

Simulating Energy Usage Impact of Retrofitting Residential Registers with a Simple Damper System

by

Colin E. Skinner

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

Master of Science Mechanical Engineering

at

TUFTS UNIVERSITY

May 2016

© Tufts University 2016. All rights reserved.

Author
Colin E. Skinner
Department of Mechanical Engineering
April 22, 2016

Certified by
Luisa Chiesa, Ph.D.
Associate Professor
Thesis Supervisor

This masters thesis has been examined by a Committee of the
Department of Mechanical Engineering as follows:

Professor Luisa Chiesa, Ph.D.....
Thesis Advisor, Thesis Committee
Associate Professor of Mechanical Engineering
Tufts University

Professor Robert Hannemann, Ph.D.....
Thesis Committee
Professor of the Practice of Mechanical Engineering
Tufts University

Professor Michael Gevelber, Ph.D.....
Thesis Committee
Associate Professor of Mechanical Engineering
Boston University

Simulating Energy Usage Impact of Retrofitting Residential Registers with a Simple Damper System

by

Colin E. Skinner

Submitted to the Department of Mechanical Engineering
on April 22, 2016, in partial fulfillment of the
requirements for the degree of
Master of Science Mechanical Engineering

Abstract

Air conditioning and heating comprised 47.7% of total energy usage in residential homes in the United States in 2009 equating to 4.86 quad (5.13 EJ) energy used. According to the U.S. Energy Information Administration (EIA) this is down from 58% in 1993. This is in large part due to the difference types of energy efficiency measures, from installing more efficient equipment to drafting better building codes that are inclusive of energy saving measures. Generally, these measures are very effective for new buildings. However, older buildings may still rely on less efficient materials and equipment thus inflating the building's energy usage.

The installation of simple dampers on the registers of a two-story, 2400 sq. ft. residential house as a retrofit measure to increase energy efficiency of its heating, cooling, and ventilation (HVAC) system is explored in this thesis. A residential house was modeled in EnergyPlus (v8.4), a whole-building energy simulation software available from the U.S. Department of Energy (DOE). The house was simulated for total energy usage with a typical HVAC system serving seven rooms; it was compared to a simulation of the same system with simple dampers installed on the registers.

It is shown that by installing dampers that self-fluctuate for local room temperatures, the system has an 11% reduction in energy usage in the Boston, Massachusetts climate zone. Additionally, the dampers are able to reduce hot and cold spots within the building and reduce, on average, the difference between the first and second floor temperatures. It is also shown that the effects of overpressurization of the HVAC system could be minor through an airflow simulation using CONTAM and EnergyPlus, but more experimentation is required. Seven other climate zones in the US were also simulated.

Thesis Supervisor: Luisa Chiesa, Ph.D.
Title: Associate Professor

Acknowledgments

This work, in large part, could not have been produced without the helping hand from my thesis committee, class mates, friends, and family.

I would like to thank my advisor, Dr. Luisa Chiesa, who constantly pushed me to produce the highest quality work possible and helped me grown professionally.

Dr. Robert Hannemann, who shares a passion for renewable energy sources and energy efficiency ideas and whose Power Generation class helped spark the initial desire to aid in the search for better energy management systems.

Dr. Michael Gevelber, who helped brainstorm the initial idea for the thesis and was a constant sounding board during the entire process.

I would also like to thank Michael Blasnik, Senior Building Scientist at Nest, for discussing the initial design ideas for this work. Your experience and information was invaluable during the entire thesis.

My newfound friends and colleagues for being both inspirations and distractions.

Lastly, I'd like to give my heartfelt thanks to my dearest friends and my family. Both of which have kept me going and been constant sources of motivation. This work is dedicated to them.

Contents

1	Introduction & Motivations	1
1.1	Motivations	1
1.2	Thesis Overview	2
2	Background	3
2.1	A Brief Overview of Residential HVAC	3
2.1.1	Current Residential HVAC Technologies	3
2.1.2	Single Thermostat Control	8
2.2	Energy Usage & Retrofitting	10
2.2.1	Elementary Case: Air Redistribution	14
2.3	Thermal Comfort	15
3	Methods & Limitations	21
3.1	Simulation Tool	21
3.1.1	Building Model	22
3.2	Investigations	32
3.2.1	Extreme Temperatures	32
3.2.2	Annual Energy Usage	33
3.2.3	Duct Flow & System Performance	34
4	Results	39
4.1	Validation: Elementary Case	39
4.2	Thermal Balancing	43

4.2.1	Low Outside Ambient Temperature	45
4.2.2	High Outside Ambient Temperature	49
4.3	Annual Simulation	53
4.3.1	Total Energy Usage vs Climates	54
4.3.2	Thermal Comfort	56
4.4	Impact on HVAC System	62
4.4.1	Generic Ductwork	62
4.4.2	Air Flow Network Modeling	65
5	Discussion & Conclusions	67
5.1	Energy Saving Potential	67
5.2	System Impact	70
5.3	Conclusions	71
5.3.1	Future Work	72
A	Section 4.2 Tables & Graphs	75

List of Figures

2.1	Typical Residential HVAC Installation	5
2.2	Residential floor register with manual damper	5
2.3	Characteristics of HVAC system during cooling cycle.	6
2.4	Characteristics of HVAC system during heating cycle.	7
2.5	Visualization of a typical thermostat dead-band setpoint.	9
2.6	Elementary air redistribution cases.	15
2.7	Fanger PMV Scale.	18
2.8	Fanger PPD vs PMV.	19
3.1	EnergyPlus Program Schematic	23
3.2	Schematic of model building.	24
3.3	Simplified floor plans for model building and potential airflow pathways.	25
3.4	Schematic of the wall construction in the Boston model and simplified heat transfer	25
3.5	EnergyPlus AirTerminal:SingleDuct:VAV:HeatAndCool:NoReheat ob- ject.	29
3.6	Generic extended plenum system	35
3.7	Generic radial system	35
3.8	Generic fan curve and system performance graph.	36
3.9	Simple five section duct system	37
4.1	Elementary case for constant, high ambient air temperature (36°C). .	40
4.2	Elementary case for constant, high ambient air temperature (36°C) and unbalanced loads.	42

4.3	Elementary case for constant, low ambient air temperature (0°C) and unbalanced loads.	44
4.4	Base Case: Frequency of room temperatures for during cold temperature run.	45
4.5	Base Case: Daily mean temperature during cold temperature run. . .	46
4.6	Dampers: Frequency of room temperatures during cold temperature run.	47
4.7	Dampers: Daily mean temperature during cold temperature run. . . .	48
4.8	Base Case: Frequency of room temperatures during hot temperature run.	50
4.9	Base Case: Daily mean temperature (°C) during hot temperature run.	50
4.10	Dampers: Frequency of room temperatures (°C) for hot temperature run.	51
4.11	Dampers: Daily mean temperature (°C) during hot temperature run.	52
4.12	Frequency of Room Temps: Boston Base Case.	57
4.13	Frequency of Room Temperatures: Boston Dampers.	57
4.14	Yearly energy usage summary and percent differences between base case and dampers model.	58
4.15	Yearly cost of energy summary for base case and dampers model. . .	58
4.16	Mean building temperature: Boston Base Case.	59
4.17	Mean building temperature: Boston Dampers.	59
4.18	Predicted percentage dissatisfied: Boston No Dampers.	61
4.19	Predicted percentage dissatisfied: Boston Dampers.	61
4.20	Schematic of small duct system with 3 registers.	62
4.21	System pressure vs. damper configurations for a small HVAC system.	63
4.22	Schematic of upscaled duct system with seven registers.	64
4.23	Supply Airflow vs. damper configurations for a small HVAC system. .	64
A.1	Frequency of Room Temps: Albuquerque No Dampers	75
A.2	Frequency of Room Temperatures: Albuquerque Dampers	76
A.3	Mean building temperature: Albuquerque No Dampers	76

A.4	Mean building temperature: Albuquerque Dampers	77
A.5	Frequency of Room Temps: Colorado Springs No Dampers	78
A.6	Frequency of Room Temperatures: Colorado Springs Dampers	78
A.7	Mean building temperature: Colorado Springs No Dampers	79
A.8	Mean building temperature: Colorado Springs Dampers	79
A.9	Frequency of Room Temps: Los Angeles No Dampers	80
A.10	Frequency of Room Temperatures: Los Angeles Dampers	80
A.11	Mean building temperature: Los Angeles No Dampers	81
A.12	Mean building temperature: Los Angeles Dampers	81
A.13	Frequency of Room Temps: Phoenix No Dampers	82
A.14	Frequency of Room Temperatures: Phoenix Dampers	82
A.15	Mean building temperature: Phoenix No Dampers	83
A.16	Mean building temperature: Phoenix Dampers	83
A.17	Frequency of Room Temps: Atlanta No Dampers	84
A.18	Frequency of Room Temperatures: Atlanta Dampers	84
A.19	Mean building temperature: Atlanta No Dampers	85
A.20	Mean building temperature: Atlanta Dampers	85
A.21	Frequency of Room Temps: Baltimore No Dampers	86
A.22	Frequency of Room Temperatures: Baltimore Dampers	86
A.23	Mean building temperature: Baltimore No Dampers	87
A.24	Mean building temperature: Baltimore Dampers	87
A.25	Frequency of Room Temps: Houston No Dampers	88
A.26	Frequency of Room Temperatures: Houston Dampers	88
A.27	Mean building temperature: Houston No Dampers	89
A.28	Mean building temperature: Houston Dampers	89

THIS PAGE INTENTIONALLY LEFT BLANK

List of Tables

2.1	Conventional Residential HVAC Systems.	4
2.2	Summary of previous studies done on residential register dampers . .	12
2.3	Heat transfer components in definition of heat load on a clothed body.	17
2.4	Thermal load characteristic parameters and assumed values.	18
3.1	EnergyPlus initial heat transfer equation parameters	22
3.2	Climate zones, locations and characteristic qualities	23
3.3	Material characteristics for external wall construction in the Boston model	26
3.4	DX cooling coil model coefficients (SI units)	27
3.5	Boston model envelope and equipment assumptions.	28
3.6	EnergyPlus damper control variables.	29
3.7	EnergyPlus simulation overview and main objects.	38
4.1	Base Case: Temperature (°C) statistics for cold days.	46
4.2	Dampers: Temperature (°C) statistics cold days and % difference from base case (Table 4.1).	48
4.3	Airflow rate (m^3/s) differences between base case and damper case heating cycle; total for duration of simulation.	48
4.4	Base Case: Temperature (°C) statistics for hot days.	50
4.5	Dampers: Temperature (°C) statistics for hot days and % difference from base case (Table 4.4).	51
4.6	Airflow rate (m^3/s) differences between base case and damper case cooling cycle; total for duration of simulation.	52

4.7	Average cost of electricity and natural gas from 2014, EIA RECS. . .	55
4.8	Average Coefficient of Performance (COP) for base case and dampers.	56
4.9	Temperature (°C) statistics for Boston base case and dampers model.	60
4.10	Summary of AFN models.	65
A.1	Temperature (°C) statistics for Albuquerque base case and dampers model	75
A.2	Temperature (°C) statistics for Colorado Springs base case and dampers model	78
A.3	Temperature (°C) statistics for Los Angeles base case and dampers model	80
A.4	Temperature (°C) statistics for Phoenix base case and dampers model	82
A.5	Temperature (°C) statistics for Atlanta base case and dampers model	84
A.6	Temperature (°C) statistics for Baltimore base case and dampers model	86
A.7	Temperature (°C) statistics for Houston base case and dampers model	88

Chapter 1

Introduction & Motivations

The research objectives of this thesis are to investigate register damper impacts on (1) thermal comfort, (2) energy usage and (3) system performance through the use of simulation using EnergyPlus (v8.4), primarily, and CONTAM (v3.2). This chapter presents the reader with the motivations for the investigation and an overview of the thesis layout.

1.1 Motivations

The majority of energy consumption in a residential home in the US comes from conditioning the air in the home. This breaks down to 41% and 6% consumed in heating and cooling respectively [1]. Research into energy efficient schemes for residential homes has become increasingly important with rising concerns regarding energy usage, carbon footprint and global warming. Energy efficient schemes for residential homes range wildly on a scale of effectiveness and capital cost, from changing heating and cooling set points to installing a wind turbine or solar panels to offset electricity usage.

New buildings are constructed with better insulation and more energy efficient heating, cooling, and ventilation (HVAC) equipment. Older homes may have a larger thermal load than necessary due to degrading construction materials and aging equipment running at reduced capacity [2]. Energy companies have started to create in-

centives for homeowners to invest in retrofitting their homes to increase the home's energy efficiency. Typically, retrofits focus on upgrading insulation, reducing duct leakage and replacing older equipment with newer high efficiency models. Retrofit incentives are given out in the form of tax breaks or rebates [2].

One such energy saving scheme that has been discussed over the past few decades is the use of automatic dampers the registers in a residential home [3]. The dampers are designed to redistribute the air of a duct system such that the building is brought to a more equal temperature throughout the home. The effectiveness of the system can be investigated across a variety of climate zones and building types quickly by leveraging current simulation capabilities. An ideal damper system would increase thermal comfort, decrease energy usage and either neutrally or positively effect system performance. Sacrificing one for the sake of another would represent a non-ideal system.

1.2 Thesis Overview

This thesis is presented in five sections. Section 2 provides background knowledge of residential HVAC systems and a brief review of previous research using a damper system in a residential setting. Most of the previous studies are focused on zoning a residential home rather than evenly distributing the thermal load throughout the house. The background section also discusses the use of Fanger's thermal comfort model as a metric for the simulations [4].

Section 3 will outline the methods used for each investigation and potential limitations that could affect the results. Section 4 presents the results of all investigations focusing mainly on room and building temperature as well as total energy use and cost analysis. Lastly, Section 5 discusses the results and effectiveness of a damper system for use in a residential setting. Conclusions and future work are also presented in this section.

Chapter 2

Background

This chapter will look to provide the reader with a basic understanding of residential forced-air central heating and cooling systems. A brief overview of possible equipment choices and fuels is presented. A review of previous research on residential dampers and an elementary case to illustrate their usage is introduced. The most common control system, a centralized and singular temperature thermostat, is then discussed. Finally, a discussion on a main metric of interest to the thesis, thermal comfort, and its quantification is presented.

2.1 A Brief Overview of Residential HVAC

2.1.1 Current Residential HVAC Technologies

Residential HVAC systems are designed to provide a general level of thermal comfort to occupied space. The type of system is mainly dependent on the climate zone and the fuel sources available. The three groups of heating and cooling systems are (1) central forced-air, (2) central hydronic, and (3) zoned systems. In addition to heating and cooling, the HVAC system can be equipped to provide air cleaning and humidification capabilities when the air composition and psychrometric conditions make it required for more adequate thermal comfort and/or health concerns. The typical fuel sources, distribution mediums, distribution systems and terminal equipment are

summarized in Table 2.1. The fuel and distribution options in Table 2.1 covers 90% of current technologies used in single-family residential buildings [5, 1]. A central forced-air system conditions the spaces in a residence by delivering heated or cooled air.

	Central Forced Air	Central Hydronic	Zoned
Most common energy sources	Gas Oil Electricity	Gas Oil Electricity	Gas Electricity
Distribution Medium	Air	Water Steam	Air Water Refrigerant
Distribution System	Ducting	Piping	Ducting Piping Free Delivery
Terminal Devices	Diffusers Registers Grilles	Radiators Radiant Panels Fan-Coil Units	Included with product or same as forced-air or hydronic systems

Table 2.1: Conventional Residential HVAC Systems [6].

A typical forced-air system is comprised of a circulating blower used to force air from the return duct through an air filter into the inlet of the furnace (Figure 2.1). The air handler unit (AHU) forces the air over two heat exchangers; an evaporating coil for cooling and a heating coil for heating. When cooling is required, refrigerant is pumped through supply lines to the evaporator and outside to a condensing unit. The condensate that forms on the evaporator is collected in a trap and drained. Optionally, the supply air from the furnace can pass through a humidifier to provide moisture to the heated air which is then distributed throughout the house in a main supply duct. Ductwork is used to distribute the conditioned air to the various spaces being conditioned. Typical residential HVAC systems will have one or two inlets per

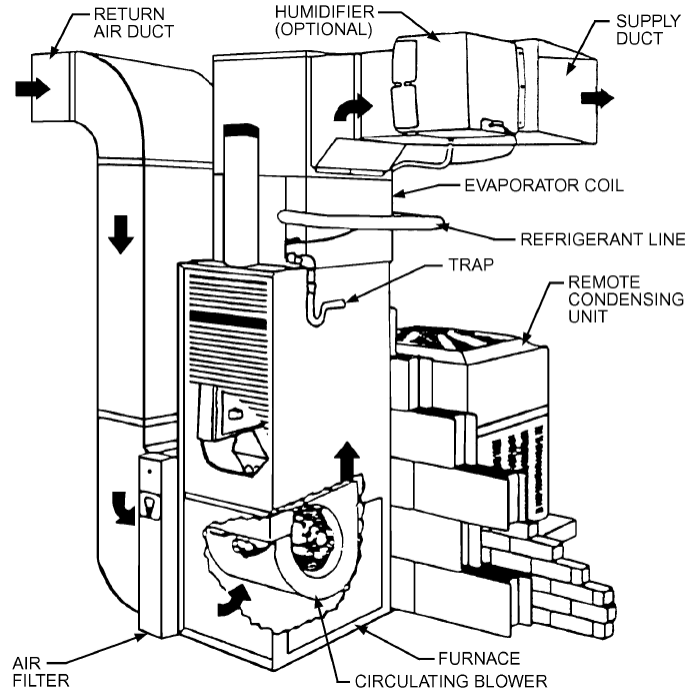


Figure 2.1: Typical Residential HVAC Installation [7].

room with the air passing through a register or grille (Figure 2.2), and one or two outlets per floor connected to a return duct back to the furnace equipment.

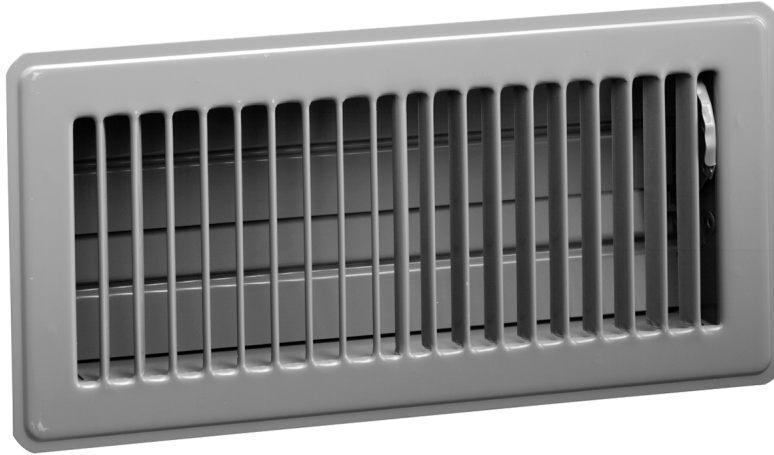


Figure 2.2: Residential floor register with manual damper [8].

The total heat-extraction capacity of the outside condensing unit is usually measured in tons of refrigeration where $1 \text{ TR} = 12,000 \text{ Btu/h} = 3.5 \text{ kWh}$. The term

tons of refrigeration is defined as the heat of fusion absorbed by 2000 lb of pure ice at 0 °C in a 24 hour period. The energy used in the evaporating coil is generated using a vapor compression cycle; it relies on a refrigerant's ability to absorb large quantities of heat during a phase change. The conditioned air that passed over the evaporation coil is supplied via the supply registers. It is then heated by the ambient air temperature, occupants in the building, solar irradiance, appliances and lighting. The now warm air is returned via the return duct to again be conditioned (Figure 2.3). These condensing units are typically sold as separate, add-on/remote air cooling units that are installed in conjunction with the heating furnace (Figure 2.1).

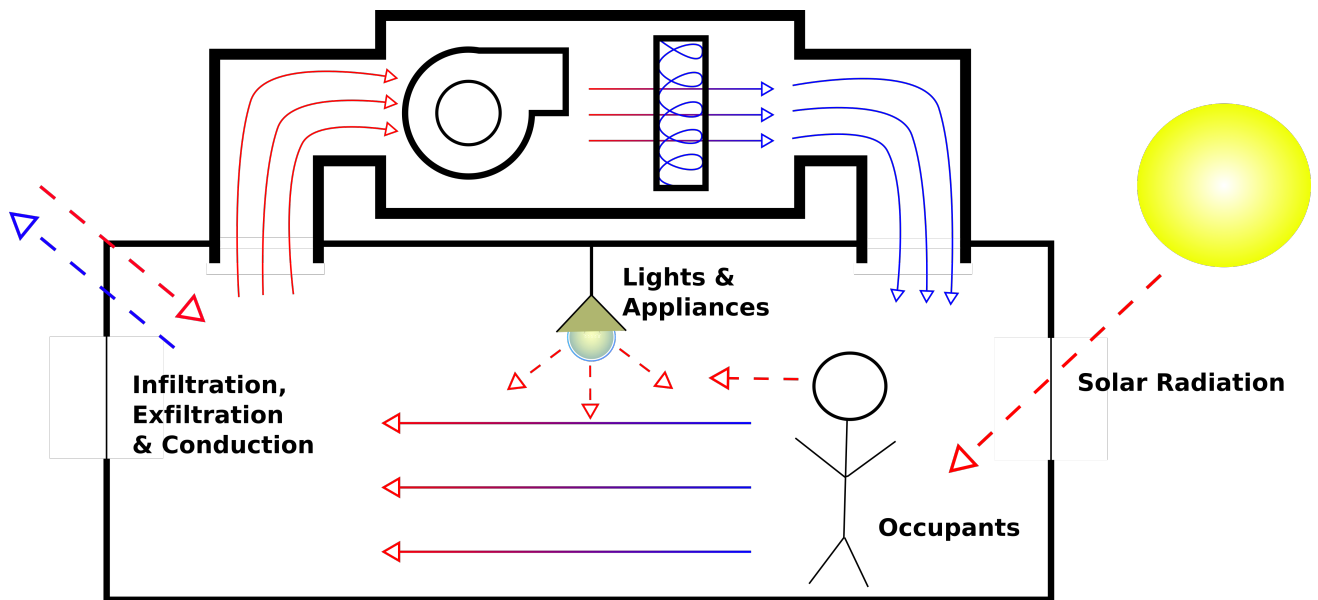


Figure 2.3: Characteristics of HVAC system during cooling cycle.

There are many fuels available for use in a central forced-air heating system. These include oil, natural gas, wood or another combustible material. The furnace intakes separate air from the supply for combustion. This heated air is passed through a heat exchanger and then exhausted back to the outside. The cold supply air from the return duct is passed over this heat exchanger and supplied to the registers throughout the home (Figure 2.4).

Electric resistance heaters and heat pumps may be used instead of a gas fueled

furnace. However, taking into account source energy, which includes conversion and transmission losses, gas furnaces have a better effective efficiency over most electric sourced heating methods, excluding site produced renewable energy [9]. Heat pumps utilize the reverse vapor compression cycle in order to provide heat to the heat exchanger in the furnace. Heat pumps can extract heat from air, ground or water sources. Each type of heat pump has its own limitations for example, air sourced heat pumps typically need a small supplemental heating source due to its inability to properly function at low outside temperatures ($< 0\text{ }^{\circ}\text{C}$).

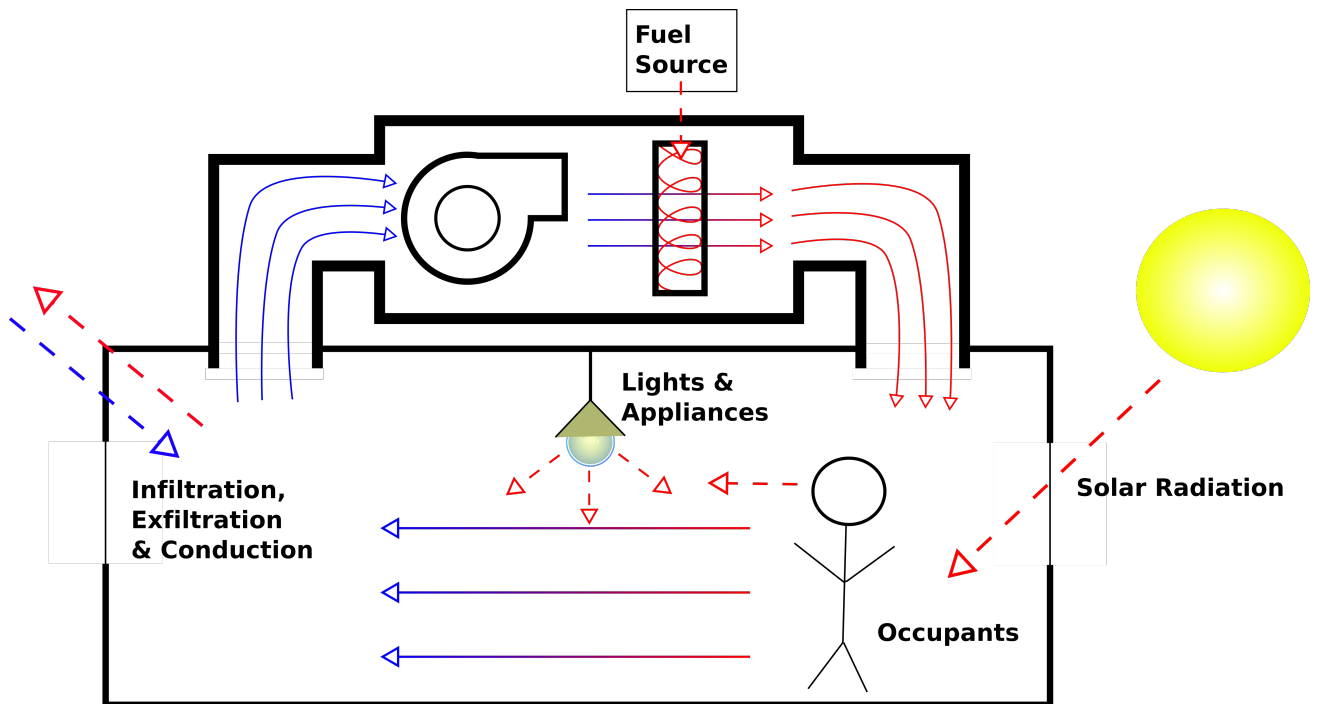


Figure 2.4: Characteristics of HVAC system during heating cycle.

Residential HVAC systems commonly utilize a constant air volume (CAV) fan to produce the pressure differential required to move air throughout the ductwork. The ductwork has an associated system resistance, the static pressure required to be overcome by the fan in the furnace in order to produce flow out of the supply registers. Supply registers may have manual dampers which can be opened or closed in order to produce different flow patterns. Closing dampers can increase total system

pressure, which may negatively impact the operation of the CAV fan reducing its life expectancy. The operation of dampers is better suited for a central system that utilizes a variable air volume (VAV) fan that can change its operating speed based on system pressure changes due to damper position. Most residential central air systems have CAV fans installed though recently, newer high-efficiency systems have begun to adopt VAV fans, for example, the Carrier Infinity series furnace [10, 11].

HVAC fans are driven by two types of motors that correspond with CAV and VAV: permanent-split capacitor (PSC) and electronically commutated (ECM) motors respectively. PSC motors are on/off motors and run at a single speed, while ECM are designed to respond to required system characteristics to run at an optimal speed. As expected, PSC motors are more typical in older systems and ECMs in newer systems. ECMs have an energy efficiency advantage over PSC motors due to their programmable nature and adaptability to changing system states and have become the prevailing motor type in new residential HVAC installations.

The capacity of the HVAC system is an integral part of installation. HVAC systems are designed (sized) such that the system can comfortably deliver the required air flow to meet the building's average cooling and heating demands but still able to function properly under peak loads (e.g. on the hottest and coldest days of the year). Heating and cooling loads can be calculated following Air Conditioning Contractors of America's (ACCA) Manual J and following building codes for structure and insulation requirements [12].

