Explaining Inefficiencies in Buildings Providing Ancillary Services

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ABSTRACT

In a power system, having a high level of renewable energy penetration requires a large amount of ancillary services to balance the supply and demand in real time. Commercial buildings have significant thermal capacity and so offer large potential for providing such services. Recent research has shown that the power consumption of the Heating, Ventilation, and Air Conditioning (HVAC) system can be varied to track regulation signals arising from frequency regulation services, while maintaining a comfortable indoor climate. However, experimental results from a 30,000 m^2 office building suggest that tracking zero-mean power variation signals may cause an increase in the HVAC energy consumption. This energy loss translates to additional costs and environmental impacts for commercial building HVAC systems that provide ancillary services.

This paper investigates potential causes for this efficiency loss, and in particular considers the impact of thermal dynamics and control design. In the former case, we analyze a variety of factors including nonlinearity in the supply air fan and the heat exchange process between rooms and the ambient environment. The control design incorporates a nonlinear mapping between room thermostat set-point deviations and the resulting changes in the fan power. We investigate this design to ascertain its impact on efficiency and also consider interactions with the building automation system.

The analyses in this paper help us better understand the mechanisms underlying efficiency loss when commercial building HVAC systems are used for ancillary services. These investigations underpin the design of controls that offer improved efficiency.

Introduction

In a power system, electricity supply and demand have to be kept in balance to maintain the functionality of the system. With more renewable energy sources being integrated into the power system, more uncertainties, such as forecast errors, are introduced. Thus, more ancillary services are needed to correct the supply-demand mismatch in real time (Makarov et al. 2009).

Traditionally, ancillary services are provided by conventional generators, which hold some capacity in reserve so that they can ramp up or down according to the power grid's needs. Recently, researchers have explored the potential of using the demand-side to provide ancillary services. Similar to conventional generators, electric loads can increase or decrease their consumption to help balance the power system. A few examples include: residential loads (Mathieu, Koch, and Callaway 2013), electric vehicles (Sioshansi and Denholm 2010), and pool pumps (Meyn et al. 2013).

Commercial buildings offer another potential demand-side option for providing ancillary services. Commercial buildings consume about 40% of the electricity in the United States, and half of it is by the HVAC system (US Department of Energy 2011). Also, the large thermal inertia of commercial buildings makes it possible to provide ancillary services without significantly affecting the indoor climate (Vrettos et al. 2014, Maasoumy et al. 2014, Hao et al. 2014, Zhao et al. 2013, Lin et al. 2015).

Although it has been demonstrated that commercial building HVAC systems can provide satisfactory ancillary services, the impacts of providing such services on the energy consumption of the system is not well understood. In experimental results in Beil, Hiskens, and Backhaus (2015), it was observed that even if the ancillary service reference signal is zero-mean, there is significant energy loss. This translates to additional costs for providing such services.

In this paper, we investigate the causes for this energy loss. A model for a commercial building and its HVAC system is developed, and simulations are undertaken to study the impacts on energy consumption of providing ancillary services. We find that multiple factors contribute to the change in energy consumption, including nonlinearity in the fan power and thermal dynamics, heat exchange with the outside, control actions, and baseline estimation error. We also discuss the impacts of several parameters on the simulation results.

Problem Formulation

Previous experimental results

This study is partially inspired by the experiments results reported in Beil, Hiskens, and Backhaus (2015). The experiments were conducted in a 30,000 m^2 office building at Los Alamos National Lab. In the experiments, the room temperature set-points were controlled, so that the supply air fan power deviation from the baseline tracks a square wave signal. Figure 1 shows the zero-mean square wave reference signal, the actual power consumption, and the estimated baseline power consumption. We call each square wave an ancillary service event. In the events shown in Figure 1, the power increases in the first period and decreases in the second period, which we call up-down sequence. The down-up sequence, in which the power decreases in the first period and increases in the second period, was also tested in the experiments.

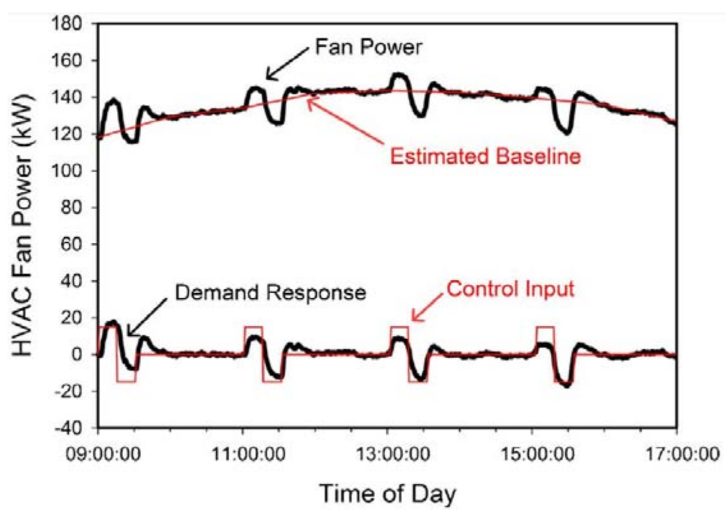

Figure 1. Square wave reference signal, the actual power consumption, and the estimated baseline power consumption in experiments in Beil, Hiskens, and Backhaus (2015). The figure is from Beil, Hiskens, and Backhaus (2015).

Results of a typical ancillary service event are shown in Figure 2. It was observed that after the ancillary service event ended, the fan power did not return to the baseline power immediately. Instead, there was a long overshoot, which leads to additional fan energy consumption. It was also observed that the sequence of the square wave reference signal affects the results and the chiller energy consumption showed similar trends.

