Lu and Zhen Song, “Energy Management Control Framework of Optimization Control and Operation for Energy Efficient Buildings”, 61/606,630
3. Kun Ji and Yan Lu , “System and Method of Total Cost Optimization for Buildings with Hybrid Ventilation”, 61/603,517
4. Shaopeng Zhang, Xianjun Zheng, Yan Lu, Yanzi Chen and Zhen Song, “ADVANCED HUMAN-MACHINE INTERFACE FOR COLLABORATIVE BUILDING CONTROL”, 61/546,725
5. Zhen Song, Xianjun Zheng, System and Method for Energy Efficient Collaborative High Performance Building Control, application number: PCT/US2012/049167
6. Zhen Song, Ji, Kun, Yan Lu, Dong Wei, Linxia Liao, Experimental Study on Control-oriented Models for Building Control and Energy Management application number: PCT/US2012/039033