2.1.2 Single Thermostat Control

The heating and cooling cycles were described briefly in the previous section. These cycles, while not complex, would be daunting to control for most people if every part of the cycle had to be controlled manually. The thermostat was created in order to provide an automatic way to control the timing of each cycle. The thermostat allows the occupant to set a preferred comfort level via a temperature setpoint for the building. The most common control method for controlling the heating and cooling cycles is to use a single, centrally located thermostat. The thermostat is centrally

located to be the least effected by outdoor conditions and better representative of the building as a whole. The thermostat is used to cycle on and off the central HVAC system in order to meet the temperature requirements of the temperature setpoint.

Thermostats historically used a bimetallic strip as a method to measure ambient temperature. The strip was constructed by joining two metals with different heat expansion rates. With both ends fixed, the strip coiled and the mechanical displacement is converted into a temperature reading. The use of bimetallic strips only allows for a single temperature setpoint to be used. The occupant would have to remember to switch setpoints depending on the season or even during a short spell of unseasonal weather. Newer thermostats utilize thermistors or thermocouples to measure ambient room temperature. These thermostats are typically programmable with multiple occupant preferences which can be automatically altered depending on the season.

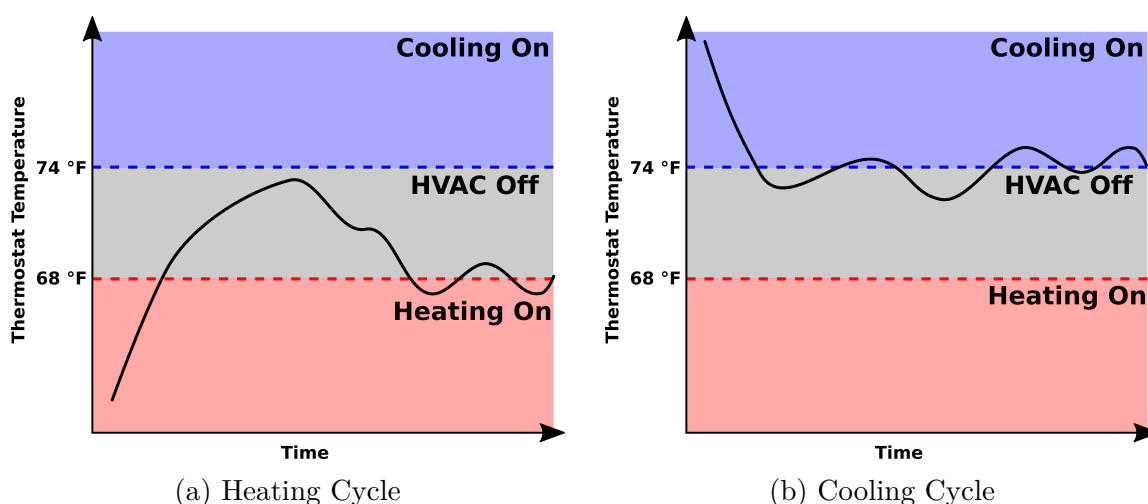


Figure 2.5: Visualization of a typical thermostat dead-band setpoint.

The use of programmable thermostats affords the occupant the ability to create schedules that aid in reducing energy bills. For example, an occupant could ensure that the HVAC system is running at low heating and high cooling setpoints when no one is expected to be in the house as well as scheduling for the occupant's regular preferences to take over right before they are home. This is called a "setback" schedule and proper implementation can aid in reducing energy usage throughout the year due to less frequent conditioning of the air when no one is home. This setback can also be used during the night while occupants are sleeping. Additionally, the programmable

thermostat can be used to create a "dead-band" temperature setpoint where a dual setpoint, one for heating and one for cooling, are scheduled together (Figures 2.5a-b). The area in between the two setpoints creates a dead zone where the occupant feels the household will be comfortable during the entire range and thus does not need the HVAC system to cycle on. However, even with the power of control afforded to an occupant with the usage of a programmable thermostat, the majority of survey participants of one study were shown to operate their programmable thermostats manually and thus were not able to benefit from the advantages afforded by them [13]. Occupants learning to leverage this advantage is important considering almost 50% of total residential energy use is being controlled by thermostats [1].

2.2 Energy Usage & Retrofitting

Energy conservation in the residential sector is becoming increasingly necessary to not only reduce greenhouse emissions but to also reduce energy costs for homeowners. Regardless of source, the average price of energy supplied to residential homes across the United States is expected to climb steadily every year [14]. Building codes are updated frequently to reflect the need for better energy efficiency in the residential sector, for example, California's *Title 24* is updated on a triennial cycle, most recently in 2013 [15]. New buildings are constructed with the newest materials and equipment but older buildings which no longer meet current building codes tend to have energy efficiency problems. The method in which these issues are assessed is via retrofits.

Retrofitting is either done specifically on singular issues or on the entirety of the building as a retrofitting package. Usual concerns which are addressed are building envelope thermal resistance and insulation quality, HVAC equipment quality, air distribution (duct) leakage, and thermostat control schemes. Suggested building upgrades usually cover installing new, more efficient HVAC equipment (furnace and outside compressor), increasing duct insulation if in an unconditioned space (such as an attic or unfinished basement), and increasing building envelope insulation. Many of these suggestions can have a substantial capital cost and may have long payback

periods.

Multiple energy saving schemes can be employed as a retrofit. Vakiloroya et. al, while mostly looking into commercial building saving schemes, represented a few possibilities, such as; using hybrid HVAC systems (forced air and hydronic) or using thermal storage systems in ways to mitigate disadvantages from single HVAC systems and inherent system losses which could be implemented in the residential sector [16]. Meyers et. al used a high level approach to investigate overall energy usage in the home, including appliance choices as well as HVAC equipment. Meyers pinpointed unoccupied, but conditioned rooms, as the largest waste in energy in a residential home [17]. Cetin also investigated overall residential energy consumption focusing on appliance usage patterns, and found that "thermostat set point temperature has the greatest influence on long-term occupant thermal comfort" [18]. She then shows that energy modeling could be effectively used to detect HVAC faults that contribute to extra power consumption. Lastly, Walker investigated HVAC maintenance retrofits in the AHU which could largely impact energy usage, such as updating the fan type and motor type [19].

One such retrofitting aid with considerable curiosity in research is the installation of automatic register dampers in place of manual register dampers. Opening and closing dampers allows the occupant to redirect conditioned air into areas of a house more commonly occupied, effectively reducing the square footage of the house needed to be served by the HVAC system. However, results in practice have been varied over the past few decades regarding whether register dampers can be an effective tool in the energy reduction market for retrofitting residential buildings. Mixed results of studies focused on energy saving schemes involving register dampers was compiled by Proctor Engineering Group, Ltd. (Table 2.2) [3].

The main focus in the majority of older studies have been on zoning a residential house and the associated energy saving potential available. Leslie & Kramer focused on comparing a typical central heating system to a variable volume, modulating furnace scheme and found that comfort levels increased but at an increased cost [20]. Some energy was saved when the basement of the single story test house was kept

Study Author(s)	Year	Energy Use Compared to Not Zoned	
		Heating	Cooling
Kenney & Barbour	1994	148% ↑ 76% ↓	71% ↓
Oppenheim (From Kenney & Barbour)	1991		135% ↑
Oppenheim & Carrier	1992		121% ↑ 84% ↓
Oppenheim/ASHRAE	1991	107% ↑ 88% ↓	
Leslie & Kramer	1989	112% ↑ 99% ↔	
Heflin & Keller	1993	118% ↑	113% ↑
Temple	2005		106% ↑

Table 2.2: Summary of previous studies done on residential register dampers [3].

unconditioned but this only occurred during cold weather and not during moderate weather. Kenney & Barbour and the NAHB Research Center, Inc. conducted a year long research study on the impacts of zoning to quantify comfort levels and energy usage in both heating and cooling cycles in two separate schemes; the first with a single zone and centrally located thermostat representing a central heating and cooling system most commonly found, and the second a zoned system with five thermal zones [21]. The study showed a 27% and 29% decrease in energy savings for cooling and heating respectively. The study also found that thermal comfort increased when register dampers were installed, however the median temperature of the house was increased by 1.67 °C during the cooling cycle.

Oppenheim also conducted research on zoned forced-air systems but found energy savings of around 12% for the cooling season and a 6% increase in energy usage during heating season [22]. The study compared a central system with a nightly setback scheme to a zoned system with an extra setback and recovery period. The results showed that "potential energy savings are dependent on thermostat schedule(s)." Temple also compared a zoned forced-air system running in both unzoned and zoned schemes [23]. Room-to-room temperature differences and air temperature stratification was investigated during the cooling cycle only. While room-to-room

temperature variations were found to be smaller compared to the unzoned running scheme, the cooling cycle energy usage increased slightly.

Further adding to the mixed results, Heflin & Keller found that using a damper system resulted in reduced capacity of the heating and cooling system [24]. The control of building temperature was increased and power consumption decreased slightly for cooling but increased slightly for heating. Heflin & Keller also used a computer-simulation of the air-conditioning unit in an attempt to replicate experimental results of performance indicators. They found the computer-simulation to be overall an "un-realistic comparison".

The Heflin & Keller study was performed on an HVAC system that made use of a bypass duct to redirect air from the supply plenum back to the return plenum. The bypass duct was designed to counteract any potential over-pressurization of the furnace and ductwork. The use of a bypass damper has been met with varied acceptance and in some cases has been completely banned, such as in California for newly constructed low-rise, residential buildings [15]. The bypass duct has been shown to decrease cooling capacity of the HVAC system which could lead to a potential increase in energy usage and thus should be avoided [3].

Saunders & Kenny looked solely into the effects residential zoning has on air stratification on a room-by-room basis [25]. Air temperature differences throughout the rooms of the test-house were found to be decreased when utilizing a zoning scheme. However, they found the effects on thermal comfort were dominated by several other criteria in the heating and cooling system other than altering the air distribution system such as room location, supply air temperature and supply and return register locations. Rooms located on the second floor experienced a reduction in stratification due to heat losses from the first floor into the second floor.

While results have been mixed throughout early investigations, recent studies have focused on implementing optimized controls for a zoned system and investigating equipment impacts. One of the most influential is Walker's where, unlike previous experiments, used a test chamber built in a hangar instead of an actual house [26]. The experiment involved methodically closing a set of ten supply registers one-by-

one, waiting for steady operating conditions and measuring duct pressures and system performance across eight different configurations for duct leakage. The study found that "the reduction in building load due to not conditioning the entire house was more than offset by increased duct losses mostly due to increased duct leakage." Brown further investigated the idea of multizone control in a residential setting and found that an "[optimized] configuration is only chosen if the increased volume of air delivered to a zone can outweigh the increased internal losses" [27].

The same internal losses from Walker's investigation were seen in Brown's, however Brown saw 26% energy savings from the typical central air system. This is in contrast to Walker's results because Brown also used an occupancy schedule to guess when zones would be unoccupied and not need air conditioning, where "the key to energy savings in the multizone system is the ability to condition *only* occupied zones that are below the setpoint" [27]. Brown focused mainly on optimizing the damper control on a test house in California, which was a continuation of Watts' study on the feasibility of the dampers on the same test house. Watts designed a damper system that was tied to a central control system to control damper positions throughout the day depending on required heating for the room the register served [28]. Watts displayed the possibility of energy reduction while Brown attempted to optimize the model for better control.

The varied results make it difficult to compare energy saving strategies but one persistent detail seems to prevail: energy saving scheme potential is strongly effected by the building in which it is being employed. The potential is influenced by building type, construction materials, air tightness, HVAC equipment selection and age, and thermostat control schemes, including occupant thermal comfort preferences.

2.2.1 Elementary Case: Air Redistribution

The expectations of a damper system can be explored in the following elementary case. Two rooms of equal volume are connected with a solid wall as shown in Figure 2.6a. The two rooms are supplied with equal airflows and heating or cooling energy represented by $\dot{Q}_{1,sup}$ and $\dot{Q}_{2,sup}$. If the ambient outside air temperature (T_a) is

constant and solar and wind effects are ignored, it can be assumed that the room temperatures, T_1 and T_2 , are equal. In this case, it is assumed that $\dot{Q}_{1,2} = \dot{Q}_{2,1} = 0$ because the two room temperatures are always equal. This case represents a two room system with uncontrolled registers where the airflows from the distribution system are shared equally.

The model is now altered to unbalance the thermal load requirements of each room. A heat source is added to the second room as shown in Figure 2.6b. If it is assumed that both rooms continue to receive an equal amount of airflow, then it would be expected that the room temperatures would no longer be equal with $T_1 < T_2$.

The use of dampers on the registers would allow for the redistribution of airflow from one room to another to re-balance the system for the unbalanced heat loads. During the heating cycle, it would be expected that the zone 2 damper would be at a lower position and the zone 1 damper at a higher position increasing the flow into zone 1 by redirecting the air from zone 2 ($\dot{Q}_{1,sup} > \dot{Q}_{2,sup}$). The opposite would be expected during the cooling cycle ($\dot{Q}_{1,sup} < \dot{Q}_{2,sup}$). This redistribution balances the system again and brings the room temperatures to the same temperature. The airflows in this system are limited by the fan where $\dot{Q}_{fan} = \dot{Q}_{1,sup} + \dot{Q}_{2,sup}$ always holds true.

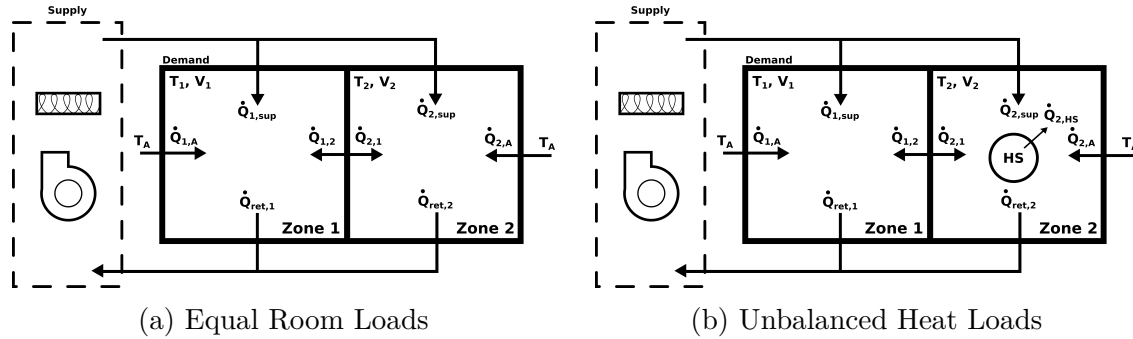


Figure 2.6: Elementary air redistribution cases.

2.3 Thermal Comfort

The main purpose of an HVAC system is to provide the space it serves with appropriate levels of thermal comfort. Thermal comfort is defined by the American

National Standards Institute/American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ANSI/ASHRAE) *Standard 55* as "the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" [29]. The most widely accepted method for quantifying thermal comfort comes from the decades of research by Povl Old Fanger who developed the Predicted Mean Vote (PMV) and Percentage Predicted Dissatisfied (PPD) methods for estimating perceived thermal comfort levels in an indoor environment [4].

The PMV method expands the first law of thermodynamics to solve for the human body heat losses and load, where the net heat transfer of the body is a combination of external and internal means. The thermal load (L) on a body is the metabolic heat gain minus the heat lost to the environment (Equation 2.1) [30]:

$$\begin{aligned}
\dot{Q}_{body,total} &= \dot{Q}_{skin} + \dot{Q}_{lungs} \\
&= (\dot{Q}_{sensible} + \dot{Q}_{latent})_{skin} + (\dot{Q}_{sensible} + \dot{Q}_{latent})_{lungs} \\
&= (\dot{Q}_{convection} + \dot{Q}_{radiation} + \dot{Q}_{latent})_{skin} + (\dot{Q}_{convection} + \dot{Q}_{latent})_{lungs}
\end{aligned} \tag{2.1}$$

Fanger's PMV model uses this heat load and an assumed metabolic rate to calculate an indicator of thermal comfort (Equation 2.2).

$$PMV = (0.303e^{-0.036M} + 0.028)L \tag{2.2}$$

where M is the metabolic rate and L is defined by Equations 2.3-8 with its parameters defined in Tables 2.3-4.

$$L = H - E_d - E_{sw} - E_{re} - L_R - R - C \tag{2.3}$$

While the heat load on a clothed body is a complex process, the equation for L, as used in the PMV model, can be simplified to a few characteristic parameters.

Symbol	Definition
H	Internal heat production
E_d	Heat loss due to water diffusion through skin
E_{sw}	Heat loss due to sweat
E_{re}	Latent heat loss due to respiration
L_R	Dry respiration heat loss
R	Heat loss by radiation from the surface of a clothed body
C	Heat loss by convection from the surface of a clothed body

Table 2.3: Heat transfer components in definition of heat load on a clothed body.

$$\begin{aligned}
L = (M - W) - (3.96 \times 10^{-8})f_{cl} \left[(t_{cl} + 273)^4 - (t_r + 273)^4 \right] - f_{cl}h_c(t_{cl} - t_a) \\
- 3.05 [5.73 - 0.007(M - W) - P_a] - 0.42 [(M - W) - 58.15] \quad (2.4) \\
- 0.0173M(5.87 - P_a) - 0.0014M(34 - t_a)
\end{aligned}$$

where

$$f_{cl} = \begin{cases} 1.0 + 0.2I_{cl}, & I_{cl} < 0.5 \\ 1.05 + 0.1I_{cl}, & I_{cl} > 0.5 \end{cases} \quad (2.5)$$

$$R_{cl} = 0.155I_{cl} \quad (2.6)$$

$$h_c = 12.1\sqrt{V} \quad (2.7)$$

$$\begin{aligned}
t_{cl} = 35.7 - 0.0275(M - W) - R_{cl}\{(M - W) - 3.05 [5.73 - 0.007(M - W) - P_a] \\
- 0.42 [(M - W) - 58.15] - 0.0173M(5.87 - P_a) - 0.0014M(34 - t_a)\} \quad (2.8)
\end{aligned}$$

The PMV equation reduces to a seven point scale ranging from values of -3 to 3 where -3 is *very cold* and 3 is *very hot*. A PMV value of 0 is ideal and the most likely to be comfortable (Figure 2.7). PMV can then be converted into a prediction of the percentage of the population expected to be uncomfortable with the conditions

Symbol	Definition	Units & Assumed Values
f_{cl}	Clothing area factor	1.15 <i>clo</i>
h_c	Convective heat transfer coefficient	5.4 $W/(m^2K)$
I_{cl}	Clothing insulation	1 <i>clo</i>
M	Metabolic Rate	70 W/m^2
P_a	Vapor pressure of air	kPa
R_{cl}	Clothing thermal insulation	0.155 Km^2/W
t_a	Ambient air temperature	$^{\circ}C$
t_{cl}	Surface temperature of clothing	$^{\circ}C$
t_r	Mean radiant temperature	$^{\circ}C$
V	Air velocity	0.2 m/s
W	External work	0 W/m^2

Table 2.4: Thermal load characteristic parameters and assumed values.

PMV	Sensation Expectation
-3	Cold
-2	Slightly Cold
-1	Cool
0	Neutral
1	Warm
2	Slightly Hot
3	Hot

Figure 2.7: Fanger PMV Scale.

within the room. Equation 2.9 is the conversion relating PPD to PMV and Figure 2.8 is a visualization of the equation.

$$PPD = 100 - 95e^{-(0.03353PMV^4 + 0.2179PMV^2)} \quad (2.9)$$

The PMV-PPD model has been refined and continually utilized since its inception. It is still widely accepted as a research standard and used as a metric for thermal comfort in this thesis. Thermal comfort is used as a metric for a HVAC system's overall performance, where an optimized scenario would show both a decrease in energy usage and an increase in thermal comfort. Any other combination of increasing/decreasing energy usage and thermal comfort would indicate an energy saving scheme not worthwhile of implementation (e.g. increased energy and decreased

comfort) or one which requires further refinement.

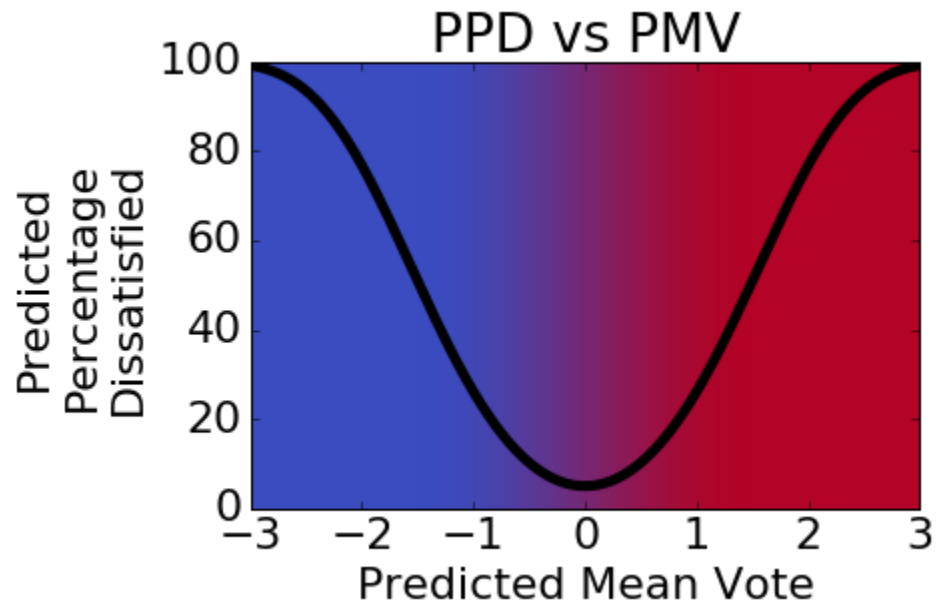


Figure 2.8: Fanger PPD vs PMV.

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 3

Methods & Limitations

Chapter 3 will cover the methods used during this thesis and the limitations and assumptions taken. The first section will introduce the simulation tools used. Following this section will be a review of the building model and climates that were investigated during the thesis. Lastly, the metrics used to compare models will be discussed.

3.1 Simulation Tool

Whole-building energy consumption estimations require significant computations using varying amounts of user input depending on the tool that is chosen. Over the past fifty years, hundreds of simulation models and tools have been created to aid the design process of commercial and residential buildings [31]. These tools have varying levels of robustness in both model ranges and granularity of output data. The process of simulating energy usage from an engineering stand-point requires a bottom-up approach. Building specifics are explicitly required such that the chosen software can accurately calculate required heat transfer and energy equation (Equation. 3.1, Table 3.1) leading to energy consumption. A simulation tool that is both robust and modular while allowing for fine-grained supply and demand side analysis was needed for this thesis. Several tools meet these criteria, but EnergyPlus (v8.4) was chosen for the required simulations [32].

Symbol	Definition
$\sum_{i=1}^{N_{sl}} \dot{Q}_i$	Sum of convective internal loads
$\sum_{i=1}^{n_{surfaces}} h_i A_i (T_{si} - T_z)$	Convective heat transfer from the zone surfaces
$\dot{m}_{inf} C_p (T_{inf} - T_z)$	Heat transfer due to infiltration of outside air
$\sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z)$	Heat transfer due to interzone air mixing
\dot{Q}_{sys}	Air systems output
$C_z \frac{dT_z}{dt}$	Energy stored in zone air
C_z	Zone heat capacity ($= \rho_{air} C_p C_T$)
ρ_{air}	Zone air density
C_p	Zone air specific heat
C_T	Sensible heat capacity multiplier

Table 3.1: EnergyPlus initial heat transfer equation parameters. Full description of simulation can be found in the Engineering Reference Guide [33]

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{n_{surfaces}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_{inf} - T_z) + \dot{Q}_{sys} \quad (3.1)$$

EnergyPlus is an open source, whole-building energy simulator developed by the United States Department of Energy (DOE) from the combination of other DOE simulation tools (DOE-2 and Energy Blast). It is the combination of multiple modules for calculating different areas of building energy consumption (Figure 3.1). It allows for quick design and implementation of models via modularity that is highly desirable for the simulation of the impact of dampers installed on residential registers. The granularity of data is dependent on user preference, ranging from hourly to minute-by-minute measurements. The simulations were run with a 15 minute time step due to the high number of outputs desired during the modeling.

3.1.1 Building Model

As discussed, prior studies primarily focused on implementing register dampers in a physical test house and sometimes included a partial or total simulation of the test house to corroborate experimental results. The focus in this thesis is on simulation of

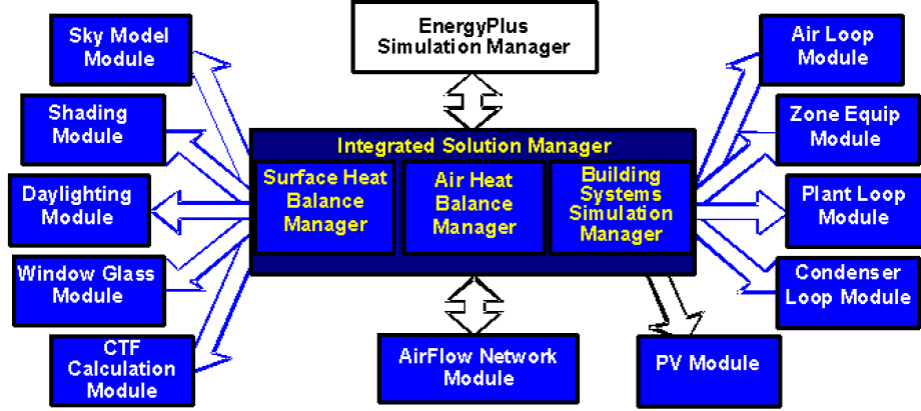


Figure 3.1: EnergyPlus Program Schematic [33].

Climate Zone	Location	Characteristic
2A	Houston, TX	Hot-Humid
2B	Phoenix, AZ	Hot-Dry
3A	Atlanta, GA	Warm-Humid
3B	Los Angeles, CA	Warm-Dry
4A	Baltimore, MD	Mixed-Humid
4B	Albuquerque, NM	Mixed-Dry
5A	Boston, MA	Cool-Humid
5B	Colorado Springs, CO	Cool-Dry

Table 3.2: Climate zones, locations and characteristic qualities [34].

a test house, the impact of dampers on energy usage and system performance, and to investigate variations effected by climate. Climates chosen for the thesis are given in Table 3.2 and discussed further in Section 3.2.2. The building envelope of the model was updated for the expected thermal resistance values as climate zones were changed in the simulation. Two resources were used in an attempt to standardize the building models.

First, the National Renewable Energy Laboratory (NREL) in Colorado released a building simulation protocol for residential buildings meant to be used by researchers as a standard for simulations [35]. Second, Pacific Northwest National Laboratory (PNNL) created residential prototype building models for every state in multiple configurations using the International Code Council (ICC) created International Energy Conservation Code (IECC) [36]. The models provide a platform upon which to build a test model house. For this thesis building models were written for EnergyPlus and

all followed the same standard.

The final building model was a 2400 ft², two story, single-family, residential house (Figure 3.2). The house was simulated with a slab-on-grade foundation to remove spatial effects on energy from an occupied or unoccupied basement which can cause unexpected behavior in a simulation. The model contains a 1200 ft² unconditioned attic where the HVAC system was located. The template PNNL models were designed to model entire building energy usage including internal loads which included lighting, appliances, and occupancy schedules.

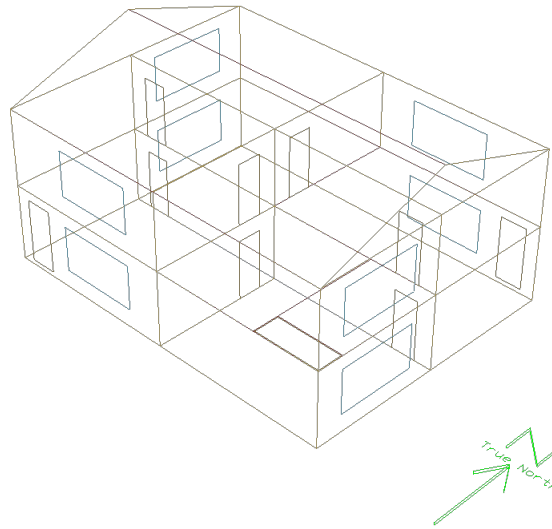


Figure 3.2: Schematic of model building.

Following the methods of Kenny & Barbour, the model was stripped of additional internal loads to model a fully unoccupied house to remove as many excess variables that could contribute to excess energy usage. This was done to isolate the effects of the damper on the model. The house required partitioning internal spaces, it was separated out by internal walls into seven thermal zones (Figure 3.3).