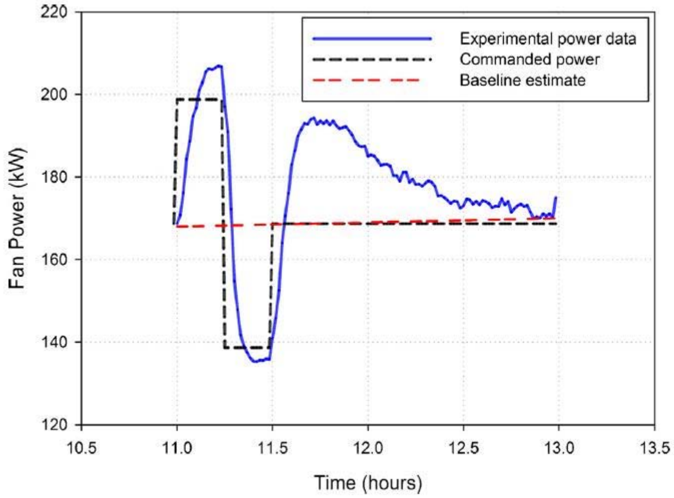

Figure 2. Experimental results of a typical ancillary service event. This figure is from Beil, Hiskens, and Backhaus (2015).

The causes of this energy loss are not thoroughly discussed in Beil, Hiskens, and Backhaus (2015). There could be multiple causes, including nonlinearity in the fan power and thermal dynamics, controller design, and baseline estimation errors. In this study, we simulate the experiments of Beil, Hiskens, and Backhaus (2015) and investigate the energy consumption impacts in simulations.

Assumptions

In this study, we make the following assumptions:

1. Humidity is not considered in the simulations. The weather is dry at the Los Alamos National Lab test bed, thus we ignore the humidity in the thermal dynamics.
2. Outdoor air temperature and occupancy load are constant during the simulation.
3. Supply air temperature is constant.
4. There is no heating in the system. The experiments were conducted during the summer, when heating was disabled.

HVAC model

In this section, we present the model we developed for the simulation study. A schematic of a single zone building and its HVAC system is shown in Figure 3. The air in the room is recirculated as return air. Part of the return air leaves the building as exhaust air, and the rest is mixed with outdoor air. The mixed air is sent through the cooling coil, where the air is cooled to the desired supply air temperature. The air leaving the cooling coil (supply air) is distributed to the room.

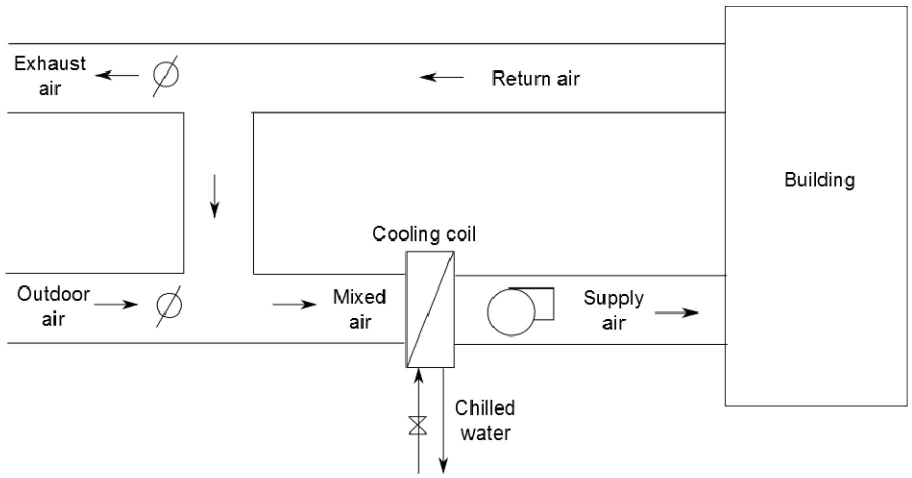

Figure 3. Schematic of the building and its HVAC system.

The thermal dynamics of the building can be described by a circuit-like model (Underwood 2002). Model accuracy depends on the number of resistors and capacitors used in the model. In this paper, we choose a 2R-2C model, shown in Figure 4, where the first state is the room temperature T, and the second state is the wall temperature T_w; T_s is the supply air temperature, T_{oa} is the outdoor air temperature, C_r and C_w are the thermal capacitances of the room and the wall, and R is the thermal resistance of the wall. The dynamics can be written as:

$$C_r\dot{T} = \frac{1}{R}(T_w - T) + m_s C_{p,a}(T_s - T) + Q$$

$$C_w\dot{T}_w = \frac{1}{R}(T - T_w) + \frac{1}{R}(T_{oa} - T_w)$$

where m_s is the supply air flow rate, $C_{p,a}$ is the specific heat of air, and Q is the occupancy load.

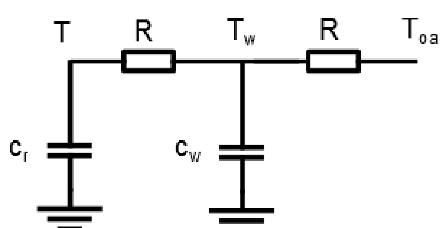

Figure 4. 2R-2C circuit model for the room thermal dynamics.

The fan and duct dynamics from desired supply air flow rate m_r to the actual supply air flow rate $m_s(s)$ are modeled as a first order linear system with DC gain of one:

$$m_s(s) = \frac{1/\tau_f}{s + 1/\tau_f} m_r(s)$$

where τ_f is the time constant of the fan and duct dynamics.

The return air and outdoor air are mixed in the mixing box. Since we do not consider humidity, the temperature of the mixed air is given by:

$$T_m = \alpha T_{oa} + (1-\alpha)T$$

where T_m is the mixed air temperature and α is the outdoor air ratio, which is the ratio of outdoor air flow rate to return air flow rate.

