ENERGY EFFECTS OF VARIOUS CONTROL STRATEGIES FOR VARIABLE-AIR-VOLUME SYSTEMS

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ABSTRACT

This study analyzes the effect of various fan system control strategies on energy consumption for a high-rise office building. Energy consumption estimates were made for each strategy at five different locations using the Building Loads Analysis and Systems Thermodynamics (BLAST) program. Except for hot, humid climates, a simple economy cycle with a proportional plus integral (PI) control system for the cooling coil and outdoor/return air dampers showed low energy consumption. Cold deck reset was also somewhat effective but increased fan power consumption significantly.

INTRODUCTION

Background

Even though variable-air-volume (VAV) systems have common components and features, a variety of control strategies have been proposed. Some can be quite complicated, using sensed zone temperature to reset the discharge air temperature controller, for example. Others can be quite simple. The introduction of direct digital hardware has increased the ease with which a variety of options can be implemented. Proportional plus integral (PI) control has also been introduced and its value is being recognized. The energy implications of choosing one control strategy over another need to be quantified. This study addresses the question, "Is more complicated better?"

Objective

The objective of this study is to determine the effect of different control strategies on energy consumption for a typical high-rise office building.

Approach

In order to accomplish the objective, a high-rise office building was simulated using the Building Loads Analysis and Systems Thermodynamics program (BLAST) (University of Illinois 1986). The BLAST program is a comprehensive set of subprograms for predicting energy consumption, energy system performance, and energy cost in buildings. Annual weather tapes were obtained for five different locations (Madison; Phoenix; Dallas; Washington, DC; and Miami) characterized by different weather profiles. The BLAST program was then used to simulate the energy performance of the prototype office building at the five different locations to assess the influence of the different control strategies on energy consumption. Details of the procedure included:

(1) define and thoroughly describe a prototypical high-rise office building;
(2) design and describe the HVAC system;
(3) simulate the various control strategies;
(4) repeat the simulation for the five different locations under study (Madison; Washington, DC; Dallas; Phoenix; and Miami); and
(5) compare the plant fuel, fan, and cooling electric consumption for the various locations.

PROCEDURE

BLAST requires a complete description of the building, its fan system, and the central plant components in order to perform accurate analysis.

The 10-story building used in this study is representative of a typical office building in the United States. Each floor (20,740 ft²) consists of a large central core zone (14,400 ft²) with 44 smaller zones on the perimeter of the core zone (Figure 1). Each of the perimeter zones has an area of 144 ft². For simplification purposes, one floor was simulated and the results multiplied by 10 to approximate a high-rise office.

Approximately 45% of the exterior walls are glass evenly distributed around the building. The walls are constructed of one-cell clay tile (3 in.) with expanded polyurethane insulation (3 in.). The floors are 6 in. medium-density concrete with carpet and a fibrous pad.

The building was assumed to be occupied from 7 a.m. to 6 p.m. Monday through Friday (standard office occupancy). The lights were on when the building was occupied and turned off at night and on weekends.

The control profile for each zone delivers cool air with variable-volume air dampers fully open at a zone temperature of 77°F and closed to their minimum at 72°F. Reheat operates between 70°F and 68°F.

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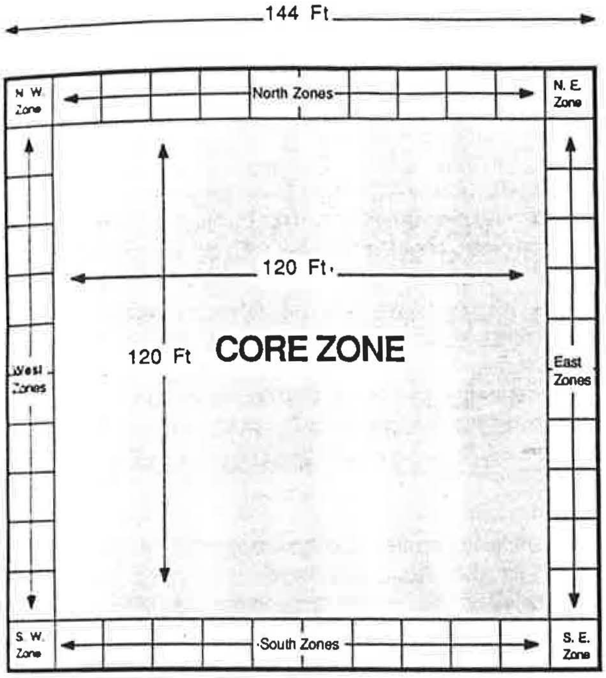

Figure 1 Floor Layout

This control operates Monday through Saturday from 7 a.m. to 7 p.m. The system is set back at night, on Sundays, and on holidays. However, the heating and cooling were assumed to be turned on when required to keep the building cooler than 100°F and warmer than 60°F.