Internal walls were used to partition thermal zones on the same floor and an interior ceiling and floor model was created to partition the two floors from each

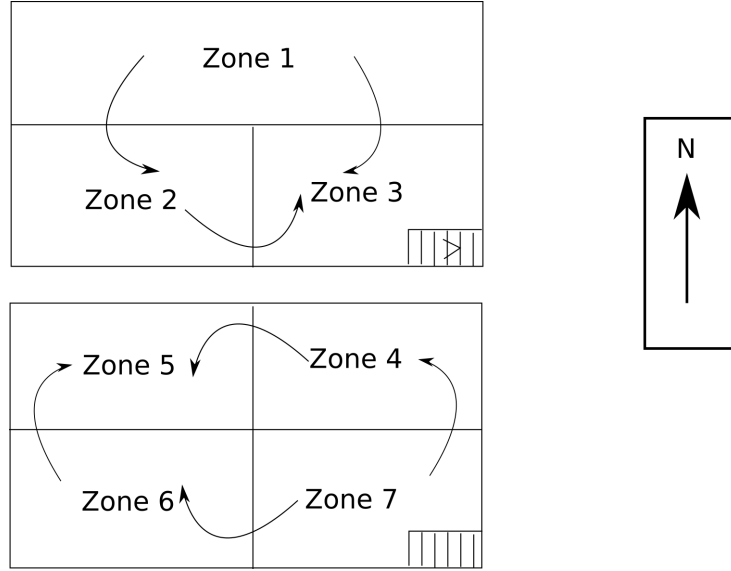


Figure 3.3: Simplified floor plans for model building and potential airflow pathways.

other. EnergyPlus simulates the heat transfer between the ambient external temperature and thermal zones across exterior walls that take into account wall material, thickness and thermal resistances. Simultaneously, the heat transfer between thermal zones is simulated across internal walls and ceilings/floors. An example construction, associated data and thermal resistance (R-value) calculation is presented in Figures 3.4, Table 3.3, Equation 3.2 respectively.

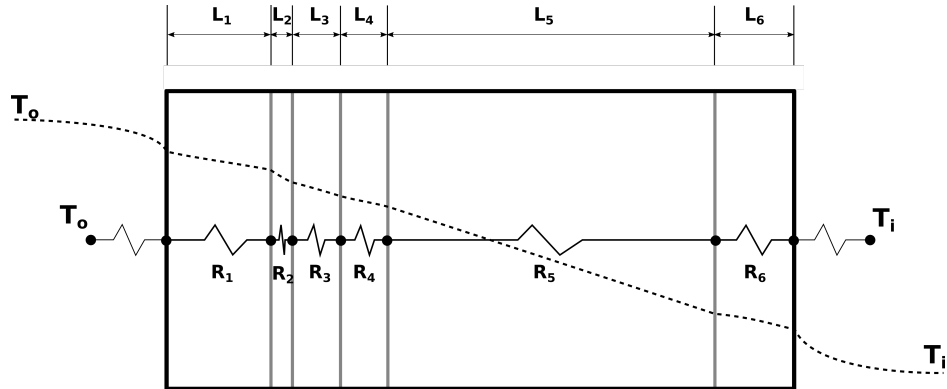


Figure 3.4: Schematic of the wall construction in the Boston model and simplified heat transfer [37].

Layer	Material	Thickness (m)	Conductivity (W/(mK))
1	Stucco	0.025	1.4
2	Building Paper	—	0.1 (m ² · K/W)
3	Sheathing	0.013	0.09
4	OSB $\frac{5}{8}$ "	0.016	0.12
5	Generic Wall	0.14	0.06
6	Dry Wall $\frac{1}{2}$ "	0.013	0.16

Table 3.3: Material characteristics for external wall construction in the Boston model [36].

$$\begin{aligned}
R_{ext,wall} &= \sum_{i=1}^{N_{layers}} R_i = \sum_{i=1}^{N_{layers}} \frac{L_i}{\lambda_i} \\
&= \frac{0.13}{0.16} + \frac{0.14}{0.06} + \frac{0.016}{0.12} + \frac{0.013}{0.09} + 0.1 + \frac{0.025}{1.4} \\
&= 2.84 m^2 \cdot K/W \approx 16 h \cdot ft^2 \cdot ^\circ F/BTU
\end{aligned} \tag{3.2}$$

The internal partitions between thermal zones have fully open doorways to allow airflow to pass between them. A large horizontal opening connects two of the thermal zones to allow airflow between floors as well. Doorways and stairwell openings can be seen in Figure 3.2. Airflow throughout the demand side of the building (thermal zones) is an important aspect required to understand the thermal effects dampers have on the building temperature. Internal doorways are kept fully open as natural ventilation effects on energy usage is not the focus of the thesis.

The reader should take note that while EnergyPlus is a powerful simulation tool for estimating energy consumption and airflows, it does have minor issues simulating horizontal openings which adds error to the calculations. However, modeling a horizontal opening as a stairwell is required to investigate damper effects on stack effect. Stack effect is the movement of air due to buoyancy forces. The most common example of stack effect in a normal residential system is the second floor being warmer than the first floor due to hotter air rising.

HVAC equipment was modeled based on the NREL simulation protocols. The heating coil modeled is gas fueled and has a 78% efficiency. Not all climates tested

Coefficient	Capacity vs. °C	EIR vs. °C	Capacity vs. FF	EIR vs. FF
a	1.55090	-0.30428	0.718605468	1.32299905
b	-0.07505	0.11805	0.410099989	-0.477711207
c	0.00310	-0.00342	-0.128705457	0.154712157
d	-0.00240	-0.00626	—	—
e	-0.00005	0.00070	—	—
f	-0.00043	-0.00047	—	—

Table 3.4: DX cooling coil model coefficients (SI units) [38].

have natural gas as the prevailing method for heating the home but this was kept consistent through all models to remain in line with the simulation protocols. The heating unit was not modulating and provided heat to the furnace heat exchanger at a single specified rate.

The target seasonal energy efficiency ratio (SEER) for the air conditioning unit was 13. The SEER rating is a measure of cooling output and electricity input. Air conditioners, by nature of the process, are controlled by the compressor performance of the unit. Modeling air conditioners requires the accurate capture of a few parameters including power, capacity, sensible heat ratio and runtime [38]. The direct-expansion (DX) cooling coil model in EnergyPlus requires the input of five equations which control the functionality and performance of the AC unit. These equations include total cooling capacity and energy input ratio as functions of both outdoor dry-bulb and wet-bulb temperatures and flow fraction. Equations 3.3-4 are the generic forms for temperature based and flow fraction based performance curves, respectively. Default values used in the template PNNL models were disregarded for coefficients developed by NREL [38]. The coefficients used for the DX cooling coil are given in Table 3.4.

$$y = a + b \cdot T_{wb} + c \cdot T_{wb}^2 + d \cdot T_{db} + e \cdot T_{db}^2 + f \cdot T_{wb} \cdot T_{db} \quad (3.3)$$

$$y = a + b \cdot FF + c \cdot FF^2 \quad (3.4)$$

A summary of building envelope and equipment assumptions used for Boston are in Table 3.5. Building envelope assumptions shown are consistent through all

Category	Assumption
Conditioned Area	2400 ft ²
Ceiling Height	8.5 ft
Exposed Wall	2300 ft ²
Roof Area	1265 ft ²
Window-to-Wall Ratio	15%
Heating Setpoint	21.7 °C
Cooling Setpoint	23.3 °C
Heating & Supply Temp.	Gas, 78% Efficiency, 54.4 °C
Cooling & Supply Temp.	SEER 13, 12 °C
Nominal Fan Size	1600 CFM

Table 3.5: Boston model envelope and equipment assumptions.

simulations with R-Values changing depending on the climate zone.

Two separate models were created: one for a standard central forced-air HVAC system and one with dampers as the air terminals serving each thermal zone. The forced-air system uses the air terminal object `AirTerminal:SingleDuct:Uncontrolled` which represents a fully open and uncontrolled register. The EnergyPlus autosize option was used to size HVAC capacity, fan size and maximum register airflows. Their values were manually input into the second system which changes the uncontrolled register object to a variable air volume object. The two models differ only in which air terminal object is used. The terminal object representing dampers is the `AirTerminal:SingleDuct:VAV:HeatAndCool:NoReheat` object. This object allows for damper modulation during both heating and cooling cycles and does not use any reheat coils.

The object is most representative of a residential register damper available in EnergyPlus. While it is representative of the register dampers, it does follow similar control to that of a commercial system. The damper control is an internal variable to EnergyPlus and for this thesis is not controlled using any optimized or custom controls. This produces a base case for energy usage with typical VAV controls. Figure 3.5 depicts the VAV box used as a damper for the simulation. Damper control is simulated by Equations 3.5-6 and the symbol definitions are given in Table 3.6 [33]. The damper position is controlled locally to each individual thermal zone. The HVAC equipment (fan and coils) is connected in series between a return air mixer

Symbol	Definition	Unit
Cp_{inlet}	Specific Heat of terminal unit inlet air	$J/kg \cdot K$
Cp_{zone}	Specific heat of zone air	$J/kg \cdot K$
T_{inlet}	Terminal unit inlet dry-bulb temperature	$^{\circ}C$
T_{zone}	Zone air dry-bulb temperature	$^{\circ}C$
\dot{Q}_{zone}	Zone load	W
\dot{m}	Terminal unit air mass flow rate	kg/s
\dot{m}_{max}	Terminal unit maximum air mass flow rate	kg/s
$MinAirFlowFrac$	User-specified zone minimum air flow fraction	—

Table 3.6: EnergyPlus damper control variables.

and supply air splitter. The demand side is allowed to be connected in parallel to the distribution system. The NullHeater input is described with the following description of the VAV box objects.

$$DeltaCpT = Cp_{inlet} \cdot T_{inlet} - Cp_{zone} \cdot T_{zone} \quad (3.5)$$

$$\dot{m} = MIN \left(\dot{m}_{max}, MAX \left(\dot{m}_{max} \cdot MinAirFlowFrac, \frac{\dot{Q}_{zone}}{DeltaCpT} \right) \right) \quad (3.6)$$

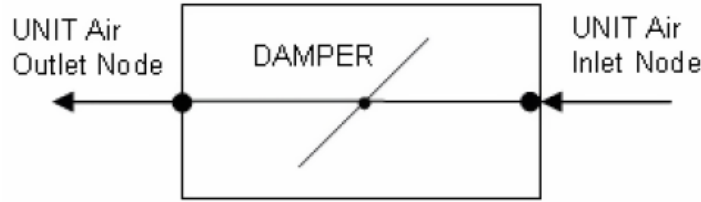


Figure 3.5: EnergyPlus AirTerminal:SingleDuct:VAV:HeatAndCool:NoReheat object.

The following code snippet is an example of one AirTerminal:SingleDuct:VAV:HeatAndCool:NoReheat object used in the EnergyPlus simulation. The input data file (IDF) format, an ASCII file, contains the building and HVAC system data to be simulated by EnergyPlus. EnergyPlus requires a high level of building and equipment knowledge in order to run a successful simulation. The simulation engine calculates

the heating and cooling loads necessary to maintain thermal control setpoints, conditions throughout the HVAC system and coil loads, and the energy consumption of the equipment. It also simulates details necessary to verify that the simulation performs close to how an actual building would perform [39].

```
!-    ===  ALL OBJECTS IN CLASS: AIRTERMINAL:SINGLEDUCT:VAV:HEATANDCOOL:NOREHEAT

AirTerminal:SingleDuct:VAV:HeatAndCool:NoReheat,
Zone1Damper,           !- Name
fanSched,              !- Availability Schedule Name
Zone 1 Inlet Node,     !- Air Outlet Node Name
Zone 1 Damper Inlet,   !- Air Inlet Node Name
0.1179868608,         !- Maximum Air Flow Rate {m3/s}
0.5;                  !- Zone Minimum Air Flow Fraction
```

EnergyPlus is mainly used to estimate building loads and is used to size HVAC equipment, develop retrofit studies, and optimize energy usage [39]. The software presents a best-case scenario assuming an idealized distribution system unless certain faults, such as duct and building envelope leaks, are directly specified by the user. The idealized system case is assumed for two out of three sections of this thesis (Sections 4.2 and 4.3). In this case, the air terminal object previously discussed is used because it is capable of providing proportional airflow control during both the heating and cooling cycles.

The software engine is also capable of simulating the internal impacts of the distribution system through the use of an alternate simulation process, the AirflowNetwork (AFN) module. This module is used to simulate both the air distribution throughout the home caused mainly by wind effects and the impacts on the HVAC equipment caused by increasing pressure from closing dampers. The AFN module is partially utilized in Sections 4.2 and 4.3 to simulate flows between rooms via doorways. The model is then altered to include a duct network in order to simulate the internals of the distribution system as dampers are used with a constant air volume fan. The

AFN module cannot use the same air terminal object as the previous two sections because only two air terminal objects have been implemented in the simulation as of version 8.4.

The only VAV air terminal object available for usage in the AFN module is the `AirTerminal:SingleDuct:VAV:Reheat` object. An example of the VAV object is given in the following code snippet. The `VAV:Reheat` object treats the heating cycle differently than the `VAV:HeatAndCool:NoReheat` object described earlier. The `VAV:Reheat` object expects the heating to be provided by a reheat coil object and does not provide proportional airflow for heat in this case. A residential damper would not make use of a reheat coil so electric reheat coil objects are created which provide 0 W of heating. This limits the usage of the `VAV:Reheat` object and the AFN module to only the cooling cycle for simulations of residential homes in this thesis and is why Section 4.4 only explores the cooling cycle. The heating cycle cannot be properly simulated until other VAV air terminal objects have been implemented in the EnergyPlus simulation engine.

```
!-    == ALL OBJECTS IN CLASS: AIRTERMINAL:SINGLEDUCT:VAV:REHEAT

AirTerminal:SingleDuct:VAV:Reheat,
Zone1Damper,           !- Name
always_avail,         !- Availability Schedule Name
NullHeater1Inlet,     !- Damper Air Outlet Node Name
Zone 1 Damper Inlet,   !- Air Inlet Node Name
0.1179868608,         !- Maximum Air Flow Rate {m3/s}
Constant,             !- Zone Minimum Air Flow Input Method
0.5,                  !- Constant Minimum Air Flow Fraction
,                      !- Fixed Minimum Air Flow Rate {m3/s}
,                      !- Minimum Air Flow Fraction Schedule Name
Coil:Heating:Electric, !- Reheat Coil Object Type
NullHeater1,          !- Reheat Coil Name
,                      !- Maximum Hot Water or Steam Flow Rate {m3/s}
```

```

,                               !- Minimum Hot Water or Steam Flow Rate {m3/s}
Zone 1 Inlet Node,             !- Air Outlet Node Name
0.001,                         !- Convergence Tolerance
Reverse;                       !- Damper Heating Action

```

The heating and cooling cycles are investigated in Sections 4.2 and 4.3 to determine the efficacy of residential dampers to thermally balance a house, reduce energy consumption, and increase thermal comfort in an ideal HVAC system. A duct network is introduced to the model in Section 4.4 and only the cooling cycle is explored. The following section contains more background into the methods used for these investigations.

3.2 Investigations

3.2.1 Extreme Temperatures

EnergyPlus is able to simulate full year energy usage by leveraging typical meteorological year (TMY) data, of which, the most recent version was used (TMY3) [40]. These files were edited for this investigation with the purpose of creating a steady outside ambient temperature on both extremes for the Boston model. While temperature, humidity and dew point are easy to maintain, the solar irradiance data within the TMY3 data was left unaltered. It was found that because the lowest temperature in the data set also coincides with no sunlight, there was no variance in room temperatures during initial tests of the two systems. Four days, each from one of the four seasons, were included in this investigation due to differing solar interactions. The hot and cold temperatures chosen were 40 °C and -11 °C respectively. These represent both extremes on the yearly temperature spectrum for the location of Boston.

Temperature setpoints were chosen on the extreme as well. High heating and low cooling setpoints were chosen in conjunction with extreme outside air temperatures in order to force the HVAC system to operate at full load during most of the simulation. Metrics of importance here were the room temperatures and in particular the

temperature differences between the first and second floor. The damper system is expected to reduce the variance in temperature between the two floors by removing hot and cold spots in the building. Energy usage is not of particular importance due to the extreme nature of the simulation temperature parameters used. However, energy usage could be used as a preliminary view into energy reduction effectiveness.

3.2.2 Annual Energy Usage

The default TMY3 files were used to run annual EnergyPlus simulations. One focus in this thesis is not only the effectiveness of a damper system on residential registers but also how climate zones can change their effectiveness. Eight locations were chosen as the focus for this investigation and are summarized in Table 3.2. This investigation focuses on thermal zone temperatures and building temperatures like the previous study. In addition, this investigation utilizes energy usage metrics to determine any energy saving potential and possible equipment performance changes. The frequency of temperatures within a thermal zone are investigated as well as the mean room temperatures and standard deviation.

The mean temperature shows both the responsiveness of the system and the system's ability to maintain a setpoint. The standard deviation of the room temperatures show the tightness of temperature control the system can maintain [21]. Energy usage is plotted against outside air temperature, as well as energy against the Julian day, to show the differences in heating and cooling cycle. The three energy consuming components of the HVAC system include electricity for fan and air-conditioner use and the natural gas for furnace use. This creates a potential of three areas where energy could be saved. The system performance of the air conditioner is of particular interest and the coefficient of performance (COP) occurrence is plotted.

Fanger's thermal comfort model is used to determine a baseline comfort level for the uncontrolled register system. The parameters are kept the same in the damper system except for room temperature, and are used to determine if the damper system increases or decreases comfort levels. The comparison between energy usage and thermal comfort is taken into account as the main metrics of the HVAC system.

An effective energy saving system would reduce energy usage while simultaneously increasing thermal comfort. Alternatively, a system which increases energy usage but also increases thermal comfort could have optimization issues that would need to be investigated.

A cost analysis of total energy usage is also done. The capital cost of a damper system for a house with seven registers is assumed to be \$2000 USD. Cost analysis is used to determine the payback period of such an installation and is compared to the capital cost, energy savings and payback period of other energy saving measures that a residential homeowner could pursue.

3.2.3 Duct Flow & System Performance

The duct flow and system performance of the central air system with register dampers is investigated in two ways: through the CONTAM (v3.2) airflow simulation software and through the airflow network capabilities of EnergyPlus.

CONTAM – A generic duct system is investigated before expanding the system to more closely match that which could be in the model house. Typical residential HVAC systems use one of two designs: extended plenum (Figure 3.6) and radial (Figure 3.7) systems [41]. Altering damper positions and changing airflow patterns have the potential for negatively impacting system performance. First and foremost, closing dampers should increase the system pressure that the circulating blower must overcome in order to supply sufficient airflow. Figure 3.8 depicts a generic graph of both a fan performance curve and the system pressure of the internals of an HVAC system. The intersection of the two curves result in the operating conditions of the fan.

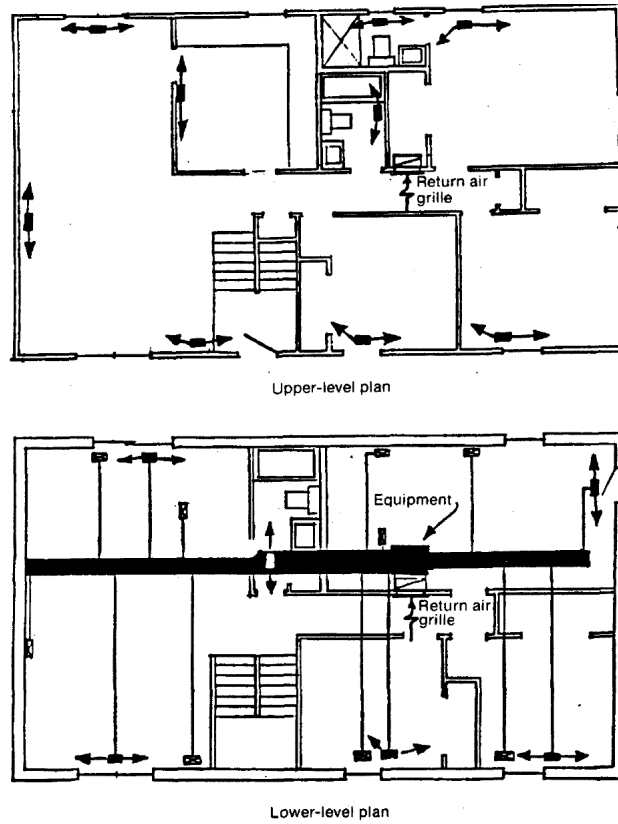


Figure 3.6: Generic extended plenum system [41].

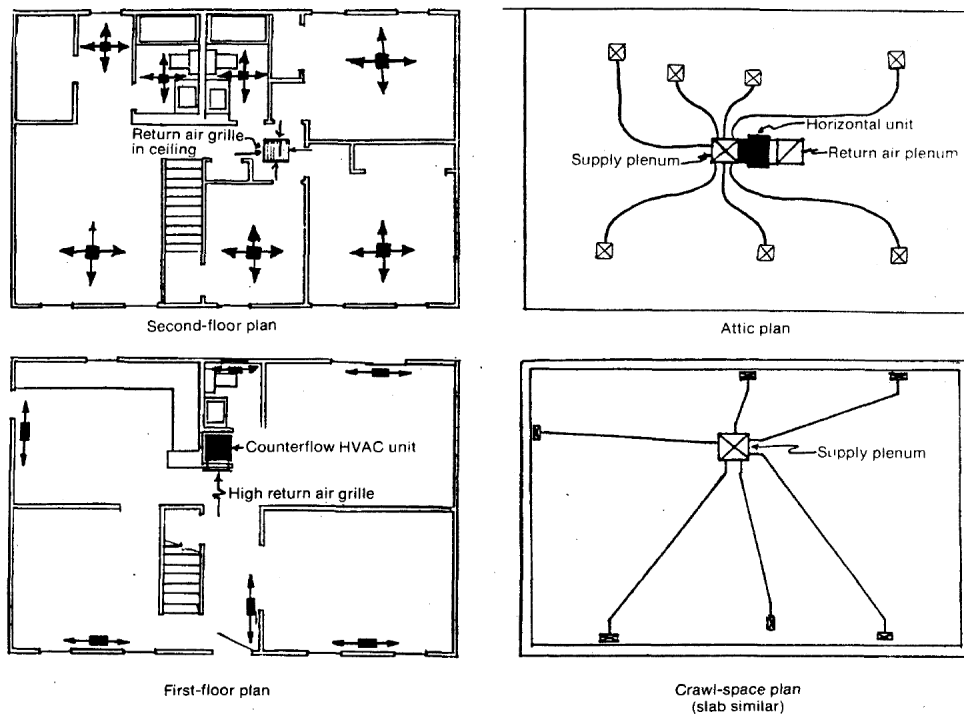


Figure 3.7: Generic radial system [41].

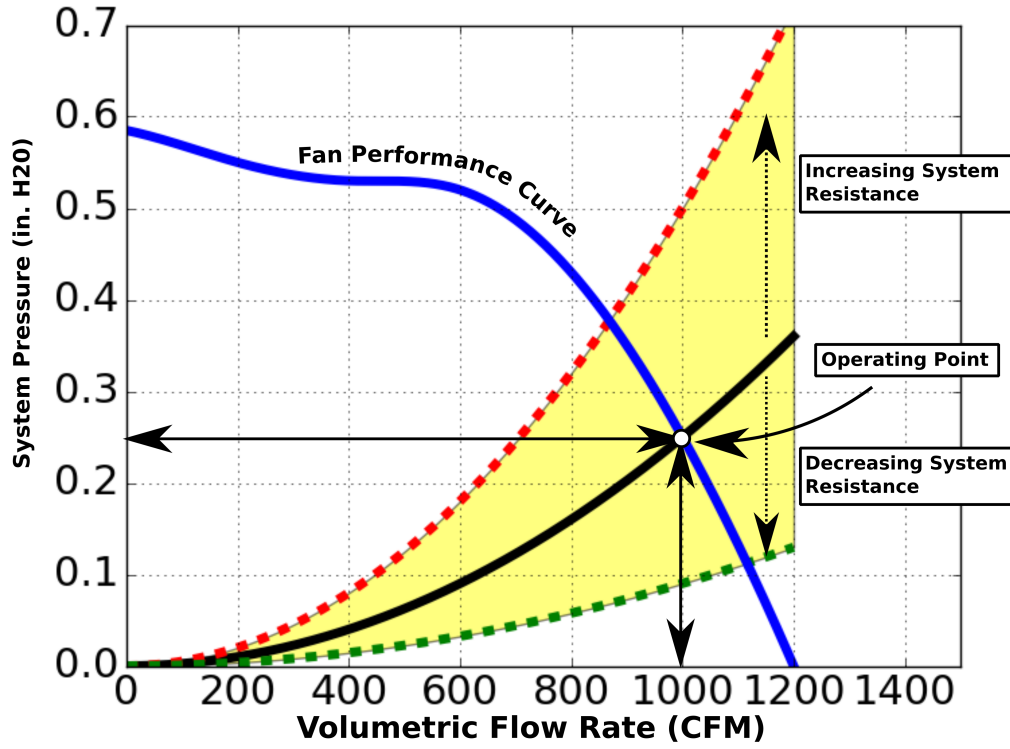


Figure 3.8: Generic fan curve and system performance graph.

The model was run with the supply ducts to obtain base flow rates for each register. The orifice model was then calibrated such that it's max cross sectional area would produce the same flow rates from the registers from the base case. From here, the orifice cross sectional area can be reduced to create a percent open/closed case in order to test system pressure of the entire ductwork and across the fan in different damper positions.

$$f = \frac{64}{Re} : Re < 2000 \quad (3.7a)$$

$$\frac{1}{\sqrt{f}} = -2 \log_{10} \left(\frac{\varepsilon}{3.7D_h} + \frac{2.51}{Re\sqrt{f}} \right) : Re > 4000 \quad (3.7b)$$

$$\Delta P = \frac{1}{2} f \frac{L\rho}{D_h} U^2 \quad (3.8)$$

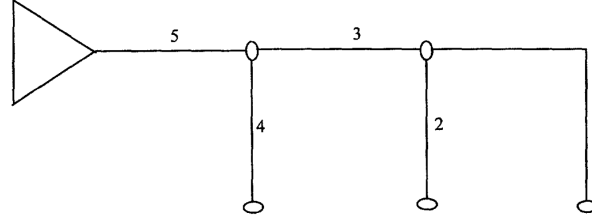


Figure 3.9: Simple five section duct system [42].

EnergyPlus – The airflow network module is used to create a radial system because *EnergyPlus* has difficulty modeling T-junctions such as the ones found in an extended plenum model [43]. The *EnergyPlus* model is then simulated for both uncontrolled and damper systems. The *EnergyPlus* AFN is limited to only using the air terminal objects `AirTerminal:SingleDuct:Uncontrolled` and `AirTerminal:SingleDuct:VAV:Reheat` so for this study the `AirTerminal:SingleDuct:VAV:HeatAndCool:NoReheat` objects are replaced with the `VAV:Reheat` objects. This object runs as expected during cooling with proportional control to each individual zone. However, the object does not have proportional control during heating. This limitation is because the `VAV:Reheat` object is expecting a reheat module to supply the heating as these objects are designed for VAV systems generally found in commercial application with hot water supplying heat to individual VAV boxes. Due to this limitation, only the cooling cycle is investigated using *EnergyPlus*’ AFN modeling capabilities for this investigation. Once other `SingleDuct:VAV` objects are implemented into the AFN module, the heating cycle can be simulated for system impact as well.