At the cooling coil, the mixed air is cooled to a pre-set supply air temperature set-point. We focus our attention on the cooling needed to condition the air stream, and we do not consider the cooling coil dynamics or the chiller dynamics. The heat exchange at the cooling coil is picked up by the chilled water, the chilled water is delivered to the chiller, and energy will be consumed at the chiller to cool the return chilled water. We do not consider these processes in this study. The rate of heat taken out of the air stream at the cooling coil, P_{cc}, is given by:

$$P_{cc} = m_s C_{p,a}(T_m - T_s)$$

Energy Consumption

We consider two components in the energy consumption: the supply air fan and the cooling needed to condition the air.

Supply air fan

The supply air fan energy consumption is determined by the supply air flow rate. It is given by:

$$E_f = \int_t P_f(t)dt$$

where the fan power $P_f(t)$ is given by a cubic function of the supply air flow rate:

$$P_f(t) = \beta m_s(t)^3$$

where β is the fan power coefficient.

Cooling

As discussed before, we focus on the cooling energy needed to condition the air stream. It is given by:

$$E_{cc} = \int_t P_{cc}(t)dt$$

For convenience of analysis, we translate the cooling energy to electric energy by assuming the cooling is served by a chiller with coefficient of performance η_{COP}:

$$E_{cc,e} = \frac{1}{\eta_{COP}} E_{cc}$$

From the definition of E_{cc}, the cooling energy can be broken up into to two parts:

$$E_{cc,e} = \frac{1}{\eta_{COP}} \int_t \left[\alpha m_s C_{p,a} (T_{oa} - T_s) + (1-\alpha) m_s C_{p,a} (T - T_s) \right] dt$$
$$= \frac{1}{\eta_{COP}} \int_t \alpha m_s C_{p,a} (T_{oa} - T_s) dt + \frac{1}{\eta_{COP}} \int_t (1-\alpha) m_s C_{p,a} (T - T_s) dt$$

We denote the first integral term $E_{oa,e}$ and the second term $E_{r,e}$. The first term $E_{oa,e}$ describes the cooling energy for cooling the outdoor air. It is determined by supply air flow rate m_s, but is not directly affected by the room temperature. The term $E_{r,e}$ is related to the room temperature dynamics. The heat received by the room is given by:

$$E_{room} = \int_t \left[\frac{1}{R} (T_w(t) - T(t)) + m_s(t) C_{p,a} (T_s - T(t)) + Q \right] dt$$

Note that $E_{r,e}$ equals the second term in the integral multiplied by $(1-\alpha)$. In normal operation, the room temperature stays at its set-point; after the ancillary services event, the room temperature also returns to its set-point. Thus, E_{room}, the total energy received by the room over the period from the start of the ancillary services event through to the post-event point where the temperature has returned to normal, is the same with or without the ancillary services event. However, the room temperature does not stay at its set-point during the ancillary services event, so $E_{r,e}$ is different with ancillary services.

Simulation Study

Simulation setup

We studied the energy consumption impacts in simulations with the model described in the previous section. The parameters in the model were calibrated from an auditorium on University of Florida campus (Lin, Barooah, and Meyn 2013). During normal building operation, a proportional integral (PI) controller was used to maintain the room temperature at its set-point by moderating the supply air flow rate. During the ancillary service event, we want the fan power to track a square wave power deviation reference signal. In the experiments in Beil, Hiskens, and Backhaus (2015), this was achieved by changing the room temperature set-point. However, the mapping between the temperature set-point and fan power deviation is non-linear and uncertain. To eliminate this uncertainty, in most simulations, we used a different PI controller for directly tracking the power deviation reference signal, so that good tracking performance was ensured during the ancillary events. After the ancillary service event ended, the power tracking control was released, and the normal operation temperature controller was used to restore the temperature to the set-point. For comparison, we also ran a separate set of simulations with the temperature set-point controller during the ancillary event, which resembled the field experiments in Beil, Hiskens, and Backhaus (2015).

In each set of simulations, we first ran the simulation without providing ancillary services; this gave us the baseline. Then we ran the simulation with an ancillary service event, where the fan power tracked the square wave reference signal on top of the baseline. We compare the results with the baseline to study the impacts on energy consumption.

In the first set of ancillary service simulations, which we call the default case, the length of the pulse was one hour, the magnitude was 20% of the baseline fan power. We then ran several sets of simulations with different parameters (reference signal and building thermal and operating parameters), compared the results with the default case, and studied the impacts of those parameters.

Metrics

To quantify the energy consumption impacts, we first look at the round-trip efficiency defined in Beil, Hiskens, and Backhaus (2015). Let E_{in} be the energy consumption above the baseline and E_{out} be the energy consumption below the baseline. The round-trip efficiency is:

$$\eta_{RT} = \frac{E_{out}}{E_{in}}$$

We also consider the ratio of the change in energy consumption to the reference signal. Let E_{SW} be the energy consumption of one pulse in the reference signal (first part of square wave in Figure 1), ΔE be the total change in energy consumption: $\Delta E = E_{AS} - E_{base}$, where E_{base} is the baseline energy consumption and E_{AS} is the energy consumption with ancillary service event. We define the ratio η_{SW} as:

$$\eta_{SW} = \frac{\Delta E}{E_{SW}}$$

Positive η_{SW} indicates an increase in energy consumption, and negative η_{SW} indicates a reduction in energy consumption.

Results

For each set of simulations, the corresponding figures show the fan power, cooling power, room temperature, and supply air flow rate. The energy consumption and efficiency results are shown in Table 1.

