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Energy Savings from Residential Zoned Air Distribution Systems

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Abstract

Unlike commercial buildings in which space heating and cooling is often optimized by zone, most Minnesota homes have forced air distribution systems with constant flows to all branches or zones. The entire house is heated or cooled based on the needs of the space where the thermostat is located. Nonuniform solar gains, internal gains, and air infiltration loads that vary throughout a day or season result in areas of the house that are over- or under-heated and cooled. This can result in uncomfortable conditions and potentially wasted energy. Residential multizone systems are available to address these concerns, but utilities have not provided incentives for them as an energy savings measure.

This project assessed the energy savings opportunities for residential multizone air distribution systems. The results include findings from interviews with equipment distributors, HVAC contractors, and utilities. Energy simulations of one- and two-story houses with single-zone and multizone distribution systems helped evaluate the impact of over- and under-heated and cooled areas on annual energy use. They also estimated the potential energy savings that multizone systems can achieve with more strategic temperature setbacks for individual zones.

Stakeholder interviews found that almost all major HVAC manufacturers have pre-packaged multizone systems for furnaces and heat pumps. About a quarter of new Minnesota homes have multizone systems. The systems are primarily installed in larger homes for improved comfort. Improved energy efficiency could be another benefit, but no Minnesota or U.S. utilities currently offer energy efficiency incentives for multizone systems. Minnesota utilities expect that energy savings could be a strong secondary benefit. The greatest barrier for incorporating multizone systems in their programs was uncertain energy savings or not being able to compute energy savings.

The modeling results from this project indicate that space heating savings could be more than 10% and cooling savings could be more than 35%. For example, the modeling estimated that a multizone system that reduced the heating season average basement and second-floor temperatures by 2°F in a newer home would reduce annual heating energy use by about 12%. A significant setback of the basement temperature could also reduce energy use by over 10%. On the other hand, a house with a single-zone system that has under-heated areas would have improved comfort but up to 15% more energy use if updated to a multizone system. There appears to be significant potential for multizone systems to reduce cooling energy use. The change in energy use for a baseline single-zone scenario compared to that of a multizone system ranged from 27% to 50% and averaged 38%.

Zonal air temperature measurements in six homes suggest that installing multizone systems in older Minnesota homes will typically improve comfort, increase space heating energy use, and decrease cooling energy use. Since no measurements were available for newer houses, it is not known whether multizone systems will typically increase or decrease space heating energy use. Additional research is necessary to confirm and expand the energy use equations generated by this project. Field studies are also needed to document typical zone temperatures and possibly identify house characteristics that are likely to generate greater savings.

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Definitions of Terms and Acronyms

AC	Air conditioning
ACH50	Air changes per hour at 50 Pa
AFUE	Annual fuel utilization efficiency
CARD	Conservation Applied Research and Development
CAV	Constant air volume
CIP	Conservation Improvement Program
COP	Coefficient of performance
DOE	Department of Energy
ECM	Electronically commutated motors
EIA	Energy information administration
eQUEST	Quick energy simulation tool
ERV	Energy Recovery Ventilator
HVAC	Heating, ventilation, and air conditioning
HRV	Heat recovery ventilator
Inter-zone TD	Difference between the average basement and second-floor temperatures and the first-floor temperature where the thermostat is located
MZ	Multizone
NOAA	National Oceanic and Atmospheric Administration
PSC	Permanent split capacitor
SEER	Seasonal Energy Efficiency Ratio
TRM	Technical Reference Manual
VAV	Variable air volume
VRF	Variable refrigerant flow

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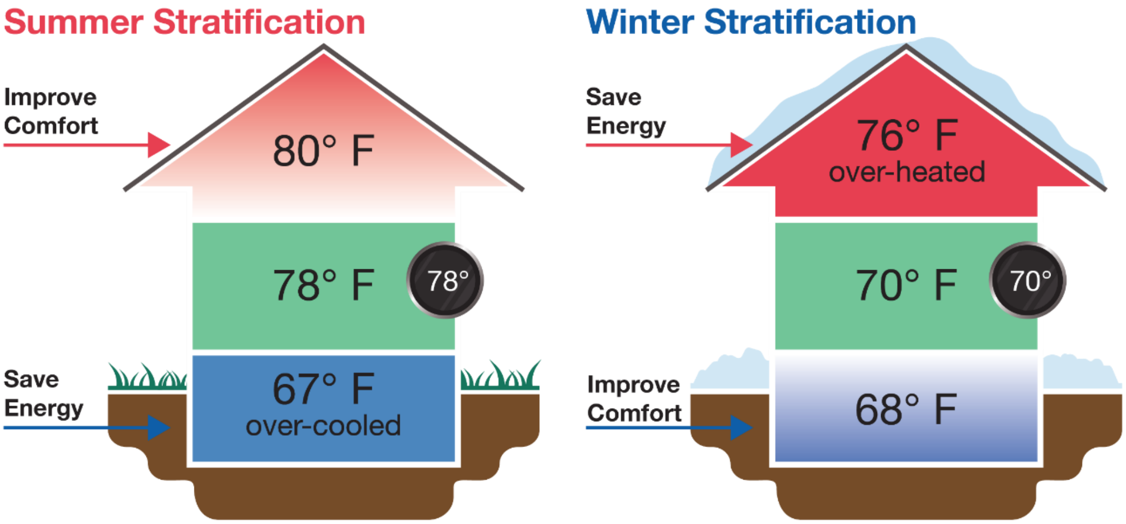
Executive Summary

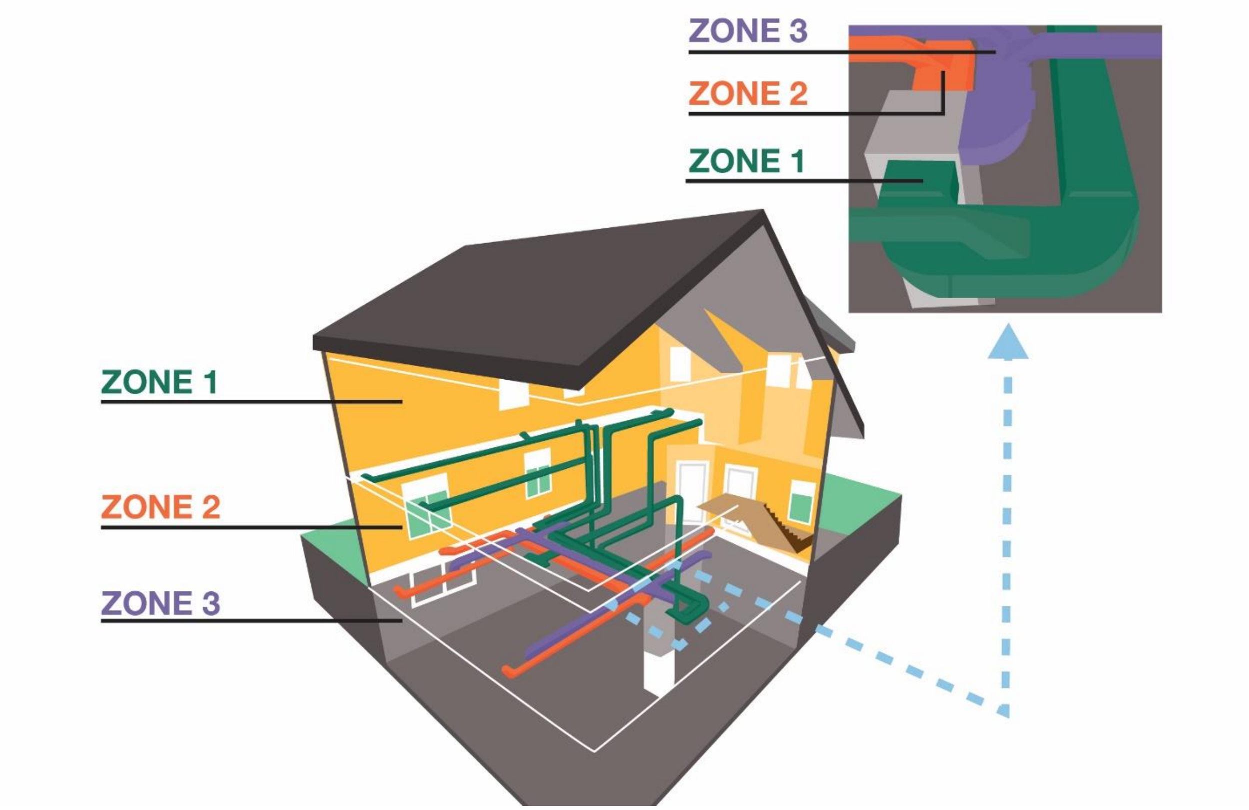
Unlike commercial buildings in which space heating and cooling is often optimized by zone, almost all forced air distribution systems in Minnesota homes provide air to all branches or zones of the system. These are referred to as single-zone distribution systems. The entire house is heated or cooled based on the needs of the space where the thermostat is located. Nonuniform solar gains, internal gains, and air infiltration loads that vary throughout a day or season result in areas of the house that are over- or under-heated and cooled. This can result in uncomfortable conditions and potentially wasted energy. The diagrams displayed in Figure 1 show examples of typical temperature variations by floor. The house on the left shows a summer situation where there isn't enough cooling to the second floor, and it is warm. There is more cooling than needed in the basement and it is cold. As a result, the second floor is uncomfortable and extra energy is used to cool a basement that doesn't need cooling. The diagram on the right shows a winter situation where the second floor is over-heated, causing more energy to be used than needed. The basement is cooler than desired. Residential multizone systems are available to address these concerns.

Figure 1. Example of summer and winter air temperature stratification



A multizone air distribution system automatically controls the heating or cooling through each branch of the ductwork to keep the air temperature of the areas at the desired level. Each area or zone has a temperature sensor that the multizone controller uses to activate the heating or cooling plant, the air handler, and supply duct dampers. As shown in Figure 2, single-family multizone systems often use a separate zone for each floor of the house. Factory-integrated multizone systems are shipped with all zoning controls and dampers pre-installed. The most effective systems adjust the heating or cooling output and air handler airflow rate based on the zones that need heating or cooling.

Figure 2. Diagram of duct layout for multizone system in a two-story house



Objectives

The overall project goal was to assess the energy savings opportunities for residential zoned air distribution systems for new and existing Minnesota single-family houses. The project had six goals, detailed below.

1. Review published information about residential zoned systems available for retrofit and new installation.
2. Describe the current market in Minnesota.
3. Model heating and cooling energy use for prototype Minnesota houses.
4. If warranted, generate a Technical Reference Manual measure for existing houses and recommend modeling for new home performance.
5. Determine whether additional research to better establish energy savings estimates and improve market penetration in Minnesota would be useful.
6. Estimate potential for energy use and carbon reductions if fully applied in Minnesota.

Technology Assessment

Product information was gathered for eight major equipment manufacturers of residential heating and cooling systems for the U.S. market. Results were:

- Seven of the eight have multizone packages for their furnaces, heat pumps, and air conditioners. While the eighth did not make a multizone package, there is a third-party manufacturer that has a package that interfaces with its equipment.
- All the manufacturers offer the multizone package for both furnaces and heat pumps except one which only offers it for heat pumps.
- Most of the furnaces and heat pumps have variable capacity, but some have only two stages.
- All the air handlers have ECMs for their fans.
- The packages use wired damper controls and all except one manufacturer have a smart phone application for system control.
- The systems found can accommodate from three to 16 zones depending on the specific manufacturer.
- All but one of the manufacturers have Wi-Fi linked applications.

Information was also collected for six third-party manufacturers that provide zoning equipment. Key information for the major manufacturer and third-party systems is shown in Appendix B.

The project team also identified and reviewed published information on residential zoned air distribution systems. Ten key references were divided into the following five categories and a list of other publications is included in Appendix A.

- Technology Assessment. A PNNL study (Metzger, Goyal, and Baechler 2017) investigates advanced HVAC control components used for commissioning, maintaining, and efficient operation of residential HVAC equipment. It provides an overview on the market characteristics, challenges, and impacts of advanced controls on energy savings in the residential building sector.
- Design Guide. A CanmetENERGY report (Natural Resources Canada 2017) assists mechanical designers with zone duct design guidelines. The Canmet project also produced a Zoning Decision Guide for Builders and papers that assess heating and cooling season peak demand and energy savings for a high velocity, zoned, combination system.
- Modeling Study. A NYU and Purdue University study (Lu and Warsinger 2020) examined energy model simulations of constant air volume (CAV) and multizone (MZ) variable air volume (VAV) systems to evaluate MZ VAV energy-saving potential. This research describes eQUEST energy model simulations of two different sized houses (average and large) with CAV-VAV systems made for all seven climate zones in the United States. The results indicate that lower fan and cooling energy use reduces VAV source energy costs (. Cooling energy reductions ranged from 36% to 51% for the average household. The VAV systems produced little space heating savings. This occurred because heating loads were higher during the night when the houses were occupied (and there was no setback) and the setback temperature was smaller relative to the difference in inside versus outside temperature.

- Laboratory Studies. An experimental study was conducted by the University of California, Davis, (Krishnamoorthya, Modera, and Harrington 2017) which evaluated the variable capacity heat pump operations and effects of both compressor and indoor fan airflow to achieve maximum system efficiency in hot and dry climates. The authors conducted and measured system operation results under two different modes: (a) total equipment capacity and blower airflow are synced and varied between 40% and 100% and (b) the equipment capacity is kept constant at various measurements and airflow is varied in 20% increments from 60% to 100%. Laboratory tests were conducted for a variety of outdoor and indoor conditions. The key findings highlight the importance of duct system insulation, leakage, and location.

  A laboratory study by Lawrence Berkeley National Laboratory (Walker 2003) investigates the impacts of conditioning fewer spaces by closing registers when the rooms are unoccupied as a means for energy savings in California. The authors tested two combinations of sequences for closing registers. Key findings were that closing registers increases the duct system pressures, therefore increasing the duct leakage for supply leaks. For the same number of closed registers, the closed registers near the supply can cause high duct leakage because of high pressures. For cooling systems, reducing air handler flow reduces the heat exchanger efficiency. The no duct leak system configuration has the highest airflow changes when registers are closed. REGCAP simulations indicate that closing registers does not save energy — in fact, more registers closed leads to higher energy usage.

- Field Studies. Research by CanmetEnergy (Sager, Armstrong, and Szadkowski 2013) compares heating season energy and comfort performance for homes with single and zoned air distribution systems. The performance of a zoned system that consists of a high velocity air distribution system with two zones (1- upper level and 2- main floor and basement) is compared to a low velocity, single-zone air distribution system. The zoned system showed 6% higher energy savings compared to the standard reference system. The single-zone system did not provide an acceptable level of comfort because of the poor match between the airflow to each floor and the cooling loads. The multizone configuration was able to maintain comfort compared to the single-zone system.

  A second study by CanmetEnergy (Sager, Glazer, Szadkowski, and Strack 2013) compares cooling season energy and comfort performance for homes with single-zone and multizone air distribution systems. The multizone system consists of a high velocity air distribution system with two zones. That is compared to low velocity, single-zone air distribution system. The zoned systems had a higher daily average cooling energy use than the non-zoned systems. The higher use was due to the additional fan energy needed to move air through the small ductwork. The zoned system used 36% less on peak energy for cooling. It was noted that high-velocity zoned combination systems cooled the second floor to the desired room temperature while the non-zoned system was not able to achieve the desired temperature for the second floor.

  A third CanmetEnergy study (Mountain, Strack, Zhou, and Lomanski 2011) evaluated the demand response capabilities of residential zoned cooling systems during summer peaks. Electrical demand for the summer peak period was compared for zoned and non-zoned systems with and without load control. Different zones are controlled during the peak demand period.

Utility interruption of ZC houses provided a 17% reduction in AC and air handler load. Effective load reduction could be achieved by only interrupting the top floor cooling. Two thirds of the sample felt that controlling cooling for individual zones was preferred to controlling cooling for the entire house. The ZC systems provided better comfort of the top floors during the nighttime.

A fourth CanmetEnergy study (Mountain, Strack, and Sager 2011) conducted an experimental analysis of 20 ZoneComfort (ZC) systems located in different Canadian regions. Statistical models used to estimate ZC systems' incremental conservation contribution. ZC systems saved 7% in natural gas, 36% in AC electricity, and compressor electricity, and 7% air handler electricity. The ZC systems were able to provide better comfort on the top floor on peak demand days.

A Davis Energy Group study (Haile and Springer 2017) evaluated the impact of smart zone control systems by assessing fan efficacy and system airflow in various operating scenarios. Both systems largely performed as intended. However, in some circumstances, smart damper systems resulted in larger duct losses and lower airflow rates, decreasing total system efficiency. Significant adjustments to the static pressure in the main branch were advised before energy savings could be realized.

Market Research

The objective was to discover where zoned systems are currently being installed, their technical potential, and barriers that would limit implementation.

Results of five distributor interviews:

- Almost all suggested that multizone systems were more common in high-end new construction
- Almost all indicated that 10% to 50% of new homes with central air distribution have zoning equipment. This is consistent with a recent new study of new Minnesota homes that found that 22% of the furnaces had zoning equipment (95% confidence interval of 14% to 33%, Pigg 2022).
- All the distributors identified direct control to individual zones and comfort as multizone systems' primary benefits, while a few suggested the potential for energy savings with modulating airflow rates.
- A few distributors suggested there had been a rise in market growth due to increased awareness of these systems, while others reported a stagnant market or gradual decline due to the emergence of new systems such as cold-climate air source heat pumps including ductless mini splits.
- Most distributors suggested that utility incentives for MZ systems could assist market growth.

Results of six contractor interviews:

- All contractors overwhelmingly expressed cost and zoning setup as challenges, especially in existing homes due to the absence of separate trunk lines.
- Three of the five contractors indicated comfort control as multizone systems' primary benefit, while energy savings were less impactful.

- All contractors agreed that zoning achieved high efficiency results with communicating variable speed systems, which could minimize the airflow rate restrictions compared to single stage models.
- Two contractors and a developer indicated that the typical additional cost to upgrade from a single-zone to multizone system ranged from $2,000 to $3,500 for a two-zone system and $3,500 to $6,000 for a three-zone system.
- Three contractors suggested that utility incentives for multizone systems could help encourage market growth, while the remaining two maintained that the market would remain stagnant due to high installation costs.

Results of three third-party suppliers of zoning equipment:

- All third-party providers of zoning equipment acknowledged that comfort and control were the systems' primary benefits.
- Two parties suggested that heating energy savings were impactful depending on utility rates and the overall system utilization.
- Complex installation processes, system operation, and high costs were the major concerns with these systems.
- The providers suggested different ways to address airflow rate restrictions such as the use of a dump zone or bypass zone and system modulation.
- All providers indicated that most of their control systems were compatible with both communicating and non-communicating HVAC systems.

Information was collected from 11 U.S. utilities to identify residential efficiency programs outside Minnesota that provide incentives to upgrade from a central, single-zone air distribution system to a multizone system. Many utilities provided upgrade incentives for the rated efficiency of furnaces, heat pumps, and air conditioners. However, this process did not identify any U.S. utilities that are currently providing incentives to upgrade from single-zone to multizone air distribution systems. Five utilities had conducted multizone system pilot projects. There were no reports available for the pilot projects. The limited information available is included in the Results section.

All four Minnesota utility representatives who provided feedback were familiar with residential multizone systems. The utilities had not evaluated the technology and had not considered incorporating it into their residential programs. One of the utilities was aware of a Canadian program that provided incentives for multizone systems, but the other three were not aware of any utility incentive programs. The utilities expected that the systems will primarily provide improved comfort, but energy savings could be a strong secondary benefit. The greatest barrier for incorporating multizone systems in their programs was uncertain energy savings or not being able to compute energy savings. It was also noted that the added cost might be a difficult sell to customers, the benefit may be demand reduction that does not provide a cost benefit to the customer, and the challenge of identifying houses where there will be savings. One of the utilities indicated that there may be a benefit to establishing a national utility working group and that the technology could provide demand reduction options. Another utility was interested in learning more about the cost effectiveness of retrofit installations.

Energy Modeling

The Energy Simulations section presented the results for a series of building energy simulations with different distributions of zonal airflow rates for the single-zone system. The simulations were performed for four house models with one or two stories and were configured to mimic new home and 1950s–1960s construction. Varying the distribution of the zonal supply airflow creates over- and under-heated or cooled zones and the degree of over- and under-heating often varies seasonally. For all four models the percent change in heating energy use for a single-zone system compared to a multizone system is strongly linearly related to the difference between the average basement and second-floor temperatures and the first-floor temperature (e.g., inter-zone TD). The same relationship holds for cooling energy use. The slope indicates the percent change in energy use for each 1°F increase in the inter-zone TD. For heating energy use the slopes ranged from 2.1% to 6.5% and averaged 4.4%. The number of stories for the models did not have as significant an effect on the results as the difference in the thermal characteristics. The average slope for the new home models was 2.55 times greater than the average for the existing home models. This suggests that energy savings results for a two-story model could be applied to a one-story house, but variations in house insulation and air leakage will significantly impact energy savings estimates. Equations (1) and (2) can be used to compute the heating season energy use for a multizone system from the energy use for a single-zone system and the inter-zone TD.

Multizone systems could provide significant space heating energy savings for houses that have basements and/or second floors that are over-heated. For example, reducing the heating season average basement and second-floor temperatures by 2°F in a newer home is estimated to reduce annual heating energy use by about 12%. However, multizone systems could also increase energy use. Zonal temperature measurements from a limited sample of three one-story and three two-story older houses showed that for five of the six houses, the basement was cooler than the first floor for both the heating and cooling seasons. One house had a warmer basement in the heating season and cooler basement in the cooling season. For that house, a multizone system should provide more comfortable conditions and energy savings. For the other five houses, the improved comfort of a multizone system would likely increase energy use. For the three two-story houses, the second-floor temperature for one house was very similar to that of the first floor. For the other two houses, the second-floor temperature was cooler than the first-floor temperature in the heating season and warmer than the first floor in the cooling season. For those two houses, a multizone would provide improved comfort and likely increase energy use. This small sample suggests that installing multizone systems in older Minnesota homes will typically improve comfort and increase energy use. Since no measurements were available for newer houses, it is not known whether multizone systems will typically increase or decrease space heating energy use. Additional research that would help determine the potential for multizone system energy savings is discussed in the Future Research section below.

The analysis of heating season energy use and inter-zone TD was also conducted for the cooling season results. There is more variation in the cooling season models than in the heating season models. There was a 14% difference in the regression slopes for the one- and two-story new home models and a 37% difference for the two existing home models. The average slope for the new home models was 0.63 times that of the average for the existing home models. Results from the new home and existing home models were combined to generate the energy change equations (4) and (5). There appears to be significant potential for multizone systems to reduce cooling energy use. The change in energy use for a baseline single-zone scenario compared to that of a multizone system ranged from 27% to 50% and averaged 38%. In addition, the temperature measurements of a limited sample of Minnesota houses showed that for five of the six houses, the basement was cooler than the first floor for both the heating and cooling seasons.

CIP Recommendations

There appears to be significant opportunity for multizone systems to provide space conditioning energy savings for new Minnesota homes. Distributor feedback from this project and the results of a recent new home study (Pigg 2022) indicate that about a quarter of new homes with air distribution systems include zoning. The modeling results from this project indicate that space heating savings could be more than 10% and cooling savings could be more than 35%. However, estimating savings for a multizone system compared to a single-zone system is not as simple as comparing the efficiency of two different systems. The potential for a multizone system to reduce space conditioning energy use primarily depends on the operation of the single-zone system being used for comparison.

A multizone system can save heating energy when a single-zone system over-heats one or more zones during the heating season. Similarly, a multizone system can save cooling energy when a single-zone system over-cools one or more zones during the cooling season. The opposite can also occur. When a zone is being under-heated in the winter by a single-zone system, a multizone system would increase the temperature of that zone to make the space more comfortable and increase energy use in the process. Additional research is necessary to confirm and expand the energy use equations generated by this project. Field studies are also needed to document typical zone temperatures and possibly identify house characteristics that are likely to generate greater savings.

TRM Additions

An addition to the Minnesota TRM to estimate multizone system savings is not recommended. Since multizone systems are primarily used for new homes, incentivizing multizone systems for new homes appears to be the best opportunity to generate space heating and cooling energy savings. It is possible that equations (1) and (4) provide reasonably accurate estimates of the space heating and cooling energy for multizone systems compared to single-zone systems. Those relationships should be confirmed by field studies. Field studies are also needed to document typical and the range of inter-zone TDs for a representative sample of new homes.

Future Research

This project developed EnergyPlus models with CONTAM generated air infiltration and inter-zone airflows for simulations of single-zone and multizone air distribution systems for four house configurations. The seasonal trends in zone air temperature matched some of the trends from six actual houses' measurements. This white paper study was not intended to verify the model estimates of multizone energy savings, nor was it expected to model a wide range of house characteristics necessary to predict energy savings for a high fraction of Minnesota housing.

Additional analysis of results for models that systematically vary the level of wall insulation, attic insulation, total house air leakage, and inter-zone airflow rates along with the distribution of air leaks is required to establish savings equations that can be applied to a broad range of houses. In addition, field studies are needed to verify these relationships. The studies could include the following.

- Alternate mode type studies with measurements of heating season zonal temperatures and space heating energy use when the distribution of supply airflow is manually adjusted at two- to four-week intervals. This would help confirm the linear relationship between changes in energy use and zonal temperatures.
- Measurements of annual space heating energy use before and after a single-zone system is replaced by a multizone system would confirm modeled energy savings estimates. Alternatively, it may be possible to operate a multizone system as a single-zone system and compare the energy use of the single-zone operation to that of the multizone operation.
- Measurements of heating season zonal air temperatures for a significant number of new and existing homes would document the degree of over- or under- heating and cooling for houses and predict whether multizone systems will typically reduce or increase energy use. This may identify specific housing characteristics that could be used to predict houses that are more likely to have reduced energy use, so those houses could be targeted for utility energy efficiency program incentives.

Background

Unlike commercial buildings in which space heating and cooling is often optimized by zone, almost all forced air distribution systems in Minnesota homes provide air to all branches or zones of the system. These are referred to as single-zone distribution systems. The entire house is heated or cooled based on the needs of the space where the thermostat is located. Nonuniform solar gains, internal gains, and air infiltration loads that vary throughout a day or season result in areas of the house that are over- or under-heated and cooled. This can result in uncomfortable conditions and potentially wasted energy. Residential multizone systems are available to address these concerns, but utilities have not provided incentives for them as an energy savings measure.

Central air distribution systems supply conditioned air from a single heating and/or cooling source throughout the home via a network of ducts. Heating is most often provided by a furnace and/or heat pump and cooling is provided by a heat pump or air conditioner (AC). A single-zone system typically has manual balancing dampers to adjust the fraction of air through each branch of the ductwork. Once the manual dampers are adjusted, the same fraction of air is delivered to each branch whenever the air handler operates.

A multizone[1] air distribution system automatically controls the heating or cooling through each branch of the ductwork to keep the air temperature of the areas at the desired level. Each area or zone has a temperature sensor that the multizone controller uses to activate the heating or cooling plant, the air handler, and supply duct dampers. As shown in Figure 3, single-family multizone systems often use a separate zone for each floor of the house. In the figure, the green colored branch serves the second floor, the orange branch serves the first floor, and the fuchsia branch serves the basement. The wired supply duct dampers are located near the central plant before each branch splits further into additional branches. Factory-integrated multizone systems are shipped with all zoning controls and dampers pre-installed. The most effective systems adjust the heating or cooling output and air handler airflow rate based on the zones that need heating or cooling. Systems can use a bypass damper when the required airflow rate is less than the air handler minimum, but this will lower system efficiency and increase energy use (Canada, Natural Resources 2017).

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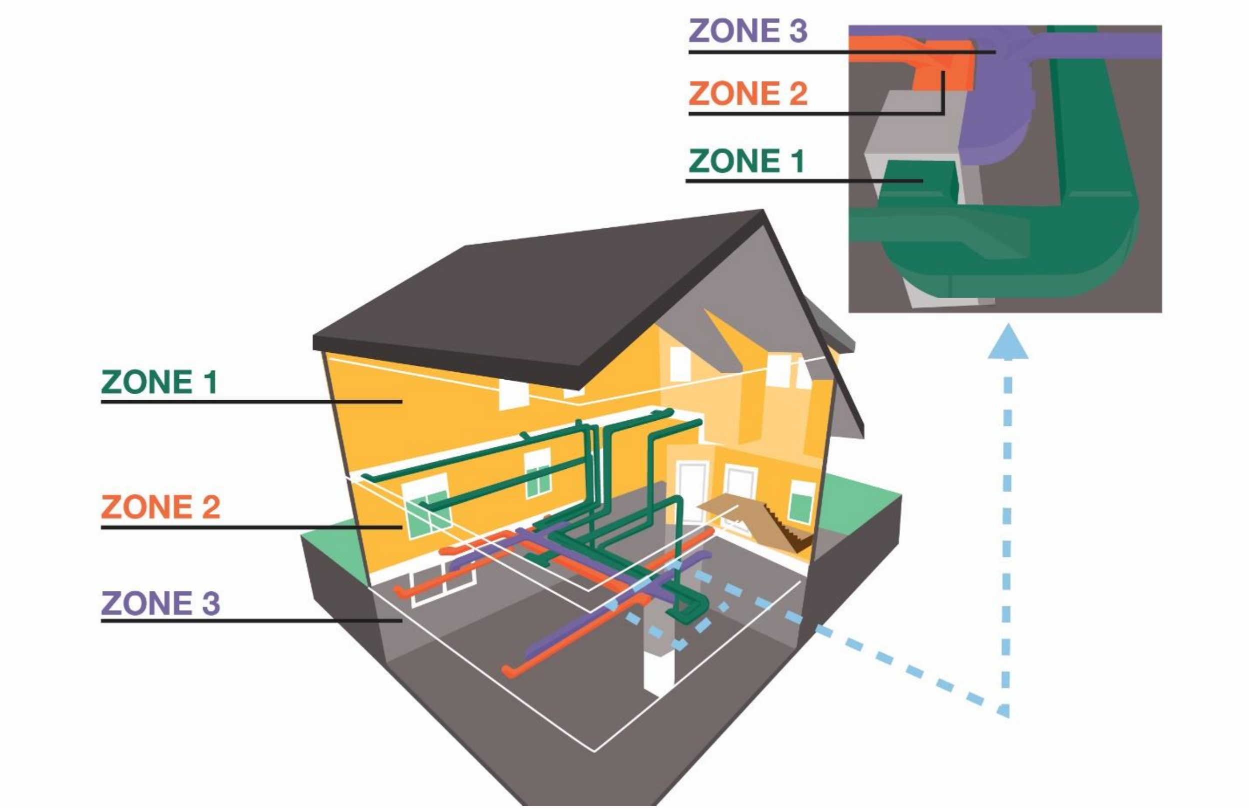
[1] A variety of methods can be used for zoned heating and/or cooling, including electric baseboards, hydronic baseboards, and mini-split ductless heat pumps. This project only focused on multizone air distribution with central heating and/or cooling. These systems are sometimes referred to simply as zoned systems.

Figure 3. Diagram of duct layout for multizone system in a two-story house



Zoned systems may be more appropriate for some types of homes than others and may be more effective in new homes than in retrofits, but the information to support energy savings decisions is not readily available. A small study in Canada reported that 70% of homes reduced energy use with zoned systems and 90% said comfort was improved. The current study combines information from literature research with energy modeling, using home designs based on Minnesota's actual building stock to fill the information gap.

Energy Savings Potential

Most studies to date focus on warmer climates with greater space cooling loads in which multizone systems are thought to have great savings potential. Those studies show HVAC savings of up to 30%; they focus on cooling and thus the ability to manage zone-to-zone variations in solar heat gain, especially in houses with large and concentrated window areas or cathedral ceilings with insufficient insulation. Because these studies have largely concerned warmer climates, there is a lack of data for Minnesota's homes, even in the commonly studied home configurations such as townhouses, multi-story homes with difficult-to-balance airflow, and homes with living and sleeping spaces on the same floor. Further, the homes studied typically lack features found in Minnesota's heating-dominated climate that can create time-varying, zonal differences in thermal loads, caused by basements, tuck-under garages, and envelope leakage. In late winter and spring, basements tend to be much cooler than first and second floors, and in Minnesota it is more common for basements to be used as living spaces. Homeowners do not typically adjust manual duct dampers to account for seasonal variations in space heating needs. In addition, stack effect induced air infiltration can cause higher space-conditioning loads for the first floor than for the second floor during colder winter weather.

Space heating energy savings in cold climates could approach those for space cooling in warmer climates if occupants are over-heating some spaces to bring others to an acceptable temperature. The impact of scheduling offers a distinct opportunity, as living spaces don't need to be kept as warm overnight and sleeping space temperatures can often be set back during the daytime.

Objectives

The overall project goal was to assess the energy savings opportunities for residential zoned air distribution systems for new and existing Minnesota single-family houses. The project had six goals, detailed below.

1. Review published information about residential zoned systems available for retrofit and new installation.
2. Describe the current market in Minnesota.
3. Model heating and cooling energy use for prototype Minnesota houses.
4. If warranted, generate a Technical Reference Manual measure for existing houses and recommend modeling for new home performance.
5. Determine whether additional research to better establish energy savings estimates and improve market penetration in Minnesota would be useful.
6. Estimate potential for energy use and carbon reductions if fully applied in Minnesota.

Methodology

This study consisted of four primary tasks:

1. The first was a technology assessment to collect manufacturer information and research reports on multizone distributions systems.
2. The second was market research to gather information on design approaches and equipment options for retrofits and new installations.
3. The third was energy modeling to compare the energy use and comfort of single-zone and multizone distribution systems.
4. Findings from the first three tasks were used to generate recommendations for including multizone distribution systems in Minnesota utility energy efficiency programs.

Technology Assessment

The technology assessment collected manufacturer information and research reports on multizone distributions systems. This effort focused on products and research with the greatest potential for energy savings for the Minnesota single-family market. Product information was gathered for seven major equipment manufacturers of residential heating and cooling systems for the U.S. market and for six third-party manufacturers of zoning equipment. The project team also identified and reviewed published information on residential zoned air distribution systems. The proposal development process identified reports from more than four U.S. and Canadian sources. This literature review was expanded to include references from those reports and searches of energy efficiency publications, ESource technology queries, and academic journals. A summary of the most relevant publications is included in the Results section and a list of other publications is included in Appendix A.

Market Research

The objective was to discover where zoned systems are currently being installed, their technical potential, and identify barriers that would limit implementation. The task included distributor, third-party manufacturer, mechanical contractor interviews to assess the current state of the market in Minnesota and which products are best for specific home configurations. Outreach to a sample of U.S. utilities was used to determine whether any of the utilities offer incentives for multizone systems. Structured interviews with utility program staff helped better understand interests and concerns regarding the inclusion of residential zoned systems in their CIP portfolios.

Stakeholder Interviews and Surveys

Distributors for Major Manufacturers

Five Minnesota residential HVAC distributors were interviewed. The interviews were conducted in conjunction with a separate CARD research project on residential furnaces. The interview questions shown below were added to the questions for that project. An option to interview representatives from major manufacturers was considered if necessary to obtain sufficient information. The distributors were knowledgeable and manufacturer interviews were not conducted.

1. Do you offer any multizone system equipment in Minnesota?
2. What percentage of new homes have multizone systems installed in them? What types of new homes are installing the systems? Of all MZ systems sold in Minnesota, what percentage do you think are being installed in new homes versus systems installed as retrofits in existing homes?
3. What do you estimate is the percentage of systems that are being used with air conditioners versus heat pumps?
4. Do you think that the market for multizone systems is growing or shrinking, and why?
5. Can you provide an estimate or range of the number of units that are sold in Minnesota each year?
6. What do you see as the primary benefits of the system? (e.g., improved comfort, energy savings)?
7. Do you think the system's heating or cooling energy savings are very significant?
8. What are the primary drawbacks (e.g., cost and installation complexity)?
9. What has been the overall response to the systems?
10. Are you aware of any utilities that offer rebates for multizone systems?
11. Do you think increased utility rebates would help increase market penetration?

Third-Party Manufacturers

The questions listed below were used to interview three third-party manufacturers who appeared most active with this technology. The interview questions are shown below.

1. What do you see as the primary benefits of the system? (e.g., improved comfort, energy savings)?
2. Do you think the heating or cooling energy savings are very significant for a colder climate like Minnesota?
3. What are the primary drawbacks to the systems (e.g., cost and installation complexity)?
4. What has been the overall response to the systems?
5. One concern with multizone systems is that the air handler airflow rate is restricted when only one of the dampers is open. The typical options for addressing that are (a) By-pass damper or dump-zone method, (b) system redirection, or (c) system modulation. Which of those methods can your system work with and which is typically used?
6. Are there specific manufacturer furnaces and heat pumps that are compatible with your zone control system?
7. For the control systems being sold in Minnesota, what do you estimate is the percentage of systems that are being used in new construction (compared to retrofit construction)?
8. For existing houses are your systems typically installed by HVAC contractors or "do it yourselfers"?

