Smart HVAC Zoning

For Residential Buildings

by

Amr M. Fairag

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Graduate Supervisory Committee:

Patrick Phelan, Chair
Luis Bocanegra
Abdelrahman Shuaib

ARIZONA STATE UNIVERSITY

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ABSTRACT

The concept of this thesis came up as a part of the efforts being devoted around the world to reduce energy consumption, CO_2 emissions, global warming and ozone layer depletion. In the United States, HVAC units in residential buildings consumed about 350 billion kWh in 2017 [1],[2]. Although HVAC manufacturers are investing in new technologies and more efficient products to reduce energy consumption, there is still room for further improvement.

One way of reducing cooling and heating energy in residential buildings is by allowing the centralized HVAC unit to supply conditioned air to only occupied portions of the house by applying smart HVAC zoning. According to the United States Energy Information Administration [3], the percentage of houses equipped with centralized HVAC units is over 70%, which makes this thesis applicable to the majority of houses in the United States. This thesis proposes to implement HVAC zoning in a smart way to eliminate all human errors, such as leaving the AC unit on all day, which turns out to be causing a serious amount of energy to be wasted.

The total amount of energy that could be saved by implementing the concepts presented in this thesis in all single-family houses in the U.S. is estimated to be about 156 billion kWh annually. This amount of energy reduction is proportional to the electricity bills and the amount of dollars paid annually on energy that is technically being wasted.

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NOMENCLATURE

HVAC	Heating, ventilation and air conditioning
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
RECS	Residential Energy Consumption Survey
$HVAC_{Capacity}$	Total capacity of the HVAC unit [RT]
A_{house}	Total area of the selected house [m^2]
$\dot{Q}_{required}$	Heat to be removed from the house over an hour [kWh]
$T_{ambient}$	Ambient temperature [^{0} C]
T_{gained}	Gained temperature by the house over an hour [^{0} C/hr]
$t_{cooling}$	Total time required to cool down the house within an hour [min]
$\dot{Q}_{max}$	Maximum heat can be removed over an hour based on $HVAC_{Capacity}$ [kWh]
$\dot{m}$	Mass flow rate of the air supplied by the HVAC unit [kg s^{-1}]
C_p	Specific heat of air [kJ kg^{-1} K^{-1}]
COP	Coefficient of performance (assumed = 2.5)
E_{input}	Energy input required to remove $\dot{Q}_{required}$ [kWh]
C_E	Cost of energy during off-peak hours [$/month]
$C_{E, peak}$	Cost of energy during on-peak hours [$/month]
C_D	Cost of demand [$/month]
$E_{off-peak}$	Total energy consumed off-peak hours [kWh/month]
$E_{on-peak}$	Total energy consumed on-peak hours [kWh/month]
$EC_{off-peak}$	Energy charge during off-peak hours [$/kWh]
$EC_{on-peak}$	Energy charge during on-peak hours [$/kWh]

E_{max} Energy required to remove $HVAC_{Capacity}$ [kW]

Demand Maximum electricity demand value occurred within a month [kW/month]

t_{max} Maximum $t_{cooling}$ occurring within a month [min]

DC Demand charge [$/kW]

1. INTRODUCTION

A well-known fact is that the world as a whole is moving toward saving energy and reducing emissions in many different perspectives, starting with reducing energy consumption in lighting (by switching to LED's) and ending up with manufacturing electric vehicles and investing billions of dollars by carmakers in this field [4]. Residential buildings are no exception, as they have a huge opportunity to reduce energy consumption significantly. In the United States alone, residential buildings consumed 1.4 trillion kWh in 2017. According to the U.S. Energy Information Administration (EIA), cooling and heating energy represents 25% of the total energy consumed by the residential sector. In other words, cooling and heating energy represented 350 billion kWh nationwide in 2017 [1],[2].

1.1. Objectives

This thesis addresses the possibility of reducing cooling and heating energy consumption by eliminating waste energy that is consumed in cooling/heating non-occupied zones of a house. By implementing smart HVAC zoning, this thesis estimates that residential buildings can save up to 80% of current energy consumption as shown in Chapters 3 through 5.

1.2. Literature Review

In the HVAC market, manufacturers are devoting millions of dollars to enhance cooling/heating efficiency, and as a result reducing energy consumption. Apparently, not all homeowners are ready to replace their old (or existing) equipment with new ones to save energy. Therefore, homeowners tend to move toward less expensive technologies to save energy, such as smart thermostats.

Smart thermostats are helping a lot in saving cooling / heating energy; homeowners reported an average savings of up to 23% [5]. Many smart thermostats are made to consider occupancy within the house through utilization of occupancy detectors. Some smart thermostats can be integrated with up to 32 motion detectors (Figure 1.1). Accordingly, it can decide, intelligently, what temperature should be maintained for the most comfort. In other words, if occupancy is only in the living area, the thermostat will ignore all temperature readings in other areas to avoid overcooling/overheating the occupied zone (in this case, the living area). Although smart thermostats are saving a significant amount of energy, there is still some amount of energy being wasted due to supplying cold/hot air to non-occupied zones.

Figure 1.1: Example of one of the smart thermostats with its motion detector [5]

HVAC zoning, on the other hand, has a different philosophy in saving energy. A zoned duct system contains some number of dampers, depending on the house size, duct design and number of zones. Those dampers are connected to a control panel that is also connected to several thermostats. Each thermostat measures the temperature in its own zone, then a signal is sent to the control panel. The control panel starts evaluating the demand and estimates how much cooling/heating is required and in which zone. Based on that, closing/opening signals are sent to each damper to eliminate zones that require no conditioning (Figure 1.2).

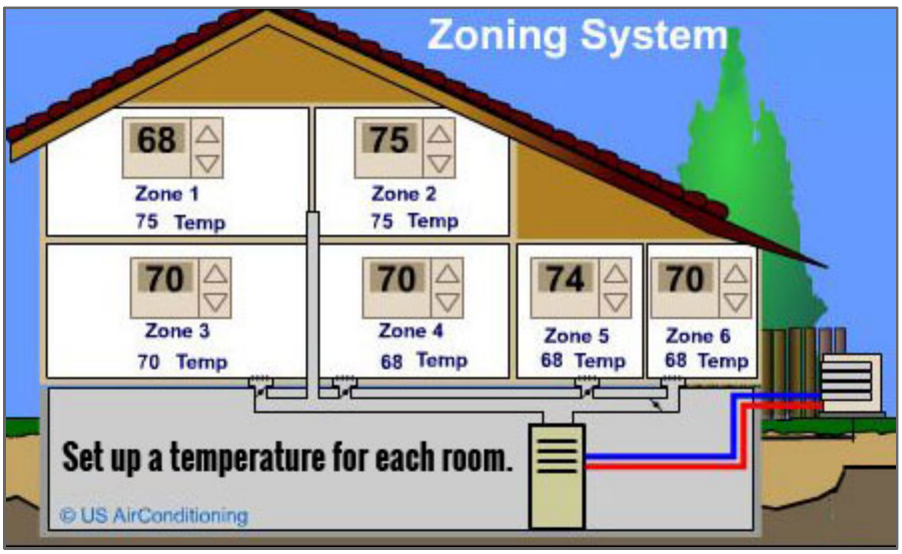

Figure 1.2: Main elements of a zoned HVAC system [7]

HVAC zoning is not a new invention—it has been in the market for about 50 years. However, average energy savings were reported to be in the range of 20% - 30% [6], which is very similar to the savings results reported by smart thermostat users [5]. This thesis evaluates the level of success that could be achieved when both technologies are integrated together, smart thermostats *and* HVAC zoning.

1.3. Value Added to Previous Studies

There are relatively few published studies on HVAC zoning in residential buildings. The latest study was published by Sookoor and Whitehouse in 2013 [8], where zoning was approached through manipulating with ordinary thermostats to allow communication between thermostats and duct dampers. This study showed about 15% energy savings. By implementing the approach proposed in this thesis (see Ch. 3 & 4), the percentage of energy savings is found to exceed 70%, which is higher than Sookoor's study and the results reported by homeowners (see Ch. 1.1) [5],[6].

In addition, ZoneFirst[1] and Sookoor have both reported that there are some pressure issues with duct systems due to very low airflow requirements [6],[8]. ZoneFirst suggested to implement some bypass ducts [6]. Although bypassing may solve the issue, there will be some amount of conditioned air being supplied to non-occupied zones, and hence energy being wasted. This thesis, on the other hand, addresses some other solutions that can eliminate the issue of having back pressure and damaging the equipment (more details in Ch. 3).

1.4. How Zoning Works

As mentioned in Ch 1.1, HVAC zoned systems require some major equipment to allow the HVAC unit to supply air to specific zones. This equipment includes the control panel, duct dampers and multiple thermostats in different zones. By having a different thermostat in each zone, temperature settings can be different from zone to zone. In the bedrooms' zone, for example, temperature requirements are usually lower

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[1] ZoneFirst is one of the first companies to develop HVAC Zoning

than the temperature settings in the living area or the kitchen [3]. Assume the living area zone is set to 25º C and the bedrooms are set to 23º C, in this case, the HVAC unit will be supplying conditioned air to both zones (assuming only two zones in this case). Technically, the living area will reach 25º C before the bedrooms' zone reaches 23º C, if the house is being cooled. Accordingly, the control panel will receive a signal from the living zone thermostat, "temperature is already 25º C". Instead of turning off the HVAC system, as ordinary houses do, only the duct dampers that are serving the living zone will be shut off. As a result, conditioned air will only be supplied to the bedrooms' zone. Once the bedrooms' zone reaches an average temperature of 23º C, the HVAC unit will be turned off.

Beside energy savings that are expected to occur by implementing the concept of combining zoning with smart thermostats, HVAC zoning provides the most comfort in all zones. By having some dampers that are open and others are shut off, all occupants in all zones can have the desired temperature they require without causing overheating or overcooling in other zones.

2. DATA COLLECTION

Before digging deep into finding solutions to cooling/heating energy savings, it is highly important to understand how people usually behave in their houses. Do people set the thermostat at a very low temperature and ignore electricity bills? Or do they only use low temperatures during bed time? What about when people are out of the house? Do they turn the HVAC unit off, or just set it at a higher temperature until they come back?

This chapter shows how data were collected and analyzed to come up with a practical solution for cooling/heating energy savings. Such a practical solution should take into account how people would accept implementing this technology and how much savings they can achieve. One major part of it is *not* mandating people to change an existing behavior.

2.1. Occupants' Behavior

Thermostat settings and how often occupants turn off the HVAC unit are the first considerations when coming up with a practical solution. The Energy Information Administration in the United States (EIA) conducts a Residential Energy Consumption Survey (RECS) every five years. The latest survey was published in 2017 (one year before this thesis was written). One can get informative energy consumption data by referring back to RECS, as a large amount of detailed data related to energy consumption and household' behavior can be found in there. The surveys' outputs can be filtered based on need, in this case survey data are filtered based on climate zones.[2] Starting with a hot/dry climate region, such as Phoenix, Arizona, people tend to set the thermostat at about 25º C during the day, whereas at night, thermostat settings go as low as 23º C as shown in Figures 2.1 and 2.2, respectively [3].

[2] Analyzing by climate zone makes future research easier when it comes to selecting a specific region or city to conduct the study; more details are provided in Chapter 3.

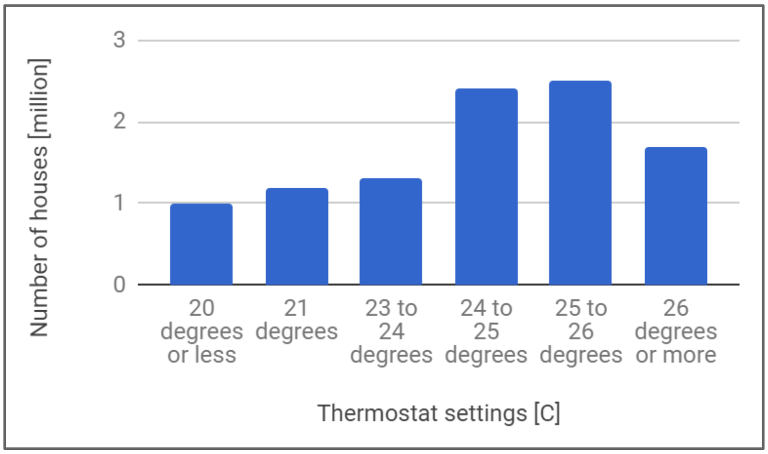

Figure 2.1: How occupants tend to set the thermostat in hot/dry regions during the day [3]

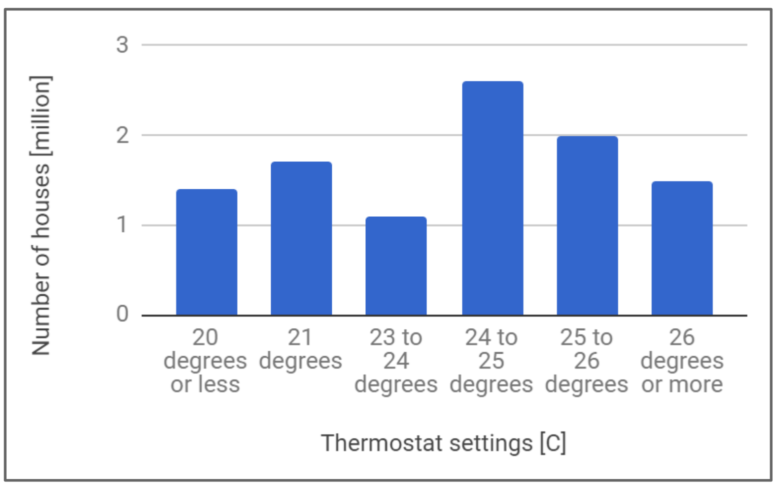

Figure 2.2: How occupants tend to set the thermostat in hot/dry regions during the night [3]

Part of coming up with a practical solution that can fit most homeowners, if not all, is to generalize the study, hence cold regions have to be taken into consideration. In this case, extremely cold climate zones are also considered, such as Chicago, Illinois. According to the EIA [3], cold region residents tend to set the thermostat at about 23º C during the day and about 21º C during the night as shown in Figures 2.3 and 2.4, respectively.

