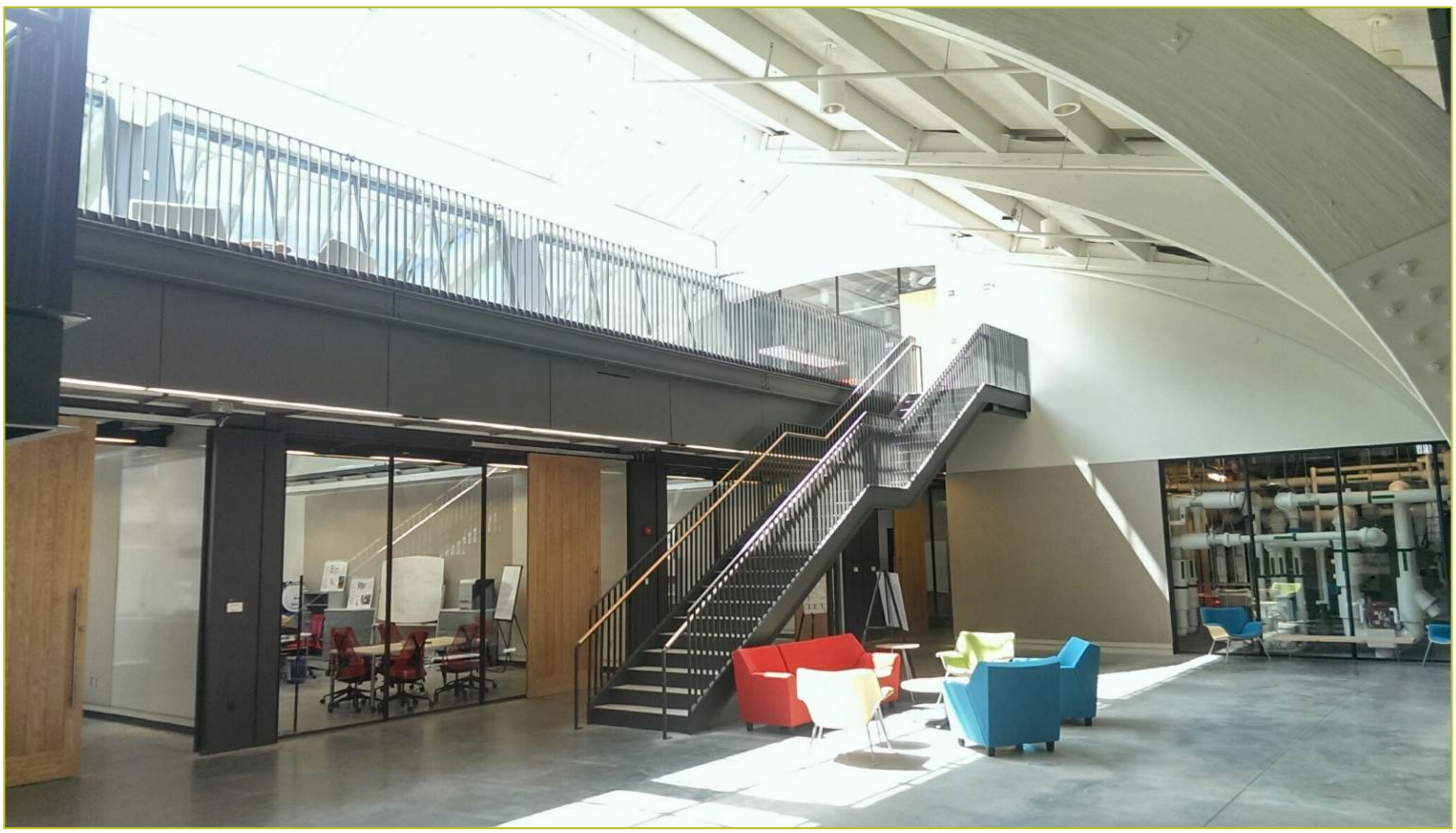
CONSORTIUM for BUILDING ENERGY INNOVATION

REPORT

Title: Integrated Controls for Retail Stores with Refrigerated Cases

Report Date: April 30, 2016

Report Authors: Donghun Kim and James Braun



Funded by U.S. DOE

CONSORTIUM for BUILDING ENERGY INNOVATION

REPORT

Report Abstract

Retail stores equipped with both air handling and refrigeration systems are ubiquitous in much of the developed world. Furthermore, there are significant opportunities in energy savings and peak electric demand reduction for this type of building through improved controls. The overall objectives of this project were to: 1) to develop a virtual testbed for evaluating integrated control of RTUs and refrigeration equipment in convenience stores; 2) to develop and access integrated control approaches using the testbed for a case study convenience store. A detailed simulation model was developed using a reduced-order CFD model coupling approach and the model was validated with field measurements. The model captures important dynamics of the building and spatial temperature variations which are critical in evaluating controller performance, especially for assessing peak electric demand for multiple pieces of equipment that are cycling in response to variable and coupled loads. The RTU coordinator developed during BP4 and BP5 was extended to buildings equipped with air conditioning and refrigeration units and tested using the simulation testbed for a convenience store. In this case study, significant electric peak demand reduction for cooling compared to a conventional thermostat control algorithm was achieved (18 %) using the unit coordinator, while energy savings for cooling were about 8%. Depending on the electric utility rates, this could lead to cost savings in the range of 10 to 15% for this particular case study building. Additional savings may be possible in buildings having equipment with a more diverse set of performance characteristics.