Mechanical Contractors

Home heating and cooling contractors tend to have a very strong influence on consumer choices in both system design and operation, so in-depth discussions with them were a critical project focus. The distributors interviewed for this project were asked to recommend two to three contractors who have installed their multizone equipment and who would be likely to talk with us. Six mechanical contractors who have installed multizone systems were interviewed. These interviews explored barriers and opportunities in relation to contractors' opinions about the zone space control products currently available, as well as service and installation issues and customer attitudes. The interview questions are shown below.

1. What do you see as the primary benefits of the system (e.g., improved comfort and energy -savings)?
2. Do you think the heating or cooling energy savings are very significant for a colder climate like Minnesota?
3. What are the primary drawbacks (e.g., cost and installation complexity)?
4. What has been homeowners' overall response to the systems?
5. Are you aware of any utility rebates for multizone systems?
6. Do you think increased utility rebates would help increase market penetration?
7. For all the systems being sold in Minnesota, what do you estimate is the percentage of systems that are being used installed in new construction versus existing houses (compared to replacement systems)?
8. What type of homes are they being installed in (e.g., low or moderate price versus high end; small versus large; ranch versus two story)?
9. Do you think that the market for MZ systems is growing or shrinking? Why?
10. One concern with multizone systems is that the air handler airflow rate is restricted when only one of the dampers is open. The typical options for addressing that are (a) a by-pass damper or dump-zone method, (b) system redirection, or (c) system modulation. Which of those methods is typically used?
11. How does zoning work with new variable speed equipment (e.g. a variable speed blower or two-stage furnace) compared to a single-stage model?
12. What are the primary challenges during the installation process and how does it differ for new construction versus retrofits?
13. Does the existing house typically have separate branches of ductwork per floor or do they have duct branches to separate sides of the house?
14. Do you think existing houses can be zoned effectively without significant changes to duct layout?
15. What is the typical added cost to upgrade from a single-zone to a multizone system?[2]

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[2] This question was not asked during the initial interview. It was added as a follow-up question.

Homeowners

The initial goal was to survey five or more homeowners who have multizone systems. The online survey instrument shown below was designed to collect homeowners' feedback on their system including primary benefit(s), primary drawback(s), level of satisfaction with comfort, how they operate their system (e.g., temperature setpoints), and perceived energy savings. We expected that information on how homeowners operate their system might impact how the systems are operated for our building energy simulations. We asked the mechanical contractors we interviewed to contact two to three homeowners who have multizone equipment and ask them to complete the online survey. Unfortunately, after numerous attempts to have the contractors reach out to their customers, no homeowners with appropriate systems completed the survey. It was determined that energy model prototype houses and configurations could be generated without homeowner feedback.

> *We are interested in information on residential multizone air distribution systems. These are systems that have central air handlers with ductwork and zone dampers that control heating and cooling to each zone of the house. We would like to know where and how often they are being installed, why people have installed them, and feedback on the performance of the systems. Please complete this questionnaire if your house has a multizone system.*
>
> House Information
>
> 1. Type of house (ranch, 1.5-story, split, 2-story, 3-story):
> 2. Approximate floor area (< 2,000 sq. feet, 2,000–2,500 sq. feet, 2,500–3,000 sq. feet, 3,000+ sq. feet):
> 3. Year of construction:
>
> Multizone System Information
>
> 4. System manufacturer {e.g. Carrier, Trane, Lennox, etc.) and what year was it installed: Manufacturer __ Year Installed: ___
> 5. How many zones does the multizone system have {2 – 8} and how are they separated {By floor or space area}? # zones: _______ How separated:
> 6. Please describe how you set the temperatures for each zone. Are they all set to the same temperature or are some higher or lower than the others? Do you setback the temperatures in all/some/none of the zones? Is the amount of setback the same for all zones?
>
> System Feedback
>
> 7. Have you been pleased with the system operation and performance? (Yes, Somewhat, No)
> 8. What do you see as the primary benefits of the system? (e.g., improved comfort, energy savings)
> 9. Do you think the heating or cooling energy savings are very significant for a colder climate like Minnesota?
> 10. What are the primary drawbacks (e.g., cost and complexity)?
> 11. How much was the cost considered for selecting a multizone system?
> 12. What could be done to improve the systems?

> *If we have questions regarding your responses, could we contact you for a brief follow up? If yes, please provide your name and phone number or email address.*

Assess the Potential for Utility Efficiency Programs

U.S. Utility Outreach

The objective was to identify U.S. utility residential efficiency programs outside of Minnesota that provide incentives to upgrade from a central, single-zone air distribution system to a multizone system. Information about measures and program approaches that may be transferable to the Minnesota market were to be obtained for any applicable programs. The process included a query of ESource's DSM database, outreach to energy efficiency organizations across the U.S., and outreach to utility energy efficiency program managers at major U.S. utilities. The outreach included 11 utilities on the east coast (3), west coast (5), Midwest (2), and mountain states (1). In addition to gathering information on efficiency program incentives, the utilities were also asked to provide information on multizone pilot projects that were conducted by the utilities.

Minnesota Utility Outreach

A representative sample of Minnesota utility program staff were interviewed to better understand specific areas of interest and concern with regard to residential zoned systems. These were somewhat open-ended interviews. Utility program managers were also asked about what they hear from end users and trade allies about requests to add multizone distribution systems to the CIP portfolio for existing and/or new homes. Seven utilities were contacted to participate in this project and the following four utilities responded: Dakota Electric, Great River Energy, Minnesota Power, and Xcel Energy. The nine interview questions are shown below.

1. Are you familiar with residential multizone systems?
2. What is your general impression of multizone systems?
3. Has anyone at your utility evaluated this technology and possible energy savings benefits?
4. Do you think these systems might generate space cooling or heating energy savings?
5. Are you aware of any utility programs that have provided incentives for multizone systems?
6. Have you considered incorporating multizone systems into your residential new construction or retrofit programs? If yes, what did you decide and why?
7. What are the barriers to including multizone systems in your programs?
8. Have you had any interactions with customers about using a multizone system in their home or contractors interested in installing them in homes? What type of feedback did you receive?
9. Do you have any other information about multizone systems that you would like to share?

House Energy Use and Indoor Air Temperature Model

The third task was energy modeling of single-zone and multizone distribution systems. EnergyPlus models of prototype Minnesota single-family houses were used to evaluate the energy use and improved comfort of multizone air distribution systems. The performance of single-zone and multizone distribution systems were modeled for one- and two-story single-family houses with configurations consistent with current and 1950–1960s construction characteristics. In addition, air temperature measurements from previous research projects in Minnesota houses were analyzed to document the seasonal variation in house air temperatures by floor. The measured temperatures were not intended to calibrate the models. Instead, the results were used to verify that the modeled seasonal trends and relationships between floor temperatures have been observed in actual houses.

Air Temperature Measurements

Monitored indoor air temperatures from previous and current research projects conducted by the Center for Energy and Environment were used for model verification. The six selected houses had single-zone air distribution systems as the only source of space heating and cooling with the thermostat located on the first floor and the furnace located in the basement. All the houses had basements and either one or two stories above grade. The measurements were conducted on each floor. The basement sensor was typically located near the furnace, the first floor sensor was near the thermostat, and the second floor sensor located in a central area on the second floor. The data was collected at a minimum interval of five minutes and used to generate hourly averages. The measured house air temperatures were merged with hourly data from a local National Oceanic and Atmospheric Administration (NOAA) weather station. Data was available for at least a portion of the heating season (October to March), cooling season (June to August), and shoulder periods. The hourly data was grouped by 10°F outdoor temperature bins. Box and whisker plots were generated for the binned data. Results were generated for three two-story houses and three one-story houses.

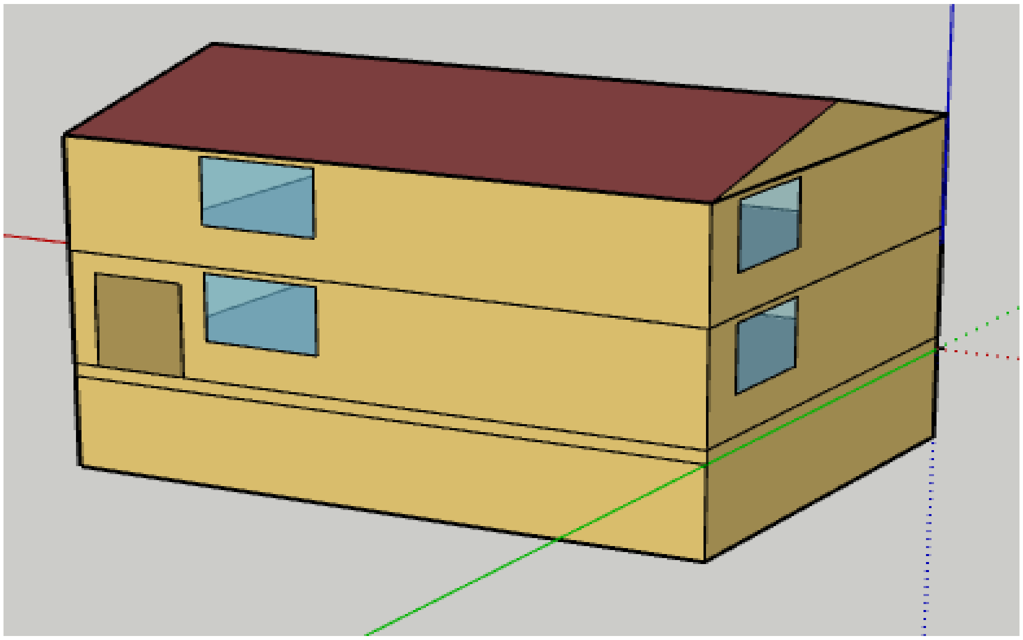
Energy Simulations

Building energy simulations of prototype one- and two-story Minnesota single-family houses were used to evaluate the energy use and improved comfort of zoned air distribution systems. The prototype houses were modeled for two different distribution systems: single-zone constant air volume and multizone variable air volume. In addition, the models were configured for two levels of insulation and envelope air leakage. One configuration complied with current Minnesota energy code thermal requirements to evaluate new home performance, and a second had thermal properties consistent with 1950–1960s housing to evaluate existing home performance. EnergyPlus™ (v 9.10) multizone building energy modeling software (Crawley, et al. 2001) was used to generate hourly interior air temperature and energy use results. The CONTAM multizone airflow simulation program was used to generate hourly average air infiltration and interzone airflow rates. Those airflow rates were imported to EnergyPlus™. It was expected that the hourly and seasonal variations in air infiltration by floor and airflow between zones could significantly impact interior air temperatures. Consequently, it was necessary to use a simulation program such as CONTAM that computes airflow rates based on specified leakage paths and driving forces. EnergyPlus and CONTAM simulations used typical meteorological year 3 weather data from the Minneapolis-St. Paul National Oceanic and Atmospheric Administration station.

Building Dimensions

A single-family model developed by the Pacific Northwest National Laboratory[3] (PNNL) that complied with 2018 International Energy Conservation Code® (IECC 2018) was modified for the simulations. The first prototype building was a two-story, single-family building with basement, first floor, second floor, and an unconditioned, peaked attic (see Figure 4). Each level had the same rectangular footprint with a floor area of 1,188 square feet for a total floor area of 3,566 square feet. The height of the first and second floor was 8.5 feet while the basement height was 8 feet with 1.5 feet of the walls exposed to outside air. For each floor the window area was the same for all four sides of the house. The total window area for the first and second floors were 143 square feet, and the window area of the basement was 15 square feet. The garage was detached and not included in the model. The one-story model was identical to the two-story model except the first floor was removed. The total floor area of the one-story model was 2,377 square feet.

Figure 4. Diagram of two-story house



Thermal Properties

The prototype buildings had a fully heated basement under the first floor, with 1.5feet of the basement walls exposed to outside air and the remaining portion of the walls in ground contact. Each floor was

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[3] The U.S. Department of Energy Building Energy Codes Program Prototype Building Models for residential buildings web page provides a residential prototype Energy Plus model that complies with IECC 2018. (https://www.energycodes.gov/prototype-building-models#Residential)

treated as a separate thermal zone with uniform conditions for each floor. In other words, there was no air temperature variation within each floor. For the new construction configuration, the thermal properties of windows, doors, opaque walls, basement walls, and roof were selected to comply with the 2020 version of the State of Minnesota 2020 Energy Code. The Minnesota code is based on the 2018 International Energy Conservation Code® (IECC 2018) with amendments. The exterior walls had stucco cladding R-21 insulation that produced a U-factor of 0.048 Btu/(hr ft^2 F). The ceiling with attic spaces included R-49 insulation for a U-factor of 0.026 Btu/(hr ft^2 F). The basement had wood foundation walls with insulation and framing of R-19 that produce a U-factor of 0.063 Btu/(hr ft^2 F) and the windows had a U-factor of 0.3 Btu/(hr ft^2 F). There was no insulation under the basement slab.

For the existing 1950–1960s construction house configuration, changes were made to thermal properties of windows, exterior walls and attic insulations based on a recent analysis of Minnesota single-family house characteristics (Quinnell and Genty, 2021). The exterior walls had stucco cladding with 2” by 4” walls that contained R-9 insulation that produced a U-factor of 0.11 Btu/(hr.ft2.F). The ceiling with attic spaces included R-25 insulation for a U-factor of 0.04 Btu/(hr.ft2.F) and the windows had a U-factor of 0.7 Btu/(hr.ft2.F).

Interior Loads and Occupancy

Table 1. Occupancy schedules

Day of Week	6am – 8am	8am -5pm	5pm – 10pm	10pm – 6am
Two-story Models				
Weekday	3 people in 1st floor	0 people	1 in basement, 1 in 1st flr and 1 in 2nd flr	3 people in 2nd floor
Weekend	3 people in 1st floor	1 in basement, 1 in 1st flr and 1 in 2nd flr	1 in basement, 1 in 1st flr and 1 in 2nd flr	3 people in 2nd floor
One-story Models				
Weekday	3 people in 1st floor	0 people	1 in basement, and 2 in 1st floor	3 people in 1st floor
Weekend	3 people in 1st floor	1 in basement, and 2 in 1st floor	1 in basement, and 2 in 1st floor	3 people in 1st floor

Prototype building models were setup with dishwasher, refrigerator, stove, oven, and television appliances on the first floor, with a clothes washer and dryer in the basement. Lighting and plug loads were maintained constant on all three floors. Internal gains for all the appliances including lighting and plug loads were assumed based on the PNNL residential prototype building based on 2018 IECC to comply with the state of Minnesota 2020 Energy Code. The lighting and plug loads for a floor of the house were 0.10 and 0.04 watt/ft^2 respectively when a floor was occupied. Custom weekday and weekend occupancy schedules were created for both single-story and two-story building configurations to resemble common residential occupancy schedules (see Table 1).

Air Infiltration and Interzone Mixing

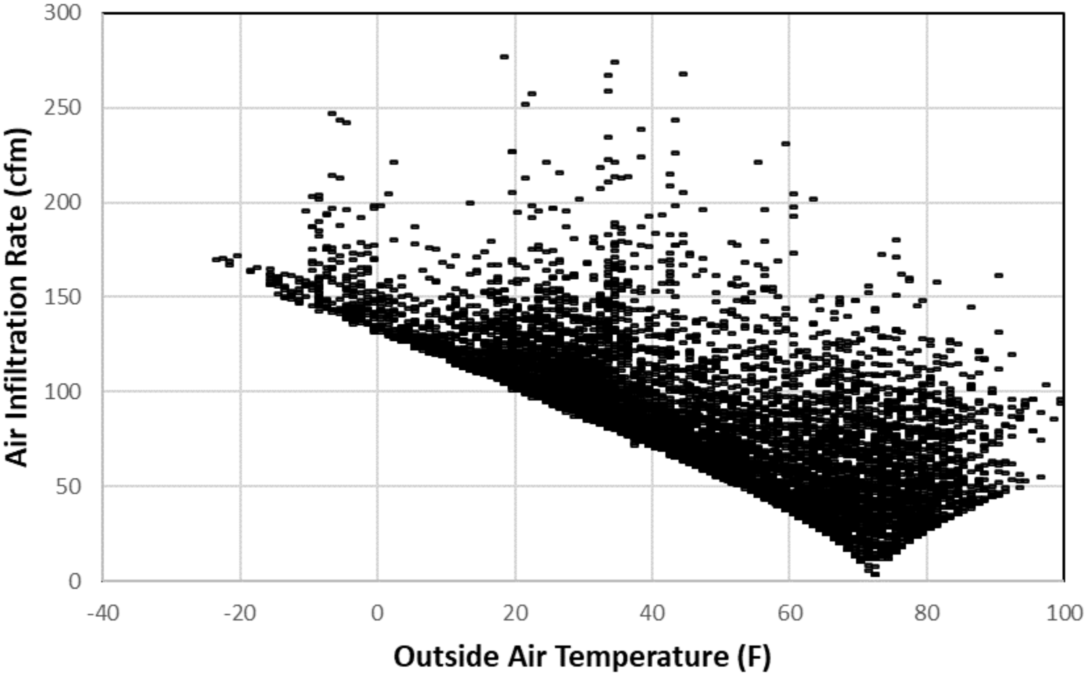
It was expected that the hourly and seasonal variations in air infiltration by floor and airflow between zones could significantly impact interior air temperatures. The CONTAM (v 3.3.0.0) multizone airflow and contaminant transport program was used to generate hourly average air infiltration and interzone airflow rates. CONTAM was developed by the National Institute of Standards and Technology to calculate time-varying infiltration, exfiltration, and zone-to-zone building airflow rates (Dols and Polidoro 2015). The model includes inputs that determine driving forces due to HVAC flows, wind pressures, and thermal buoyancy effects. The driving forces are applied to a user-defined network of airflow paths to compute interzone airflow rates. That includes airflow between the outside and each interior zone as well as the airflow between interior zones (e.g., between each of the floors and from the top floor to the attic).

For each floor of the house the exterior envelope air leakage paths were distributed equally to the four exterior walls. Multiple leakage paths were spaced vertically on each wall to provide for thermal buoyancy driven airflow within the floor. Three air leaks were included on each side of the house for the above grade floors and two leaks were included for each side of the basement. A 24 sq. feet open stairway was included between the basement and first floor and the first and second floors. For the two-story house models 20% of the exterior leakage was placed in the basement walls, 25% in the first-floor walls, 25% in the second-floor walls, and 30% in the second-floor ceiling. The resulting neutral level was 0.7 feet above the first-floor ceiling.

For the one-story house models, 30% of the exterior leakage was placed in the basement walls, 38% in the first-floor walls, and 32% in the first-floor ceiling. The resulting neutral level was 2.9 feet below the first-floor ceiling. The new construction models were configured to have a total exterior leakage of 3.0 air changes per hour at 50 Pa (ACH50), which is the maximum allowed by the current Minnesota energy code. The models for existing houses had an exterior leakage of 7.35 ACH50. The attics were well vented. Suburban terrain was assumed to compute the wind speed modifier. No mechanical systems were included in the models since the new construction houses had balanced ventilation and the existing had no mechanical ventilation.

As shown in Figure 5 the thermal stack effect causes the minimum total house air infiltration rate to vary linearly with outside temperatures below and above the interior temperature of 72°F. The scatter in the infiltration is due to wind effects that can cause the air infiltration at a given temperature to increase by more than a factor of two. The wind effect has a relatively larger impact for milder outdoor temperatures.

Figure 5. Two-story house hourly air infiltration rate



A box and whisker chart of the hourly air infiltration rates is shown in Figure 6. For outdoor air temperatures below 60°F the basement has the highest air infiltration. The second-floor infiltration is lowest and only driven by higher wind conditions. The average air infiltration rates when temperatures are below 60°F are 47, 40, 14, and 101 cfm for the basement, first floor, second floor, and house total respectively. The total infiltration is approximately equal to the house leakage rate of 1,486 CFM50 divided by 15.

For outside air temperatures above 70°F, the second floor has the highest infiltration due to the inverse stack effect. The average air infiltration rates when temperatures are above 70°F are 14, 19, 25, and 58 cfm for the basement, first floor, second floor, and house total respectively. The commonly used air infiltration models for EnergyPlus are not able to model these trends in infiltration since the thermal stack effect is computed from the absolute value of the outdoor to indoor temperature difference.

The box and whisker chart for interzone airflow rates is shown in Figure 7. For outside air temperatures below 70°F, the interzone flow rates are relatively consistent, are almost always from the lower to upper floor, and vary linearly with outside temperature. The flow from the first floor to the second floor is about 1.7 times higher than the flow from the basement to the first floor. For outside temperatures above 80°F, the interzone airflows are almost always from the upper to the lower floor.

Figure 6. Two-story house air infiltration by floor

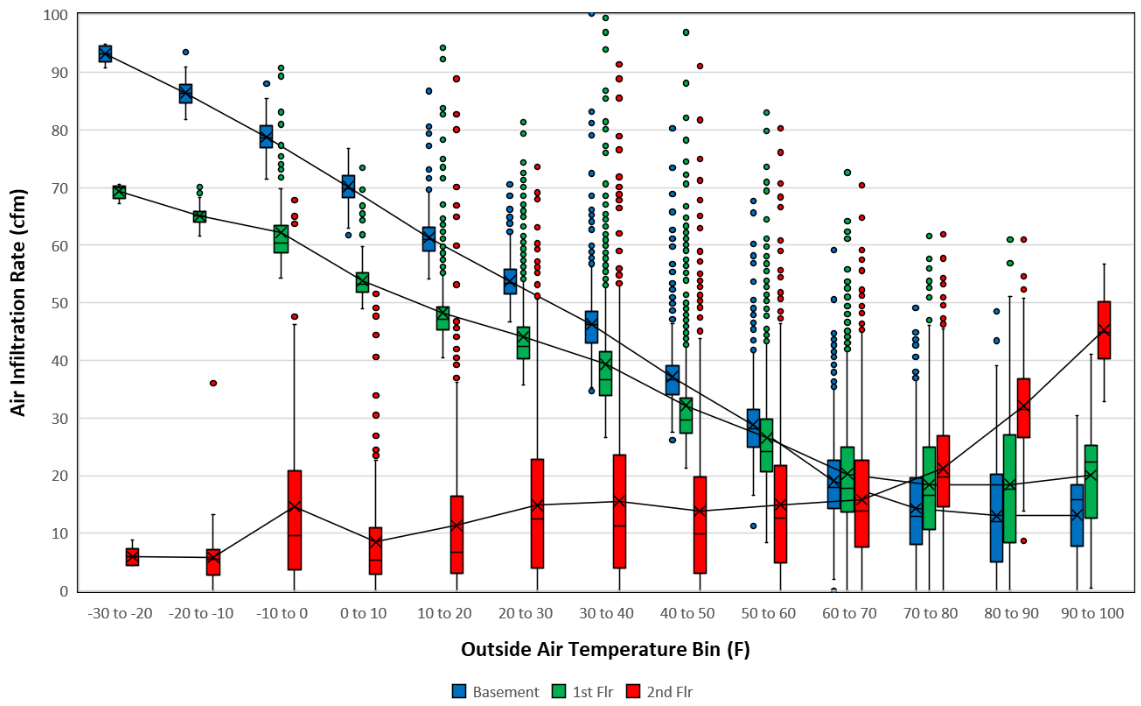
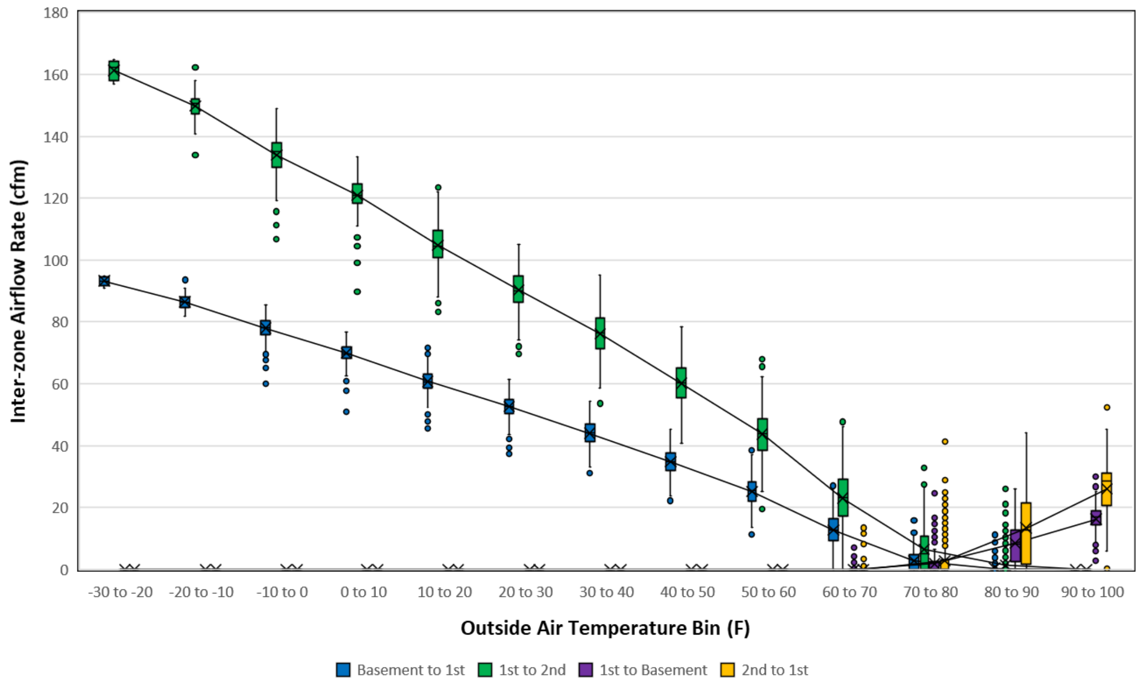


Figure 7. Two-story house hourly inter-zone airflow rate



A similar pair of infiltration and interzone box and whisker charts for the one-story house CONTAM model are displayed in Figure 8 and Figure 9.

Figure 8. One-story house air infiltration by floor

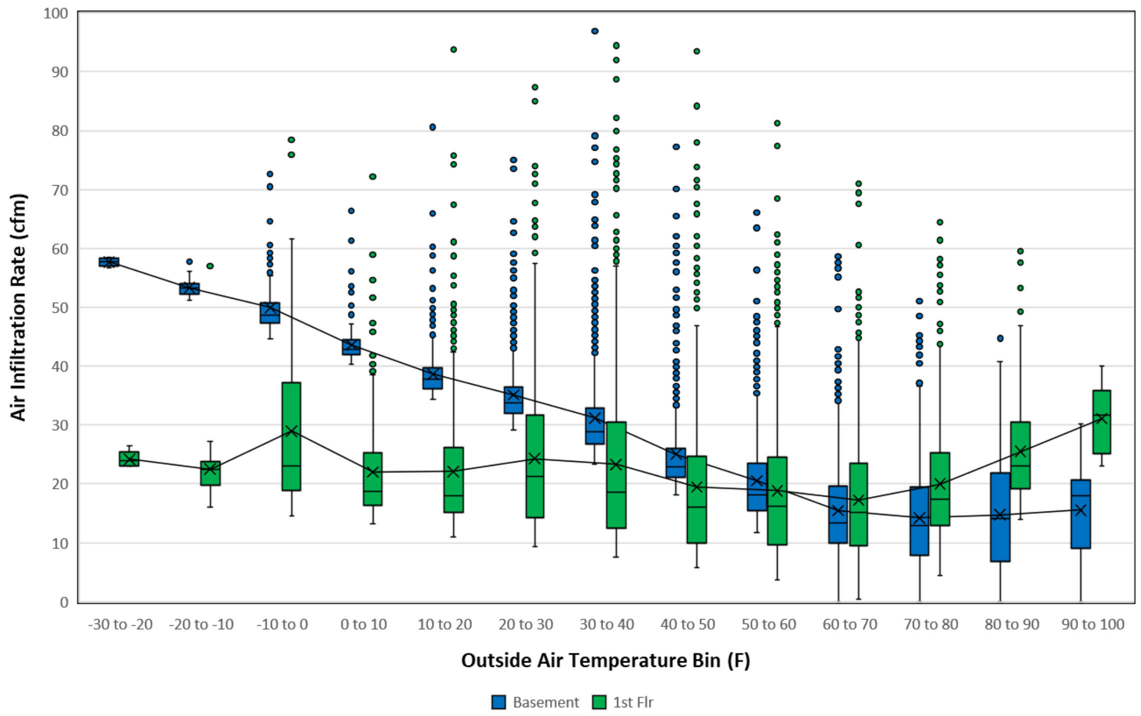
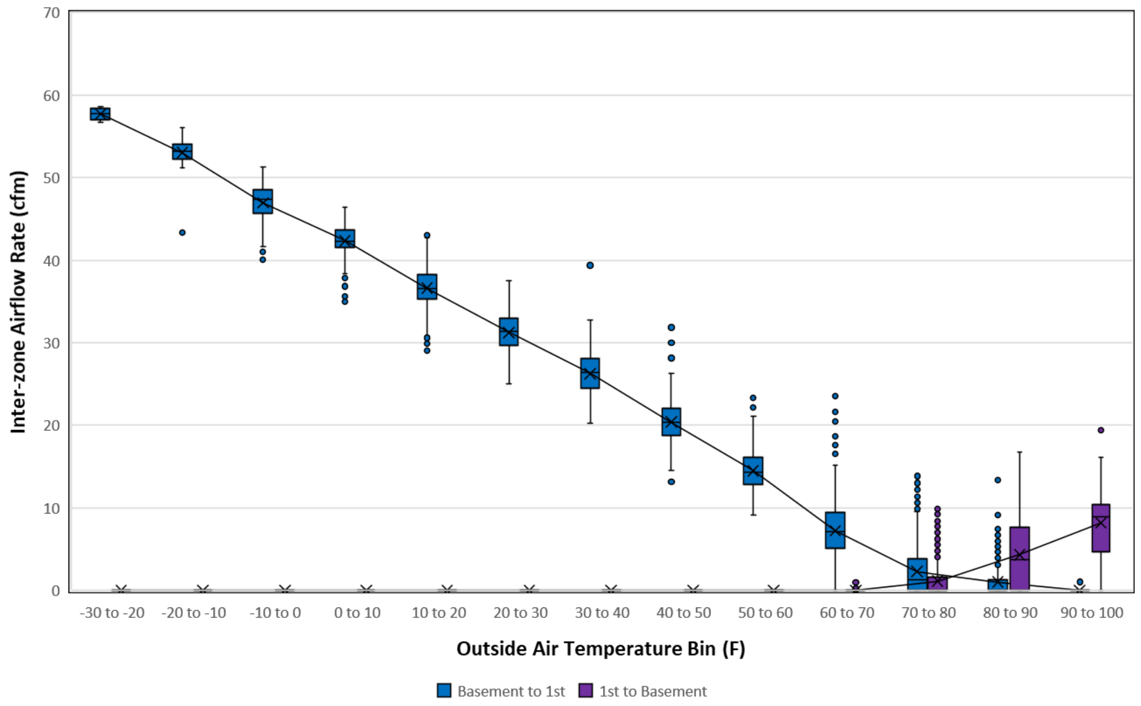


Figure 9. One-story house hourly inter-zone airflow rate



The trends are similar to those for the two-story house model. For outdoor air temperatures below 60°F, the average air infiltration rates are 31, 22, and 53 cfm for the basement, first floor, and house total respectively. The total infiltration is approximately equal to the house leakage rate of 981 CFM50 divided by 18.[4] For outside air temperatures above 70°F, the average air infiltration rates are 14, 22, and 36 cfm for the basement, first floor, and house total respectively. For outside air temperatures below 70°F, the interzone flow is almost always from the first floor to the basement and when the temperature is above 80°F the flow is almost always from the first floor to the basement. The trends are similar to those for the two-story house model. For outdoor air temperatures below 60°F, the average air infiltration rates are 31, 22, and 53 cfm for the basement, first floor, and house total respectively. The total infiltration is approximately equal to the house leakage rate of 981 CFM50 divided by 18.[5] For outside air temperatures above 70°F, the average air infiltration rates are 14, 22, and 36 cfm for the basement, first floor, and house total respectively. For outside air temperatures below 70°F, the interzone flow is almost always from the first floor to the basement and when the temperature is above 80°F the flow is almost always from the first floor to the basement.

Space Heating, Cooling, and Ventilation

The Minnesota residential code currently requires continuously operating, balanced mechanical ventilation. This is commonly achieved with a heat recovery ventilation (HRV) system that has outdoor air ducted to the return system with a house exhaust air duct located upstream of the outdoor air duct (Pigg, Lord, and Koski 2020)[6]. The air handler runs either continuously or a fraction of each hour to distribute outdoor air to all zones. This mechanical ventilation system was included for the new construction models using continuous air handler operation. The HRV sensible recovery efficiency was 78%. The Minnesota code requirement for continuous ventilation was used to specify a ventilation flow rate of 73.2 cfm for the two-story models and 53.8 cfm for the one-story models. Minnesota codes in the 1950s to 1960s did not require mechanical ventilation for single-family houses. The models for existing houses did not include continuous mechanical ventilation and the air handler only operated during periods of heating or cooling.

All of the models had dedicated unitary HVAC systems with a direct expansion cooling coil (COP = 3.8) and a natural gas heating coil (AFUE = 80%)[7]. The ductwork was located within the thermal boundary of the house with no exterior leakage. This is consistent with typical Minnesota home construction. The baseline model had a 70°F heating set point and 78°F[8] cooling set point. Space heating was enabled

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[4] A relatively lower average air infiltration is expected for shorter houses due to a smaller stack effect.

[5] A relatively lower average air infiltration is expected for shorter houses due to a smaller stack effect.

[6] This 2020 study of Minnesota new homes found an even split between HRV and ERVs, 80% had a “simplified” configuration that connected the exhaust and fresh air ducts to the central air distribution system, and the sensible recovery efficiency ranged from 60% to 80% with an average of 70%.

[7] The selected COP and AFUE are the minimum required values. The study by Pigg, Lord, and Koski (2020) indicated an average furnace AFUE of 94% and COP of 4.0. Using these higher values would have decreased the absolute differences in energy use, but would not have affected the relative changes.

[8] EPA Energy Star recommended setpoints.

when the outside temperature was below 50°F and cooling was enabled for outside air temperatures above 60°F. The 10°F dead band between 50°F and 60°F helped reduce the number of days when there was both heating and cooling. The author's experience is that most Minnesota homeowners set their thermostat to either the heating-only or cooling-only mode and manually switch between the two modes.

The single-zone systems had a constant volume fan that supplied a constant airflow rate to each floor. The return airflow rate from each floor matched the supply airflow. The supply airflow rates for the base configuration were computed using the EnergyPlus auto size option. The supply airflow rates by floor for the four baseline model configurations are shown in Table 2. Configurations with over- or under-heated and -cooled zones were produced by modifying the distribution of the supply airflow by zone while keeping the total flowrate the same. For example, the baseline configuration was changed by increasing the supply airflow to the basement by 50 cfm and decreasing the airflow to the first floor by 50 cfm. The system operation was controlled by a thermostat located on the first floor.

Table 2. Baseline model supply airflow rates,

Model Configuration	Basement[a]	First Floor	Second Floor	Total
Two-story new	220/24%	345/38%	336/38%	901
Two-story existing	441/25%	644/36%	681/39%	1,766
One-story new	198/34%	389/66%	-	587
One-story existing	441/39%	703/61%	-	1,145

a) Airflow rate in cfm/% of total

Multizone systems use supply duct dampers to control the airflow to each zone. The damper and heating/cooling operation is controlled by a thermostat located in the corresponding zone. The airflow rate through the air handler is equal to the sum of the supply airflow to all of the zones. The EnergyPlus model used a simplification of this system. A separate constant volume heating and cooling systems was used for each zone. The zone supply airflow rates were the same as those for the baseline configuration of the single-zone systems. For the existing home configuration that did not have an HRV, the air handler for each zone operated only when there was a call for heating or cooling. This accurately simulates the performance of a staged multizone system in existing homes. For the new home configuration, the air handlers operated continuously to distribute HRV ventilation air. The heating or cooling was active as needed. This properly simulates the heating and cooling performance of a staged multizone system in new homes. Depending on the integration of the HRV with the multizone system, this simulation may overestimate air handler operation and energy use.

Results and Discussion

Technology Assessment

This section includes a list of 10 key references relevant to residential multizone air distribution systems. The references are separated into five categories: Technology Assessment (1), Design Guide (1), Modeling Study (1), Laboratory Studies (2), Field Studies (4). The parenthetical values indicate the number of references in the category. Each category contains a summary section with the work scope and key findings, the references for each paper, and citation information.