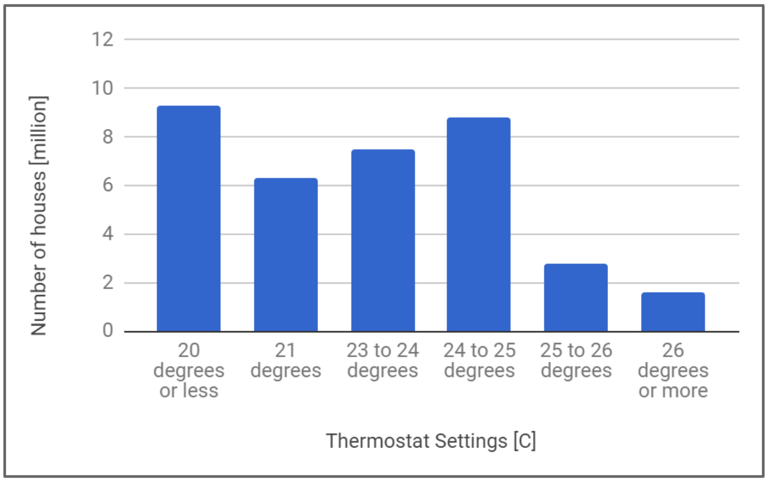

Figure 2.3: How occupants tend to set the thermostat in cold regions during the day [3]

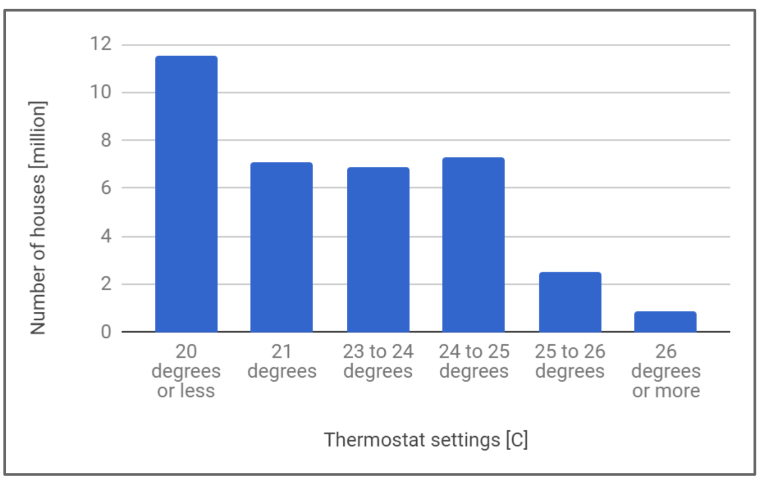

Figure 2.4: How occupants tend to set the thermostat in cold regions during the night [3]

In addition to thermostat settings, it worthwhile to find out how likely people would schedule their programmable thermostats at home.[3] Do most people tend to make use of scheduling features available in their thermostats, or just change the settings manually? How about leaving the thermostat at one temperature all day? How many residents tend to turn their equipment on/off as needed?

It turns out that 44% of the households in the United States tend to leave the thermostat settings at one temperature all day [3]. Which means that, unfortunately, a serious amount of cooling/heating energy is being wasted by almost half of the households nationwide. Throughout the nation, only 18% of the households utilize their programmable thermostats as shown in Figure 2.5.

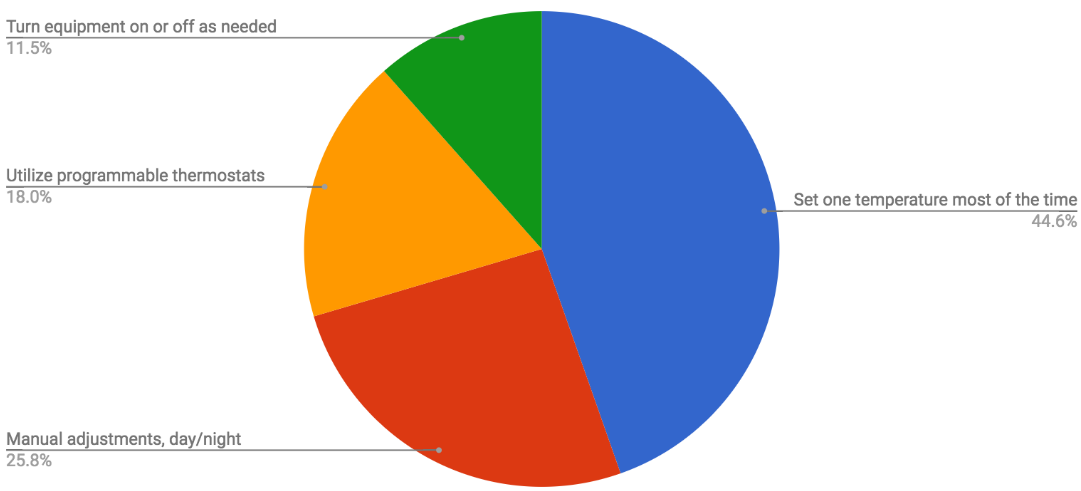

Figure 2.5: Households' behavior with thermostat settings nationwide [3]

[3] More than 68% of single-family houses are equipped with a programmable thermostat (see Appendix A)

A zoned HVAC system requires the households to either utilize the scheduling feature or, at least, manually adjust each zone's thermostat settings. Since most households tend to leave the thermostat settings as they are most of the time, energy savings with zoned HVAC systems are limited due to this kind of human error. Here comes the intelligence of smart thermostats, with occupancy detection features, as smart thermostats can figure out when the house is occupied and when it is not. Accordingly, the HVAC unit is turned off completely, or at least the settings automatically changed to higher temperature when no one is home. As a result, minimal energy is wasted when the house is unoccupied. Over time, smart thermostats learn and predict the usual times when occupants return back home, and based on that precooling and preheating is provided to ensure the most comfortable temperature is provided for the occupants.

2.2. Time of Occupancy

Time of occupancy, or in other words, time of use needs to be considered to come up with a fair comparison between HVAC energy consumed by an ordinary HVAC system and a smart zoned HVAC system. Considering the energy demand during a typical day in Figure 2.6, it can be observed that the highest demand for energy in residential buildings occurs in the afternoon till late evening.

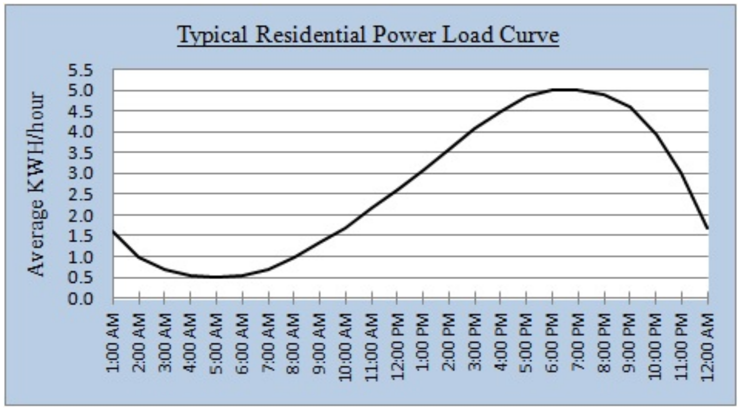

Figure 2.6: Daily energy demand in a typical day [9]

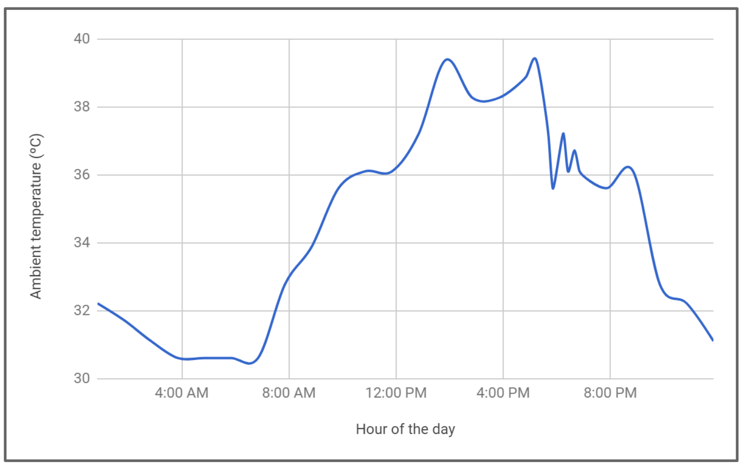

Figure 2.7: Ambient Temperature on a typical day in Phoenix [10]

Comparing the data in Figure 2.6 with a typical day ambient temperature (Figure 2.7), it can be noticed that the demand increases as the temperature increases. Additionally, one can observe that house occupancy is directly related to energy demand. Figure 2.8 shows the level of occupants' activity in a three-resident house over a 24-hour period. Accordingly, a typical family house can be assumed to have minimal occupant activity in the morning, and by noon time occupants start coming back home and that is assumed to be the case till the next morning [11].

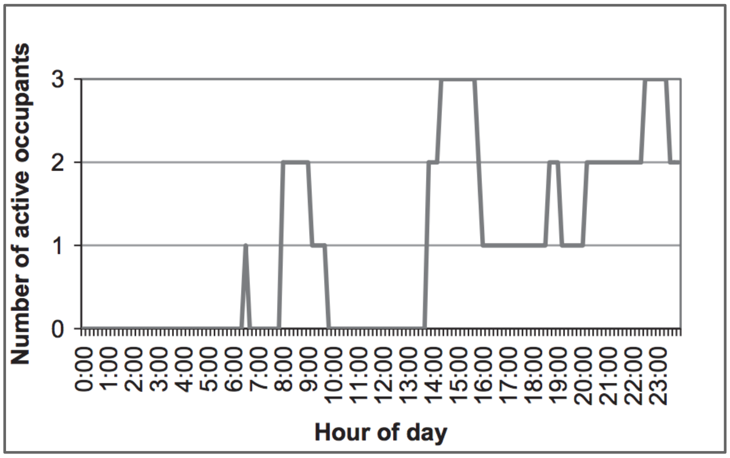

Figure 2.8: Level of activity in a 3-resident house [11]

2.3. Selecting a House Layout

After finding out and knowing exactly how most households deal with their thermostats, the following step is to select a typical single-family house layout on which to base this thesis. The same house is used in both cities, Phoenix and Chicago. In both cases, the entrance of the house is assumed to be facing north (Figure 2.9).

The house layout shown in Figure 2.9 has a total area of 265 m^2 (2,852 ft^2). It consists of four bedrooms, three bathrooms and a great room. There are some areas that are assumed to remain unconditioned (i.e. don't require cooling), such as the garage and secondary bathrooms. The master bathroom is assumed to be cooled by the same duct that supplies the master bedroom.

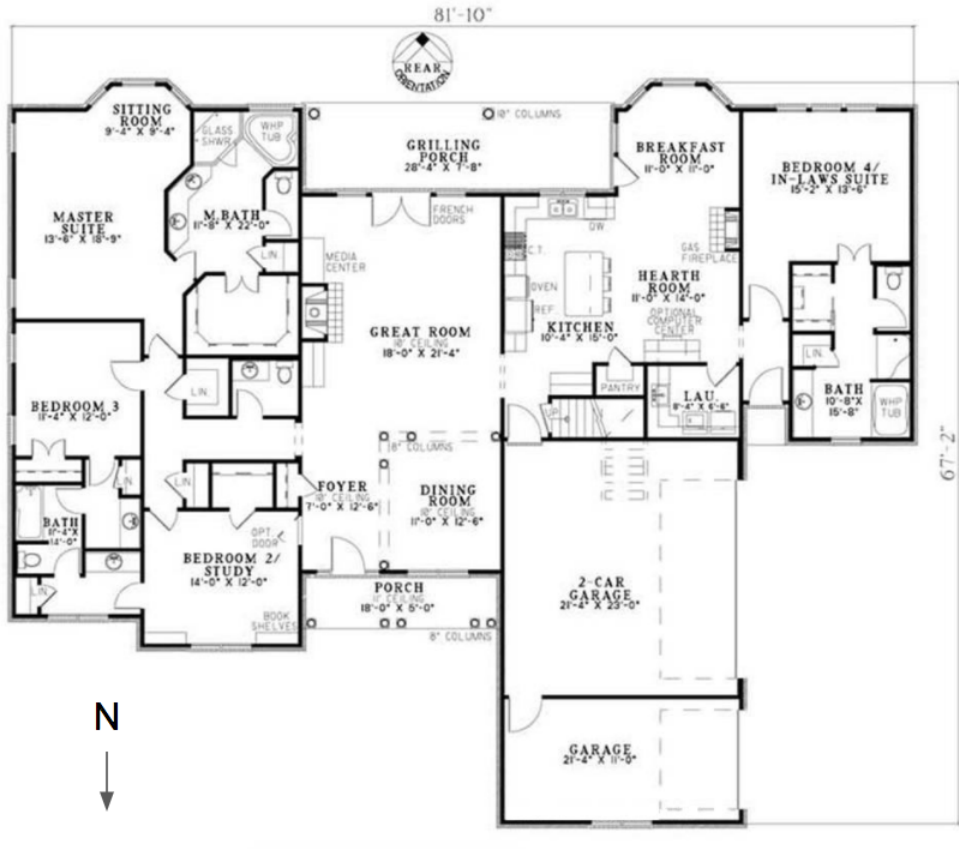

Figure 2.9: Typical single-family house [12].

In most single-family houses, the HVAC unit is placed on either side of the house. In this house, the HVAC unit is assumed to be placed on the right side of the house (the west side). Figure 2.10 shows how the main ductwork layout is expected to be in this particular house layout.

