# Energy Management Control Framework of Optimization Control and Operation for Energy Efficient Buildings

*Kun Ji, Yan Lu and Zhen Song, Siemens Corporate Research*
*Yuebin Yu, Carnegie Mellon University*

## ABSTRACT

This paper proposes an optimization control based Energy Management Control (EMC) framework that integrates predictive dynamic building models, day-ahead forecasts of load, energy price, and occupancy needs, and enables micro-zoning based active occupant-driven control. Based on a dual-loop control design and implemented in the outer-loop, the EMC serves as a high level strategy planner which enables the building automation system (BAS) to fully utilize all information available such as weather forecast data, occupant schedule and task needs, real-time energy price and so on for optimal planning and operation including micro-zoning control, optimized load shaping and natural ventilation. A real live-lab building, the Intelligent Workplace (IW) in Carnegie Mellon University, is used as the test bed and experiments are performed to verify the feasibility and effectiveness of the proposed EMC framework. The energy saving potential of the proposed EMC framework is verified by simulations with several practical EMC strategies categorized in this paper.

## Introduction

With more and more mature building modeling tools such as EnergyPlus and TRNSYS being available, a building control and operation paradigm shift from reactive control to proactive control is taking place [1, 2]. The energy performance of a building is strongly affected by dynamic disturbances evolving at different time scales. These disturbances include load demands, energy prices, and weather conditions, among others. In an attempt to minimize energy consumption and maximize occupant comfort, high performance building systems need a complete and efficient EMC framework that integrates all useful information available such as weather data, occupancy data, and energy market price into building control and operations. The operational decisions of the BAS are decomposed in a hierarchical manner into dual-loop control strategies. The outer control loop is the supervisory optimization layer which proactively adjusts the set-points according to the dynamic disturbances. The inner control loop modulates the individual devices to track the optimal set-points from the supervisory loop. The current trend of BAS control research is focusing increasingly on model and knowledge-based proactive control approach [3].

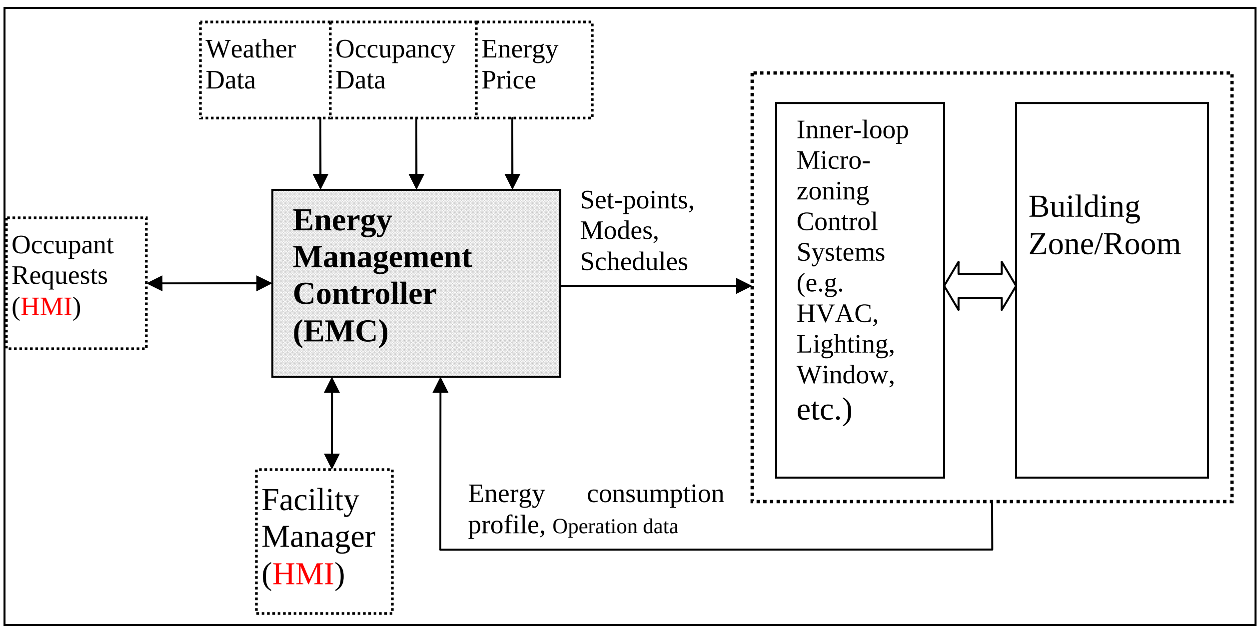
One of the important goals of applying BAS is to use the optimization and control strategies to satisfy occupants' comfort requirements with minimal energy use [4, 5]. Today, the BAS generally operates according to fixed schedule, maximum occupancy assumptions, fixed occupant comfort ranges at all times. For high performance BAS, the occupants should be actively involved in the energy saving strategy being deployed to best fulfill the occupant comfort requirement [6]. There is a great potential to reduce building energy consumption by integrating active occupant-driven control into the BAS EMC framework. Efficient prediction of building load demand based on more external available information such as occupant schedule and task needs enables better planning for the building control and operations towards more energy saving. In this paper, an optimization control based EMC framework is developed that integrates predictive dynamic building models, day-ahead forecasts of load, energy price, and occupancy needs that can affect efficiency and costs, and enables micro-zoning based active occupant-driven control.

This paper is organized as follows: The first part presents a brief description of the proposed advanced EMC framework. The next two parts illustrate the main functionalities of the proposed EMC framework and its sub-components and the EMC strategies enabled by this framework. Then the co-simulation platform coupling Matlab/Simulink and EnergyPlus is implemented to simulate the EMC strategies and the occupant driven micro-zoning control. The paper concludes by indicating our current plans for future work.

## Proactive Energy Management Control Framework

Figure 1 shows the control diagram of this proactive EMC framework. Based on the dual-loop control structure, the EMC framework is implemented as the outer control loop.