Simulation 1 is the default case; the results of this case are shown in Figure 5 and Table 1. The ancillary service event starts at hour 5; the reference signal changes sign at hour 6; and the event ends at hour 7. We see that in the up-down sequence, the temperature is higher than the set-point when the ancillary service event ends. Thus, additional cooling and higher fan power is needed after the event ends. This leads to an increase in the energy consumption. In contrast, for the down-up sequence, the temperature is lower than the set-point when the ancillary service event ends. Thus, less cooling and lower fan power is observed after the event ends. This leads to a decrease in the energy consumption. We also vary the magnitude of the square wave to be 10% and 40% of the baseline; similar results are shown in Table 1 (rows Magnitude 10% and Magnitude 40%).

In simulation 2, we change the width of the pulse in the reference signal to be 15 minutes. The results are shown in Figure 6 and Table 1 (rows 15-min). Since the event is shorter, the temperature variation is smaller, and the impacts on energy consumption are smaller.

In simulation 3, we changed the controller. The overshoot after the event ends has a significant impact, so we adopt a less aggressive controller with lower gain in this case. The results are shown in Figure 7 and Table 1 (rows New controller). We see that the overshoot in the up-down sequence is smaller compared to the default case; the increase in energy consumption is also less.

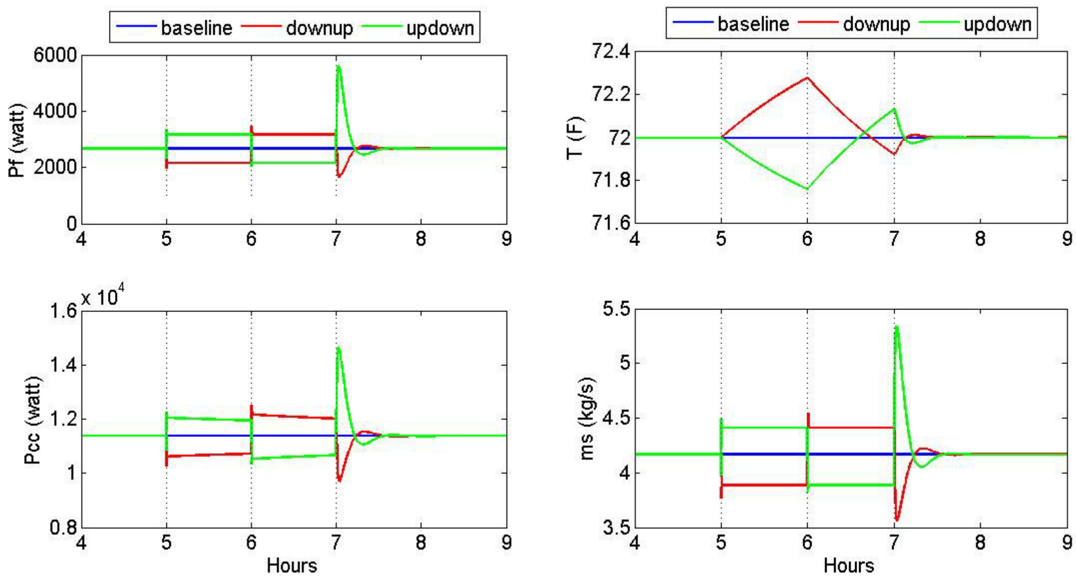

Figure 5. Simulation results for the default case. Plots show comparison among the baseline, the up-down sequence, and the down-up sequence. Upper left: fan power; lower left: cooling power; upper right: room temperature; lower right: supply air flow rate.

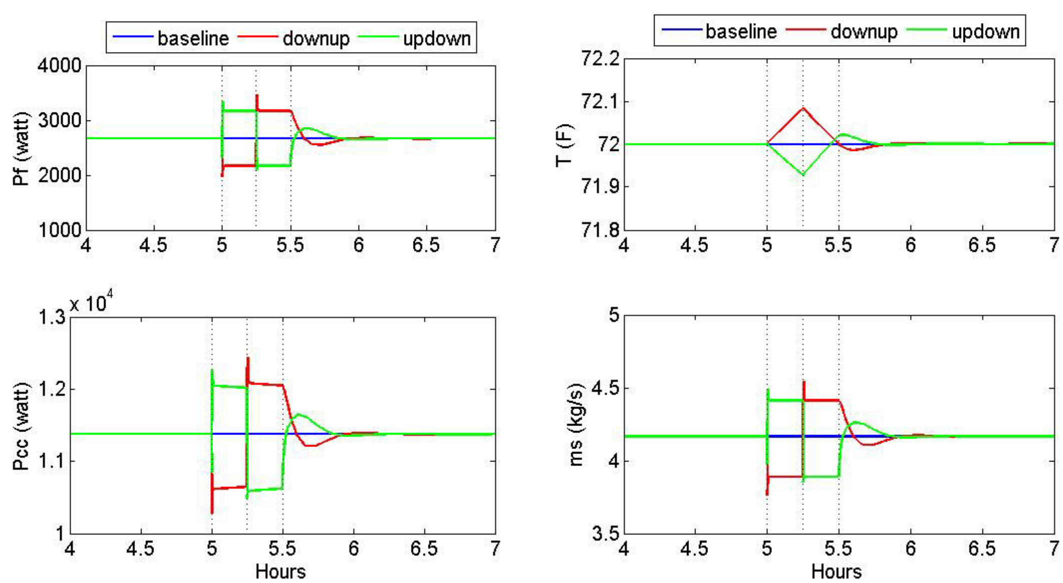

Figure 6. Simulation 2 results with 15 minutes square wave reference signal. Plots show comparison among the baseline, the up-down sequence, and the down-up sequence. Upper left: fan power; lower left: cooling power; upper right: room temperature; lower right: supply air flow rate.