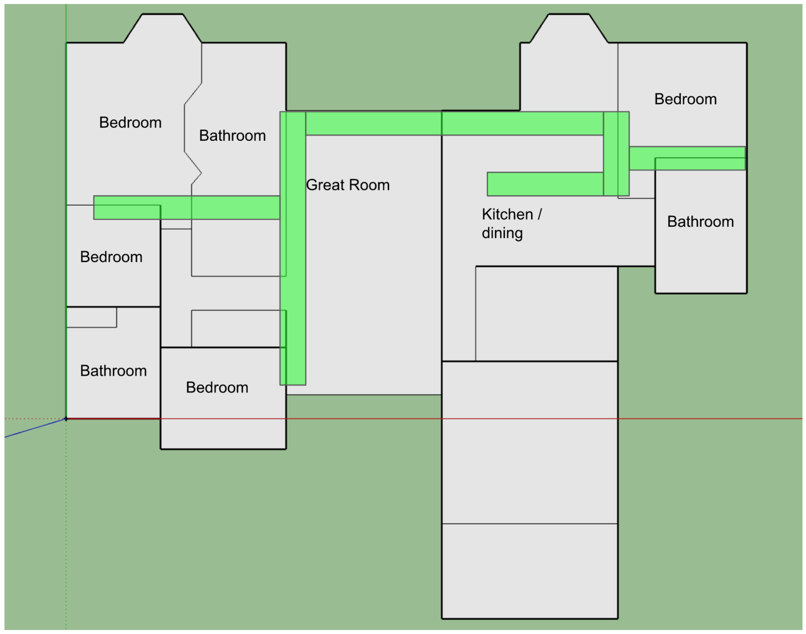

Figure 2.10: Main ductwork layout in the house.

3. MANUAL ANALYSIS

In this chapter, all calculations and estimates are listed in detail. Manual analysis includes all calculations that were done manually, either with or without the help of Excel. Basic equations will be utilized to estimate the most suitable HVAC unit for the selected house layout. Following that will be how zoning is applied and how the level of occupancy affects the annual energy consumption. Thanks to smart thermostats, occupants do not have to worry about scheduling the thermostat nor changing temperature settings frequently, which will play a crucial role in the success of this thesis.

3.1. Current Operating Conditions

The first step taken to start the manual calculations is to estimate the size of the HVAC unit, using the rule of thumb that each 37 m^2 requires one refrigerant ton of cooling capacity [13]. Since most HVAC contractors are making use of this rule, it is assumed to be the method used to select the HVAC unit in this house [13]:

$$HVAC_{Capacity} = \frac{A_{house}}{37\ m^2/RT} = \frac{265\ m^2}{37\ m^2/RT} \simeq 7RT \qquad eqn. 3.1$$

Where:

$HVAC_{Capacity}$: Total capacity of the HVAC unit [RT]

A_{house}: Total area of the selected house layout [m^2]

The following step is to find a reliable source for hourly ambient temperature in the desired city (or location). In this case, ambient temperature data was pulled from the National Solar Radiation Data Base using Typical Meteorological Year 3 (TMY3) [14].

Following that is an estimate of how much time is approximately needed to cool down a full house by 3º C, for example. By doing simple measurements in a single-family house, it turns out that the HVAC unit needs about 6 minutes to reduce the house temperature by 3 degrees over an hour. In other words, if the thermostat is set to 23 degrees, then every 20 minutes the HVAC unit will run for about two minutes. Accordingly, it can be assumed that if a house gains 3 degrees over an hour, then the

HVAC unit will run for about 6 minutes to bring the temperature down from 26º C to 23º C.

Based on the assumptions made above, Table 3.1 shows the estimated temperature gain over an hour depending on ambient temperature. It also shows how much time the HVAC unit needs to run to bring the house temperature back to the thermostat setpoint. Equations 3.2 and 3.3 show how the numbers in Table 3.1 are calculated.

$$\dot{Q}_{required} = \dot{m} \times C_p \times \frac{T\_gained}{hour} \qquad eqn. 3.2$$

$$t_{cooling} = \frac{\dot{Q}_{required}}{\dot{Q}_{max}} \times 60\ min \qquad eqn. 3.3$$

Where:

$\dot{Q}_{required}$: Heat gained over an hour [kWh]

$\dot{Q}_{max}$: Maximum heat can be removed over an hour based on $HVAC_{Capacity}$ [kWh]

$\dot{m}$: Mass flow rate of the air supplied by the HVAC unit [kg s^{-1}]

C_P: Specific heat of air [kJ kg^{-1} K^{-1}]

T_{gained}: Gained temperature by the house over an hour [°C hr^{-1}]

$t_{cooling}$: Total time required to remove the gained heat within an hour [min]

By estimating the cooling capacity of the HVAC unit (in eqn. 3.1) and the total heat to be removed over an hour (in eqn. 3.2), the total time required ($t_{cooling}$) by the HVAC unit to remove that gained heat ($\dot{Q}_{required}$) is estimated using Equation 3.3. To clarify this concept, one may assume that if the thermostat setpoint is 23º C and the HVAC unit is shut off, after an hour the temperature of the house will increase by T_{gained} as shown in Table 3.1. Accordingly, the total heat required to be removed from the house can be calculated.

Table 3.1: Estimated gained temperature and cooling time required over an hour depending on ambient temperature.

$T_{ambient}$ [ºC]	T_{gained} [ºC/hr]	$t_{cooling}$ [min]
< 21	< 1	< 1
≤ 26	3	6
≤ 32	4	10
≤ 38	5	13
> 38	6	15

Noticeably, the mass flow rate ($\dot{m}$) and specific heat (C_p) are required in Eqn. 3.2. The fact is, those two variables can be easily estimated. Since the size of the HVAC unit is determined to be 7 RT, then by design the maximum airflow rate must be in the range of 1.32 m^3/s (2,800 CFM) [13]. Besides the airflow rate, the density is needed to calculate the mass flow rate ($\dot{m}$). Under such operating conditions the density is estimated to be 1.16 kg m^{-3} [15]. On the other hand, the specific heat of air does not vary much between 21º C and 27º C, [4] and thus the specific heat is estimated to be 1.007 kJ kg^{-1} K^{-1} [15].

[4] Operating conditions of the house are assumed to be in the range of 21º C to 27º C.

3.2. Zoning the House

Before starting the detailed analysis of how zoning is applied, one has to know that HVAC zoning may not be applied to all houses. However, in this thesis, the analysis is made based on the output results of RECS 2015 (refer to Ch. 2.1). One major limitation that could prevent a homeowner from implementing this thesis is having an HVAC unit with a single-speed compressor and single-speed fan. In such a case, the HVAC unit is designed to be supplying conditioned air to the entire house using the rule of thumb [13]. As a result, the unit is designed to supply conditioned air at a ratio of 0.19 m^3/s per ton. Hence, shutting off some ductwork using duct dampers may result in having back pressure, which could damage the HVAC unit.

Most houses are currently equipped with multi-speed fans (see appendix A) [3]. On the other hand, only 5% of the houses in the United States are equipped with a Variable Speed Drive (VSD) compressor [16]. As an assurance that this thesis applies to most existing houses, the house considered here is assumed to have a single-speed compressor with a 3-speed fan. In other words, the HVAC unit in this case is designed to supply conditioned air at a flow rate of 1.32, 0.85 and 0.44 m^3/s, which is represented by 100%, 66% and 33% airflow rate, respectively [17].

Referring back to Figure 2.9, it can be noticed that the house has three main zones: the bedrooms, the living area and the kitchen area. Figure 3.1 shows all three zones, each represented in a different color. In Chapter 2.3, it was assumed that the HVAC unit is placed on the right side of the house (west side). Accordingly, the main ductwork will have duct dampers installed based on that assumption. In other words, the supply of conditioned air comes from the right-hand side of the house as shown in Figure 3.2.

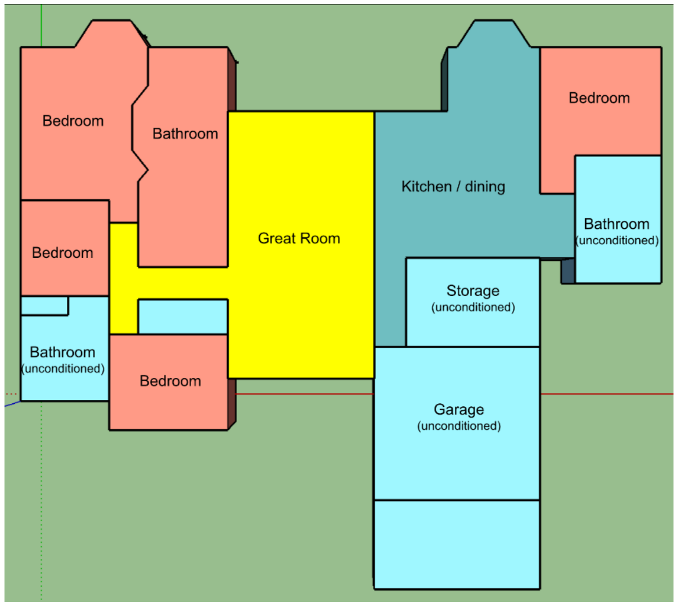

Figure 3.1: The house layout split into 3 conditioned zones

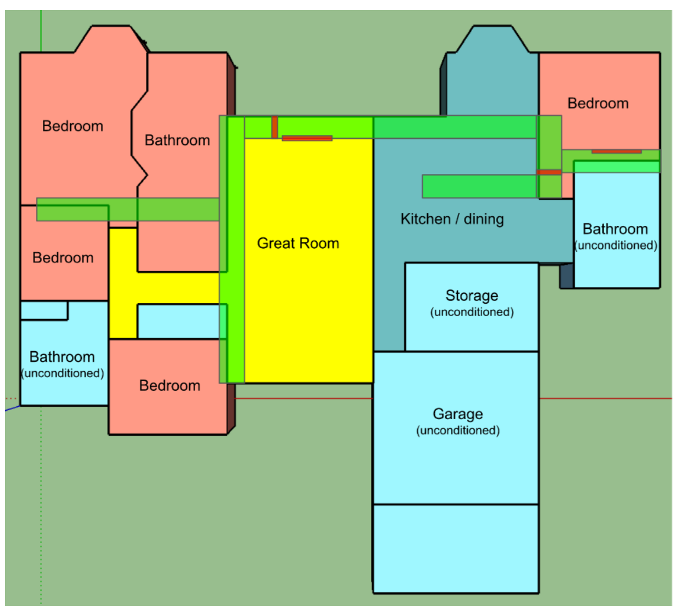

Figure 3.2: Main ductwork with the duct dampers installed

The next step in zoning is to estimate how the smart thermostat is going to schedule the times of operation. Scheduling is a built-in feature in smart thermostats, however the smart thermostat can override any pre-programed schedule by predicting the usual times of occupancy [5]. Based on the information collected in Chapter 2.2, the occupancy in this house can be estimated as shown in Figure 3.3.

By observing Figure 3.3, it is now obvious that the typical occupancy of the house is always less than 100%, area wise. Which gives a good indication of why zoning can save a significant amount of cooling/heating energy. In other words, one may conclude that existing HVAC units are always running at full capacity to supply the entire house with conditioned air, while most of the time the house is not fully occupied.

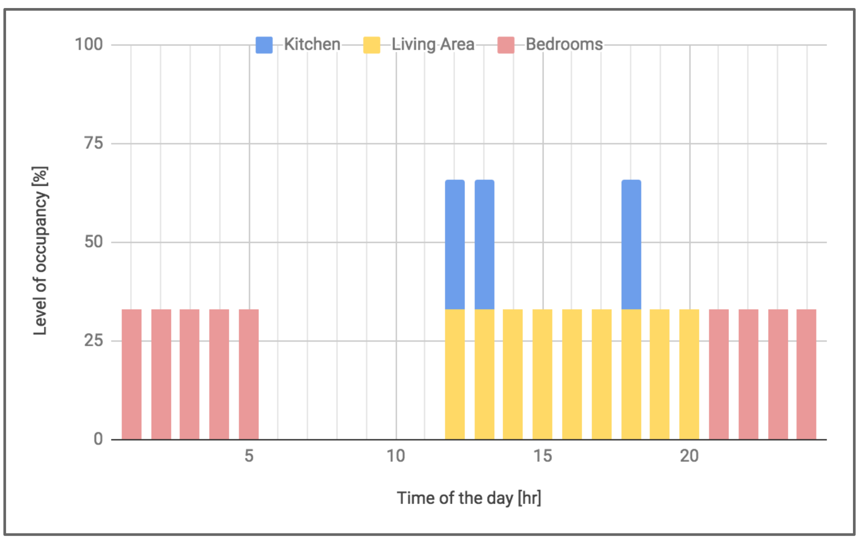

Figure 3.3: Level of occupancy within the house in a typical day

Based on the information shown in Figure 3.3, the total amount of HVAC energy consumption can be calculated. Provided the fact that the HVAC unit can run at three different speeds, the main variable to be altered in Equation 3.2 is the mass flow rate. Going back to Figure 2.9, it turns out that the bedrooms represent about 30% of the total area. Based on their fraction of the total area, the bedrooms' zone alone needs about 2 RT, which is about 30% of the HVAC unit size. Since the compressor can only operate at full capacity, the airflow rate is reduced instead. In this case, the bedrooms' zone needs only the lowest fan speed, which is 0.44 m^3/s.

As shown in Figure 3.3, the living area is the only zone that needs to be supplied with conditioned air between 2 PM - 6 PM. Referring back to Figure 2.9, the living area has a total area of about 60 m^2, using the rule of thumb [13], the living area requires only 22% of the total capacity that the HVAC unit can supply. However, the lowest fan speed in the selected HVAC unit cannot go below 33%, thus, the HVAC unit will be running at 33% to supply conditioned air to the living area.

There are two times when the kitchen zone and the living zone are occupied, 12 PM to 2 PM and 6 PM to 7 PM. During those two periods, the total area needing to be conditioned becomes 98 m^2. Accordingly, it is assumed that the HVAC unit needs to run at 66% to ensure the occupants' comfort.

