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Multizone register controlled residential heating: optimized for energy use and comfort

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Multizone register controlled residential heating:

Optimized for energy use and comfort

by

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1. Introduction

In the United States today, most residential heating systems are single zone. This means that all rooms must be either conditioned or not, which often leads to large unoccupied areas being conditioned to satisfy comfort needs in the occupied zones. Furthermore, these systems typically have only one sensor, which is often not representative of all zones. It would be desirable to have better control, but multizone systems are expensive and invasive to install if one wants to retrofit an existing residential single zone heating system into a multizone system.

A new multizone system is currently being developed at UC Berkeley to provide an inexpensive, simple retrofit strategy. This consists of a wireless vent register control system. The new registers have been fitted with a mote (a small wireless device) that can send and receive signals in order to open and close vents in a house, allowing the system to only condition the desired zones. Motes fitted with temperature sensors are also placed in the zones and outside to provide additional temperature readings to the control system. Therefore, the house can take on properties of a multizone system by only changing the registers. The goal of the overall project is to design a simple, inexpensive system that can save energy while providing thermal comfort comparable to or better than that of a traditional single zone system.

Since smaller volumes will be conditioned at a time, the heating system can potentially reach setpoint quicker, therefore running for a shorter period of

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time. The new system has been tested using a 1988 house in Danville, CA. This test was to verify that the system works as expected and whether target zones reach setpoint faster.

While multizone systems can conceptually allow the user to fine-tune conditioning needs, the control algorithms will be more complicated. A single zone system only needs to actuate heating, cooling, and fan modes with one setpoint at a time. With the wireless vent control, the system must track which zones need to be conditioned and choose an appropriate vent configuration, in addition to the control needs of the single zone system. To optimize this system in a real house would be prohibitively complicated and time consuming. Therefore, an optimization model has been developed to determine optimal control sequences based on setpoint and occupancy. This optimization models the actual house, using real house data such as insulation values, flow rates, and fan power. It automates the choice of optimal configuration, rather than completing thousands and thousands of runs in real time in the actual house.

The Background section of this thesis will provide an overview of existing residential heating options. Specifically, it outlines the research that has been done on the effectiveness of existing multizone control strategies. It will also describe the new multizone system being developed in the UC Berkeley Demand Response Enabling Technology group. This system provides wireless control of vent registers.

A statement of the problem and objectives follows the background. Next the Methods section provides a detailed description of the hardware and

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software used in the wireless multizone control system. The development of the hardware and software for this project is the subject of William Watt's thesis, *Multizone HVAC Control with Smart Vent Louvers* (2007). This section discusses the initial house testing and the measurements. The Methods section also contains an overview of the optimization model developed in this work, including an explanation of the thermal calculations, logic, occupancy schedules, and weather data. The initial optimization model (and the resulting write-up) began as a final project in ER 220: Modeling Energy, Environmental, and Resource Systems. Petek Gursel and Arman Shehabi contributed to this project. This thesis contains an updated model with enhanced thermal calculations and more detailed analysis.

The Results section provides tables and figures from both the basecase (single zone control) and the multizone control runs, and also presents the sensitivity analysis.

The Discussion, Future Work, Conclusion, and References sections follow. Finally, many people have been involved in the completion of this thesis. Acknowledgements can be found at the end of the paper.

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2. Background

2.1 Residential HVAC

2.1.1 Performance

Buildings represent approximately 40% of the energy usage in the United States (Emery, 2005). New houses are continuously getting bigger and the occupants desire the same level of comfort that they have grown accustomed to in smaller houses. However, since single zone systems are so common, this results in much larger volumes being conditioned when it is not required. In addition, as electricity prices are increasing, many new homes are switching to natural gas. In recent years in the US, the demand for natural gas has been increasing 15-18% each year, while the supply has been dropping 5-7% annually (Emery, 2005). Therefore, whether heating with electricity or natural gas, the price has been rising and the supply is limited.

2.1.2 Control

In the United States, the most common residential heating systems are constant air volume (CAV) forced air systems. While other options do exist, such as electric baseboard heat and hydronic control, the CAV systems represent a large portion of the market in which the entire house is treated as a single zone.

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The ASHRAE Handbook of Systems and Equipment (2004) recommends the use of multizone control when a single thermostat is not representative of all rooms. While thermostats should have the ability to monitor multiple zones of a house, this does not mean that all zones should be the same temperature. "For efficiency, the thermostat should really know more subtle patterns of occupancy (expected return based on day of the week, departure time that day, weather conditions, and recent schedule, for example). It must also consider the time required to heat the house, which depends on outdoor conditions" (Mozer, 1999). In addition, only rooms that are likely to be occupied in the near future should be heated.

Existing technologies do exist to provide multizone control in residential forced air systems. For example, variable air volume (VAV) delivery in conjunction with dampers in individual supply ducts is being used in new construction. However, to retrofit an existing single zone system into a multizone one would be both very expensive and invasive. While many users would prefer the multizone system over a single zone one, most would not opt to perform the extensive and invasive retrofit.

A second multizone option is a CAV system with dampers on individual supply ducts and a bypass loop to handle excess air (Oppenheim, 1991). However, Heflin and Keller (1993) tested a CAV system with a bypass loop and they found that "the bypass damper reduced the system capacity as desired but the power consumption remained relatively constant resulting in a reduction in

efficiency with increasing amount of bypassed air" (Temple, 2004). Therefore, such a system can provide zoned control, but it will not save energy.

A third multizone option is to use separate heating/cooling units for each zone (Oppenheim, 1991). However, this method is expensive and the increase in comfort is often not worth the added cost to homeowners (Powell, 1992).

In recent years, there have been studies looking at the effectiveness of various multizone systems. In 2004, Temple provided a summary of a number of these studies. Baskin and Vineyard (2003) found room-to-room temperature differences of 4.2°F in addition to vertical stratification issues in single zone forced air systems. So, there is a need to have the ability to address zones as needed, rather than actuating around a single zone. Leslie and Kazmer (1989) compared multizone control to conventional single zone control, both using setbacks. In houses with heated basements, the multizone control did not save energy, but it did provide more uniform temperatures. However, in similar tests without basement heat, the multizone control was able to save energy in cold weather (but not moderate). Oppenheim (1992) compared residential multizone systems to conventional single zone control using various setback strategies. Since many modern thermostats allow the user to program different setpoints throughout the day, allowing a setback in the basecase is reasonable. The baseline single zone control used a setpoint of 72°F with an 8-hour 12°F setback. When using an 18-hour setback for the bedrooms and an 8-hour setback in the living room, this study actually found a 6% increase in energy usage but enhanced comfort control on a seasonal basis in Washington, DC.

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However, when a 22-hour setback was chosen for both the living room and the bedrooms, the multizone system used 12% less energy and maintained better comfort control during occupied periods. In general, these studies agree that multizone systems can provide better comfort control, but the energy saving potential is varied. To assess the practical viability of multizone strategies, system cost must be weighed against the potential savings. The balance between comfort and heating cost should be optimized (Mozer, 1999; Grassnick, 2001).

Some users have attempted to control their house more efficiently by closing off vent registers themselves in certain rooms. While this could potentially be effective, manually opening and closing vents to track usage can become quite complicated, with each zone opening and closing throughout the day. Therefore, the Demand Response Enabling Technology Development (DRETD) group at UC Berkeley has been designing a system that can automate this control. This project aims to provide a simple, non-invasive, affordable solution to multizone control. In addition, this multizone system should provide enhanced thermal control with the ability to reduce overall energy usage.