Two VAV systems with reheat were simulated—one for the core zone and the other for the perimeter zones. Using a separate VAV system for the core zone represents a more realistic simulation due to its different load profile. Some of the features of the VAV system simulated in this study include a supply fan pressure of 4.50 in. of water and proportional control of the discharge air temperature (cold deck temperature) with a 10°F throttling range for the baseline simulation. The cold deck temperature was assumed to be 59°F under full-load conditions, dropping to 49°F under no-load conditions. A minimum air fraction of 0.3 was used. This means that the variable-air-volume boxes were assumed to have a flow rate of not less than 30% of the design maximum flow. A minimum of 15% outdoor air was assumed to be introduced during the occupied hours for ventilation purposes. The reheat coil was scheduled to operate 24 hours a day from October 16th through April 15th but could turn on only when the VAV system was operating. For the rest of the calendar year, the reheat is allowed to operate only during the day to prevent overcooling when VAV dampers are at their minimum and the cooling load is low.

To meet the peak hot and chilled water demands, suitable size boilers and chillers (two of each) were selected for the central plant simulation. Multiple boilers and chillers were used to avoid poor part-load performance and thereby improve boiler efficiency and chiller coefficient of performance (COP).

The building, with its VAV system and central plant parameters, was simulated at Phoenix; Dallas; Washington, DC; Miami; and Madison. It was intended that these sites be typical of different climates throughout the U.S. (Table 1). The various control strategies investigated in this study were: baseline (proportional control with 10°F throttling range), economy no PI, PI no economy, PI with economy, cold deck reset, and cold deck reset (perimeter).

TABLE 1
Weather Sites

Site	Summer	Winter	Humidity
Madison, WI	Moderate	Cold	Moderate
Washington, DC	Very warm	Moderate	High
Phoenix, AZ	Very hot	Mild	Dry
Dallas, TX	Hot	Mild	High
Miami, FL	Hot	Warm	Very humid

RESULTS AND DISCUSSION

The results of the simulation for each of the five locations with their control-related alternatives are shown in Table 2 and in Figures 2 through 6.

The plots reveal a general trend of lower energy consumption by the HVAC system under the cases of "economy plus PI" and "cold deck reset" for the various locations investigated.

The annual energy performance plot of the building simulation at Washington, DC, can be considered as representative of the trend for the five different locations investigated. Washington weather is warm and moderately humid, yet it still gets cold during the winter months.

TABLE 2A
Phoenix
Annual Energy Consumption (KBtu/ft²·yr)

	Plant Fuel	Cooling Electric	Fan Electric
Baseline	19.09	13.80	5.21
Economy no PI	19.76	11.01	5.05
PI no economy	9.76	13.66	9.46
PI w/economy	9.76	9.79	9.46
Cold deck reset	4.09	9.94	15.73
Cold deck reset, perimeter	5.43	9.80	12.16

TABLE 2B
Washington, DC
Annual Energy Consumption (KBtu/ft²·yr)

	Plant Fuel	Cooling Electric	Fan Electric
Baseline	32.05	13.21	4.62
Economy no PI	32.74	7.63	4.47
PI no economy	21.39	12.97	8.32
PI w/economy	21.39	5.98	8.32
Cold deck reset	15.43	5.93	13.51
Cold deck reset, perimeter	16.64	6.00	9.93

TABLE 2C
Dallas
Annual Energy Consumption (KBtu/ft²·yr)

	Plant Fuel	Cooling Electric	Fan Electric
Baseline	24.56	13.05	4.82
Economy no PI	25.14	9.90	4.76
PI no economy	14.34	12.24	8.60
PI w/economy	14.34	8.19	8.60
Cold deck reset	8.64	8.35	14.74
Cold deck reset, perimeter	9.97	8.34	11.16

TABLE 2D
Madison
Annual Energy Consumption (KBtu/ft²·yr)

	Plant Fuel	Cooling Electric	Fan Electric
Baseline	49.44	12.58	4.67
Economy no PI	50.37	5.21	4.46
PI no economy	36.46	10.46	8.12
PI w/economy	36.46	3.82	8.12
Cold deck reset	30.50	3.66	13.26
Cold deck reset, perimeter	31.69	3.78	9.69

TABLE 2E
Miami
Annual Energy Consumption (KBtu/ft²·yr)