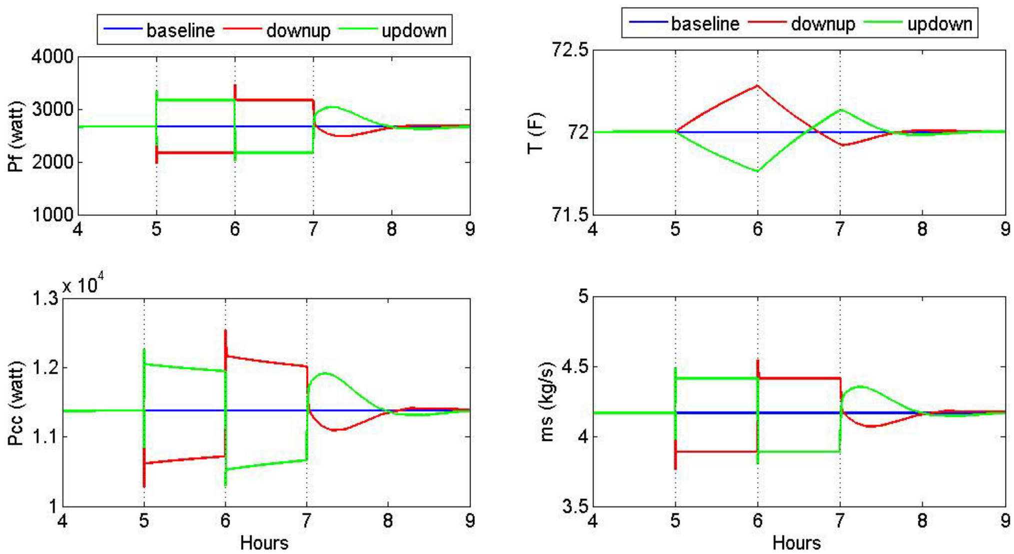

Figure 7. Simulation 3 results with less aggressive controller. Plots show comparison among the baseline, the up-down sequence, and the down-up sequence. Upper left: fan power; lower left: cooling power; upper right: room temperature; lower right: supply air flow rate.

In simulation 4, we change the reference signal. This new reference signal is the frequency regulation signal RegD from the PJM Interconnection (PJM 2014). The square wave is a rather extreme reference signal, where it remains its maximum magnitude for the entire control period. A realistic ancillary service signal usually has more oscillations and does not stay at maximum magnitude. The results are shown in Figure 8 and Table 1 (row RegD). We see that the temperature variation is very small in this case, and the energy impacts are also insignificant.

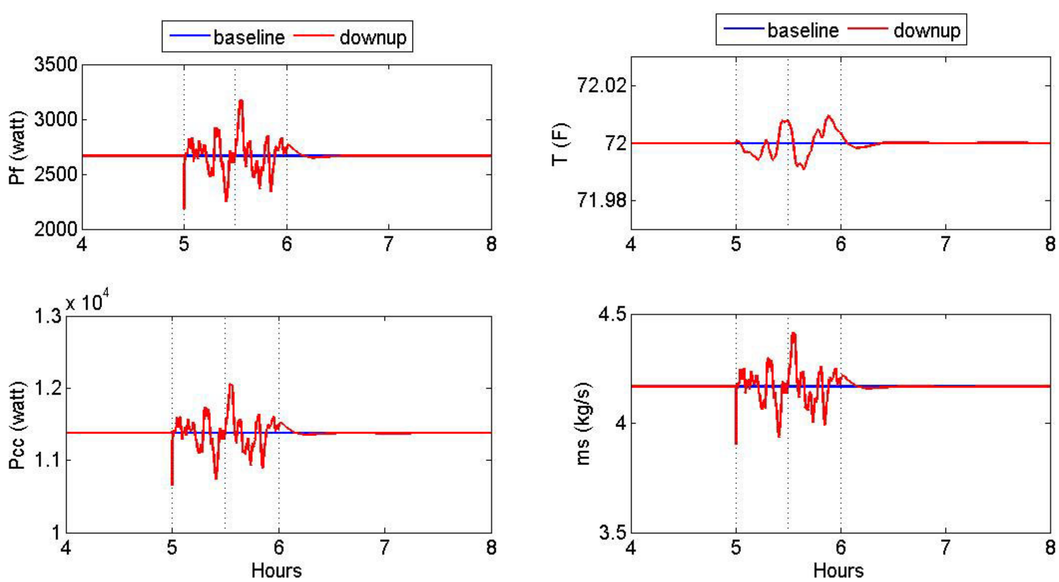

Figure 8. Simulation 4 results with RegD as reference signal. Plots show comparison among the baseline, the up-down sequence, and the down-up sequence. Upper left: fan power; lower left: cooling power; upper right: room temperature; lower right: supply air flow rate.

In Simulation 5, we set the room and wall capacitances (C_r and C_w) to half of those in the default case. The results are shown if Figure 9 and Table 1 (rows Lower C). In this case, the temperature variation is larger, leading to a larger overshoot and higher energy consumption in the up-down sequence.