In *Register Closing Effects of Forced Air Heating System Performance*, I.S. Walker studied the effectiveness of using vent registers to provide multizone control. Walker concluded that this system would not save energy. Walker used REGCAP, a detailed HVAC model as the basis of his model. In order to model the effect of opening and closing of vents based on the thermal properties of the house, he varied the UA value of the house. When registers closed off a zone, he treated the zone as a buffer between the conditioned inside spaces and the

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unconditioned outside. He assumed that each vent conditioned an equal portion of the house and that each section contributed equally to the overall UA value. Therefore, as vents were closed, a proportional amount of insulation was added to the overall UA value, decreasing with each vent closed. While an actual house could, in theory, exist in this configuration, it is unlikely. In most houses, individual vents control varied volumes with different envelopes. For example, single vents could be used to condition a small bathroom or an entire kitchen in a house. In general, it is a safe assumption that the bathrooms (and often the bedrooms) will be smaller than the common living spaces. Furthermore, zones can have different thermal properties. Closing off a kitchen with cathedral ceilings and a large amount of glazing would have a different effect than closing off a more insulated zone. By setting each register zone to be the same size with the same thermal properties, one of the driving needs for a multizone system is lost. Specifically, in most houses all zones are not the same size with the same thermal properties. The single thermostat is often not representative of the thermal conditions in the entire house, but multizone control can help to address this issue. Walker's paper does provide useful insights about HVAC performance such as system limits. But, more detailed thermal data is desired to determine the energy saving potential. To accurately predict energy savings, more realistic house geometries should be used. A starting point is to model an exisiting house.

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2.2 Technology

In the past, residential multizone control systems were uncommon because of the increased cost of wiring multiple sensors and actuators. However, the use of new wireless technology can now produce simple, affordable multizone solutions.

2.2.1 Wireless Sensors and Actuators

A new system is being developed in the UC Berkeley Demand Response Enabling Technology Development group (DRETD) to use wireless technology for residential multizone control. Rather than replacing the entire conditioning system, existing single zone forced air systems can be upgraded simply by wirelessly controlling the vent registers. The idea is that the registers can be opened and closed to independently control zones. As zones are closed off, more air will be pushed into the conditioned zones. Therefore, the zones left on should, in theory be able to reach setpoint faster and save energy overall. In addition, the system will be able to control each zone separately, rather than depending on a single sensor for the entire house.

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3. Statement of the Problem and Objectives

With the introduction of wireless sensors and actuators, this project aims to introduce a simple, inexpensive solution to multizone control, which is currently lacking in the residential sector.

How does the energy use and thermal control of optimal multizone control compare to that of single zone control? Given house data, occupancy schedules, and weather data, what is the best way to control this system?

This thesis will focus on the optimization model developed to explore the control of the wirelessly actuated registers. The optimization results will be used to determine whether such a system could save energy and provide enhanced thermal control as well as to provide insight into how these registers should be actuated based on weather and occupancy patterns.

4. Methods

4.1 Introduction

While some users have attempted to open and close their vent registers manually, providing a wireless, an automated system is a novel introduction to the field. It provides an option to retrofit to multizone control while remaining simple and non-invasive. In addition, it is a system that could also be marketed to new construction.

However, since this is a new technology, we tested its feasibility and developed an optimization model. The hardware and software testing was performed by William Watts. I started the optimization model as a class group project with Petek Gursel and Arman Shahabi. After the completion of the class, I developed an enhanced version of the optimization model for this thesis, which is described in detail in the Methods section.

4.2 Technology

The hardware and software development of this system has been performed by various students from the DRETD group and is the subject of William Watts' thesis, *Multizone HVAC Control with Smart Vent Louvers* (2007). More detailed information about the setup of the system can be found there.

This system has been developed using the Tmote (Teleosb) platform from Moteiv. An NSLU2 Linksys storage link USB server running NSLU2-Linux (SLUG) was used to control the system. To start, vent registers were retrofitted

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with a low-power servo motor that was controlled by a Tmote and powered by a battery pack, as shown in Figure 1. Temperature sensors were placed throughout the house to allow for multiple sensing input for the control. The existing thermostat was retrofitted to be controlled by a Tmote which actuated the heater, AC, or fan. A manual switch was also installed to allow the user to return to normal thermostat control in the event of a system failure. A webpage interface was developed to allow the user to control the system either locally or remotely. Overall, the temperature motes sent information to the server, which then compared the information to the zone setpoints and actuated the heat and vent registers appropriately. All sensor and actuator information data was stored in a mySQL database, which could be viewed and graphed by a PHP enabled website.

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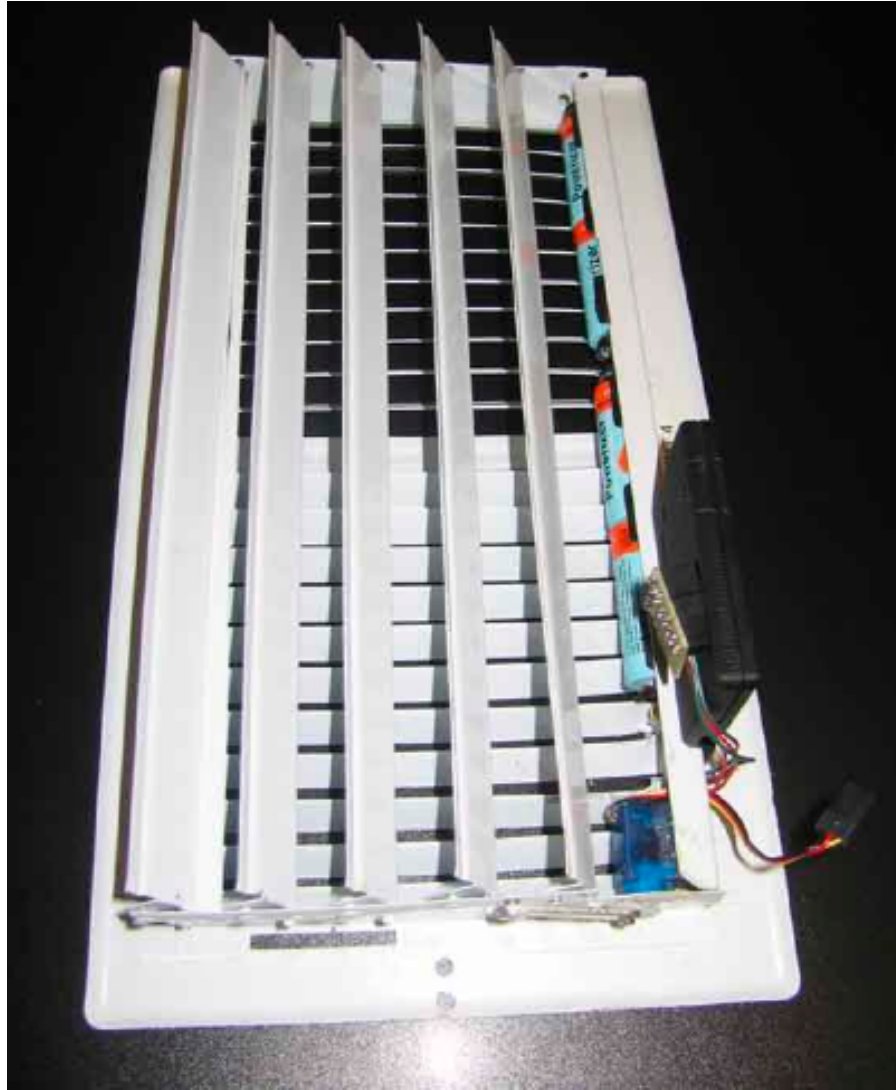
Figure 1: Retrofitted vent register (courtesy of Mike Koplow)

4.3 House Tests

4.3.1 House Type: year, climate, construction

Since there were many questions about how a system like this might work, initial feasibility tests were done in a house in Danville, CA.   It is a single-family, two story house built in 1988. Danville is located in California Climate Zone 12, which has about 2750 heating degree days (base 65). Typically, this climate zone averages about 75°F in July and 45°F in December. This house represents typical California construction post Title 24.   Houses built before Title 24 often lack sufficient insulation and other basic energy efficient measures. Since our house had to meet all Title 24 requirements, it is a good candidate for other upgrades, such as our vent system.   However, our system could also potentially be installed in a older house, where envelope losses are much larger.