**Figure 1. EMC as the Outer-loop Controller for Building Automation System**

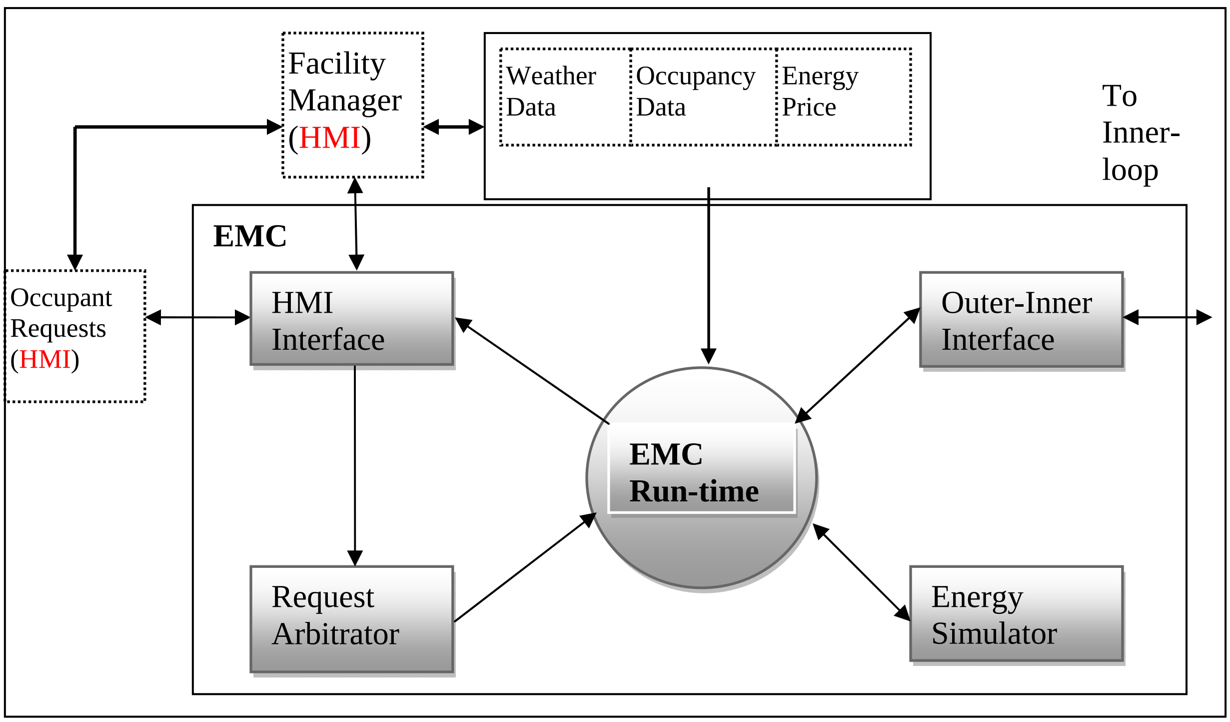



The inputs to the EMC are information available for optimal planning and operation such as occupant and facility manager run-time requests, occupant task schedules, weather data, and real-time energy price. The occupant driven control is enabled by the human machine interface (HMI) that is used by the occupants to provide their zone schedules, zone preferences, and real-time requests such as changing thermal set-points, changing lights, and opening or closing operable windows. 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. The inner-loop controller enables micro-zoning and does the local optimization control of all the equipment to achieve the set-point requirements from the EMC.

## Functional Modules of EMC Framework

The outer-loop controller EMC serves as the high level strategy planner which enables the building automation system to (1) utilize weather data, occupancy need, and load peak price for better planning and real-time operation, (2) exploit building's thermal storage capacity for load shedding, (3) coordinate occupants' real-time requests for micro-zoning, (4) prioritize and sequences the different energy supply resources (e.g. natural ventilation, natural cooling, etc), and (5) predict daily energy demand profile for automatic demand response. The inner-loop controller depicted in Figure 1 then implements the micro-zoning concept and enables independent control of low level equipment of individual zones. The internal modules of this EMC framework are shown in the box of Figure 2. The proposed EMC framework consists of the following five internal modules.

**Figure 2. Internal Modules of the EMC Framework**




### HMI Interface

This module is the user interface for EMC to communicate with occupants and facility manager for rules and requests aggregation. Dedicated web-based HMI for occupants provides occupants a convenient way to individualize their own zones/rooms with the capability of storing their task schedules and preferences associated with the different tasks. HMI for the facility manager collects and presents the information of overall occupants' preferences, task schedules and demand response request to the facility manager so the facility manager can make rules of operations and decisions during demand response period.