The AFN model requires a shorter timestep to reach convergence and reduce the likelihood of oscillatory behavior in the the simulation. The simulation is run for three summer days. The AFN couples airflow with the heat transfer throughout the building. The temperature setpoint for the system is set to the maximum outside ambient temperatures for the runtime to let the building model reach equilibrium with the hot outside temperatures before the HVAC system is able to cycle on. The time response for cooling the building is of importance and the central and damper models are both run through this experiment. The thermal zone temperatures and time to setpoint are investigated. The fan and cooling coil run times as well as their

Simulation	Mode	Main Object	Assumption
Thermal Balance Heating	No Damper	Air Terminal Uncontrolled	Outside Ambient Temperature (0°C)
Thermal Balance Cooling	No Damper	Air Terminal Uncontrolled	Outside Ambient Temperature (36°C)
Thermal Balance Heating	Damper	Air Terminal VAV Heat and Cool	Outside Ambient Temperature (0°C)
Thermal Balance Cooling	Damper	Air Terminal VAV Heat and Cool	Outside Ambient Temperature (36°C)
Annual Energy Consumption	No Damper	Air Terminal Uncontrolled	Climate Zone TMY3 File
Annual Energy Consumption	Damper	Air Terminal VAV Heat and Cool	Climate Zone TMY3 File
AFN Cooling	No Damper	Air Terminal Uncontrolled	Boston TMY3, 15-17 July
AFN Cooling	Damper	Air Terminal VAV Reheat & Coil Heating Electric (set to 0 W)	Boston TMY3, 15-17 July

Table 3.7: EnergyPlus simulation overview and main objects.

energy usage are used as indicators for areas of potential energy savings. Table 3.7 summarizes the main EnergyPlus objects used for the simulations.

Chapter 4

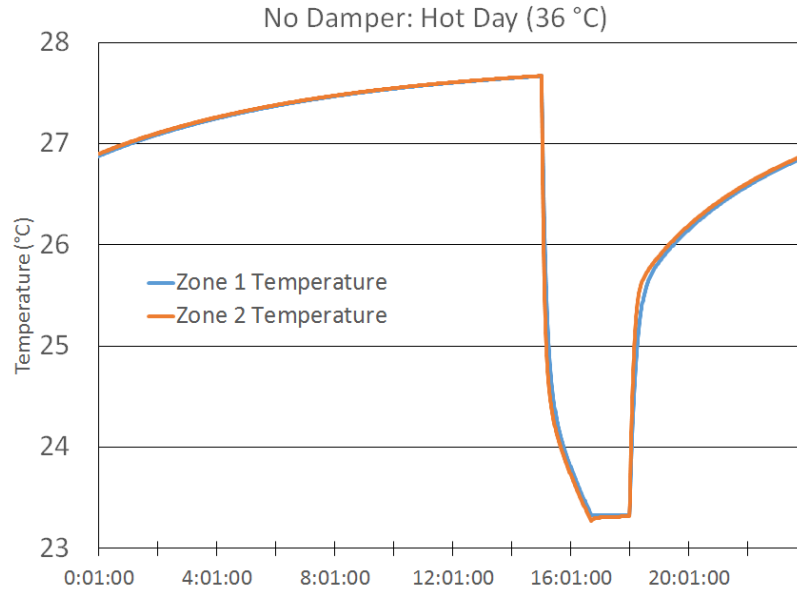
Results

This chapter covers validation of EnergyPlus (v8.4) with an elementary case and the results of the three investigations undertaken. Section 4.1 presents validation of the damper objects used in the scaled up EnergyPlus model by simulating an elementary case. Section 4.2 displays the results of tests to show if residential dampers have the ability to thermally balance a residential home, effectively reducing the variations in room temperatures between floors and throughout the entire building. Section 4.3 goes through the annual simulations from multiple climate zones around the U.S. Energy usage and cost analysis are compared to determine if residential dampers have the ability to reduce energy usage, increase thermal comfort, and in the case energy reduction does occur, where the energy reduction takes place. Section 4.4 goes through results of early testing of the impacts on the internals of the HVAC system with residential dampers installed.

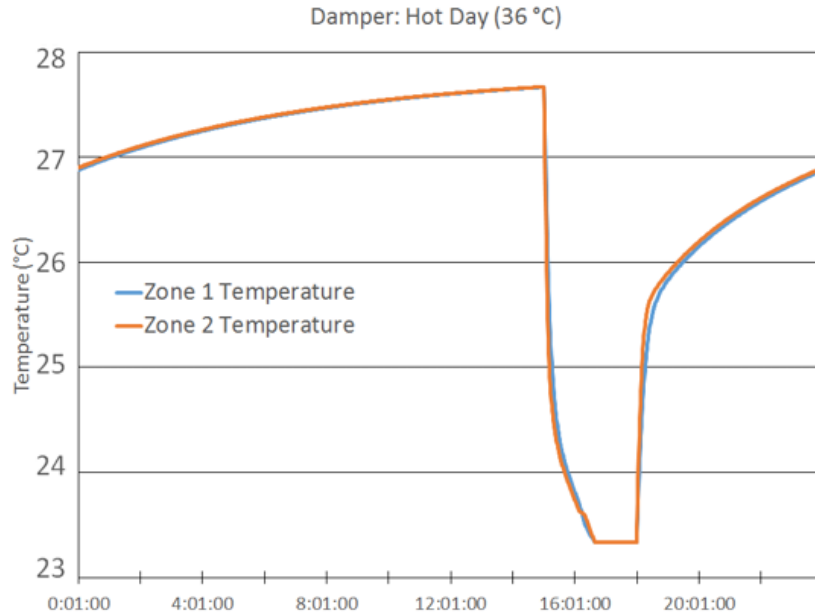
4.1 Validation: Elementary Case

The elementary case introduced in Section 2.2.1 is simulated using EnergyPlus to validate the use of the `AirTerminal:SingleDuct:VAV:HeatAndCool:NoReheat` object in the simulation of an ideal system in a residential model. A two zone model was designed in EnergyPlus with equal sized registers serving each zone. The no damper case uses the air terminal object `AirTerminal:SingleDuct:Uncontrolled` while the damper

case utilizes the object `AirTerminal:SingleDuct:VAV:HeatAndCool:NoReheat`. The model was simulated using a modified TMY3 weather file to keep the ambient outside air temperature constant while removing wind and solar effects. The simulation was allowed to autosize the air distribution system using the design days in the TMY3 weather file.



(a) No Damper Case



(b) Damper Case

Figure 4.1: Elementary case for constant, high ambient air temperature (36°C).

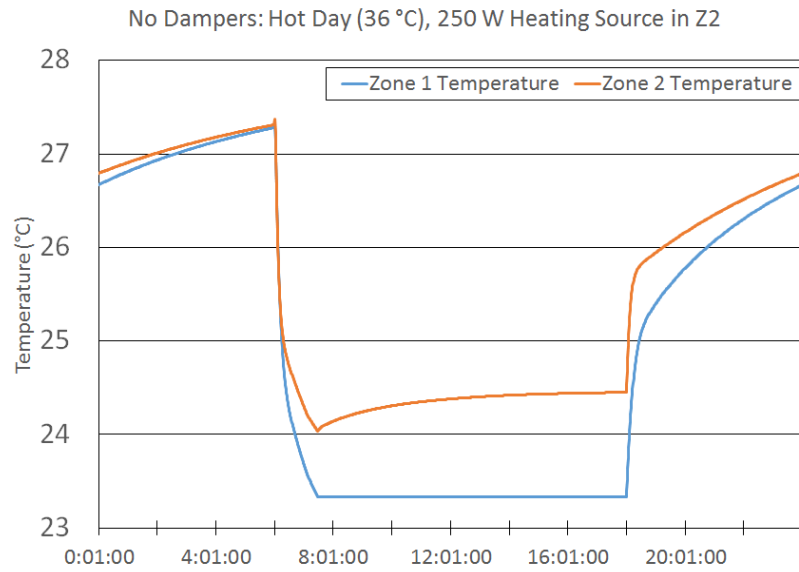
The simulation was run for a single day with the HVAC system allowed to cycle on from 15:00 until 18:00 as shown in Figure 4.1. The no damper case (Figure 4.1a) and the damper case (Figure 4.1b) show identical temperatures in both zones as expected. The registers are the same size and both zones are supplied with the same amount of cooling. This model represents the expectation from the elementary case presented in Figure 2.6a.

A 250 W light bulb was added to the model in EnergyPlus to the second zone to represent a heating source. The heating source unbalances the load between the two zones and represents the elementary case in Figure 2.6b. The two zone temperatures for both the no damper case and damper case are shown in Figures 4.2a and 4.2b, respectively.

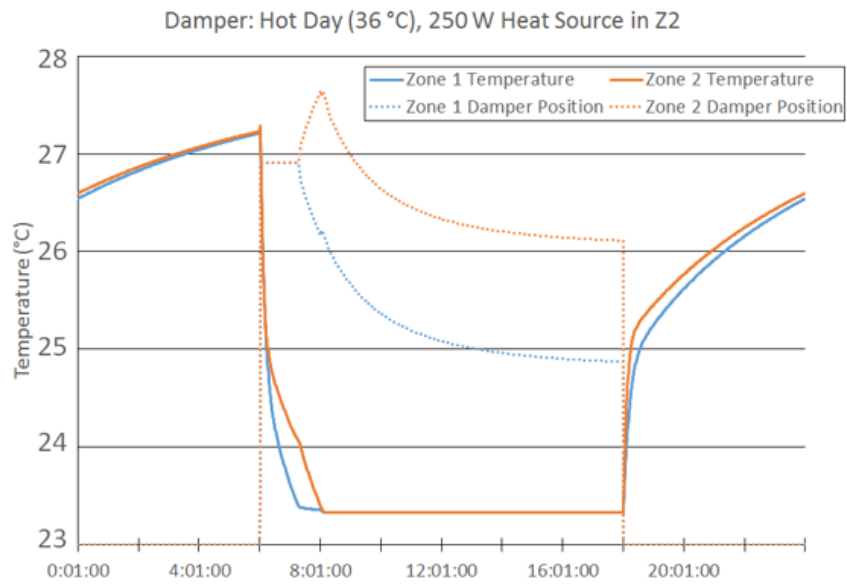
The HVAC system is allowed to cycle on and off and the light bulb turns on between 06:00 and 18:00. It should be noted that zone 1 is the controlling zone for the HVAC system to cycle. The no damper case shows that zone 2 is at a warmer temperature during the time the heat source is on. The damper case shows how the dampers react to their local room temperatures. The dotted lines show the damper positions with the colors corresponding to the zone temperature color lines. The dampers are allowed to modulate between 10-100% maximum flow. In this case, both dampers at 70% represents both zones being supplied identical volumes of air.

The dampers are maintained at an equal position as both rooms require as much cooling that can be provided initially. As zone 1 nears the temperature setpoint, its damper begins to close and the damper to zone 2 begins to open allowing for more air to flow into zone 2 to balance the extra cooling required. The dampers begin to reach some optimal position which optimizes the airflows supplied to each room and maintains both rooms at the same temperature.

The previous simulation was also run for a constant, low ambient air temperature of 0°C. Again, the no damper case (Figure 4.3a) shows that zone 2 has a higher temperature while the HVAC system is allowed to cycle on and off due to the added heat source. The damper case (Figure 4.3b) shows the opposite behavior from the previous case as expected. The dampers to both zones are maintained at the same



(a) No Damper Case



(b) Damper Case

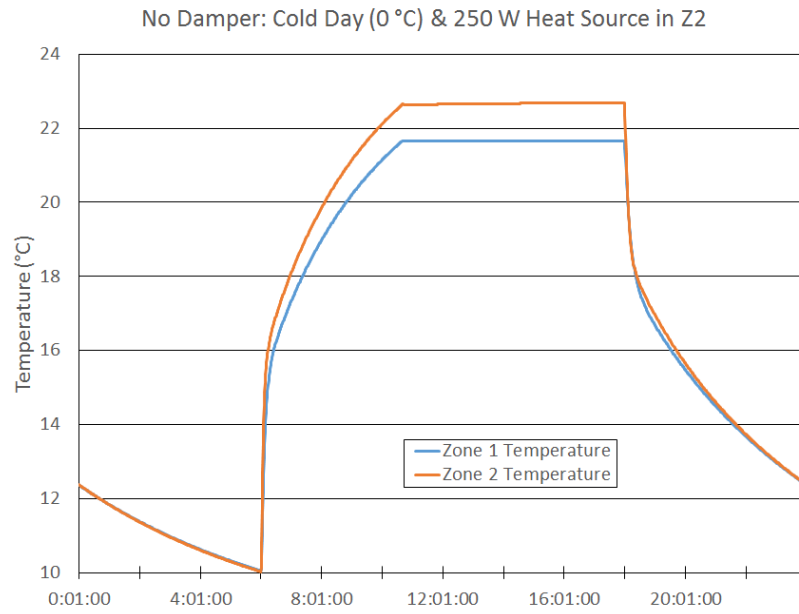
Figure 4.2: Elementary case for constant, high ambient air temperature (36°C) and unbalanced loads.

position as both require maximum heating available which evenly splits the airflows. As zone 2 reaches the temperature setpoint, its damper begins to close and the damper to zone 1 begins to open allowing for more air to flow to zone 1 increasing its heating rate. Once both rooms reach the temperature setpoint, the dampers are maintained at an optimal position to offset the reduced heating required in zone 2.

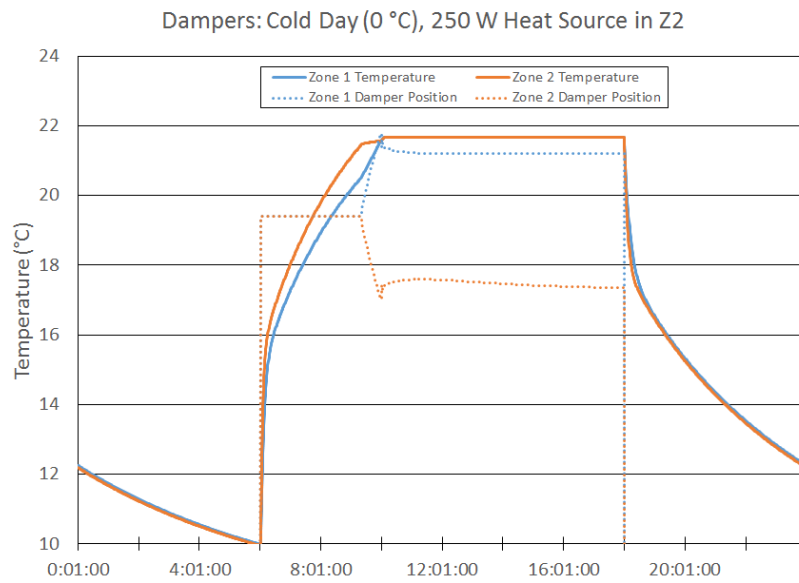
The results in this section show that the damper objects allow for the redistribution of airflow between different zones in order to balance their heat loads. This re-balancing of heat loads brings the zone temperatures both to the setpoint. The zones are maintained at separate temperatures when both zones receive equal heating and cooling from the air distribution system. The small scale model is now scaled up to be better representative of a two story, single family home.

4.2 Thermal Balancing

The research objective of this section is to investigate if a damper system can reduce the occurrence of hot and cold spots in a residential house. The dampers measure the local temperature and set a damper position based on the expected zone load in that instance. The dampers in this investigation are locally controlled only and no attempt at an optimized control scheme is made. Simulations during this section are done using modified weather files with constant outside temperatures to provide an extreme case where the HVAC systems must cycle more frequently than usual to maintain the building temperature set point. The extreme outside temperatures are coupled with more demanding heating/cooling set points than typical. In the next subsections, the frequency of room temperature figures show temperature setpoints slightly offset their actual values due to binning the temperatures in 0.5°C increments. The heating setpoint in Section 4.2.1 is 23.3°C and the cooling setpoint in Section 4.2.2 is 21.7]°C.



(a) No Damper Case



(b) Damper Case

Figure 4.3: Elementary case for constant, low ambient air temperature (0°C) and unbalanced loads.

4.2.1 Low Outside Ambient Temperature

Figure 4.4 shows the frequency of room temperatures for a system with no dampers installed and is thus the base case. The frequency of room temperature figures represent the number of occurrences that each room was at the temperature along the x-axis. The temperatures are binned in 0.5°increments.

As expected, the controlling zone (Zone 1 temperature controls HVAC on/off) is very frequently within 1 °C of the heating setpoint of 23.3 °C with the peak at 47%. Additionally, the other zones on the first floor (zones 2 & 3) are also frequently within 1 °C of the heating point. All zones on the second floor (zones 4, 5, 6 & 7) are frequently at a high ambient temperature (over 30 °C). The total run time fraction of the HVAC system is 95% (e.g. the system was on for 95% of the simulation). The HVAC system is on almost constantly to keep Zone 1 at the specified set point, which provides a lot of heat to the second floor, even when the second floor is clearly well above the set point. The maximum temperature during the simulation was 38 °C.

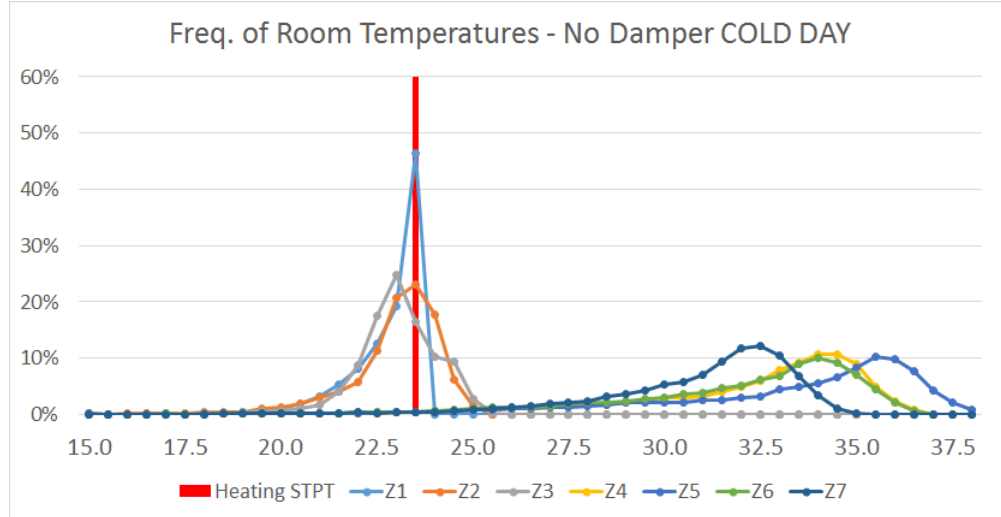


Figure 4.4: Base Case: Frequency of room temperatures for during cold temperature run.

Table 4.1 provides a statistical overview of room and building temperatures. Figure 4.5 depicts the daily mean building temperature during the simulation where the

closer to the red heating setpoint line the better. The mean temperature of the second floor is significantly higher than the second floor (30% warmer) and in the case of this investigation is exaggerated from reality due to both the low temperature chosen and the HVAC cycling that was required to maintain the controlling zone at the set point.

Zone	Mean	STDEV	% Difference of Mean & Set Point
Zone 1	22.52	1.13	-4%
Zone 2	22.69	1.32	-3%
Zone 3	22.72	1.19	-3%
Zone 4	31.75	3.50	36%
Zone 5	32.70	3.98	40%
Zone 6	31.38	3.61	34%
Zone 7	30.48	2.85	31%
Building	27.75	5.25	19%

Table 4.1: Base Case: Temperature ($^{\circ}\text{C}$) statistics for cold days.

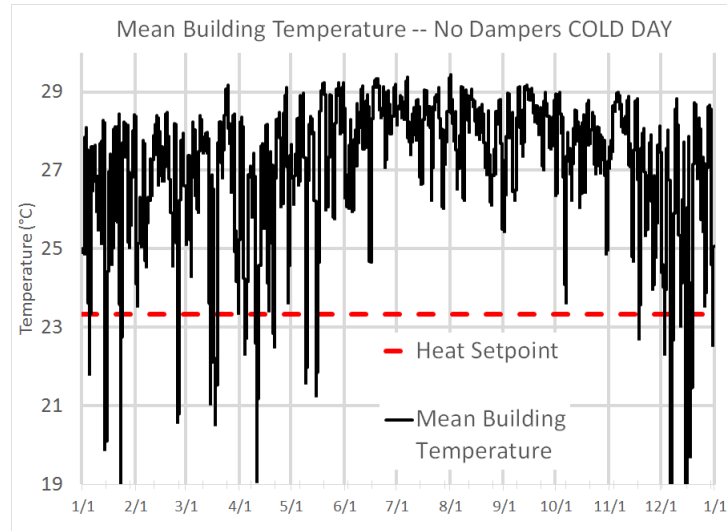


Figure 4.5: Base Case: Daily mean temperature during cold temperature run.

Figure 4.6 shows the frequency of zone temperatures for the model with dampers installed on the register. All other equipment remained the same. While, on average, the first floor increased in temperature slightly, the second floor decreased in temperature significantly. The second floor is on average within 1 $^{\circ}\text{C}$ of the heating set

point 40% of time. This is in part due to the run time fraction of the HVAC fan being significantly lower than the base case at 81% of the simulation. Even with the reduced run time of the flow (and thus less total airflow for the simulation), the first floor received a larger amount of airflow from the HVAC system.

The damper system had 7% less airflow, but the first floor received 8% more than the base case and the second floor received 19% less. The airflow results are summarized in Table 4.3. To note, since all equipment is the same and run period the same, a 19% decrease in run time fraction of the fan should equate to 19% decrease of total airflow. However, Table 4.3 shows that the damper system has a 22% decrease in total airflow, which could possibly indicate decreased performance of the fan in the damper system. Figure 4.7 also depicts the daily mean temperature for the dampers model during the cold day simulation. Table 4.2 depicts the zone and building temperature statistics as well as the percent difference from the base case. The maximum temperature during the damper simulation for the cold ambient temperature was 33.4 °C, a 14% decrease from the base case.

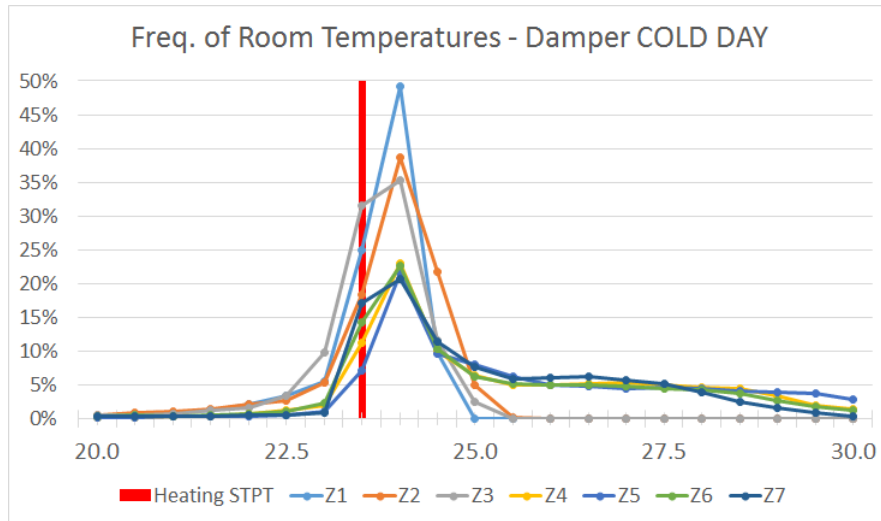


Figure 4.6: Dampers: Frequency of room temperatures during cold temperature run.

Zone	Mean	% Diff Mean	STDEV	% Diff STDEV	% Diff of Mean & Set Point
Zone 1	23.30	3.5%	1.06	-5.7%	-0.1%
Zone 2	23.44	3.3%	1.20	-9.0%	-0.5%
Zone 3	23.32	2.6%	1.03	-13.2%	-0.1%
Zone 4	25.12	-20.8%	2.26	-35.9%	7.7%
Zone 5	25.59	-21.7%	2.51	-36.9%	9.7%
Zone 6	24.92	-20.6%	2.21	-38.8%	6.8%
Zone 7	24.83	-18.5%	1.90	-33.1%	6.4%
Building	24.36	-12.2%	2.04	-61.1%	4.4%

Table 4.2: Dampers: Temperature ($^{\circ}\text{C}$) statistics cold days and % difference from base case (Table 4.1).

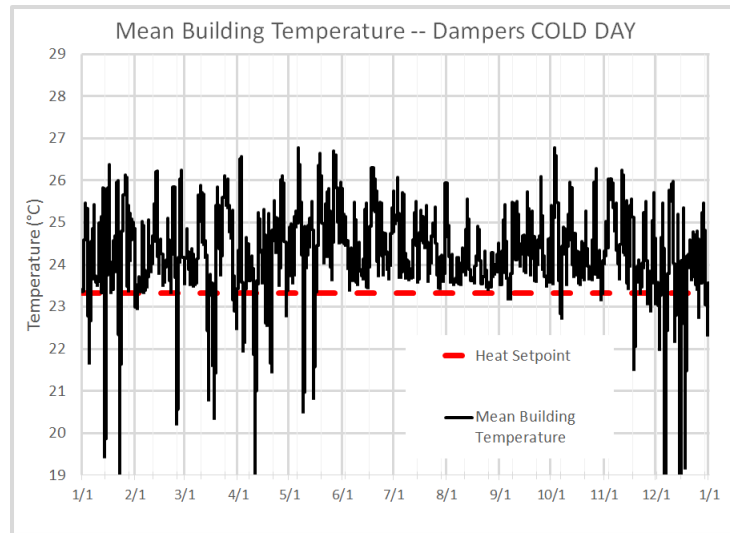


Figure 4.7: Dampers: Daily mean temperature during cold temperature run.

Zone	Base Case	Dampers	% Difference
Zone 1	5196.6	5420.8	4%
Zone 2	3693.5	3743.7	1%
Zone 3	3295.3	3566.9	8%
Zone 4	3861.9	2314.6	-40%
Zone 5	6192.8	3624.5	-41%
Zone 6	3152.9	2170.0	-31%
Zone 7	3966.4	2199.4	-45%
Total	29359.3	23039.8	-22%

Table 4.3: Airflow rate (m^3/s) differences between base case and damper case heating cycle; total for duration of simulation.

The damper model shows that for an ideal HVAC system, dampers on the registers have the ability to significantly reduce the occurrence of hot spots in a residential building during the heating cycle. Of note, the the mean building temperature is maintained closer to the heating set point with dampers controlling the airflow into each zone. The mean building temperature shows the HVAC system's ability to maintain a set point and the standard deviate of temperatures shows the tightness of control the system has, with a lower standard deviation being more desirable. These results also seem to indicate a potential for reduced energy usage through a reduction in HVAC cycling times, thus reducing the amount of electricity and natural gas consumed during a heating cycle.

4.2.2 High Outside Ambient Temperature

Figure 4.8 shows the frequency of room temperatures for the base case for the high cooling demand scenario: high outside ambient temperature (40 °C) and low cooling set point (21.7 °C). Again, as expected, the controlling zone is within 1 °C of the cooling set point with a high degree of frequency (90%). The rest of the thermal zones on the first floor are frequently (both greater than 80%) within 1 °C of the set point. The second floor is again often a few degrees warmer than the first floor, though not as dramatically as the low outside temperature simulation. In this case, the maximum temperature found during the simulation is 28.8 °C. The total run time fraction of the HVAC system is 67%.

Table 4.4 provides a statistical overview of the room and building temperatures for the base case. Figure 4.9 depicts the daily mean building temperature where the blue line is the cooling set point.

Figure 4.10 depicts the frequency of room temperatures for the hot day simulation of the dampers model. The simulation shows a slight reduction in the the average

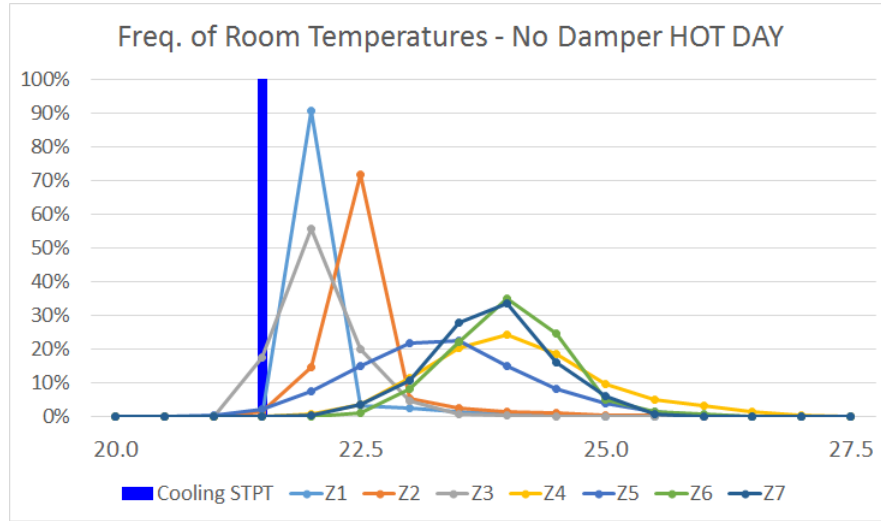


Figure 4.8: Base Case: Frequency of room temperatures during hot temperature run.