After deciding the operating conditions that the HVAC unit will run under, it is time to select a location on which to apply this study. First, a hot/dry climate zone is selected, in this case Phoenix, Arizona. With the help of Excel, TMY3 weather data and Table 3.1, Equations 3.2 and 3.4 can be applied throughout the year. Figure 3.4 shows the impact of implementing smart HVAC zoning over a 24-hour period. On that specific day, Aug 30th, the total energy saved by applying this study is 68%.

$$COP = \frac{\dot{Q}_{required}}{E_{input}} \qquad eqn. 3.4$$

Where:

COP: Coefficient of performance (assumed = 2.5)[5] [18]

E_{input}: Energy input required to remove $\dot{Q}_{required}$ [kWh]

Note: Since all energy consumption in these calculations are calculated over an hour, $\dot{Q}_{required}$ *and* E_{input} *are represented in [kWh].*

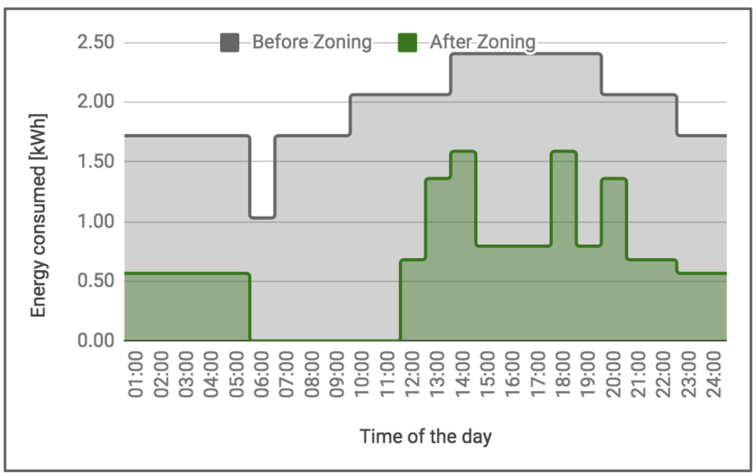

Figure 3.4: Energy consumed over a single day before and after zoning[6]

One may observe Figure 3.4 and ask: how this thesis is going to change the behavior of households and make them turn off the HVAC unit during non-occupancy periods? Another question that may be asked is how can someone guarantee that the

[5] More details can be found in Appendix D.

[6] Sample of calculations is provided in Appendix D

households are willing to change the thermostat settings in each zone? The fact is, no one needs to change anyone's behavior. Actually, all scheduling and thermostat settings will be altered by the smart thermostat based on occupancy. As mentioned earlier, the intelligence of smart thermostats allows them to predict when it is the right time to turn off the HVAC unit completely, and when to change temperature settings (more details in Ch. 1.1).

Although picking one day throughout the year gives a good impression about how smart zoning affects energy consumption, it worth finding out how energy consumption is going to be affected throughout the entire year. Figure 3.5 shows how much energy is consumed in each month. The savings shown in Figure 3.5 represent about 66% of the annual energy consumed before zoning.

Note: Generalization analysis, hence implementation of zoning in Chicago, Illinois is found in Chapter 4.4.

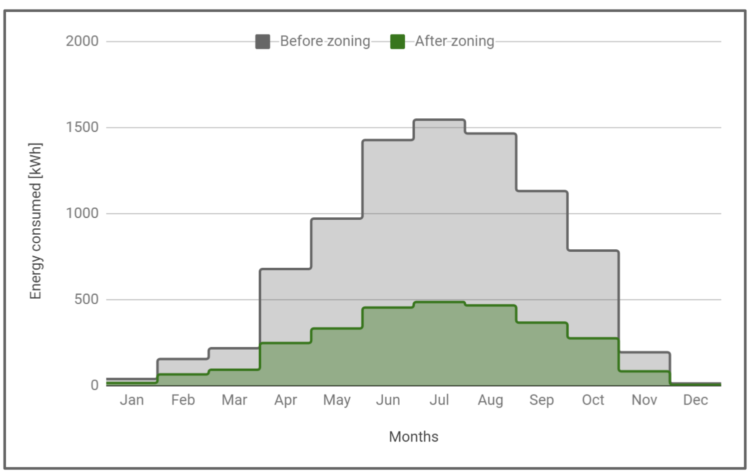

Figure 3.5: Impact of zoning over the entire year in Phoenix, Arizona

3.3. Ultimate Number of Zones

In Chapter 3.2, the house was split into three different zones for the reason that the house has three different areas are not likely to be occupied at once. In this chapter, the house will be divided into different numbers of zones to determine how the number of zones impacts the energy savings.

The objective of this chapter is to estimate how likely energy savings would increase by having more or fewer zones. This estimate is highly beneficial for households who are expecting the level of occupancy to change over time. Similarly, this can be beneficial to those who are expecting some zones to be occupied for short periods throughout the year. For example, parents who are expecting kids to leave the house soon, either for college or moving forward with their own lives. In such a case, not all bedrooms will be occupied, the house may end up with one bedroom being vacant most of the year, or by having all kids leaving the house only the master bedroom is going to be occupied throughout the year (i.e., the remaining four bedrooms are vacant all year, most likely).

Since the house has four bedrooms, each bedroom will be removed from the main bedrooms' zone one at a time. In other words, it will be assumed that one room will be vacant at a time, assuming the first kid is leaving first, then the second and the third. Eventually, the house will have only one bedroom being occupied throughout the year.

Referring back to Figure 3.2, it can be noticed that the ductwork has four dampers although the house is divided into only three zones. The reason is that one bedroom is located on the other side of the house, hence there is no one main duct that serves all bedrooms, and thus that bedroom must have its own duct damper. Figure 3.2 indicates that the number of duct dampers cannot be less than four in the case of having two zones, three zones or four zones. One may ask why two zones cannot go with fewer number of dampers? Obviously, the kitchen and the living zones are not sharing one main duct, accordingly each area has to have its own damper, keeping in mind that both dampers (for the kitchen and the living areas) will be operated simultaneously in the case of having two zones only (one for the bedrooms and another for the living and the kitchen areas).

Since this chapter analyzes the energy savings impact of different number of zones, the duct dampers layout must be changed as the number of zones goes beyond four. Figures 3.6 and 3.7 show how the duct dampers layout is going to change in the case of five zones and six zones, respectively.

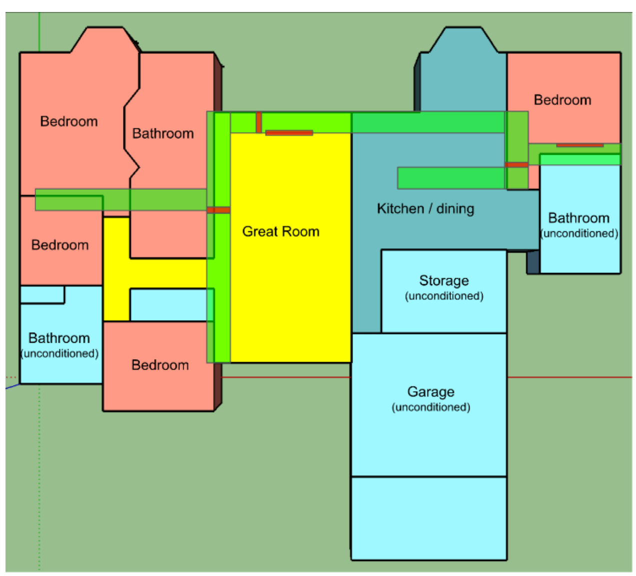

Figure 3.6: Duct dampers layout for five zones

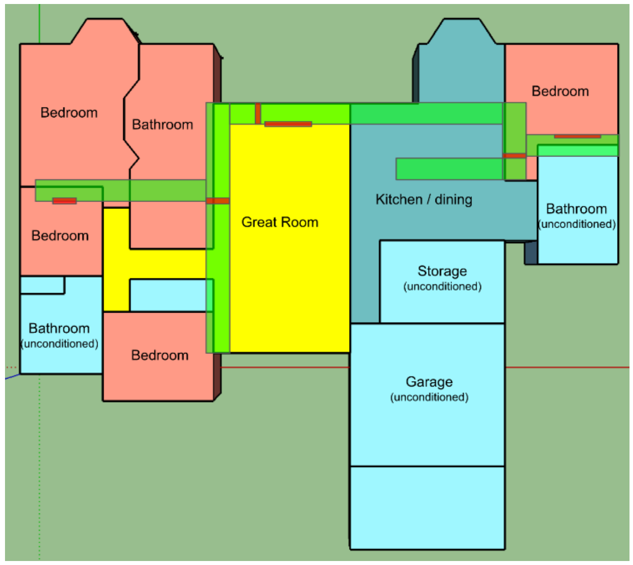

Figure 3.7: Duct dampers layout for six zones

By changing the number of zones, it can be noticed in Figure 3.8 that having only two zones can save up to 55% of annual energy. In the case of three zones, savings can be as high as 66%. One may notice that in the case of four to six zones energy consumption remains almost the same. That can be explained by referring back to Ch. 3.2, where it was mentioned that the HVAC unit in this house is assumed to have a single-speed compressor and a 3-speed fan. As a result, the HVAC unit could be in danger if it is forced to run below design conditions. Causes of danger (unit failure) can be either back pressure in the ductwork or having too many short cycles, which may shorten the life of the HVAC unit.

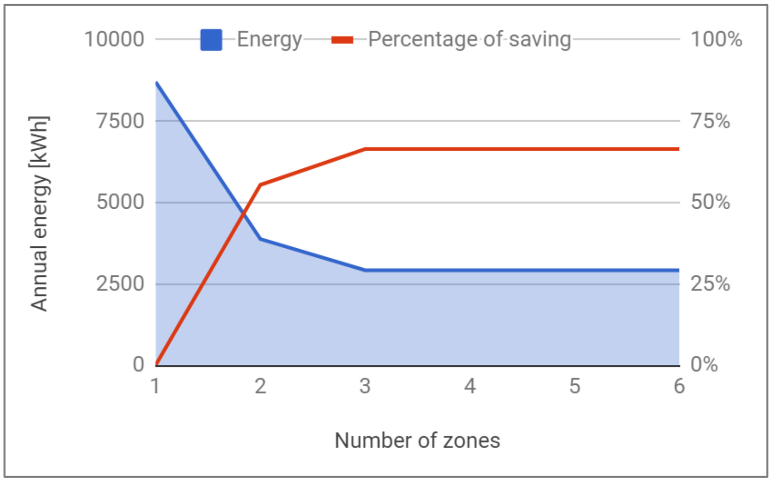

Figure 3.8: Change in annual energy consumption as the number of zones changes

According to Figure 3.8, it turns out that for this specific house and HVAC unit, three zones is the optimal number of zones that should be implemented. More zones will increase the capital cost with no significant impact on energy savings; more details are given in Ch. 5.

3.4. Introducing Variable Speed Drive (VSD)

In the previous chapter, it was observed that a single-speed compressor limits the zoning system from even greater energy reductions. However, there are some cases where an existing HVAC unit is equipped with a Variable Speed Drive (VSD) compressor. This type of compressor can run at different speeds based on need, going as low as 25% of full capacity [19]. Taking the selected unit size as an example, with VSD the 7 RT compressor can go as low as 1.75 RT instead of constantly running at full capacity.

Figure 3.9 shows how energy consumption decreases as the number of zones increases when a VSD compressor is utilized. Noticeably, energy consumption becomes lower and lower as the number of zones increases. Thanks to the VSD compressor, cooling capacity can go as low as 1.75 RT without harming the HVAC unit or causing short cycling. In this case, energy consumption can be as low as 20% of the total energy consumed before zoning is applied (80% of savings). It is shown afterwards in Chapter 5 how VSD units affect the payback period and the savings in bills.

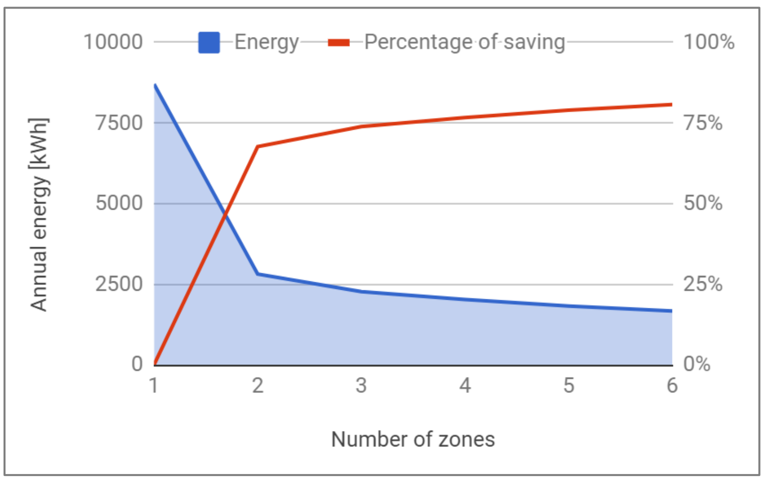

Figure 3.9: VSD impact on annual energy consumption

Variable speed drives not only save energy, they also increase the level of comfort by reducing operating noise. Keep in mind that not only does the compressor run at a variable speed, but so does the fan. As a result, a VSD compressor and air blower can both run at low capacities. Accordingly, there will be no major limitations with the number of zones and the size of each zone. Hence, neither back pressure nor short cycling are issues.

4. SIMULATION ANALYSIS

In this chapter, all analysis and calculations are done in a simulation software to verify the manual analysis. The chapter will start with selecting an appropriate software that suits this thesis the most. Following that will be the house layout development, in other words the house selected in this study will be sketched up from scratch in one of the sketching tools. Once the layout is ready, zones will be identified and the smart HVAC zoning concept will be simulated in the software. At that stage, a comparison will be made between the manual analysis and simulation analysis. Lastly, the chapter will carry out the generalization part, where the same analysis will be applied in a different climate zone to ensure that this thesis can be implemented in different locations around the world.

4.1. Selecting a Simulation Tool

There are many different software packages in the market that can make such an analysis. In this thesis EnergyPlus is selected to process all required analysis. EnergyPlus is one of the most powerful tools when it comes to energy consumption simulation in buildings. The software is developed by the Department of Energy (DOE) in the United States, and a lot of efforts is exerted by DOE to keep the software up to date [20], which surely helps engineers and architects around the world to make use of it and depend on it in estimating energy consumption in a building before construction even starts.