	Plant Fuel	Cooling Electric	Fan Electric
Baseline	7.23	12.00	4.67
Economy no PI	7.20	12.68	4.81
PI no economy	2.89	12.30	8.73
PI w/economy	2.89	12.32	8.73
Cold deck reset	0.58	13.00	15.41
Cold deck reset, perimeter	1.95	12.66	11.83

TABLE 3
Washington, DC
Additional Simulations (KBtu/ft²·yr)

	Plant Fuel	Cooling Electric	Fan Electric
PI w/economy	21.39	5.98	8.32
Cold deck reset	15.43	5.93	13.51
PI w/ economy (zone peak)	21.21	6.02	8.41
Cold deck reset (zone peak)	17.25	6.02	11.52
PI w/ economy (55°F)	23.45	6.58	6.41
Cold deck reset (55°F)	15.61	6.20	11.11

The baseline case represents a conventional proportional cold deck control with 10°F throttling range. The cold deck design temperature is set at 59°F and the actual delivery air temperature will swing from 59°F at full load to 49°F at no load.

The next case, labeled "economy no PI," is similar to the baseline case but with the addition of the economy cycle, which allows outdoor air to be admitted when its temperature is lower than the return air. A drop of almost 40% in cooling electric consumption was observed. This drop, when coupled with the slight increase in the annual plant fuel consumption, reflects a savings of almost 10% in total energy consumption by the HVAC system. The increase in plant fuel consumption is due to the reduced average load on the cooling coil, which results when the economy cycle is used. With proportional-only control, the use of cool outdoor air lowers the coil load, resulting in a drop in the discharge air temperature as the cooling coil valve closes. Extra reheating will be needed whenever the VAV dampers are at their minimum.

The next case, labeled "PI no economy," is similar to the baseline case but the cooling coil is controlled by a proportional plus integral controller with a setpoint of 59°F. The PI controller fixes the cold deck temperature at 59°F without drop or offset. This results in a significant savings in plant fuel consumption since the delivery air temperature does not drop toward 49°F as the cooling load decreases. The total energy savings is 15% compared to the baseline case and is even larger than that achieved when an economy cycle is used with the proportional-only control

The fourth case, labeled "economy with PI," is an economy cycle with a PI-controlled cooling coil and PI-controlled return and outdoor air dampers. In this case, additional reduction in the cooling electric consumption was achieved, producing a total savings on the order of 30% compared to the baseline case.

The fifth case, labeled "cold deck reset," is the same as the "economy with PI" but with the addition of a setpoint reset of the cooling coil and damper controllers. The cold deck setpoint temperature is based on the zone requiring the most cooling (not lower than 55°F). Since two separate VAV systems were used—one for the perimeter zones and the other for the core zone—the cold deck reset strategy was simulated for both VAV systems. The additional energy savings achieved were minute, on the order of 2.3% compared to the "PI w/economy" case. These savings, resulting from a decline in both cooling electric and reheat demands, were offset almost completely by a significant increase in fan electric consumption. This jump in the fan power demand was mainly due to the increase in the average airflow rate to the core zone. Since the core zone has its own VAV system, the cold deck reset strategy will deliver the maximum airflow rate at all times. This, when coupled with a corresponding increase in the cold deck temperature, will achieve the required cooling. As a result, a high fan electric consumption is obtained. Note that using cold deck reset only for the VAV system controlling the perimeter zones would result in an additional 9% savings when compared to using reset on both systems (see case labeled "cold deck reset, perimeter").

The above results are representative of the general trend for the energy performance of the prototypical office building at the various sites under investigation. The exception to this trend is observed in Miami, which is characterized by hot, very humid weather all year round. As seen in Figure 6, use of the economy cycle resulted in a negative savings of -4%. These negative savings are attributed to an increase in the cooling electric demand due to the admission of extremely humid outdoor air by the controller. Even though this outdoor air is a little cooler than the return air, it has higher enthalpy due to its moisture content, thus requiring more cooling. The use of PI control with or without the economy cycle did not offer any measurable savings over the baseline simulation. As for the cold deck reset, there was a negative savings of -20% compared to the baseline despite the drop in reheat demand. This was caused by a significant increase in the fan power demand accompanied by a fairly constant cooling electric demand under the various control schemes simulated.

With the exception of the Miami site, the plots reveal that the two most energy-efficient control schemes are the "PI with economy" and the "cold deck reset."