**Request Arbitrator**

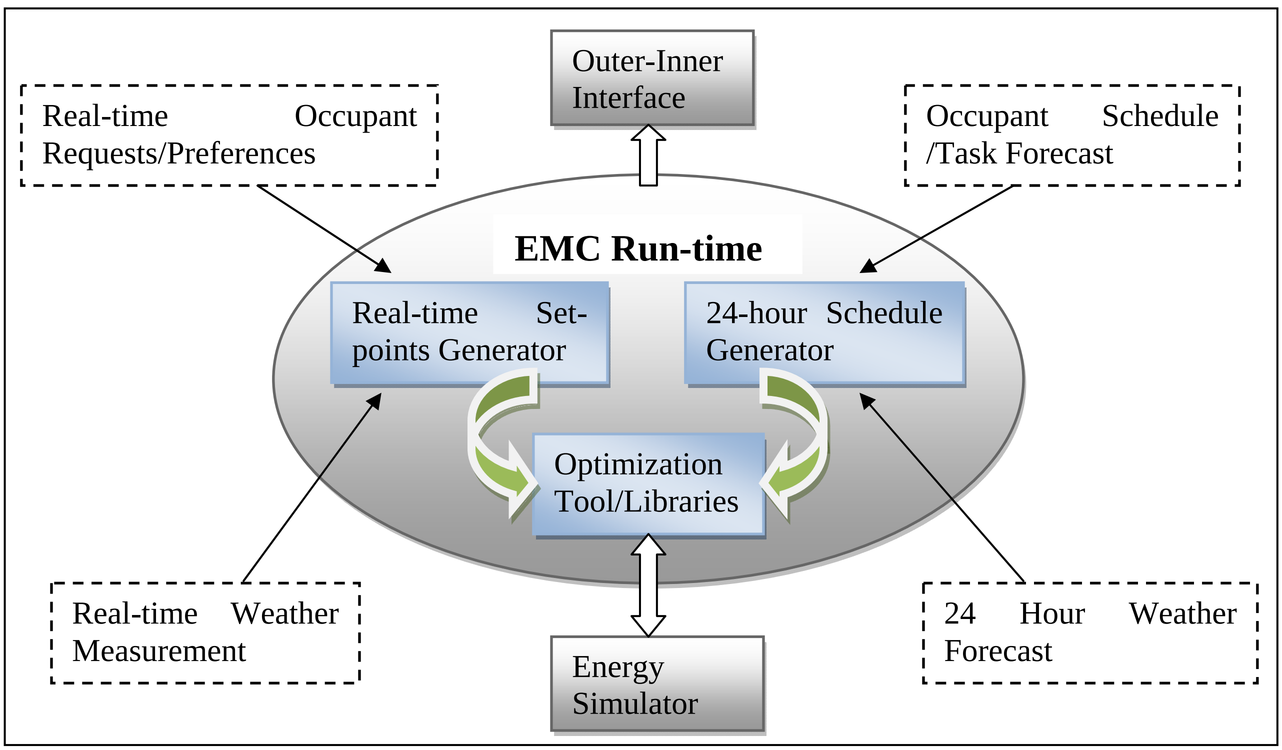
The demands from the occupants via the HMI are not implemented directly since they might include unreasonable or conflicting points. Request Arbitrator is a conflict solver to coordinate occupants' requests based on the rules made by the facility manager or experts regarding the bound of comfort settings and other rules (such as not allowing windows to be open when the HVAC system is on, for example). Occupant requests that fall in the predefined bound set or permitted by the rules will be accommodated and the others are declined.

**HMI Run-time**

EMC Run-time (EMCR) engine is the core component to generate EMC strategies based on the forecast data (weather data, occupancy data and energy price) and the inputs from the HMIs. It has three functional sub-modules as decomposed in Figure 3.

1. 24-hour Schedule Generator
2. Real-time Set-points Generator
3. Optimization Tool/Libraries

**Figure 3. Internal Functional Sub-modules of the EMC Run-time Module**




As shown in Figure 3, the 24-hour Schedule Generator generates the operational schedule including hourly set-points for the individual zone for the next 24-hours based on the weather forecast and zone-based occupant schedule/task forecast. This schedule will be used by the BAS as the default schedule and applied when no new real-time set-points are provided by the Real-time Set-points Generator which might otherwise override the set-points based on the pre-filtered real-time occupant requests and weather measurements. The information used by this EMC Run-time includes the occupants' data, weather real-time measurement data, weather forecast data, and energy price. The occupants' data, including the real-time requests and task schedule information, are provided through the HMIs and screened by the Request Arbitrator. Both the 24-hour Schedule Generator and Real-time Set-points Generator use the Optimization Tool/Libraries and the Energy Simulator to do optimization related simulation and find the optimal schedule and set-points.

**Energy Simulator**

EnergyPlus [7] is used as the energy simulation tool in this study to try out the EMC strategies and find out the most energy efficient one. Since the the Intelligent Workplace (IW) in Carnegie Mellon University (the test bed building of this paper) is using water mullion based HVAC system, the energy consumption is calculated and provided by EnergyPlus using sensible heating/cooling energy instead of meters in the EnergyPlus model. This module works with the EMC Run-time sub-module Optimization Tool/Libraries as indicated in Figures 2 and 3. This runtime component encapsulates all requests for energy simulation and passes them into a separate thread running EnergyPlus to perform simulations. After performing the simulations, the results will be passed back to Energy Simulator component and the best strategy will be applied to the inner loop through the Outer-Inner Loop Interface of the EMC Run-time.

**Outer-Inner Loop Interface**

This interface is the channel for the outer-loop EMC to communicate with the inner-loop controllers to apply the optimal strategy in terms of zone schedules and occupant preferred set-points for each zone. In real application, BACnet communication is used to connect EMC and micro-zoning control systems.

## EMC Strategies

The above EMC framework enables the following EMC strategies (summarized in Table 1) to explore the energy/cost saving potential of optimization on building operations and control with the occupants involved in the decision making process. These strategies are practical and easy to implement in reality. For energy consumption comparison purpose, the first strategy is picked as a 24-7 base line scenario. Strategies 2 to 6 are energy saving approaches with different energy/cost saving potentials. EMC strategies from 1 through 6 have an increasing energy saving potentials with the incremental information available to the EMC regarding occupants' schedules and preferences, weather forecast, and peak load energy price. Strategy 2 simply uses business hours as the schedule for building control system to control and operate the supply side equipments. Strategy 3 is called occupant schedule based control that utilizes the occupants' schedules and preferences to do micro-zoning control, i.e. each zone has different set-points at different time periods of the day depending on the occupancy information available. In addition to the occupant schedule data, Strategy 4 uses knowledge of occupant tasks data to further perform energy saving on lighting. The rationale is that different occupant tasks require different luminance. Lighting energy could be unnecessarily wasted for some occupant activities during the periods when less than maximum luminance is already adequate. In addition, there is a substantial energy saving potential if the zone lighting setting matches the occupant task in that zone at different time period of the day. This is called the knowledge (occupant task) based lighting control strategy. Strategy 5 incorporates additional weather forecast data into the building control planning and enables natural ventilation when outdoor weather permits. Strategy 6 deals with peak load limiting problem and reduces the total energy cost by shifting the peak load to the time period when the energy price is low.