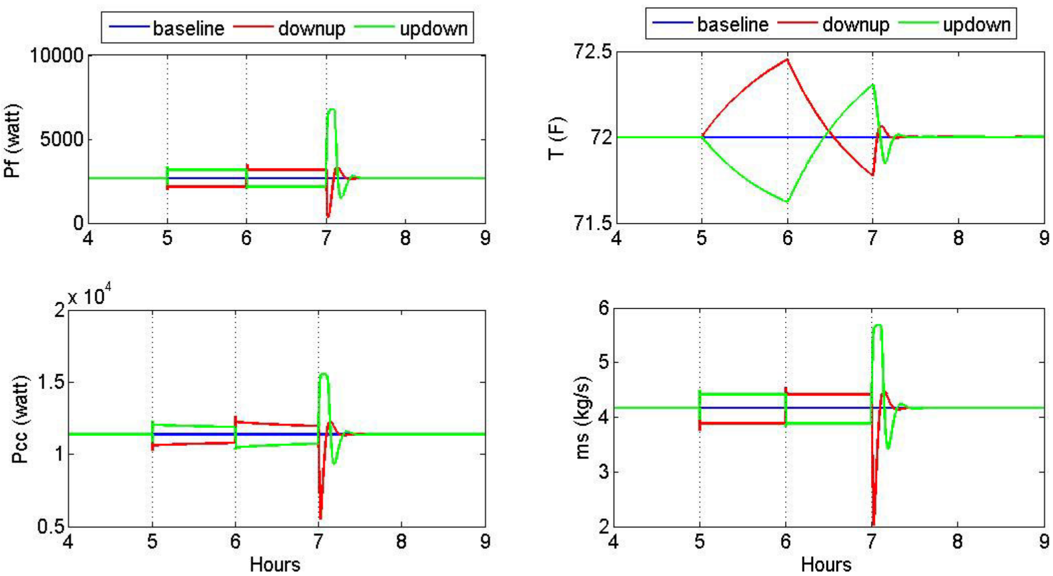

Figure 9. Simulation 5 results with lower thermal capacitances. Plots show comparison among the baseline, the up-down sequence, and the down-up sequence. Upper left: fan power; lower left: cooling power; upper right: room temperature; lower right: supply air flow rate.

In simulation 6, we reduce the outdoor air ratio from 0.4 to 0.2. The results are shown in Figure 10 and Table 1 (rows Lower α). Cooling the outdoor air is a significant part in the energy consumption. In this case, we see that the cooling required to cool the outdoor air reduces as the outdoor air ratio decreases.

In simulation 7, we use the temperature set-point controller, which is similar to the controller used in Beil, Hiskens, and Backhaus (2015). The controller and the change in set-point are turned so that the power variation is similar to the default case. The results are shown in Figure 11 and Table 1 (rows Temperature controller). Note that to obtain good tracking performance, the controller is slow. During the event, the building operation is similar to the default case, since the fan power is similar no matter the power controller or the temperature set-point controller is used for tracking. Thus, the temperatures at the end of the event are also similar. The difference in energy consumption between the default case and this case is caused by the different control actions after the ancillary service event ends.

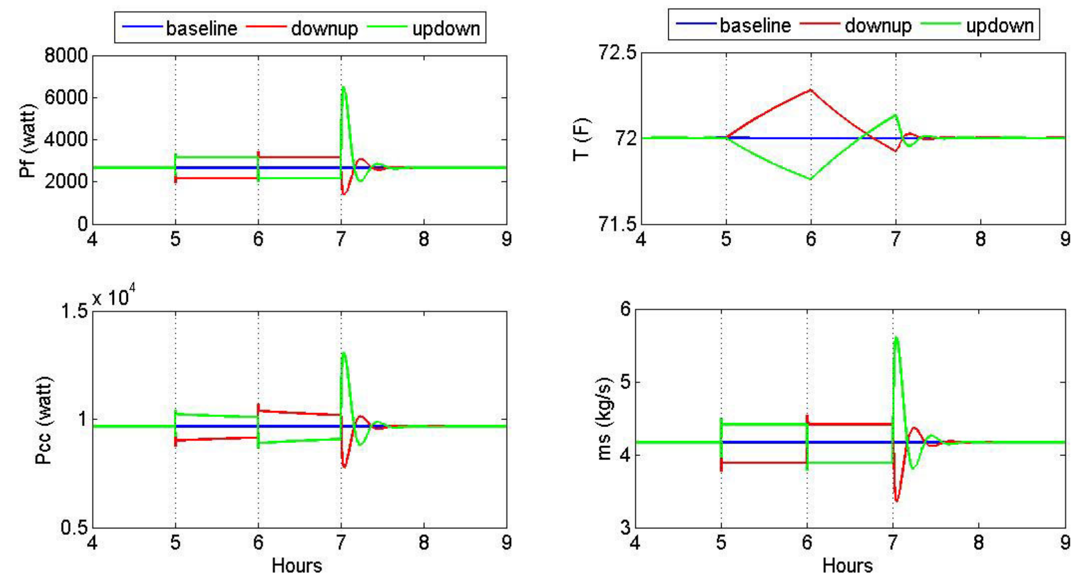

Figure 10. Simulation 6 results with lower outdoor air ratio. Plots show comparison among the baseline, the up-down sequence, and the down-up sequence. Upper left: fan power; lower left: cooling power; upper right: room temperature; lower right: supply air flow rate.