Zone	Mean	STDEV	% Difference of Mean & Set Point
Zone 1	21.79	0.44	-0.6%
Zone 2	22.24	0.53	-2.6%
Zone 3	21.83	0.43	-0.8%
Zone 4	23.85	0.90	10.1%
Zone 5	23.09	0.91	6.6%
Zone 6	23.77	0.62	9.7%
Zone 7	22.88	0.62	8.9%
Building	22.88	1.07	5.6%

Table 4.4: Base Case: Temperature (°C) statistics for hot days.

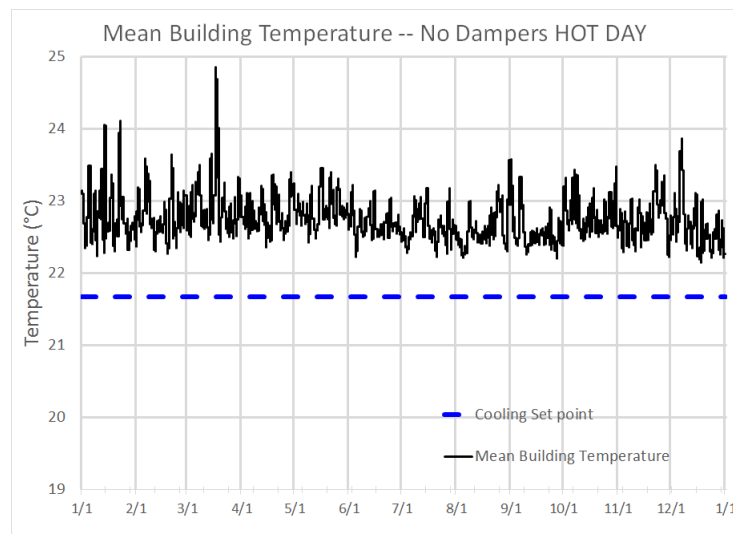


Figure 4.9: Base Case: Daily mean temperature (°C) during hot temperature run.

second floor temperatures. The building is often maintained at the same temperature with the dampers in place. The first floor building temperatures remain relatively the same. However, the total run time fraction of the HVAC system in this case is 71%, an increase of 4% from the base case. The maximum temperature is insignificantly decreased from 28.8 °C in the base case to 28.6 °C. Table 4.5 presents a statistical overview of the room and building temperatures including a percent difference between the base case and the dampers model.

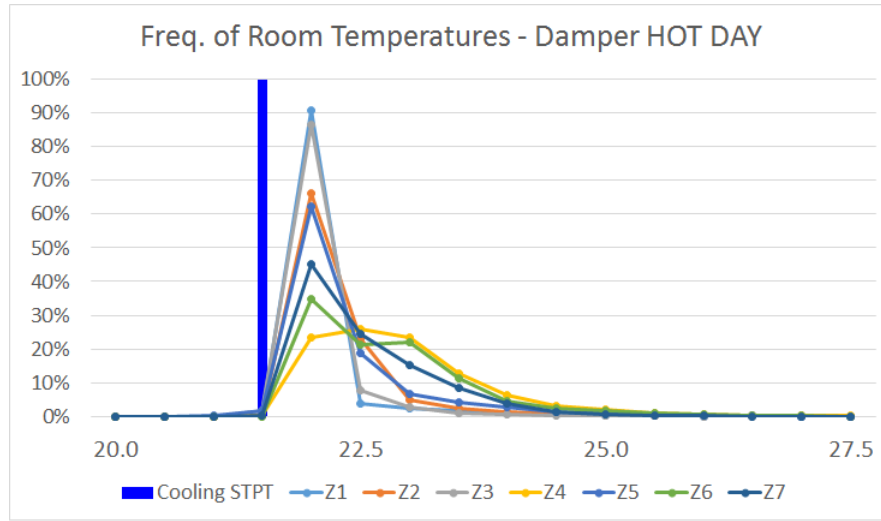


Figure 4.10: Dampers: Frequency of room temperatures (°C) for hot temperature run.

Zone	Mean	% Diff Mean	STDEV	% Diff STDEV	% Diff of Mean & Set Point
Zone 1	21.89	0.5%	0.40	-10%	1.0%
Zone 2	22.08	-0.7%	0.55	4.0%	1.9%
Zone 3	21.86	0.1%	0.32	-26.0%	0.9%
Zone 4	22.68	-4.9%	0.86	-5.0%	4.7%
Zone 5	22.15	-4.1%	0.70	-23.0%	2.2%
Zone 6	22.56	-5.1%	0.83	33.0%	4.1%
Zone 7	22.33	-5.4%	0.65	4.0%	3.1%
Building	22.22	-2.9%	0.71	-34.0%	2.6%

Table 4.5: Dampers: Temperature (°C) statistics for hot days and % difference from base case (Table 4.4).

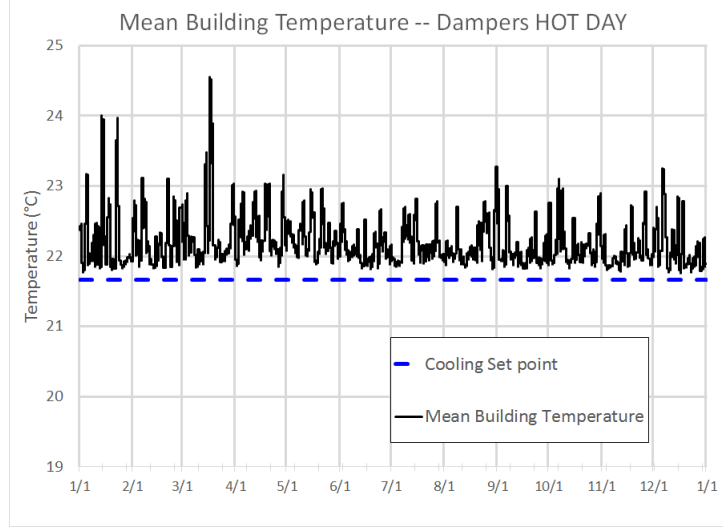


Figure 4.11: Dampers: Daily mean temperature (°C) during hot temperature run.

Zone	Base Case	Dampers	% Difference
Zone 1	7902.9	7185.7	-9%
Zone 2	3175.4	3529.3	11%
Zone 3	4197.5	3488.1	-17%
Zone 4	2026.0	2629.9	30%
Zone 5	6663.3	6495.6	-3%
Zone 6	3504.0	4306.3	23%
Zone 7	4219.1	5115.7	21%
Total	31688.3	32750.6	3%

Table 4.6: Airflow rate (m^3/s) differences between base case and damper case cooling cycle; total for duration of simulation.

The cooling cycle for this model does not show the same responsiveness to the system as the heating cycle had. The second floor temperature was not exaggerated through an extended run time like during the cooling cycle. In this case, there is a slight decrease (5%) in the airflow delivered to the first floor compared to the base case. There was, on average, an 18% increase of airflow to the second floor with a total increase of airflow by 3% when compared to the base case. Table 4.6 summarizes the total airflow rates for both the base case and the damper model.

The damper model, in this case, shows a similar result for thermally balancing a residential building as the previous simulation. The plots of mean building temper-

ature for both cases show that the damper model operates at a temperature much closer to the heating and cooling set points. However, unlike the first experiment, the damper system required a larger amount of electricity to maintain the building temperature at a more uniform temperature. The base case required 60,000 kBTU of total energy while the the damper system required 62,000 kBTU to maintain the same set point.

Both cases show that a damper system can be used to thermally balance a single-family residential building. The heating cycle case showed a significant reduction in fan run time to maintain a more uniform building temperature while the cooling cycle showed a minor increase in energy usage. In both cases, it is assumed that thermal comfort levels would increase due to operating closer to the chosen temperature set point. It should also be noted that due to the varying differences in building loads required during the heating and cooling cycles for the hot and low outside temperature simulations, that the HVAC equipment (fan, heating coil, cooling coil and max flow rates available to each zone) were not kept consistent between the two simulations. HVAC equipment was kept the same between the no damper and damper cases within each simulation.

4.3 Annual Simulation

The research objective of this section is to further build on the previous results and investigate the possible energy reduction capabilities of a damper system installed on a single-family residential building. A base case with uncontrolled registers and a damper model case are both simulated through an annual run period for multiple climates. Building on previous results, the expectation after running the simulation through multiple climates will be that milder, more heating-dominant climates will have a greater possibility of energy savings due solely to a damper installation when compared with warmer climates because of the increased heating cycle length and decreased cooling cycle length. In addition to the local control supplied by the the dampers, all simulations use a dead-band thermostat control in the controlling zone

where the heating set point is 21.6 °C and the cooling set point is 23.3 °C [35]. The HVAC system is off while the ambient temperature is between the two set points in the controlling zone.

Along with room and building temperatures and energy usage being investigated, the overall comfort of the buildings during the run period is simulated. The aim is to see which systems have the greatest overall possibilities of energy savings while also possibly increasing comfort levels.

4.3.1 Total Energy Usage vs Climates

Yearly simulations were done on the base building model with varying envelope thermal resistances based on typical values for that climate. The climate zones investigated span from 2A (Hot-Humid) to 5B (Cool-Dry) based on the ASHRAE climate zone definitions. The base case building model equipment is autosized using Energy-Plus' autosizing function. These values were then used in the damper case for each corresponding building model. Figure 4.12 summarizes the energy consumption during the yearly simulations and Figure 4.13 summarizes the total cost in US Dollar (USD) for the energy use. Table 4.7 displays the cost assumptions used to do the cost analysis. Data for typical electricity and natural gas cost was taken from the US Energy Information Administration's (EIA) Residential Energy Consumption Survey (RECS) [1].

Conversions from kBTU to USD using the two rates for electricity and natural gas are as follows. The conversion for total cost of electricity (C_E) is straight forward.

$$1 \text{ kBTU} \approx 0.29 \text{ kWh}$$

$$C_E = (kBTU) \left(\frac{0.29 \text{ kWh}}{1 \text{ kBTU}} \right) \left(\frac{\text{¢}}{\text{kWh}} \right) \left(\frac{1 \$}{100 \text{ ¢}} \right)$$

However, the conversion of kBTU into USD requires some estimation. The International Gas Union estimates that 1 cf of NG $\approx 900 - 1200 \text{ BTU}$ thus $1 \text{ kBTU} \approx 1.11 \text{ cf}$ of NG. Converting from kBTU to cost of gas (C_G) is then as follows:

$$C_G = (kBTU) \left(\frac{1.11 \text{ cf}}{kBTU} \right) \left(\frac{1 \text{ Mcf}}{1000 \text{ cf}} \right) \left(\frac{\$}{\text{Mcf}} \right)$$

Location	Electricity Cost (¢/kWh)	Natural Gas Cost (\$/Mcf)
Albuquerque	0.1228	10.13
Colorado Springs	0.1218	8.89
Los Angeles	0.1625	11.51
Phoenix	0.1190	17.20
Atlanta	0.1165	14.45
Baltimore	0.1363	12.21
Boston	0.1739	14.50
Houston	0.1739	11.16

Table 4.7: Average cost of electricity and natural gas from 2014, EIA RECS.

An indicator of potential system performance increase or decrease with usage of dampers is to look at the coefficient of performance (COP) during the cooling cycle. COP is the ratio of heat removed and work consumed to provide cooling. A summary of the average COP values for each climate is in Table 4.8. The COP is neither positively or negatively impacted significantly with the addition of dampers. It should be noted this is for an ideal system and Section 4.4 will provide better insight into actual effects on the cooling coil.

The energy consumption across all climates decreased with the installation of dampers. There is a slight trend for milder climates showing a larger amount of possible energy to save compared to warmer climates, with the two largest amounts of saved energy coming from climate zones 4B (Mixed-Dry) and 5B (Cool-Dry). The two climates with the smallest amounts of saved energy are 2B (Hot-Dry) and 2A (Hot-Humid). The largest amount of energy savings from all climates came during the heating cycle and the smallest from the cooling cycle. The cost analysis for a year's worth of energy usage show significant energy savings in most of the climates with the minimum saved just over \$50.00 (2A) and the maximum at just under \$200.00 (5B). It should be noted that the amount of possible money saved is highly dependent on current costs of energy. With energy costs trending up across the nation, any amount saved could be useful. With a clear indication of possible energy savings, it is also

important to investigate the thermal comfort in the building during the simulations.

Climate Zone	Location	Average COP	
		Base Case	Dampers
4B	Albuquerque	4.9	5.1
5B	Colorado Springs	4.9	4.9
3B	Los Angeles	5.1	5.1
2B	Phoenix	4.0	4.0
3A	Atlanta	4.7	4.9
4A	Baltimore	4.8	4.9
5A	Boston	4.9	4.9
2A	Houston	4.5	4.9

Table 4.8: Average Coefficient of Performance (COP) for base case and dampers.

4.3.2 Thermal Comfort

Thermal comfort is the main function of a central HVAC system. A system is deemed undesirable if it cannot adequately condition the space of which it serves. Along with investigating any possible energy savings, one must also look into possible issues with the thermal comfort of the test building. Fanger’s PMV-PPD model is used here to determine the likelihood of comfort during all the simulations. This section will focus on the metrics used for Boston followed by a brief summary of all the climates and their thermal comfort levels. The metrics for all climates not shown in this section can be found in Appendix A. Boston is chosen as an example due to the large potential for energy savings shown in the previous section and the short buy back period.

As in the previous section, the mean and standard deviation of thermal zones and the building and the frequency of temperatures throughout the simulation are used as main metrics. Figures 4.14-15 depict the frequency of thermal zone temperatures for Boston for both the base case and damper model respectively.

The frequency of the temperatures on the first floor is high in between the two set points for both simulations. The second floor is frequently warmer than the first floor. The damper case shows the second floor temperatures are reduced significantly from the base case and are more likely between the heating and cooling setpoints. The HVAC system with dampers installed is able to maintain a tighter level of control of

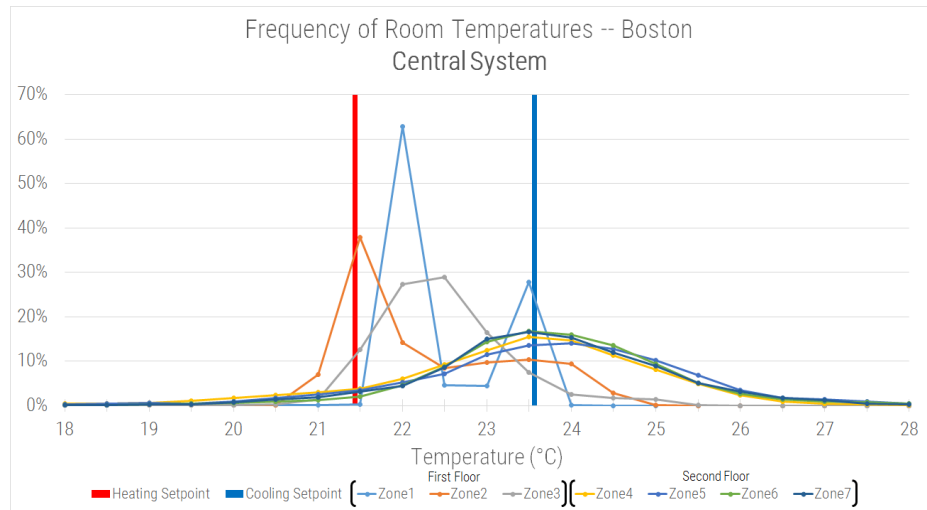


Figure 4.12: Frequency of Room Temps: Boston Base Case.

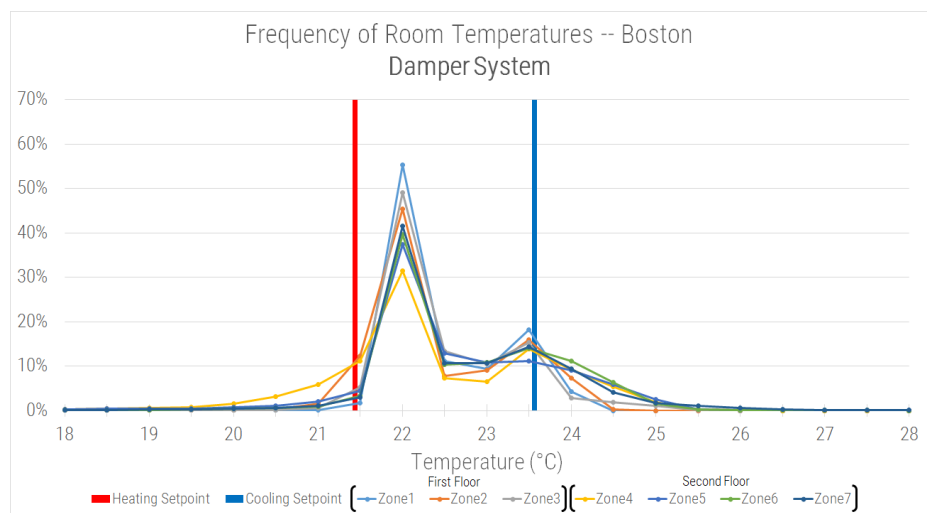


Figure 4.13: Frequency of Room Temperatures: Boston Dampers.

		NO DAMPERS				DAMPERS				NEGATIVE IS BETTER			
Climate	Location	Site Fan (kBTU)	Site Cooling (kBTU)	Site Heating (kBTU)	Total Site Energy (kBTU)	Site Fan (kBTU)	Site Cooling (kBTU)	Site Heating (kBTU)	Total Site Energy (kBTU)	% Difference Fan	% Difference Cooling	% Difference Heating	% Difference Total
4B	Albuquerque	8318	11141	42305	61764	7365	10735	35049	53148	-11%	-4%	-17%	-14%
5B	Colorado Springs	7966	7554	65241	80761	7073	7259	55790	70122	-11%	-4%	-14%	-13%
3B	Los Angeles	5830	9168	15121	30119	5350	8853	13036	27238	-8%	-3%	-14%	-10%
2B	Phoenix	9737	26998	13372	50107	9311	26961	11394	47666	-4%	0%	-15%	-5%
3A	Atlanta	6836	11793	37068	55697	6324	11554	32199	50077	-7%	-2%	-13%	-10%
4A	Baltimore	7277	8725	57749	73752	6583	8576	49660	64818	-10%	-2%	-14%	-12%
5A	Boston	7037	6334	83327	96698	6411	6178	73832	86421	-9%	-2%	-11%	-11%
2A	Houston	7057	15739	22782	45578	6613	15576	19218	41407	-6%	-1%	-16%	-9%
										More potential for saving money from changing heating habits. On average, 41% of energy usage in the home is heating while only 6% is cooling in the US			

Figure 4.14: Yearly energy usage summary and percent differences between base case and dampers model.

		NO DAMPERS				DAMPERS				Savings		Assuming \$2000 capital cost for installation
Climate	Location	Site Fan Cost	Site Cooling Cost	Site Heating Cost	Total Site Cost	Site Fan Cost	Site Cooling Cost	Site Heating Cost	Total Site Cost	Total Saved	% Saved	Buy Back Period (Yrs)
4B	Albuquerque	\$ 299.37	\$ 400.96	\$ 476.12	\$ 1,176.45	\$ 265.05	\$ 386.33	\$ 394.46	\$ 1,045.83	\$ 130.62	11.10%	15.31
5B	Colorado Springs	\$ 284.36	\$ 269.63	\$ 644.37	\$ 1,198.37	\$ 252.47	\$ 259.12	\$ 551.02	\$ 1,062.61	\$ 135.75	11.33%	14.73
3B	Los Angeles	\$ 277.63	\$ 436.60	\$ 193.36	\$ 907.60	\$ 254.76	\$ 421.61	\$ 166.70	\$ 843.07	\$ 64.53	7.11%	31.00
2B	Phoenix	\$ 339.57	\$ 941.58	\$ 255.53	\$ 1,536.68	\$ 324.72	\$ 940.27	\$ 217.73	\$ 1,482.73	\$ 53.95	3.51%	37.07
3A	Atlanta	\$ 233.41	\$ 402.63	\$ 595.08	\$ 1,231.13	\$ 215.93	\$ 394.49	\$ 516.91	\$ 1,127.34	\$ 103.79	8.43%	19.27
4A	Baltimore	\$ 290.70	\$ 348.53	\$ 783.38	\$ 1,422.62	\$ 262.94	\$ 342.56	\$ 673.65	\$ 1,279.16	\$ 143.46	10.08%	13.94
5A	Boston	\$ 358.64	\$ 322.83	\$ 1,342.35	\$ 2,023.82	\$ 326.72	\$ 314.85	\$ 1,189.40	\$ 1,830.98	\$ 192.84	9.53%	10.37
2A	Houston	\$ 245.29	\$ 547.05	\$ 282.47	\$ 1,074.81	\$ 229.86	\$ 541.40	\$ 238.28	\$ 1,009.54	\$ 65.27	6.07%	30.64

Figure 4.15: Yearly cost of energy summary for base case and dampers model.

the building temperature further enforced by Figures 14.16-17 which show the mean building temperatures for the base case and damper system respectively. Table 4.9 shows a statistical overview for both cases.

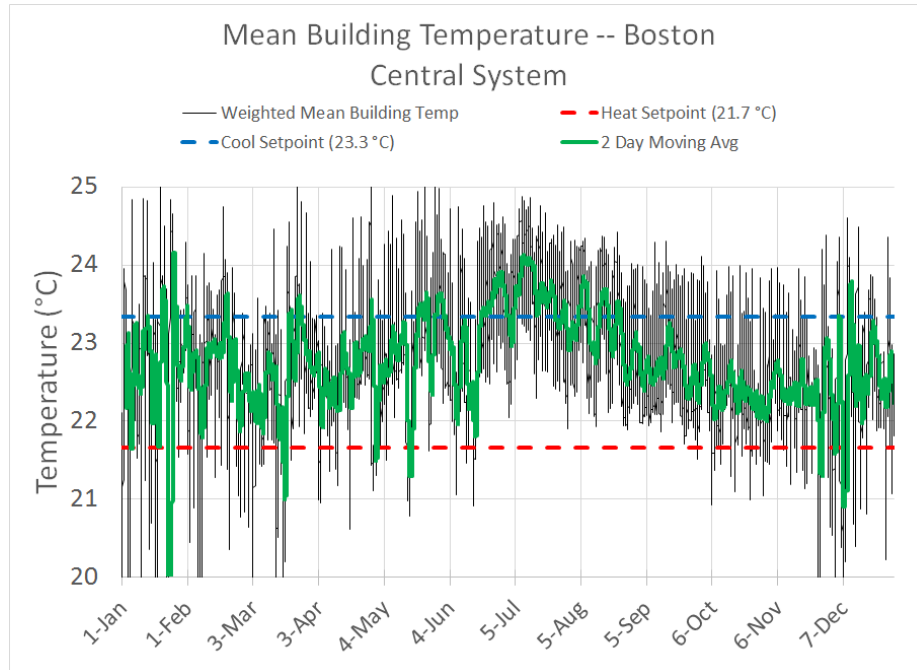


Figure 4.16: Mean building temperature: Boston Base Case.

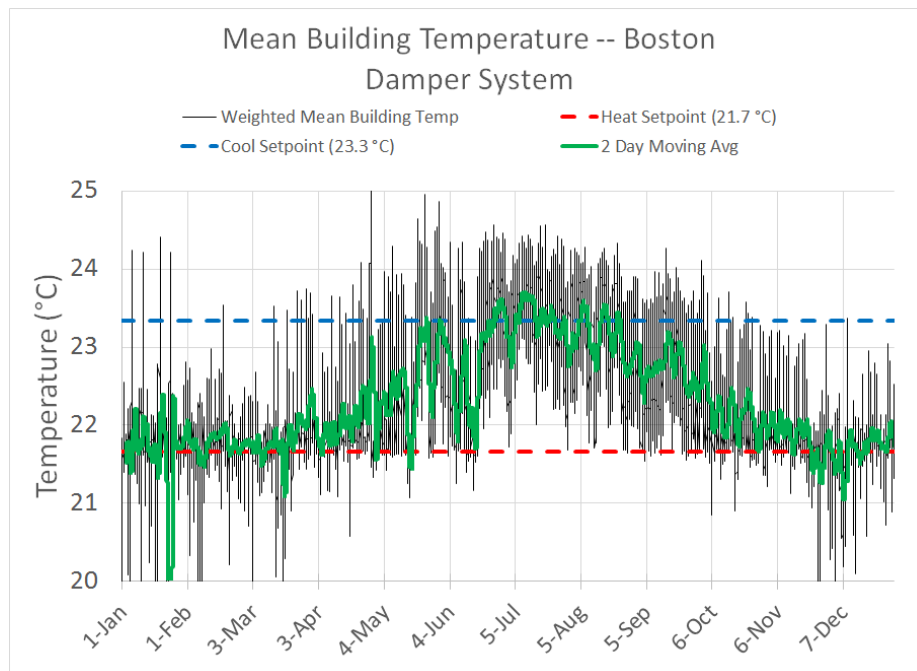


Figure 4.17: Mean building temperature: Boston Dampers.

Zone	No Damper		Damper	
	Mean	STDEV	Mean	STDEV
Zone 1	22.19	0.80	22.24	0.75
Zone 2	22.02	1.05	22.17	0.87
Zone 3	22.21	0.78	22.25	0.79
Zone 4	23.07	1.67	22.15	1.33
Zone 5	23.46	1.74	22.38	1.21
Zone 6	23.51	1.44	22.50	1.08
Zone 7	23.42	1.44	22.47	1.09
Building	22.84	1.46	22.31	1.04

Table 4.9: Temperature ($^{\circ}\text{C}$) statistics for Boston base case and dampers model.

The mean temperature of the damper system operates closer to the heating set point during the heating season when compared to the base case, which has larger swings in temperature values. The mean thermal zone temperatures show a decrease of about 1°C on the second floor with a slight increase on the first floor. The standard deviation of all thermal zones decreases during the damper model simulation. With slightly better control of the system, one should expect a better level of thermal comfort that is being delivered by the system as the tighter control limits outliers and reduces temperature swings between floors. Figures 4.18-19 depict the predicted percentage dissatisfied for the two models. The assumed values are given in Table 2.4.

The PPD is an estimation of the likelihood that percentage of the population would be uncomfortable in the current room conditions. A clothing insulation value of 1 represents a typical office outfit of trousers, long-sleeved shirt and a sweater. PPD is increased slightly in all cases which is shown in the frequency of room temperature figures in Appendix A. The second floor temperatures are consistently able to be reduced and brought closer to the dead-band temperature setpoints in all cases. This reduction in thermal zone temperatures drives the increase in thermal comfort.

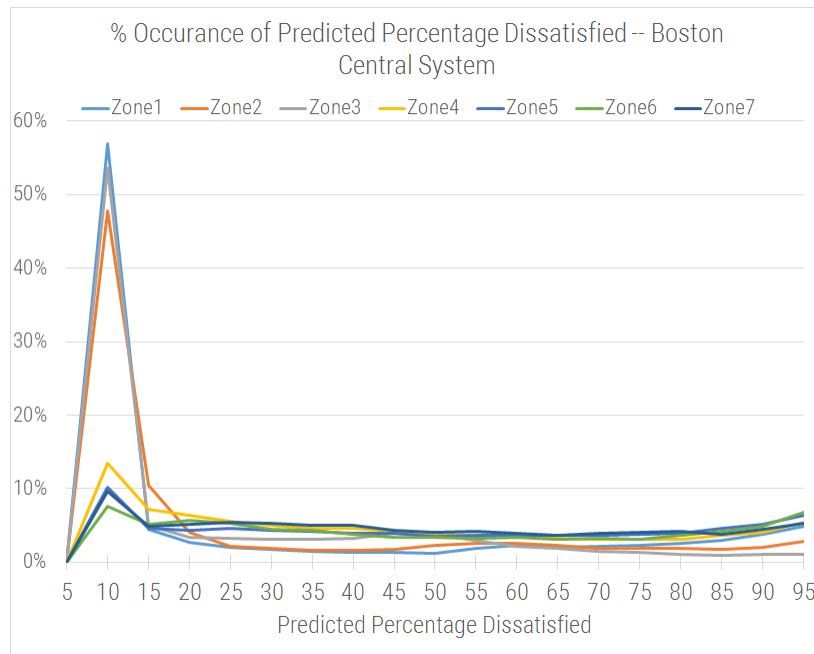


Figure 4.18: Predicted percentage dissatisfied: Boston No Dampers.