Contact Information for lead researcher

Name: James E. Braun
Institution: Purdue University
Email address: jbraun@purdue.edu
Phone number: 765-494-9157

Contributors

Purdue - Donghun Kim, Sugirdhalakshmi Ramaraj and James E. Braun
Virginia Tech- Samah Ben Ayed, Eugene M. Cliff and Jeff T. Borggaard

1. INTRODUCTION

Retail stores with refrigerated display cases are ubiquitous in much of the developed world. An initial analysis of data from a (USA) retail directory indicates that there is approximately 3 billion square feet of buildings that incorporate both air conditioning and refrigeration equipment (big box super-centers, supermarkets, convenience stores, large drug stores, etc) with approximate electrical energy consumption of 1283 trillion BTU per year [1]. This represents about 10% of the total electrical energy used in commercial buildings across the USA. A conventional control approach for these buildings relies on local feedback control, where each unit is cycled on and off using its own thermostat. Because a thermostat operates regardless of the overall building's behavior, the conventional control approach could result in unnecessary energy use and high electrical peak demand via poor coordination among the units. Therefore significant energy savings and/or electrical peak demand reduction can be achieved by optimally coordinating both air conditioning and refrigeration equipment.

The goal of this project was to develop and evaluate a practical control algorithm for on/off staging of multiple air conditioning and refrigeration units. In a previous milestone report (M2.6b), a candidate control approach, which was previously developed during budget periods BP4 and BP5 and designed to coordinate multiple rooftop units in an optimized manner, was proposed for energy or demand savings in retail stores that include both air conditioning and refrigeration. The focus of this report is to document and evaluate the control algorithm using a simulation platform.

The control algorithm, termed the Plug-and-Play (PnP) RTU Coordinator [2], is discussed in Section 2. Section 3 describes the experimental validation of the simulation testbed applied to a Home Depot Convenience (H-DC) Store in Acworth, GA, which is a CBEI demonstration site. Development of the reduced-order CFD coupled model for this retail store was presented in a previous report (M2.6a). Results of controller evaluations for the store over the summer are provided in Section 4. In Section 5, the economic benefits of the PnP controller are estimated based on the results of Section 4.

2. CONTROL APPROACH FOR RETAIL STORES

2.1 Difference between RTU control and RTU coordination

Since a conventional thermostat control approach does not consider overall building performance, it is natural to design a controller targeting reduction of energy consumption and peak demand in a centralized manner.

During budget periods BP4 and BP5, a control algorithm coordinating an open space building served by multiple rooftop units (RTU) was developed and demonstrated. The control approach, termed the plug-and-play (PnP) RTU Coordinator [2], was designed to minimize the time required to configure the control strategy in order to enable a more cost effective control implementation for small/medium commercial building applications in which buildings are served by multiple RTUs. The control solution is not site-specific and provides reduced energy consumption and peak demand with low sensor requirements. Therefore it is a strong candidate to provide energy/demand savings for retail store applications.

Due to its unique characteristic that it relies only on thermostat signals, i.e. temperatures and ON/OFF stage commands, the coordination algorithm can be directly applied to buildings equipped with both air handling and refrigeration units as depicted in Fig. 1.

The RTU Coordinator has been slightly modified in order to apply to retail store buildings having refrigeration equipment. This is because the RTU Coordinator was designed for open space building applications while many retail store buildings, e.g. convenience stores, have separated zones served by different units. The algorithm details are explained in the following section.