Technology Assessment

Review of Residential Comfort Control Products and Opportunities

2017. C.E. Metzger, S. Goyal, and M.C. Baechler (Pacific Northwest National Laboratory).

Summary: This study investigates advanced HVAC control components used for commissioning, maintaining, and efficiently operating residential HVAC equipment. It also evaluates the interactions of each component in complex sensor and control applications related to HVAC equipment. The paper provides an overview on the market characteristics, challenges, and impacts of advanced controls on energy savings in the residential building sector.

Design Guide

Zoning Design Guide

2017. Canada, Natural Resources.

Summary: The report assists mechanical designers with zone duct design guidelines. The project also produced a Zoning Decision Guide for Builders and papers that assess heating and cooling season peak demand and energy savings for a high velocity, zoned, combination system. The Zoning Design Guide describes all the necessary steps in detail, starting with:

Recommended Prerequisites

- Prerequisite guide is commonly used to design duct systems for forced air systems.
- This guide is primarily used to summarize the HVAC system key features and its applicability at the residential level.

Determine Heating and Cooling Loads

- Gather construction documents and detailed envelope specifications such as air tightness level, orientation, and heating equipment location.
- Once these inputs are gathered, room-by-room heat loss and gain can be calculated based on the CSA F280-12.

- Based on comfort and energy considerations, the house can be divided into various heating and cooling zones. The report provides some common zoning plans such as zone per floor, grouping floors into single zones or custom zones.
- The report allows the designer to group the calculated results of room-by-room heat loss and gain into proposed zones.
- Zoning plan can be evaluated with an equal size criteria option if the proposed zone for the heating loads falls under the target range.

Heating and Cooling Equipment Requirements

The report outlines a five-step process for selecting a reliable HVAC zone equipment.

- Air distribution strategy: Based on the type of heating equipment, operating static pressure determines whether air distribution system falls within the zoning duct design scope and provides recommendations for suitable diffusers for zone duct design. The report also details two supply duct options (central supply and traditional supply) including the advantages and planning implementation requirements for each.
- Type of zone Installation: Choose HVAC equipment type based on air distribution strategy and zoning checklist. The report describes the three options.
    - Factory-integrated: Zoning controls and dampers are pre-assembled and shipped in a single box. Straightforward installation is slightly more onerous than single zone.
    - Site-assembled: Built-up system from multiple components sourced from one or more suppliers. Zone thermostats, zoning controller, and heating/cooling equipment use field-installed wiring. Installation and commissioning require more time and expertise than a single-zone system.
    - Zone-ready: Uses zoned ducting design implemented as a single-zone system. Ready for zoned control in the future.
- Meeting single zone demand: During most heating/cooling calls, only one zone supply damper will be open. To reduce the airflow restrictions from the HVAC equipment, these systems need to be equipped with automatic adapt operation or deliver high airflow rates to limit temperature rise value during heating and avoid evaporator freeze up while cooling. The various single-zone control options (system modulation, system redirection, and bypass damper) and their compatibility with the HVAC equipment are discussed.
    a. System modulation (preferred): Airflow and possibly thermal output vary to maintain acceptable operating conditions.
    b. System redirection: Combination of directing some airflow to non-calling zones and possibly modulate or stage airflow and thermal output.
    c. Bypass damper: Uses bypass damper to recirculate conditioned supply air to the return.

  Option A is preferred. Option B with modulating or staged equipment also works well. Option C should be avoided. Factory integration and site assembly with major components from a single manufacturer typically use options A and B. Site assembly built-up from different suppliers' components commonly uses option C.

- Changeover approach between heating and cooling: The different changeover options include the following: (a) zone controller allows manual switchover between heating and cooling option and (b) automatic switching between heating and cooling based on individual zone thermostat. These changeover options can also be adjusted based on the zoned HVAC equipment installed in the field.
- Specify equipment output capacity: The guidelines for zone heating are to size equipment as close to 100% of the calculated equipment heating load as possible and to size the zone cooling equipment up to 80% of the total cooling load equipment.

Return Air Ducting Requirements

- Describes the common types such as joist-trunk return or hard-ducted return air duct installations and their features.
- Identifies types of return inlet layouts (simplified or standard return) and describes the best practices of various return outlets such as high-wall, low-wall, and floor inlets.
- Provides ideas for best practice basement return ducts and duct route layouts.
- The sizing for the return duct follows a step-by-step procedure outlined in residential air system design manual for air heating and cooling systems.

Supply Air Ducting Requirements

- Specifying the ideal supply air ducting layout between traditional supply ducts and central supply ducts. Best practices for placement of supply outlets are described for a better understanding of which installation type and outlet configurations are suitable.
- The type of duct system used for supply branches should be specified, and duct sizing calculations should be provided for flexibility. Supply air duct layout duct design should be coordinated with the joist and framing plan. Choose the more suitable supply trunk duct type between traditional rectangular or round/oval ductwork.
- Zone supply trunk size depends on design airflow requirements and air velocity and noise levels during the single-zone operation.
- Duct sealing can improve effective air distribution. Standard sealing practices should be followed or upgraded to Class A. Identification number labels should be attached to the air supply trunk.

Thermostat Requirements

- Determine the ideal thermostat location per zone. Hallway, master bedroom, and top-level thermostat placements are ideal for location. Black plates should be placed to cover unused thermostat wires.
- Unique zone identifier wire labels should be consistent with the zone supply trunk. Programmable, smart programmable, and non-programmable are types of thermostats available for residential designs.

HVAC Installation and Commissioning

- All HVAC equipment must be in accordance with the manufacturer's instructions, which include zone supply connection, thermostat wiring, and duct labeling.
- These instructions act as guidelines for HVAC installers and commissioning agents.

Modeling Study

Energy Savings of Retrofitting Residential Building with Variable Air Volume System

2020. Daniel B. Lu and David M. Warsinger.

Summary: This NYU and Purdue University study examined energy model simulations of constant air volume (CAV) and multizone (MZ) variable air volume (VAV) systems to evaluate MZ VAV energy-saving potential. The paper discusses CAV systems, the importance of VAV systems in the residential space, and how recent technological advancements in building automation controls make it easier to implement MZ VAV systems at a lower cost.

This research describes eQUEST energy model simulations of two different sized houses (average and large) with CAV-VAV systems made for all seven climate zones in the United States. The CAV system is assumed as the baseline model for a single-family house with thermal zone for each of the two floors. Heating is provided by natural gas and cooling by expansion coil and air-cooled AC unit. Certain assumptions were made, such as temperature and occupied hours, based on the Energy Information Administration (EIA). The only key change observed in the proposed VAV system is how the system serves houses based on zone occupancy. Each room has its own thermostatic control, thus enabling the control system to determine which zone needs heating or cooling. Room dimensions, glazing HVAC system parameters, occupancy, lighting, and equipment power densities are constant. HVAC efficiencies were also assumed, along with 80% furnace heating. HVAC system supply fan flow rate, as well as heating and cooling capacities, were also kept constant between CAV and VAV models across all climate zones. The first set is for small to average-sized single-family buildings and the other set is for larger houses. Energy unit prices for electricity and natural gas are provided. Present energy cost savings are calculated based on average stay time for a single-family home.

The results indicate that lower fan and cooling energy use reduces VAV source energy costs. Cooling energy reductions ranged from 36% to 51% for the average household. Cooling savings were significant because (1) the temperature setback is large relative to the inside/outside temperature difference and (2) cooling loads are larger during the day when the house was modeled as unoccupied with higher setback temperatures. The VAV systems produced little space heating savings. This occurred because heating loads were higher during the night when the houses were occupied (and there was no setback) and the setback temperature was smaller relative to the difference in inside versus outside temperature. VAV systems achieved net energy savings, ranging between 24% and 42%. As the site-to-source ratio for electricity is nearly three times the site-to-source ratio for natural gas, the fan and cooling energy savings are magnified. Cooling-dominant energy models achieve greater source EUI savings as a result. Large house models had lower source EUI savings than their average house counterparts, ranging from 18% to 35%.

The authors acknowledge that retrofits can present challenges depending on the age of the house, utility rebates, occupant patterns, further studies on room usage patterns, and thermostat setpoints, as well as changes to room geometry that could improve the energy performance. The authors recognize that simulated test results are based on ideal conditions. Because of the various complexities that could surface during the design and installation stages, field tests must be done to gain a better understanding of these systems and their impact.

Notes:

There were a few issues with the modeling that may have created unrealistic operation.

1. It appears that the models for CAV operation assumed that the air handler operated continuously and not just when there was heating or cooling. That is not typical for Minnesota houses. The fan electric savings would not be as significant if the air handler only operated when there was a call for heating or cooling for CAV mode.
2. The model description indicates that each room was treated as a separate zone. If that was the case, there would have been six zones: four-bedroom zones and zones for the kitchen/dining and living rooms. Most MZ systems only have the capacity for four zones.
3. For the CAV model there was a daytime setback during the week. There was no night setback. It appears the thermostat was located on the first floor. Figure 9 in the paper shows that the first floor living room temperature was fairly close to the setpoint. However, in the winter the air temperature in the second-floor master bedroom varied from 61°F (16°C) in the early morning to 73.4°F (23°C) at noon on the weekends. That seems like an unacceptably large variation. The constant operation of the air handler should have provided some mixing between the rooms and levels of the house. The low second floor temperatures during the winter could have produced an erroneously low energy use for the CAV system. They didn’t describe how air flow between zones was modeled and air infiltration was set to be constant and equal in all zones. Would a CONTAM model that included varying air infiltration due to thermal stack produce more uniform temperatures in the house?

Key References:

A. Hesaraki. 2015. Demand-controlled ventilation in new residential buildings: consequences on indoor air quality and energy savings. *A typical single family houses’ central HVAC system consists of constant air volume (CAV) air handler unit providing a constant amount of conditioned air to the house.*

R.J. Meyers. 2010. Scoping the potential of monitoring and control technologies to reduce energy use in homes. *Previous studies estimate that about 15.9% of primary energy is wasted heating and cooling unoccupied rooms.*

A. Demeure. 2015. Building and using home automation systems: a field study. *Recent technological and market developments are attempting to lower the economic and cognitive barriers to adopting VAV systems in residential buildings.*

R. Ford. 2016. Assessing players, products, and perceptions of home energy management, PG&E's Emerging Technologies Program. *Recent technological and market developments are attempting to lower the economic and cognitive barriers to adopting VAV systems in residential buildings.*

T. Sookoor. 2012. Feasibility of retrofitting centralized HVAC systems for room-level zoning. *Several field-measurement studies have also demonstrated the energy saving potential of retrofitting existing residential central HVAC systems with wireless temperature sensor and vent louver actuator prototypes, single-story, 7-room, 1400 ft^2 (130 m^2) house. Over two consecutive ten-day periods, first serving the whole house then serving zones as needed, Sookoor found that the WSN system can save around 20% of energy use. Sookoor also performed simulations in EnergyPlus on five hypothetical buildings of varying sizes (5 m2–65 m2) to demonstrate the energy savings from gradually decreasing conditioned volume with constant HVAC system heating capacity.*

W. Watts. 2007. Application of multizone HVAC control using wireless sensor networks and actuating vent registers. *Several field-measurement studies have also demonstrated the energy saving potential of retrofitting existing residential central HVAC systems with wireless temperature sensor and vent louver actuator prototypes. Watts et al. tested the performance of a WSN system serving four thermal zones over three days for a two-story, 11-room house in northern California.*

M.M. Ardehali. 1996. Evaluation of variable volume and temperature HVAC system for commercial and residential buildings. *Ardehali and Smith performed energy simulations in a 1995 study comparing a CAV system to a variable volume and temperature (VVT) system for a 2500 ft^2 (232 m^2) house in Des Moines, Iowa. Their study estimated that capital cost recovery of a VVT retrofit would take around six months to one and a half years depending on the scope of retrofit.*

Y. Kialashaki. 2019. Energy and economic analysis of model-based air dampers strategies on a VAV system. *Most recently, Kialashaki compared CAV and VAV systems using an hourly simulation of a single-story residential building in Iran over a representative summer and winter day.*

Laboratory Studies

Efficiency Optimization of Variable Capacity Heat Pump Energy and Building

2017. Sreenidhi Krishnamoorthya, Mark Modera, Curtis Harrington.

Summary: An experimental study was conducted by the University of California, Davis, which evaluated the variable capacity heat pump operations and effects of both compressor and indoor fan airflow to achieve maximum system efficiency in hot and dry climates. The paper reported that over 45% of the total energy consumed in U.S. residential buildings is to achieve comfortable heating and cooling temperatures, and past efforts have not evaluated the optimization of variable speed compressors or variable speed fan systems for specific climate conditions, which could have significant energy-saving potential.

The report outlines the experimental process. First, a heat pump is connected to a residential duct system in a full-scale laboratory designed to simulate and measure both the indoor and outdoor climate conditions. Second, a duct system is arranged on the shelves to prevent thermal contact between ducts. The report continues to discuss the various equipment and apparatus used for testing.

The authors conducted and measured system operation results under two different modes: (a) total equipment capacity and blower airflow are synced and varied between 40% and 100% and (b) the equipment capacity is kept constant at various measurements and airflow is varied in 20% increments from 60% to 100%. One series of tests was performed by maintaining the outdoor and indoor chambers at 115°F and 80°F (46°C and 26.7°C) respectively, while, for the other series, the indoor temperature was maintained at 75°F (24°C) and the outdoor chamber temperature was increased in 10°F (5.6°C) increments from 84°F to 115°F (29°C to 46°C).

The report summarizes the major results obtained during the laboratory test.

- At any compressor speed, the system COP decreases monotonically with increase in outside air temperature (ducted zone air temperature), for fixed outside air temperature COP is not monotonous with the compressor speed. This is because at higher outside air temperatures, the heat pump cannot extract cold air, which requires the compressor to work more to maintain the inside temperature. This highlights the importance of duct system insulation and location.
- The compressor speed and airflows vary vastly. The effective delivery variation provides a reason to further investigate the performance of a multizone application.
- Increased fan flow tends to reduce the COP because the additional fan power required for increasing the airflow cancels the improvement at higher fan flow rate.
- Conduction losses are significantly higher when the ducts are in the attics. Increasing both the duct insulation and air velocity through the duct system improves the overall system effectiveness.
- The compressor-only COP, which does not include distribution system losses, increases with increase in airflow. At the same, the increased airflow causes the evaporator air temperature to be high, which increases the refrigerant evaporation temperature and efficiency.

Key Reference:

T. Fazli. 2015. Modeling the energy and cost impacts of excess static pressure in central forced-air heating and air-conditioning systems in single-family residences in the US. *Cooling and heating to achieve comfortable temperature and humidity levels accounts for over 45% of the total energy consumed in US residential buildings.*

Register Closing Effect on Forced Air Heating System Performance

2003. I.S. Walker.

Summary: A laboratory study by Lawrence Berkeley National Laboratory investigates the impacts of conditioning fewer spaces by closing registers when the rooms are unoccupied as a means for energy savings in California. This experimental study measures the airflow rate, duct leakage, and distribution system performance to analyze the changes in heating and cooling system performance.

The report details a single-zone experiment setup for testing and describes the testing chamber location and the type of materials used for construction and insulation to keep it tightly sealed. To evaluate measurements over a wide range of house leakage conditions, six holes were added to the testing envelope. Pressure tests were conducted to ensure the air leakage is close to the default state value. The paper outlines the duct system construction and pressure monitoring during the experiment.

The authors tested two combinations of sequences for closing registers. For the first combination the registers were closed starting at the farthest end of the air handler system, while the second closed registers starting from those closest to the air handler. There were 11 register closing and eight leakage configurations. The registers were closed one at a time and the measurements total system airflow, plenum and boot pressures, and leak flows were measured at each register closing. The report summarizes the major results obtained during the laboratory test. Additionally, REGCAP models were simulated to estimate the steady-state distribution system efficiency.

- Closing registers near the supply plenum increases the duct pressure throughout the system, while closing distant registers has less effect on supply boot and plenum pressures.
- Closing registers increases the duct system pressures, therefore increasing the duct leakage for supply leaks. For the same number of closed registers, the closed registers near the supply can cause high duct leakage because of high pressures.
- When the air handler flow is recorded with a specific number of registers closed, the return plenum leakage is constant, which implies that system performance changes the least with low pressure boot leakage at the return plenum.
- For cooling systems, reducing air handler flow reduces the heat exchanger efficiency. The no-leak system configuration has the highest airflow changes when registers are closed. Due to alternative flow paths, the leaky system configuration will have the lowest air low changes.
- For the no-leak system, closing the far registers first means the airflow reductions are steady and flow drop is significant when the last couple of registers are closed.
- Power consumption showed less variation than the airflow due to system airflow being reduced as the pressure difference across the air handler increased.
- Leakage imbalance was considerably high for cases with supply plenum and registers, resulting in depressurization. For far registers closed first, the depressurization limit was reached much faster compared to the nearer registers.
- The REGCAP simulations provide similar results, with the trend that closing registers does not save energy — in fact, more registers closed leads to higher energy usage.

The authors conclude that reduction in loads was offset by increased duct leakage and system losses. Closings (more than 60%) could add to severe airflow restrictions and air leakage for the system.

Key Reference:

I.S. Walker. 2001. Simulation of residential HVAC system performance. *The REGCAP model has been used in several previous studies by LBNL.*

Field Studies

Performance Assessment of High-Velocity Zoned Combination System

2013. Jeremy Sager, M. Armstrong, and F. Szadkowski.

Summary: This research by Canmet compares heating season energy and comfort performance for homes with single and zoned air distribution systems. The zoned system consists of a high velocity air distribution system with two zones: (1) upper level and (2) main floor/basement. It uses a condensing tankless water (EF = 0.83) heater combi system for space heating. There are two different storage tank designs. One has an indirect tank and the second a buffer tank. Those are compared to low velocity, single-zone air distribution systems with a condensing furnace and power-vent tank type water heater. The report discusses the equipment used for air circulation, space heating and cooling, water heating, and ventilation, along with system operating conditions and instruments used for measurements in the test houses.

The report summarizes the results obtained during experiment:

- Energy Comparison: Zoned systems with a buffer tank provided the highest energy savings even at greater load periods. The system showed 6% higher energy savings compared to the standard reference system, while a non-zoned system with a buffer tank showed 3% savings against the standard system. The zoned system with an indirect buffer storage tank did not have any significant savings.
- Comfort Comparison: In both zoned system configurations, temperature setbacks at night were significantly greater compared to the reference system. Because of significant solar gains that contribute to heating and an open stairwell that allows the heat from the main floor to rise to the second floor of the house, energy savings and comfort were not achieved. The single-zone system did not provide an acceptable level of comfort because of the poor match between the airflow to each floor and the cooling loads. The multizone configuration was able to maintain comfort compared to the single-zone system.

An Assessment of Peak Demand Reductions and Energy Savings of a High-Velocity, Centrally Zoned Combination System

2013. Jeremy Sager, R. Glazer, F. Szadkowski, and Terry Strack.

Summary: This report by Canmet compares cooling season energy and comfort performance for homes with single-zone and multizone air distribution systems. The multizone system consists of a high velocity air distribution system with two zones: (1) upper level and (2) main floor and basement. That is compared to low velocity, single-zone air distribution systems. Both types have a SEER 13 air conditioner. The report discusses the equipment used for air circulation, space heating and cooling, water heating, and ventilation, along with system operating conditions and instruments used for measurements in the test houses. The monitoring captures information at five-minute intervals. The experiment compares the overall cooling energy consumption and comfort performance between the residences with two-zone and single-zone systems. The experiment results are summarized below.

- Energy consumption: The zoned systems had a higher daily average cooling energy use than the non-zoned systems. The zoned system used less on peak energy for cooling, and peak savings were 36%. Non-zoned systems showed 13% peak energy savings against the standard system. The higher daily energy consumption for the high velocity zoned systems is due to additional fan energy needed to move air through the small ductwork.
- Comfort comparison: It was noted that high-velocity zoned combination systems cooled the second floor to the desired room temperature while the non-zoned system was not able to achieve the desired temperature for the second floor. For a high-velocity zoned cooling system, the nighttime set-forward schedule on the main floor resulted in temperature decreases overnight on the main floor. This was primarily because there was no occupant heat gain during night and there was continuous air circulation and cold air movement from the second to the main floor. The authors tested the high-velocity zoned system with non-zoned configuration and both zone supply dampers open; this setup used less energy than the zoned system. Ultimately, however, it was less effective to provide cooling to the second floor. Similar to the experimental results, the modeled residential cooling system energy use showed similar energy savings for zoned high velocity systems during peak demand.

The Zone-Saver Field Trial: Utility-Controlled Demand Response with Residential Zoned Cooling

2011. Dean Mountain, Terry Strack, Wen Zhou, and Bartosz Lomanski.

Summary: The paper describes a field study that evaluates the demand response capabilities of residential zoned cooling systems during summer peaks. Electrical demand for the summer peak period is compared for zoned and non-zoned systems with and without load control. Different zones are controlled during the peak demand period. The study documents the effects of load control on daily cooling energy consumption and zone system ability to maintain indoor comfort. The experiment monitored ten homes with ZoneComfort (ZC) systems. Utility load-controlled air conditioning was applied to specific zones. Additionally, ZC homes were compared to nine furnace homes and two peak-saver homes. Questionnaires were used to gather data on dwelling houses' characteristics, demographics, and lifestyles pertaining to the ZC system. Detailed field experiment empirical models were developed to evaluate utility-controlled cooling loads for residential zoned systems.

The authors developed a zoned cooling energy simulation model to study the impacts of seasonal residential energy consumption for residential zoned air conditioning systems. The model results were compared to those from the empirical method. The report summarizes the major findings:

- Small peak changes occur for a ZoneComfort house without utility interruption. The authors observed that the maximum change occurs during the 1:00 p.m. to 5:00 p.m. peak period. The zoned systems offered benefits by allowing the utility interruption schedules to be changed for different demographics.
- Air conditioning condenser and fan load during summer for zoned houses is 17% below non-zoned houses.
- Utility-interrupted ZC houses generated a 12.3% reduction in air-conditioned kWh usage compared to non-zoned houses.

- Four-hour air conditioning interruption in the upper floor during the day shows an average change of -0.52 kW. This is twice the reduction of air conditioning cycling for the entire house. ZC systems produced greater indoor comfort conditions on the upper floors of the house during the nighttime.
- About two thirds of the participants preferred individual zone cooling control over controlling cooling for the whole house.
- Like the field experiments, the simulation results showed potential to utilize zoned cooling systems to reduce peak electricity demands to off-peak evening hours. Comparing the zoned and non-zoned simulations highlights the advantage of setpoint schedule for the zoned system, thereby addressing the comfort issues in the bedrooms.

Advanced Residential Load Reduction Pilot Project

2011. Dean Mountain, Terry Strack, and Jeremy Sager.

Summary: The experimental analysis of ZoneComfort (ZC) systems was conducted and monitored across 20 occupied sites in different Canadian regions. Monitoring systems were installed in these occupied sites to collect temperature and humidity information. The monitoring system also evaluated the demand and energy performance of the HVAC system for a 16-month period. Both the electricity and natural gas usage was collected from regional utilities for each site.

The authors discussed the impact of ZC systems on the energy usage by both the air condenser and the air handling unit. These values were used to formulate statistical models used to estimate ZC systems' incremental conservation contribution while controlling for weather and dwelling characteristics. Based on the field data the authors summarized the following.

- Savings varies depending on the type of ZC configuration. ZC systems save 7% in natural gas and 36% in electricity for air conditioning condensers.
- The indoor comfort conditions were compared for ZC systems and non-ZC houses. Both systems provided comfort that was within the ASHRAE comfort zone. The ZC systems were able to maintain better comfort conditions on the top floor of the house overnight.
- Up to 90% of the occupants thought the comfort was better for the ZC controlled systems. Also, 70% of the occupants felt that the ZC systems reduced energy consumption and provided better indoor comfort conditions.

Laboratory House Test of Smart Damper Control Systems to Provide Zoning

2017. James Haile, David Springer, and Davis Energy Group, Inc.

Summary: The researchers evaluated whether two HVAC smart damper zoning systems passed the Title-24 diagnostic testing procedures. They also evaluated the impact of smart zone control systems by assessing fan efficacy and system airflow in various operating scenarios. Both systems largely performed as intended. However, when a limited number of dampers were open, smart damper systems resulted in larger duct losses and lower airflow rates, decreasing total system efficiency. Significant adjustments to the static pressure in the main branch were advised before energy savings could be realized.

Market Research

Our goal was to discover where zoned systems are currently being installed and what their technical potential is, as well as identify barriers that would limit implementation and installation cost variation by type of existing system and type of equipment.

Stakeholder Interviews and Surveys

Distributors for Major Manufacturers

Feedback was sought from five distributors on multizone (MZ) residential air distribution systems offered in MN, estimated percentage of units sold, benefits, and market penetration. Almost all five distributors interviewed suggested that multizone systems were more common in high-end new construction and indicated that 10% to 50% of new homes with central air distribution have zoning equipment. This is consistent with a recent new study of new Minnesota homes that found that 22% of the furnaces had zoning equipment (95% confidence interval of 14% to 33%, Pigg 2022). The distributors were unable to provide an estimated percentage of MZ system sales. Three distributors offered flagship multizone models along with third-party products, while the others only offered third-party damper and control products. All the distributors identified direct control to individual zones and comfort as MZ systems' primary benefits, while a few suggested the potential for energy savings with modulating airflow rates. In regard to market penetration, there was less consensus among the distributors; a few suggested there had been a rise in market growth due to the awareness of these systems, while others saw a stagnant market or gradual decline due to the emergence of new systems such as VRF, VAV, and ductless mini splits. However, most distributors suggested that utility incentives for MZ systems could help with market growth.

1. Three of the five distributors surveyed in Minnesota offered both manufacturer flagship multizone systems as well as third-party damper and control products. The remaining two distributors offered third-party modulating zone controllers and dampers.
2. The five distributors provided different estimates for the percentage of new homes that have multizone systems. The estimates for new homes with multizone systems ranged from 10% to 50% and averaged 24%. Four of the five distributors indicated that multizone systems are more common in higher-end houses. These four also indicated that the systems are installed less often in existing houses than in new houses.
3. All five distributors surveyed suggested that the percentage of systems varied based on region. Two of the five estimated 90% to 95% of the metro area used AC, whereas in rural areas 60% used AC and 40% used a heat pump with backup reheat.
4. Two of the five distributors surveyed stated that the market for multizone (MZ) systems has remained stagnant year to year. Among the remaining three distributors, one indicated that the market for ducted MZ systems was shrinking due to the rise of VRF, VRV, and ductless mini splits as they can operate at lower temperatures by providing flexibility and efficiency. The other two distributors suggested that the market for MZ systems was growing thanks to increased awareness.

5. All five distributors surveyed were not able to provide an estimated range for MZ systems sold in Minnesota.
6. All five distributors surveyed saw comfort as MZ systems' primary benefit as they provide direct control to each individual zone.
7. All five distributors surveyed suggested that energy savings could be significant for MZ systems that modulate air handler airflow.
8. Installation complexity, particularly with ductwork and zoning, was the primary drawback for four of the five distributors surveyed. Relative humidity issues due to condensation during winter was an additional major factor for another distributor.
9. Two of the five distributors surveyed expressed positive feedback from homeowners and an increase in MZ system demand. The remaining three distributors suggested that there was a lack of customer interest primarily because of equipment reliability, duct sealing, and static pressure. Three distributors had positive feedback (e.g., "people love it when they have it installed") and the fourth said that people are avoiding the systems. Two noted concerns with proper installation for duct static pressure and duct sealing.
10. All five distributors surveyed stated that none of the Minnesota utilities offer rebates especially for MZ systems, noting that there have been incentive options for system efficiency and thermostats.
11. All five distributors surveyed suggested that utility rebates would drive market penetration for MZ systems. Besides rebates, some distributors also indicated that the use of multi-stage equipment and proper installation could increase market penetration.

Third-Party Manufacturers

Feedback was sought from three third-party manufacturers on multizone residential air distribution systems' overall response, compatibility, and sales in Minnesota. All third parties acknowledged that comfort and control were the systems' primary benefits. Two parties suggested that heating energy savings were impactful depending on utility rates and the overall system utilization. Complex installation processes, system operation, and high costs were the major concerns with these systems. The third parties suggested different ways to address airflow rate restrictions such as the use of a dump zone or bypass zone and system modulation. All third parties highlighted that these systems were sold significantly less often but indicated that most of their control systems were compatible with both communicating and non-communicating HVAC systems.

1. All three third-party manufacturers saw comfort and control as the primary benefits of multizone (MZ) systems.
2. One third-party manufacturers suggested that both heating and cooling energy savings were important. Another third-party manufacturer indicated that heating savings were more important than cooling. The remaining manufacturer suggested that savings depended on utility rates and how rooms were utilized.
3. All three third-party manufacturers agreed that MZ systems have a complex installation process and high cost. One stated that customers might have a difficult time understanding the system operation. Another manufacturer emphasized that not all rooms can be zoned, and when installation is done incorrectly it damages the MZ systems.

4. All three third-party manufacturers surveyed expressed positive feedback from customers.
5. Two of the manufacturers agreed that the bypass damper or dump zone method was the most common approach to address restricted airflow rate. The remaining manufacturer said they used system modulation to address restricted airflow.
6. One of third-party manufacturer indicated that their control systems were compatible with all communicating and non-communicating HVAC systems. Another third-party manufacturer mentioned their control system was compatible with ComfortNet™ and Daikin communicating HVAC systems along with all the non-communicating HVAC systems. The remaining third-party manufacturer suggested their control systems are compatible with only non-communicating systems.
7. Two third-party manufacturers were not able to provide a proper estimate for systems sold. Another indicated that they do not sell many controls in Minnesota.
8. All third-party manufacturers surveyed agreed that these HVAC systems should only be installed by contractors.

Mechanical Contractors

Feedback was sought from six contractors on multizone residential air distribution systems' installation setup, performance, and market penetration. All the contractors overwhelmingly expressed cost and zoning setup to be challenging, especially in existing homes due to the absence of separate trunk lines. Three of the five contractors (60%) indicated comfort control as multizone systems' primary benefit, while energy savings were less impactful. All contractors agreed that zoning achieved high efficiency results with communicating variable speed systems, which could minimize the airflow rate restrictions compared to single stage models. Three contractors suggested that utility incentives for MZ systems could help encourage market growth, while the remaining two maintained that the market would remain stagnant due to high installation costs.

1. All five contractors stated that comfort control and occasionally energy savings were the primary benefits of multizone (MZ) systems.
2. Three of the five contractors suggested that energy savings were not significant enough to make an impact. One of the two other contractors said there were too many variables that can impact the savings, while the final contractor mentioned that the savings were important for both heating and cooling seasons.
3. The main challenge that all five contractors expressed was the high cost of installation. One contractor indicated that installation would be an issue for non-variable speed systems. Two contractors also suggested that there would be installation issues if the homes were not set up for zoning.
4. All five distributors surveyed cited a positive response from homeowners thanks to the comfort benefits of MZ systems.
5. All five contractors surveyed stated that utilities offer rebates specifically for system efficiency and thermostats and not for adding zoning.
6. Four of the five contractors suggested that utility rebates would help market penetration for MZ systems.

7. Three of the five contractors suggested that MZ systems were installed in new constructions, but estimated percentage varied by contractor. The remaining two contractors estimated that about 1% of MZ systems were installed as retrofits.
8. All the contractors agreed that high-end homes were the most common houses in which MZ systems were installed. Two contractors also noted that, except for low-priced houses, all other house types were prime candidates for MZ systems.
9. Three of the five contractors indicated that the market for MZ systems was growing largely thanks to comfort control for individual zones. One of the contractors commented that the market for MZ systems was shrinking due to high installation costs. Another contractor suggested that the market was stagnant.
10. Four of the five contractors specified that Carrier/Bryant evolution and other communication systems applied system modulation method to adjust the CFM and airflow rate, while the dump-zone method was used for non-communicating systems. One contractor used pneumatic dampers to address the airflow rate.
11. All five contractors suggested that variable speed equipment worked much better for zoning compared to single-stage model. A few of the contractors also advised that communicating systems should be used with variable capacity to achieve better system efficiencies.
12. All five contractors agreed that the installation process is relatively easy for new construction compared to retrofits because existing houses would need to be set up for zoning with separate trunk lines to make retrofits possible.
13. Four contractors stated that it is much more common to find separate branches per floor for new construction houses compared to houses that are 10 to 15 years old. One contractor has not come across separate branches of ductwork.
14. Four contractors indicated that zoning depended on existing duct layout and unfinished basement. One contractor applied pneumatic damper systems to exiting, which did not significantly impact the duct layout.
15. As a follow up to the initial interview, contractors were contacted and asked the typical additional cost to upgrade from a single-zone to multizone system. Two contractors responded. One indicated the cost was $2,000 to $2,500 for a two-zone system and $3,500 to $4,000 for a three-zone system. The other indicated a cost of $2,500 to $3,500 for a two-zone and $5,00 to $6,000 for a three-zone system. A local developer of townhouses indicated that the cost for a buyer to upgrade to a two-zone system was $2,550 and $5,225 for a three-zone system.

Assess the Potential for Utility Efficiency Programs

U.S. Utility Outreach

The objective was to identify U.S. utility residential efficiency programs outside Minnesota that provide incentives to upgrade from a central, single-zone air distribution system to a multizone system. The outreach included a query of ESource's DSM database, communications with energy efficiency organizations across the U.S., and contacts with 11 utility energy efficiency program managers at major U.S. utilities (see list below). Many utilities provided upgrade incentives for the rated efficiency of furnaces, heat pumps, and air conditioners. However, this process did not identify any U.S. utilities that are currently providing incentives to upgrade from single-zone to multizone air distribution systems.

- East Coast: Mass Save (Massachusetts), New Jersey Board of Public Utilities (New Jersey), PSE&G (New Jersey / New York)
- Midwest: ComEd (Illinois), Consumers Energy (Michigan)
- Mountain States: Efficiency Works (Colorado)
- West Coast: Bonneville Power Administration (Northwest), Pacific Gas & Electric (California), Puget Sound Energy (Washington), San Diego Gas and Electric (California), Southern California Edison (California)

Five utilities had conducted multizone system pilot projects. There were no reports available for the pilot projects. The limited information available is shown below.

- Enbridge Gas. Ecovent Smart Vents. Project completed. Recommended for additional research. No report provided.
- Pacific Gas & Electric. Laboratory House Test of Smart Damper Control Systems to Provide Zoning. Not recommended for program adoption (as of 2017). The researchers evaluated whether two HVAC smart damper zoning systems passed the Title-24 diagnostic testing procedures and the impact of smart zone control systems by assessing fan efficacy and system airflow in various operating scenarios. For the most part, both systems performed as intended. However, in some circumstances smart damper systems resulted in larger duct losses and lower airflow rates, decreasing total system efficiency. Significant adjustments to the static pressure in the main branch were advised before energy savings can be realized.
- Sacramento Municipal Utility District. Residential HVAC Zoning savings. The project was cancelled. No reason specified. No report is available online.
- Consumers Energy. The Smart Vent Zoning project was cancelled. Energy savings were not identified. No published report.
- Sothern California Gas Company. Ecovent SFR HVAC Controls at Air Registers (Smart Vents) project was cancelled. Additional technical evaluation was required. No report is available.

Nicor Gas conducted a project using Ecovent's dynamic air balancing system. The results are not included here because the system was applied to a commercial building with two roof top units.

Minnesota Utility Outreach

Feedback was obtained from a representative sample of utility program staff from four Minnesota utilities. They provided information on their specific areas of interest and concern with regard to residential zoned systems. They were also asked about what they hear from end users and trade allies about requests to add multizone distribution systems to the CIP portfolio for existing and/or new homes. A summary of the responses to the nine interview questions are shown below.

1. All of the utility staff were familiar with residential multizone systems.
2. There is an expectation that the systems will primarily provide improved comfort, but energy savings could be a strong secondary benefit. One was concerned that the added cost would not justify the potential energy savings.

3. None of the utilities had evaluated this technology and possible energy savings benefits.
4. All of the utilities felt that the systems could generate space cooling and/or heating energy savings.
5. One of the utilities was aware of a Canadian program that provided incentives for multizone systems, but the other three were not aware of any utility incentive programs.
6. None of the utilities had considered incorporating multizone systems into their residential new construction or retrofit programs. One of the utilities indicated that there may be a benefit to establishing a national utility working group and that the technology could provide demand reduction options.
7. The greatest barrier for incorporating multizone systems in their programs was uncertain energy savings or not being able to compute energy savings. It was also noted that the added cost might be a difficult sell to customers, the benefit may be demand reduction that does not provide a benefit to the customer, and it may be challenging to identify houses where there will be savings.
8. Three of the utility staff had not had any interactions with customers about using a multizone system in their home or contractors interested in installing them in homes. One had interactions with customers regarding improved comfort.
9. One utility was interested in learning more about the cost effectiveness of retrofit installations. Another mentioned the possibility of reducing cooling energy use by simply circulating air to enable cooler basement air to help cool the rest of the house. There was also a question regarding the use of return air dampers for multizone systems.