At this point, the performance of the HVAC system using these two strategies was investigated under poor operating conditions. Such conditions may include a low discharge air temperature due to load peaking at one of the zones. Therefore, additional simulations of the HVAC system were carried out for the Washington site (Figure 7). The cases labeled "PI with economy (zone peak)" and "cold deck reset (zone peak)" represent energy performance of the system when one of the zones encounters a large increase in the cooling load demand. This might occur if additional computer equipment was installed in a zone without increasing the design air volume flow rate.

For the "PI with economy (zone peak)" case, an increase in the fan and cooling electric was observed; however, that increase was offset by a drop in the plant fuel consumption (reheat), resulting in a 0.2% savings. In many

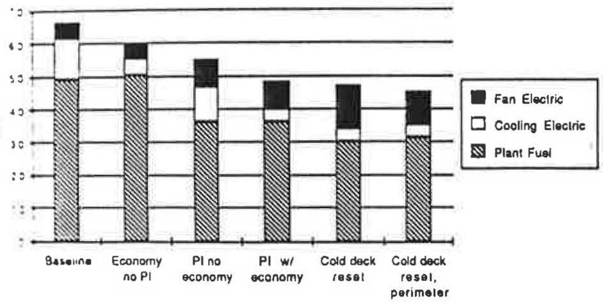

Figure 2 *Annual energy consumption, Madison*

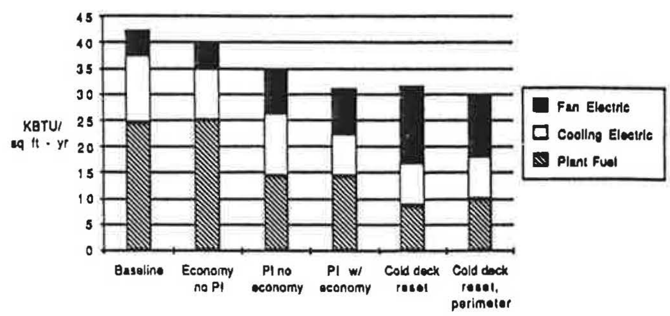

Figure 5 *Annual energy consumption, Dallas*

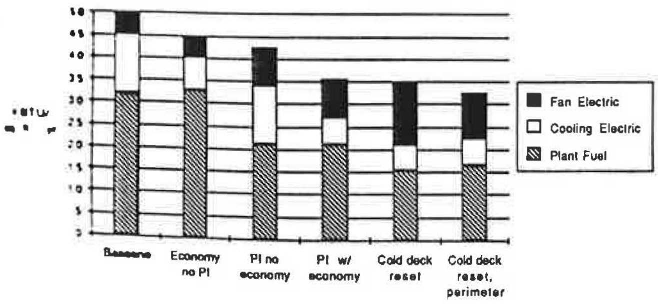

Figure 3 *Annual energy consumption, Washington*

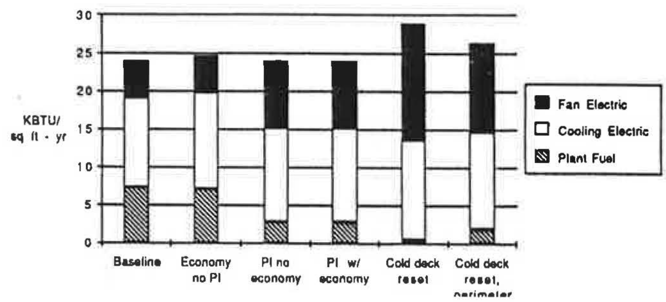

Figure 6 *Annual energy consumption, Miami*

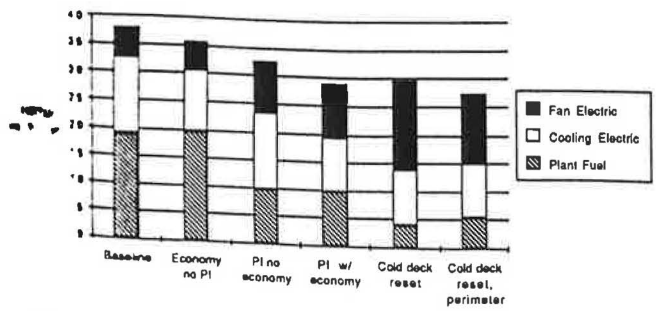

Figure 4 *Annual energy consumption, Phoenix*

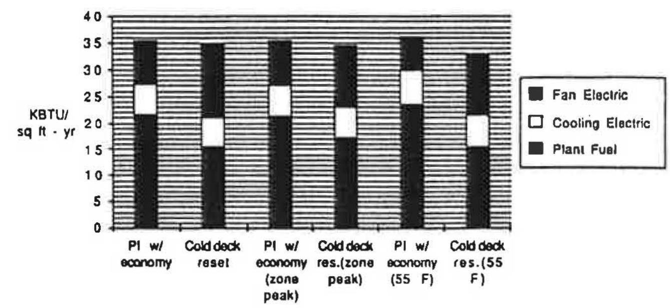

Figure 7 *Additional simulations, Washington*

locations, these savings would be negative when measured in dollar value since the cost of electricity is often significantly higher than plant fuel.