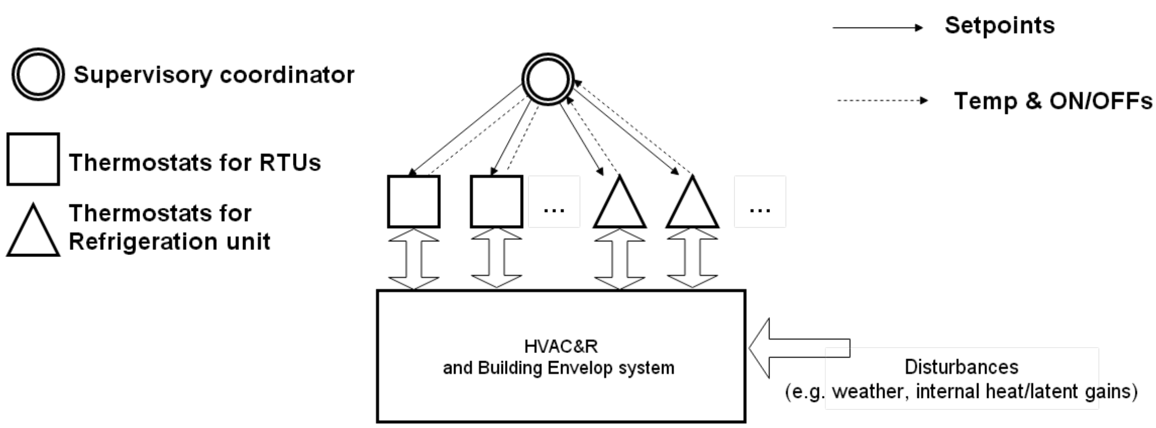


Figure 1: Unit coordinator elements and I/O for retail store applications

2.2 Control problem formulation of unit coordinator

To formulate the control problem for optimal coordination between air conditioning and refrigeration units, let $p \in \mathbb{N}$ (a natural number) be the number of thermostats or equivalently the number of air conditioning and refrigeration units. The measured outputs are the thermostat temperatures, denoted as $y(k) \in \mathbb{R}^p$. The manipulated variables are the unit stages, denoted as $u(k) \in \mathbb{N}^p$.

The control problem at a current time step k is:

$$\min_{u(j)\in \mathbb{N}^p, \delta \in \mathbb{R}^+, \Gamma_l \in \mathbb{R}^{p+}, \Gamma_u \in \mathbb{R}^{p+}} \sum_{j=1}^{N_p} \sum_{i=1}^{p} P_i u_i(k+j) + d \cdot \delta + c_l^T \Gamma_l + c_u^T \Gamma_u \qquad \text{Eqn. (1)}$$

$$T_l - \Gamma_l \le E(y(k+N_p) \mid G_k) \le T_u + \Gamma_u$$

$$\sum_{i=1}^{p} P_i u_i(k+j) \le \delta \quad (\forall j \in \{1, \ldots, N_p\})$$

where P_i is the rated power for i[th] unit, and hence the first term in the control objective represents a scaled energy consumption over a predicted horizon, N_p. $E(y(k+N_p) \mid G_k)$ is the optimal N_p-step prediction given data $G_k = \{y(k-1), y(k-2), \ldots, u(k+N_p-1), u(k+N_p), \ldots, u(k-1), u(k-2), \ldots\}$. $T_u, T_l \ (\in \mathbb{R}^{p})$ are temperature upper and lower bounds, respectively. $c_l, c_u \ (\in \mathbb{R}^{p+})$ and $d \ (\in \mathbb{R}^{+})$ are weights on optimization variables of $\Gamma_l, \Gamma_u \ (\in \mathbb{R}^{p+})$ and $\delta \ (\in \mathbb{R}^{+})$.

From the last constraints, it can be seen that δ is an upper bound on each instantaneous electric demand over the prediction horizon. Therefore minimizing δ will naturally lower an electric peak demand over a prediction horizon. In addition, note that δ is dependent on all sequences of stages of p-units. Therefore it is clear that the control problem supervises both air conditioning and refrigeration units.

Γ_l and Γ_u can be seen as comfort violations from the first constraint of (1). These variables are required to guarantee the existence of solution of the optimization problem.

Note also that we only want to regulate the N_p-step ahead predicted temperatures within a temperature bound and not each of the predicted temperatures for less than the N_p steps. This is acceptable because our prediction horizon, N_p, is relatively short, e.g. 30 min to 1 hour. The N_p-step temperature regulation reduces the large number of inequality constraints that would be necessary if all of the predicted temperatures were constrained.

The control problem of the RTU Coordinator can be obtained by eliminating δ, Γ_l and Γ_u in the objective and constraints in (1) (See [2]). Therefore, the unit coordinator can be seen as a generalized version of the RTU Coordinator.

3. DEVELOPMENT AND VALIDATION OF CONVENIENCE STORE BUILDING MODEL

A simulation study is essential in evaluating the overall benefits of the unit coordinator as compared with conventional control especially for a long period of time. This is because it was not possible to perform long-term side-by-side testing of the unit coordinator and conventional control for this site. During this project, a detailed model was developed and is briefly described in this section. This model was used as a virtual testbed to evaluate performance of the unit coordinator.