Similar to Matlab and Engineering Equation Solver (EES), EnergyPlus is a coding-based software. However, coding sometimes can be hard to deal with especially when it comes to modeling a building and going deep into construction details such as selecting equipment and materials within the building. Thus, the DOE has developed many applications and tools that make use of EnergyPlus features without the need of learning its codes. In this thesis, SketchUp and OpenStudio® are the tools utilized to simplify the EnergyPlus analysis. SketchUp is mainly used to design a building layout and identify zones. OpenStudio®, on the other hand, is an extremely helpful tool that identifies the equipment used inside the house. By developing the building layout and identifying the equipment to be evaluated, OpenStudio® runs the simulation through EnergyPlus and produces a detailed report that includes all energy consumed by the house. Hence, no coding needs to be typed manually by the user.

4.2. Zoning Analysis

As mentioned earlier, the first step in simulation is to develop the building layout and to identify all zones. Sketching the house layout has to be done carefully to ensure that all dimensions are accurate and match the selected layout (see Figure 4.1).

After having the layout ready in a two-dimensional drawing, it has to be converted into a three-dimensional model as shown in Figure 4.2. Each room, wall, door and window has to be carefully sketched to avoid any errors that may cause the simulation analysis to fail.

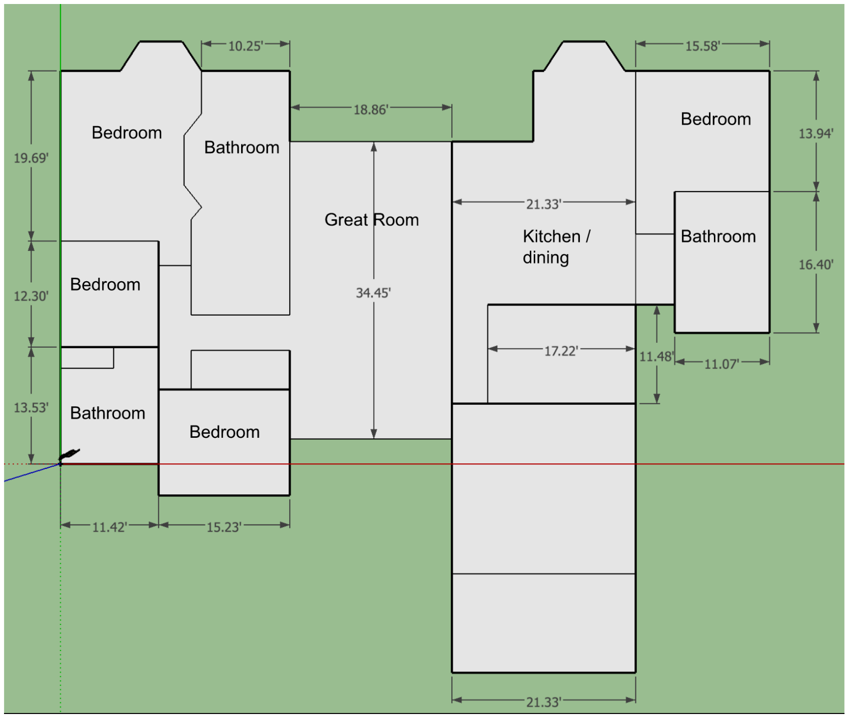

Figure 4.1: Drawing of the house layout in SketchUp

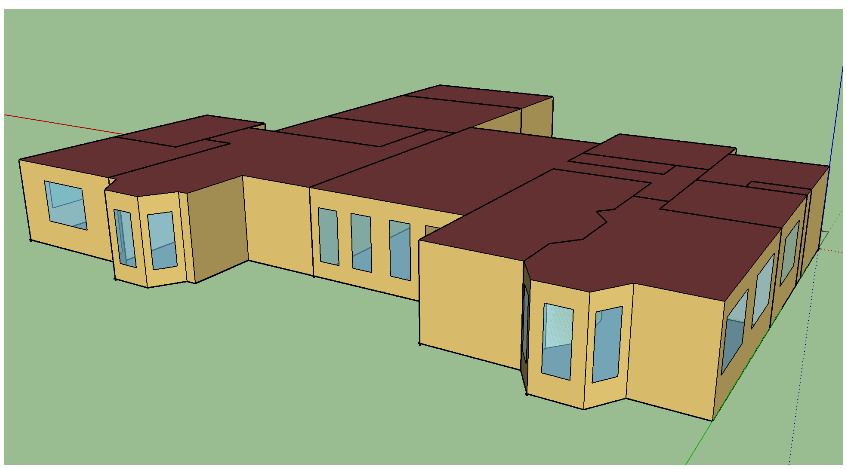

Figure 4.2: House layout in a 3D model

After the three-dimensional model is ready, the software has to have the zones identified. Similar to manual analysis, three zones in the house will be identified and evaluated. It is important to notice that, in SketchUp, all spaces have to be assigned to thermal zones, including unconditioned areas such as the garage, storage area and secondary bathrooms. Figure 4.3 shows how the house layout appears after having all zones identified.

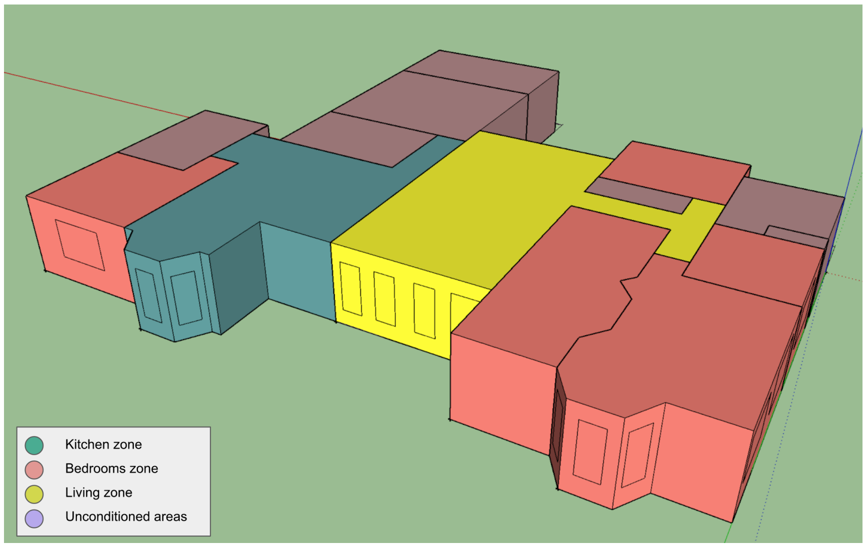

Figure 4.3: House layout with the zones identified

OpenStudio® is the next tool needed after having all zones identified. Since this thesis is mainly concerned about HVAC zoning, the focus will be on selecting the appropriate HVAC equipment for the house. In this case, the selected cooling unit is a packaged roof heat pump.

In order to have a fair comparison, the simulation analysis will run first at default settings, hence no scheduling settings and no zoning. Figure 4.4 shows the HVAC system layout at default settings—a single-speed compressor, a multi-speed fan and a single zone. In Figure 4.5, the HVAC layout has been altered based on the zones identified earlier. Noticeably, three zones are identified and this is how the software can understand what zone is to be conditioned.

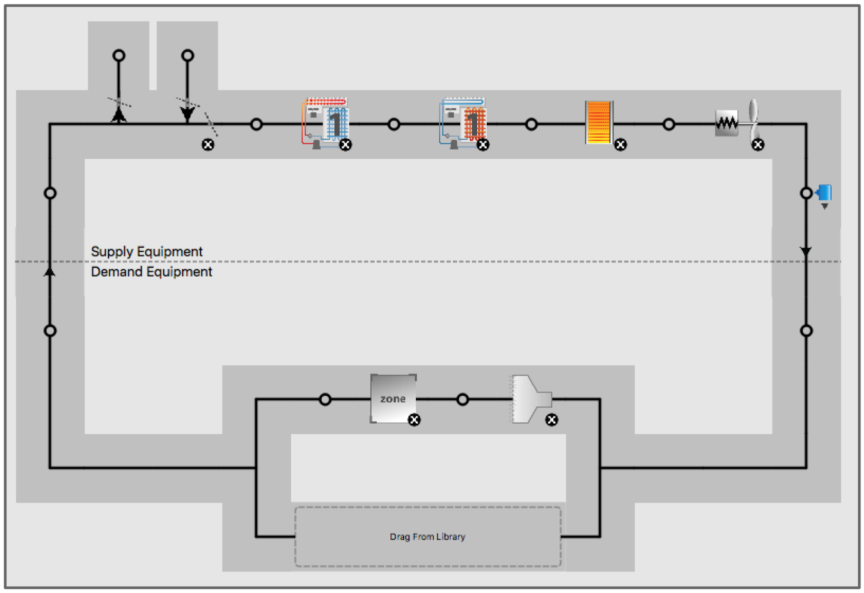

Figure 4.4: HVAC system layout before zoning

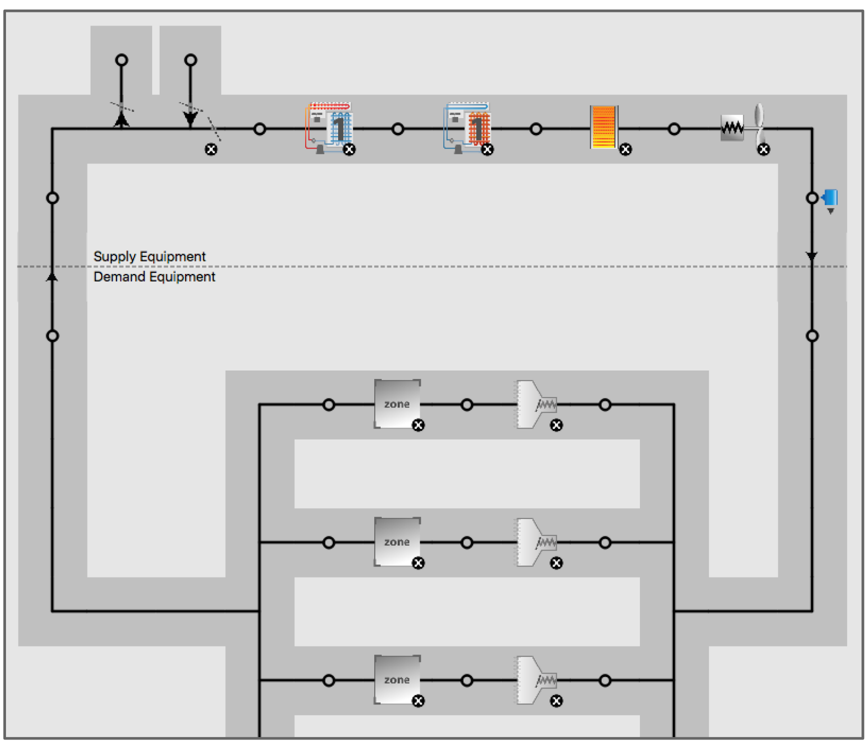

Figure 4.5: HVAC system layout after zoning

Before running the simulation analysis, the scheduling settings have to be changed since they will be representing how the smart thermostat is going to operate based on the level of occupancy. Figure 4.6 shows an example of thermostat settings over a 24-hour period; in this case the bedrooms' cooling schedule is shown.

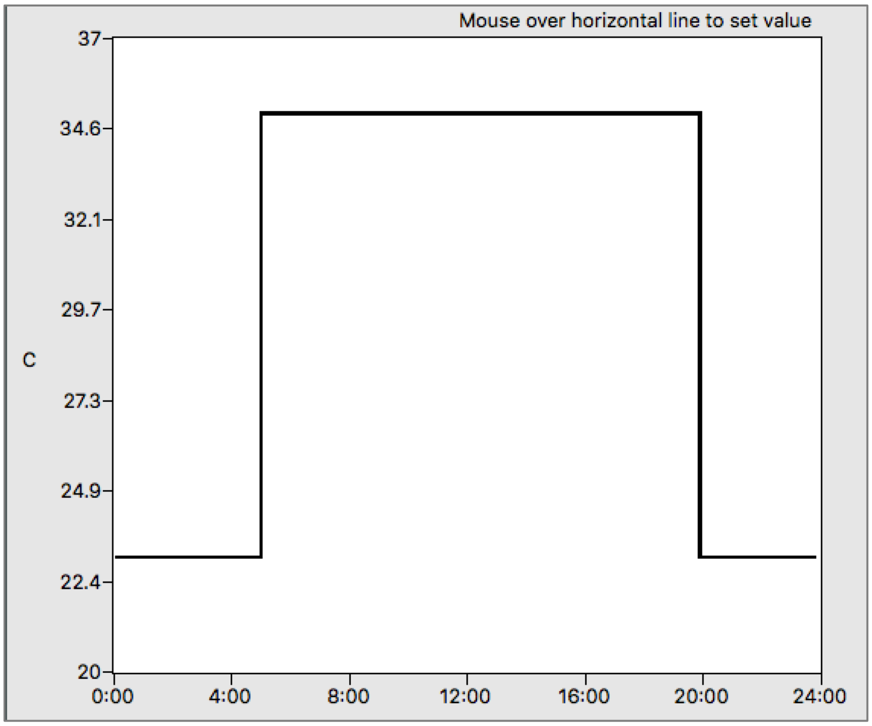

Figure 4.6: Temperature settings for the bedrooms' zone

Noticeably, the thermostat settings show 23º C during bed time (8 PM - 5 AM). Temperature settings were selected according to the RECS 2015 (see Ch. 2.1 for details). During non-occupancy, the smart thermostat will detect no occupancy which would result in turning off the HVAC unit, more precisely the duct dampers serving the bedrooms' zone will be shut off. Unfortunately, OpenStudio® does not allow a single schedule to have the HVAC unit on and off, thus thermostat settings are scheduled to be at a high temperature (35º C) to ensure no cooling occurs during non-occupancy, or at least minimum cooling will be required. One may therefore ask, would the software establish heating when the zone's temperature is below 35º C? The answer is no, because the software deals with cooling and heating as totally different schedules as shown in Figure 4.7. In other words, the cooling thermostat schedule does not establish heating by having such thermostat settings.