4.3.2 Zoning

The Danville test house has been grouped into four zones based on usage patterns.   The kitchen and living room are grouped into Zone 1. The laundry and bathrooms, low-usage areas, are grouped into Zone 2. Zone 3 includes the bedrooms. Finally, Zone 4 is the office. Figure 2 below provides a schematic of the house layout.
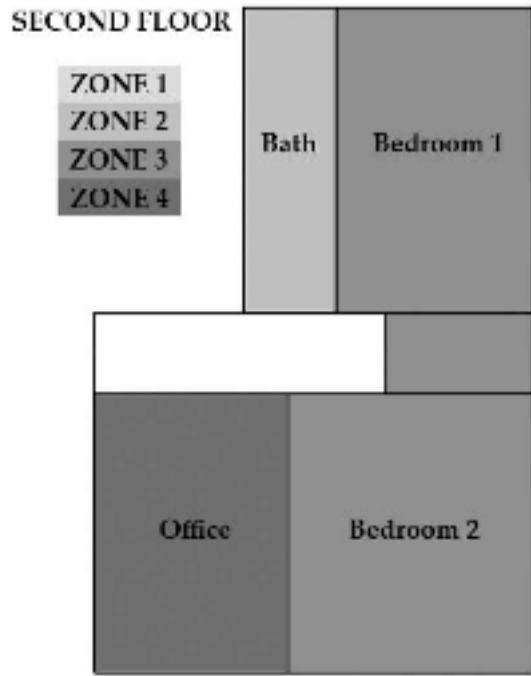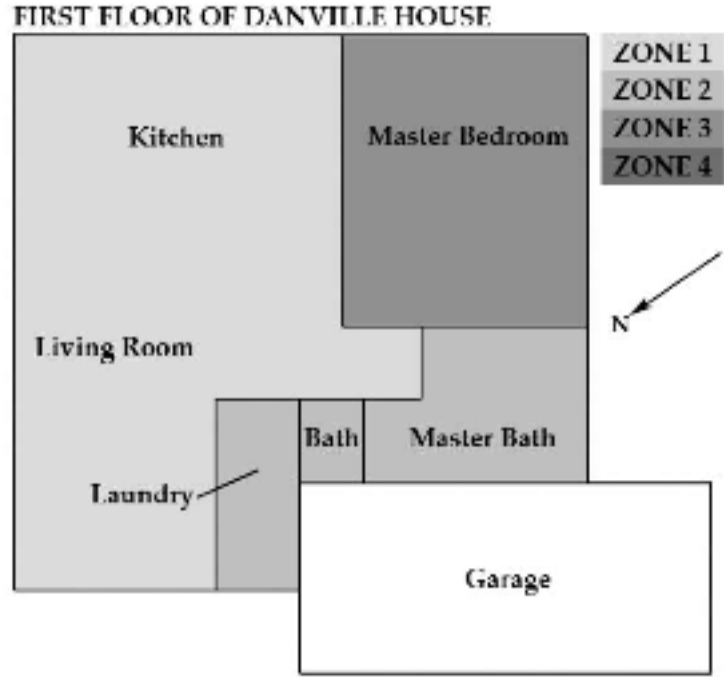
Figure 2: Danville house floorplan and zones

The vent registers can either be set in a completely open or closed position, allowing the zone to be in either a conditioning mode or a non-conditioning mode. When all zones are being conditioned, one would leave all registers open and turn the system on and off, rather then running the system and opening or closing the registers. Therefore, having all of the zones either open or closed is essentially the same configuration because running the system with all registers closed is a nonsensical choice. This results in 15 different possible ventilation configurations for the heating system.

4.3.3 Flow and Power Measurements

A common concern about closing off vents is that it will place too much pressure on the system or cause the fan to use more power. Therefore, before testing in the house, we measured airflow and fan power under each configuration. For every configuration, we systematically opened and closed the registers and measured the airflow using a flow hood at the Danville house.

We found that while fan power does vary by configuration, the shifts were very small in comparison to overall system power (ranging from 5.4 to 5.8 amps). Our measurements showed that fan power decreased as vents were shut off. So, the fan power decreased as overall flow in the system decreased. While the *total* flow decreased as vents were shut off, the flow to *conditioned* zones always increased. Therefore, when shutting off vents, more air reached the conditioned rooms, while at the same time using less power. However, this

efficiency must also be weighed against the increased internal losses from conditioned to unconditioned zones. Figure 3 shows the relationship between the measured fan power (in watts) and airflow (in cubic feet per minute) A linear model has been fitted to the data.
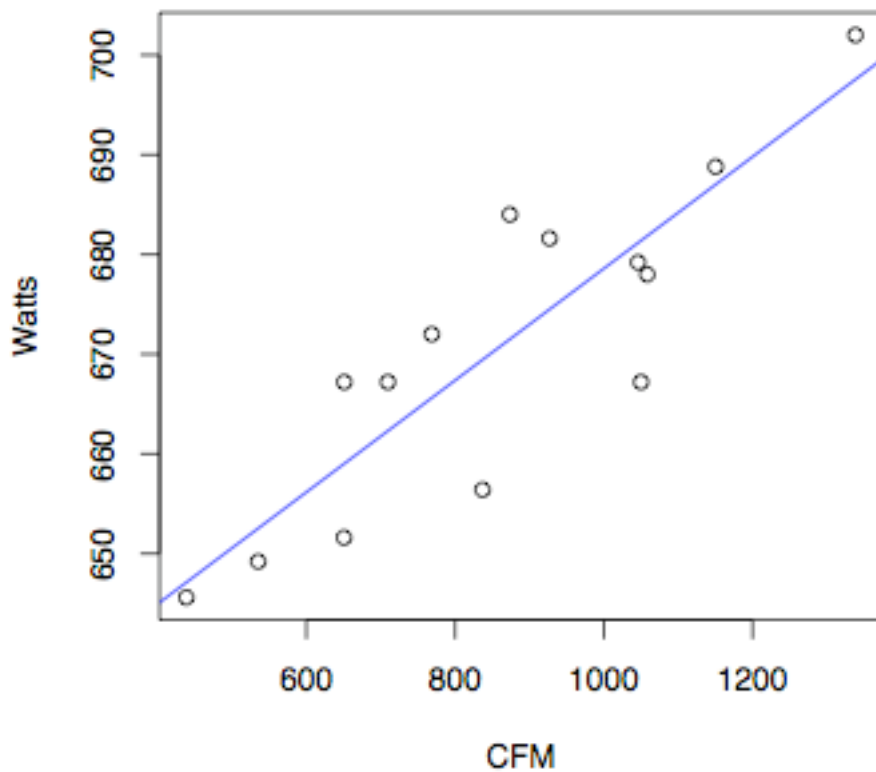
Figure 3: Danville house fan power and cfm

After measuring the flow rates at the registers in each zone for each configuration, two configurations were dropped from the study. The office was zoned by itself so that usage could be turned off separately. However, in the

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configuration where only the office is open, over 60% of the total flow is shut off. This could place too much pressure on the system to operate properly (Walker, 2003). Similarly, the bathrooms and laundry room were zoned into one utility zone, but when this zone is the only one open in the house, the system stress is too high (possibly causing the coils to overheat), so it was also removed from the study. However, it would be unlikely that an occupant would wish to condition only the bathroom and laundry room anyway. This resulted in 13 viable vent configurations.