The Home Depot convenience store (floor area 223.6 m^2, satellite view in Fig. 2, which is a CBEI demonstration site, is located in Acworth GA. The store has four zones as shown in Fig. 3. The blue zone is the main customer service area served by two equivalent 3-ton rooftop units. The green zone is a medium temperature walk-in refrigerated chamber served by two identical cooler units (< 2 ton) for beverages. The red zone is a low temperature (freezer) case having one unit (< 1 ton). The three refrigeration units have their own refrigeration circuit consisting of an air-cooled condenser and several evaporator coils. The pink zone is storage/office space served by one RTU. Each unit is controlled by a separate thermostat and is shown as circles in the Fig. 3 (the thermostat locations for the storage and freezer are not shown).

A detail model for the building was developed and previously reported in milestone 2.6a. The uniqueness of the model is that it captures spatial temperature variations for open space areas, e.g. the main service and cooler zones in this building, using a reduced-order coupled computational fluid dynamics (CFD) model [3].

Figure 2:   Google satellite view of the store

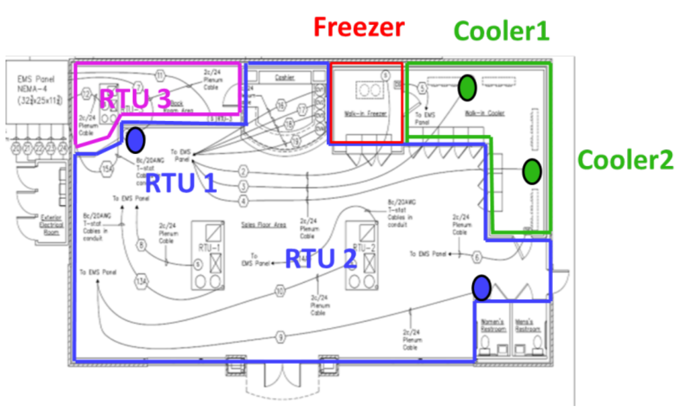


Figure 3: Zoning and unit numbering for Home Depot convenience store

For experimental validation, measured input data was selected and provided to the model. Corresponding model outputs were recorded for comparison with measured outputs. As inputs, the supply air temperature/humidity for each unit (3 RTUs, 2 coolers and 1 freezer), the outdoor air temperature and percent door openings were selected. Four sensors which record percent door openings over 5 minutes were installed at the main store entrance door and display doors for the cooler and freezer as shown in Fig. 4. The information of % door opening at the main door was used to estimate an occupancy profile and the others were used to estimate heat and moisture transfers through traffic of display doors as discussed later.

Due to technical issues (e.g. time delay of thermostats), the return air temperatures to the units were selected as outputs instead of thermostat temperatures. It was assumed that the comparison of the return air temperatures provides a good metric for model validation. The return air temperature/humidity sensors were located at the upstream inlets of the units. Supply air temperature/humidty sensors were located downstream of the units. Sensor locations are shown in Fig. 4.

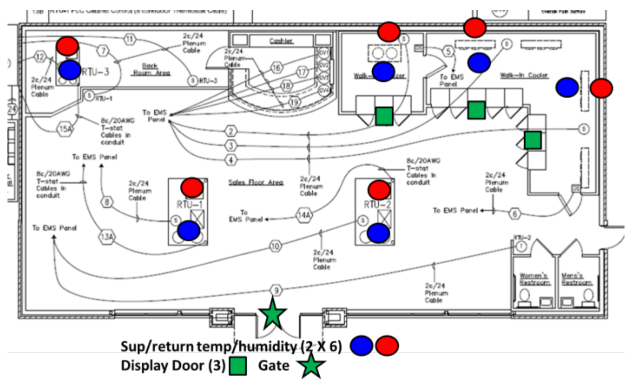


Figure 4: Sensor locations

A sample input data set for model validation is shown in Fig. 5[1]. As shown in Fig. 4, sensors for measuring % door openings were not installed for all doors. However, the integrated model needs averaged % door openings for cooler and freezer. Therefore we performed an hour moving average on raw measurement data assuming that the time average approximates the space average over all display doors. The filtered % door openings for freezer and cooler were fed to the reduced-order CFD coupled model and are shown in Fig. 5b.