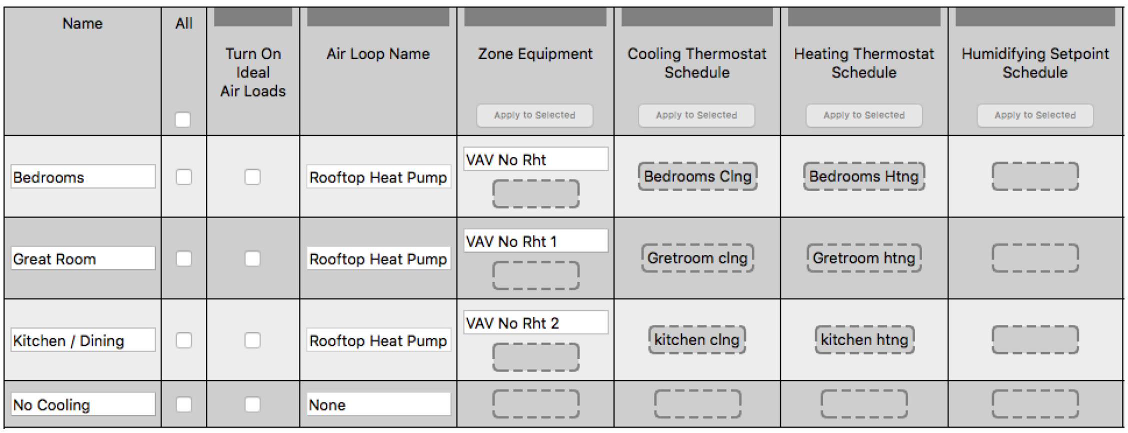

Figure 4.7: Cooling thermostat settings are different from heating thermostat settings

4.3. Manual Analysis vs. Simulation Analysis

In the previous chapter, the procedures for simulation analysis were shown in detail as well as how each step has to be carefully done to avoid errors and simulation failures. In this chapter, a comparison between the manual analysis and simulation analysis will be shown as a percentage of savings. Referring back to Chapter 3, the manual analysis indicated annual energy savings of about 55% - 66% for the house in Phoenix, Arizona. Figure 4.8 compares the percentage of savings with respect to the number of zones between the manual analysis and the simulation analysis. Obviously, both analyses show very similar percentages of energy savings in the case of a single-speed compressor and multi-speed fan; simulation results showed energy savings of 48% - 72%.

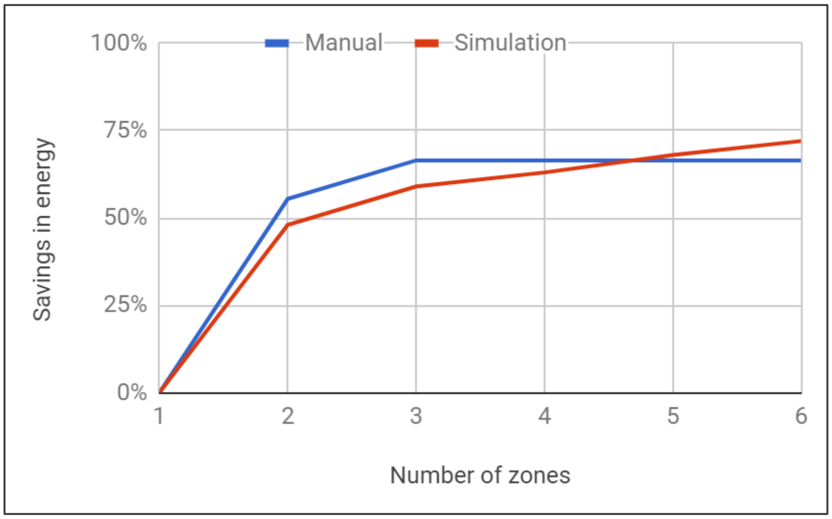

Figure 4.8: Energy saving percentages (manual vs. simulation)

It can be noticed that in Figure 4.8 the simulation analysis continues to reduce energy consumption even after the fourth zone, whereas the manual analysis does not. In the manual analysis the number of zones was limited to four zones to avoid too short cycling that may damage the HVAC system. However, simulation analysis does not take that issue into consideration.

After validating the manual analysis done in Chapter 3, it worthwhile to find out how accurate the results are when it comes to VSD compressors. Unfortunately, HVAC equipment in OpenStudio® are still under development, hence compressor speeds are limited to single speed and 2-speed types (see Appendix B).

The percentage of energy savings shown in Figure 4.9 represents the comparison between manual and simulation analysis when a VSD compressor (manual) and 2-speed compressor (simulation) are utilized. The percentage of savings indicates that the numbers found in Chapter 3 are realistic. Manual analysis showed 81% as a maximum percentage of savings, whereas the simulation analysis showed 79% of energy savings under the same operating conditions.

Figure 4.9 not only indicates that VSD units save more energy, it also indicates that savings could be even more with variable speed compressors, keeping in mind that the simulation analysis was done utilizing only a two-speed compressor.

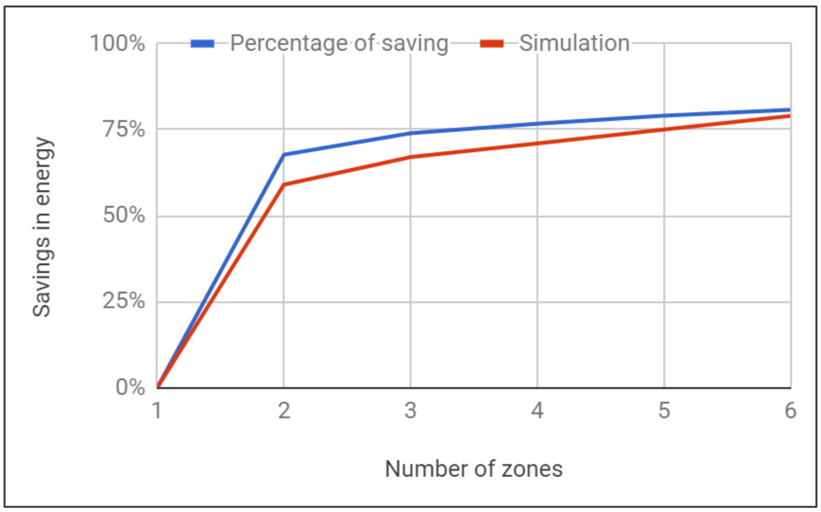

Figure 4.9: Percentage of energy savings when utilizing VSD (Manual) and 2-speed (Simulation) compressor

4.4. Different Climate Zone Consideration

As part of generalizing this thesis, a different climate zone is taken into consideration. All analysis done earlier was for a hot climate zone, specifically Phoenix, AZ, where most of the year the HVAC unit runs in cooling mode. But how about a different climate zone to be considered, a city where both cooling and heating are required?

In this chapter, a cold climate zone is selected to ensure that this analysis and results can be applied (almost) everywhere. Chicago, Illinois is the city on which the analysis is applied. What makes Chicago an attractive city to study is that the annual temperature varies widely, around 35º C in the summer and -22º C in winter [14]. Thus, zoning analysis can be tested against different operating conditions (extreme cold weather). In order to keep the houses identical, the HVAC unit in Chicago is assumed to be a heat pump similar to Phoenix.

Although heating energy consumption is extremely high when compared to cooling energy, smart HVAC zoning still shows attractive results for energy savings in Chicago. As depicted in Figure 4.10, the total energy saved for both cooling and heating energy consumption was as high as 75% of the total energy consumed annually by the same HVAC system before zoning.

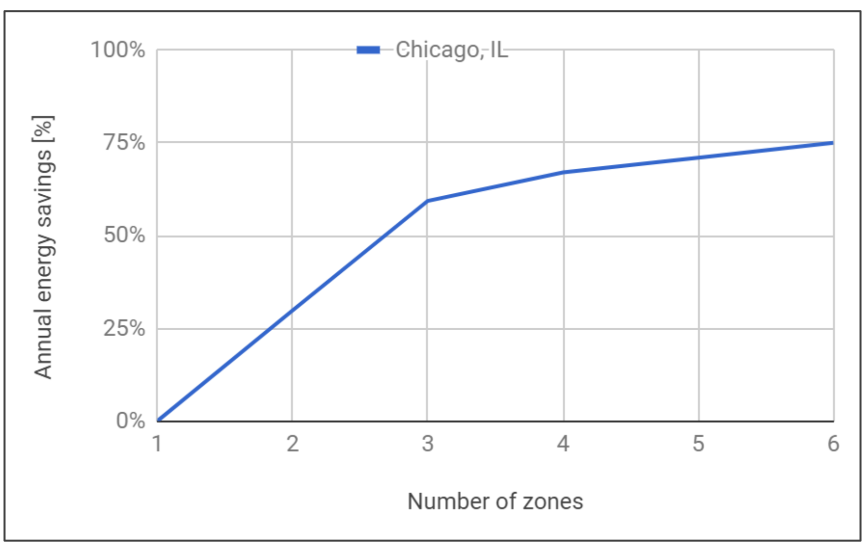

Figure 4.10: Energy savings when smart HVAC zoning is applied in Chicago, IL

Based on the results shown in Figure 4.10, one may conclude that this study can be applied to different climate zones with no major difference in energy savings percentage.

5. FINANCIAL ANALYSIS

In this chapter, all energy savings found earlier are translated into dollar values. Financial analysis starts with the approximate capital cost of implementation and ends up with the best payback periods based on the number of zones. In other words, the ultimate number of zones is determined from a financial point of view.

5.1. Capital Cost

The initial step in the financial analysis is determining the capital cost of implementing such a smart thermostat system coupled with zoning. The initial cost of investment is the top concern homeowners will look for before proceeding with applying this thesis. The initial cost, of course, affects the number of years homeowners need to wait before starting to realize actual cost savings.

Based on the analysis done in Chapters 3 and 4, the selected house layout has to have some duct dampers installed, a smart thermostat in each zone and a control panel to establish a communication channel between the dampers and thermostats. Table 5.1 shows a list of the average prices for each device [21], [22].

Table 5.1: Average prices of zoning devices[7]

Item	Price
Smart thermostat + one room sensor	$149
Room sensors (pack of 2)	$79
Control panel	$400
Duct dampers	$250

Each smart thermostat has an occupancy detector sensor built-in, with additional room sensors more rooms can be linked to the same thermostat to detect occupancy in all rooms within the same zone. In the three-zone layout, the bedrooms' zone has a total of four rooms controlled by the same thermostat. Thus, a pack of room sensors has to be purchased in order to realize the best savings and the most comfort in all four bedrooms. In addition to the listed devices, a labor cost of about $500 is added to the capital cost for installation.

5.2. Electricity Cost Savings

Electricity cost savings are not only about how much energy is being saved; calculating monthly bills includes a major component, electricity demand in addition to energy consumption. The remaining bill items are consistent in each bill and do not change or alter, such as delivery charges and bundled costs. Since these items are not changing, they are not considered in the analysis of this chapter.

[7] Average prices and number of devices may vary based on selected brands and the house layout.

Electricity demand (kW) is a key value that has to be taken into consideration, as it can actually lead, in some cases, to higher costs than the energy consumption (kWh). Demand values are relatively difficult to calculate. Some utilities consider demand during on-peak hours only, whereas others consider demand for both on-peak and off-peak hours. In both cases, the demand is basically represented by the maximum amount of electricity [kW] being consumed during a certain period of time and then averaged over an hour [23]. By the end of the month, the maximum value occurring in that month is considered in the bill.

The main reason behind a utility implementing demand charges is, basically, encouraging households to reduce the amount of electricity being consumed at the same time. In other words, households should not tend to use all appliances at once. Instead, e.g., laundry should be taken care of at a different time from dishwashing, ironing should be taken care of during off-peak hours to avoid high bills, etc. The air conditioning unit is no exception; it can play a crucial role in increasing (or decreasing) electricity demand over a given time.

Since the compressor in the selected HVAC unit can only operate at full capacity, the demand will always be 9.84 kW (see equation 5.3) before being averaged over an hour. However, by implementing smart zoning, the compressor will run at 9.84 kW but for shorter periods of time. In other words, if the entire house needs 12 min to be cooled down by certain degrees, the same unit will need only 6 min to cool down one half of the house.

After knowing how demand and energy are both important in calculating the cost of the monthly bill, a plan has to be selected in order to make accurate financial calculations. By referring to Arizona Public Services Electric Company (APS), the ECT2 plan turns out to be an appropriate plan for the selected house layout [24]. Table 5.2 shows the cost of energy and demand based on the selected plan. The on-peak time period is 12 p.m. to 7 p.m. Monday through Friday. All other hours are off-peak hours.

Table 5.2: Energy and demand rates in the ECT2 plan[8]

	Summer	Winter
On-peak demand charge	\$15.614 / kW	\$10.756 / kW
On-peak energy charge	\$0.10256 / kWh	\$0.06647 / kWh
Off-peak energy charge	\$0.05109 / kWh	\$0.04750 / kWh

Based on the information shown in Table 5.2, the total energy savings can be translated into dollars. Figure 5.1 shows the impact of smart HVAC zoning on energy and demand costs; calculations of energy and demand costs were done based on the results illustrated in the manual analysis with the help of Equations 5.1 through 5.5.

$$C_E = E_{off-peak} \times EC_{off-peak} \qquad eqn. 5.1$$

$$C_{E,peak} = E_{on-peak} \times EC_{on-peak} \qquad eqn. 5.2$$

$$COP = \frac{\mathrm{HVAC}_{capacity}}{E_{max}} \qquad eqn. 5.3$$

$$Demand = E_{max} \times t_{max} / 60\, min \qquad eqn. 5.4$$

$$C_D = Demand \times DC \qquad eqn. 5.5$$

[8] ECT2 plan has been voided on March 2018, new plans may have different rates.