Table 1 shows the power and corresponding zone airflows measured at the house.

Table 1: Empirical Danville house data

	Fan Power	Flow Rate (CFM)				Total Flow
		Kitchen/LR	Utility	Bedrooms	Office	
1	5.85	400	306.4	507.7	124	1338.1
2	5.78	415	319	530		1264
3	5.56	487	357.7		205	1049.7
4	5.74	429.3		555	166	1150.3
5	5.65		330.1	561	167.3	1058.4
6	5.47	512.6	411.6			924.2
7	5.56	501.3			208.3	709.6
8	5.66	450.7		595.3		1046
9	5.68		342	647		989
10	5.43		424.7		226	650.7
11	5.6			591.7	177	768.7
12	5.56			651		651
13	5.41	535.5				535.5

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4.3.4 Initial Feasibility Study

The Danville house was retrofitted with the mote-controlled vents by William Watts in the fall of 2006. Reliability testing of the software and hardware was performed in the house for two weeks and they performed as expected. The results that are most relevant for the current study are presented here, and more detailed results from these tests can be found in Watts' thesis: *Multizone HVAC Control with Smart Vent Louvers* (2007).

The thermostat was located in the living room of the Danville house. This was zoned together with the kitchen, which had both cathedral ceilings and a large amount of window surface area. Of particular note from these tests, it was found that the thermostat was not representative of the rest of the house. In winter conditions, the zone with the thermostat was always the coldest zone. Since the house was actuated by the temperature in this zone, significant overheating occurred in the rest of the house. Specifically, the bedrooms were found to be up to 8 degrees higher than the setpoint temperature. This suggests that the house would benefit from multizone control, since the zones could be controlled as needed, rather than actuating around the living room temperature.

4.4 Optimization Model

4.4.1 Overview

The residential vent register control system is designed to direct airflow only to building zones that require conditioning. Energy efficiency benefits are gained when tailoring airflow to zone demand, reducing the overall heating system-on-time (SOT) and some fan energy. An optimization model was developed to determine the optimal vent configuration schedule for the Danville house and to estimate the energy savings associated with that configuration schedule. Building heating energy use is approximated as the sum of the fan and furnace energy. The fan power varies by ventilation configuration due to changes in the airflow demands. The empirical values taken at the Danville house are used to represent the fan power for each ventilation configuration. The furnace power is considered to be constant at 100,000 Btu/h (1 therm/h). Energy use is then calculated by multiplying the furnace power and the fan power from each configuration by the SOT of that vent configuration. In the actual system, the furnace turns on before the fan, and then the fan stays on longer than the furnace. However, these shifts are close in size, so we have assumed that the SOT is the same for both.

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Equation 1

$$\text{Energy Use} = \left(FP_{vc} + HP\right) \times SOT_{vc}$$

where:

FP_{vc} is the power used by the fan in a specific configuration

HP is the furnace power

SOT_{vc} is the system on time for a specific vent configuration

The vent configuration adjusts to zone conditioning demands as occupants move throughout the house and outside climate conditions change, as predicted by a schedule. Energy use is evaluated on hourly intervals, allowing the vent registers to change configuration every hour of the day. A weekly energy use is evaluated by calculating a weekday and weekend energy use, and then assuming a consistent daily occupancy schedule throughout the week and another daily occupancy schedule on the weekend. The weekly energy use is then estimated by determining the vent configuration, and the corresponding energy use, for 48 different hours. The objective function of this optimization is minimizing the weekly energy use.

Equation 2

$$\text{MIN : Weekly Energy Use} = \left[5 \times \sum_{i=1}^{24}\left(\left(FP_i + HP\right) \times SOT_i\right)\right] + \left[2 \times \sum_{i=25}^{48}\left(\left(FP_i + HP\right) \times SOT_i\right)\right]$$

The optimization model is designed to evaluate the SOT for each hour, in each zone, for 13 ventilation configurations. The SOT within a designated hour is calculated by monitoring the number of minutes the system operates while complying with given thermal constraints. From the system's point of view,

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thermal comfort in this case is defined and maintained by the setpoint and deadband. The setpoint is the ideal temperature that the system is trying to maintain. To keep the conditioning equipment from continuously toggling on and off, a deadband is set around the setpoint. The optimization model is designed to have the heating system operate whenever the temperature in any occupied zone drops below the specified lower bound of the deadband. The system shuts off when temperatures in all occupied zones reach the setpoint.

The model calculates changes in zone temperature for all of the different scenarios for each hour. Zone temperature is also influenced by parameters specific to the hour and zone, such as external temperature, occupancy level, and thermal conductivity (UA) . Each zone has separate internal and external UA values that have been calculated from reference values. These values represent the thermal conductivity of the internal and external wall of the zone and depend on the orientation of the zone within the house. Changes to the zone temperature as the heating system turns on and off are discussed in more detail in the thermal section.

4.4.2 Optimization Logic

The incremental changes to the zone temperatures are calculated based on whether the airflow rate into the zone is the open-flow rate, which is an empirical value specific to the zone and vent configuration, or the closed-flow rate, which assumes a 10% leakage (estimate of leakage through closed registers

seen in the Danville house). The flow rate for each minute is set to the open or closed position based on the following conditional logic:

1. *Vents:*
   The position of the vents (open/closed) is designated for each zone by the vent configuration.

2. *Heating System:*
   The heating system is in the off mode when the temperature in all of the occupied zones is greater than the setpoint. The heating system is in the on mode when the temperature of any of the occupied zone is less than the lower bound of the deadband. Otherwise the heating system stays in the mode of the previous time step.

3. *Flow Rate:*
   If either the vents are closed or the system is off, the zone receives the closed-flow rate. Otherwise the zone receives the open-flow rate.

While temperature is monitored in all four zones, the heating system operation is based only on occupied zones. The unoccupied zones are removed from the conditional statement with an occupancy binary value. The number of minutes the heating system operates in an hour is then counted to represent the SOT for each vent configuration. Energy use required for each configuration is then calculated by multiplying the vent configuration SOT by the vent configuration fan and furnace power.

A single vent configuration is chosen for each hour by applying a binary constraint. 13 binary variables are used to represent the 13 vent configurations, where the sum of the binary variables must equal 1. The energy use, SOT, and zone temperatures for each vent configuration are then multiplied by the corresponding binary variable to determine the optimal vent configuration, SOT, and zone conditions. This method is expressed mathematically for energy

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demand in hour *i*, as the following equation. Zone temperatures are calculated in a similar manner.

Equation 3

$$\text{Min} = kWh_{i1}X_{i1} + kWh_{i2}X_{i2} + kWh_{i3}X_{i3} + kWh_{i4}X_{i4} + kWh_{i5}X_{i5} + kWh_{i6}X_{i6}$$
$$+ kWh_{i7}X_{i7} + kWh_{i8}X_{i8} + kWh_{i9}X_{i9} + kWh_{i10}X_{i10} + kWh_{i11}X_{i11}$$
$$+ kWh_{i12}X_{i12} + kWh_{i13}X_{i13}$$

> where: kWh represents the energy usage for each configuration
>
> X is a binary variable for each configuration

Equation 4

$$\text{Where}: \ X_{i1} + X_{i2} + X_{i3} + X_{i4} + X_{i5} + X_{i6} + X_{i7} + X_{i8} + X_{i9}$$
$$+ X_{i10} + X_{i11} + X_{i12} + X_{i13} = 1$$

By forcing the binary variable X of each configuration to add to 1, only 1 configuration can be chosen each hour.