House Energy Use and Indoor Air Temperature Model

EnergyPlus models of prototype Minnesota single-family houses were used to evaluate the energy use and improved comfort of multizone air distribution systems. The performance of single-zone and multizone distribution systems were modeled for one- and two-story single-family houses with configurations consistent with current and 1950s–1960s construction characteristics. In addition, air temperature measurements from previous research projects in Minnesota houses were analyzed to document the seasonal variation in house air temperatures by floor.

Air Temperature Measurements

Air temperature measurements from previous research projects in Minnesota houses were analyzed to document the seasonal variation in house air temperatures by floor. The results were used to verify that the modeled seasonal trends and relationships between floor temperatures have been observed in actual houses. Data was obtained from three single-family houses with two floors above grade (e.g., two and 1.5 stories) and three with one floor above grade. The set of houses is a convenience sample and not intended to represent the population of Minnesota houses. Table 3 provides a list of key house characteristics. Five of the six houses are in the Twin Cities Metro area and one is in central-western Minnesota. Five of the six houses were built in or before 1940 and one was built in 2002. Two of the houses have unfished basements, two have partially finished basements, and two have fully finished basements. A total of 81 to 589 days of measured air temperatures were available for the houses.

Table 3. House characteristics for measured temperatures

House ID	# Stories	Year Built	City	Floor Area (sq. feet)	# Bedrooms	Basement Finished?	# Days of Data
2-2	1.5	1924	Minneapolis	1,036	2	No	120
2-3	2	2002	Fergus Falls	1,344	3	Yes	81
2-4	2	1925	Minneapolis	1,812	4	Yes	158
1-1	1	1900	Minneapolis	1,228	3	No	380
1-2	1	1940	Minneapolis	1,196	3	Partial	259
1-3	1	1932	Crystal	729	2	Partial	589

A summary of the heating season average temperatures by floor is shown in Table 4. The right side of the table shows average temperatures by floor for outside temperatures from 20°F to 50°F and the left side shows averages for outside temperatures less than 20°F. In addition to the averages, the columns labeled “Diff.” provide the difference between the first-floor average temperature and the basement or second floor average. For milder outdoor conditions (i.e., outside temperatures from 20°F to 50°F), the average first floor temperature varies from 64.7°F to 72.5°F, and the average for the six houses is 68.4°F. During colder outdoor conditions (i.e., outside temperatures less than 20°F), the average for the six houses’ first-floor temperature is only 0.6°F less than that for the milder weather. This suggests that the houses able 4 a fairly consistent first floor temperature throughout the heating season.

A key finding is that there is only one house that has a zone or floor that has a warmer temperature than the first floor during the heating season. The basement in house 1-2 is 2.6°F warmer than the 1st floor during milder weather and 6.4°F warmer in colder weather. For all other houses and floors, the first floor is the warmest part of the house. On average, the basements were 3.3°F cooler than the first floors during mild weather and 4.0°F cooler during colder weather. The second floors were 3.7°F cooler than the first floors during mild weather and 7.3°F cooler during colder weather. This suggests that there is very limited potential for a multizone distribution system to reduce heating season energy use for this small sample of houses. It is more likely that an MZ system would produce more comfortable temperatures for the basements and second floor areas. However, it is possible that individual zone control could allow the occupants to set back the temperatures in the basements and second floors to a greater degree than what they currently set back for the first floor. It should also be noted that not only is this a small sample, but also almost all the houses are older (built in 1940 or earlier) and less likely to have insulation than new houses. These measurements need to be conducted for newer houses to evaluate the heating season energy savings for new houses.

Table 4. Heating season measured house temperatures by floor

		Outside temperature < 20°F					Outside temperature 20°F to 50°F				
		Basement		1st Flr.	2nd Floor		Basement		1st Flr.	2nd Floor	
ID	# Stories	Avg.	Diff.[a]	Avg.	Avg.	Diff.	Avg.	Diff.	Avg.	Avg.	Diff.
2-2	1.5	56.7	-7.7	64.3	55.8	-8.5	58.4	-7.4	65.8	59.3	-6.6
2-3	2	(b)	-	-	-	-	65.5	-2.3	67.8	67.6	-0.2
2-4	2	66.2	-1.6	67.8	61.7	-6.1	68.0	-1.4	69.4	65.2	-4.2
1-1	1	60.1	-5.4	65.5	-	-	61.3	-3.4	64.7	-	-
1-2	1	77.4	6.4	71.0	-	-	75.1	2.6	72.5	-	-
1-3 Yr1	1	58.8	-11.6	70.4	-	-	62.2	-7.7	69.9	-	-
1-3 Yr2	1	61.8	-7.8	69.6	-	-	63.2	-6.3	69.4	-	-
Average[c]	-	63.8	-4.0	67.8	58.8	-7.3	65.1	-3.3	68.4	64.0	-3.7
Min.	1	56.7	-11.6	64.3	55.8	-8.5	58.4	-7.7	64.7	59.3	-6.6
Max.	2	77.4	6.4	71.0	61.7	-6.1	75.1	2.6	72.5	67.6	-0.2

a) Difference from 1st floor average

b) No data available for house 2-3 for outside temperatures below 20°F.

c) Does not include data from year 2 of house 1-3.

Table 5 shows a summary of the cooling season (outside temperatures greater than 75°F) average temperatures by floor. The first-floor temperature averages vary from 72.3°F to 79.9°F, and the average for all six houses is 75.7°F. For all three two-story houses, the average second floor temperature is higher than the first-floor average. The average difference between the first and second floors was 3.3°F. For all six houses, the basement average temperature is lower than the first-floor average. The difference ranged from 3.8°F to 8.0°F and averaged 6.1°F. This suggests that a multizone could significantly improve comfort and may provide cooling energy savings. Multizone systems could reduce cooling to basements where it may not be needed, while increasing cooling to the second floors of two-story houses.

Table 5. Cooling season measured house temperatures by floor

		Outside temperature > 75F				
		Basement		1st Flr	2nd Floor	
ID	# Stories	Avg.	Diff.[a]	Avg.	Avg.	Diff.
2-2	1.5	69.4	-6.3	75.7	81.5	5.8
2-3	2	68.1	-5.6	73.7	74.4	0.7
2-4	2	70.4	-5.8	76.3	79.5	3.2
1-1	1	64.3	-8.0	72.3	-	-
1-2	1	72.9	-7.1	79.9	-	-
1-3 Yr1	1	72.6	-3.8	76.4	-	-
1-3 Yr2	1	66.8	-7.0	73.8	-	-
Average[b]	-	69.6	-6.1	75.7	78.5	3.3
Min.	1	64.3	-8.0	72.3	74.4	0.7
Max.	2	72.9	-3.8	79.9	81.5	5.8

a) Difference from 1st floor average

b) Excludes data from year 2 of house 1-3

A series of box and whisker charts for the hourly data binned by outside temperature are shown in Figure 10 to Figure 16 for the six houses.[9] These charts reinforce the results shown in Table 4 and provide additional details on seasonal temperature variations and differences between zones. Some useful observations follow.

- For most houses, there is a transition for outside temperatures from 50°F to 70°F when the first-floor temperature shifts from a lower heating season temperature to a higher cooling season temperature. For five of the houses, the first-floor temperature stays consistent throughout the heating season.

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[9] House 1-3 had almost two years of data. The data was split into two separate years and a chart was generated for each year of data.

- For five of the six houses, the basement is cooler than the first floor for both the heating and cooling seasons. House 1-2 has a warmer basement in the heating season and cooler basement in the cooling season. This suggests that the basement has potential for both heating and cooling savings for house 1-2.
- The first and second floor temperatures of house 2-3 are very similar in both the heating and cooling seasons.
- The second-floor temperature of houses 2-3 and 2-4 is lower than the first floor during the heating season and higher during the cooling season. This suggests that either manually balancing supply branch airflows or using a multizone system could improve comfort in those two houses.
- The seasonal temperature variations are similar for year one and year two of house 1-3. The basement temperature is slightly cooler in year two.

Figure 10. House 2-2 measured air temperatures by floor

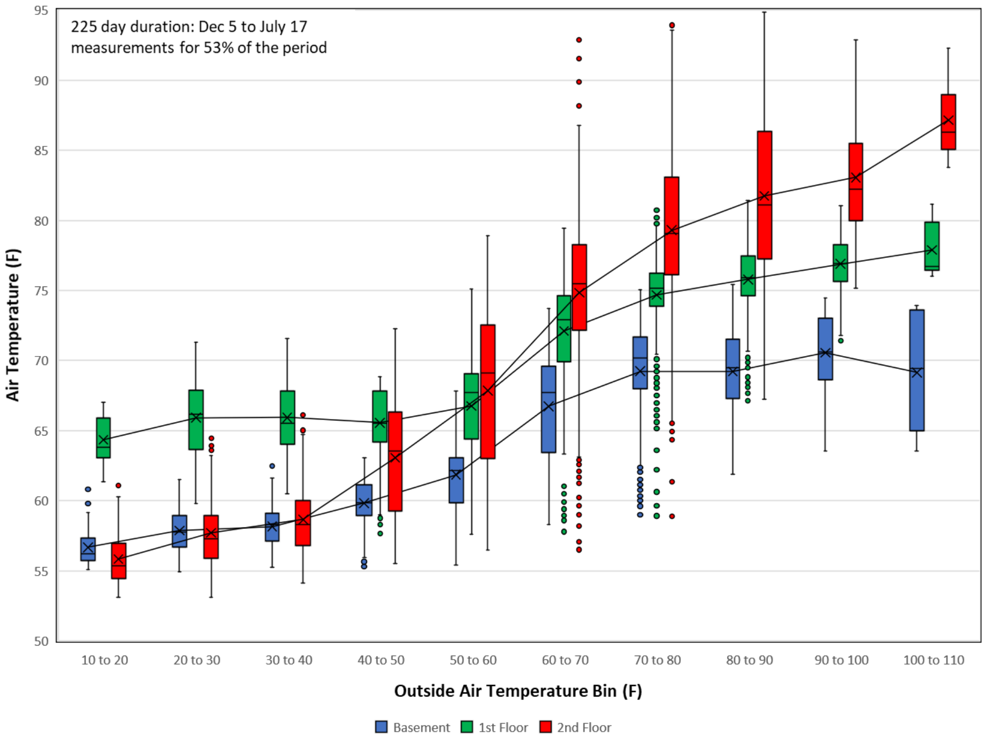


Figure 11. House 2-3 measured air temperatures by floor

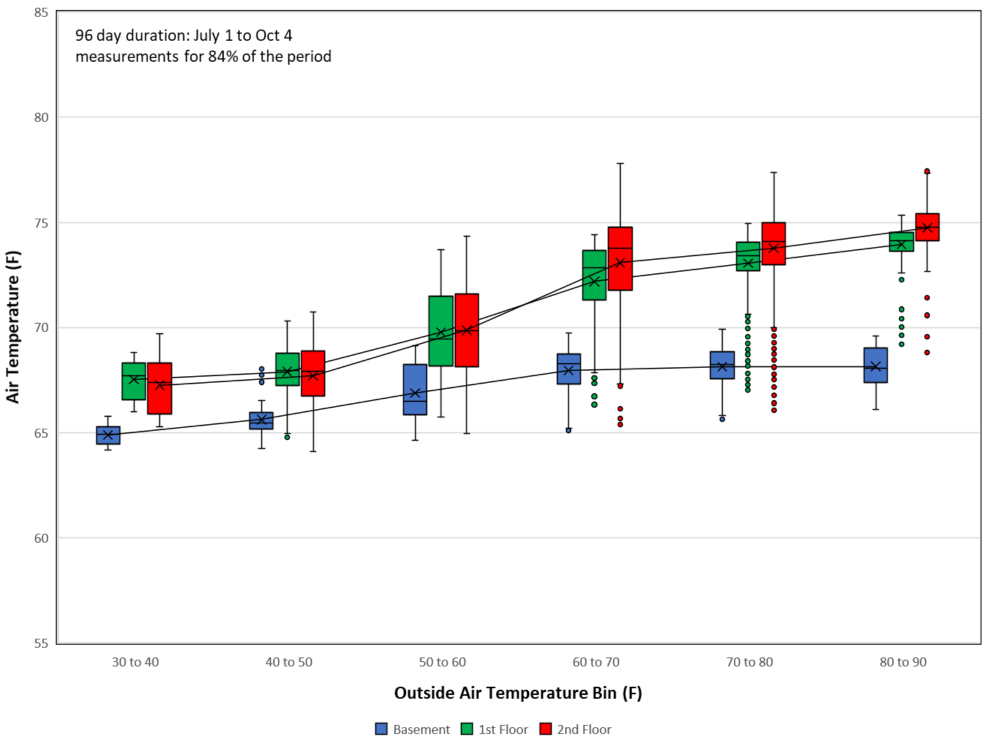


Figure 12. House 2-4 measured air temperatures by floor

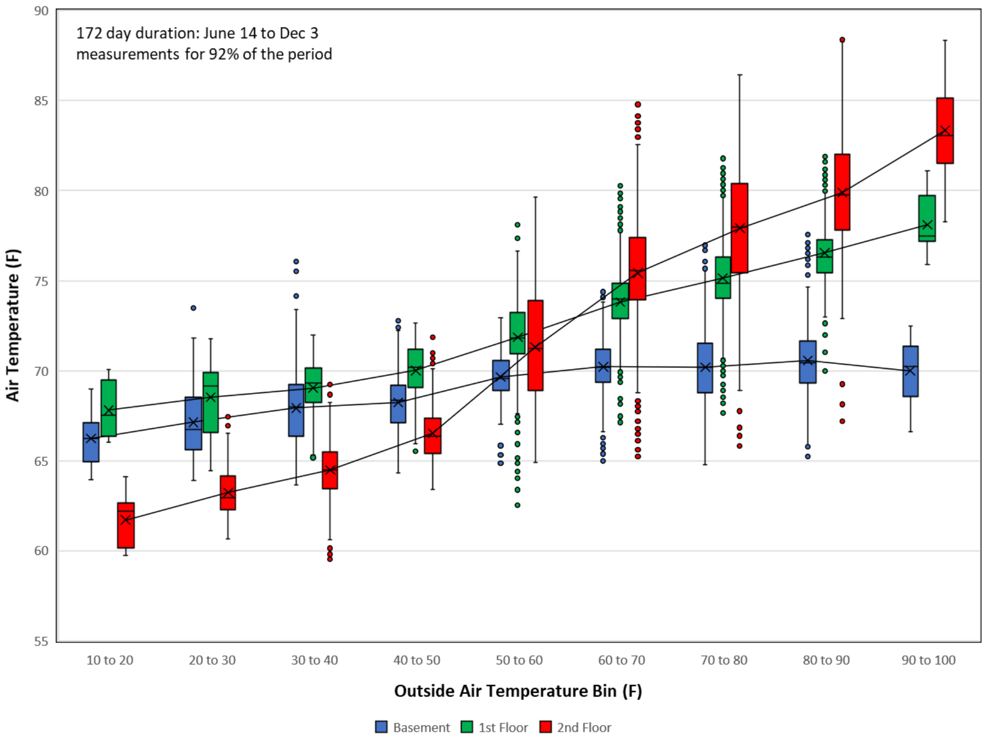


Figure 13. House 1-1 measured air temperatures by floor

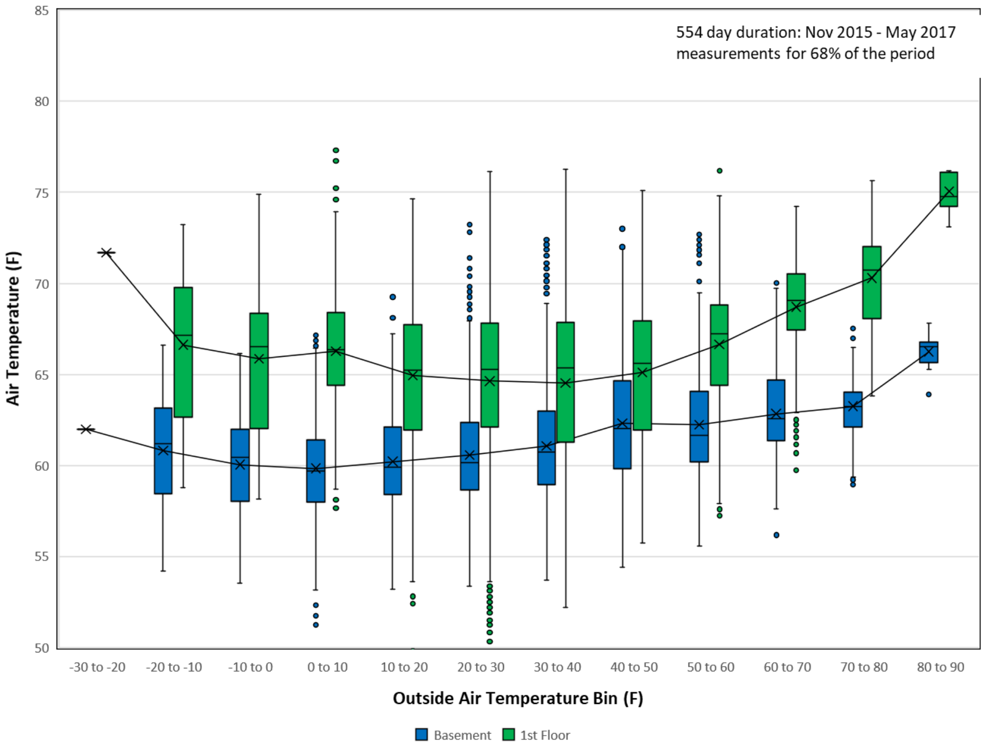


Figure 14. House 1-2 measured air temperatures by floor

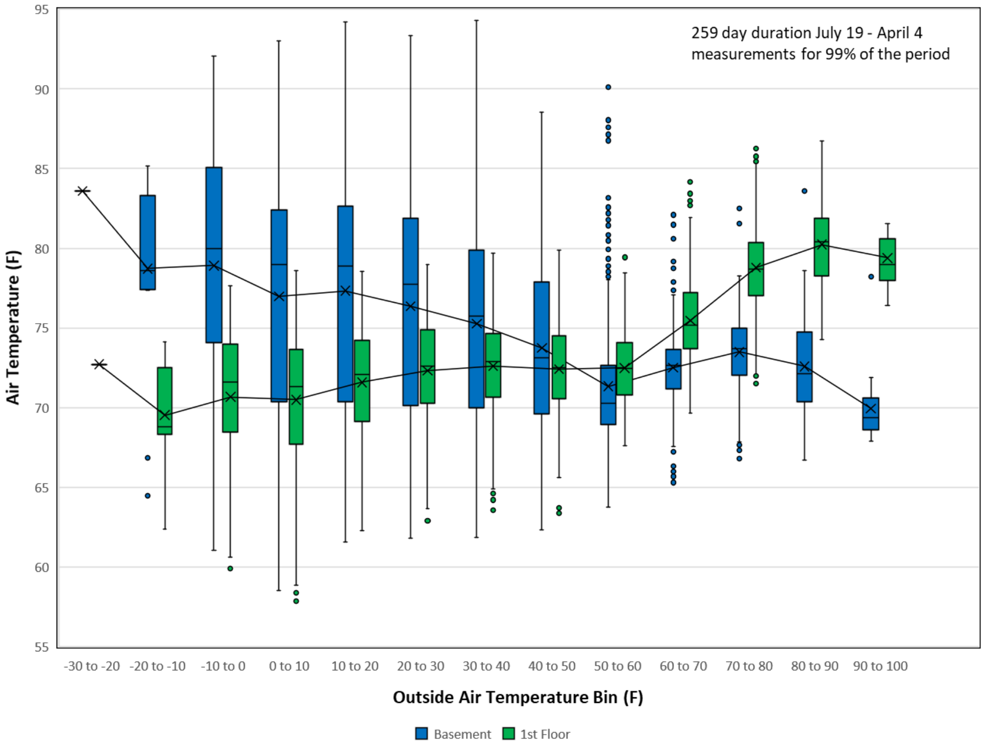


Figure 15. House 1-3 Year 1 measured air temperatures by floor

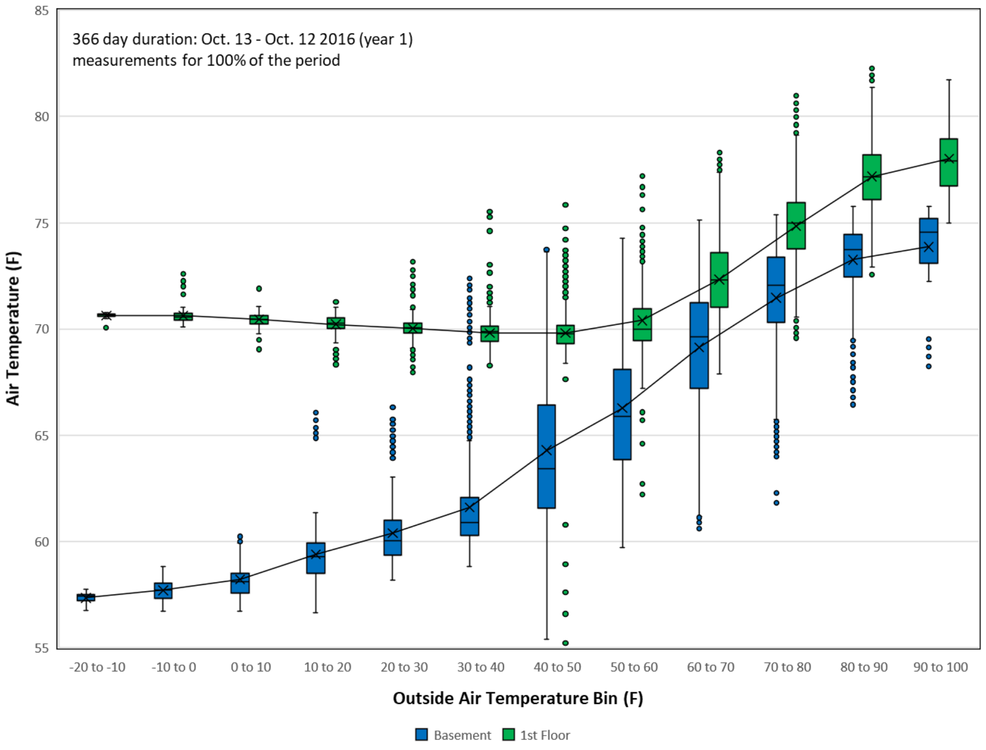
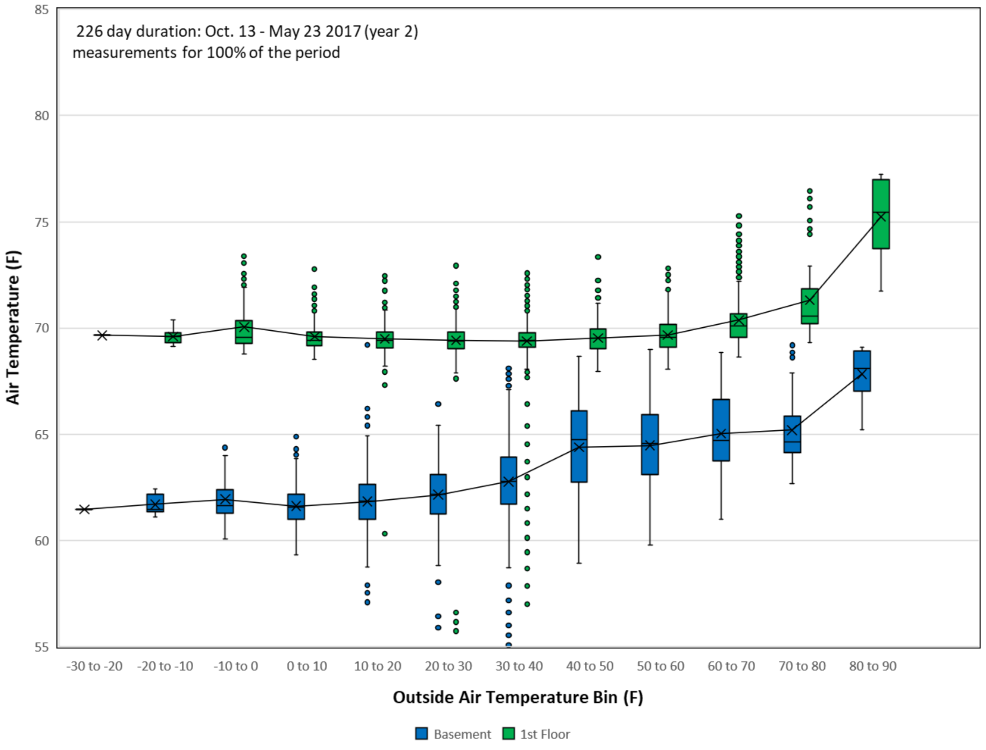
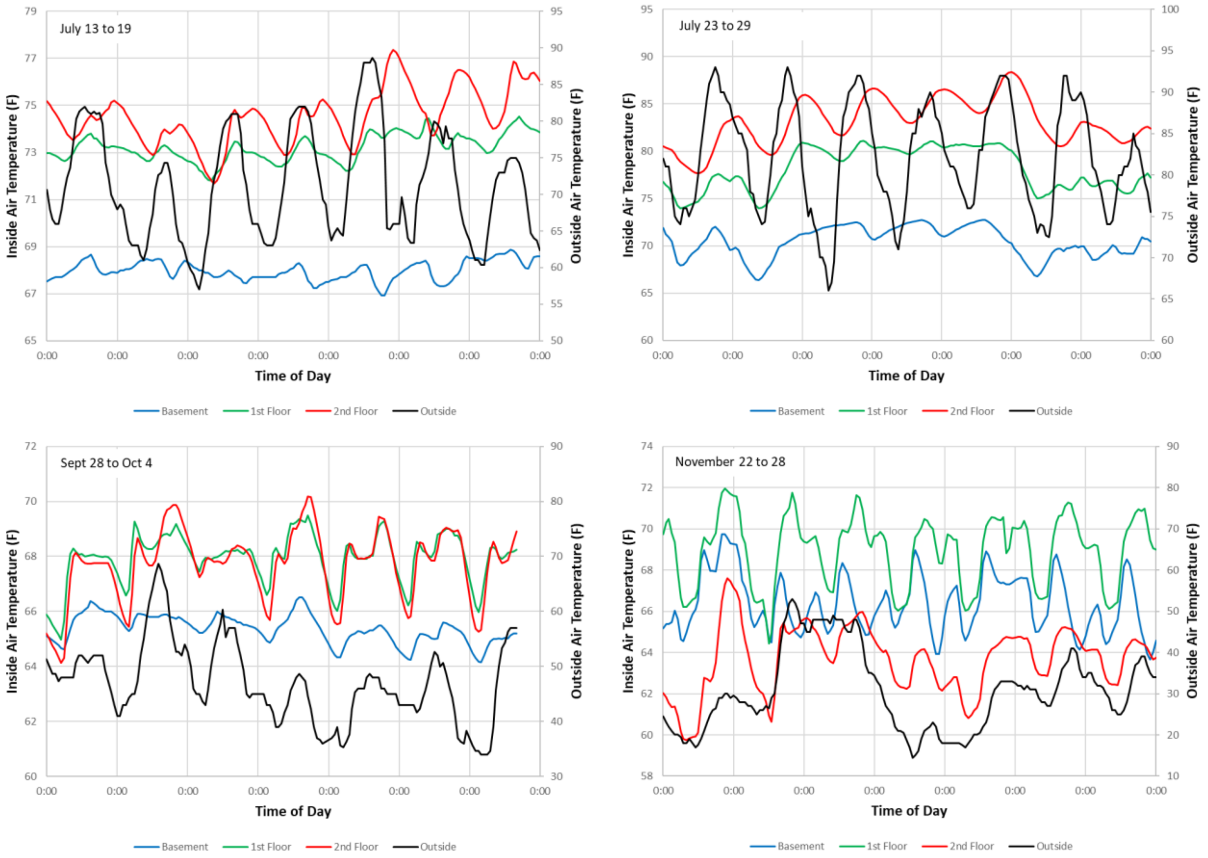


Figure 16. House 1-3 Year 2 measured air temperatures by floor



Charts with hourly cooling and heating season temperature data for houses 2-3 and 2-4 are shown in Figure 17. The charts on the left side of the figure show that the first and second floor temperatures of house 2-3 are almost identical for the heating season, but the second floor temperature is somewhat higher than the first floor during the cooling season. The charts on the right side of the figure show what appears to be a nighttime set back during the heating season. While the daytime temperature for the first floor returns to about 70°F, neither the basement nor the second-floor temperatures increase to that level. This suggests that there is not sufficient heat provided to those zones.[10]

Figure 17. House 2-3 (left) and 2-4 (right) hourly data



Energy Simulations

Building energy simulations of four prototype houses were used to evaluate the energy use and improved comfort of zoned air distribution systems. Two of the four models were configured with one story above grade, while the other two had two stories above grade. Each pair of configurations had one version with insulation, envelope leakage, and ventilation characteristics consistent with Minnesota code requirements for new homes and a second version with characteristics consistent with 1950s–

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[10] Unless the occupants prefer to have the basement and second floor cooler than the first floor.

1960s housing. The prototype houses were modeled for two different distribution systems: single-zone and multizone.

The single-zone systems had a constant volume fan that supplied a constant airflow rate to each floor when the air handler was active. Heating and cooling to the house was controlled by a thermostat located on the first floor. For the new home configuration, the air handler operated continuously to distribute outside air from the HRV. For the existing home configuration, the air handler operated when the heating or cooling was active.[11]

The EnergyPlus model implemented a staged multizone system. A separate constant volume heating and cooling component was used for each zone. This provides zone temperatures that are at the setpoint for almost all conditions. For the existing home configuration, the air handler for each zone operated only when there was a call for heating or cooling. This accurately simulates the performance of a staged multizone system. For the new home configuration, the air handlers operated continuously to distribute ventilation air and the heating or cooling was active as needed. This properly simulates the heating and cooling performance of a staged multizone system. Depending on the integration of the HRV with the multizone system, this simulation may overestimate air handler operation and electric energy use.

The baseline models used the EnergyPlus auto size option to compute the supply airflow rate for each floor (see Table 2 in the Methodology section). For the single-zone distribution systems, over- or under-heated and -cooled zones were produced by modifying the supply airflow's distribution by zone while keeping the air handler total flowrate the same. Table 6 displays the change in airflow by zone for the four supply airflow configurations for the one-story models[12] and six configurations for the two-story houses. In addition to the models with modified supply airflows, the single-zone system baseline configuration was run with the heating setpoint increased to 75°F. This was included to determine the increased energy use that would occur if it was necessary to increase the first-floor thermostat temperature setpoint in order to provide improved comfort for the basement and second floor (label = SP 75°F). Four scenarios were included to determine decreased energy savings for various temperature setbacks. The single-zone baseline configuration was run with a night setback from 10:00 p.m. to 6:00 a.m. that reduced the heating setpoint to 62°F and increased the cooling setpoint to 82°F (label = SZ Night Setback). Three additional thermostat setback models were run for the multizone systems. The first used a 10:00 p.m. to 6:00 a.m. setback for all zones with the same night temperatures as the Night Setback configuration (label = MZ Night Setback). The second reduced the basement setpoint to 62°F from 10:00 p.m. to 2:00 p.m. (label = Bsmt Setback). This may be desired if the basement is only used from mid-afternoon to evening. The third configuration used the same overnight adjustments as Night Setback and set back the temperatures of all zones from 8:00 a.m. to 2:00 p.m. on weekdays (label = Max Setback).

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[11] Often referred to as "auto" mode.

[12] First four rows of the table.

Table 6. Change to supply airflows from baseline

Label	Basement[a]	First Floor	Second Floor
SZ Base, MZ Base	0	0	0
+50 Bsmnt	+50	-50	0
+100 Bsmnt	+100	-100	0
+150 Bsmnt	+150	-150	0
+50 2nd	0	-50	+50
+100 B split	+50	-100	+50

a) Airflow rates in cfm

The following sections provide the energy use and comfort results from the EnergyPlus simulations of the four prototype houses. The first part of each section presents the heating season results and the second part presents the cooling season results. The analysis of indoor temperatures defined the heating season as time periods when the outside temperature was less than 50°F and the cooling season included hours when the outside temperature was above 60°F.

Two-story new home

It is helpful to understand the typical trends for indoor temperatures produced by the distribution systems to interpret the energy use and comfort results. The box and whisker (B&W) charts displayed in Figure 18 and Figure 19 show the seasonal variation of the zone air temperatures for the multizone and single-zone baseline scenarios, respectively. The zone air temperatures are filtered into 10°F outdoor air temperature bins. The box and whiskers indicate the distribution of the data within each bin.[13] The blue, green, and red boxes indicate values for the basement, first floor, and second floor respectively. For outside temperatures below 20°F, the multizone system keeps all zone temperatures at the 70°F setpoint temperature. For outdoor air temperatures above 20°F, there are times when the first- and second-floor temperatures drift above the setpoint. This is due to solar heating on sunny afternoons. For outside temperatures between 45°F to 60°F, little or no space heating is needed and the indoor temperatures float above the heating setpoint. For outdoor temperatures above 60°F, the system keeps the first- and second-floor temperatures at the 78°F cooling setpoint. There is little or no cooling required in the basement and that temperature drifts below the setpoint.

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[13] The median is represented by a horizontal line within the box. The X is the average, the bottom and top of the box are the first and third quartiles, and the end of the whiskers are local minimums and maximums. The small circles outside the whiskers are outliers that are more than 1.5 times the length of the box from the top or bottom.

Figure 18. Zone temperature B&W charts, multizone baseline scenario: two-story new home

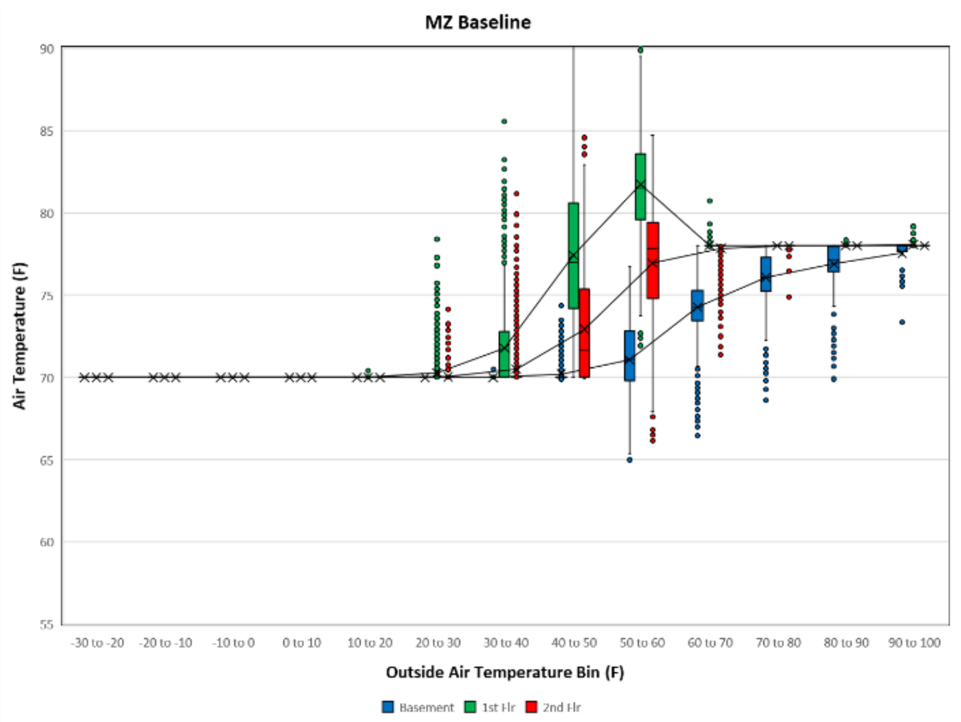
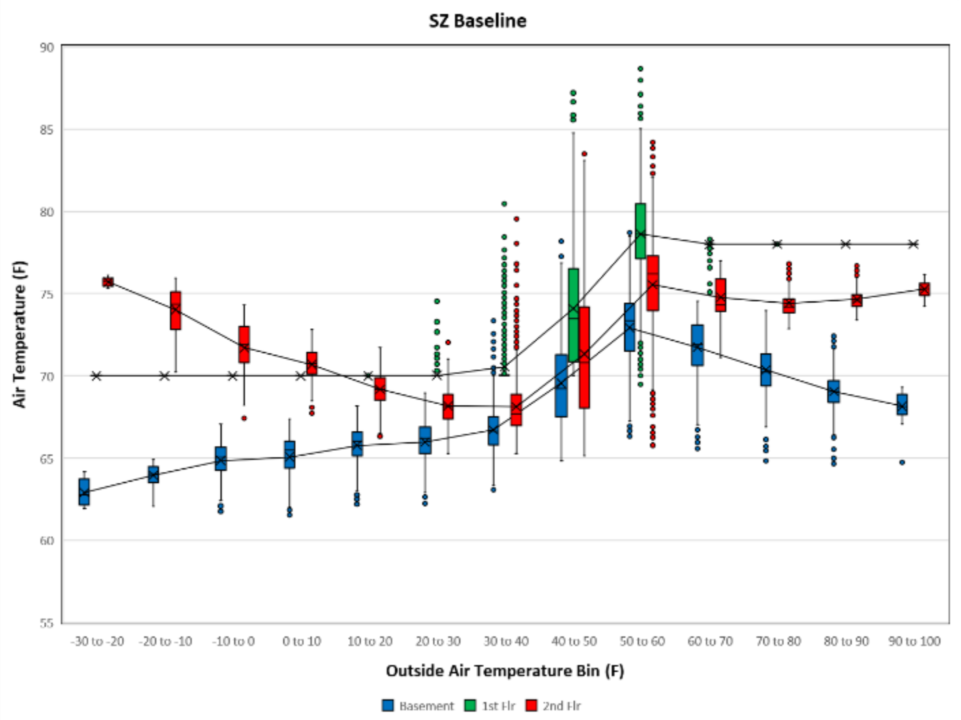


Figure 19. Zone temperature B&W charts, single-zone baseline scenario: two-story new home



For the single-zone system baseline scenario, the first-floor temperatures are very similar to those for the multizone system (see Figure 22). This should be expected since the thermostat is located in the first floor. In contrast, the single-zone basement and second-floor temperatures vary significantly from those for the multizone system. The EnergyPlus autosize supply airflows result in basement temperatures that are always below heating and cooling setpoints. The basement average temperature is 66.7°F for outside temperatures from 30°F to 40°F and steadily decreases to 62.9°F for outdoor temperatures from -30°F to -20°F. This indicates that the fraction of supply airflow to the basement is less than what is necessary to keep the basement at the desired temperature during the heating season. In addition, the basement is over-cooled during the summer cooling season. The basement results are consistent with trends for almost all for one- and two-story house measurements shown in the previous section. For five of the six houses, the basement temperature was less than the first-floor temperature for the entire heating season, and during the cooling season all basement temperatures were below the first-floor temperature for all six houses.