**Table 1. EMC Strategies**

| Strategy No. | Strategy Name | Description | Inputs |
|---|---|---|---|
| 1 | 24-7 baseline | Fixed schedule at all time and fixed set-points at all time | One set-point |
| 2 | Time of day control (night set-back) | Business hours based schedule and fixed set-points during business hours | Business hours<br>Two set-points |
| 3 | Occupancy schedule based control | Different set-points for occupied and unoccupied period and zone | Occupancy schedule and preference (multi-set-points) for individual zone |
| 4 | Knowledge (occupant task) based control | Different light settings for different schedule and task | Occupancy schedule and task info. e.g. computer task, read task, and lab task |
| 5 | Weather based control | Natural ventilation enabled | Weather forecast |
| 6 | Load Shifting for peak load limiting | Total energy cost optimization by shifting the peak load to the time period when energy price is low | Peak load energy price, energy rate, Pre-cooling/heating set-point |

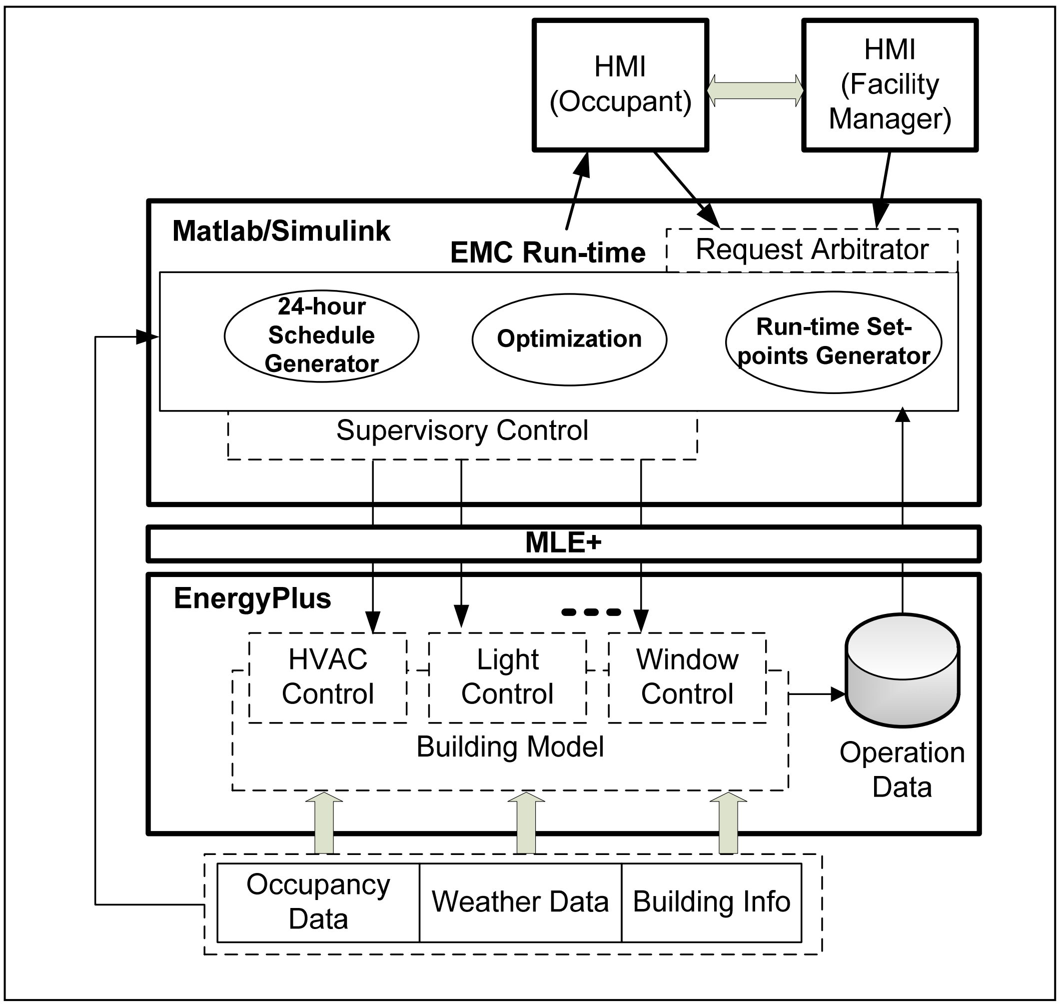
A co-simulation test bed is utilized to simulate the above EMC strategies and verify their energy saving potentials. The following section describes this simulation test bed implemented based on the proposed EMC framework.

## Simulation Test Bed

A co-simulation test bed shown in Figure 4 connecting MATLAB and EnergyPlus with MLE+ [8] is established for the control development and validation. The dedicated web-based HMI provides occupants' data including schedules, tasks and preferences for active occupant driven control and micro-zoning control. The EMC framework and strategies proposed in the previous sections are implemented in the MATLAB/SIMULINK. EnergyPlus is used as the building simulation tool. In this paper, the building model is taken from Robert L. Preger

Intelligent Workplace (IW) that is sitting atop Margaret Morrison Carnegie Hall at Carnegie Mellon University and a living and lived-in laboratory for the research on high performance building technologies [9]. The weather file used in the EnergyPlus simulaiton is 2010 Pittsburgh Airport Weather file. This co-simulation platform can also be used to evaluate the EMC strategies on any benchmark EnegyPlus models developed by DoE