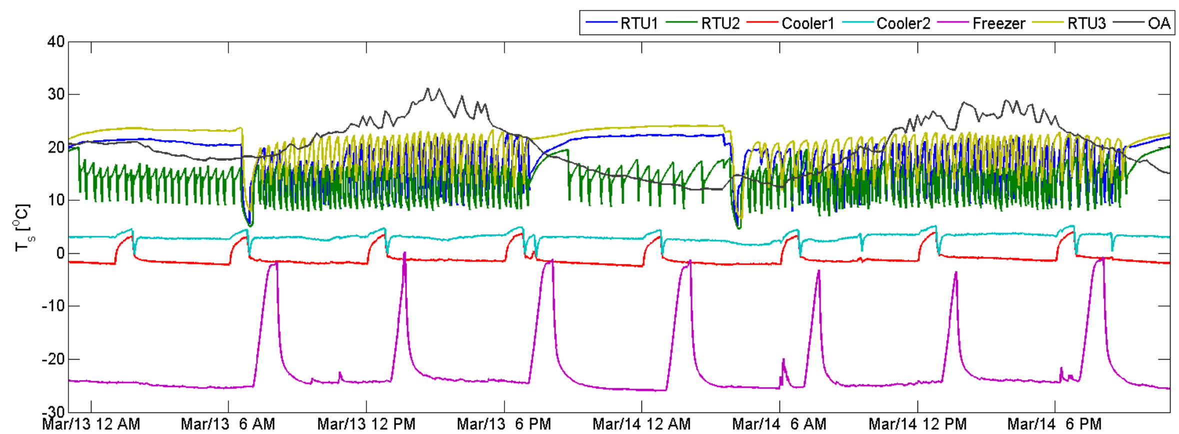
Raw data for % door openings for the main door are shown with a red line in Fig. 5b. It was assumed that the % door openings for the main door approximate the occupancy profile (scaled to 100) for the store. The estimated occupancy profile was used to calculate occupant and lighting load for RTU zones based on assumptions of maximum occupancy and nominal heat rates [4]. It is very interesting that the main door was not fully closed after midnight for this particular period, although the store should be closed during this time (See Fig. 5b). Since it is clear there is no occupant load for the store, we enforced the estimated load for RTU zones being zero from 12:00 AM to 6:00 AM when the store should closed despite the measurement. The estimated load was fed to the model as input. In most of the other time periods where store opening data was collected, the main door was closed when the store was closed.

Corresponding output comparisons associated with the input data are shown in Fig. 6 (see Fig.3 for locations of units associated with the different plots). For each plot (i.e., each unit), the green line represents the output response for return air temperature of the coupled model, whereas the blue line is the measured output. However, there is a bias in the predictions especially for the main service area (RTU1 and RTU2) and cooler2. Some possible explanations include: 1) There could be significant unknown heat gains, because of lack of measurements and many assumptions made in calculation of

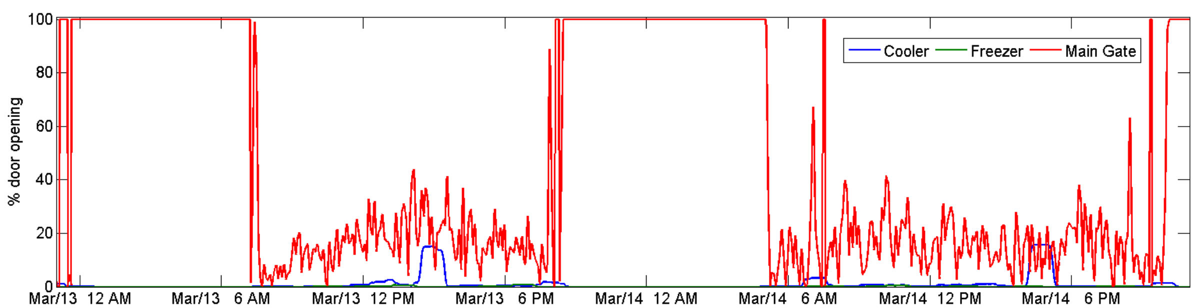
[1] Supply air humidities are not shown.

loads. 2) The CFD model was linearized at a typical daytime operating condition for the assessment of the unit coordinator but the experiment includes night time periods. 3) The initial conditions may not be well matched. Although the fast air dynamics attenuate the effect of the mismatched condition for the air states, the slow dynamics of the building structure could act as pseudo heat sources/sinks for the coupled model if the initial conditions differ significantly.

Despite the biases, the model properly captures the overall building dynamics, especially the dynamics due to unit cycling.



a) Supply temperatures (°C)



b) % door openings

Figure 5: Input data for the validation of a reduced order CFD coupled model for the Home Depot convenience store