4.4.3 Thermal Calculations

To compare the energy usage of the heating system under the various vent configurations, the model predicts when the system is on and off during the day. To predict how many degrees the temperature moves in a time step, the model must track several thermal transfers given the volume of air supplied to

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the room in a time step, the area of the conditioned zones, and the thermal mass of the building.

The first version of the optimization model was developed with Petek Gursel and Arman Shehabi in ER220. For simplicity, we assumed a static temperature difference between conditioned and unconditioned zones. We tested this model with 5°F and 15°F temperature differences. From these initial runs, we determined that the temperature between conditioned and unconditioned zones was a key variable in energy usage. Therefore, more accurate modeling of these differences was needed. The results from this first model can be found in the Initial Runs section of the Results.

For this thesis, I updated the model to track the temperature difference between conditioned and unconditioned zones, which is described below. Since this required fundamental changes to the model, I also took the opportunity to add supply air temperature, infiltration, and more detailed solar gains. This section describes the updated version of the model.

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The amount of heat that the heating system can deliver to a zone can be described as follows:

Equation 5

$$q_{hvac} = 1.08 \times Q \times (T_{supply} - T_{zone})$$

where: 1.08 is the heat capacity of air in Btu/(hr*°F*cfm)

Q is the ft^3/minute of air delivered to the zone (cfm)

T_{supply} is the supply air temperature (F)

T_{zone} is the temperature in the zone (F)

As heat is being transferred to the zone through the heating system, it is also being transferred between walls, ceilings, and floors. This heat transfer is dependent on the UA-value. The U-value represents the rate of thermal transfer through the wall. For example, the U-value of a window is much higher than that of the surrounding wall, and both are used to determine a single value for that wall. The U-value of each material is multiplied by the area of that material to determine the overall UA-value. To differentiate between upward and downward heat flow between floors, winter horizontal surface airfilms were include in the UA values of floors and ceilings (ASHRAE, 2005). To calculate this heat transfer (q_{UA}) from a zone to the outside and adjacent zones, the following equation is used:

Equation 6

$$q_{UA} = UA_{interior} \times (T_{zone} - T_{adjacent}) + UA_{exterior}(T_{zone} - T_{outside})$$

where:

U is the U-value (heat transfer rate) of the walls, ceiling, and floor of the conditioned zone

A is the area of the corresponding walls, ceiling, and floor in square feet

T_{zone} is the temperature in the conditioned zone

$T_{adjacent}$ is the temperature in adjacent unconditioned zones

$T_{outside}$ is the outside temperature

The temperatures used in Equation 6 should be instantaneous values, but to simplify, the model uses values from the previous time step (5 minutes). The temperature in the zone is set to the temperature that the zone reached at the end of the previous timestep by linking the values. Similarly, the temperatures of adjacent zones are set to the average of these ending values. Finally, the outside temperature is taken from hourly TMY2 weather data for California climate zone 12.

The heat transfer due to infiltration (q_{inf}) can be expressed as:

Equation 7

$$q_{inf} = (1.08 \times vol \times ACH)(T_{zone} - T_{outside})$$

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The model also needs to calculate heat transfer due to internal and solar gains. Internal gains include heat gains from sources such as lights, electrical equipment, people (approximately 100 watts/person), water heaters, etc. Running a simulation with Energy10, we determined that the internal gains should be approximately 0.1 Btu/min-sf. Hourly solar gain values were also taken from Energy10 simulations.

Equation 8

$$q_{gain} = q_{internal} + q_{solar}$$

Combining the above equations:

Equation 9

$$q_{total} = q_{hvac} - q_{UA} - q_{inf} + q_{gain}$$

The amount of time that it takes the house to heat or cool is dependent on the thermal mass. For example, a building with a large amount of concrete would heat more slowly, but it would also retain this heat for a longer period of time. The model uses a constant conversion value for a light mass building taken from CalRes, which allows the model to determine how much the temperature changes in a timestep given the mass of the building. Using this constant, Equation 10 calculates how many degrees the temperature in a zone changes in an hour (or in timestep).

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Equation 10

$$\frac{\degree F}{hr} = \frac{q_{hvac} - q_{UA} - q_{\inf} + q_{gain}}{3.5A}$$

where: A is the area of the conditioned zone in ft^2

(3.5 Btu/F-ft^2) is the default light mass constant from CalRes

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4.4.4 Occupancy Schedule

Occupancy schedules for a weekend day can be seen below in Table 2

Table 2: Hourly outdoor temperature and occupancy schedule						
			Occ. #			
Hour	OA Temp	Set-point	Zone 1	Zone 2	Zone 3	Zone 4
1	40	70	0	0	4	0
2	39	70	0	0	4	0
3	38	70	0	0	4	0
4	38	70	0	0	4	0
5	38	70	0	0	4	0
6	37	70	0	0	4	0
7	37	70	1	1	3	0
8	39	70	2	0	2	0
9	43	70	3	1	0	0
10	45	70	4	0	0	0
11	49	70	4	0	0	0
12	53	70	3	0	0	1
13	56	70	3	0	0	1
14	57	70	3	0	0	1
15	56	70	4	0	0	0
16	56	70	4	0	0	0
17	53	70	4	0	0	0
18	49	70	4	0	0	0
19	45	70	4	0	0	0
20	43	70	3	0	0	1
21	41	70	3	1	0	0
22	39	70	3	1	0	0
23	40	70	0	0	4	0
24	42	70	0	0	4	0

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4.4.5 Weather Data

The weather data used in the model is a TMY2 file of California climate zone 12. This file provided hourly data for a typical year.

5. Results

This section describes five different runs using the optimization model. Section 5.1 describes the first three runs. These were the first runs done on the initial model: basecase, multizone with 5°F difference, and multizone with 15°F temperature difference.

Sections 5.2 and 5.3 describe the runs completed with the updated model, one basecase and one multizone run. All of the runs are based on a typical weekend occupancy schedule with weather data as described in Table 2.

5.1 Initial Runs

An initial model was developed and the results of three runs are summarized in Table 3 below. Note that energy in kWh accounts for both fan and furnace energy use. The fan is electric while the furnace is run on natural gas. The furnace is rated at 100,000 Btus/hr or 1 therm/hr. This is equivalent to 29.3 kW, which was used to convert the furnace power to kW in order to have a common unit of energy for the optimization.

The basecase forces the model to leave all vents open (configuration 1) and to see all zones as occupied, which forces all zones to actuate together. In this model, static temperatures differences were assigned to conditioned and unconditioned zones to provide a first pass model. Vent control with a 15°F change assumes that the temperature change between a conditioned space and

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an unconditioned space is 15°F. Similarly, the vent control with a 5°F change assumes that this temperature change is only 5°F.

When the $UA_{internal}$ temperature change was assumed to be 15°F, the total energy use is nearly the same as that of the basecase. The basecase and hourly register control modes use 188 and 189 kWh respectively. However, the distribution of energy used in a day is quite different. Whereas the basecase tends to distribute the energy usage more evenly, the register control mode concentrates energy usage in the morning hours. For the first six hours of the day, zone 3 (bedrooms) is the only occupied zone. The model controls the heating based on the temperature in this zone and only conditions a few minutes each hour. As a result, zone 1 (kitchen and living room) begins to cool. The constraint that no zone can drop below 55°F forces the heat to turn on in hour 6 because zone 1 cools to this level. In the next hour, zone 1 is occupied, so the system continues to stay on in an effort to reach the setpoint. The heating system needs to stay on for almost three hours straight in hours six through eight. However, unlike the basecase, the multizone control has the ability to only control the zones that are below setpoint. Therefore, zones 2 and 3 do not reach the high temperatures seen in the basecase.