Where,

C_E: Cost of energy during off-peak hours [$/month]

$C_{E,\ peak}$: Cost of energy during on-peak hours [$/month]

C_D: Cost of demand [$/month]

$E_{off\text{-}peak}$: Total energy consumed off-peak hours [kWh/month]

$E_{on\text{-}peak}$: Total energy consumed on-peak hours [kWh/month]

$EC_{off\text{-}peak}$: Energy charge during off-peak hours [$/kWh]

$EC_{on\text{-}peak}$: Energy charge during on-peak hours [$/kWh]

E_{max}: Energy required to remove $HVAC_{capacity}$ [kW]

Demand: Maximum electricity demand value occurring within a month [kW/month]

t_{max}: Maximum $t_{cooling}$ occurred within a month period [min]

DC: Demand charge [$/kW]

By observing Figure 5.1, it turns out that the demand costs much more than energy does when calculated over a year. One may observe as well that the demand does not change much by having more zones. As it turns out, demand savings over the entire year did not exceed 51%. The reason for not having more demand savings is that the HVAC unit needs to run at full capacity due to having a single-speed compressor. The only factor affecting demand savings in this case is the period of time that requires the HVAC unit to be running.

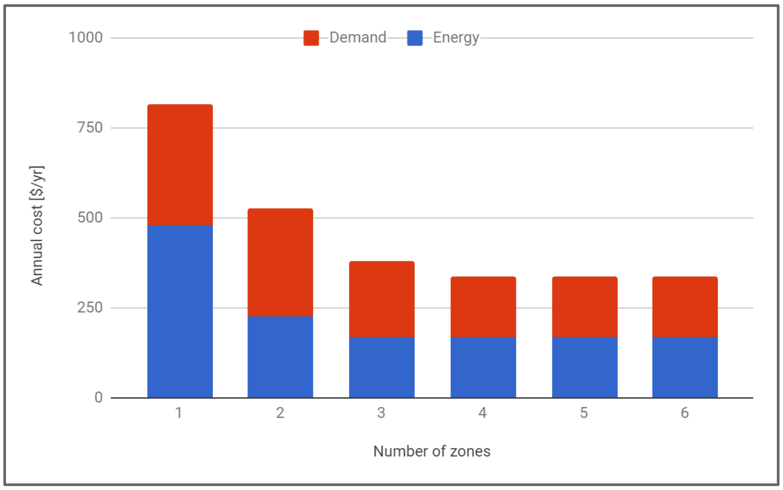

Figure 5.1: Annual cost of energy and demand based on the number of zones, for a single-speed compressor

After finding out the total savings in dollars, the payback period can be estimated using Equation 5.6. Looking at Figure 5.2, one can observe that the optimal number of zones is either three or four for the case of a single-speed compressor. Having only two zones does not save much energy and requires a relatively longer payback period. Beyond the fourth zone, the more zones added to the house the longer the payback period becomes.

$$Payback = \frac{Total\ Capital\ Cost}{Total\ Annual\ Savings} \qquad eqn. 5.6$$

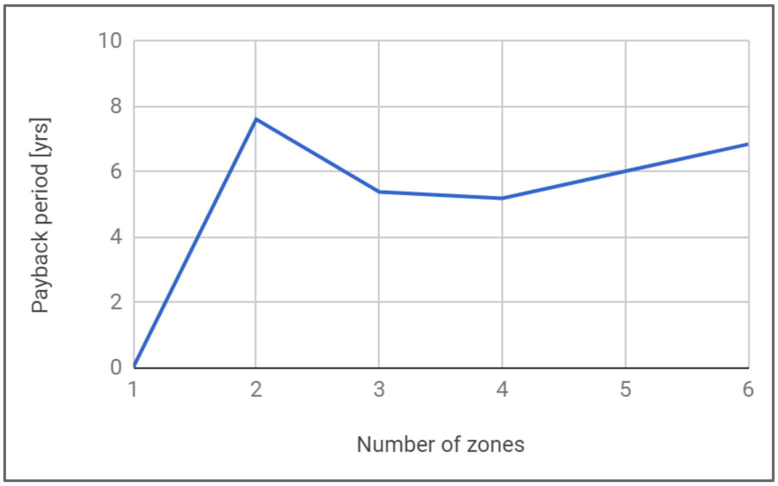

Figure 5.2: Payback period based on number of zones

5.3. Consideration of Variable Speed Drive (VSD)

This chapter estimates the costs that could be saved annually when a VSD is utilized. VSD savings can be estimated using the same equations as in Ch. 5.2. The major difference between single-speed drives and variable ones, is that the cooling capacity no longer needs to remain constant at 7 RT. Thus, the value of E_{max} in Equation 5.4 will vary based on the size of the zone that requires cooling. As a result, Equation 5.4 is altered to fit the operating conditions for a VSD as shown in Equation 5.7.

$$Demand = E_{VSD} \times t_{max} / 60\ min \qquad eqn. 5.7$$

By replacing E_{max} with E_{VSD}, the demand will depend on two variables instead of one, t_{max} and E_{VSD}, which will result in having even more savings than those from single-speed drives. Figure 5.3 shows that the impact of VSD compressors is extreme and can result in even more substantial savings. A well-known fact is that the compressor is the most energy consuming component in any HVAC system, thus by having that energy reduced to as low as 25% the savings in electricity bills can be significant.

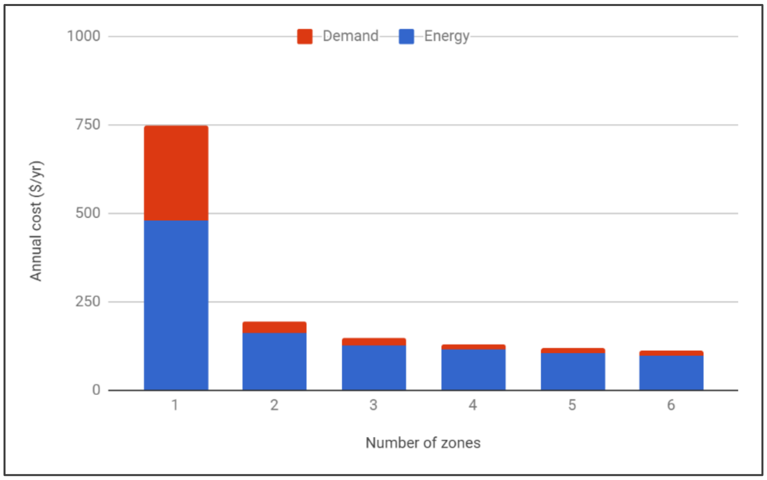

Figure 5.3: Impact of VSD on annual bills

The savings in electricity bills shown in Figure 5.3 represent about 86% of the annual bill before zoning was applied. Less airflow rate and less cooling capacity results in having a significant amount of savings in annual electricity bills.

The consideration of VSD in this chapter is based on operating conditions in Phoenix, AZ. It is good to note that, in the case of heating VSD compressors are not required. The main goal of having a variable-speed compressor is to reduce cooling capacity when only a small portion of the house is occupied. On the other hand, the heat pump does not need a compressor to heat up the house, hence heating supplied to the house is already based on need. In a cold area, such as Chicago, cooling energy consumed annually is much less than heating energy, and as a result VSD would not save a noticeable amount of energy when utilized.

It was shown previously, in Ch. 3.2, that VSD units are not common in the United States, hence not so many households can make use of the results shown in this chapter. Since this study is made to reach out to the highest possible number of homeowners, it is worthwhile to find out how VSD units will affect the payback period. Figure 5.4 presents how the payback period is affected in a house already equipped with a VSD unit. It also shows the payback period for homeowners who are planning to upgrade their aged units to VSD ones, in addition to implementing the approach proposed in this thesis.

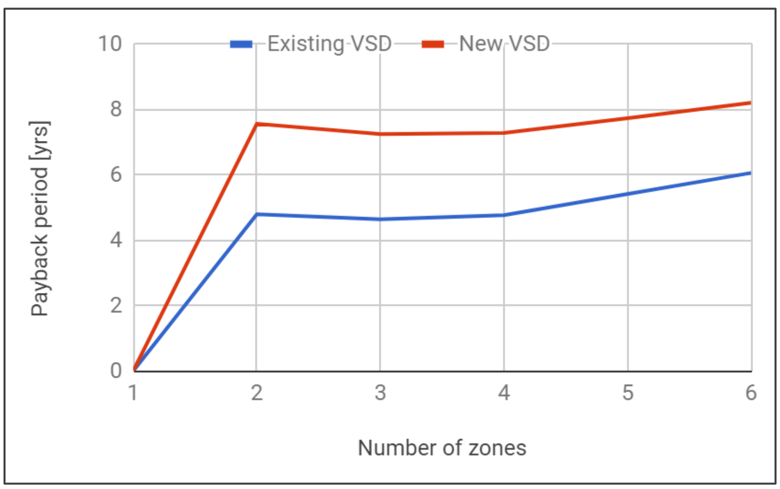

Figure 5.4: Payback period when VSD units are utilized

For homeowners who already have VSD units, investing in splitting their houses to 3 or 4 independent zones can be very attractive since the payback period does not exceed four years, and even in the case of 6 zones the payback period is still around six years. Whereas, for homeowners who are willing to upgrade their existing units the investment is still attractive. A new VSD unit with smart HVAC zoning can have a total payback period of less than 8 years, assuming a new VSD unit costs about $8,000 and a new single-speed unit costs about $5,500 [25].

According to Figure A.2, most homeowners upgrade their HVAC units after about 15 years. Thus, investing in a new VSD unit is still attractive since the HVAC unit will be paying for itself in, at least, 7-8 years before the homeowner has them replaced (or upgraded).

6. CONCLUSION

This thesis showed how HVAC zoning can be effective in saving energy, however due to human errors energy savings of HVAC zoning systems were limited to 20% - 30% [6]. As a result, this thesis suggested to introduce smart thermostats and integrate them with HVAC zoning systems; smart thermostats eliminate human errors and ensure the most comfortable air conditioning in all zones and all rooms.

Theoretical analysis in this thesis showed that the HVAC energy savings can be as high as 80%, which was validated in Chapter 4 by conducting simulation using EnergyPlus software. Simulation analysis also showed that this thesis can be implemented in different climate zones. Although hot areas showed more savings in energy, yet cold climate zones showed very similar results as presented in Figure 6.1. Implementing smart thermostats with zones on all single-family houses in the United States can save the nation 156 billion kWh in site energy savings (see Appendix C). In other words, more than $11.7 billion spent on energy in 2017 can be saved [26]. It turns out that the amount of energy can be saved is equivalent to 116 million metric tons of CO_2, which is the same amount emitted by more than 28 coal-fired power plants in one year [27].

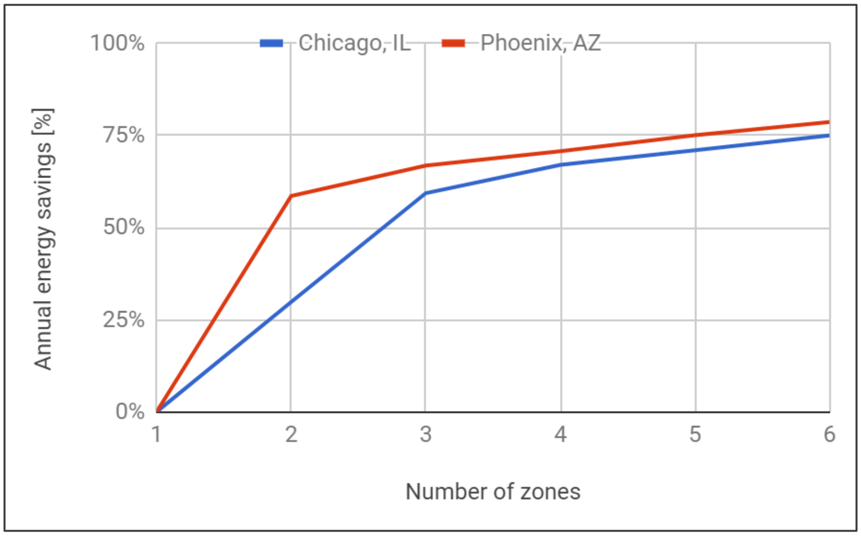

Figure 6.1: Comparison of energy savings in two different locations

In the financial analysis, it was shown that energy consumption is not the only concern that needs to be taken into consideration. It turns out that demand consumption is as important as energy consumption. Thanks to smart HVAC zoning, values of energy consumed and demand were both reduced significantly, which resulted in having savings in annual electricity bills of about 60% and 86% in the case of single-speed drive and VSD compressors, respectively (see Figure 6.2).

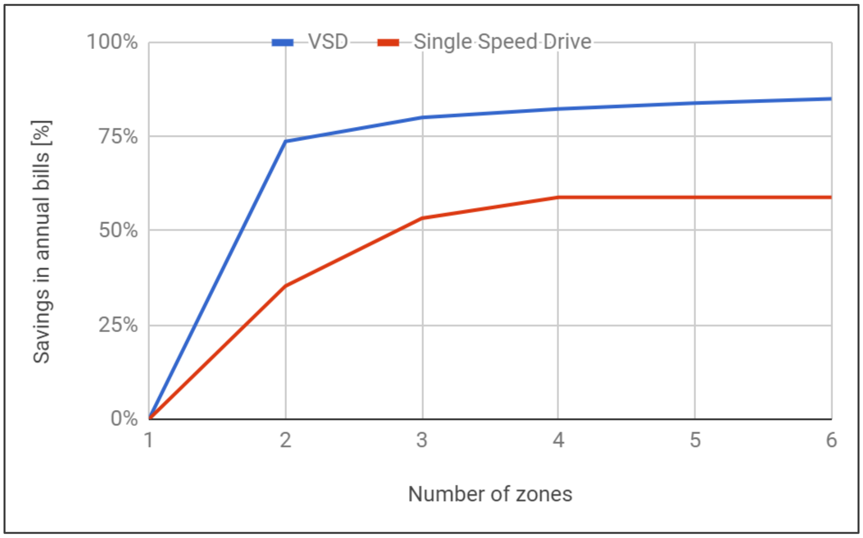

Figure 6.2: Savings in annual electricity bills after implementation of smart HVAC zoning

Generalization of the thesis was not limited to evaluating it in two different climate zones, as households who have existing VSD HVAC units were considered as well. This thesis did not stop there; a new case was made for those who are willing to invest in upgrading their aged HVAC units. In all cases, payback periods were attractive when implementing three or four-zone systems, which turned out to be the ultimate number of zones.