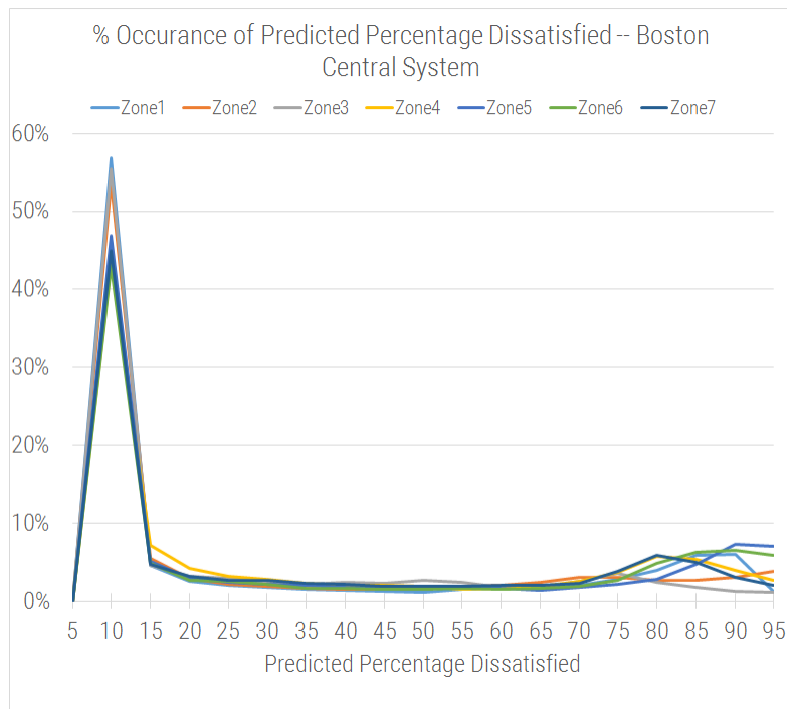


Figure 4.19: Predicted percentage dissatisfied: Boston Dampers.

4.4 Impact on HVAC System

The last research objective is to investigate the impact a damper system would have on a HVAC system through the EnergyPlus simulation. First, a generic branched duct system is designed and tested using the software CONTAM to research the effects closing dampers on registers has on the supply fan pressure and air flow. The CONTAM results are compared with Walker's hangar results [26]. A radial system is designed for the base case model using the AFN module in EnergyPlus. The airflows and pressures for each thermal zone are investigated as indicators of altered system performance.

4.4.1 Generic Ductwork

A small ductwork is designed to do a quick pressure and damper configuration study. Figure 4.21 shows the system pressures the fan must overcome for multiple damper configurations. The duct system is made up a constant air volume fan object connected to three sections of 12 in. x 6 in. rectangular ducts and are 7 ft. in length to form the main trunk with three branches coming off after each section. The branches are 6 in. radius circular ducts and an orifice object is used to model a damper as it can be altered to restrict flow by decreasing the orifice size. The damper position of the nearest branch on the x-axis and the configurations change mostly the positions of the middle and furthest damper.

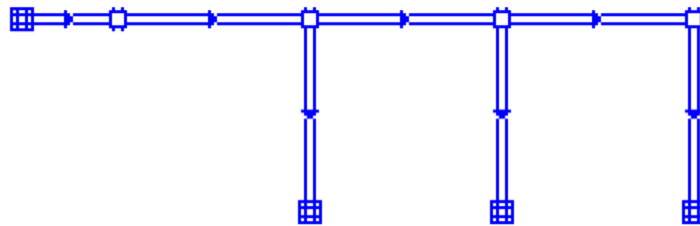


Figure 4.20: Schematic of small duct system with 3 registers.

For most configurations, the system pressure increases only slightly from the base case of dampers being full open (from $0.17 \text{ in.}H_2O$) with only the configuration with the middle damper at 50% and the furthest damper at 30% having a point which is

above the maximum operating point of the fan used. It should be noted that most residential systems look to operate under 0.25 $in.H_2O$ however some systems do have operating pressures above this, usually 0.4-0.6 $in.H_2O$.

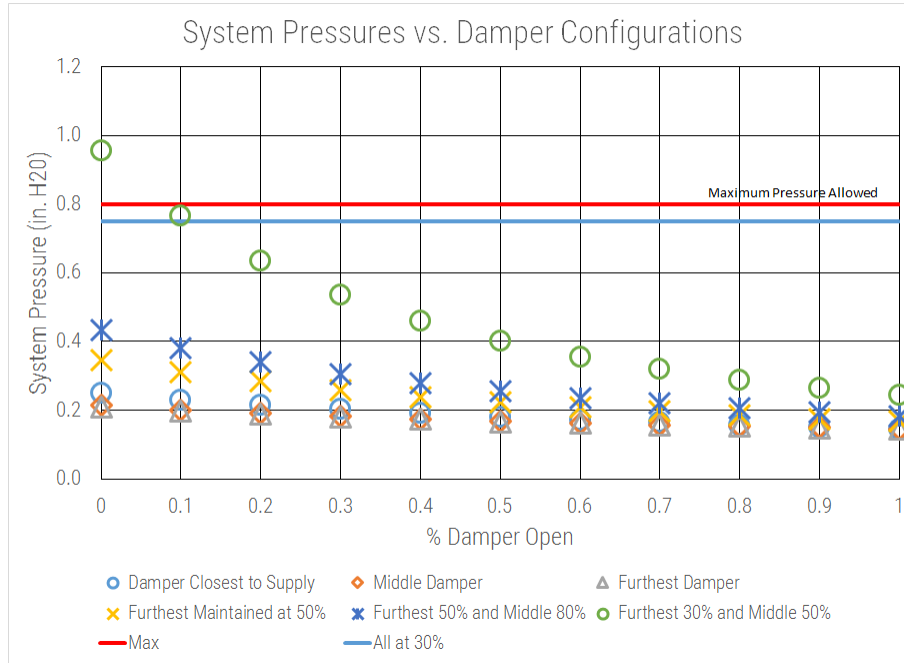


Figure 4.21: System pressure vs. damper configurations for a small HVAC system.

The duct system was then upscaled to be similar to a duct system that could be used for the test house for the previous investigations. The main trunk is made up of several sections of 12 in. x 8 in. rectangular ducts of varying length. There are seven branches coming off the main trunk, each 6 in. circular duct work with two lengths used (9 ft. & 15 ft.). The system pressure of the fan is simulated as dampers are fully closed in two configurations: from nearest to furthest and from furthest to nearest.

Figure 4.23 shows the results which seem to show the same behavior that Walker showed [26]. The supply fan volumetric flow rate remains at a consistent value for the first few dampers being closed but quickly reduces in flow rate after the third register is closed fully in both configurations. The ductwork in these simulations were simulated with no leakage which contributes to the drastic loss in supply airflow as the number of registers closed increases beyond three. These two results show that while system pressure and supply airflow could be largely unaffected by the initial closing of registers, there is a point at which the system pressure would become too

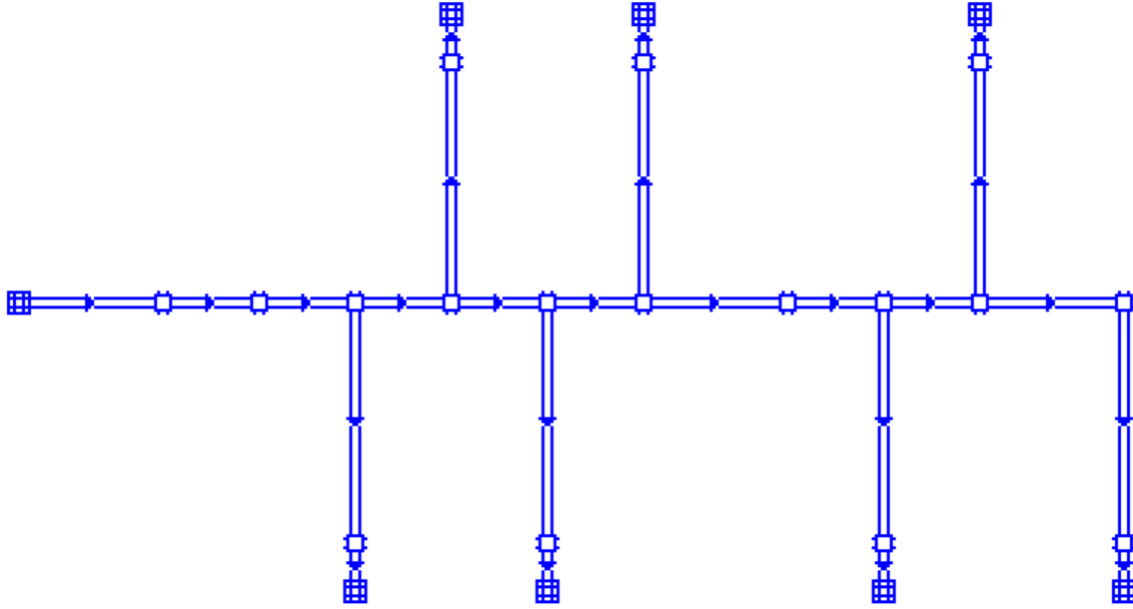


Figure 4.22: Schematic of upscaled duct system with seven registers.

great to overcome and losses in system performance would occur. To further illustrate this point, the building model from the previous sections was simulated with a duct system to see how heating and cooling loads could also be affected by closing dampers.

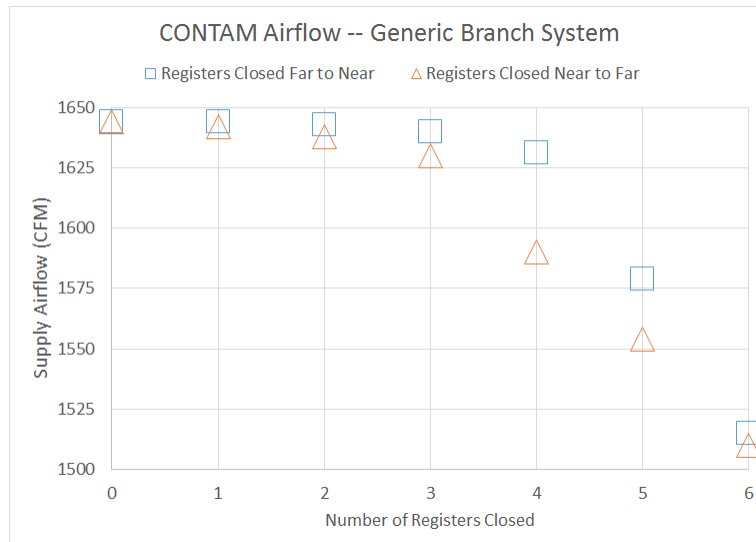


Figure 4.23: Supply Airflow vs. damper configurations for a small HVAC system.

4.4.2 Air Flow Network Modeling

The building model from the previous sections was altered to include a typical HVAC ductwork system. From the base case model, the damper object was input into the duct system so that the ductwork is the same between the two models except for dampers at the end of each supply branch in the damper model. This model was then simulated through a typical summer day for Boston. It was found that the time step for the simulation needed to be as short as possible in order for the model to converge. Even so, the damper model showed some oscillatory behavior as the model was not able to converge to a single value at some of the time steps. These results should be seen as precursors for a future investigation into EnergyPlus' ability to simulate damper impact on internal HVAC performance.

Table 4.10 is a summary of the base case and damper model operating conditions during the simulations. It is shown that the damper system inherently operates at a higher pressure range than the base case equipment. The equipment in all cases was able to maintain the building temperature set point of 23.3 °C however the damper system required a significant increase in fan run time to do so. This shows an increase in energy consumption and possibly a decrease in performance and component life expectancy due to a higher range of operating pressures. A restrictive model was run where the dampers are allowed to run with a minimum flow fraction of 10% but found no significant difference over the operation of the HVAC system when compared to a less restrictive model with a minimum flow fraction of 50%.

Metric	Base Case	Damper (10% MinDamp)	Damper (50% MinDamp)
Min Pressure (Pa)	18.0	32.2	32.2
Max Pressure (Pa)	21.5	38.0	38.0
Fan RTF	18.5%	29.4%	26.9%
Mean Building Temp (°C)	23.3	23.0	23.0
STDEV Building Temp (°C)	1.1	1.1	1.3

Table 4.10: Summary of AFN models.

Due to the limitations in the EnergyPlus VAV:Reheat object used in the AFN, the heating cycle could not be adequately modeled as the damper positions and heating

rate could not be coupled together in the same way as that the VAV:HeatAndCool object does. The heating cycle would be of great interest due to previous results showing the larger potential for energy savings within the heating cycle when compared to the cooling cycle. However, the cooling cycle should be of interest on overall system impact because cooling coil equipment performance is more closely tied to airflows through the furnace and thus is more susceptible to failure if the increased system pressures get too high.

Chapter 5

Discussion & Conclusions

In the previous chapter, the results from all investigations were presented. In this chapter, the results are discussed within two sections. Section 5.1 is an overview of the potential for energy savings and Section 5.2 is an overview of system impact indicators. Finally, Section 5.3 will assess the merit of using controllable dampers on the registers of a single-family residential home as a whole in the conclusions section.

5.1 Energy Saving Potential

The aim of this thesis was to investigate if a damper system in a residential setting could be an effective way to thermally balance the building and if there was any potential for the system to be an effective energy saving scheme for retrofits on older homes. The use of EnergyPlus as the research medium allowed for quick prototyping of a base case system and providing a close interpretation of energy use expectations. Section 4.1 and 4.2 present results pertaining to the use of dampers as a retrofit for homes with a single, centrally located thermostat controller.

With the use of dampers, the temperature difference between the first and second floors was decreased bringing the building closer to thermal equilibrium. During the heating cycle, the second floor was especially warmer than the first due to the larger thermal load on the controlling zone for the system. The thermal zones on the second floor were brought well above the heating set point while the controlling zone was

brought up to the temperature set point. Redistributing this heating energy away from the second floor and towards the first allowed not only for the first floor to be heating more quickly, but also for the second floor to not be heated as much.

The EnergyPlus models create an approximate estimate for expected thermal loads and energy use throughout the building. The HVAC system runtime was reduced especially during the heating cycle. The cooling cycle however showed a much lower potential for energy savings than heating. HVAC runtime increased slightly during the cooling cycle of the damper model indicating that the cooling cycle may not have much potential for effective use of a damper system. This was reiterated during the climate zone investigations where hotter/drier climates tended to have less potential for energy savings when compared to milder climates.

There is perhaps some bias towards the potential of energy savings for heating over cooling. According to the most recent EIA RECS (2009) data available, 41% of total energy use in the home comes from heating while only 6% comes from cooling on average in the US [1]. With more energy used to begin with during the heating cycle on average, there is a larger possible margin for reducing energy use. When compared with the national average, Arizona averages 25% of total household energy use coming from air conditioning. It was unexpected that even with such a large margin potential for energy reduction that the Phoenix model showed only a 4% reduction during the cooling cycle. The cost analysis could also be skewed because average prices were used for the entire year even though energy prices change throughout it.

It should also be noted that every model uses a single thermostat to control the cycling of the HVAC system. This creates a "single point of failure" for ensuring every room reaches the temperature setpoint. Having the thermostat on the first floor is beneficial during the heating cycle because hotter air from the second floor is redirected to the first floor. This reduces the overheating of the second floor while simultaneously heating the first floor faster. This increased heating rate implies that the HVAC system is expected to run less frequently and it should be easier to maintain the entire building within the temperature setpoint specified in the zone with the thermostat.

The opposite effect occurs during the cooling cycle which could reduce energy saving potential as seen in Section 4.4. The second floor requires a larger amount of cooling energy and the dampers redirect air away from the first floor and the controlling zone to provide the extra cooling. This decreases the temperature of the second floor and increases the thermal comfort, however, it decreases the rate of cooling to the first floor and increases the temperature which in turn decreases the thermal comfort slightly. Investigating multiple locations for a single thermostat or the use of multiple thermostats would be advantageous in exploring the overall effectiveness of a residential damper system.

The thermal comfort changes going from the base case to the damper model was also investigated. As stated earlier, an ideal energy saving scheme would not only reduce energy usage but also increase thermal comfort. In this case, the expected comfort levels were increased during all simulations going from the base case to the damper model. It should be noted that Fanger's PMV-PPD model is not a perfect indicator of thermal comfort but is currently an accepted method. There is potential for bias as it is attempting to quantify a perceived comfort level which can differ seasonally and amongst individuals. Coupled with the reduction in energy use, an increase in perceived comfort levels predicted shows the potential for a properly designed damper system to both decrease energy use and increase comfort.

The damper model was run "as is"; there was no effort to optimize the control of the dampers, such as synchronizing them to some pressure set point within the furnace, and no thermostat controls were used other than a constant dead-band control. Coupling the dampers with a set-back schedule could further increase saving potential. In this case, the HVAC system is assumed to be ideal (no duct losses) and utilizes a VAV box which can provide proportional airflow control during both the heating and cooling cycles.

5.2 System Impact

Previous models were run under the assumption of an ideal HVAC system where the simulations provided an approximate estimate of how much energy would be required with the given equipment. The internals of the system however are sensitive to flow and pressure changes through the entire ductwork and a preliminary investigation was conducted using EnergyPlus' AFN module. While EnergyPlus models are robust and modular, the AFN model proved to be difficult to work with. Convergence issues were common and producing a working model for even a small duct system demonstrated to be a highly intensive trial and error exercise.

A CONTAM model was tested first to try and replicate Walker's results [19]. While the model did not exactly match, the same trends of pressure and airflow changes were seen. With a large number of outlets for the air to flow into, the pressure increases due to closing dampers fully seemed to be offset at first with the first few dampers closing because of the many branches for the pressure to dissipate through. There is a point at which the percentage of the outlet area is decreased where the system performance of the supply fan degrades rapidly. This backs up Walker's results through simulation and would seem to indicate that dampers that are locally controlled and not coupled to a pressure sensor in the furnace could potentially cause serious harm to the life expectancy of the HVAC components.

The AFN model was run only for cooling as the ability to properly simulate the heating cycle for this case has not been implemented in EnergyPlus yet. The model showed that with dampers installed, the same equipment, indeed, runs at a higher operating pressure range. This pressure range increase can reach beyond the operating performance of the supply fan and cause the motor to stall. The damper model was run in two separate configurations with the dampers able to close to 10% and 50% of the register's maximum flow rate respectively. The more restrictive case did not increase the system pressures operation range but did increase the required flow most likely due to an altered flow pattern throughout the simulation based on the heating loads and minimum damper position allowed.

The total energy used for the damper model in this case was increased from the base case and seems to be in agreement with the idealized HVAC equipment case from the previous simulation example. However, the increase in energy was much higher than expected. This could be due to a lowering of total airflow available because of increased system pressure and is an indication of an overall degradation of system performance, especially in the cooling cycle where the cooling coil has a higher chance of freeze over as the airflow rate decreases. Additional investigations, beyond these preliminary results, will be required to gain confidence in the AFN module of EnergyPlus.

5.3 Conclusions

The research objectives of this thesis were to determine through simulation if a residential damper system could reduce the spread of temperatures throughout a home and what impacts they have on energy use and system performance. In Section 4.2, the damper model was able to reduce the variance of temperatures between the first and second floor effectively bringing the mean temperature of the entire building closer to the desired setpoint of a centrally located thermostat controller. In Section 4.3, the impact on energy consumption of a damper system was investigated and showed a trend for milder climates to have a larger decrease in energy consumption versus a warmer climate. These simulations were done for both the cooling and heating cycles. Lastly, Section 4.4 presented a preliminary investigation into system impact during the cooling cycle through airflow simulation. While the duct model seemed to confirm previous results in decreased system performance with increased number of dampers closed, the airflow network model was inconclusive in regards to overall system performance. The AFN did show the ability for use of EnergyPlus to model the performance of the system and could be used to further investigate the system performance of the HVAC system with dampers.

Air conditioning is the single largest source of energy consumption in a residential home in the US today. With energy costs trending upwards around the nation, it is in

the best interest to research all options into energy saving schemes for both new and old homes. Newer homes have the benefit of better building materials and equipment being available which when coupled with more energy efficient focused building codes can become highly efficient homes. Older homes are up against a battle of aging construction materials and HVAC equipment effectively increasing the thermal load the building requires as the building ages. Different retrofitting packages are available and using dampers to effectively reduce the square footage of the house has been a common topic to determine its overall effectiveness. Buildings present a difficult testing medium due to the variances between houses built even by the same company with the same materials. EnergyPlus, while generally a design aid, allows a researcher to prototype houses quickly to test different energy saving schemes and weight the options against each other for effectiveness and cost.

Automatic dampers are a low cost alternative to other retrofitting schemes, such as upgrading building envelope with better insulation, replacing windows, or installing a renewable energy source. Individual control over room temperature through a redistribution of air can effectively reduce the temperature differences throughout a home and potentially reduce energy consumption. The increase in energy consumption during the cooling cycle in the AFN model is however disconcerting and a working AFN model for the heating cycle is required to fully evaluate the system.

5.3.1 Future Work

The results presented here are encouraging but far from the complete picture on damper efficacy. The building model will be updated with an improved duct system that is better representative of what would be available for the building type. A properly balanced duct system for the building model will reduce the possibility of failing to converge which was a constant issue throughout trying to test system performance with an airflow network. Additionally, all simulations were run without internal loads such as lights, appliances and occupants. The addition of these thermal loads to the model should decrease the heating load required during the heating cycle but increase the cooling load required during the cooling cycle. This would further

show the large potential of energy savings during the heating cycle.

Further focus will be put into investigating replacing the constant air volume fan with a variable speed fan which can dynamically alter its speed to offset increasing pressure due to closing dampers. The addition of a VAV fan is expected to increase the energy consumption from the fan, but the increased consumption may be offset by avoiding reduction of airflow at a higher system pressure. The model will also have duct leakage added. Duct leakage increases as duct system pressure increases but Walker showed that the fan is less susceptible to lowered system performance with duct leakage added. The loss of capacity to leaks into unconditioned areas will be taken into account in the model. Lastly, following Brown and Watt's research into an optimized control algorithm is imperative for a damper system to operate properly, especially in a system which uses a CAV fan. Dynamically changing damper positions based on local thermal loads while still maintaining an internal system pressure would be highly desirable.

This research will be done using EnergyPlus but it should also be verified with experimental results. The results from previous studies will also be investigated in EnergyPlus if building envelope details can be obtained. Coupling EnergyPlus' thermal modeling with the controls capabilities of MatLab or Dymola via co-simulation would be an efficient path to investigating optimal control schemes for such damper systems. A desktop model will be designed and built to provide some insight into the relationship between fan operation and damper positions. The small model will then be upscaled to a similar size of Walker's research but with the addition of different thermal zones with unbalanced heating loads. Unbalancing heating requirements will begin to show the possibility for some optimal way for a damper system to be controlled and will provide experimental results for a real building.

THIS PAGE INTENTIONALLY LEFT BLANK

Appendix A

Section 4.2 Tables & Graphs

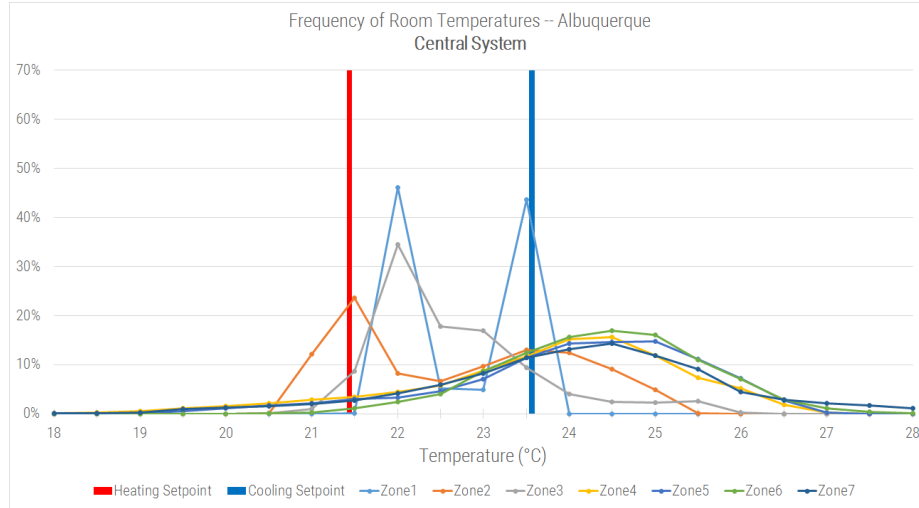


Figure A.1: Frequency of Room Temps: Albuquerque No Dampers

Zone	No Damper		Damper	
	Mean	STDEV	Mean	STDEV
Zone 1	22.48	0.78	22.52	0.73
Zone 2	22.46	1.26	22.56	0.94
Zone 3	22.41	0.94	22.61	0.89
Zone 4	23.48	1.58	22.75	1.16
Zone 5	23.81	1.48	22.90	1.06
Zone 6	24.13	1.15	23.14	0.98
Zone 7	23.82	1.69	23.07	1.20
Building	23.23	1.48	22.79	1.03

Table A.1: Temperature (°C) statistics for Albuquerque base case and dampers model