**Figure 4. Co-simulation Test Bed with Dual-loop Control using Matlab/Simulink and EnergyPlus**




## Simulation Results

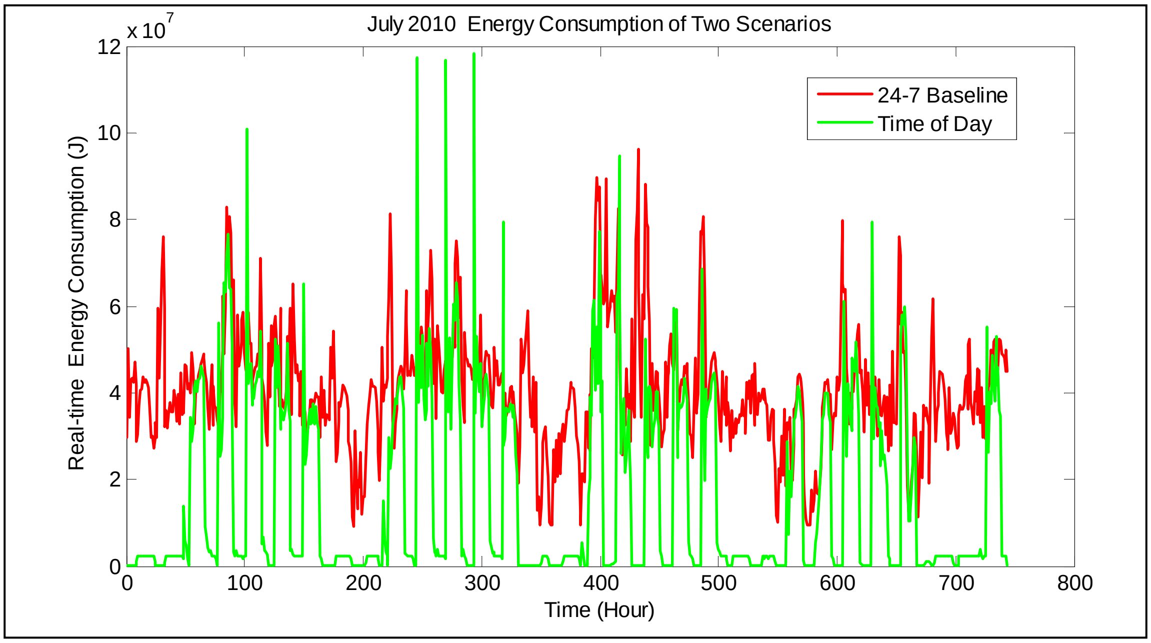
The EMC strategies listed in the previous EMC Strategies section are verified through above co-simulation test bed. For the baseline (Strategy 1), the default winter heating set-point is $21^{o}$C and summer cooling set-point is $25^{o}$C. For the time of day control (Strategy 2), the night set-back set-point is 15 $^{o}$C for heating and 33 $^{o}$C for cooling. Business hours setting is from 8:00 am to 6:00 pm. The results and comparison are presented below.

**Time of Day Control (Strategy 2) vs. Baseline (Strategy 1)**

**Real Time Energy Consumption (July 2010)**

Figure 5 shows the real-time energy consumption profile comparison between Strategy 2 and baseline. It is clear that simple night set-back can save substantial energy. Without ramping up control, at the beginning of the business hours, more energy would be required to cool the building to the set-point after the night set-back. The point is shown as the green spikes in Figure 5**.**

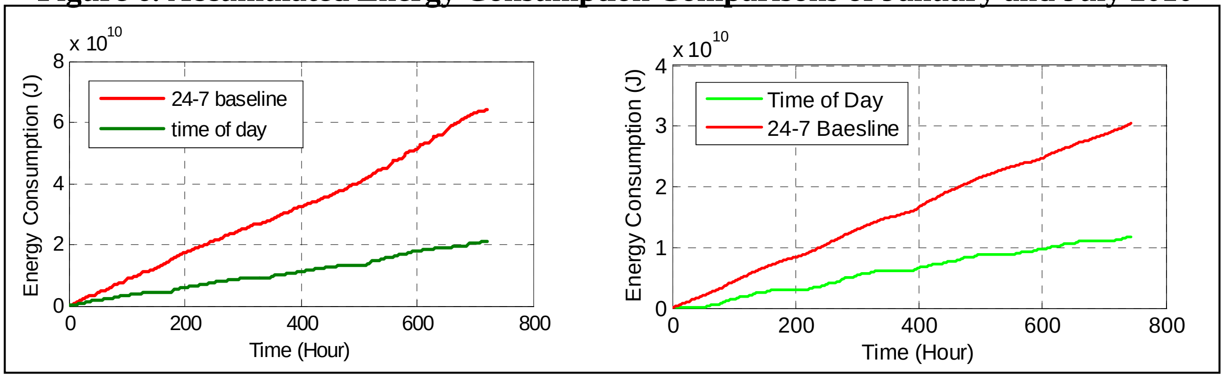
**Figure 5. Real Time Energy Consumption Comparison of July 2010**




**Accumulated Energy Consumption (January and July 2010)**

From Figures 6 and 7, it is clear that Strategy 2 can significantly save energy by up to 70% in winter and 60% in summer compared to the baseline for the case building. The quantity of actual energy saving depends on the schedule of business hours, weather conditions, and night set-back set-points. Those conditions can be easily modified and simulated in the proposed EMC test bed in the future.