For outside temperatures from 40°F to 60°F, the second-floor temperatures for the single-zone system are similar to those for the multizone system. However, for outside temperatures from 10°F to 40°F, the second-floor temperatures are below setpoint. When the outdoor temperatures are below 10°F, the second-floor temperatures are higher than the setpoint. That indicates that the relationship between the first- and second-floor heating loads changes with outside temperature. This is at least partially due to the heating season change in air infiltration. The basement and first- floor infiltration increases linearly with decreasing outside temperature while the-second floor infiltration decreases slightly (see Figure 6). During the summer cooling season, the second-floor temperature is about 3°F below the setpoint. This suggests that the second-floor airflow rate is greater than required. For the three two-story houses with measured temperatures, the second-floor temperature was above the first-floor temperature.

Figure 20 displays B&W charts for four single-zone system scenarios with modified supply airflow rates. For the two scenarios with increased basement and reduced second-floor airflow (labeled +50 basement and +150 basement on the right side of the figure), the added basement airflow increases the basement temperature during the heating season and reduces the temperature during the cooling season. In addition, the added furnace runtime also results in slightly higher second-floor temperatures during the heating season and slightly lower temperatures during the cooling season. A 50 cfm increase in the second-floor and 50 cfm decrease in the first-floor airflows (label +50 2nd Floor) results in over-heated conditions for the second floor for almost the entire heating season and over-cooled conditions during the cooling season. Increasing the basement airflow by 100 cfm and decreasing the first- and second-floor airflows by 50 cfm provides temperatures that are typically within 3°F of the setpoint for the entire heating season. However, that also produces significantly low basement temperatures during the cooling season. Overall, there is no distribution of supply airflow by zone for a single-zone system that produces zone temperatures that are within 3°F of the setpoint for the entire heating and cooling seasons. That can only be achieved through seasonal changes to manual balancing dampers or with a multizone system.

Figure 20. Zone temperature B&W charts, single-zone supply airflow scenario: two-story new home

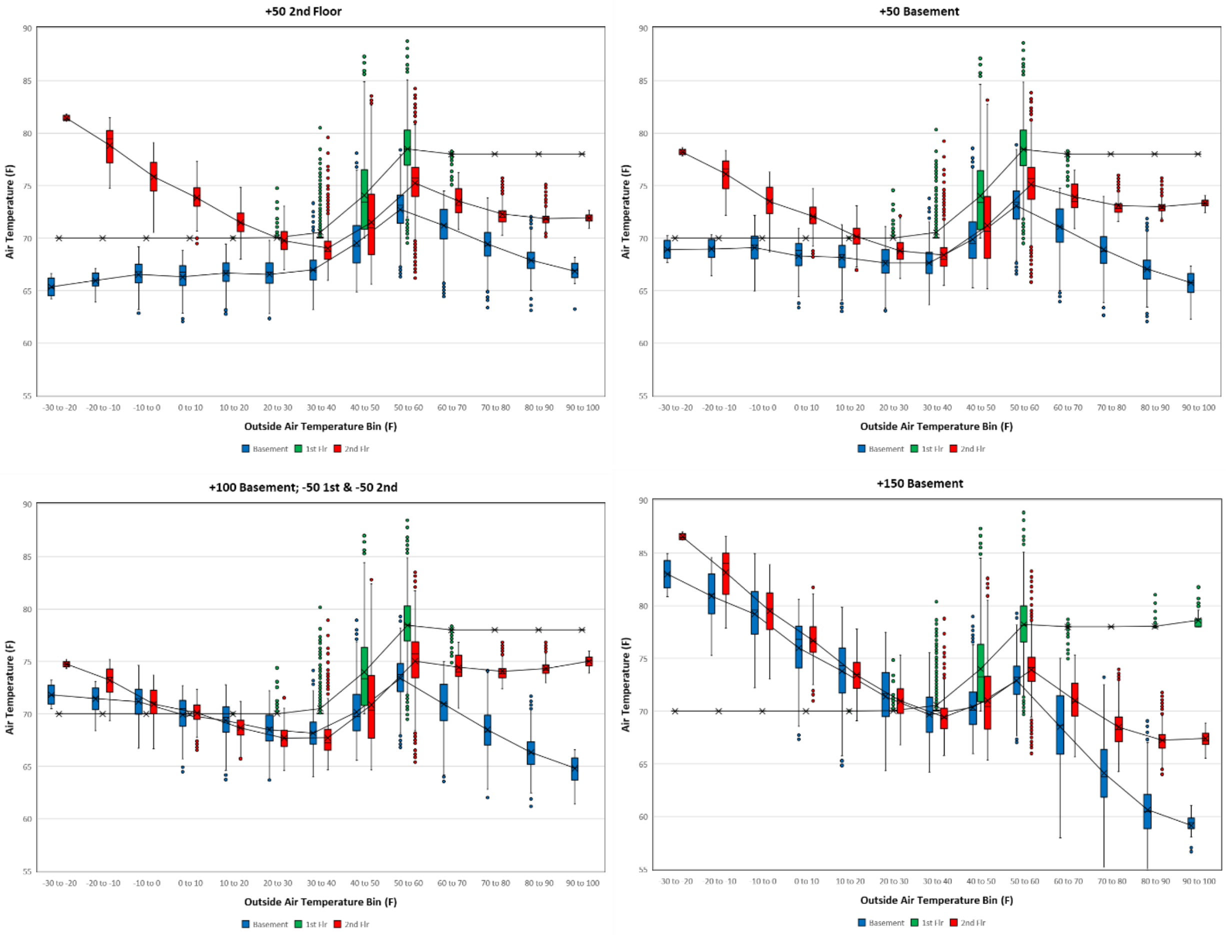


Table 7 and Figure 21 present the heating season annual energy use and average zone temperatures for the eight single-zone and four multizone system scenarios. The space heating annual energy use for the baseline multizone scenario was 419 therms/yr (0.12 therms/yr sq. feet normalized by floor area). The multizone heating energy use was greater than that for five of the six scenarios for the single-zone system with the same 70°F setpoint (i.e., excluding the setback scenarios). The heating energy for the single-zone systems compared to the baseline multizone system ranged from -14.9% to 7.8% and averaged -6.1%. The single-zone baseline scenario had the lowest energy use,[14] which was -14.9% less than that for the multizone system. For the five single-zone scenarios with lower energy use, the basements and/or second floors are under-heated. The multizone system addresses the under-heating and provides improved comfort, but at the cost of increased energy use. For the one single-zone scenario with higher energy use, the supply airflow to the basement was increased by 150 cfm and the airflow to the first floor was reduced by 150 cfm. This produced basement and second-floor temperatures that were 0.7°F higher than the first-floor temperature and energy use that was 7.8% higher than that of the multizone system. For that single-zone scenario, the basement and second-floor

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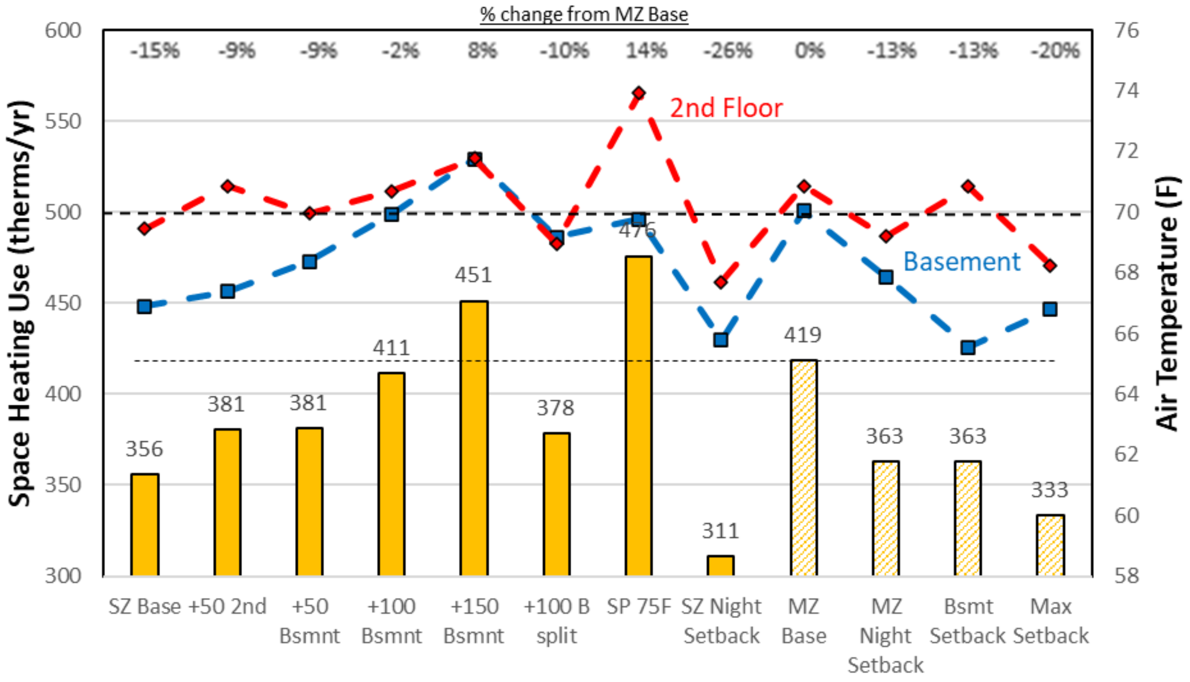
[14] Indicated by the red circle in the figure.

zones are slightly over-heated and the multizone system provides better comfort with reduced energy use.

Table 7. Heating season annual energy use and comfort: two-story new home

	Space Heating	Change	From MZ Base	Heating	Season	Avg.	Temp. (°F)
Label	**(therm)**	**(therm)**	**(%)**	**Basement & 2nd Floor**	**Basement**	**1st Floor**	**2nd Floor**
SZ Base	356	-63	-14.9%	68.2	66.9	71.2	69.5
+50 2nd	381	-38	-9.1%	69.1	67.4	71.2	70.9
+50 Bsmnt	381	-37	-9.0%	69.2	68.4	71.1	70.0
+100 Bsmnt	411	-7	-1.7%	70.3	69.9	71.1	70.7
+150 Bsmnt	451	33	7.8%	71.8	71.8	71.1	71.8
+100 B split	378	-40	-9.6%	69.1	69.2	71.1	69.0
SP 75°F	476	57	13.6%	71.8	69.8	75.4	73.9
SZ Night Setback	311	-108	-25.7%	66.7	65.8	69.5	67.7
MZ Base	419	0	0.0%	70.5	70.1	72.3	70.9
MZ Night Setback	363	-56	-13.3%	68.5	67.9	70.8	69.2
Bsmt Setback	363	-55	-13.2%	68.2	65.5	72.2	70.8
Max Setback	333	-85	-20.3%	67.5	66.8	70.0	68.2

Figure 21. Heating season annual energy use and comfort: two-story new home



The trends shown in Figure 21 suggest that the lower energy use for the single-zone systems occurred because those scenarios had cooler basement and second-floor air temperatures than the basement and second-floor temperatures for the multizone system. This is confirmed by Figure 22, which shows that the percent change in heating energy use from the multizone baseline scenario is strongly linearly related to the difference between the average basement and second-floor temperatures and the first-floor temperature ($R^2 = 0.999$). The regression slope indicates that there is a 6.3% increase in energy use for each 1°F increase in the difference between the average basement and second-floor temperatures and the first-floor temperature (e.g., inter-zone TD).[15] The inter-zone TD for zero percent difference between the multizone and single-zone system energy use was -0.6°F. This is 1.3°F greater than the inter-zone TD of -1.9°F for the multizone baseline scenario. Results from all models will be used to evaluate the trends in the regression slopes and intercepts.

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[15] For this report the difference between the average basement and second-floor temperatures and the first-floor temperature is referred to as the “inter-zone TD.”

Figure 22. Relationship between % change in single-zone heating energy use and inter-zone TD: two-story new home

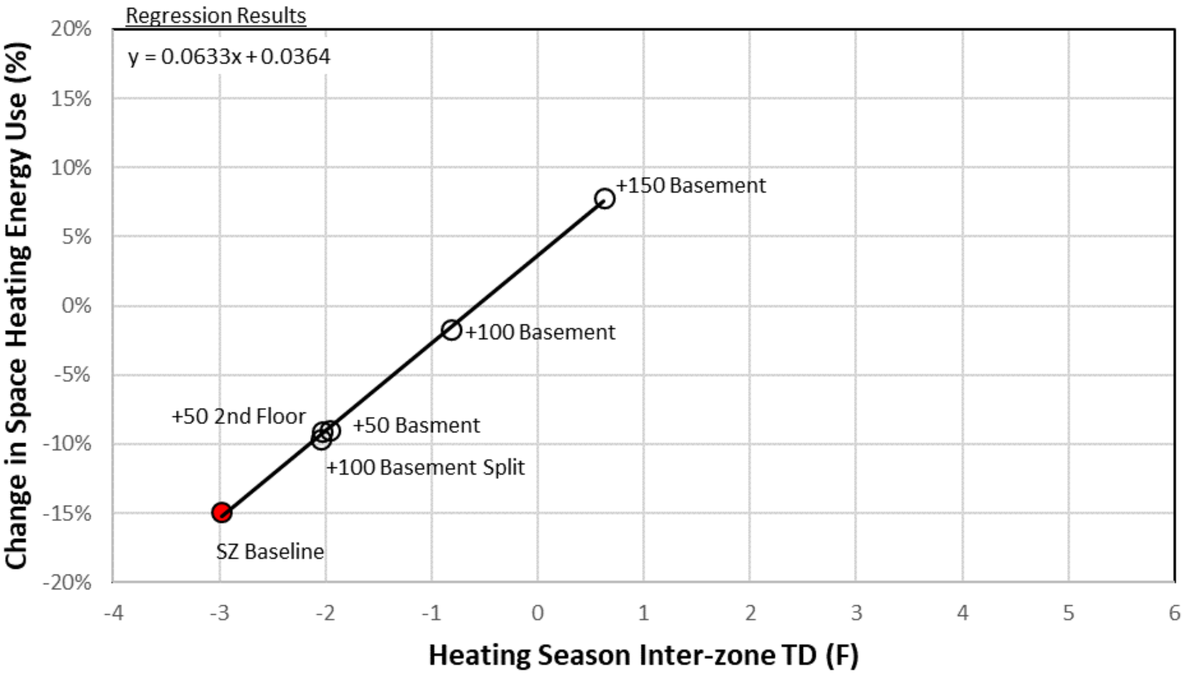

Table 8 and Figure 23 display the percentage of time during the heating season that the basement and second-floor temperatures were less than 67.5°F (low) and greater than 72°F (high) for the six single-zone scenarios. These values were computed to indicate the level of comfort achieved by the single-zone system with varying supply airflow rates. For the baseline scenario and two scenarios that increased the basement and second-floor supply airflows by 50 cfm,[16] the basement temperature was low more than 30% of the time. Increasing the basement supply airflow rate by 100 cfm and 150 cfm decreased the percentage of time the temperature was low to between 11% and 21%. However, the increased airflows also increased the percentage of time that the basement temperature was high. If minimizing the sum of the low and high temperatures is an indicator of better comfort, the best option of these scenarios was to increase the basement airflow by 100 cfm and decrease both the first- and second-floor airflows by 50 cfm (+100 B split). For that scenario, the heating energy use is 9.6% less than that of the multizone baseline. In addition, that scenario also results in a low second-floor temperature for 33% of the heating season, which is more than any other scenario. As noted previously, there is no distribution of supply airflow by zone for a single-zone system that produces zone temperatures that are within 3°F of the setpoint for the entire heating and cooling seasons. That can only be achieved through seasonal changes to manual balancing dampers or with a multizone system.

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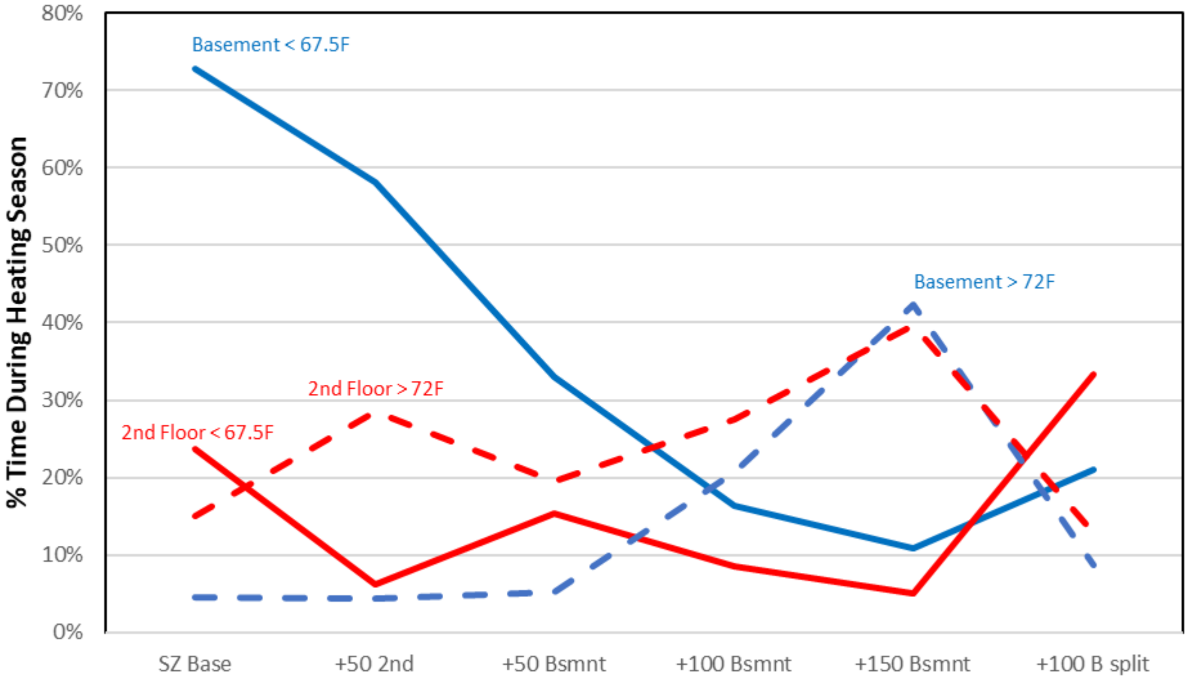
[16] A 22% increase in the basement airflow and 15% increase in the second-floor airflow.

Table 8. Heating season temperature deviation from setpoint: two-story new home

	Basement			2nd Floor		
Label	**< 67.5°F**	**> 72°F**	**Sum**	**< 67.5°F**	**> 72°F**	**Sum**
SZ Base	73%	5%	77%	24%	15%	39%
+50 2nd	58%	4%	63%	6%	29%	35%
+50 Bsmnt	33%	5%	38%	15%	19%	35%
+100 Bsmnt	16%	21%	37%	9%	28%	36%
+150 Bsmnt	11%	42%	53%	5%	40%	45%
+100 B split	21%	9%	30%	33%	13%	46%

Figure 23. Heating season temperature deviation from setpoint: two-story new home



Another option to improve the comfort of the basement and second-floor zones is to increase the first-floor thermostat setpoint to 75°F. This produces an average basement temperature of 69.8°F but over-heats the second-floor to an average temperature of 73.9°F and increases heating energy by 13.6% compared to the multizone baseline. Table 7 and Figure 21 include the heating season annual energy use and average zone temperatures for the one single-zone and three multizone system scenarios with variations in thermostat temperature setback. The single-zone night setback scenario reduces heating energy by 45 therm per year (13%) compared to the single-zone baseline, and the multizone night setback reduces it by 56 therm per year (13%). One advantage of multizone systems is the ability to set back the temperature for individual zones. For example, the multizone basement setback scenario reduces the basement setpoint to 62°F from 10:00 p.m. to 2:00 p.m. the next day. This decreases the heating energy by almost the same amount as the night setback scenario (55 therms per year or 13%) without having to decrease the temperature in the first and second floors. The max setback scenario combines the night setback with a weekday daytime setback, which generates energy savings of 85 therms per year (20%).

Table 9 and Figure 24 present the cooling season annual energy use and average zone temperatures for the eight single-zone and four multizone system scenarios. The space cooling annual energy use for the baseline multizone scenario was 1,676 kWh per year (0.47 kWh/yr sq. feet normalized by floor area). The multizone cooling energy use was less than that for all six scenarios for the single-zone system with the same 70°F setpoint. The cooling energy for the single-zone systems compared to the baseline multizone system ranged from 31% to 66% and averaged 44%. That equates to annual savings from 522 kWh to 1,108 kWh with an average of 738 kWh (0.21 kWh/yr sq. feet normalized by floor area). The single-zone baseline scenario cooling energy use[17] was 31% higher than that of the multizone baseline scenario. This is the opposite result than what was measured for heating energy, in which the single-zone system had a lower energy use than the multizone system. The high percent cooling savings are consistent with results from other modeling (Lu and Warsinger 2020) and field (Mountain et al. 2011 and Sager et al. 2013) studies. However, heating energy dominates space energy use in Minnesota. The cooling energy savings of 738 kWh (25.2 therms) is only 6% of the heating energy use for the multizone baseline scenario.

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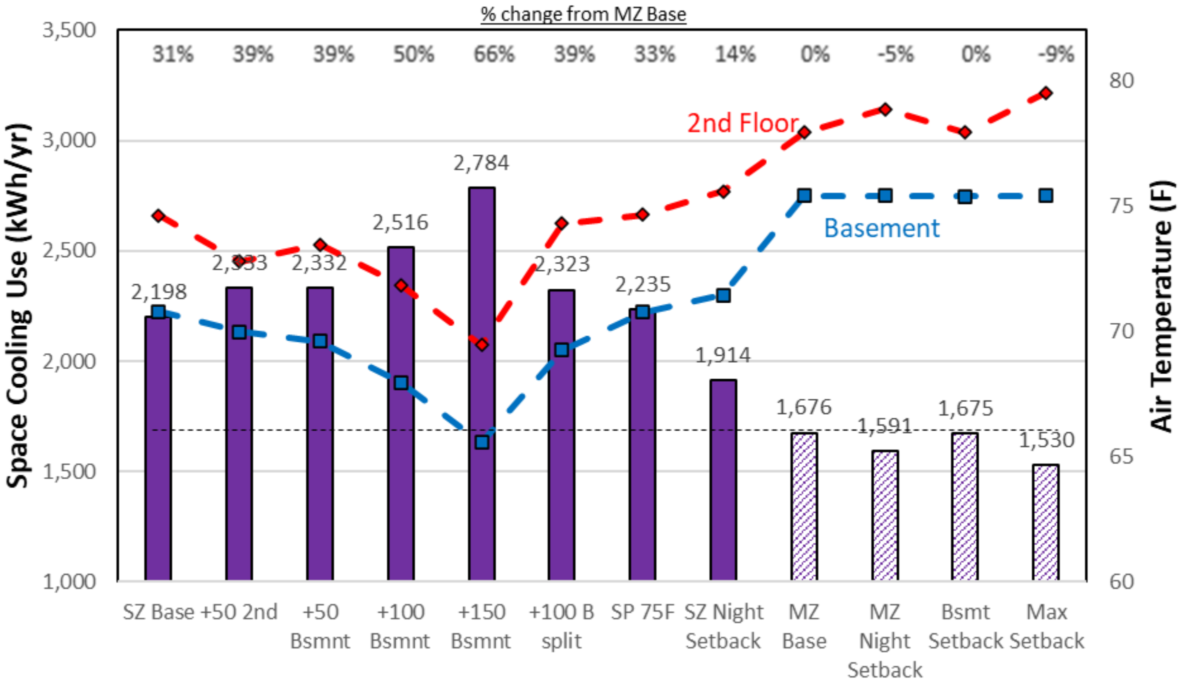
[17] Indicated by the red circle in the figure.

Table 9. Cooling season energy use and comfort: two-story new home

	Space Cooling	Change From MZ Base		Cooling Season Avg. Temp. (°F)			
Label	(kWh)	(kWh)	(%)	Basement & 2nd Floor	Basement	1st Floor	2nd Floor
SZ Base	2,198	-63	-14.9%	72.7	70.8	78.0	74.6
+50 2nd	2,333	-38	-9.1%	71.4	70.0	78.0	72.8
+50 Bsmnt	2,332	-37	-9.0%	71.5	69.6	78.0	73.5
+100 Bsmnt	2,516	-7	-1.7%	69.9	68.0	78.0	71.8
+150 Bsmnt	2,784	33	7.8%	67.5	65.6	78.0	69.4
+100 B split	2,323	-40	-9.6%	71.8	69.3	78.0	74.3
SP 75°F	2,235	57	13.6%	72.7	70.8	78.0	74.6
SZ Night Setback	1,914	-108	-25.7%	73.5	71.4	79.0	75.6
MZ Base	1,676	0	0.0%	76.7	75.4	78.0	77.9
MZ Night Setback	1,591	-56	-13.3%	77.1	75.4	79.0	78.8
Bsmt Setback	1,675	-55	-13.2%	76.6	75.4	78.0	77.9
Max Setback	1,530	-85	-20.3%	77.5	75.4	70.0	79.5

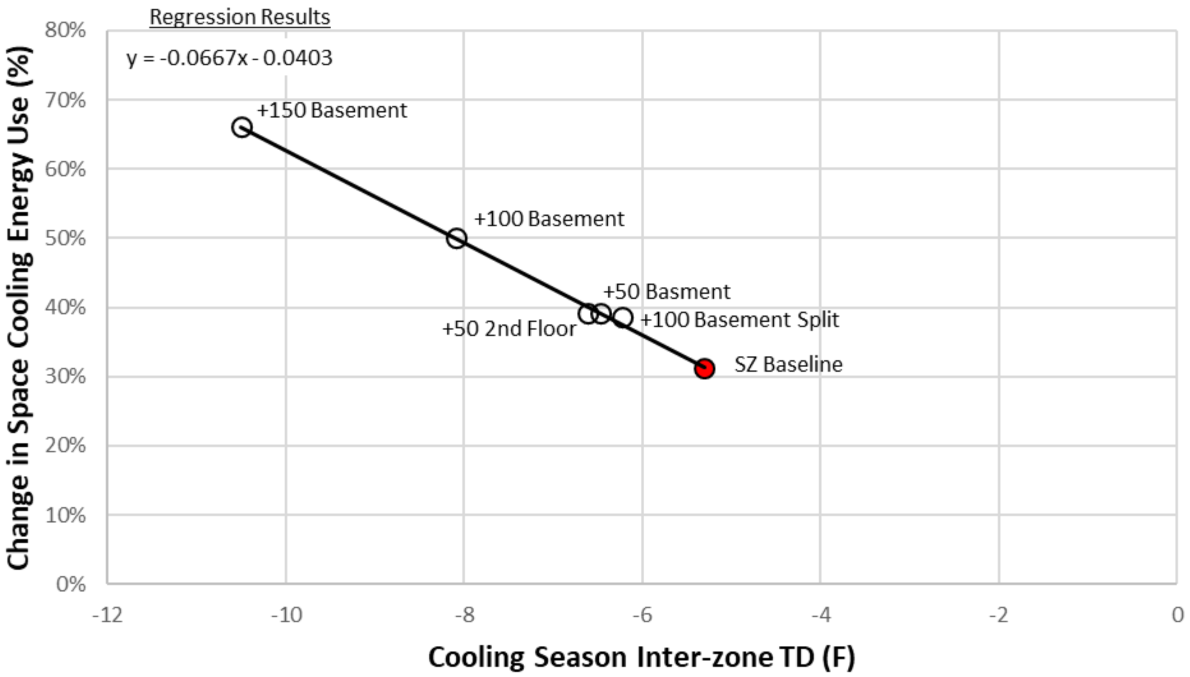
Figure 24. Cooling season energy use and comfort: two-story new home



The energy use for the single-zone scenarios is higher because both the basement and second floor are over-cooled. The cooling season temperatures range from 65.6°F to 70.8°F for the basement and 69.4°F to 74.6°F for the second floor. The trends shown in Figure 24 suggest that the higher energy use for the single-zone systems correlate with lower basement and second-floor temperatures. This is confirmed by Figure 25, which shows that the percent change in cooling energy use from the multizone baseline scenario is strongly linearly related to the inter-zone TD ($R^2 = 0.997$). The multizone system provides improved comfort and decreases energy use. The regression slope indicates that there is a 6.7% decrease in energy use for each 1°F increase in the inter-zone TD. The inter-zone TD for zero percent difference between the multizone and single-zone system energy use was -0.6°F. This is 0.8°F greater than the inter-zone TD of -1.4°F for the multizone baseline scenario. Results from all models will be used to evaluate the trends in the regression slopes and intercepts.

Table 9 and Figure 24 include the cooling season annual energy use and average zone temperatures for the one single-zone and three multizone system scenarios with variations in thermostat temperature setback. The single-zone night setback scenario reduces cooling energy by 284 kWh per year (17%) compared to the single-zone baseline, and the multizone night setback reduces it by 85 kWh per year (5.1%). One advantage of multizone systems is the ability to set back the temperature for individual zones. Since little cooling is required for the basement, the set temperature for the basement has almost no impact on cooling energy use. The max setback scenario combines the night setback with a weekday daytime setback, which generates energy savings of 146 kWh per year (8.7%).

Figure 25. Relationship between % change in single-zone cooling energy use and inter-zone TD: two-story new home



Two-story existing home

The B&W charts displayed in Figure 26 show the seasonal variation of the zone air temperatures for multizone baseline, single-zone baseline, and four single-zone system with modified supply airflow rates scenarios. The multizone baseline scenarios' trends for the new and existing home models are similar, but there are noticeable differences. For the existing home model, the zone temperatures generally remain at the setpoint of 70°F until the outside temperature is above 50°F, while occurring at lower temperatures for the new home model. This is because the heat loss rate is greater for the existing home model, which has lower levels of insulation and greater air infiltration. The additional heat loss requires space heating at warmer temperatures. For example, a regression of the daily gas use to outside air temperature yields a balance point temperature[18] of 49.9°F for the new home model and 56.3°F for the existing home model. This confirms that the existing home configuration often requires space heating when the daily average outside temperature is above 50°F but rarely for the new home configuration. For the cooling season (e.g., outdoor temperatures above 70°F), the system keeps the first- and second-floor temperatures at the 78°F cooling setpoint. There is little or no cooling required in the basement and that temperature drifts below the setpoint.

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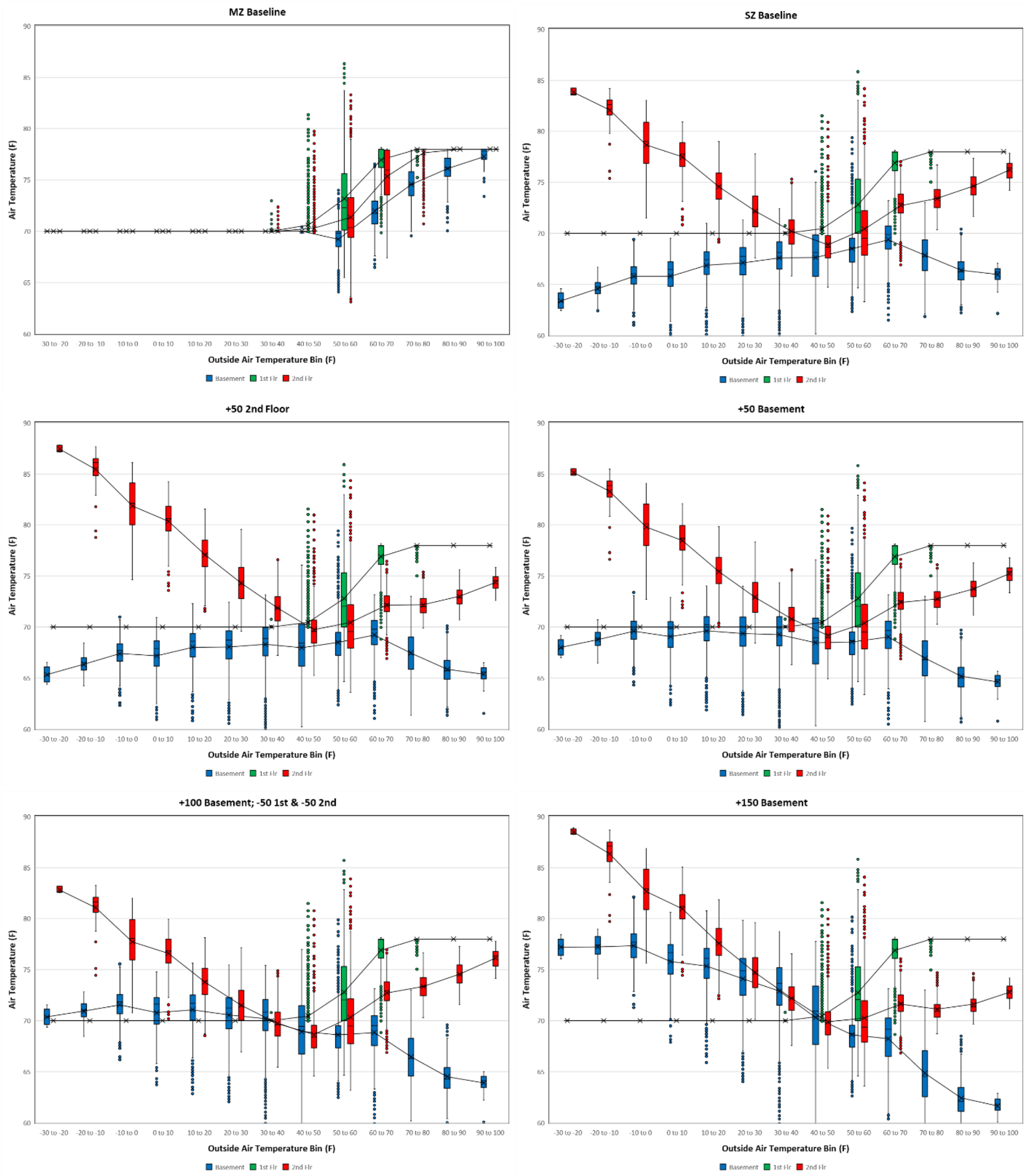
[18] Balance point temperature is defined as the temperature below which space heating is required = -regression intercept/slope.

Figure 26. Zone temperature B&W charts: two-story existing home



The single-zone baseline scenarios’ basement temperature trends are nearly identical for the new and existing home models. The shift in higher first-floor temperatures at moderate outside temperatures that occurred for the multizone new and existing models also occurred for the single-zone systems. The second-floor temperatures have the most significant difference between the new and existing home models. The second-floor temperatures for the existing home model were above the 70°F setpoint for outside temperatures below 40°F, while over-heating occurred in the new home model for outside temperatures below about 10°F. This indicates more second-floor over-heating for the existing home model and suggests that there would be higher heating energy savings for multizone systems for existing homes than new homes.

The differences in temperature trends for the new home and existing home models for the single-zone baseline model also occurred for the scenarios with changes in the single-zone supply airflow rates.