For the "cold deck reset (zone peak)" case, the cold deck temperature was allowed to drop down to 52°F. In this case, the increase in the plant fuel and cooling electric consumption, when coupled with the noticeable decline in fan electric consumption, resulted in a 0.25% savings compared to the "cold deck reset" case. Such a minor change in energy consumption indicates that the cold deck reset strategy is fairly insensitive to zone peaks when using a high-pressure fan system.

Finally, the influence of choosing a lower cold deck design temperature was investigated. 55°F was selected instead of 59°F. The "PI with economy (55°F)" case reflected a negative savings of -2.1% when compared to the "PI with economy" case. As expected, the increase in plant fuel and cooling electric were due to increased reheating, increased dehumidification, and reduced effectiveness of the economy cycle when a 55°F design supply air temperature is used. The decrease in the fan electric was not enough to offset this increase, thus producing the negative savings. As for the "cold deck reset (55°F)" case, the drop in the fan power consumption was large enough to offset the increase in both the cooling electric and plant fuel consumptions, thus producing a 5.6% savings compared to the equivalent cold deck reset case with 59°F supply air. These results are a direct indication of the dominating effect of the high-pressure fan system.

CONCLUSIONS

This study has led to the following conclusions:

(1) For most climates, with the exception of hot, humid ones (Miami), the two most effective control strategies for VAV systems are "PI with economy" and "cold deck reset (perimeter)."

(2) The use of the economy cycle is not recommended in hot, humid climates. A suitable control strategy for such a climate would be the standard proportional control or the PI control with no economy.

(3) With the use of medium- or high-pressure fan systems, the fan electric consumption becomes significant, especially with the use of the cold deck reset strategy. Thus, using cold deck reset might lead to an increase in operating cost, making the use of the simpler PI with economy strategy more attractive. It is therefore important to consider the dollar value of the energy saved when selecting a suitable control strategy.

(4) The PI control is a very effective energy-saving scheme and its use is recommended for most climates.

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DISCUSSION

P. Haves, Department of Engineering Science, Oxford University, Oxford, UK: Given the mixed performance of the reset strategies, what is the minimum additional information required by the control system to obtain a more optimal trade-off between chiller energy and fan energy?

D.C. Hittle: Measuring the fan and chiller energy might be enough, but we did not study this detail.

G. Atkinson, Atkinson Electronics, Inc., Salt Lake City, UT: Did you consider resetting the discharge air temperature for minimizing cold weather VAV box minimum air reheating requirements?

Hittle: Yes. This is exactly what was accomplished with the cold deck reset strategy.

H. Levin, Hal Levin & Associates, Santa Cruz, CA: What minimum quantity of outside air did you use in your simulations? Did you use ASHRAE Standard 62-1981 or 62-1989?

Hittle: We used the 1989 standard.

S. LeViseur, Senior Engineer, RS&H, Jacksonville, FL: Did you maintain 5 cfm/occ (i.e., one lump number) or was it reduced as air volume was reduced?

Hittle: We maintained the minimum even at low flow rates.

R. Smith, Technical Director, Lioret Electrical Systems Ltd., Sutton, Surrey, England: How intelligent were the terminal unit controls under review?

Hittle: The terminals are simple devices that proportion air flow in response to the room thermostat.

G. Shavit, Chief Engineer, Honeywell, Arlington Heights, IL: Your analysis did not allow for activation of control strategies by seasons. What will be the impact on the results if you consider that?

Hittle: There may be some impact. For example, deactivating the economy cycle in summer might reduce dehumidification penalties.

T. Farnfield, J. Roger Preston & Partners, Maidenhead, England: The paper concentrated on the use of chilled-water systems. It would be interesting to see a comparative study carried out for DX systems.

Hittle: I think the general trends would apply for DX systems.

D.R. Griffith, P.E., Indiana University, Bloomington: The baseline analysis was made using a 10°F control range for the proportional control. (1) What was the basis for using this range for the baseline? (2) Have you found that this range is typical of systems operating today?

Hittle: The 10°F throttling range was based on experience, discussions with control manufacturers, and assessment of systems stability. We feel that any smaller throttling range could result in unstable control at low air-flow rates.