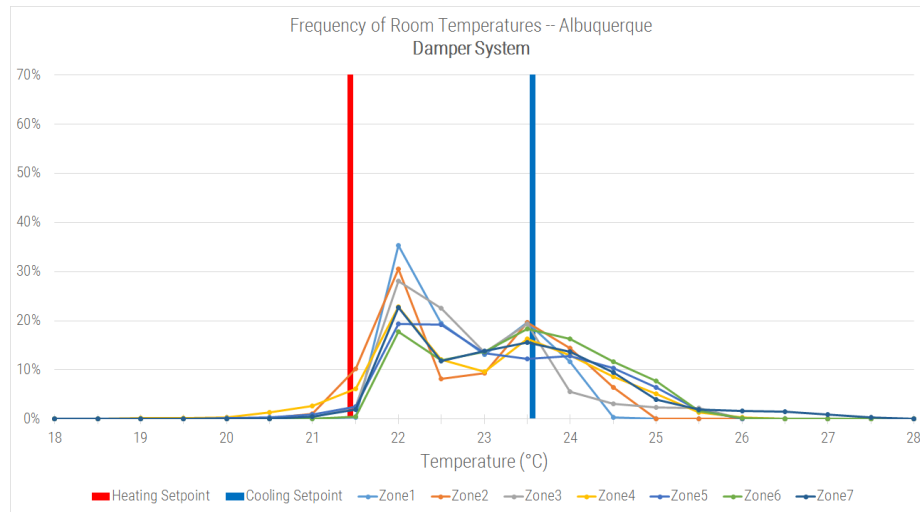


Figure A.2: Frequency of Room Temperatures: Albuquerque Dampers

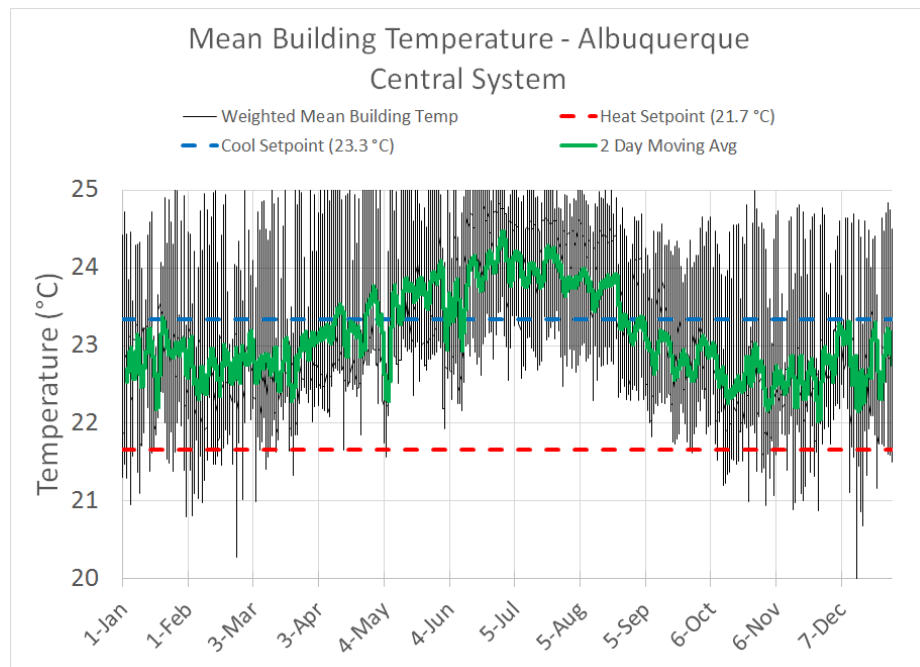


Figure A.3: Mean building temperature: Albuquerque No Dampers

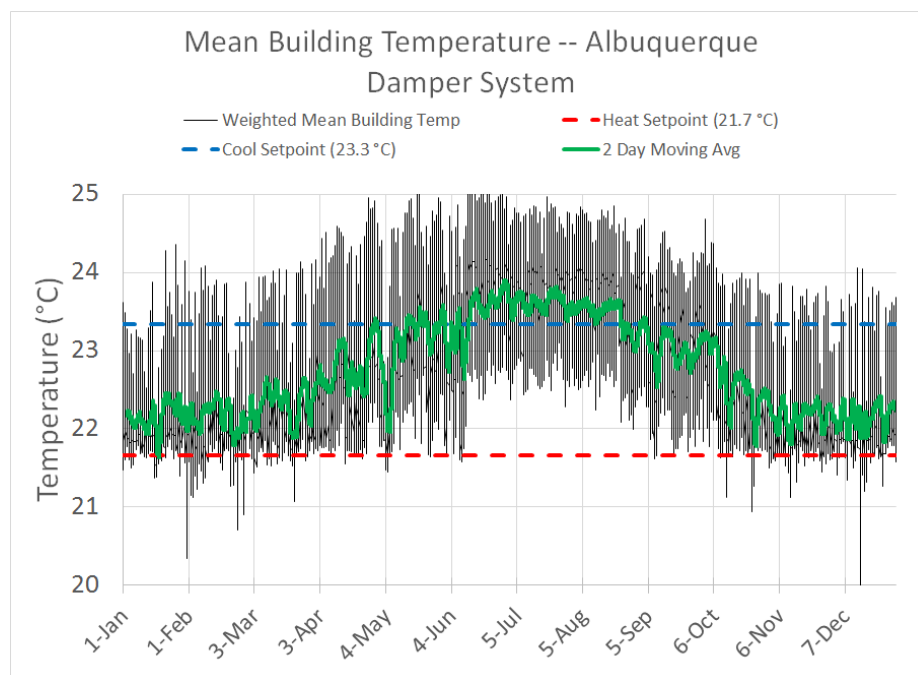


Figure A.4: Mean building temperature: Albuquerque Dampers

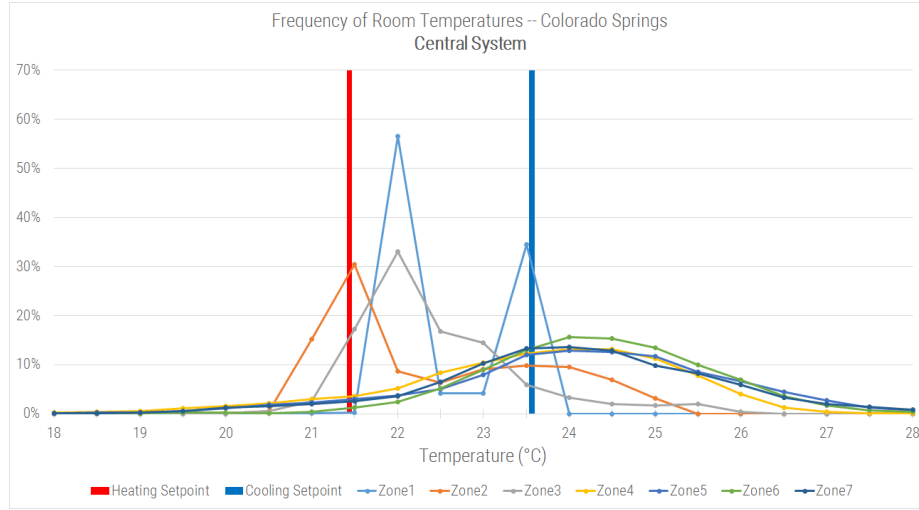


Figure A.5: Frequency of Room Temps: Colorado Springs No Dampers

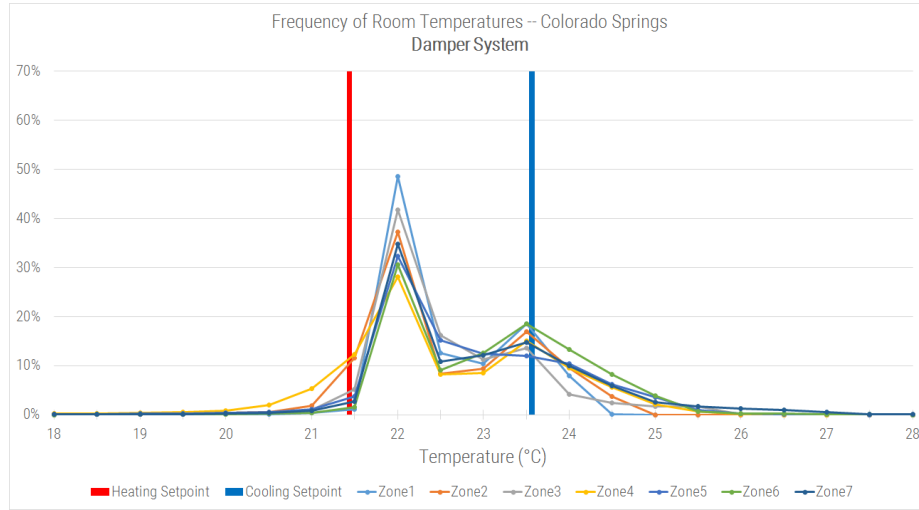


Figure A.6: Frequency of Room Temperatures: Colorado Springs Dampers

Zone	No Damper		Damper	
	Mean	STDEV	Mean	STDEV
Zone 1	22.31	0.77	22.34	0.75
Zone 2	22.16	1.23	22.31	0.95
Zone 3	22.20	0.95	22.36	0.90
Zone 4	23.33	1.63	22.31	1.23
Zone 5	23.87	1.72	22.58	1.09
Zone 6	24.08	1.33	22.81	1.02
Zone 7	23.78	1.63	22.72	1.17
Building	23.10	1.58	22.49	1.05

Table A.2: Temperature (°C) statistics for Colorado Springs base case and dampers model

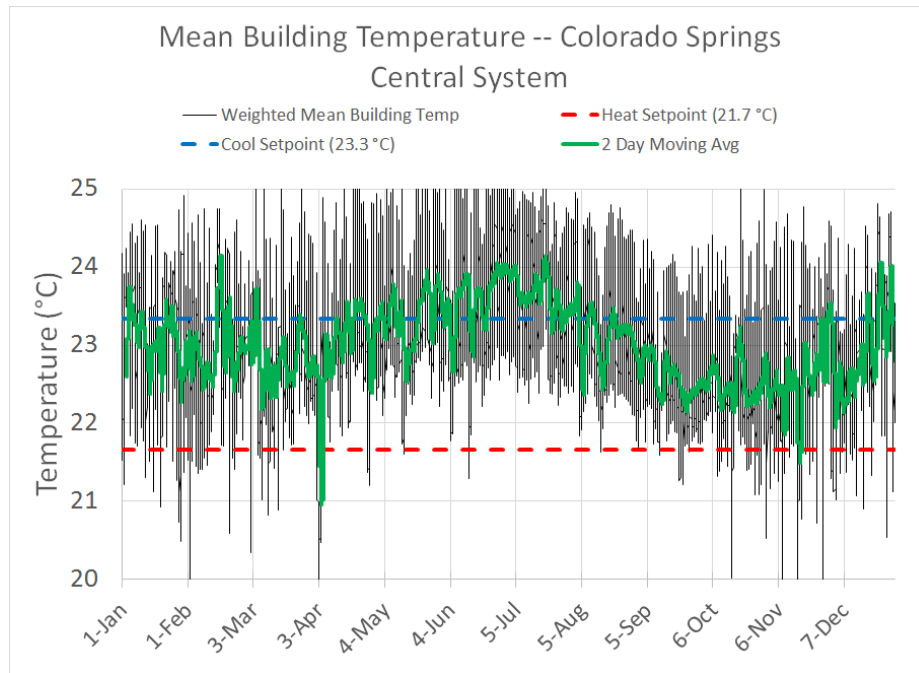


Figure A.7: Mean building temperature: Colorado Springs No Dampers

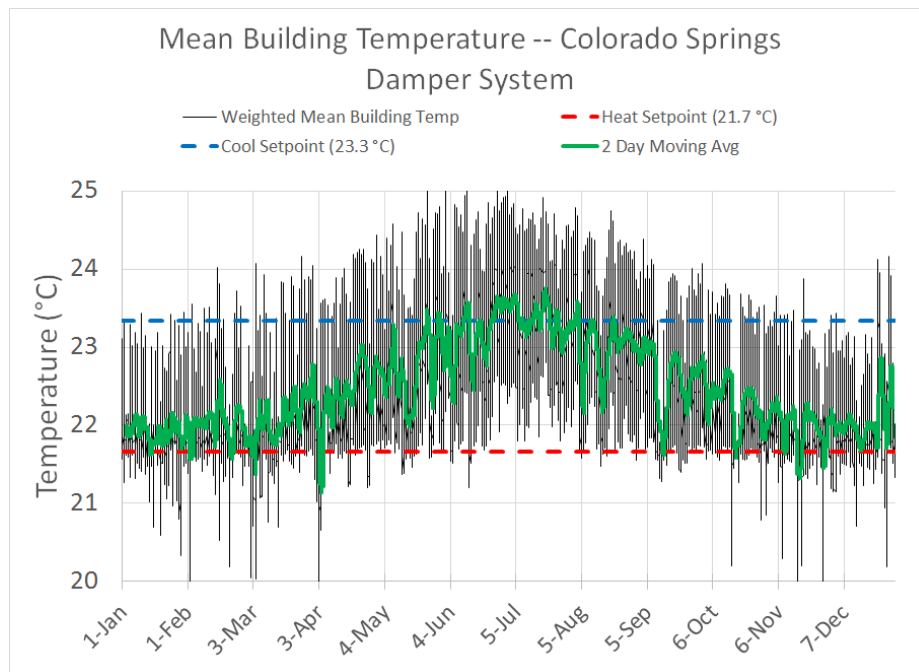


Figure A.8: Mean building temperature: Colorado Springs Dampers

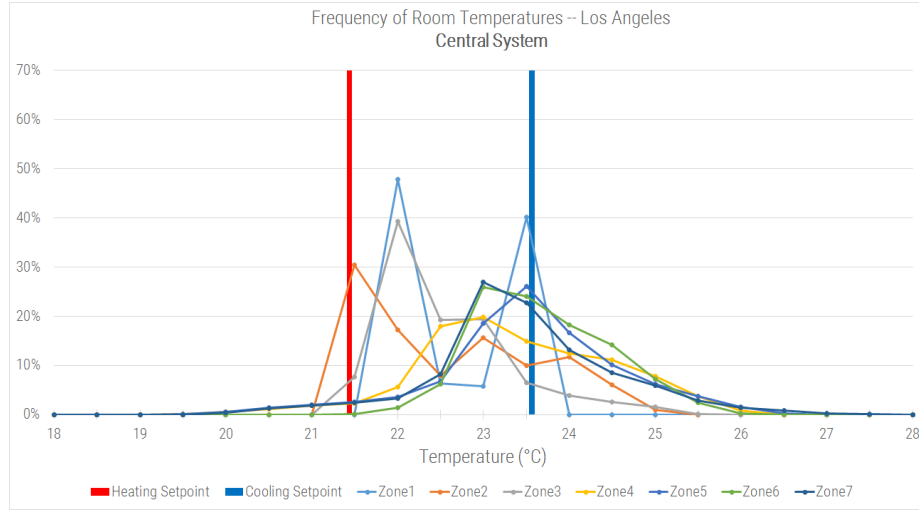


Figure A.9: Frequency of Room Temps: Los Angeles No Dampers

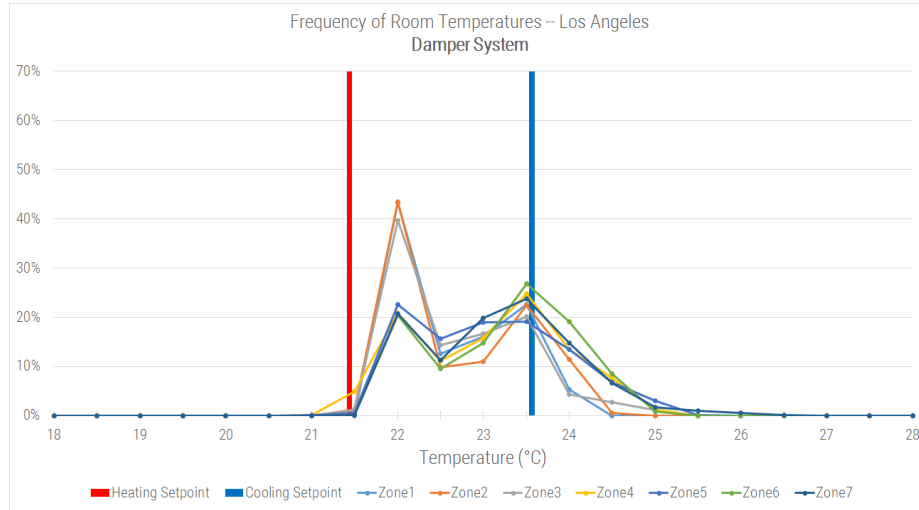


Figure A.10: Frequency of Room Temperatures: Los Angeles Dampers

Zone	No Damper		Damper	
	Mean	STDEV	Mean	STDEV
Zone 1	22.44	0.77	22.42	0.69
Zone 2	22.37	0.99	22.48	0.77
Zone 3	22.29	0.76	22.47	0.75
Zone 4	23.13	1.10	22.81	0.86
Zone 5	23.27	1.07	22.83	0.83
Zone 6	23.43	0.76	22.97	0.80
Zone 7	23.21	1.07	22.92	0.84
Building	22.95	1.07	22.75	0.83

Table A.3: Temperature ($^{\circ}\text{C}$) statistics for Los Angeles base case and dampers model

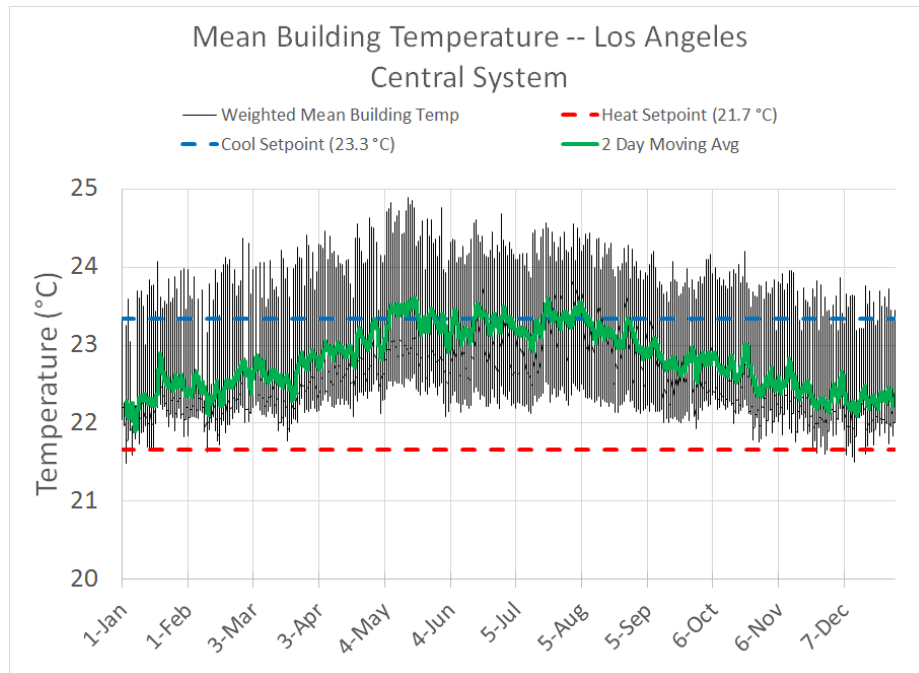


Figure A.11: Mean building temperature: Los Angeles No Dampers

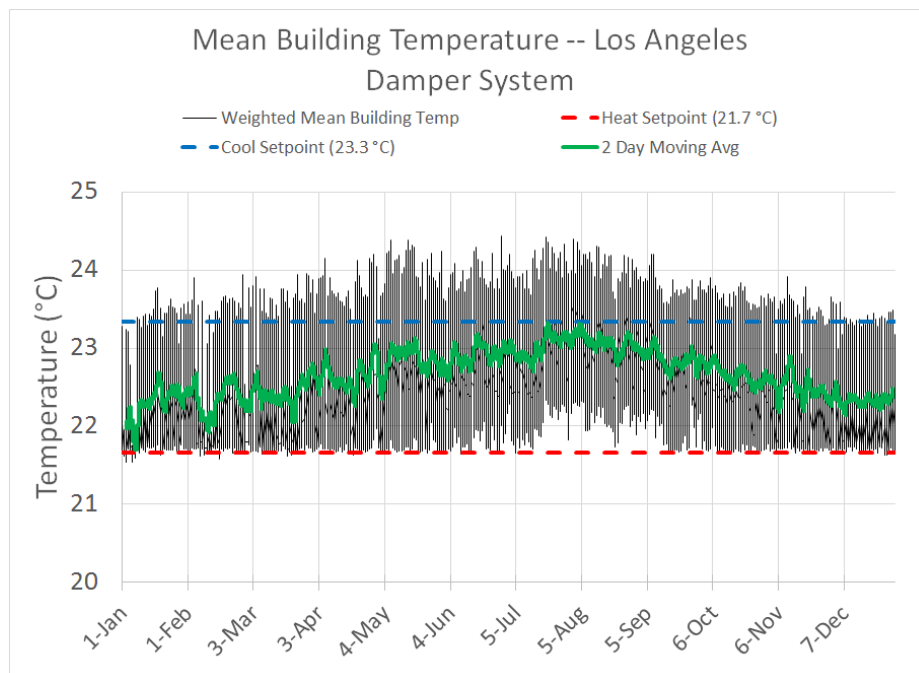


Figure A.12: Mean building temperature: Los Angeles Dampers

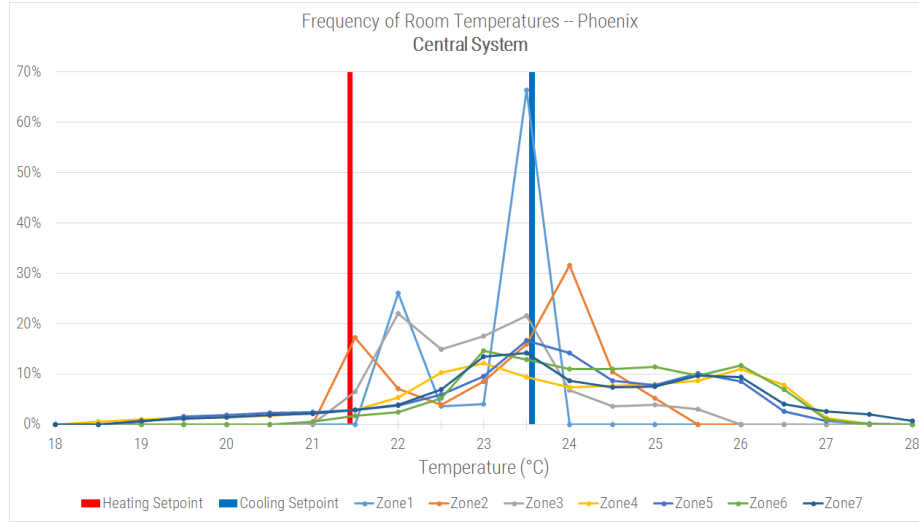


Figure A.13: Frequency of Room Temps: Phoenix No Dampers

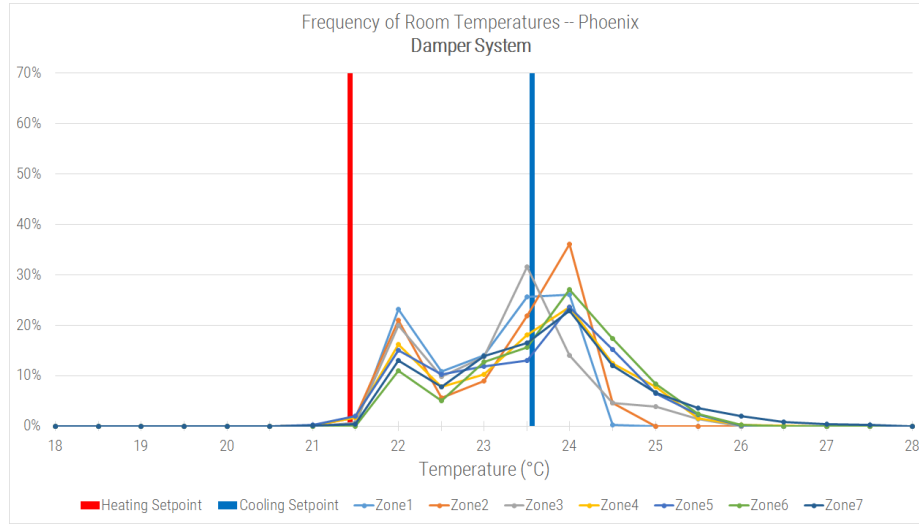


Figure A.14: Frequency of Room Temperatures: Phoenix Dampers

Zone	No Damper		Damper	
	Mean	STDEV	Mean	STDEV
Zone 1	22.84	0.72	22.85	0.75
Zone 2	23.05	1.07	23.01	0.82
Zone 3	22.75	0.97	22.97	0.85
Zone 4	23.62	1.85	23.25	0.98
Zone 5	23.54	1.64	23.24	1.00
Zone 6	24.11	1.32	23.47	0.90
Zone 7	23.76	1.79	23.41	1.05
Building	23.47	1.55	23.23	0.96

Table A.4: Temperature (°C) statistics for Phoenix base case and dampers model

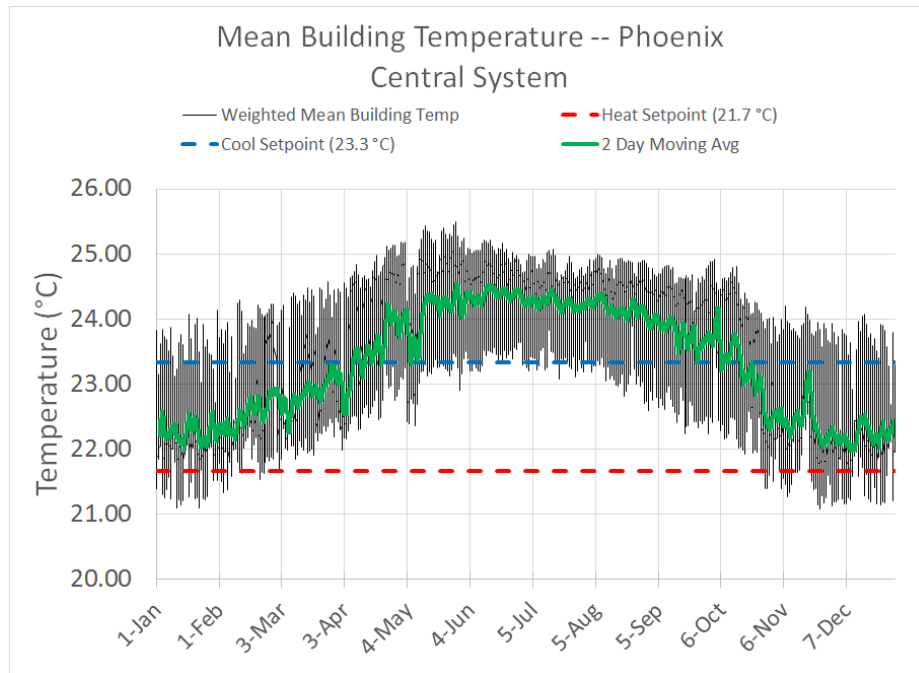


Figure A.15: Mean building temperature: Phoenix No Dampers

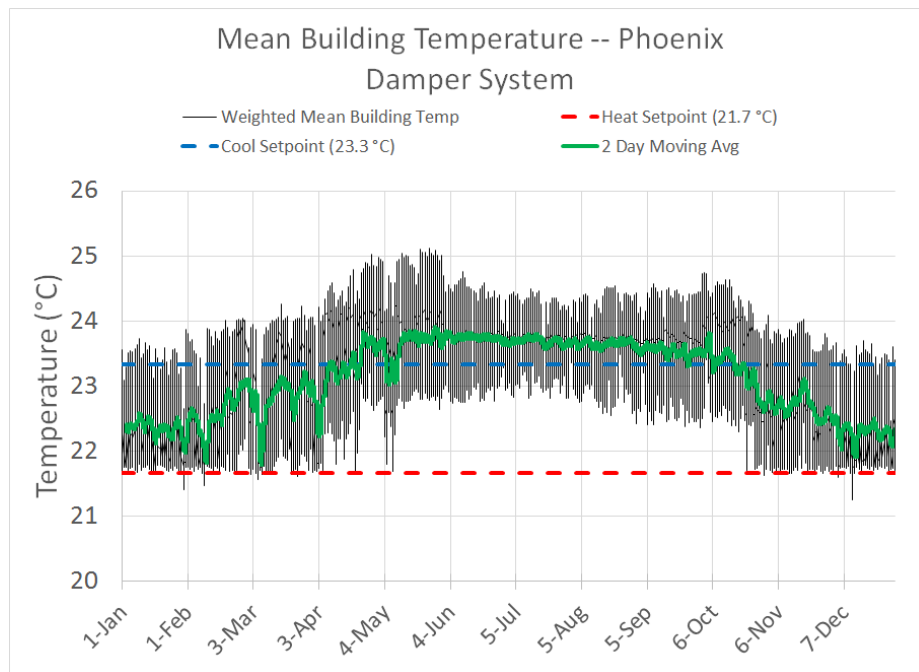


Figure A.16: Mean building temperature: Phoenix Dampers

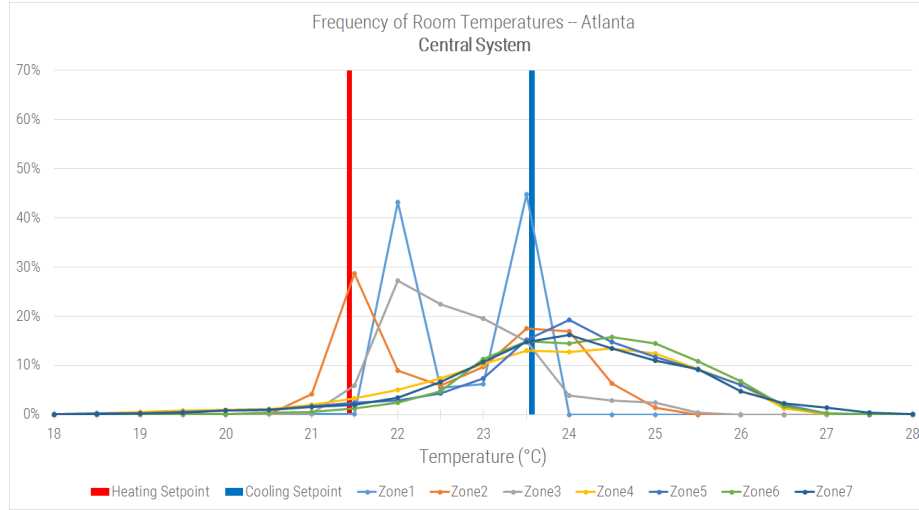


Figure A.17: Frequency of Room Temps: Atlanta No Dampers

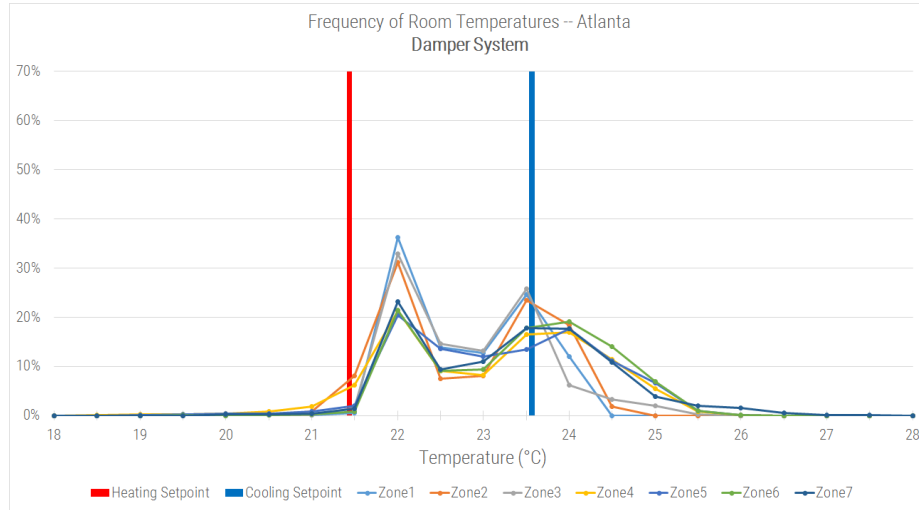


Figure A.18: Frequency of Room Temperatures: Atlanta Dampers

Zone	No Damper		Damper	
	Mean	STDEV	Mean	STDEV
Zone 1	22.51	0.78	22.55	0.74
Zone 2	22.49	1.13	22.57	0.91
Zone 3	22.48	0.80	22.62	0.81
Zone 4	23.55	1.51	22.86	1.16
Zone 5	23.75	1.38	22.97	1.07
Zone 6	23.95	1.16	23.12	1.00
Zone 7	23.73	1.39	23.06	1.08
Building	23.21	1.35	22.82	1.00