When the $UA_{internal}$ temperature change is assumed to be 5°F, the optimal vent configurations are very different than those chosen in the 15°F case. Here, there are less internal losses from conditioned zones. In the early morning hours, with the decreased losses, zone 1 is able to reach the setpoint in a much shorter time period (about half). During the day when zone 1 is usually occupied

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MS Thesis, Dept. of Architecture, UC Berkeley 2007   https://escholarship.org/uc/item/5j1996rn

and has the highest losses to the outside, configuration 13, which only conditions zone 1 is the most common choice. During the night, the configuration choice varies depending on the number of people in each zone. The optimal solution with the decreased internal losses uses about 25 kWh less than both the register control with higher internal losses and the basecase. This is probably because the zone can reach the setpoint temperature in less time and does not experience the increased decay rate that is seen in the 15°F case.

	Basecase			Vent control with 15F change			Vent control with 5F change		
hour	Config	Op Time	kWh	Config	Op Time	kWh	Config	Op Time	kWh
1	1	17	8.5	1	5	2.5	9	4	2
2	1	20	10.0	1	6	3.0	1	5	2
3	1	20	10.0	5	7	3.5	4	6	3
4	1	20	10.0	5	7	3.5	5	9	4
5	1	20	10.0	5	6	3.0	4	6	3
6	1	22	11.0	14	60	30.0	12	12	6
7	1	22	11.0	14	60	30.0	14	60	30
8	1	17	8.5	8	57	28.4	14	20	10
9	1	19	9.5	6	13	6.5	14	14	7
10	1	14	7.0	14	15	7.5	14	14	7
11	1	13	6.5	3	11	5.5	14	13	6
12	1	10	5.0	6	11	5.5	14	14	7
13	1	7	3.5	2	6	3.0	6	14	7
14	1	8	4.0	6	8	4.0	14	13	6
15	1	7	3.5	2	7	3.5	14	14	7
16	1	8	4.0	3	8	3.5	6	13	6
17	1	11	5.5	6	10	5.0	14	14	7
18	1	14	7.0	6	12	6.0	7	14	7
19	1	15	7.5	14	14	7.0	6	14	7
20	1	16	8.0	6	14	7.0	6	14	7
21	1	20	10.0	14	17	8.5	6	14	7
22	1	19	9.5	14	16	8.0	14	13	6
23	1	17	8.5	9	4	2.0	1	11	5
24	1	20	10.0	1	5	2.5	2	6	3
Total	376 min		188 kWh	379 min		189 kWh	331 min		162 kWh

Table 3: Simplified hourly model results

From these initial runs, we found that these internal temperature differences played a large role in both configuration selection and energy usage. When using a 15°F difference, the basecase performed as well as the multizone control. But, when a 5°F difference was used, the multizone control used about 14% less energy. Therefore, the model was updated to track zone temperature differences at every time step.

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5.2 Updated Basecase Runs

5.2.1 Energy Use

Table 4 shows the operation time and energy use for the basecase runs in the updated model. These values are higher than those from the initial runs. This is largely due to infiltration, which was not accounted for in the previous version of the model.

Table 4: Basecase operation time and energy usage

Hour	SOT	Total kWh
1	35	17.5
2	35	17.5
3	40	20.0
4	35	17.5
5	35	17.5
6	40	20.0
7	35	17.5
8	35	17.5
9	35	17.5
10	30	15.0
11	20	10.0
12	20	10.0
13	15	7.5
14	15	7.5
15	15	7.5
16	15	7.5
17	20	10.0
18	30	15.0
19	30	15.0
20	30	15.0
21	35	17.5
22	35	17.5
23	35	17.5
24	35	17.5
Total	705	351.8

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5.2.2 Temperature distribution

Figure 4 shows the temperature distribution in the zones from the basecase run in the updated model. As in the previous baseline case, the energy use is spread fairly evenly throughout the day. As seen in Figure 4, the basecase model clearly actuates around the temperature in zone 1. Throughout the day, zone 1 remains at the setpoint while the other zones become significantly overheated. While initial data from the house did show that the upstairs was significantly warmer than the downstairs, the results in the model are probably somewhat exaggerated. However, more house runs would be needed to fine-tune the model.
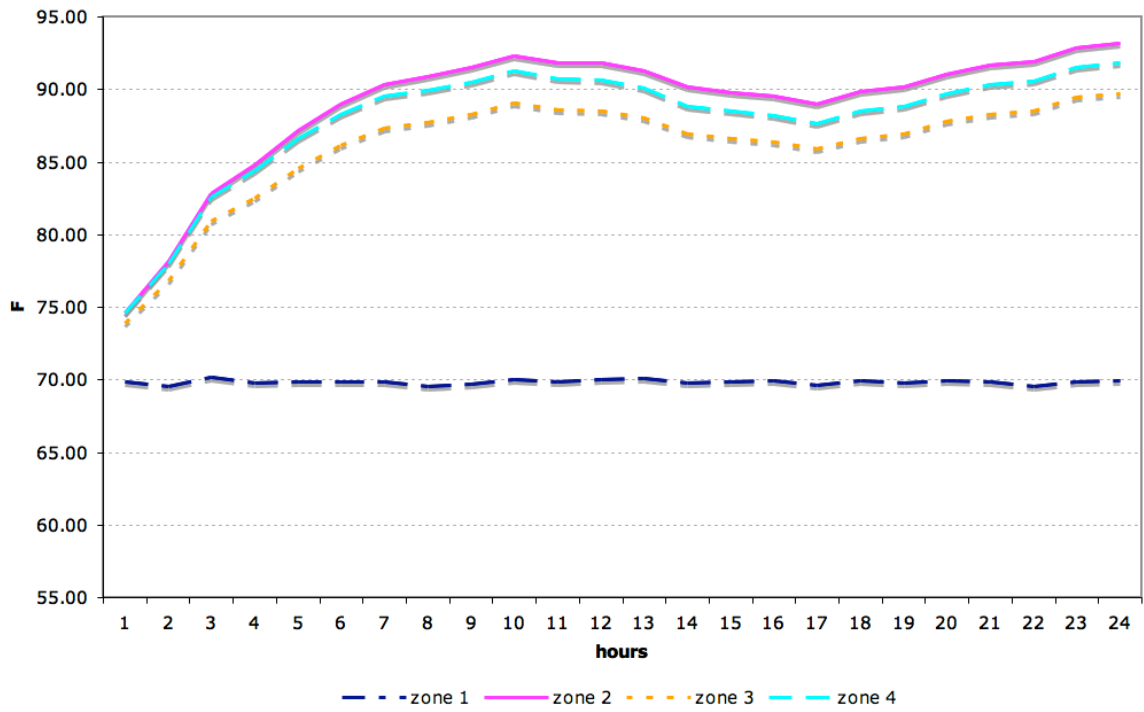
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Figure 4: Basecase temperature distribution

5.3 Updated Zoned Runs

5.3.1 Energy use

Table 5 outlines the results from the updated multizone run which uses about 26% less energy than the basecase run.