**Figure 6. Accumulated Energy Consumption Comparisons of January and July 2010**




**Occupancy Based Control (Strategy 3) vs. (Time of Day Control (Strategy 2) and Baseline (Strategy 1)**

**Figure 7. Accumulated Energy Consumption Comparison of Jan.1~Jan.14 2010**

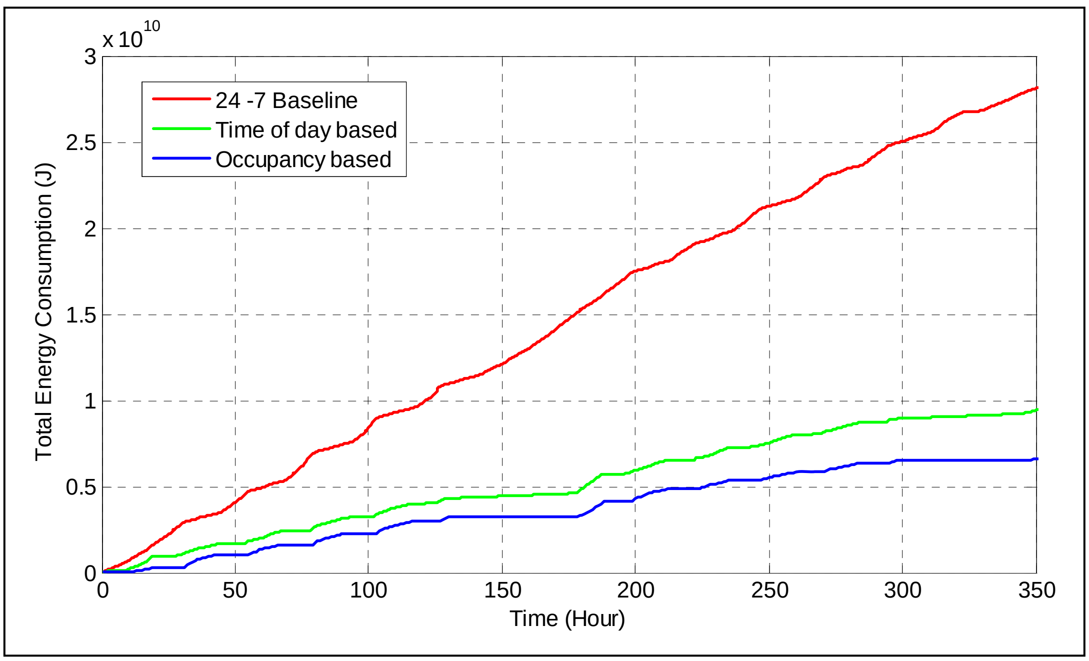


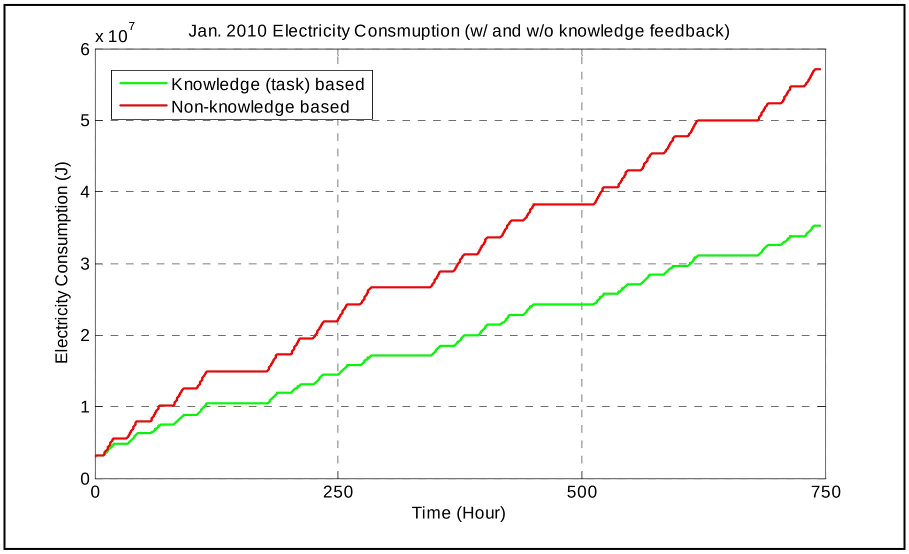

Figure 7 shows that Strategy 3 can save up to 20% energy consumption comparing to Strategy 2 with occupancy information embedded. The magnitude of energy savings depends on the occupancy information, its accuracy, and the length of the unoccupied period. In this simulation, we use a statistic model to simulate the occupancy schedule data which is stored in the HMI and provided by the occupants.

**Energy Saving Potential of Strategy 4 vs. Strategy 3 on Lighting.**

In this Strategy 4, only lighting control is considered. Three different occupant tasks are defined as: 1) computer task which requires the minimum luminance, 2) reading task which requires medium luminance, and 3) lab task which requires the maximum luminance. Assuming each zone has different occupant tasks during different time periods of the day, the simulation result of Strategy 4 on lighting energy consumption is given in Figure 8.

Figure 8 shows that Strategy 4 can save up to 40% energy consumption on lighting compared to non-knowledge based strategy (Strategy 3). As a fact, the amount of energy saving depends on the occupancy task schedule information. The occupants can provide this information via the occupant HMI. This verifies the energy saving potential of occupant-driven control and micro-zoning control methodology.

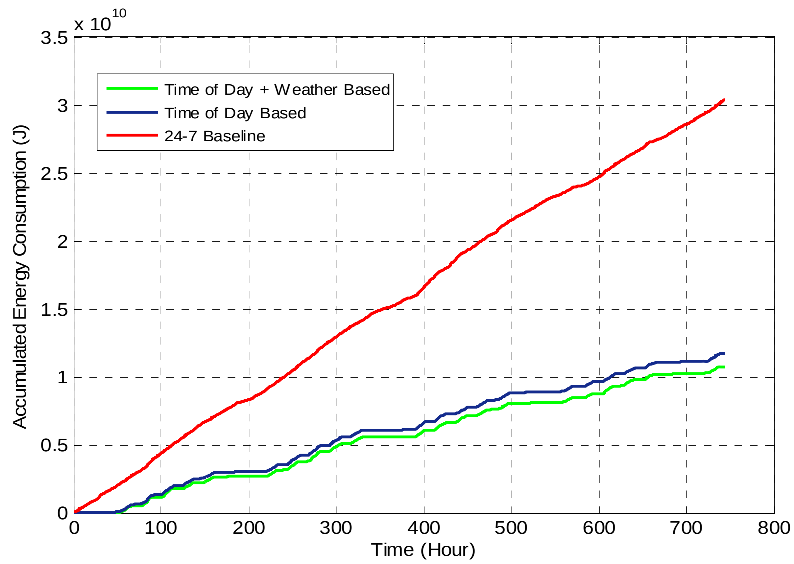
**Figure 8. Accumulated Energy Consumption on Lighting Comparison of Jan 2010**




### Weather Based Control (Strategy 5) Saving Potential

Many new energy efficient buildings are equipped with operable windows to enable natural ventilation and minimize the energy consumption while maintaining acceptable indoor air quality and thermal comfort during working hours. Natural ventilation is feasible for IWn building in the Pittsburgh climate area [9]. Simple simulation is performed with natural ventilation enabled IWn EnergyPlus model and the result is shown in Figure 9. Operation of natural ventilation depends heavily on the weather conditions such as raining information, outdoor humidity, and outdoor temperature.