Table A.5: Temperature (°C) statistics for Atlanta base case and dampers model

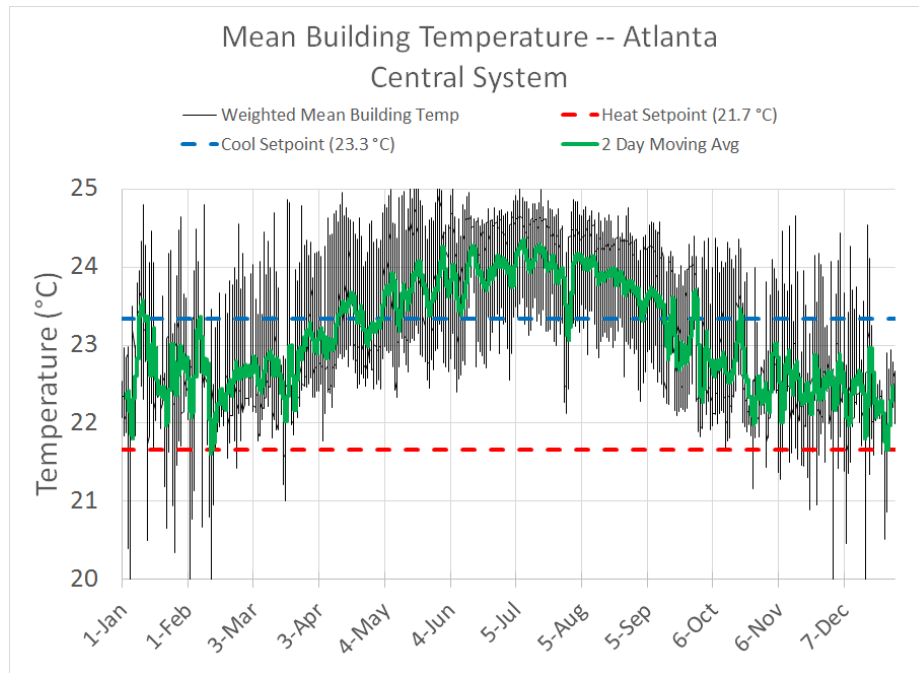


Figure A.19: Mean building temperature: Atlanta No Dampers

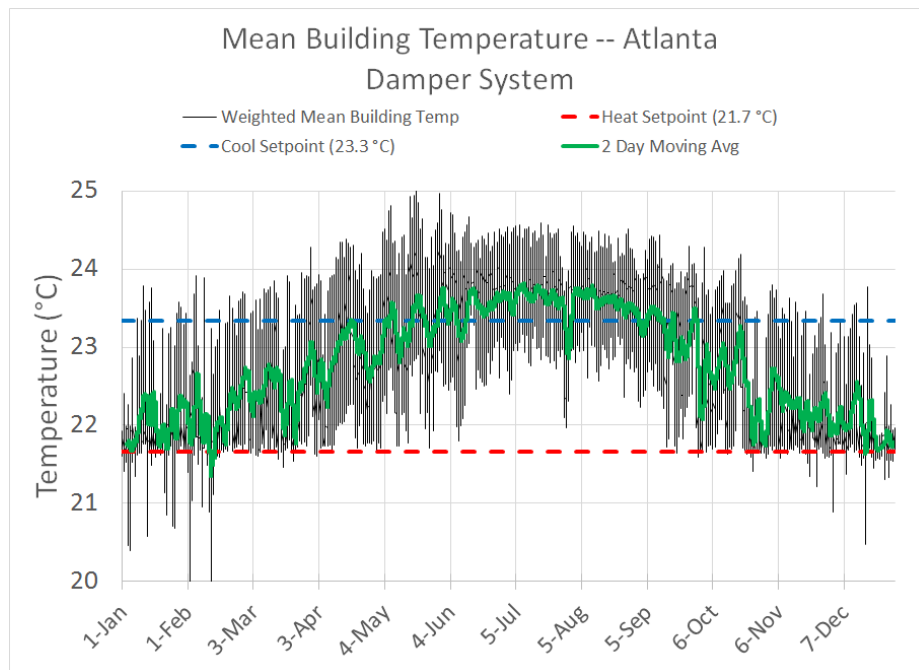


Figure A.20: Mean building temperature: Atlanta Dampers

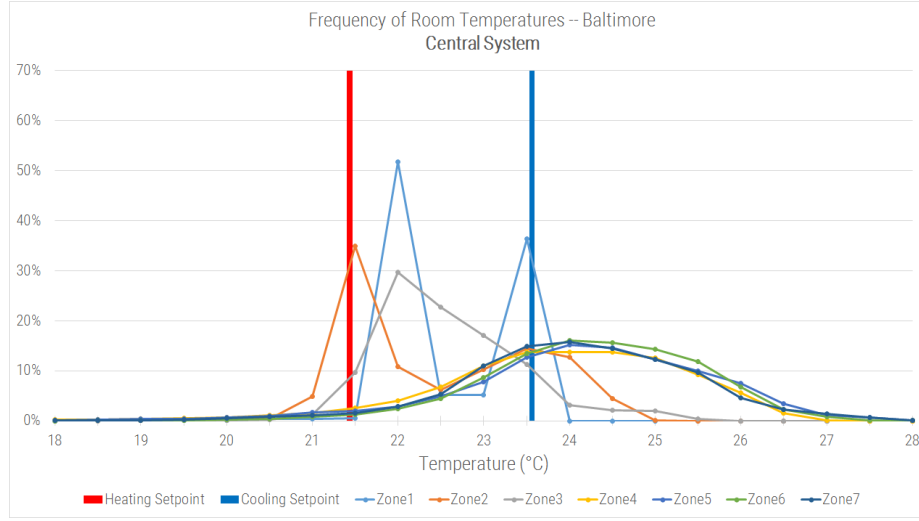


Figure A.21: Frequency of Room Temps: Baltimore No Dampers

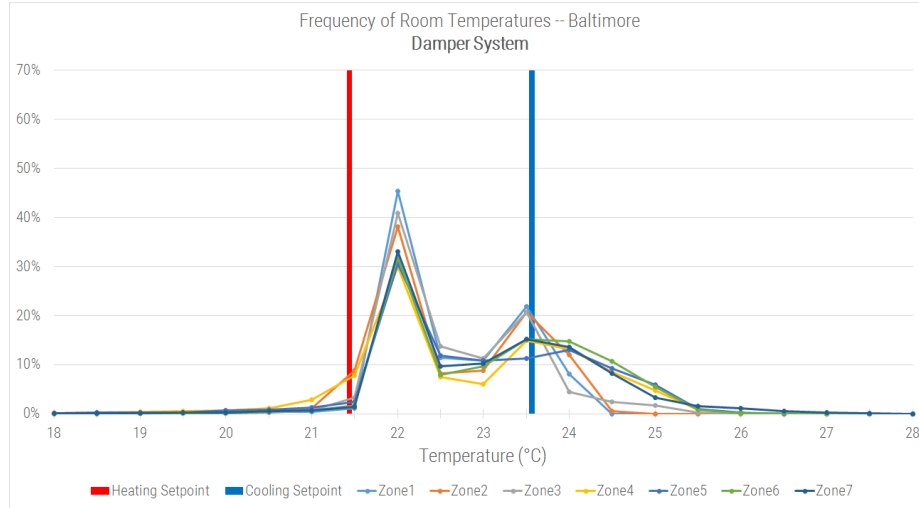


Figure A.22: Frequency of Room Temperatures: Baltimore Dampers

Zone	No Damper		Damper	
	Mean	STDEV	Mean	STDEV
Zone 1	22.34	0.80	22.38	0.79
Zone 2	22.22	1.11	22.35	0.93
Zone 3	22.33	0.82	22.43	0.84
Zone 4	23.60	1.50	22.57	1.28
Zone 5	23.89	1.52	22.71	1.19
Zone 6	24.01	1.24	22.85	1.08
Zone 7	23.83	1.36	22.80	1.15
Building	23.17	1.45	22.59	1.07

Table A.6: Temperature (°C) statistics for Baltimore base case and dampers model

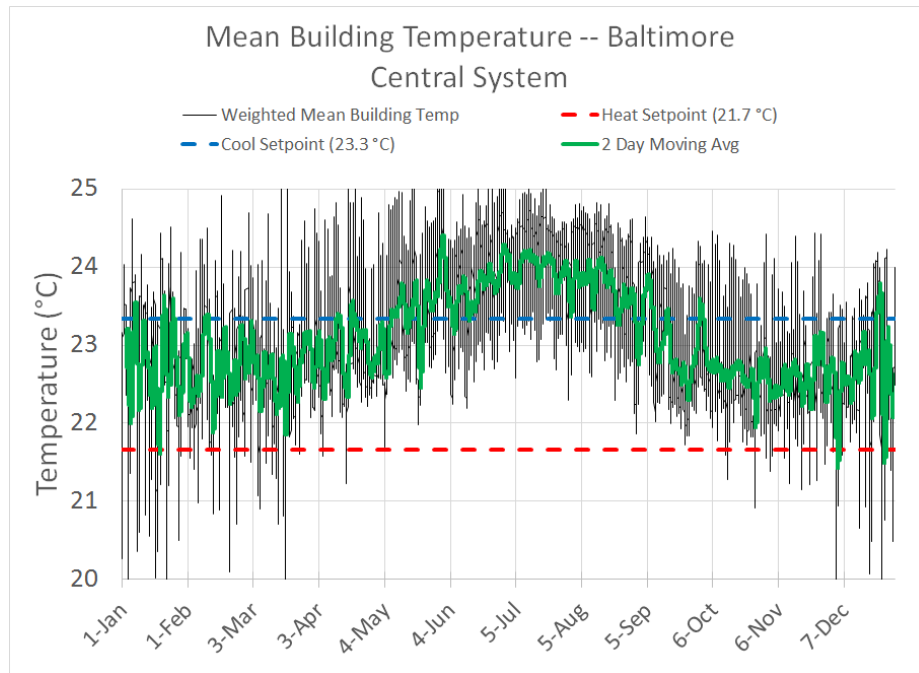


Figure A.23: Mean building temperature: Baltimore No Dampers

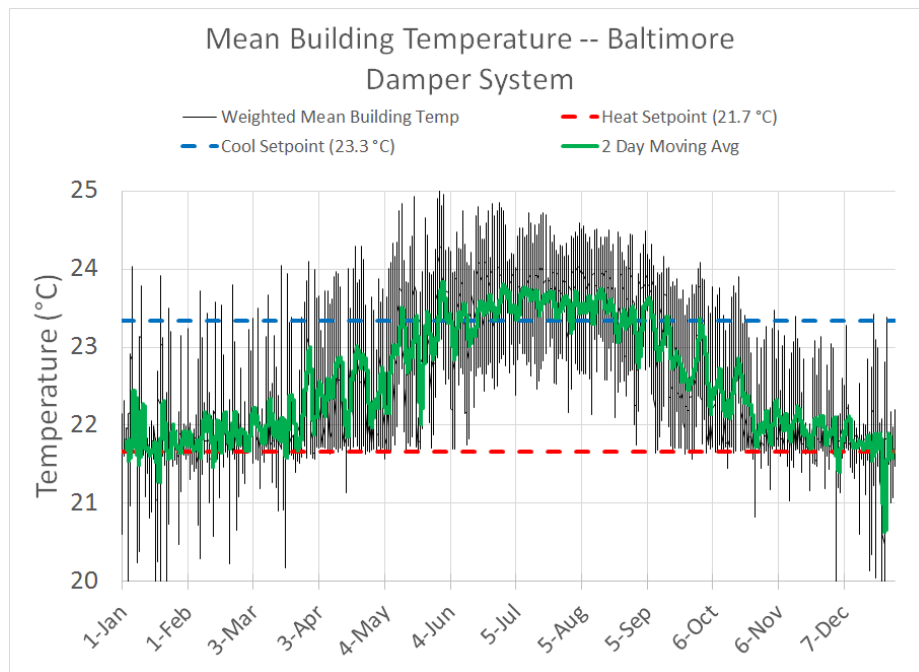


Figure A.24: Mean building temperature: Baltimore Dampers

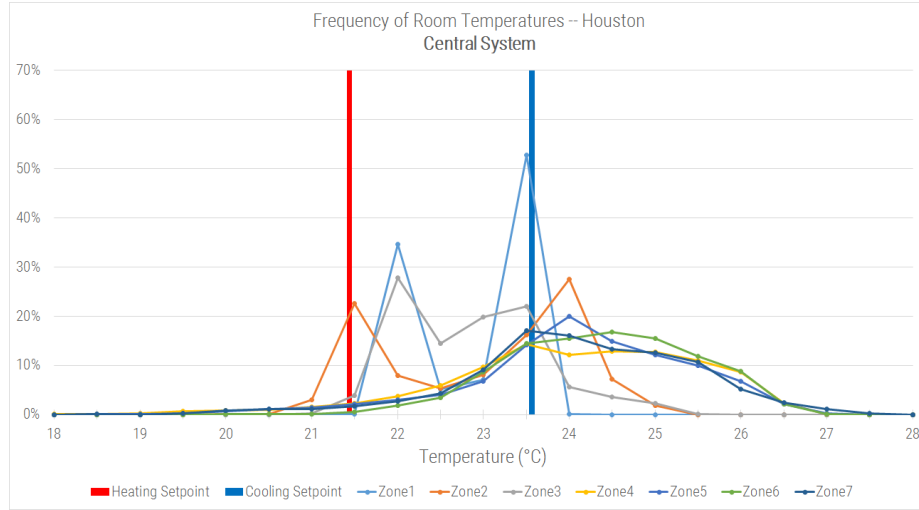


Figure A.25: Frequency of Room Temps: Houston No Dampers

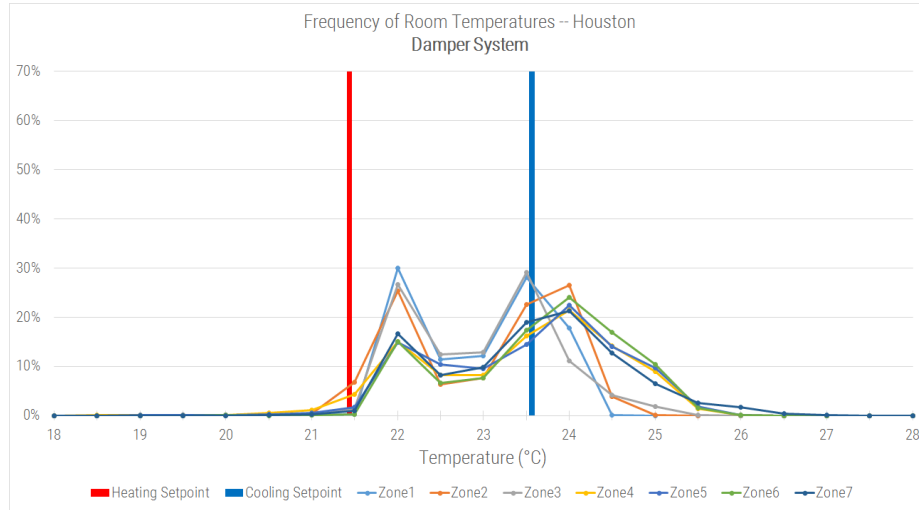


Figure A.26: Frequency of Room Temperatures: Houston Dampers

Zone	No Damper		Damper	
	Mean	STDEV	Mean	STDEV
Zone 1	22.65	0.76	22.69	0.76
Zone 2	22.74	1.12	22.77	0.93
Zone 3	22.62	0.81	22.76	0.82
Zone 4	23.78	1.44	23.18	1.10
Zone 5	23.85	1.30	22.25	1.04
Zone 6	24.13	1.06	23.40	0.96
Zone 7	23.85	1.32	23.28	1.04
Building	23.37	1.30	23.05	0.99

Table A.7: Temperature (°C) statistics for Houston base case and dampers model

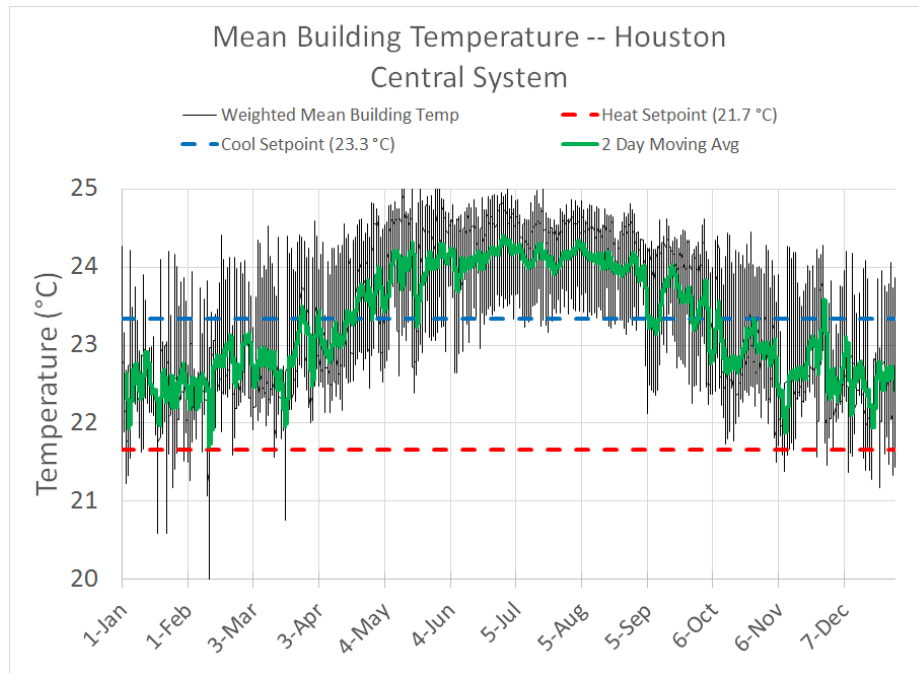


Figure A.27: Mean building temperature: Houston No Dampers

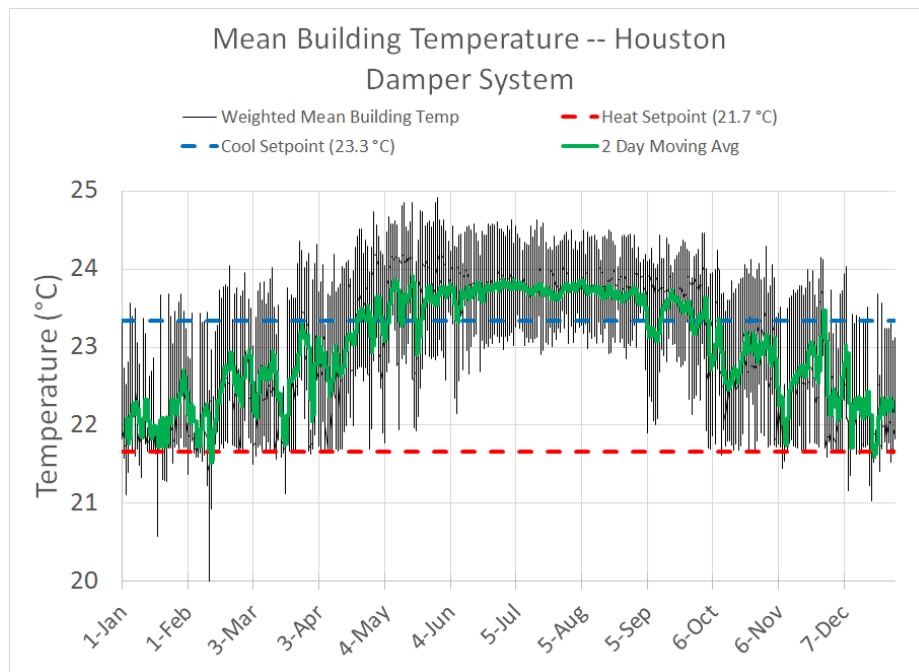


Figure A.28: Mean building temperature: Houston Dampers

THIS PAGE INTENTIONALLY LEFT BLANK

Bibliography

- [1] DOE EIA. Residential energy consumption survey (recs). 2009.
- [2] Rachel Cluett and Jennifer Amann. Residential deep energy retrofits. 2014.
- [3] John Proctor. Zoning ducted air conditioners, heat pumps and furnaces: Summary of a case study prepared for the california statewide utility codes and standards program.
- [4] Poul O Fanger et al. Thermal comfort. analysis and applications in environmental engineering. *Thermal comfort. Analysis and applications in environmental engineering.*, 1970.
- [5] Buildings Energy Data Book. Energy efficiency and renewable energy. *US Department of Energy*, 2011.
- [6] ASHRAE. *ASHRAE Handbook: Fundamentals*. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc.
- [7] ASHRAE. *ASHRAE Handbook: Applications*. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc.
- [8] Hart & Cooley Inc. *Residential Grilles, Registers & Diffusers*. Hart & Cooley Inc., Grand Rapids, MI, 5th edition.
- [9] Kohta Ueno and John Straube. Understanding primary/source and site energy. *BSC: BSD-151*, 2010.
- [10] John E Traister. *Residential heating, ventilating, and air conditioning: design and application*. Prentice Hall, 1990.
- [11] Carrier. *Owner’s Manual for Carrier Infinity Gas Furnace*. Carrier, Farmington, CT.
- [12] ACCA. *Manual J*, 1995.
- [13] Alan Meier, Cecilia Aragon, Therese Pepper, Daniel Perry, and Marco Pritoni. Usability of residential thermostats: Preliminary investigations. *Building and Environment*, 46(10):1891 – 1898, 2011.

- [14] Annual Energy Outlook 2015. Energy information administration. *Department of Energy*, 2014.
- [15] California Building Standards Commission and International Conference of Building Officials. California building standards code. International Conference of Building Officials, 2013.
- [16] Vahid Vakiloroaya, Bijan Samali, Ahmad Fakhar, and Kambiz Pishghadam. A review of different strategies for hvac energy saving. *Energy Conversion and Management*, 77:738–754, 2014.
- [17] Robert J Meyers, Eric D Williams, and H Scott Matthews. Scoping the potential of monitoring and control technologies to reduce energy use in homes. *Energy and Buildings*, 42(5):563–569, 2010.
- [18] Kristen Sara Cetin. *Smart technology enabled residential building energy use and peak load reduction and their effects on occupant thermal comfort*. PhD thesis, University of Texas, 2015.
- [19] Iain S Walker, Jennifer A McWilliams, and Steven J Konopacki. Case study field evaluation of a systems approach to retrofitting a residential hvac system. *Lawrence Berkeley National Laboratory*, 2003.
- [20] NP Leslie and KC Kazmer. Performance of a residential zoned heating system in an unoccupied research house. *ASHRAE transactions*, 95:903–909, 1989.
- [21] T.M. Kenney and C.E. Barbour. Field investigation of carrier residential zoning system.
- [22] Paul Oppenheim. Energy-saving potential of a zoned forced-air heating system. In *ASHRAE Winter Meeting, Anaheim, CA, USA, 01/25-29/92*, pages 1247–1257, 1992.
- [23] Keith A Temple. Field performance of a zoned forced-air cooling system in an energy-efficient home. *ASHRAE transactions*, 111(2), 2005.
- [24] C Heflin and FJ Keller. Steady-state analysis of single-speed residential split systems with zoning bypass. *ASHRAE Transactions-American Society of Heating Refrigerating Airconditioning Engin*, 99(2):40–51, 1993.
- [25] DH Saunders, TM Kenny, and WW Bassett. Factors influencing thermal stratification and thermal comfort in four heated residential buildings. *ASHRAE Transactions*, 98(1):1258–1265, 1992.
- [26] Iain S Walker. Register closing effects on forced air heating system performance. *Lawrence Berkeley National Laboratory*, 2003.
- [27] CA. Brown. Multizone register controlled residential heating: Optimized for energy use and comfort. Master’s thesis, University of California, Berkeley, 2007.

- [28] William Watts, Mike Koplow, Andrew Redfern, and Paul Wright. Application of multizone hvac control using wireless sensor networks and actuating vent registers. 2007.
- [29] ANSI Ashrae. Standard 55-2004, thermal environmental conditions for human occupancy. *American Society of Heating, Refrigerating and Air-Conditioning Engineering, Atlanta, GA*, 2004.
- [30] A Cengel Yunus et al. Heat transfer: a practical approach. *MacGraw Hill, New York*, 2003.
- [31] International Building Performance Simulation Association. Best energy software tools, 2016.
- [32] Drury B Crawley, Linda K Lawrie, Frederick C Winkelmann, Walter F Buhl, Y Joe Huang, Curtis O Pedersen, Richard K Strand, Richard J Liesen, Daniel E Fisher, Michael J Witte, et al. Energyplus: creating a new-generation building energy simulation program. *Energy and buildings*, 33(4):319–331, 2001.
- [33] US DOE. Energyplus engineering reference. *The Reference to EnergyPlus Calculations*, 2010.
- [34] Standard ASHRAE. Standard 90.1-2007 normative appendix b: Building envelope climate criteria. *Energy Standard for Buildings Except Low-Rise Residential Buildings*, 2007.
- [35] Horowitz Wilson, Metzger and Hendon. *2014 Building America house simulation protocols*. National Renewable Energy Laboratory Golden, CO, 2014.
- [36] Joshua Kneifel. *Prototype Residential Building Designs for Energy and Sustainability Assessment*.
- [37] Hugo Hens. *Building Physics: Heat, Air and Moisture*. Wilhelm Ernst & Sohn, Rotherstr 21, 10245 Berlin, Germany, 2 edition, 3 2012.
- [38] D Cutler, J Winkler, N Kruis, C Christensen, and M Brandemuehl. Improved modeling of residential air conditioners and heat pumps for energy calculations. 303:275–3000, 2013.
- [39] US DOE. Getting started with energyplus. 2009.
- [40] Stephen Wilcox. National solar radiation database 1991-2005 update: User’s manual. Technical report, National Renewable Energy Laboratory (NREL), Golden, CO., 2007.
- [41] Luebs DF Yingling, RK and RJ Johnson. *Residential Duct Systems - Selection and Design of Ducted HVAC Systems*. National Association of Home Builders of the U.S., 1981.

- [42] Yaw Asiedu, Robert W Besant, and Peihua Gu. A simplified procedure for hvac duct sizing. Technical report, Univ. of Saskatchewan (CA), 2000.
- [43] DM Lorenzetti and CP Wray. Air-handling system modeling in energyplus: Recommendations for meeting stakeholder needs. 2014.