Table 5: Vent control operation time and energy use

Hour	SOT	Total kWh
1	10	5.0
2	10	5.0
3	10	5.0
4	15	7.5
5	10	5.0
6	15	7.5
7	15	7.5
8	60	29.9
9	60	29.9
10	30	14.9
11	10	5.0
12	45	22.4
13	10	5.0
14	10	5.0
15	5	2.5
16	20	10.0
17	15	7.5
18	20	10.0
19	25	12.5
20	25	12.5
21	40	19.9
22	20	10.0
23	30	15.0
24	10	5.0
Total	**520**	**259.2**

5.3.2 Temperature distribution

Figure 5 shows the temperature distribution in the updated multizone runs. Here, the occupied zones dominate the temperature. In the late and early hours of the day, only the bedrooms (zone 3) are occupied. At this time, the bedrooms stay at the setpoint while the rest of the house is allowed to cool. Around hour 6, when zones 1 and 4 reach the minimum allowed temperature of 55°F, the system begins to heat these zones. This occurs just before these zones are occupied. Throughout the day, zone 1 has the most consistent occupancy and tends to remain close to the setpoint. However, since the system has the ability to only control occupied zones, the rest of the house does not reach the high temperatures seen in the basecase. Overall, the multizone control allows the house to be heated more appropriately based on occupancy. In addition to increased thermal control, the multizone control also used about 26% less energy. Again, the energy usage was concentrated in the early morning hours after zone 1 reached the minimum allowed temperature. If the minimum temperature was increased, the energy usage would be more evenly spread throughout the day, but there would also be decreased energy savings.
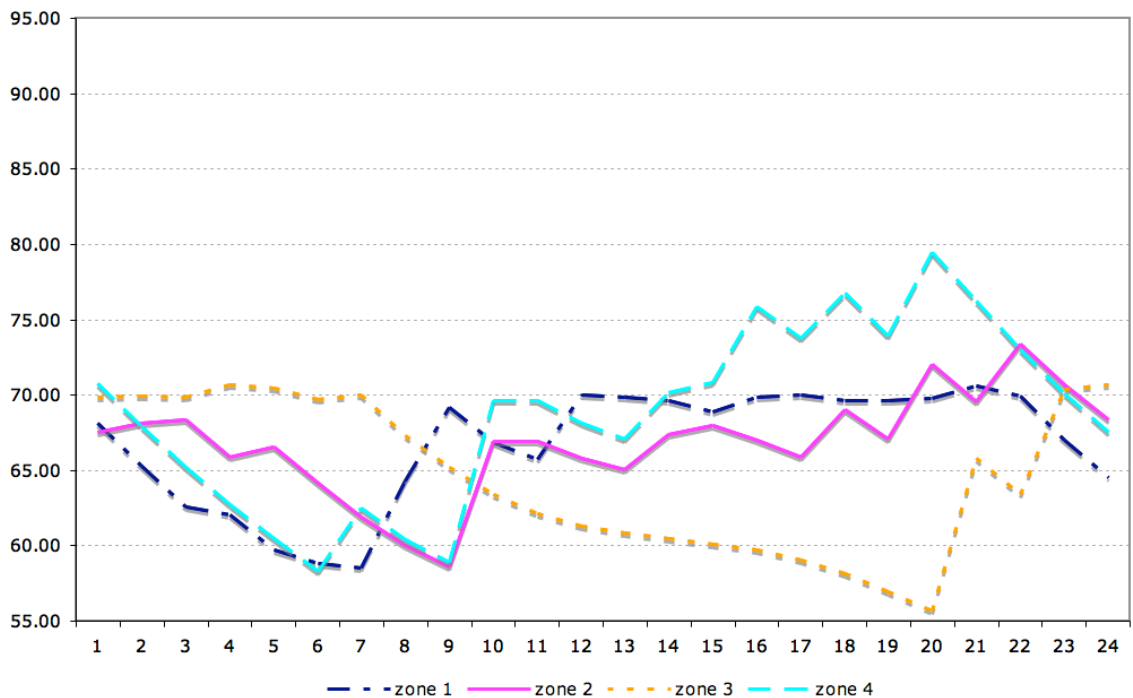
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Figure 5: Vent control hourly temperature distribution
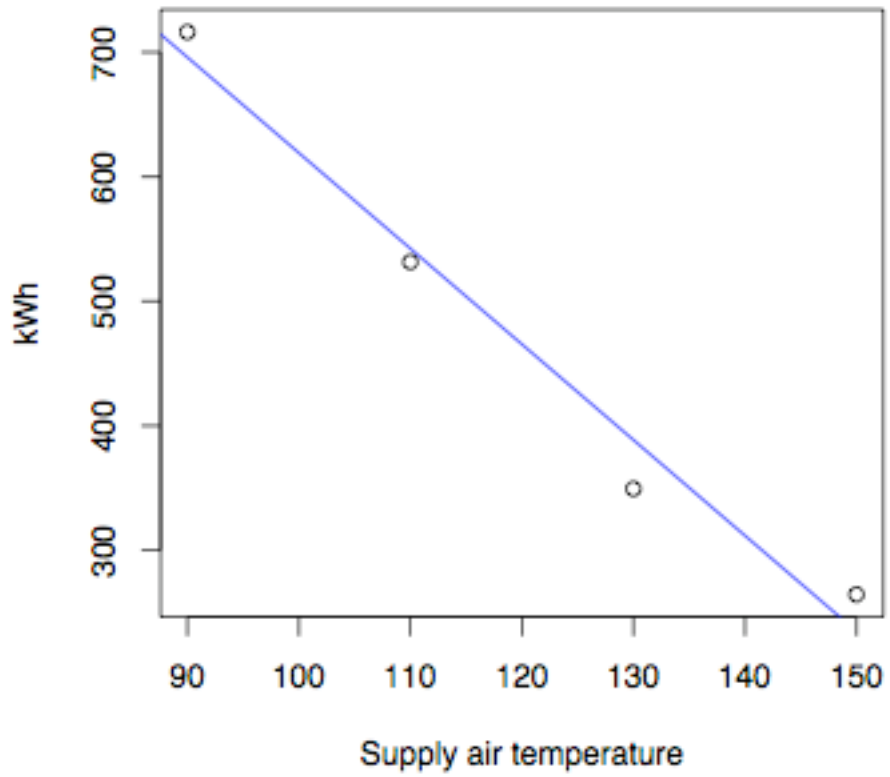
5.4 Sensitivity Analysis

There are many variables determining the effects of zoning, which vary widely by building type. In this model two of the major unknowns are supply air temperature and infiltration. Therefore, a basic sensitivity analysis was conducted to determine if the effects of these variables were linear. The infiltration was varied by setting the air changes per hour (ACH) from 0.5, which represents a fairly tight house, to 5.0, which represents an extremely leaky house. Likewise, the supply air temperature was varied within the range of 90

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and 150°F. Figure 6 and Figure 7 below display these results of the kWh used in a 24-hour period. In both cases a linear model has been fit to the results.
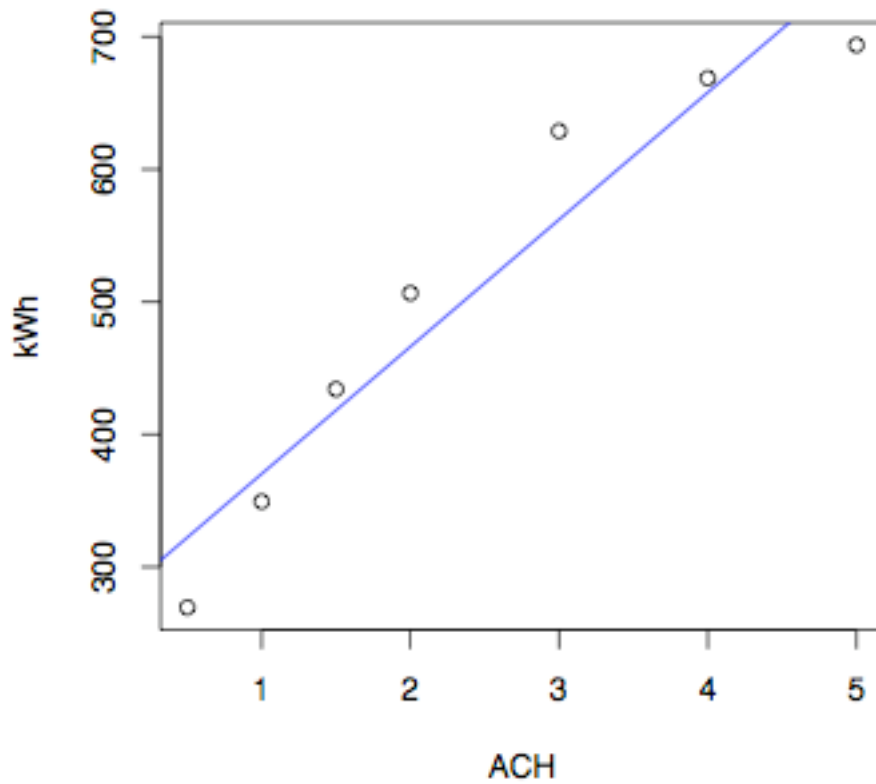
Figure 6: Basecase ACH sensitivity analysis (constant supply air temperature)