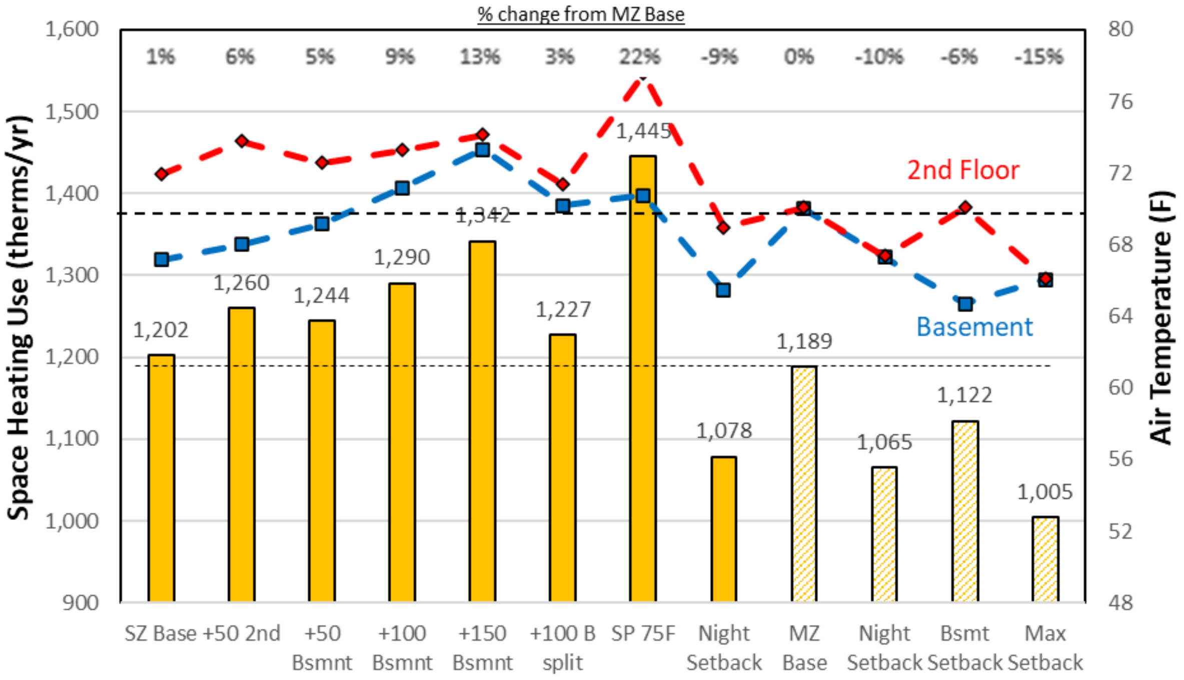
- The basement temperature trends are nearly identical.
- There are slightly higher first-floor temperatures for the existing home model at moderate outside temperatures.
- There are significantly higher second-floor temperatures for the existing home model for the entire heating season.

Table 10 and Figure 27 present the heating season annual energy use and average zone temperatures for the eight single-zone and four multizone system scenarios. The space heating annual energy use for the baseline multizone scenario was 1,189 therms/yr (0.33 therms/yr sq. feet normalized by floor area). The multizone heating energy use was less than that for all six scenarios for the single-zone system with the same 70°F setpoint. The heating energy use for the existing home model is 2.84 times greater than heating energy use for the new home model. The increase is due to reduced levels of insulation and increased air infiltration, which increases the heat load at a specific outside temperature and increases the outside temperatures for which heating is required (e.g., extends the length of the heating season). The heating energy for the single-zone systems compared to the baseline multizone system ranged from 1.1% to 12.9% and averaged 6.1%. The single-zone baseline scenario had the lowest energy use, which was 1.1% greater than the multizone system's energy use. The difference between the single-zone and multizone energy use for the existing home model is opposite of the new home model's results in which the single-zone use was less than that of the multizone system. For the existing home model, the single-zone use is greater than that of the multizone system because the second-floor is overheated for the entire heating season while that was not true for the new home model.

Table 10. Heating season energy use and comfort: two-story existing home

Label	Space Heating (therm)	Change From MZ Base (therm)	Change From MZ Base (%)	Heating Season Avg. Temp. (°F) Basement & 2nd Floor	Heating Season Avg. Temp. (°F) Basement	Heating Season Avg. Temp. (°F) 1st Floor	Heating Season Avg. Temp. (°F) 2nd Floor
SZ Base	1,202	13	1.1%	69.5	67.2	70.1	71.9
+50 2nd	1,260	71	6.0%	70.9	68.0	70.1	73.8
+50 Bsmnt	1,244	55	4.6%	70.8	69.1	70.1	72.6
+100 Bsmnt	1,290	101	8.5%	72.2	71.2	70.1	73.3
+150 Bsmnt	1,342	153	12.9%	73.7	73.3	70.1	74.1
+100 B split	1,227	39	3.2%	70.8	70.2	70.1	71.4
SP 75°F	1,445	256	21.6%	74.2	70.7	75.0	77.6
SZ Night Setback	1,078	-110	-9.3%	67.2	65.4	67.5	69.0
MZ Base	1,189	0	0.0%	70.0	70.0	70.2	70.1
MZ Night Setback	1,065	-124	-10.4%	67.3	67.3	67.5	67.4
Bsmt Setback	1,122	-67	-5.6%	67.4	64.7	70.1	70.1
Max Setback	1,005	-184	-15.5%	66.1	66.1	66.3	66.1

Figure 27. Heating season energy use and comfort: two-story existing home



Similar to the new home model results, the multizone system reduces energy use when the second floor and/or basement is overheated, as indicated by the heating season average temperatures in those zones. This is confirmed by Figure 28, which shows that the percent change in heating energy use from the multizone baseline scenario is strongly linearly related to the inter-zone TD (R^2 = 0.97). However, there is slightly more variation in the relationship for the two scenarios that included a change in the second-floor airflow rate (+100 Basement Split and +50 2nd Floor). The regression slope indicates that there is a 2.9% increase in energy use for each 1°F increase in the inter-zone TD. The inter-zone TD for zero percent difference between the multizone and single-zone system energy use was -0.9°F. This is 0.8°F less than the inter-zone TD of -0.1°F for the multizone baseline scenario. Results from all models will be used to evaluate the trends in the regression slopes and intercepts.

Figure 28. Relationship between % change in single-zone heating energy use and inter-zone TD: two-story existing home

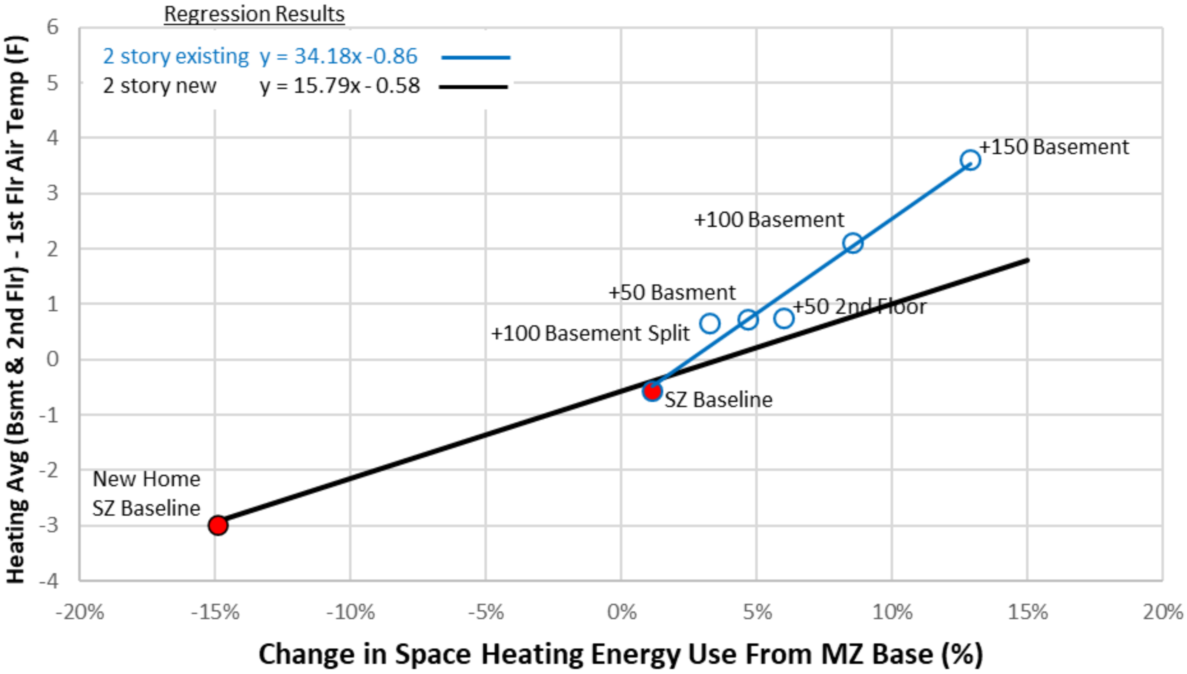


Table 11 displays the percentage of time during the heating season that the basement and second-floor temperatures were less than 67.5°F (low) and greater than 72°F (high) for the six single-zone scenarios. For the baseline scenario and two scenarios that increased the basement and second-floor supply airflows by 50 cfm, the basement temperature was low more than 20% of the time. Increasing the basement supply airflow rate by 100 cfm and 150 cfm decreased the percentage of time the temperature was low to between 9% and 17%. However, the increased airflows also increased the percentage of time that the basement temperature was high. If minimizing the sum of the low and high temperatures is an indicator of better comfort, the best option was to increase the basement airflow by 50 cfm and decrease the first-floor airflow by 50 cfm (+50 Bsmnt). For that scenario, the heating energy use is 4.6% greater than that of the multizone baseline. In addition, that scenario also results in a high second-floor temperature for 48% of the heating season. As noted previously, there is no distribution of supply airflow by zone for a single-zone system that produces zone temperatures that are within 3°F of the setpoint for the entire heating and cooling seasons. That can only be achieved through seasonal changes to manual balancing dampers or with a multizone system.

Table 11. Heating season temperature deviation from setpoint: two-story existing home

	Basement			2nd Floor		
Label	< 67.5°F	> 72°F	Sum	< 67.5°F	> 72°F	Sum
SZ Base	48%	1%	49%	7%	42%	48%
+50 2nd	33%	3%	36%	3%	61%	63%
+50 Bsmnt	23%	10%	33%	5%	48%	53%
+100 Bsmnt	14%	50%	64%	3%	56%	59%
+150 Bsmnt	9%	70%	80%	2%	65%	67%
+100 B split	17%	30%	47%	9%	36%	45%

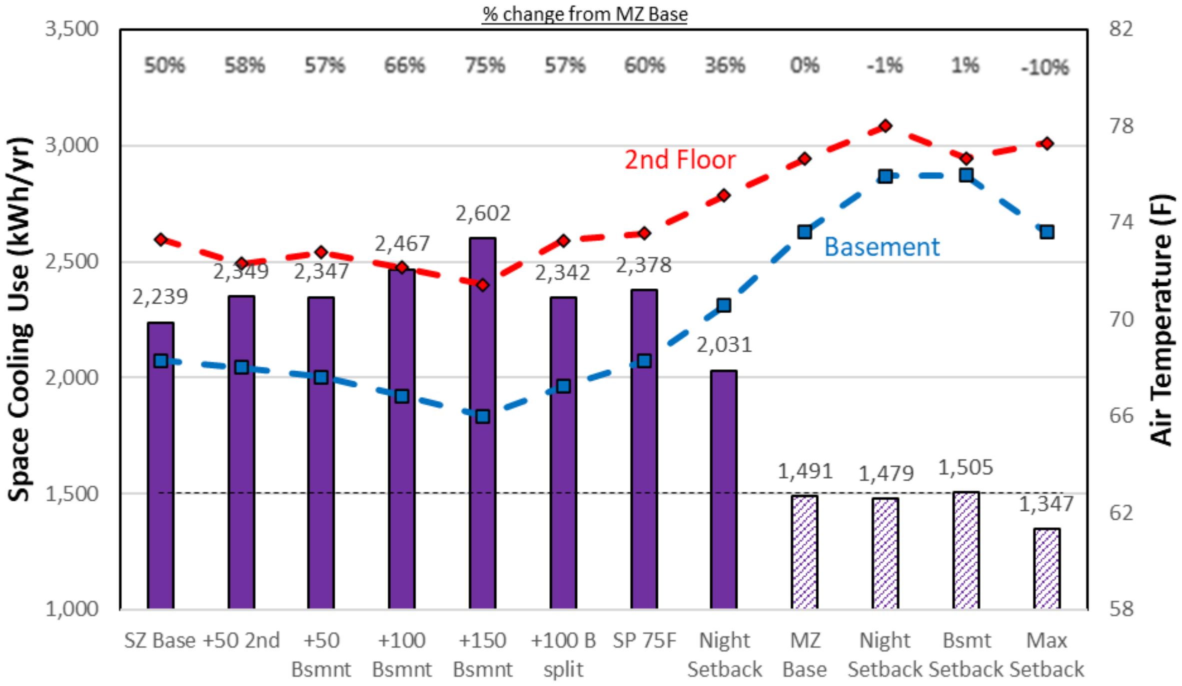
Another option to improve the comfort of the basement and second-floor zones is to increase the first-floor thermostat setpoint to 75°F. This produces an average basement temperature of 70.7°F but over-heats the second floor to an average temperature of 77.6°F and increases heating energy by 21.6% compared to the multizone baseline. Table 10 and Figure 27 include the heating season annual energy use and average zone temperatures for the one single-zone and three multizone system scenarios with variations in thermostat temperature setback. The single-zone night setback scenario reduces heating energy by 124 therm per year (10.3%) compared to the single-zone baseline, and the multizone night setback reduces it by 124 therm per year. The multizone basement setback scenario decreases the heating energy by somewhat less than that for the night setback scenario (67 therms per year). The max setback scenario combines the night setback with a weekday daytime setback, which generates energy savings of 184 therms per year or 15.5%.

Table 12 and Figure 29 present the cooling season annual energy use and average zone temperatures for the eight single-zone and four multizone system scenarios. The space cooling annual energy use for the baseline multizone scenario was 1,491 kWh per year (0.42 kWh/yr sq. feet normalized by floor area). The cooling energy use for the existing home was 0.89 times that for the new home model. This may seem counterintuitive since the existing home model had lower levels of insulation and greater air infiltration. However, due to solar and internal gains there are times when cooling is required when the outside temperature is less than the cooling setpoint of 78°F. In those situations, the higher heat loss through the house envelope and higher air infiltration reduces the cooling load.

Table 12. Cooling season energy use and comfort: two-story existing home

Label	Space Cooling	Change From MZ Base		Cooling Season Avg. Temp. (°F)			
	(kWh)	(kWh)	(%)	Basement & 2nd Floor	Basement	1st Floor	2nd Floor
SZ Base	2,239	748	50.2%	70.8	68.3	77.5	73.3
+50 2nd	2,349	858	57.6%	70.2	68.0	77.5	72.3
+50 Bsmnt	2,347	856	57.4%	70.2	67.6	77.5	72.8
+100 Bsmnt	2,467	976	65.5%	69.5	66.9	77.5	72.2
+150 Bsmnt	2,602	1,111	74.6%	68.7	66.0	77.5	71.5
+100 B split	2,342	852	57.1%	70.3	67.2	77.5	73.3
SP 75°F	2,378	888	59.6%	70.9	68.3	77.6	73.6
SZ Night Setback	2,031	540	36.2%	72.9	70.6	78.3	75.1
MZ Base	1,491	0	0.0%	75.2	73.6	77.5	76.7
MZ Night Setback	1,479	-12	-0.8%	77.0	75.9	78.7	78.0
Bsmt Setback	1,505	14	1.0%	76.3	76.0	77.6	76.7
Max Setback	1,347	-143	-9.6%	75.5	73.6	78.7	77.3

Figure 29. Cooling season energy use and comfort: two-story existing home



The multizone cooling energy use was less than the cooling energy use of all six scenarios for the single-zone system with the same 70°F setpoint. The cooling energy for the single-zone systems compared to the baseline multizone system ranged from 50% to 75% and averaged 60%. That equates to annual savings from 748 kWh to 1,111 kWh with an average of 900 kWh (0.25 kWh/yr. sq. feet normalized by floor area). The energy use for the multizone baseline scenario was 50% less than the use for the single-zone baseline scenario. This is 19 percentage points greater than the 31% difference between the single-zone and multizone baseline scenarios for the new home model. The higher savings for the multizone systems for the existing home model is likely due to the lower average basement and second-floor temperatures for the single-zone system during the cooling season. As noted previously, the cooling energy savings is less than 10% of the heating energy use for the multizone baseline scenario.

Similar to the results for the new home model, the trends shown in Figure 29 indicate that the higher energy use for the single-zone systems correlate with lower basement and second-floor temperatures. This is confirmed by Figure 30, which shows that the percent change in cooling energy use from the multizone baseline scenario is strongly linearly related to the inter-zone TD (R^2 = 0.999). The multizone system provides improved comfort and decreases energy use. The regression slope indicates that there is a 12% decrease in energy use for each 1°F increase in the inter-zone TD. The inter-zone TD for zero percent difference between the multizone and single-zone system energy use was -2.4°F. This is equal to the inter-zone TD for the multizone baseline scenario. Results from all models will be used to evaluate the trends in the regression slopes and intercepts.

Figure 30. Relationship between % change in single-zone cooling energy use and inter-zone TD: two-story existing home

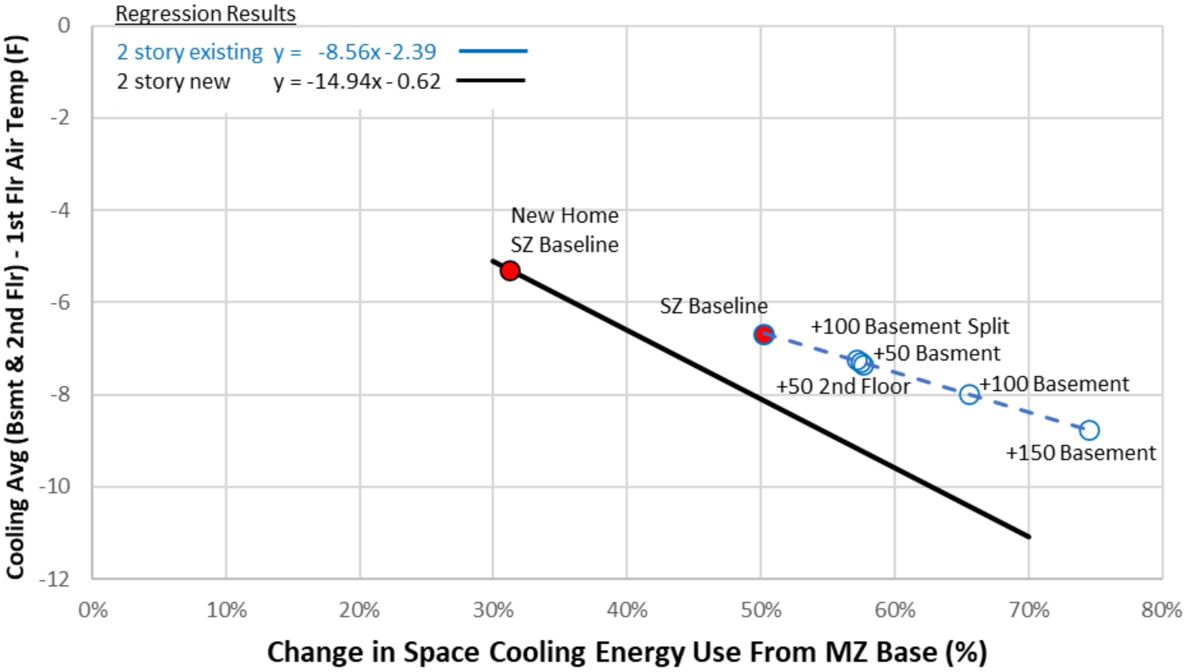


Table 12 and Figure 29 include the cooling season annual energy use and average zone temperatures for the one single-zone and three multizone system scenarios with variations in thermostat temperature setback. The single-zone night setback scenario reduces cooling energy by 208 kWh per year compared to the single-zone baseline, and the multizone night setback reduces it by 85 kWh per year. One advantage of multizone systems is the ability to set back the temperature for individual zones. Since little cooling is required for the basement, the set temperature for the basement has almost no impact on cooling energy use. The max setback scenario combines the night setback with a weekday daytime setback, which generates energy savings of 143 kWh per year.

One-story new home

The B&W charts displayed in **Error! Reference source not found.** show the seasonal variation of the zone air temperatures for multizone baseline, single-zone baseline, and two single-zone systems with modified supply airflow rates scenarios. Overall, there was little difference between the seasonal average and the binned basement and first-floor temperatures for two-story and one-story new home models. The heating season average basement temperatures for the two-story new home scenarios were 0.2°F to 2.1°F higher than the corresponding ones for the one-story scenarios and the average difference was 1.1°F. The cooling season average basement temperatures for the scenarios are 0.1°F to 1.1°F higher for the two-story new home model and the average difference was 0.3°F. Consequently, the trends described for the two-story new home model also apply to the results for the one-story new home model.

Figure 31. Zone temperature B&W charts: one-story new home

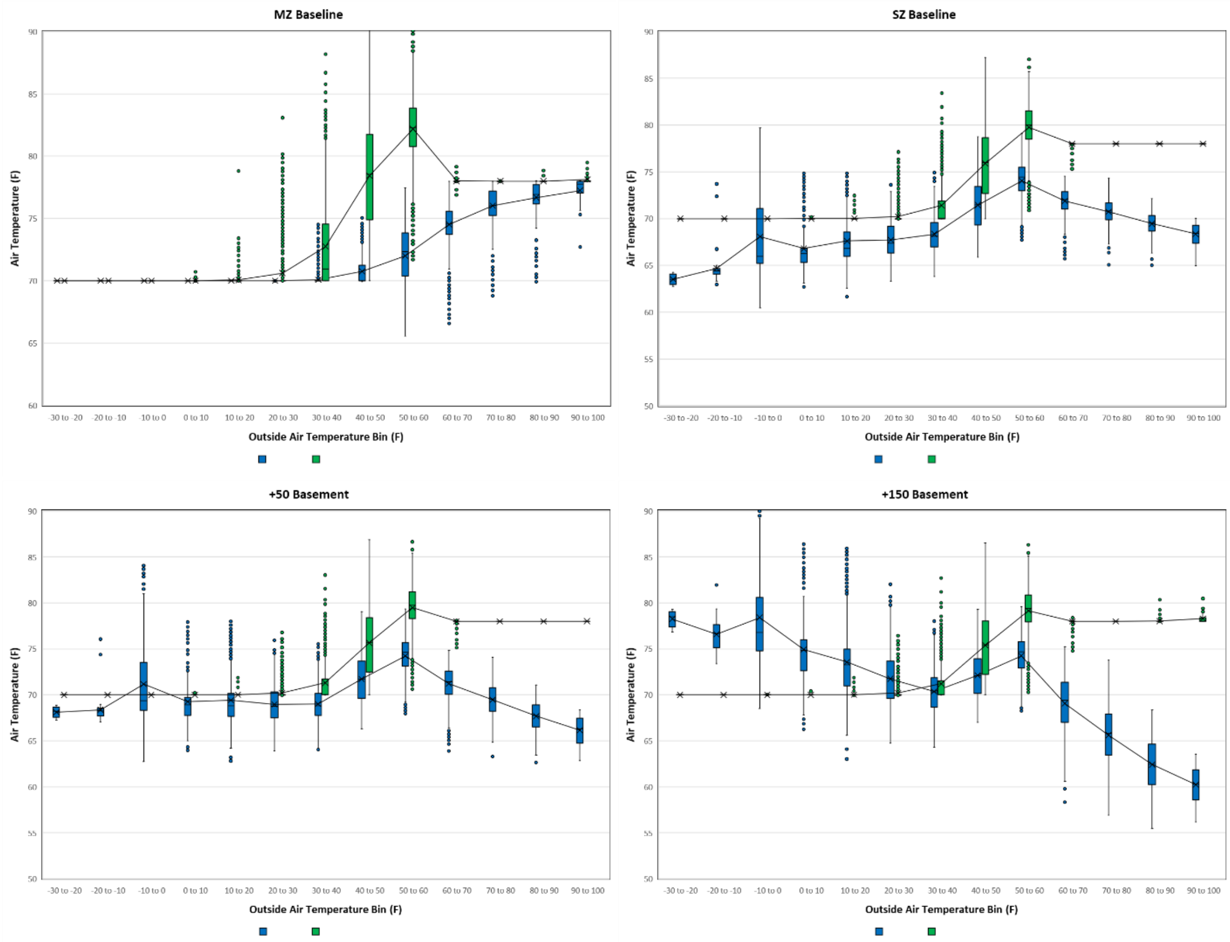
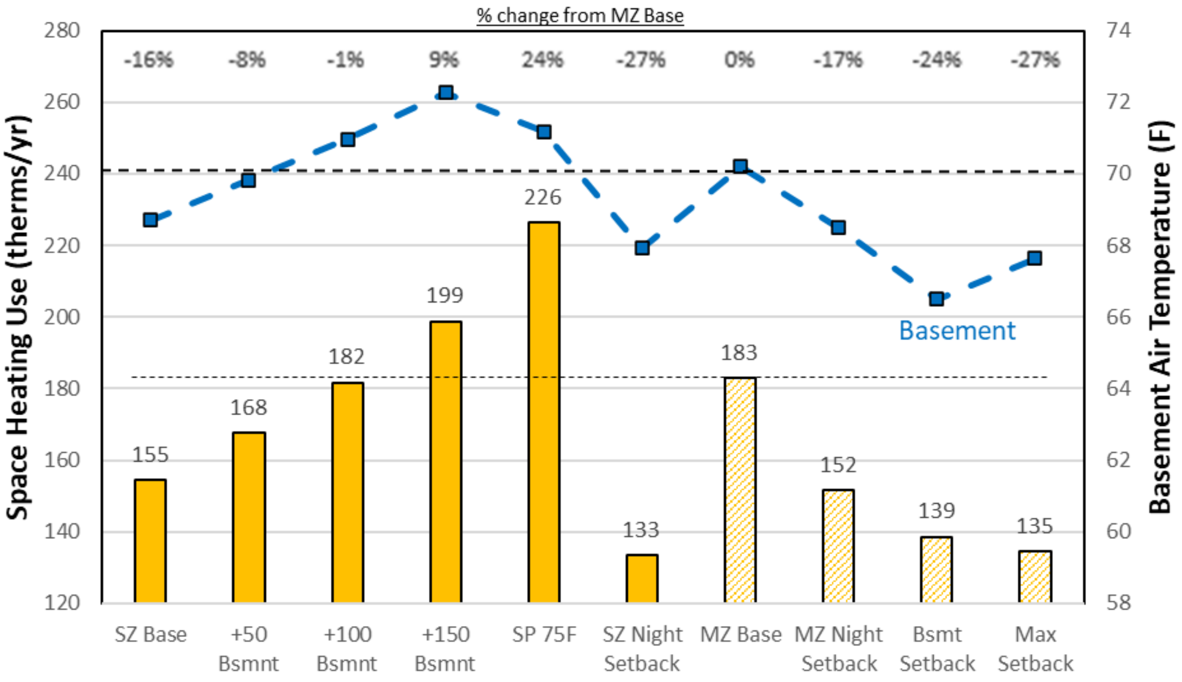


Table 13 and Figure 32 present the heating season annual energy use and average zone temperatures for the six single-zone and four multizone system scenarios. The space heating annual energy use for the baseline multizone scenario was 183 therms per year (normalized by floor area). The floor area normalized use of 0.077 therms per year sq. feet was 34% less than that for the two-story new home model. The floor area of each level was the same and the heat loss through the basement was significantly less than the heat loss from the above-grade levels. Removing one of the above-grade floors from the two-story model to generate the one-story model significantly reduced the floor area normalized heat loss.

Table 13. Heating season energy use and comfort: one-story new home

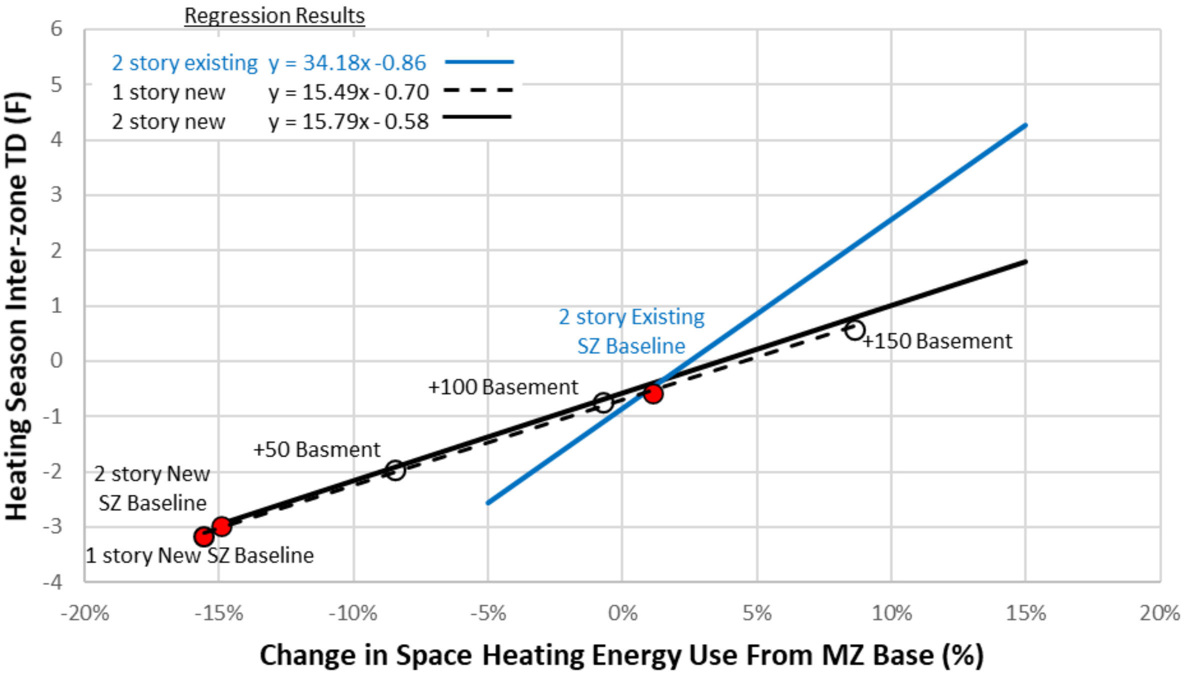
	Space Heating	Change From MZ Base		Heating Season Average Temp (°F)	
Label	(therm)	(therm)	(%)	Basement	1st Floor
SZ Base	155	-28	-15.6%	68.7	71.9
+50 Bsmnt	168	-16	-8.5%	69.8	71.8
+100 Bsmnt	182	-1	-0.7%	71.0	71.7
+150 Bsmnt	199	16	8.6%	72.3	71.7
SP 75°F	226	43	23.7%	71.2	75.7
SZ Night Setback	133	-50	-27.1%	67.9	70.7
MZ Base	183	0	0.0%	70.2	72.9
MZ Night Setback	152	-31	-17.2%	68.5	71.9
Bsmt Setback	139	-44	-24.3%	66.5	72.9
Max Setback	135	-49	-26.5%	67.6	71.2

Figure 32. Heating season energy use and comfort: one-story new home



The multizone heating energy use was greater than heating energy use for three of the four single-zone system scenarios with the same 70°F setpoint (i.e., excluding the setback scenarios). The heating energy for the single-zone systems compared to the baseline multizone system ranged from -15.6% to 8.6% and averaged -4.0%. The single-zone baseline scenario had the lowest energy use, which was -15.6% less than that of the multizone system. Consistent with the results for the previous models, Figure 33 shows that the percent change in heating energy use from the multizone baseline scenario is strongly linearly related to the inter-zone TD (R^2 = 0.998). The regression slope indicates that there is a 6.5% increase in energy use for each 1°F increase in the inter-zone TD. The inter-zone TD for zero percent difference between the multizone and single-zone system energy use was -0.7°F. This is 2.0°F greater than the inter-zone TD of -2.7°F for the multizone baseline scenario. Results from all models will be used to evaluate the trends in the regression slopes and intercepts.

Figure 33. Relationship between % change in single-zone heating energy use and inter-zone TD: one-story new home.



Another option to improve the comfort of the basement and second-floor zones is to increase the first-floor thermostat setpoint to 75°F. This produces an average basement temperature of 71.2°F but increases heating energy by 23.7% compared to the multizone baseline. Table 13 and Figure 32 include the heating season annual energy use and average zone temperatures for the one single-zone and three multizone system scenarios with variations in thermostat temperature setback. The single-zone night setback scenario reduces heating energy by 21 therm per year (14%) compared to the single-zone baseline, and the multizone night setback reduces it by 31 therm per year (17%). One advantage of multizone systems is the ability to set back the temperature for individual zones. This decreases the heating energy by more than the night setback scenario (44 therms per year, 24%) without having to decrease the temperature in the first floor. The max setback scenario combines the night setback with a weekday daytime setback, which generates energy savings of 49 therms per year (27%).

Table 14 displays the percentage of time during the heating season that the basement temperatures were less than 67.5°F (low) and greater than 72°F (high) for the four single-zone scenarios. For the baseline scenario, the basement temperature was low 43% of the time. Increasing the basement supply airflow rate by 50 cfm, 100 cfm, and 150 cfm decreased the percentage of time the temperature was low to 18%, 10%, and 6%, respectively. However, increasing the basement airflow by 50 cfm, 100 cfm, and 150 cfm also increased the heating energy use by 13, 27, and 44 therms per year (8%, 18%, and 29%), respectively. If minimizing the sum of the low and high temperatures is an indicator of better comfort, the best option was to increase the basement airflow by about 50 cfm to 100 cfm. As noted previously, there is no distribution of supply airflow by zone for a single-zone system that produces zone temperatures that are within 3°F of the setpoint for the entire heating and cooling seasons.

Table 14. Heating season temperature deviation from setpoint: one-story new home

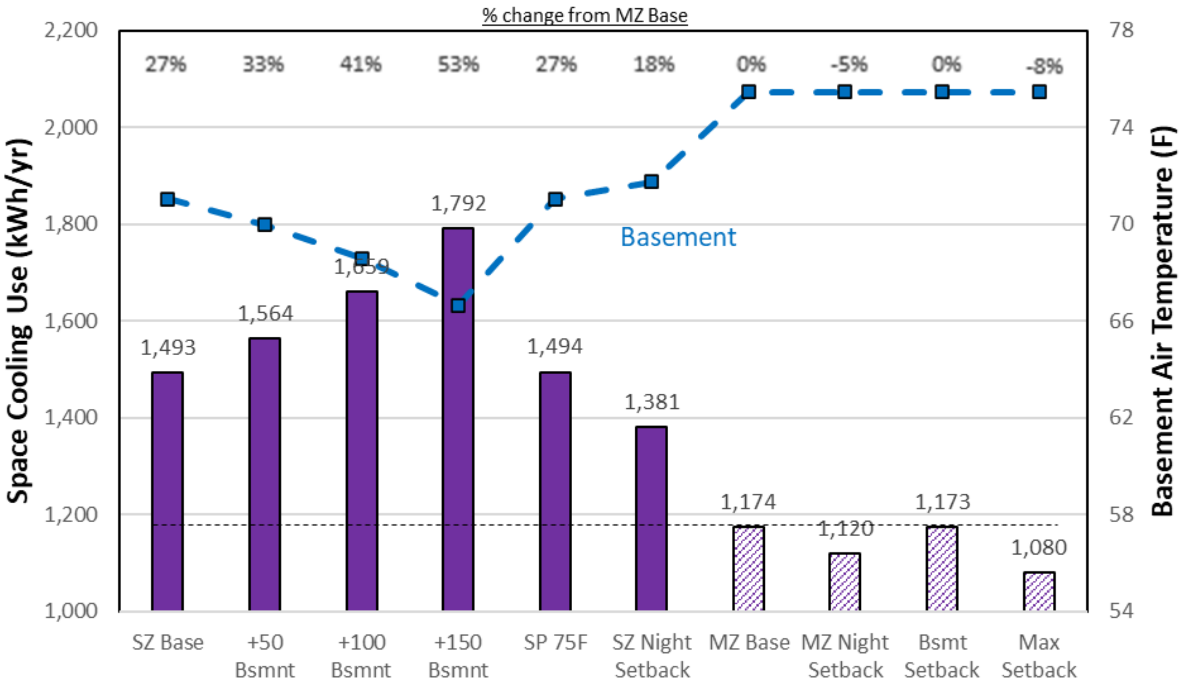
Label	Basement		
	< 67.5F	> 72F	Sum
SZ Base	43%	15%	58%
+50 Bsmnt	18%	21%	39%
+100 Bsmnt	10%	31%	41%
+150 Bsmnt	6%	49%	54%

Table 15 and Figure 34 present the cooling season annual energy use and average zone temperatures for the six single-zone and four multizone system scenarios. The space cooling annual energy use for the baseline multizone scenario was 1,120 kWh per year (0.49 kWh/yr sq. feet normalized by floor area). The floor area normalized cooling energy was slightly greater than that for the two-story new home model. The multizone cooling energy use was less than that for all four scenarios for the single-zone system with the same 70°F setpoint. The cooling energy for the single-zone systems compared to the baseline multizone system ranged from 27% to 53% and averaged 39%. That equates to annual savings from 319 kWh to 617 kWh, with an average of 453 kWh (0.19 kWh/yr sq. feet normalized by floor area). The single-zone baseline scenario cooling energy use was 27% higher than that of the multizone baseline scenario. Similar to the results for the two-story models, the single-zone system had a lower heating energy use than the multizone system and a higher cooling energy use. The multizone cooling energy savings of 319 kWh (10.9 therms) is only 7% of the heating energy use for the multizone baseline scenario.