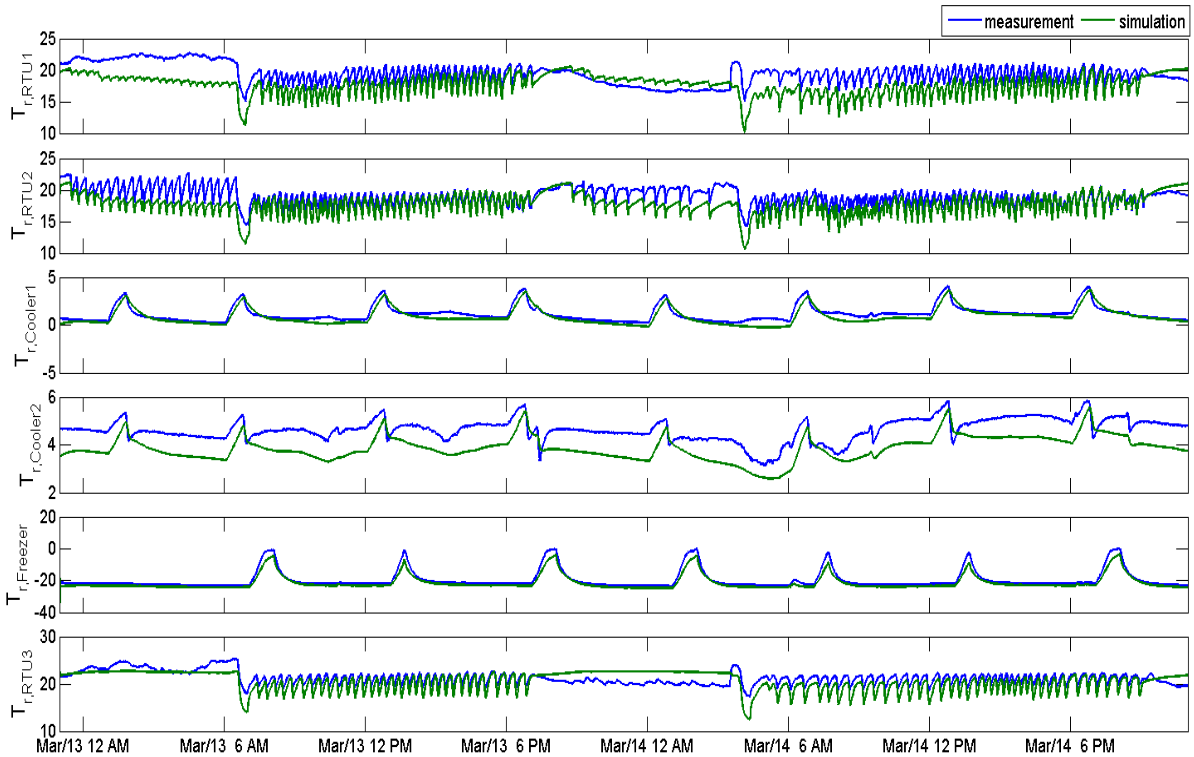


Figure 6: Output comparisons for Home Depot store, Tr,i: return air temperature for ith unit

4. RESULTS AND DISCUSSIONS

4.1 Example PnP Control Behavior for Home Depot Convenience Store

The simulation model described in Section 3 was executed in the Matlab Simulink environment with a stiff ordinary differential equation numerical solver, *ode15s*, that provides variable simulation time steps. The set-points for the conventional controls during an occupied period (6:00AM to 12:00AM) were set as (22 ^oC, 4 ^oC, -15 ^oC) for RTUs, coolers and freezer, respectively. Deadbands of 1^oC were used for all thermostats.

The unit coordinator controls predicted temperatures between 20 to 23 ^oC for RTUs, between 2 to 5 ^oC for coolers, and between -17 to -13 ^oC for the freezer, respectively. An ARX(3,2) model structure with two weeks of historical I/O data were used to establish the controller model for the unit coordinator. A 30-min look ahead horizon was used for the controller in this study. For the penalty terms of δ, Γ_l and Γ_u, 100, 1000 and 1000 were assigned in this simulation study.

A 5-minute sampling time was applied for both the conventional and unit coordinator controllers. The sampling time for the conventional control is to account for anti-cycling time for units to avoid too frequent cycling. A four-month simulation, from May to Aug, was performed for each controller with TMY3 data. It should be mentioned that the cooler and freezer RTUs in the Home Depot store are undersized. This can be checked from Fig. 5a: Units for cooler 1 and freezer are always operating except for the periods of defrost. This case is not suitable for assessing the unit coordinator, since there is no opportunity for coordination. For this reason, we reduced the plug loads for the cooler and freezer from those used for the model validation in order to perform the case study.

In a setting with multiple RTU's with different efficiency ratings, it's possible to save energy by increased use of the more efficient units. Since the two RTUs for the main service area are identical and two coolers are also identical, the primary expected benefit of coordination for this case is demand reduction. Fig. 7-8 show sample comparisons between the conventional and unit coordination controls from the four-month simulation results. The left hand side of the figures indicates the thermostat temperatures and the right hand side indicates the unit staging for the controls. For the conventional case, all units cycle significantly during the day due to part-load conditions. There are some situations where 5 units are operating at the same time resulting in high peak power consumption. An example can be seen at around 2:00 PM in Fig. 7. The total HVAC power at this time is around 15 kW as shown in the left hand side of Fig. 9.

However, the Unit Coordinator algorithm predicts 30-min ahead and supervises unit stages that can bring the zone temperatures within the comfort bounds with the minimum peak power for the 30-min ahead prediction period. This coordination can be seen in Fig. 8. When there is a need for operating several air conditioning units at a same time, e.g. marked as red dashed lines in Fig. 8 where both RTU1 and RTU2 were turned on, the coordinator adjusts sequences of stages of refrigeration equipment in order to reduce electric peak demand. This reduces the peak demand from 15 kW to 9 kW as shown in Fig. 9. Of course, when the cooling load is close to full capacity, there is no opportunity for demand reduction. However, in practice, units are selected to meet a peak load that may occur for only a few days a year and units work under a part-load condition for most times. This means there is significant peak demand reduction potential in most cases with greater potential.