7. FUTURE WORK

Although analysis of this study was validated through simulation software, yet even more validations can be made by conducting an actual experiment. Future work may also include some further analysis to cover houses equipped with more than one HVAC unit. One may suggest to merge the ductwork for existing units and have only one unit serve the entire house with smart HVAC zoning.

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APPENDIX A

TYPE AND AGE OF HVAC EQUIPMENT USED BY MAJORITY OF HOUSEHOLDS IN THE UNITED STATES

APPENDIX A

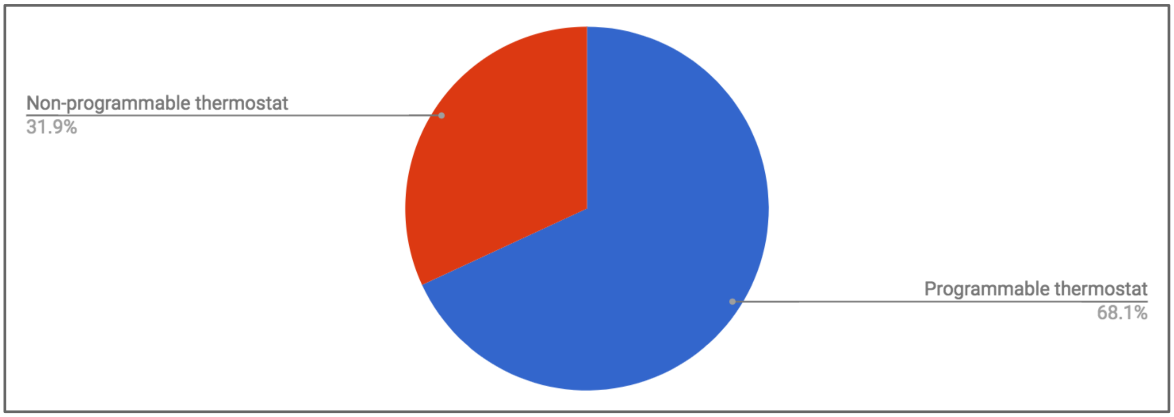

Figure A.1: Percentage of single-family houses equipped with a programmable thermostat [3]

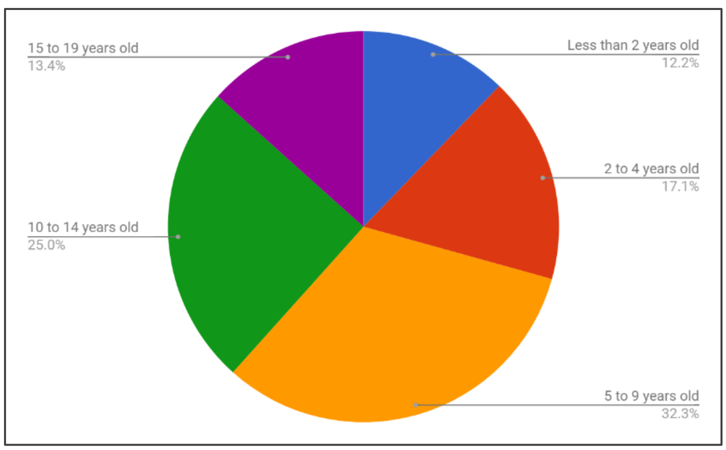

Figure A.2: Age of centralized HVAC units nationwide [3]

Figures A.1 and A.2 give a better understanding of how common programmable thermostats are and how old existing HVAC units are. Since most programmable thermostats have an option to select a fan speed, it can be concluded that most existing HVAC units are relatively new and are assumed to have a multi-speed fan.

APPENDIX B

HVAC EQUIPMENT AVAILABLE IN OPENSTUDIO®

APPENDIX B

According to DOE, HVAC equipment modeled in OpenStudio® are still under development and will be frequently updated to ensure that most equipment in the market are available in the software. Figure B.1 shows that VSD compressors are only available for ductless HVAC units, while Figure B.2 shows the list of available cooling units that can be utilized in the software.

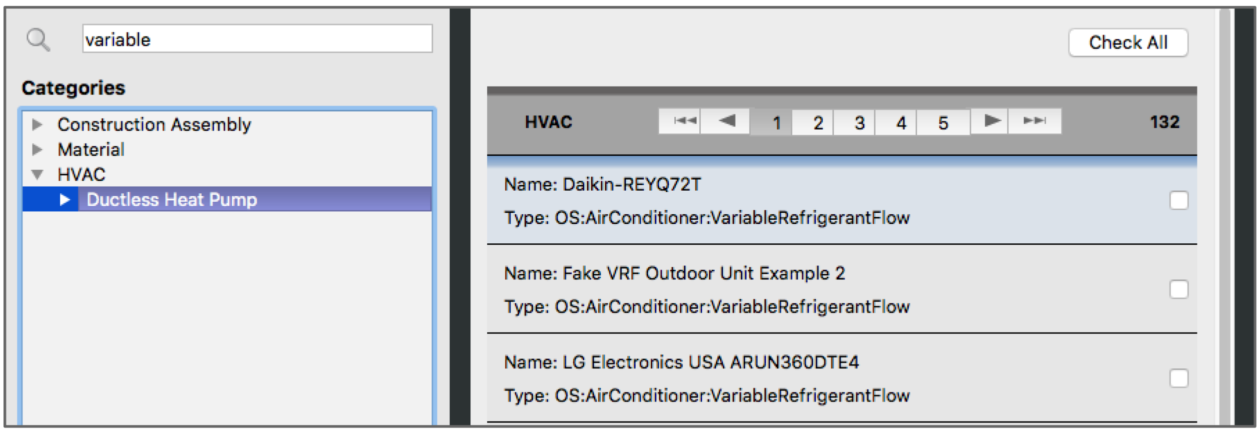

Figure B.1: VSD components are only available for ductless systems

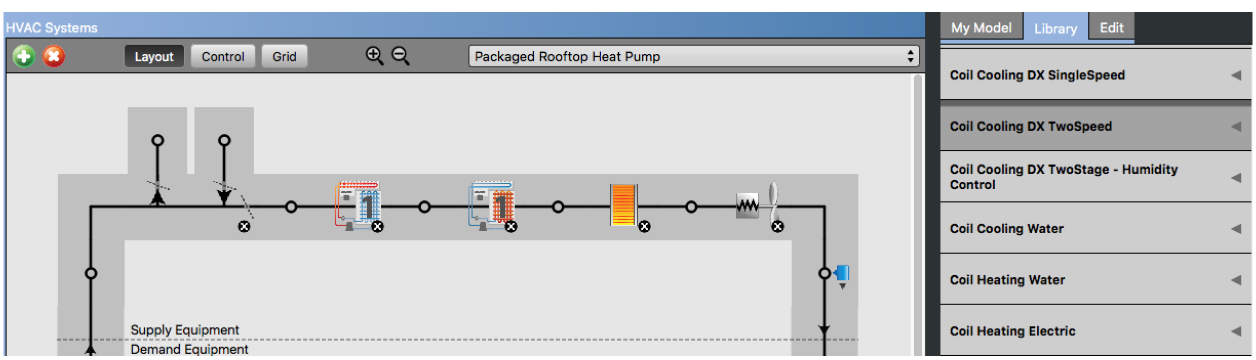

Figure B.2: List of equipment (on the right-hand side) contains only single-speed and 2-speed cooling coils

APPENDIX C

HEATING AND COOLING ENERGY CONSUMED BY SINGLE-FAMILY HOUSES

APPENDIX C

EIA Outlook 2018 showed that the average energy consumed by cooling and heating is about 2800 kWh per household [1]. Using the data collected by RECS 2015, the total number of single-family houses in the United States is about 80 million houses [2]. Accordingly, the total heating and cooling energy consumed in single-family houses alone can be estimated to be 224 billion kWh throughout the year of 2017. Since smart HVAC zoning saves an average of 70% of cooling and heating energy, the estimated total savings of implementation are 156 billion kWh nationwide.

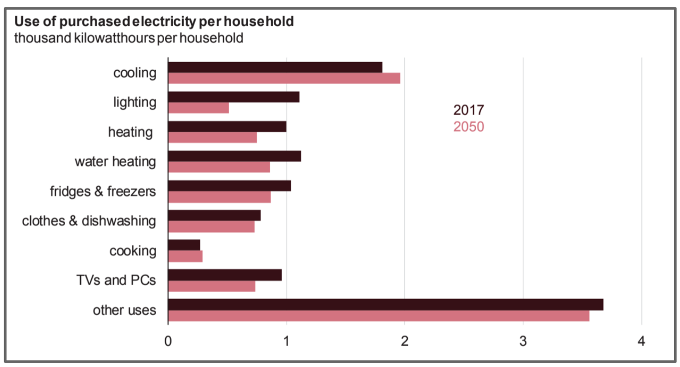

Figure C.1: Electricity consumption per household in 2017 [1]

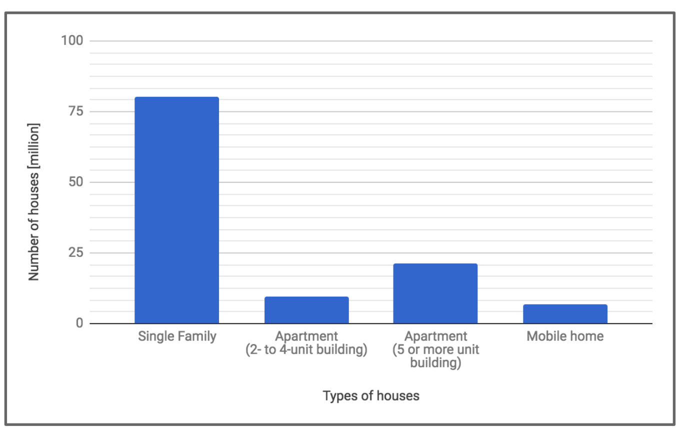

Figure C.2: Types of houses in the United States [2]

APPENDIX D

SAMPLE OF CALCULATION - ENERGY CONSUMPTION

APPENDIX D

Using equations 3.2 through 3.4 and the given information in Table 3.1 the results shown in Figures 3.4 and 3.5 can be found as follows:

$$\dot{Q}_{required} = \dot{m} \times C_p \times \frac{T\_gained}{hour}$$

Mass flowrate ($\dot{m}$) can be found using the airflow supplied by the HVAC system and the density of air at a given temperature. In this case, the ambient temperature at 2 PM on August 30th is 32°C, according to table 3.1 T_{gained} is approximated to be 4 degrees. Since the house is expected to be cooled down to 25°C, the density of air is found to be 1.16 kg m^{-3} and the specific heat is found to be 1.007 kJ kg^{-1} K^{-1} [15]. The maximum airflow rate can be supplied by the HVAC system is 1.32 m^3/s (2,800 CFM) [13]. Thus:

$$\dot{Q}_{required} = (1.16\frac{kg}{m^3}.1.32\ \frac{m^3}{s})(1.007\frac{kJ}{kg.K})(\frac{4^oC}{hour})$$

$= 6.2\ kWh$

And then,

$$E_{required} = \frac{\dot{Q}_{required}}{COP}$$

$$= \frac{6.2\ kWh}{2.5} = 2.5\ kWh$$

And that is how the values in Figure 3.4 were found (before zoning). After zoning, however, the amount of heat to be removed is less due to having smaller area. At 2PM the kitchen zone and living zone are expected to be occupied, using the rule of thumb the amount of cooling required for those zones is:

$$Zone_{requirement} = \frac{98\ m^2}{37\,\frac{m^2}{RT}}$$

$$= 2.65\ RT$$

This estimates the amount of cooling required in the case of only supplying conditioned air to the living zone and the kitchen zone. As a result, those two zones require about 40% of the total HVAC capacity (7 RT). Since it was assumed that the HVAC unit is equipped with a single speed compressor, the amount of cooling should be either 60% or 30%. Provided the fact that the occupants' comfort may be compromised by supplying only 30% of cooling, the HVAC unit is assumed to supply 60% at that specific hour to ensure occupants' comfort. Thus:

$$E_{zones} = 0.6 \times 2.5\ kWh$$

$$= 1.5\ kWh$$

And that represents the amount of energy expected to be consumed at 2 PM after zoning is applied.

In this thesis, the value of COP was assumed to be 2.5 based on the fact that most HVAC units are in the age range of 10 years [3] (see Appendix A). Referring back to the HVAC units manufactured in 2007 – 2008 the COP value of 2.5 is reasonable. It is worthwhile to highlight that the value of COP was used to estimate the impact of energy over a given period of time and higher values of COP do not affect the percentage of saving. The reason is that as the load of the zone changes, the requirement of cooling changes accordingly. Thus, the COP value will not have a significant impact on the percentage of savings.

$$Energy\ Savings\ \% = \left(1 - \frac{E_{zone}}{E_{required}}\right) \times 100$$

$$= \left(1 - \frac{\frac{\dot{Q}_{zone}}{\cancel{COP}}}{\frac{\dot{Q}_{required}}{\cancel{COP}}}\right) \times 100$$

$$= (1 - \frac{\dot{Q}_{zone}}{\dot{Q}_{required}}) \times 100$$

$\dot{Q}_{required}$ in this equation represents the total amount of heat required to be removed before zoning, hence from the entire house.

In the case of VSD, the percentage of motor speed is not limited to 66% or 33%. Instead, it will vary and match the need of the zones' load, hence the kitchen zone and the living zone can be supplied with 40% instead of rounding up to 60%. Even in the case of supplying conditioned air to the living zone alone in the afternoon, the compressor can run at about 25% of its full capacity, and that is what makes the VSD compressor highly efficient with Smart Zoning.