Table 15. Cooling season energy use and comfort: one-story new home

	Space Cooling	Change From MZ Base		Cooling Season Avg. Temp (°F)	
Label	**(kWh)**	**(kWh)**	**(%)**	**Basement**	**1st Floor**
SZ Base	1,493	319	27.2%	71.0	78.0
+50 Bsmnt	1,564	390	33.2%	70.0	78.0
+100 Bsmnt	1,659	485	41.3%	68.6	78.0
+150 Bsmnt	1,792	617	52.6%	66.7	78.0
SP 75°F	1,494	320	27.3%	71.0	78.0
SZ Night Setback	1,381	207	17.6%	71.8	79.0
MZ Base	1,174	0	0.0%	75.5	78.0
MZ Night Setback	1,120	-54	-4.6%	75.5	79.0
Bsmt Setback	1,173	-1	-0.1%	75.4	78.0
Max Setback	1,080	-94	-8.0%	75.5	79.9

Figure 34. Cooling season energy use and comfort: one-story new home



The energy use for the single-zone scenarios is higher because the basement was over-cooled. For the four single-zone scenarios, the cooling season basement temperatures ranged from 66.7°F to 71.0°F and averaged 69.1°F. Consistent with previous results, the results displayed in Figure 35 show that the percent change in cooling energy use from the multizone baseline scenario is strongly linearly related to the inter-zone TD ($R^2 = 0.999$). The multizone system provides improved comfort and decreases energy use. The regression slope indicates that there is a 5.8% decrease in energy use for each 1°F increase in the inter-zone TD. The inter-zone TD for zero percent difference between the multizone and single-zone system energy use was -2.3°F. This is 0.3°F greater than the inter-zone TD of -2.6°F for the multizone baseline scenario. Results from all models will be used to evaluate the trends in the regression slopes and intercepts.

Figure 35. Relationship between % change in single-zone cooling energy use and inter-zone TD: one-story new home

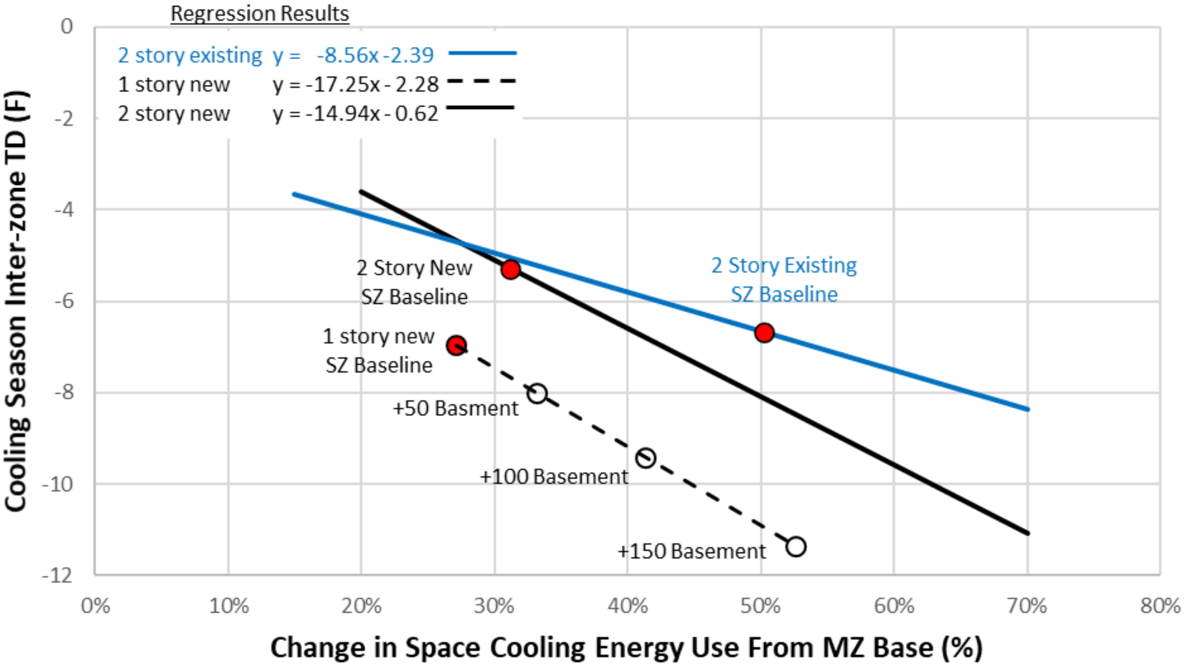


Table 15 and Figure 34 include the cooling season annual energy use and average zone temperatures for the one single-zone and three multizone system scenarios with variations in thermostat temperature setback. The single-zone night setback scenario reduces cooling energy by 112 kWh per year (7.5%) compared to the single-zone baseline, and the multizone night setback reduces it by 54 kWh per year (4.6%). Since little cooling is required for the basement, the set temperature for the basement has almost no impact on cooling energy use. The max setback scenario combines the night setback with a weekday daytime setback, which generates energy savings of 94 kWh per year (8.0%).

One-story existing home

The B&W charts displayed in Figure 36 show the seasonal variation of the zone air temperatures for multizone baseline, single-zone baseline, and two single-zone systems with modified supply airflow rates scenarios. Overall, there was little difference between the seasonal average and the binned basement and first-floor temperatures for two-story and one-story existing home models. The cooling season average basement temperatures for the two-story model were within 0.3°F of the corresponding temperatures for all one-story model scenarios. The heating season average basement temperatures for the two-story model were 0.0°F to 0.7°F higher than the corresponding temperatures of the one-story model for the multizone scenarios. The one notable difference in basement temperatures between the two models was the heating season temperatures for the single-zone scenarios. The heating season average basement temperatures for the two-story model were 2.1°F to 3.7°F higher than the corresponding temperatures of the one-story model for the single-zone scenarios. The higher one-story model system heating season basement temperatures for the single-zone system compared to those of the two-story model was likely due to the higher fraction of supply airflow to the basement for the one-story model. For the one-story model, 39% of the supply airflow was delivered to the basement, while 25% of the supply airflow was to the basement for the two-story model.

Figure 36. Zone temperature B&W charts: one-story existing home

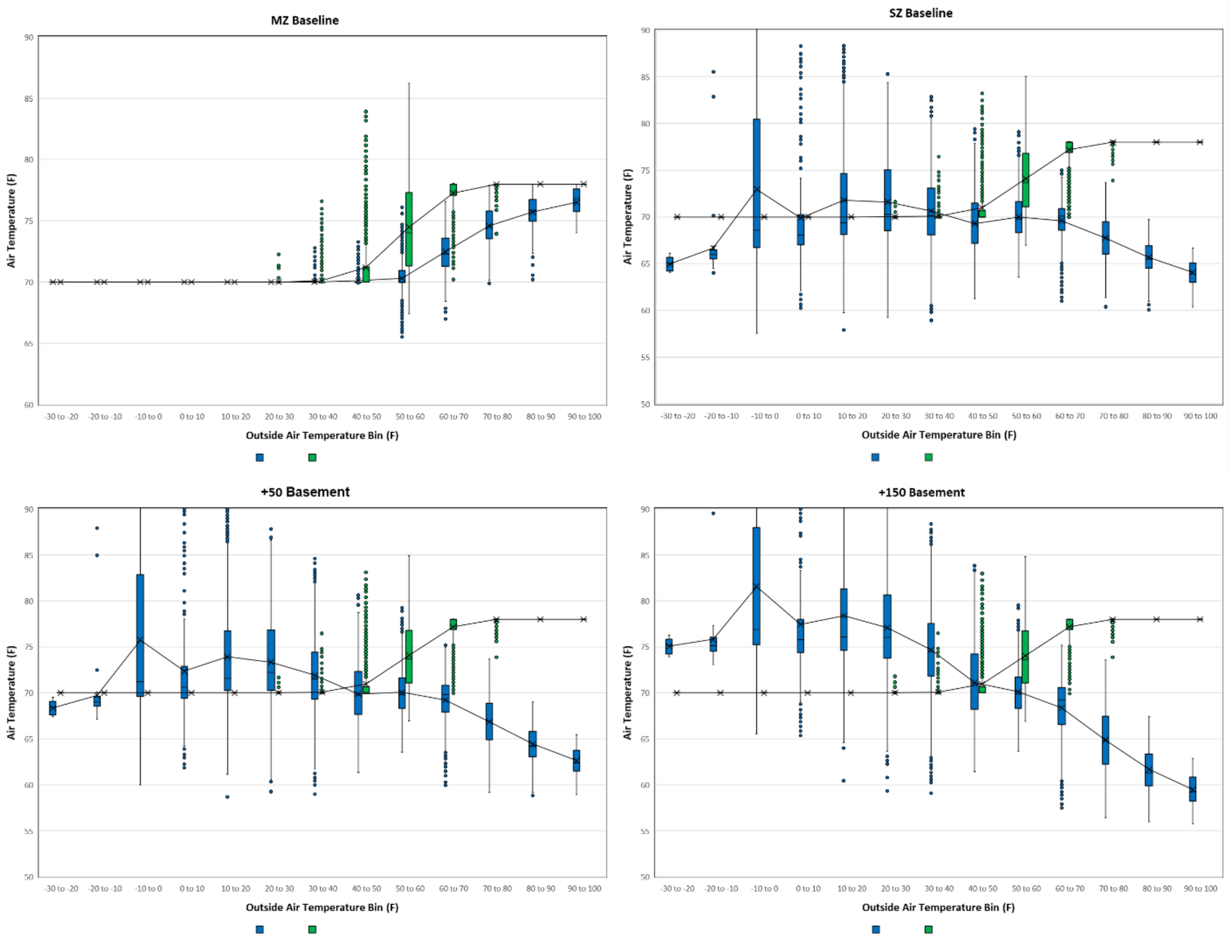


Table 16 and Figure 37 present the heating season annual energy use and average zone temperatures for the six single-zone and four multizone system scenarios. The space heating annual energy use for the baseline multizone scenario was 547 therms per year (0.23 therms/yr sq. feet normalized by floor area). The floor area normalized use of 0.23 therms per year sq. feet was 32% less than that of the two-story existing home model. The floor area of each level was the same, and the heat loss through the basement was significantly less than the heat loss from the above-grade levels. Removing one of the above-grade floors from the two-story model to generate the one-story model significantly reduced the floor area normalized heat loss.

Table 16. Heating season energy use and comfort: one-story existing home

	Space Heating	Change From MZ Base		Heating Season Average Temp (°F)	
Label	(therm)	(therm)	(%)	Basement	1st Floor
SZ Base	547	9	1.7%	70.7	70.3
+50 Bsmnt	563	25	4.7%	72.2	70.3
+100 Bsmnt	581	43	7.9%	73.8	70.3
+150 Bsmnt	599	61	11.4%	75.4	70.3
SP 75°F	689	151	28.0%	74.4	75.1
SZ Night Setback	482	-56	-10.4%	69.2	67.9
MZ Base	538	0	0.0%	70.0	70.3
MZ Night Setback	469	-69	-12.8%	67.7	68.0
Bsmt Setback	483	-55	-10.3%	65.4	70.3
Max Setback	435	-103	-19.2%	66.6	66.8

Figure 37. Heating season energy use and comfort: one-story existing home

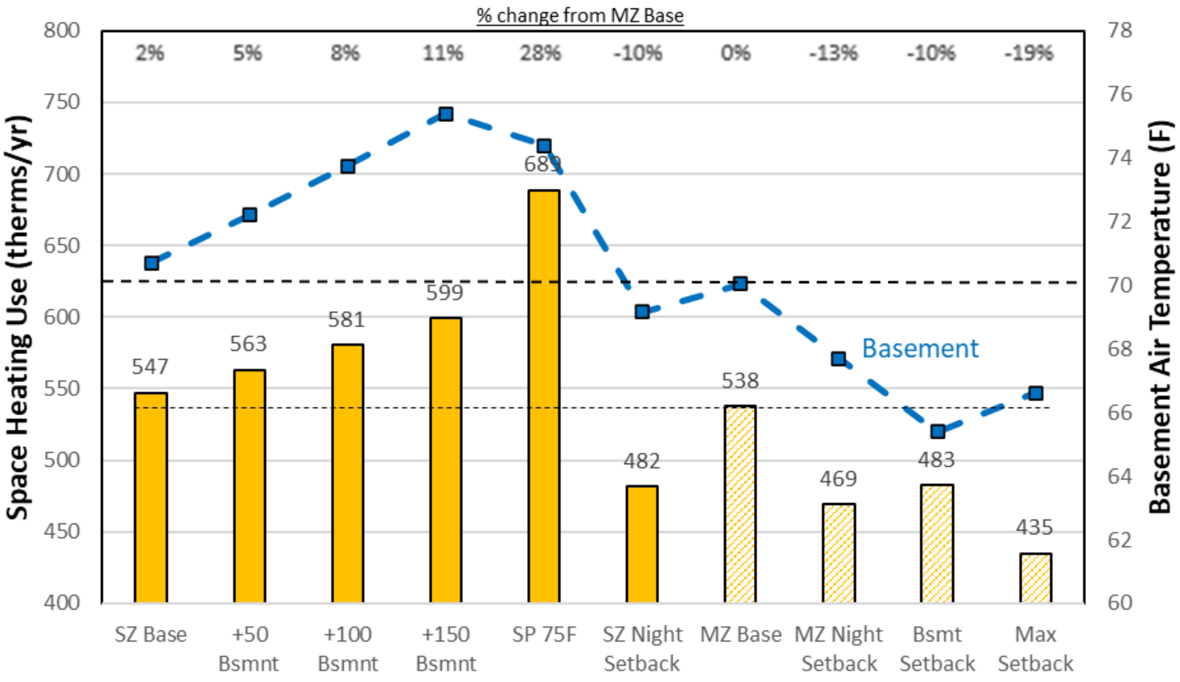
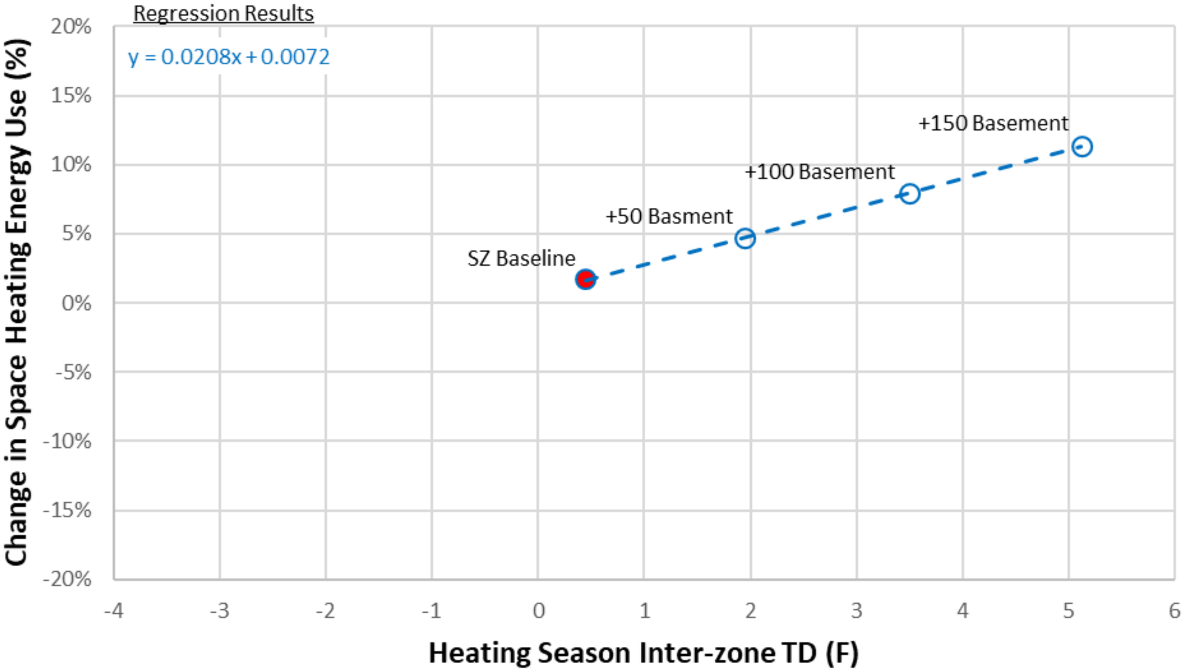


Figure 38. Relationship between % change in single-zone heating energy use and inter-zone TD: one-story existing home



Conversely, there is significant variation in the regression slopes. The slope indicates the change in temperature required to produce a 100% change in the energy use. For the four models, the slope ranges from 15.5°F to 48.2°F and averages 28.4°F with a coefficient of variation equal to 0.56. The similarity of the slopes for the two new home models suggests that the house characteristics impact the slope. Additional models that systematically vary the level of wall insulation, attic insulation, total house air leakage, and inter-zone airflow rates along with the distribution of air leaks may be required to determine which characteristics have the most impact on the slope and whether it is possible to establish slopes for real houses.

Table 16 and Figure 37 include the heating season annual energy use and average zone temperatures for the one single-zone and three multizone system scenarios with variations in thermostat temperature setback. The single-zone night setback scenario reduces heating energy by 65 therms per year (12%) compared to the single-zone baseline, and the multizone night setback reduces it by 69 therms per year (13%). The multizone basement setback scenario decreases the heating energy by somewhat less than that of the night setback scenario (55 therms per year or 10%). The max setback scenario combines the night setback with a weekday daytime setback, which generates energy savings of 103 therms per year (19%).

Table 17 displays the percentage of time during the heating season that the basement temperatures were less than 67.5°F (low) and greater than 72°F (high) for the four single-zone scenarios. For the baseline scenario, the basement temperature was low 24% of the time. Increasing the basement supply airflow rate by 50 cfm, 100 cfm, and 150 cfm decreased the percentage of time the temperature was low to 15%, 12%, and 10%, respectively. However, increasing the basement airflow by 50 cfm, 100 cfm, and 150 cfm also increased the heating energy use by 16, 34, and 52 therms per year (3%, 6%, and 10%), respectively. If minimizing the sum of the low and high temperatures is an indicator of better comfort, the best option was the baseline scenario. As noted previously, there is no distribution of supply airflow by zone for a single-zone system that produces zone temperatures that are within 3°F of the setpoint for the entire heating and cooling seasons.

Table 17. Heating season temperature deviation from setpoint: one-story existing home

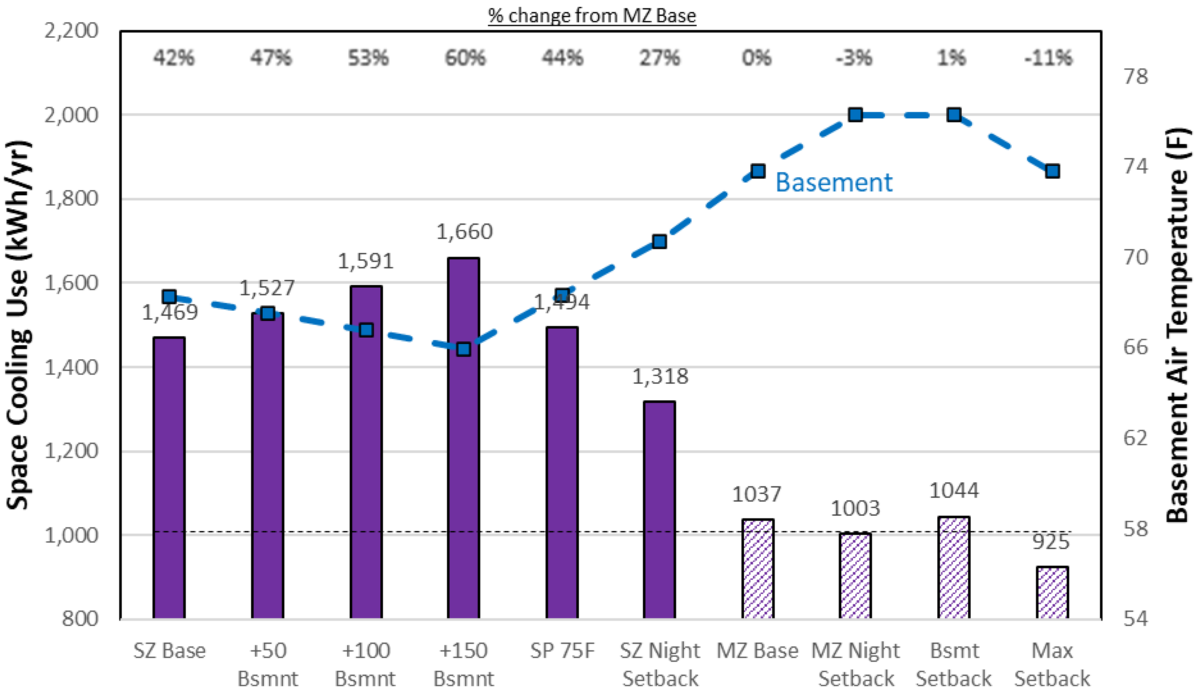
	Basement		
Label	**< 67.5F**	**> 72F**	**Sum**
SZ Base	24%	29%	52%
+50 Bsmnt	15%	41%	56%
+100 Bsmnt	12%	62%	74%
+150 Bsmnt	10%	72%	82%

Table 18 and Figure 39 present the cooling season annual energy use and average zone temperatures for the six single-zone and four multizone system scenarios. The space cooling annual energy use for the baseline multizone scenario was 1,037 kWh per year (0.44 kWh/yr sq. feet normalized by floor area). The floor area normalized cooling energy was slightly less than that of the two-story existing home model. The multizone cooling energy use was less than that of all four scenarios for the single-zone system with the same 70°F setpoint. The cooling energy for the single-zone systems compared to the baseline multizone system ranged from 42% to 60% and averaged 51%. That equates to annual savings from 432 kWh to 623 kWh with an average of 525 kWh (0.22 kWh/yr sq. feet normalized by floor area). The single-zone baseline scenario cooling energy use was 42% higher than that of the multizone baseline scenario. The multizone cooling energy savings of 525 kWh (18 therms) is only 3% of the heating energy use for the multizone baseline scenario.

Table 18. Cooling season energy use and comfort: one-story existing home

	Space Cooling	Change From MZ Base		Cooling Season Avg. Temp (°F)	
Label	(kWh)	(kWh)	(%)	Basement	1st Floor
SZ Base	1,469	432	41.6%	68.2	77.6
+50 Bsmnt	1,527	490	47.2%	67.5	77.6
+100 Bsmnt	1,591	553	53.3%	66.8	77.6
+150 Bsmnt	1,660	623	60.0%	65.9	77.6
SP 75°F	1,494	457	44.0%	68.3	77.7
SZ Night Setback	1,318	280	27.0%	70.7	78.5
MZ Base	1037	0	0.0%	73.8	77.7
MZ Night Setback	1003	-34	-3.3%	76.3	78.8
Bsmt Setback	1044	7	0.6%	76.3	77.7
Max Setback	925	-113	-10.9%	73.8	79.0

Figure 39. Cooling season energy use and comfort: one-story existing home



The cooling energy use for the single-zone scenarios were higher because the basement was over-cooled. For the four single-zone scenarios, the cooling season basement temperatures ranged from 65.9°F to 68.3°F and averaged 67.4°F. Consistent with previous results, the results displayed in Figure 40 show that the percent change in cooling energy use from the multizone baseline scenario is strongly linearly related to the inter-zone TD ($R^2 = 0.999$). The multizone system provides improved comfort and decreases energy use. The regression slope indicates that there is an 8.0% decrease in energy use for each 1°F increase in the inter-zone TD. The inter-zone TD for zero percent difference between the multizone and single-zone system energy use was -4.2°F. This is 0.3°F less than the inter-zone TD of -3.9°F for the multizone baseline scenario. Results from all models will be used to evaluate the trends in the regression slopes and intercepts.

Figure 40. Relationship between % change in single-zone cooling energy use and inter-zone TD: one-story existing home

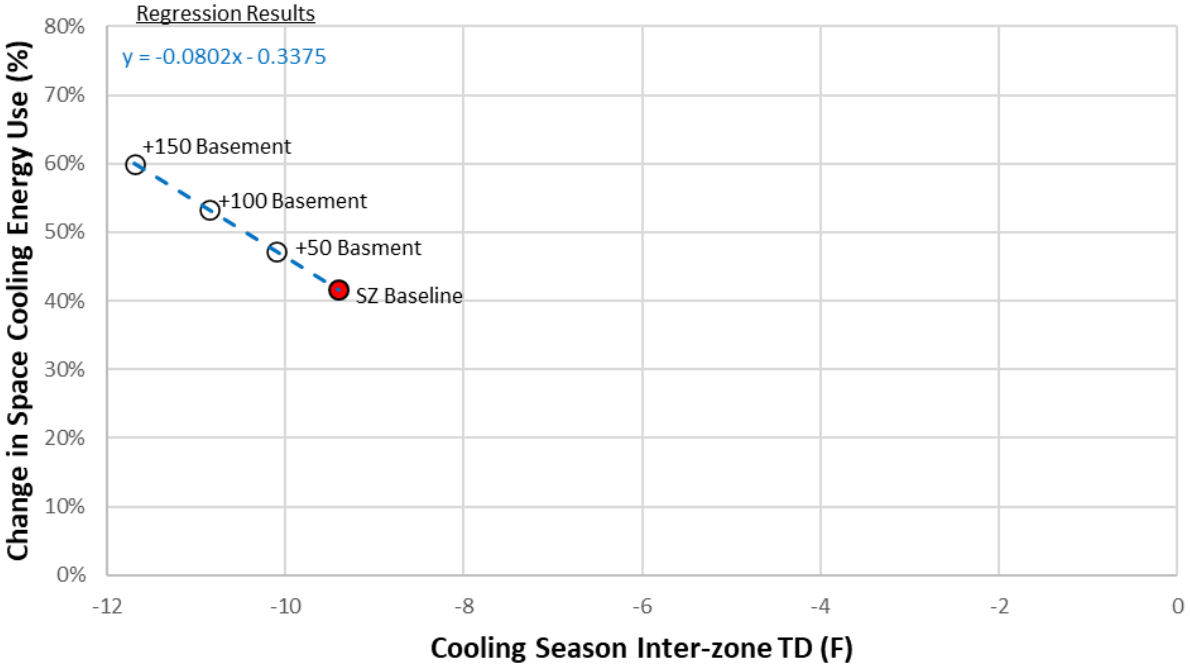


Table 18 and Figure 39 include the cooling season annual energy use and average zone temperatures for the one single-zone and three multizone system scenarios with variations in thermostat temperature setback. The single-zone night setback scenario reduces cooling energy by 152 kWh per year (10.3%) compared to the single-zone baseline, and the multizone night setback reduces it by 34 kWh per year (3.3%). Since little cooling is required for the basement, the set temperature for the basement has almost no impact on cooling energy use. The max setback scenario combines the night setback with a weekday daytime setback, which generates energy savings of 113 kWh per year (10.9%).

Energy Savings Calculations

The house energy simulations showed that a residential multizone air distribution system can save space heating and cooling energy use, or it can increase use. A multizone system's potential to reduce space conditioning energy use primarily depends on how the single-zone system being used for comparison operates. A multizone system can save heating energy when a single-zone system over-heats one or more zones during the heating season. Similarly, a multizone system can save cooling energy when a single-zone system over-cools one or more zones during the cooling season. The opposite can also occur. When a zone is being under-heated in the winter by a single-zone system, a multizone system would increase that zone's temperature to make the space more comfortable and increase energy use in the process.

EnergyPlus simulation results help illustrate the impact of over- and under-heating or cooling on space conditioning use. Figure 41 displays the season trends in zone air temperatures generated for a two-story home with a single-zone air distribution system. The first-floor temperature generally remains at the heating setpoint of 70°F during the heating season (i.e., winter) and 78°F cooling setpoint during the cooling season (i.e., summer) because the thermostat is located on the first floor. For the specified distribution of supply airflow to the three zones, the basement and second-floors are below the setpoint (i.e., under-heated) for all or almost all of the heating season and over-cooled for the cooling season. Applying a multizone distribution system with zones for the basement, first floor, and second floor to this home provides basement and second-floor temperatures that are much closer to the setpoints (see Figure 42). The only times that the zone temperatures are not at one of the setpoints are when the temperatures drift between the heating and cooling setpoints during mild weather. Also, the basement temperature is below setpoint during the cooling season because the basement requires little or no cooling during the cooling season. Since the single-zone system under-heats the basement and second floor during the heating season, the simulations show an increased heating energy use of 14.9% for the multizone system when compared to the single-zone system. Since the basement and second floor are over-cooled by the single-zone system during the cooling season, the multizone cooling energy use is 31.2% less than that of the single-zone system.

Figure 41. Zone temperature B&W charts, single-zone baseline scenario: two-story new home

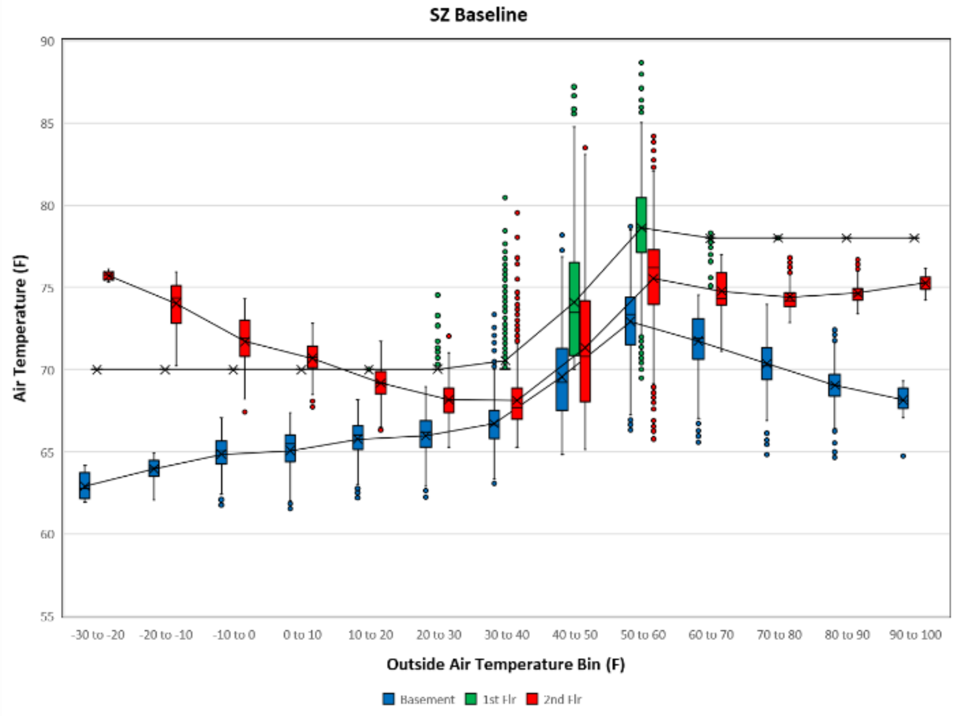
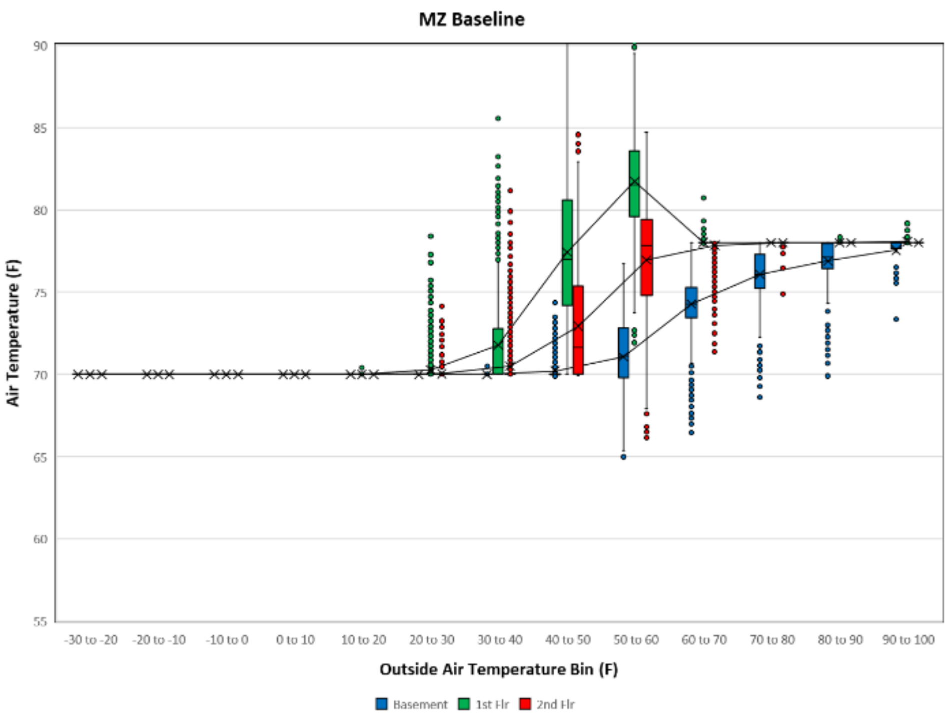


Figure 42. Zone temperature B&W charts, multizone baseline scenario: two-story new home



The Energy Simulations section presented the results for a series of building energy simulations with different distributions of zonal airflow rates for the single-zone system. The simulations were performed for four house models with one or two stories and configured to mimic new home and 1950s–1960s construction. The simulations show that varying the distribution of the zonal supply airflow can create over- and under-heated or cooled zones and that the degree of over- and under-heating often varies seasonally. An analysis of the results shows that the percent change in heating energy use for a single-zone system compared to a multizone system is strongly linearly related to the difference between the average basement and second-floor temperatures and the first-floor temperature.[19] Figure 43 shows this relationship for the two-story new home model. The regression slope indicates that there is a 6.3% increase in energy use for each 1°F increase in the inter-zone TD. The inter-zone TD for zero percent difference between the multizone and single-zone system energy use was -0.6°F. The strong linear relationship suggests that it would be possible to measure the zonal temperatures of a new two-story home over a heating season, compute the inter-zone TD from the average temperatures, and use the inter-zone TD with the regression equation ($y = 0.0633x + 0.0364$, where x is the inter-zone TD and y is the percent difference between the heating season energy use for the single-zone system and the multizone system). Positive values indicate that a multizone system would save energy and negative values indicate increased energy use.

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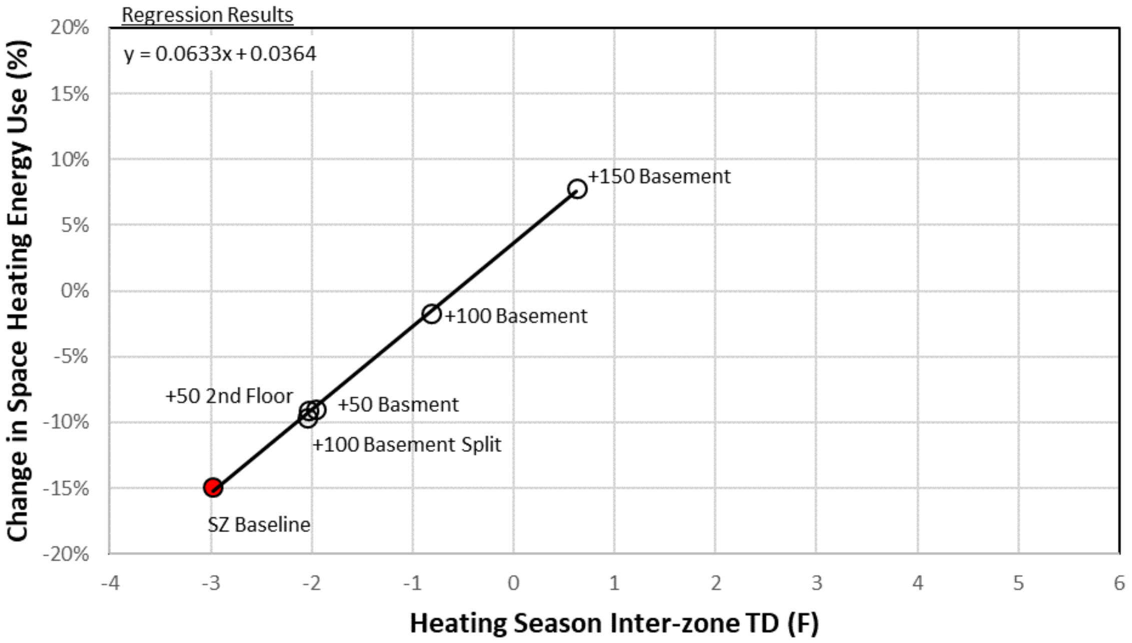
[19] As noted previously, for this report the difference between the average basement and second-floor temperatures and the first-floor temperature is referred to as the "inter-zone TD."