Due to balancing between reduction of peak demand and comfort violations (difference in thermostat temperatures from desired setpoints) of the unit coordinator as shown in (1), comfort violations for the unit coordinator are slightly higher (around $1^{o}C$) than for the conventional thermostat algorithm. However the magnitudes of the violations are in an acceptable range as shown in Fig. 9, since the unit coordinator also tends to minimize the comfort violations.

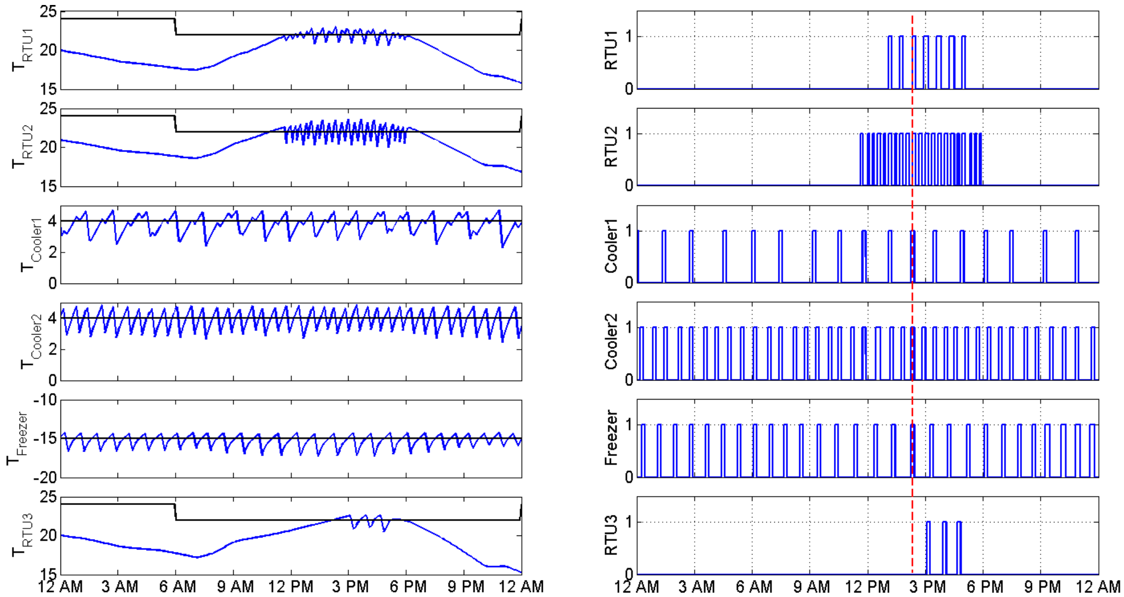


Figure 7: Representative RTU cycling and associated thermostat responses for conventional control at the Home Depot convenience store