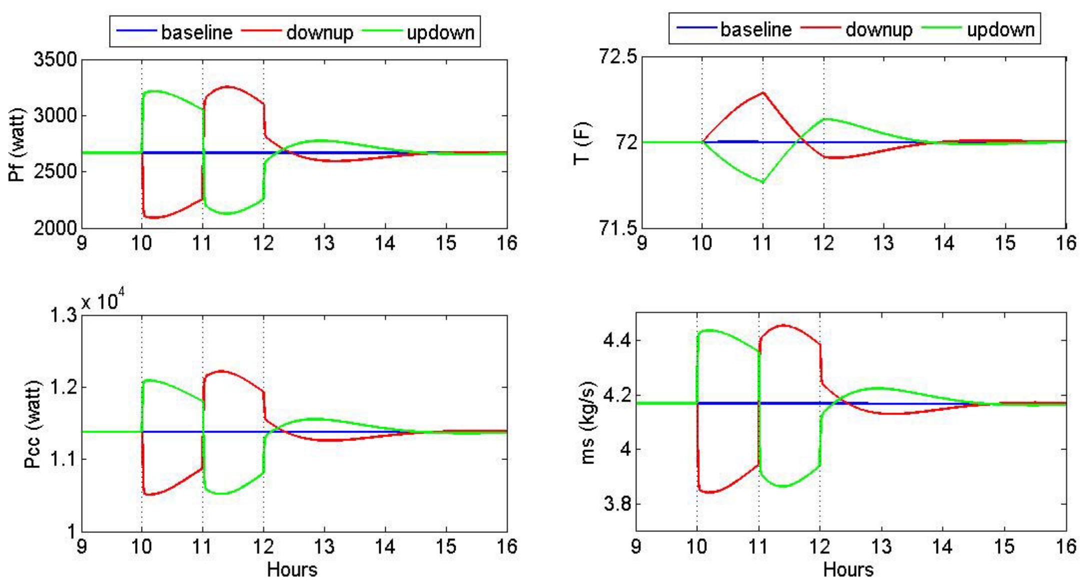

Figure 11. Simulation 7 results with temperature set-point controller. Plots show comparison among the baseline, the up-down sequence, and the down-up sequence. Upper left: fan power; lower left: cooling power; upper right: room temperature; lower right: supply air flow rate.

Table 1. Energy consumption and efficiency results.

Simulations		ΔE_f (Wh)	$\Delta E_{cc,e}$ (Wh)	$\Delta E_{oa,e}$ (Wh)	η_{RT}	η_{SW}
Default	Up-down	247.0	119.8	109.0	0.79	0.74
	Down-up	-100.5	-162.2	-147.3	1.21	-0.52
Magnitude 10%	Up-down	96.8	64.9	58.9	0.81	0.65
	Down-up	-62.2	-76.0	-68.9	1.21	-0.55
Magnitude 40%	Up-down	765.8	198.8	181.7	0.77	0.97
	Down-up	-124.1	-375.2	-340.3	1.20	-0.50
15-min	Up-down	26.7	9.0	8.2	0.90	0.29
	Down-up	3.4	-12.4	-11.5	1.03	-0.07
New controller	Up-down	182.0	100.3	91.9	0.83	0.57
	Down-up	-91.9	-141.6	-130.5	1.18	-0.47
RegD		4.1	0.5	0.3	0.97	0.01
Lower C	Up-down	366.3	143.9	133.2	0.75	1.02
	Down-up	-91.5	-207.3	-190.4	1.22	-0.60
Lower α	Up-down	281.7	69.0	54.7	0.80	0.70
	Down-up	-90.8	-93.9	-74.0	1.15	-0.37
Temperature controller	Up-down	119.6	49.5	46.0	0.89	0.34
	Down-up	-44.0	-103.8	-95.9	1.11	-0.32

Discussion

Temperature variation

The room temperature is a key variable; it affects the cooling energy directly and the fan energy indirectly by affecting the supply air flow rate. During the event period, the temperature variation depends on the sequence of the square wave. In the up-down sequence, the fan power is increased first, so the temperature is lower than the baseline; while in the down-up sequence, the fan power is decreased first, so the temperature is higher than the baseline. Consider the heat the room receives. The first term, $\frac{1}{R}(T_w(t)-T(t))$, describes the heat exchange between the room and the wall. In the simulations, the wall temperature is higher than the room temperature (summer). The second term, $m_s(t)C_{p,a}(T_s-T(t))$, describes the cooling the room receives from the supply air flow. When the room temperature is higher than the baseline, the room receives less heat from the wall and the more cooling from the supply air flow, thus the temperature is lower than the baseline at the end of the event (the temperature only crosses the set-point towards the end of the event). This is the case in the down-up sequence. In the up-down sequence, the room temperature is generally lower than the baseline (the temperature only crosses the set-point towards the end of the event), resulting in more heat from the wall and less cooling. Thus the temperature is higher than the baseline at the end of the event. During the after-event period, the temperature set-point controller drives the temperature back to its set-point.

Fan energy consumption

The fan energy is determined by m_s. During the ancillary services event, the square-wave event is designed such that the power change is symmetric between the up and down periods. Therefore electrical energy is the same as the baseline over the event. At the end of the event, the temperature could be away from its set-point. In the up-down sequence, the temperature ends higher than its set-point; so after the event, higher supply air flow rate is needed to drive the temperature back, which leads to increased energy consumption. In the down-up sequence, the temperature ends lower than its set-point; so after the event, the supply air flow rate is lower than the baseline, leading to further energy savings.

Cooling energy

There are two components in the cooling energy. The term $E_{oa,e}$ is determined by m_s, so it follows the same trend as the fan energy. From the results shown in Table 1, we see $\Delta E_{oa,e}$ is the dominating factor in the cooling energy changes. The term $E_{r,e}$ is affected by the room temperature. Since in both the baseline case and the ancillary event case, the room temperature is at its set-point when the system settles, the total heat received by the room is the same. As discussed in the temperature variation section, in the up-down sequence, the room temperature is lower than the baseline, the room receives more heat from the wall, so it has to get more total cooling from the supply air flow. This leads to a higher $E_{r,e}$. In the down-up sequence, the room temperature is higher than the baseline, the room receives less heat from the wall, so it gets less total cooling from the supply air flow, leading to a lower $E_{r,e}$.

Control design

From the simulation results, we see that the control actions after the event ends significantly affect the results. A less aggressive controller introduces smaller overshoot and is likely to have better energy consumption performance.

Baseline estimation error

In the simulation, we have exact knowledge about the baseline, which is hard to obtain in practice. During a real ancillary service event, only the total power is measured, the baseline must be estimated. The error associated with this estimation can be large (Mathieu, Callaway, and Kiliccote 2011). In Beil, Hiskens, and Backhaus (2015), the baseline is estimated by interpolating the data between the fan power before and after the ancillary service event. Both the interpolation method and the choice of data points for the interpolation may lead to estimation error. In this section, we investigate the impacts of the estimation error by a sensitivity analysis.