**Figure 9. Accumulated Energy Consumption Comparison of July 2010**




In this research, natural ventilation decision is planned and made by the EMC considering the weather forecast data and real-time weather measurement data and executed in an automatic manner. This is realized by the Real-time Set-point Generator and 24-Hour Schedule Generator inside the EMC runtime module. Yearly Simulation with Strategy 5 which also incorporates EMC Strategies 2 to 4 is performed with 2010 weather data.

**Figure 10. Accumulated Energy Consumption Comparison of July 2010**

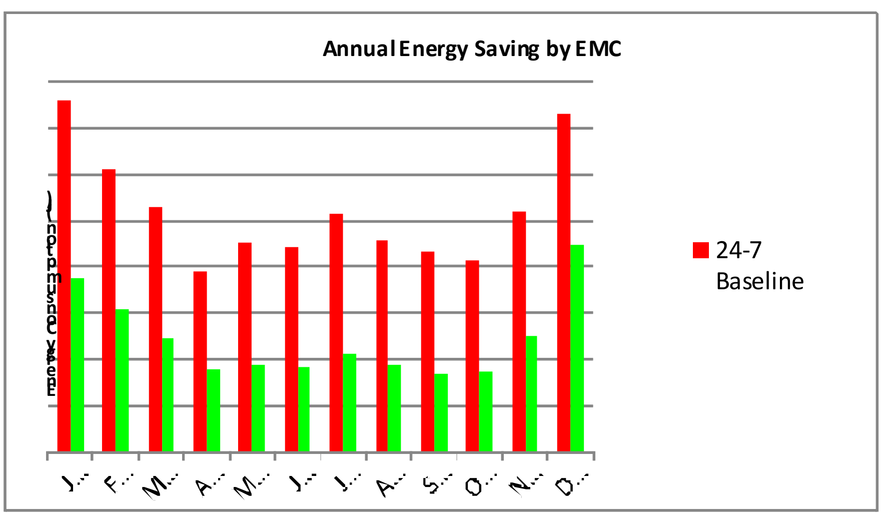



Figure 10 shows the annual energy saving potential of EMC with Strategy 5. Up to 50% energy saving can be achieved by the EMC strategy based on the proposed EMC framework.

**Strategy 6 Load Shifting for Peak Load Limiting**

For above strategies 1 to 5, the building in simulation is being operated in the way that provides the best occupancy thermal comfort. Thermal comfort zone is defined within a very narrow range, e.g. [21 $^{o}$C, 25$^{o}$C]. To further save energy cost due to the uneven utility rate and high peak load price, building thermal capacity can be utilized as storage to reduce the energy consumption during on-peak utility rate period. This can be achieved by setting the temperature set points to a lower temperature for cooling or a higher temperature for heating during off peak utility rate period. By pre-cooling/heating the building, the thermal storage available in the building mass can be released to shift cooling/heating loads during on peak utility period. Braun pointed out that, the indoor temperature of a typical concrete construction building without air conditioning and external loads would rise about 0.6-1.1C per hour [10]. This strategy of Peak Load Shifting is an approach to save energy cost and enable the Peak Load Limiting. This strategy includes optimized pre-cooling/heating before peak time. An example of the energy price model and the expected room/zone temperature and set-points are illustrated in the following Figure 11. This strategy will not reduce the total energy consumption, but it could reduce the total energy cost by shifting the load to the time period of cheaper energy price. A heuristic search based optimization method is implemented to identify the optimal start time and duration of the pre-cooling. In this paper, the cost function is defined as the sum of demand cost and energy consumption cost. Demand cost is $5.25/kW for on peak hour, $0 for off peak hour, the energy consumption cost, i.e. the utility rate is shown in Figure 11. The simulation results are shown in Figure 12 and Table 1. The day used for simulation is July 24, 2010.