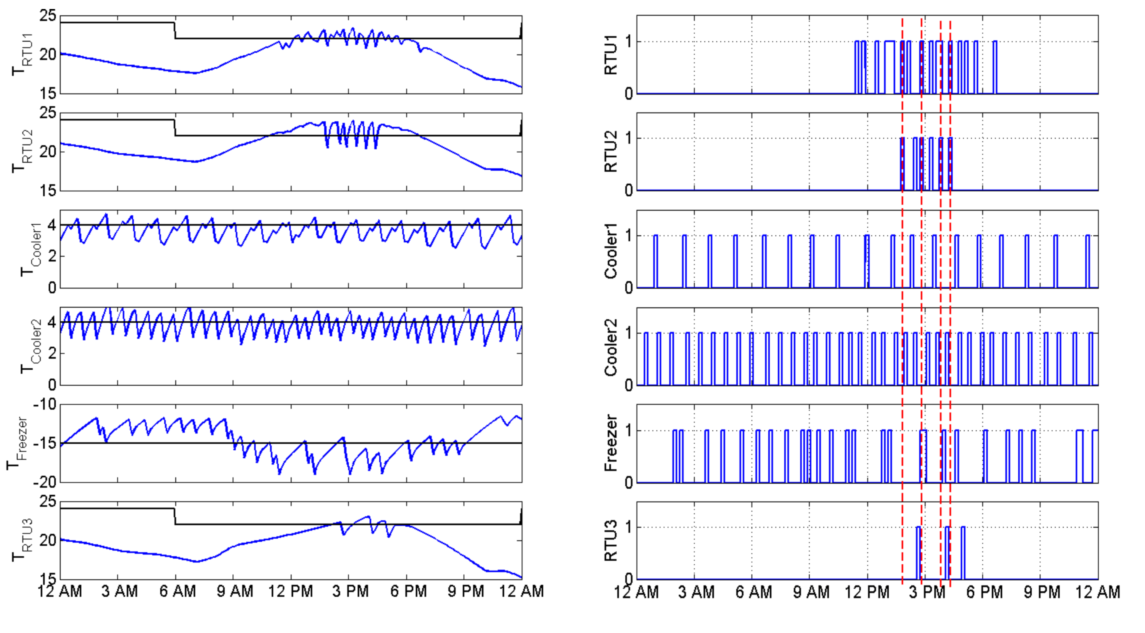


Figure 8: Representative unit cycling and associated thermostat responses for unit coordinator at the Home Depot convenience store

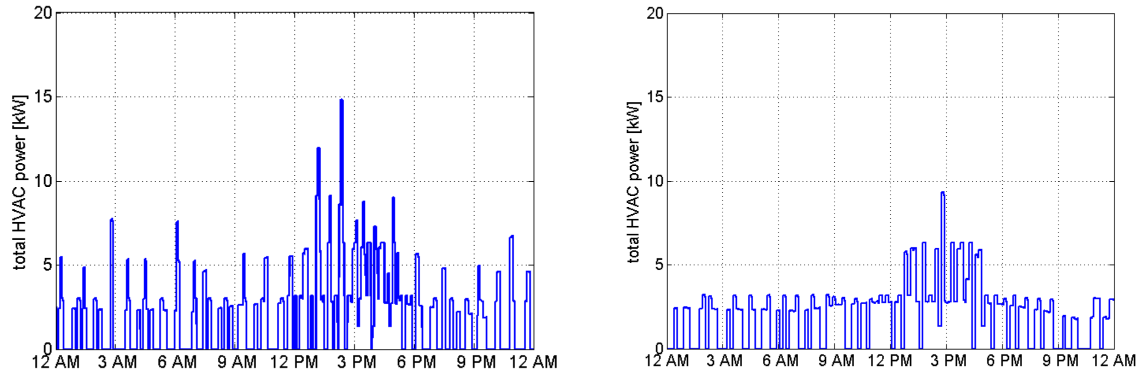


Figure 9: Profiles of total HVAC&R power for conventional (left) and unit coordinator (right) at the Home Depot convenience store

4.2 Cooling season energy and demand savings for Unit Coordinator

Comparisons between the conventional and unit coordinator for the summer season are summarized in Table 1. Peak demands were calculated after performing a 15-min moving average on instantaneous power profiles for the simulation period. As expected, the energy savings are small due to lack of diversity in unit efficiencies. However the benefit of peak demand reduction is significant. The demand savings for the unit coordinator at the Home Depot convenience store for the summer season are about 18 %.

Table 1. Cooling Season Comparisons for HD-convenience store

	May		June		July		August		4-Month Totals	
	Conv	PnP	Conv	PnP	Conv	PnP	Conv	PnP	Conv	PnP
Energy (MWh)	2.3	2.2	3.5	3.2	3.9	3.5	3.9	3.6	13.6	12.5
Peak Power (kW)	13.0	11.8	14.8	11.7	14.8	11.7	14.3	11.7	56.9	46.9
Energy Savings (%)		4.3		8.6		10.2		10.2		8.1
Peak Demand Cost Reduction (%)		9.2		20.9		20.9		18.2		17.6

5. CONCLUSIONS

A practical control algorithm for coordinating both air handling and refrigeration equipment was developed and evaluated using a simulation testbed for a convenience store in terms of energy and demand savings. The simulation testbed was validated with site data and captured important dynamics. The simulations allowed evaluations of savings for the unit coordinator compared to conventional control over an entire cooling season. Based on these evaluations, typical cooling season energy and peak demand savings are expected to be about 8 % and 18 %, respectively. The controller was designed to minimize implementation costs in that it does not require additional sensors and is self-learning. It can be generally applied to retail stores served by multiple air handling and refrigeration units.

Bibliography

[1] Commercial Buildings Energy Consumption Survey (CBECS), 2003, https://www.eia.gov/consumption/commercial/data/archive/cbecs/cbecs2003/detailed_tables_2003/2003set14/2003html/c1a.html

[2] Kim, D., Braun, J.E., Cai, J. and Fugate, D.L., 2015. Develo*pment and experimental demonstration of a plug-and-play multiple RTU coordination control algorithm for small/medium commercial buildings*. Energy and Buildings, 107, pp.279-293.

[3] Kim, D., Braun, J.E., Cliff, E.M. and Borggaard, J.T., 2015. *Development, validation and application of a coupled reduced-order CFD model for building control applications*. Building and Environment, 93, pp.97-111.

[4] ASHRAE Handbook, 2001, Fundamentals. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, 111.