First, we consider the scenario where the baseline estimation during the ancillary service event has a ±1% error of the baseline power consumption, which is a very conservative value for the estimation error (Mathieu, Callaway, and Kiliccote 2011). Take simulation 7 (Temperature controller) as an example, the -1% case is shown in Figure 12 (left). The results are shown in Table 2 (the Temperature controller rows are copied from Table 1 for comparison). We see that even a 1% error leads significant changes in the results. In the -1% case, the baseline is underestimated, resulting in a higher estimated energy consumption. In the +1% case, the baseline is overestimated, resulting in a lower estimated energy consumption.

Another interesting question is how long after the event ends do we consider the system return to its baseline. It could take a few hours for slower controllers; for example, simulation 7. Consider the scenario where the system is assumed to return to the baseline at hour 14. We take the power consumption at that point, and draw a straight line from the power consumption at the start of the event; we consider this as our baseline. Since at hour 14, the system has not completely settled, this baseline is inaccurate. This baseline error can be observed from Figure 12 (right). The energy impacts are shown in Table 2 (rows Ends at hour 14). In the up-down sequence, the power at hour 14 is higher than the baseline, so the baseline is overestimated, leading to a more favorable energy efficiency. In the down-up sequence, the power at hour 14 is lower than the baseline, so the baseline is underestimated, leading to a less favorable energy efficiency.

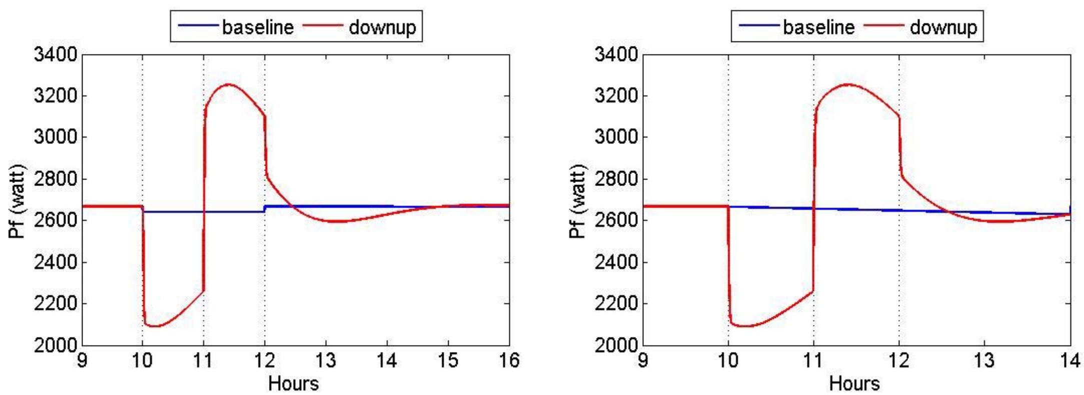

Figure 12. Examples of baseline estimation error. Left: -1% during the ancillary service event; right: early termination at hour 14.

Table 2. Impacts of baseline estimation error.

Simulations		ΔE_f (Wh)	$\Delta E_{cc,e}$ (Wh)	η_{RT}	η_{SW}
Temperature controller	Up-down	119.6	49.5	0.89	0.34
	Down-up	-44.0	-103.8	1.11	-0.32
-1% baseline	Up-down	172.9	277.1	0.72	0.80
	Down-up	9.0	123.8	0.91	0.14
+1% baseline	Up-down	66.2	-178.1	1.08	-0.11
	Down-up	-97.7	-331.4	1.35	-0.77
Ends at hour 14	Up-down	47.5	-40.3	0.99	0.06
	Down-up	35.9	5.8	0.97	0.02

Conclusion and Future work

In this paper, we investigate via simulations the impacts of providing ancillary services on building HVAC system energy consumption. We find that even if the power deviation reference signal is zero-mean, both the fan energy and cooling energy needed to condition the supply air can be significantly affected. The system takes action to return to steady state after the event ends, leading to further energy consumption changes. Many factors affect the results, and the impacts could be negative or positive. Temperature variation is important; it affects the heat exchange and the control action after the event. A few interesting findings are summarized below:

- The sequence of the square wave signal is important. In most cases, the up-down sequence consumes more energy than the baseline, since the temperature is generally lower than the set-point; while the down-up sequence consumes less than the baseline, since the temperature is higher than the set-point.
- Cooling the outdoor air could be a significant part of the energy consumption changes when the outdoor air ratio is high. This impact decreases as the outdoor air ratio decreases.
- The control action after the event is important. Different controllers result in different behavior when driving the room temperature back to its set-point. The resulting energy efficiency is also different.
- The baseline estimation error has a significant impact on the energy consumption analysis. Even a small error could lead to large changes in the results.

In the simulation study, we observed similar trends as the experimental results in Beil, Hiskens, and Backhaus (2015). For example, there could be energy inefficiency, sequence of the square waves make a big difference to the results. There are also behaviors in the experiments that are not captured in the simulations; for example, the down-up sequence increases the energy consumption in Beil, Hiskens, and Backhaus (2015), while it reduces energy consumption in the simulations. These could be explained by the baseline estimation errors, but other factors could also contribute to the behaviors.

We believe this study serves as a first step in investigating the energy consumption implications for the provision of regulation ancillary services using large building HVAC systems. There are multiple directions for future work. The model can be improved to capture more aspects of the true building HVAC system. For example, include the cooling coil and chiller dynamics and a varying outside temperature and occupancy loads. The baseline estimation problem is also important for an accurate analysis. Moreover, after the simulation study, designing field experiments to verify the analysis is a reasonable next step.

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