Figure 7: Basecase supply air temperature sensitivity analysis (constant ACH)

6. Discussion

After running several variations of the model, it is clear that the basecase and the multizone control modes act quite differently. In the basecase, the energy usage is fairly evenly spread across the day. The house tends to actuate around the living room zone, often overheating the other zones. So, we do not see the zone temperature dips that appear in unoccupied zones in the multizone control. Since all zones are conditioned throughout the day, it is assumed that there are no heat transfers between internal walls. Therefore, thermal decay in the zones is due to heat loss to the outside. The kitchen and living room area (zone 1) has the largest surface area that borders the outside (highest $UA_{external}$). In addition, this zone has cathedral ceilings and a relatively large amount of glazing. This zone loses heat more quickly than the other zones, dominating the heating control. In the real house, the thermostat is located in the living room, which generally is cooler than the other zones. Since the system must remain on until this zone is above the setpoint (or remaining above the deadband), the smaller zones continue to receive heat when they no longer need it. Specifically, the bathrooms/laundry room and the office (zones 2 and 4 respectively) are significantly overheated.

The multizone control mode tends to have more precise thermal control, but is susceptible to a lack of schedule knowledge. When running the model without future knowledge, it may choose a path that cannot be rectified in a hour's time with occupancy changes. This can be solved with a schedule based

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on expected future occupancy because the model would know to run the system for a longer period of time in the early hours.

In the multizone control, since zones are being turned on and off independently of each other, the model needs to calculate the $UA_{internal}$ heat transfers between conditioned and unconditioned zones. Rather than tracking every temperature difference, the model initially used a constant temperature difference between a conditioned and an adjacent unconditioned zone. When tested, this assumption turned out to be a large factor in optimal configuration choice and resulting energy usage. Therefore, the model was later updated with more accurate zone temperature calculations, using the average of the adjacent zones from the previous timestep's end. However, the initial runs did provide some valuable information about trends in the house.

This revamping provided an opportunity to add other enhanced thermal calculations. For example, control of the supply air temperature and infiltration levels was added. The final values chosen for the runs needed to be an educated guess since there was not corresponding house data. So, initial sensitivity analysis was completed to determine if changing the values of the supply air temperature and infiltration had a linear effect on the energy use. Figure 6 and Figure 7 show that changes in these values did, in fact, result in a roughly linear change in the overall energy use. Therefore, if the supply air temperature or infiltration levels in the house were different from our assumptions, the resulting energy comparisons would still be similar.

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This thesis was as much an exploration into developing an optimization model with thermal calculations as it was a means of getting to the end energy use results. While I was pleased with the learning process of developing such a model, it would have been useful to do some analogous runs in the house after getting results from the model. If we controlled the house for a period of time in the same way that the model controlled the zones, we could have quantitatively compared the results.

Although we did not have exact data from the Danville house to match the results, we can see that the general trends in the house are the same. In both the optimization model and the actual Danville house, Zone 1 (the kitchen and living room) tended to be the coolest in the single zone control, causing the rest of the house to overheat. We can see in both, that not only can the multizone control save energy while providing comparable or enhanced thermal control, but that the *need* for better thermal control in the house provides a gateway for energy savings when the ability to individually condition zones is introduced.

Through these optimization runs, it became clear that one of the keys to energy savings in multizone control is the ability to actuate zones based on multiple sensors, rather than a single thermostat. The thermostat in the Danville house is located in the zone that is typically the coolest. This forces the other zones to chronically overheat to meet the needs at the thermostat.

In addition, multizone control allows the house to be controlled as needed based on expected occupancy. Therefore, during the day when the bedrooms are unoccupied, these zones are able to cool. This is a major change because in

the basecase, these zones were routinely being overheated to keep the living room zone at the setpoint.

This shift from overheating unoccupied zones to allowing these zones to cool when they are empty is a key factor in multizone energy savings.

These issues are not unique to the Danville house. Thermostats on the first floor are *often* not representative of the second floor. In addition, it is rare that all zones in a house are occupied, so it does not make sense to always condition an entire house. Multizone control can allow houses to be conditioned in a more intelligent manner, addressing thermal loads as needed--as opposed to a one-size-fits-all mentality.

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7. Future Work

These results are very encouraging, but some follow-up runs should be completed in the actual house to confirm the energy savings. Specifically, some of the zones temperatures seen in the results seem high. Comparing model runs to house data would be useful to get more precise results and to have a better sense of the range of potential energy savings.

The retrofitted vents can be installed fairly easily in a house, but developing a marketable controller will be a challenge. At the early stages, optimization was a useful tool to compare all possible configuration choices throughout the day. However, it would probably be too cumbersome to implement into an actual control algorithm.

The optimization accounted for the slight differences in fan power in each configuration. Since these variations were small compared to the overall furnace power, a simple 'system-on-time' would probably be sufficient to provide accurate results.

Allowing more conditioned air to reach occupied zones by shutting off other zones is a fundamental part of the energy savings, so it seems that measuring the flow rates in the zones would be beneficial. This could be performed at the same time as the system was installed. However, it would require the controller to take flow input. This would be more complicated, but may be reasonable for a one-time commitment.

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Finally, a parallel cooling analysis should also be completed. Peak electricity loads occur during hot summer afternoons when the air conditioning load is high. So, this system could be used for demand response needs. For cooling loads, we would probably see similar trends to the heating results. The large amount of glazing in the kitchen and living room would result in high solar gains. This, in addition to the relatively large volume means that, again, the thermostat is likely to not represent the entire house. It is common in houses for zones with high thermal losses in the winter to also have high gains in the summer because of building components such as windows.

The results of this thesis suggest that we may need to reassess the way that we condition houses. With hopes of decreasing our energy usage overall, it seems that conditioning an entire house all the time no longer makes sense. The single-sensor, single-actuator model may no longer be the solution.

In general, more research should be dedicated to multi-sensor, multi-actuator systems. In addition, we need to understand how to better incorporate occupancy into our control algorithms. This could manifest in programmed occupancy schedules or real-time occupancy sensing, but work is needed to determine which route is better.

8. Conclusion

It is clear that the optimal configuration is very dependent on the internal transfers. A configuration is only chosen if the increased volume of air delivered to a zone can outweigh the increased internal losses. These internal transfers should be calculated as accurately as possible.

According to the model results, the multizone control is preferable to the basecase because zones can be shut off individually, preventing high temperatures in the smaller zones. In addition, the multizone control used about 26% less energy than the basecase. However, to appropriately control the house, an occupancy schedule should be provided. As we saw in our model, the ability to recognize that the living room and kitchen were not occupied at night and that bedrooms were empty during the day was a major driver in energy savings. When the model can see which zones need to be conditioned in both the current hour and future hours, it can choose configurations that satisfy both with the lowest energy usage possible. The key to energy savings in the multizone system is the ability to condition *only* occupied zones that are below the setpoint.

Overall, this simple, inexpensive system should be able to save energy while providing enhanced comfort control, moving us toward houses that condition in a more intelligent, energy efficient way.

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