**Figure 11. Example of Energy Price Model and Pre-cooling for Peak Load Shifting**

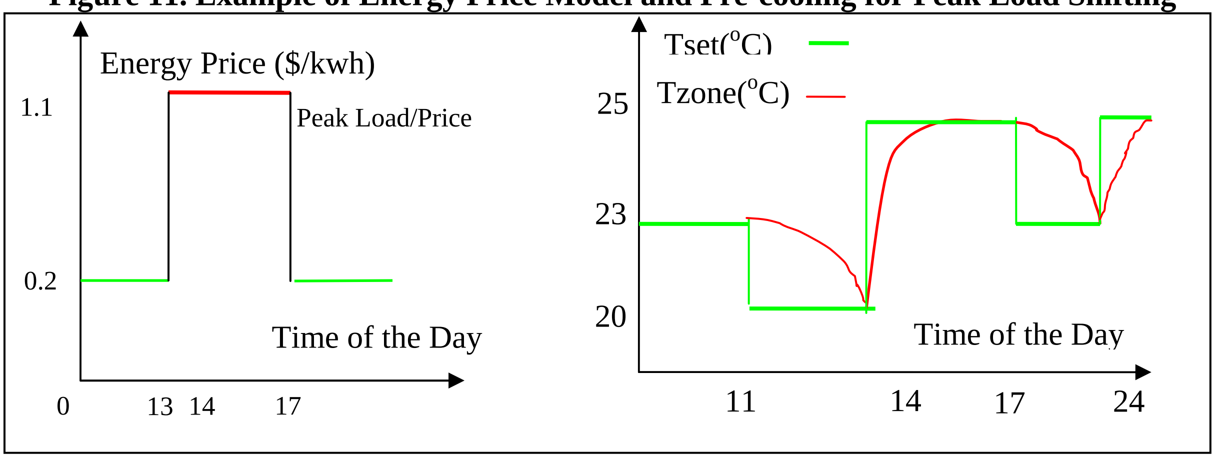
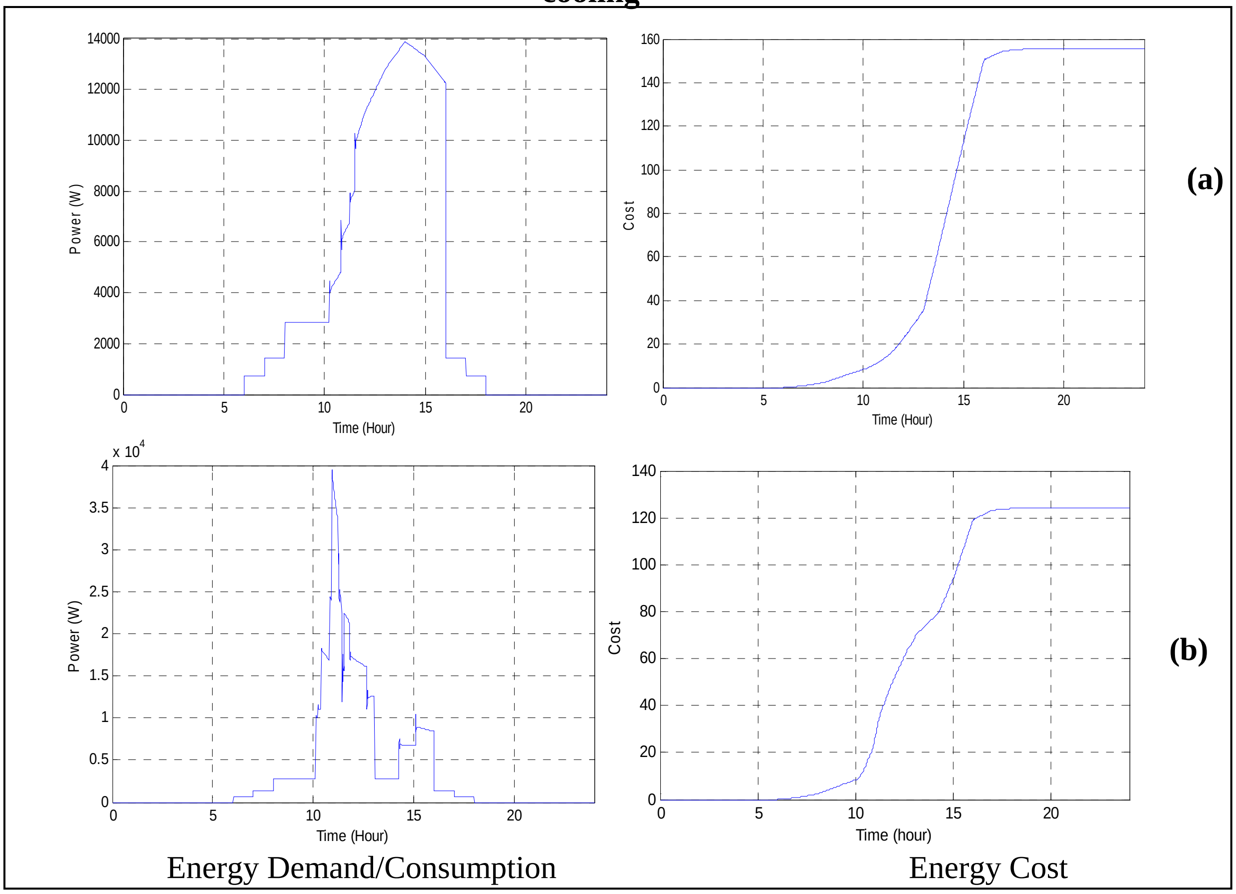



**Table 2. Cost Saving Results of Strategy 6**

| | Optimized Pre-cooling | Without pre-cooling | Cost saving (%) |
|---|---|---|---|
| Energy cost | 123.94 | 155.35 | 20.21 |
| Demand cost | 55.55 | 72.91 | 23.80 |
| Total cost | 179.49 | 228.26 | 21.37 |

**Figure 12. Peak Load Shifting Simulation Results: (a) without pre-cooling (b) with pre-cooling**




It can be observed from the simulation results that the peak loads have been shifted away, which brings saving in both energy and demand costs. Notice that the zone temperatures remain in occupancy's comfort zone. The impact of the ambient temperature inaccuracy can also be analyzed. The comparison is shown in Table I, which shows that the proposed strategy can save about 21.27% in total cost compared to non pre-cooling control strategy.

## Conclusion and Future Work

An Energy Management Control Framework for building operation optimization and control is proposed in this paper. This framework enables the exploration of the saving potential of several energy saving strategies which are also proposed in this paper. This framework is also an enabler for active occupant-driven control and micro-zoning control which incorporates occupants' real-time requests and predicted schedule and task information to optimize BAS operation and control.

Co-simulation platform with MATLAB/SIMULINK and EnergyPlus is used to implement the proposed EMC framework, strategies and simulations on a real building model that is generated from the Intelligent Workplace (IW) building at Carnegie Mellon University. The simulation results verified the feasibility and effectiveness of the proposed EMC framework and strategies.

More run-time simulations will be performed with this co-simulation platform to explore and evaluate more energy saving strategies on DoE benchmark building models. The future work also includes the implementation of this EMC framework on the real Siemens hardware and testing the EMC strategies in a real building.

## Acknowledgement

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