Figure 43. Relationship between % change in single-zone heating energy use and inter-zone TD: two-story new home



The analysis displayed in Figure 43 was repeated for the other three home models. The regression lines for the heating seasons analysis are displayed in Figure 44 and the results are included in Table 19. The red dots in Figure 44 indicate the results for the single-zone baseline scenario for which EnergyPlus auto calculated the supply airflow distribution. The number of stories for the models did not have as significant an effect on the results as the difference in the thermal characteristics. There was only a 2% difference in the regression slopes for the one- and two-story new home models and a 34% difference for the two existing home models. In contrast, the average slope for the new home models was 2.55 times greater than the average for the existing home models. This suggests that energy savings results for a two-story model could be applied to a one-story house, but variations in house insulation and air leakage will significantly impact energy savings estimates. Results from the new home and existing home models were combined to generate the energy change equations shown below. Equation (3) can be used to convert the single-zone heating season use to that for a multizone system. A positive value for K_{mz} indicates that the energy use for the multizone system will be less than that for the single-zone system.

$$\text{New Home: } (E_{sz} - E_{mz})/E_{mz} = K_{mz} = 0.064*(\text{Inter-zone TD}) + 0.040 \quad (1)$$

$$\text{Existing Home: } (E_{sz} - E_{mz})/E_{mz} = K_{mz} = 0.025*(\text{Inter-zone TD}) + 0.016 \quad (2)$$

$$E_{mz} = E_{sz}/(1 + K_{mz}) \quad (3)$$

<u>Where</u>:

E_{sz} = single-zone system space conditioning seasonal energy use, (therms/yr or kWh/yr)

E_{mz} = multizone system space conditioning seasonal energy use, (therms/yr or kWh/yr)

Inter-zone TD = difference between the average basement and second-floor temperatures and the first-floor temperature

Figure 44. Relationship between % change in single-zone heating energy use and inter-zone TD: regression results

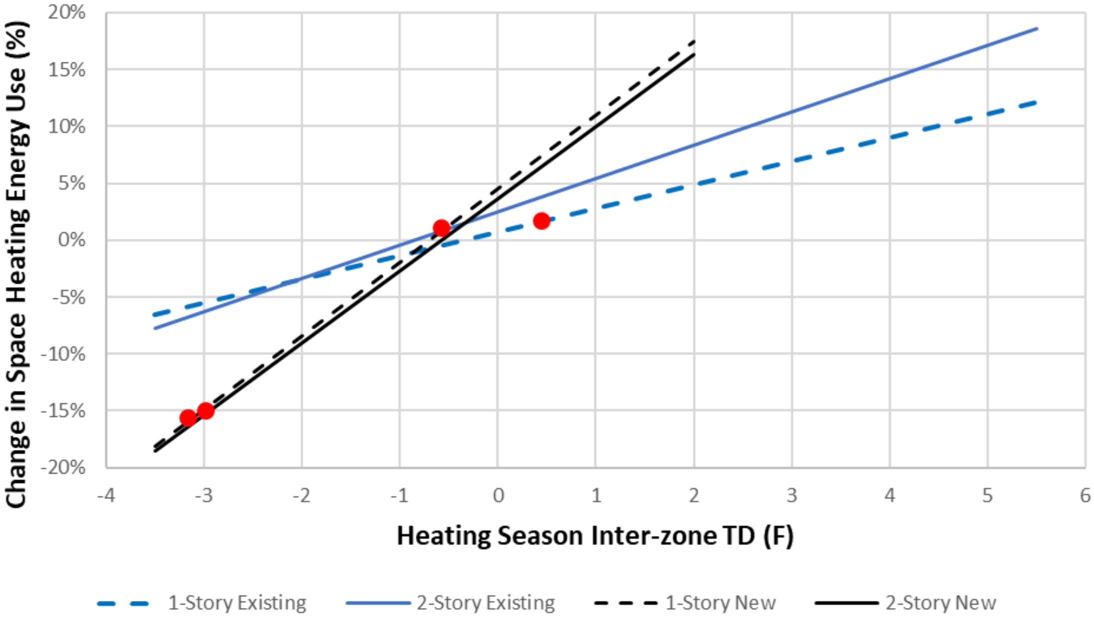


Table 19. Relationship between heating season single-zone energy use and inter-zone TD for four home models

Model	Regression Results		Inter-zone TD (°F)		
	Slope (%/°F)	Intercept (%)	For 0% Diff From MZ[a]	MZ Base Scenario	Diff.
1-Story Existing	2.1%	0.0073	-0.35	-0.30	-0.04
2-Story Existing	2.9%	0.0252	-0.86	-0.11	-0.75
1-Story New	6.5%	0.0452	-0.70	-2.74	2.04
2-Story New	6.3%	0.0364	-0.58	-1.89	1.32
Average, Existing	2.5%	0.0162	-0.61	-0.21	-0.40
Average, New	6.4%	0.0408	-0.64	-2.32	1.68
Average, All	4.4%	0.0285	-0.62	-1.26	0.64

a) Inter-zone TD for a zero percent difference between the multizone baseline scenario and single-zone system.

These results indicate that multizone systems could provide significant space heating energy savings for houses that have basements and/or second floors that are over-heated. For example, reducing the heating season average basement and second-floor temperatures by 2°F in a newer home is estimated to reduce annual heating energy use by about 12%. However, multizone systems could also increase energy use. Zonal temperature measurements from a limited sample of three one-story and three two-story older houses showed that for five of the six houses, the basement was cooler than the first floor for both the heating and cooling seasons. One house had a warmer basement in the heating season and cooler basement in the cooling season. For that house, a multizone system should provide more comfortable conditions and energy savings. For the other five houses, the improved comfort of a multizone system would likely increase energy use. For the three two-story houses, the second-floor temperature for one house was very similar to that of the first floor. For the other two houses, the second-floor temperature was cooler than the first-floor temperature in the heating season and warmer than the first floor in the cooling season. For those two houses, a multizone would provide improved comfort and likely increase energy use. This small sample suggests that installing multizone systems in older Minnesota homes will typically improve comfort and increase energy use. Since no measurements were available for newer houses, it is not known whether multizone systems will typically increase or decrease space heating energy use.

It is possible that the new homes equation (1) provides a reasonably accurate estimate for multizone energy changes for newer homes with insulation and envelope air leakage consistent with the current Minnesota energy code requirements. However, additional analysis of results for models that systematically vary the level of wall insulation, attic insulation, total house air leakage, and inter-zone airflow rates along with the distribution of air leaks is required to establish savings equations that can be applied to a broad range of houses. In addition, field studies are needed to verify these relationships. The studies could include the following.

- Alternating mode type studies with measurements of heating season zonal temperatures and space heating energy use when the distribution of supply airflow is manually adjusted at two- to four-week intervals. That would help confirm the linear relationship between changes in energy use and zonal temperatures.
- Measurements of annual space heating energy use before and after a single-zone system is replaced by a multizone system would confirm modeled energy savings estimates. Alternatively, it may be possible to operate a multizone system as a single-zone system and compare the energy use for single-zone operation to energy use of the multizone operation.
- Measurements of heating season zonal air temperatures for a significant number of new and existing homes would document the degree of over- or under-heating and cooling for houses and predict whether multizone systems would typically reduce or increase energy use. This may identify specific housing characteristics that could be used to predict houses that are more likely to have reduced energy use, so that those houses could be targeted for utility energy efficiency program incentives.

The analysis of heating season energy use and inter-zone TD was also conducted for the cooling season results. The regression lines for the heating season's analysis are displayed in

Figure 45 and the results are included in Table 20. There is more variation in the cooling season models than in the heating season models. There was a 14% difference in the regression slopes for the one- and two-story new home models and a 37% difference for the two existing home models. The average slope for the new home models was 0.63 times that of the average for the existing home models. Results from the new home and existing home models were combined to generate the energy change equations shown below. There appears to be significant potential for multizone systems to reduce cooling energy use. The change in energy use for a baseline single-zone scenario compared to that of a multizone system ranged from 27% to 50% and averaged 38%. In addition, the temperature measurements of a limited sample of Minnesota houses showed that for five of the six houses, the basement was cooler than the first floor for both the heating and cooling seasons.

New Home: $(E_{sz} – E_{mz})/E_{mz} = K_{mz} = -0.062*(\text{Inter-zone TD}) – 0.086$ (4)

Existing Home: $(E_{sz} – E_{mz})/E_{mz} = K_{mz} = -0.099*(\text{Inter-zone TD}) – 0.308$ (5)

Figure 45. Relationship between % change in single-zone cooling energy use and inter-zone TD: regression results

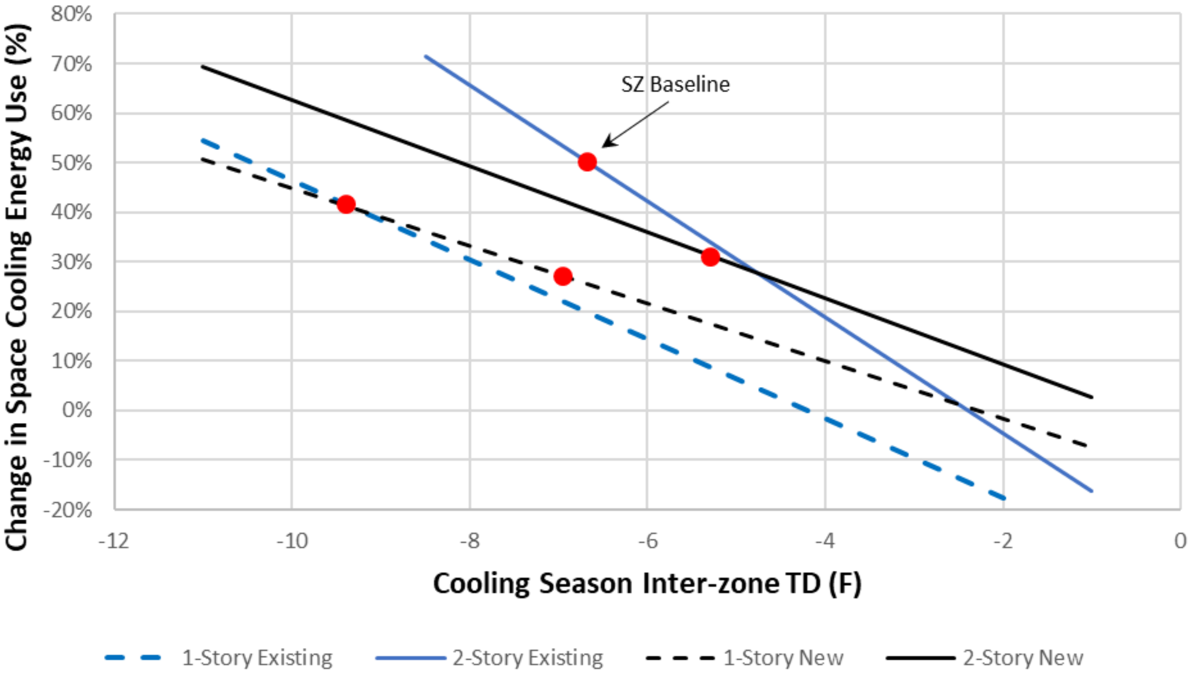


Table 20. Relationship between cooling season single-zone energy use and inter-zone TD for four home models

Model	Regression Results		Inter-zone TD (°F)		
	Slope (%/°F)	Intercept (%)	For 0% Diff From MZ[a]	MZ Base Scenario	Diff.
1-Story Existing	-8.0%	-0.338	-4.21	-3.85	-0.35
2-Story Existing	-11.7%	-0.279	-2.39	-2.37	-0.02
1-Story New	-5.8%	-0.132	-2.28	-2.55	0.27
2-Story New	-6.7%	-0.040	-0.60	-1.36	0.75
Average, Existing	-9.9%	-0.308	-3.30	-3.11	-0.19
Average, New	-6.2%	-0.086	-1.44	-1.95	0.51
Average, All	-8.0%	-0.197	-2.37	-2.53	0.16

a) Inter-zone TD for a zero percent difference between the multizone baseline scenario and single-zone system.

Conclusions and Recommendations

The overall project goal was to assess the energy savings opportunities for residential zoned air distribution systems for new and existing Minnesota single-family houses. The work included collecting data on available multizone equipment, a review of published information, surveys to evaluate the current market in Minnesota, building energy simulations to evaluate savings potential, and recommendations for incorporating multizone systems in utility CIP programs.

Technology Assessment

Product information was gathered for eight major equipment manufacturers of residential heating and cooling systems for the U.S. market. Results were:

- Seven of the eight have multizone packages. The seven manufacturers offer the multizone package for both furnaces and heat pumps except one which only offers it for heat pumps.
- Most of the furnaces and heat pumps have variable capacity, but some have only two stages.
- All the air handlers have ECMs for their fans.
- The systems can accommodate from three to 16 zones depending on the specific manufacturer.
- The packages use wired damper controls and all except one manufacturer have a smart phone application for system control.

Information was also collected for six third-party manufacturers that provide zoning equipment. Key information for the major manufacturer and third-party systems is shown in Appendix B.

Market Research

The objective was to discover where zoned systems are currently being installed, their technical potential, and barriers that would limit implementation. Results of five distributor, six contractor, and three third-party suppliers' interviews are shown below:

- Almost all distributors suggested that multizone systems were more common in high-end new construction and that 10% to 50% of new homes with central air distribution have zoning equipment. This is consistent with a recent study of new Minnesota homes that found that 22% of the furnaces had zoning equipment (95% confidence interval of 14% to 33%, Pigg 2022).
- Almost all respondents indicated comfort control as multizone systems' primary benefit, while energy savings were less impactful.
- All contractors agreed that zoning achieved high efficiency results with communicating variable speed systems, which could minimize the airflow rate restrictions compared to single stage models.
- Two contractors and a developer indicated that the typical additional cost to upgrade from a single-zone to multizone system ranged from $2,000 to $3,500 for a two-zone system and $3,500 to $6,000 for a three-zone system.
- All contractors and third-party suppliers expressed cost and zoning setup as challenges, especially in existing homes due to the absence of separate trunk lines.

- A few distributors suggested there had been a rise in market growth due to increased awareness of these systems, while others reported a stagnant market or gradual decline due to the emergence of new systems such as cold-climate air source heat pumps, including ductless mini splits.
- Most distributors and contractors suggested that utility incentives for multizone systems could assist market growth.
- The third-party suppliers indicated that most of their control systems were compatible with both communicating and non-communicating HVAC systems.

None of the 11 U.S. utilities contacted provide incentives to upgrade from single-zone to multizone air distribution systems. Five utilities had conducted multizone system pilot projects. There were no reports available for the pilot projects. The limited information available is included in the Results section.

All four Minnesota utility representatives who provided feedback were familiar with residential multizone systems. The utilities had not evaluated the technology and had not considered incorporating it into their residential programs. One of the utilities was aware of a Canadian program that provided incentives for multizone systems, but the other three were not aware of any utility incentive programs. The utilities expected that the systems will primarily provide improved comfort, but energy savings could be a strong secondary benefit. The greatest barrier for incorporating multizone systems in their programs was uncertain energy savings or not being able to compute energy savings. It was also noted that the added cost might be a difficult sell to customers, the benefit may be demand reduction that does not provide a cost benefit to the customer, and it may be challenging to identify houses where there will be savings. One of the utilities indicated that there may be a benefit to establishing a national utility working group and that the technology could provide demand reduction options. Another utility was interested in learning more about the cost effectiveness of retrofit installations.

Energy Modeling

The Energy Simulations section presented the results for a series of building energy simulations with different distributions of zonal airflow rates for the single-zone system. Varying the distribution of the zonal supply airflow creates over- and under-heated or cooled zones and the degree of over- and under-heating often varies seasonally. For all four models the percent change in heating energy use for a single-zone system compared to a multizone system is strongly linearly related to the difference between the average basement and second-floor temperatures and the first-floor temperature (e.g., inter-zone TD). The slope indicates the percent change in energy use for each 1°F increase in the inter-zone TD. For heating energy use the slopes ranged from 2.1% to 6.5% and averaged 4.4%. The results suggest that energy savings results for a two-story model could be applied to a one-story house, but variations in house insulation and air leakage will significantly impact energy savings estimates. Equations (1) and (2) can be used to compute the heating season energy use for a multizone system from the energy use for a single-zone system and the inter-zone TD. For example, reducing the heating season average basement and second-floor temperatures by 2°F in a newer home is estimated to reduce annual heating energy use by about 12%.

The analysis of heating season energy use and inter-zone TD was also conducted for the cooling season results. There is more variation in the cooling season models than in the heating season models. Results from the new home and existing home models were combined to generate the energy change equations (4) and (5). There appears to be significant potential for multizone systems to reduce cooling energy use. The change in energy use for a baseline single-zone scenario compared to that of a multizone system ranged from 27% to 50% and averaged 38%.

Zonal temperature measurements from a limited sample of three one-story and three two-story older houses showed that for five of the six houses, the basement was cooler than the first floor for both the heating and cooling seasons. For the three two-story houses, the second-floor temperature for one house was very similar to that of the first floor. For the other two houses, the second-floor temperature was cooler than the first-floor temperature in the heating season and warmer than the first floor in the cooling season. This small sample suggests that installing multizone systems in older Minnesota homes will typically improve comfort, increase space heating energy use, and decrease cooling energy use. Since no measurements were available for newer houses, it is not known whether multizone systems will typically increase or decrease space heating energy use. Additional research that would help determine the potential for multizone system energy savings is discussed in the Future Research section below.

CIP Recommendations

There appears to be significant opportunity for multizone systems to provide space conditioning energy savings for new Minnesota homes. Distributor feedback from this project and the results of a recent new home study (Pigg 2022) indicate that about a quarter of new homes with air distribution systems include zoning. The modeling results from this project indicate that space heating savings could be more than 10% and cooling savings could be more than 35% when zones are over-heated or over-cooled. However, estimating savings for a multizone system compared to a single-zone system is not as simple as comparing the efficiency of two different systems. The potential for a multizone system to reduce space conditioning energy use primarily depends on the operation of the single-zone system being used for comparison. Additional research is necessary to confirm and expand the energy use equations generated by this project. Field studies are also needed to document typical zone temperatures and possibly identify house characteristics that are likely to generate greater savings.

TRM Additions

An addition to the Minnesota TRM to estimate multizone system savings is not recommended. Since multizone systems are primarily used for new homes, incentivizing multizone systems for new homes appears to be the best opportunity to generate space heating and cooling energy savings. It is possible that equations (1) and (4) provide reasonably accurate estimates of the space heating and cooling energy for multizone systems compared to single-zone systems. Those relationships should be confirmed by field studies. Field studies are also needed to document typical and the range of inter-zone TDs for a representative sample of new homes.

Future Research

This project developed EnergyPlus models with CONTAM generated air infiltration and inter-zone airflows for simulations of single-zone and multizone air distribution systems for four house configurations. The seasonal trends in zone air temperature matched some of the trends from six actual houses' measurements. This white paper study was not intended to verify the model estimates of multizone energy savings nor was it expected to model a wide range of house characteristics necessary to predict energy savings for a high fraction of Minnesota housing.

Additional analysis of results for models that systematically vary the level of wall insulation, attic insulation, total house air leakage, and inter-zone airflow rates along with the distribution of air leaks is required to establish savings equations that can be applied to a broad range of houses. In addition, field studies are needed to verify these relationships. The studies could include the following.

- Alternate mode type studies with measurements of heating season zonal temperatures and space heating energy use when the distribution of supply airflow is manually adjusted at two- to four-week intervals. This would help confirm the linear relationship between changes in energy use and zonal temperatures.
- Measurements of annual space heating energy use before and after a single-zone system is replaced by a multizone system would confirm modeled energy savings estimates. Alternatively, it may be possible to operate a multizone system as a single-zone system and compare the energy use of the single-zone operation to that of the multizone operation.
- Measurements of heating season zonal air temperatures for a significant number of new and existing homes would document the degree of over- or under- heating and cooling for houses and predict whether multizone systems will typically reduce or increase energy use. This may identify specific housing characteristics that could be used to predict houses that are more likely to have reduced energy use, so those houses could be targeted for utility energy efficiency program incentives.

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Appendix A: Additional References

This section includes a list of 22 references relevant to residential multizone air distribution systems. Each reference includes information related to residential multizone systems, but that is not the primary focus of the reference. When available, the abstract is included.

Ardehali, Morteza M., and Theodore F. Smith. "Evaluation of Variable Volume and Temperature HVAC System for Commercial and Residential Buildings." Energy Conversion and Management 37, no. 9 (September 1, 1996): 1469–79. https://doi.org/10.1016/0196-8904(95)00219-7.

> The variable volume and temperature (VVT) system can meet energy efficiency constraints during peak and partial load conditions while maintaining thermal comfort requirements. Although there are numerous alternatives available for changeover from an existing inefficient constant-air-volume system, the VVT system is of particular interest due to the favorable economics and minimal time requirements for installation. The objectives of this paper are (1) the presentation of simulation results for constant-air-volume, variable-air-volume, and VVT systems; and (2) the comparison of annual energy consumption and economic selection factors for these systems. A typical three-story office building and a typical residential building, located in Des Moines, Iowa, were examined. The results show that the VVT system should be considered during the design stages for new projects and as a replacement in retrofit projects. For a commercial office building, the payback period for retrofit from a constant-air-volume system to the VVT system is estimated at 3–4 yr. For a residential building, capital-cost-recovery periods of 6 months for retrofit and 18 months for a new installation of the VVT system are predicted.

Cai, Jie, and James E. Braun. "A Regulation Capacity Reset Strategy for HVAC Frequency Regulation Control." Energy and Buildings 185 (February 15, 2019): 272–86. https://doi.org/10.1016/j.enbuild.2018.12.018.

> The power grid has seen record demand for frequency regulation capacity in recent years due to the increased employment of renewable energy resources worldwide. Building thermal loads are flexible and thus, can be used as regulation reserves with proper control strategies. Previous studies have shown that building HVAC equipment can provide high-quality power grid regulation service with PJM performance scores of up to 0.98 and buildings' participation in the regulation market could bring significant economic benefits for building owners. However, the power flexibility in buildings is not persistent and the available HVAC regulation capacity has significant hour-by-hour variation due to building load and other operating constraints. This paper presents a regulation capacity reset strategy for HVAC regulation control that identifies the available regulation capacity and baseline power on the fly with real-time load and operation data. The strategy relies on a steady-state HVAC performance model derived from manufacturer performance data and implements a pseudo-optimization that seeks the maximum regulation capacity while respecting all operating constraints. The proposed strategy was implemented on a variable-speed rooftop unit (RTU) and validated with laboratory tests in psychrometric chambers. The test results show that the proposed reset strategy is effective in

> providing consistent high-quality regulation service with negligible impact on the indoor temperature control; the zone temperature deviation from the setpoint was within 0.3 °C for all the performed tests. The reset strategy was also simulated with a prototypical building diurnal load model to quantify the integrated regulation capacity for a typical summer day. Simulation results indicate the integrated HVAC regulation capacity throughout a summer day equals approximately 1/4 of the daily electrical energy use; and the estimated daily regulation credit can offset up to 26% of the daily HVAC electricity cost based on PJM historical prices.

Cetin, Kristen S, Mohammad Hassan Fathollahzadeh, Niraj Kunwar, Huyen Do, and Paulo Cesar Tabares-Velasco. “Development and Validation of an HVAC on/off Controller in EnergyPlus for Energy Simulation of Residential and Small Commercial Buildings.” Energy and Buildings 183 (January 15, 2019): 467–83. https://doi.org/10.1016/j.enbuild.2018.11.005.

> Heating, ventilation, and air-conditioning (HVAC) systems are sized using design conditions, conditions that occur only a small percentage of time each year. As a result, HVAC systems frequently operate at part-load conditions since their capacity is larger than necessary except in the most extreme weather conditions. Most HVAC systems for residential and small commercial buildings in the U.S. use on/off controls, however, most energy modeling software tools do not simulate the on/off nature of this type of HVAC controls. This paper presents the development and validation of an on/off controller for residential applications in EnergyPlus using a custom EMS (energy management system). This controller is validated using minute-level field data collected for a house located in Sacramento, California with simulated occupancy and internal loads. The results obtained from EnergyPlus with and without the use of the developed on/off controller are also compared. The application of the developed on/off controller improves the HVAC energy use results accuracy around 19% in terms of the Normalized Mean Bias Error (NMBE) at the one-minute level compared to the results without the application of the on/off controller. It also makes the nature of operation and associated energy use signal of the HVAC system more realistic in terms of the on/off nature of the residential direct expansion coils. Furthermore, in this paper, the accuracy improvement of the results dominated by the internal loads is investigated by applying the one-minute schedule compared to the usual hourly schedules for the internal thermal loads.

Demeure, A., S. Caffiau, E. Elias, and C. Roux. “Building and Using Home Automation Systems: A Field Study.” In End-User Development, 125–40. Lecture Notes in Computer Science. Springer, Cham, 2015. https://doi.org/10.1007/978-3-319-18425-8_9.

> These last years, several new home automation boxes appeared on the market, the new radio-based protocols facilitating their deployment with respect to previously wired solutions. Coupled with the wider availability of connected objects, these protocols have allowed new users to set up home automation systems by themselves. In this paper, we relate an in situ observational study of these builders in order to understand why and how the smart habitats were developed and used. We led 10 semi-structured interviews in households composed of at least 2 adults and equipped for at least 1 year, and 47 home automation builders answered an online questionnaire at the end of the study. Our study confirms, specifies and exhibits

additional insights about usages and means of end-user development in the context of home automation.

Dobbs, Justin R., and Brandon M. Hencey. “Model Predictive HVAC Control with Online Occupancy Model.” Energy and Buildings 82 (October 1, 2014): 675–84. https://doi.org/10.1016/j.enbuild.2014.07.051.

This paper presents an occupancy-predicting control algorithm for heating, ventilation, and air conditioning (HVAC) systems in buildings. It incorporates the building's thermal properties, local weather predictions, and a self-tuning stochastic occupancy model to reduce energy consumption while maintaining occupant comfort. Contrasting with existing approaches, the occupancy model requires no manual training and adapts to changes in occupancy patterns during operation. A prediction-weighted cost function provides conditioning of thermal zones before occupancy begins and reduces system output before occupancy ends. Simulation results with real-world occupancy data demonstrate the algorithm's effectiveness.

Fazli, Torkan, Rou Yi Yeap, and Brent Stephens. “Modeling the Energy and Cost Impacts of Excess Static Pressure in Central Forced-Air Heating and Air-Conditioning Systems in Single-Family Residences in the U.S.” Energy and Buildings 107 (November 15, 2015): 243–53. https://doi.org/10.1016/j.enbuild.2015.08.026.

Many central residential forced-air heating and air-conditioning systems contain high pressure drop elements such as high-efficiency or dust-loaded filters, dirty coils, or constricted or undersized ductwork, which are widely assumed to have substantial energy and economic impacts. However, the overall energy and cost consequences of excess static pressures have not been explored in depth across a wide range of climates, homes, or system characteristics. Therefore, we performed 780 annual building energy simulations using BEopt and EnergyPlus to predict the energy and cost impacts of realistic excess static pressures for typical new and existing single-family homes with both permanent split capacitor (PSC) blowers and electronically commutated motors (ECM) in 15 U.S. climate zones. Results demonstrate that excess static pressures can increase annual energy consumption and costs, but the magnitude varies by blower type and climate zone. Moderate increases in static pressures (i.e., from 50 to 150Pa) were predicted to yield minimal increases in annual space conditioning energy costs (i.e., less than 3% across all homes, blowers, and climates), while more extreme increases in static pressure (i.e., from 50 to 350Pa) were predicted to yield average increases in energy costs of ∼9% with ECM blowers and ∼18% with PSC blowers.

“Feasibility of Retrofitting Centralized HVAC Systems for Room-Level Zoning.” Accessed June 1, 2021. https://ieeexplore.ieee.org/document/6322269/.

Heating, ventilation, and cooling (HVAC) accounts for 38% of building energy usage, and over 15% of all US energy usage, making it one of the nation's largest energy consumers. Many attempts have been made to optimize the control of HVAC systems by minimizing the energy wasted in conditioning buildings that are unoccupied. Systems have been proposed that turn off HVAC systems when a house is unoccupied, or put the system into an energy saving deep-

setback mode when the occupants are asleep. An area that has not been as well explored is the retrofitting of centralized HVAC systems to save energy when the residents are at home and awake. In this paper, we demonstrate how to use cheap, off-the-shelf sensors and actuators to retrofit a centralized HVAC system and enable rooms to be heated or cooled individually, in order to reduce waste caused by conditioning unoccupied rooms. We call this approach room-level zoning. Sensors are used to detect occupancy in rooms which allows the learning of occupancy patterns and prediction of room occupancy. Unoccupied rooms can be allowed to drift away from a user defined comfortable temperature if they are less likely to be used in the near future while occupied rooms are maintained at a comfortable temperature. We implement room-level zoning in a 1400 square foot house by retrofitting an existing centralized HVAC system with wireless temperature sensors to monitor room-level temperature, motion sensors to monitor occupancy, and wirelessly actuatable dampers to control the flow of conditioned air through the house. Initial analysis indicates that this method has a 20.5% energy savings over the existing single-zoned thermostat.

Ford, Rebecca, B. Karlin, A. Sanguinetti, A. Nersesyan, and M. Pritoni. “Assessing Players, Products, and Perceptions of Home Energy Management,” 2016. https://ora.ox.ac.uk/objects/uuid:51abc49d-20da-40f1-a8b4-c42c9f4ec195.

This report explores the potential role utilities may play in the emerging home energy management (HEM) marketplace and develops a roadmap to leverage, promote, and enable the use of these technologies for energy savings and grid load reduction. It takes a comprehensive view of HEMS by evaluating the evolving market in which they are developing, the technological capabilities of the products and systems, and the consumer attitudes and perceptions of these technologies. Each of these three lines of inquiry – the Industry Assessment, Technology Inventory, and Consumer Assessment – informs both immediate and longer-term recommendations for successful utility engagement with HEMS.

Hesaraki, Arefeh, and Sture Holmberg. “Demand-Controlled Ventilation in New Residential Buildings: Consequences on Indoor Air Quality and Energy Savings.” Indoor and Built Environment 24, no. 2 (April 1, 2015): 162–73. https://doi.org/10.1177/1420326X13508565.

The consequences on indoor air quality (IAQ) and potential of energy savings when using a variable air volume (VAV) ventilation system were studied in a newly built Swedish building. Computer simulations with IDA Indoor Climate and Energy 4 (ICE) and analytical models were used to study the IAQ and energy savings when switching the ventilation flow from 0.375 l·s−1·m−2 to 0.100 l·s−1·m−2 during unoccupancy. To investigate whether decreasing the ventilation rate to 0.1 l·s−1·m−2 during unoccupancy, based on Swedish building regulations, BBR, is acceptable and how long the reduction can last for an acceptable IAQ, four strategies with different VAV durations were proposed. This study revealed that decreasing the flow rate to 0.1 l·s−1·m−2 for more than 4 h in an unoccupied newly built building creates unacceptable IAQ in terms of volatile organic compounds concentration. Hence, if the duration of unoccupancy in the building is more than 4 h, it is recommended to increase the ventilation rate from 0.100 l·s−1·m−2 to 0.375 l·s−1·m−2 before the home is occupied. The study showed that when the investigated building was vacant for 10 h during weekdays, increasing the ventilation

> rate 2 h before occupants arrive home (low ventilation rate for 8 h) creates acceptable IAQ conditions. In this system, the heating requirements for ventilation air and electricity consumption for the ventilation fan were decreased by 20% and 30%, respectively.

Hjortland, Andrew L., and James E. Braun. “Load-Based Testing Methodology for Fixed-Speed and Variable-Speed Unitary Air Conditioning Equipment.” Science and Technology for the Built Environment 25, no. 2 (February 7, 2019): 233–44. https://doi.org/10.1080/23744731.2018.1520564.

> A load-based methodology for testing and rating the performance of unitary air conditioning equipment has been developed and demonstrated using a laboratory psychrometric chamber test facility. The methodology simulates representative sensible and latent loads of a commercial building as well as the thermal and latent capacitance of buildings using psychrometric chamber test facilities. The advantage of the proposed test methodology is that there is no requirement to disable the native control systems designed by equipment manufacturers. This results in more realistic representations of the installed performance of equipment that include interaction of their embedded controls with the building. The load-based control approach is described and applied to the control system of an existing psychrometric chamber test facility. Results using the developed test methodology collected from fixed-speed and variable-speed RTUs show significant differences between actual part-load performance and steady-state performance at equivalent ambient operating conditions. A test procedure that includes interaction of the equipment controls with a virtual building could enable future equipment ratings that are both climate and building-type specific. This would not be possible for the current testing approaches that override native controls with no building interaction.

Kialashaki, Y. “Energy and Economic Analysis of Model-Based Air Dampers Strategies on a VAV System.” International Journal of Environmental Science and Technology 16, no. 8 (August 1, 2019): 4687–96. https://doi.org/10.1007/s13762-018-1863-z.

> A variable air volume (VAV) air handling system can significantly reduce fan power under partial load conditions. The focus of this study is developing a modeling program to predict the potential energy saving by the secondary HVAC system strategies. Comprehensive steady-state models are established to describe the energy performance of different control strategies for secondary HVAC systems. With building loads, minimum fresh air flow rate, pressure losses, supply air temperature control, dampers control and coil characteristic as inputs, the objectives were to develop a simulation model to evaluate performance of an air handling system. The potential energy savings of constant air volume (CAV) and VAV strategies are investigated in a representative residential building. The simulation results show that about 13% of electrical power can be saved by the proposed VAV strategy in respect of the CAV. Also, life cycle cost analysis is applied on the considered system. It is found that VAV system is not economically good for the considered building because of low electricity price in Iran. Finally, a sensitivity analysis was conducted to demonstrate how the electricity price affects the economic performance of the VAV system.

Li, Bo, Peter Wild, and Andrew Rowe. "Performance of a Heat Recovery Ventilator Coupled with an Air-to-Air Heat Pump for Residential Suites in Canadian Cities." Journal of Building Engineering 21 (January 1, 2019): 343–54. https://doi.org/10.1016/j.jobe.2018.10.025.

> Heat recovery ventilation (HRV) technologies are used to satisfy indoor air quality requirements while reducing building energy consumption. In a typical installation, an HRV system is expected to decrease energy demand; however, the actual benefit depends on the mechanical system, climate conditions, and building design. Here, we assess the energy savings from sensible heat recovery in residential apartment buildings across Canada by modeling the building thermal demands and the HVAC system's energy use. We compare the annual performance of a commercial air-to-air heat pump coupled to a balanced ventilation system with and without the HRV. A hypothetical residential suite is modeled under eight different building orientations for fifteen Canadian cities. Results show that HRV use always reduces the annual heating energy consumption; however, energy consumption may increase in cooling seasons.

Meyers, Robert J., 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, no. 5 (May 1, 2010): 563–69. https://doi.org/10.1016/j.enbuild.2009.10.026.

> This scoping study takes a broad look at how information technology-enabled monitoring and control systems could assist in mitigating energy use in residences by more efficiently allocating the delivery of services by time and location. A great deal of energy is wasted in delivering services inefficiently to residents such as heating or cooling unoccupied spaces, overheating/undercooling for whole-house comfort, leakage current, and inefficient appliances. We construct a framework to estimate different categories of inefficient energy services and the result of our initial estimate is that over 39% of residential primary energy is wasted. We next discuss how monitoring and control technologies could manage home energy use to reduce waste. Technologies considered here include programmable thermostats, smart meters and outlets, zone heating, automated sensors, and wireless communications infrastructures. The level of energy services delivered is assumed to remain unchanged, with all energy savings being realized through better management. A final discussion on barriers to adoption of these systems speculates that a lack of consumer awareness of the technologies, high costs due to lack of economies of scale, and difficult user interfaces are currently the major hurdles toward adoption.

Modera, Mark. "Characterizing the Performance of Residential Air Distribution Systems." Energy and Buildings 20, no. 1 (January 1, 1993): 65–75. https://doi.org/10.1016/0378-7788(93)90039-W.

> Approximately 35% of US single-family houses contain forced-air heating and cooling ducts that pass through unconditioned spaces. These duct systems have been shown to have a potentially large influence on energy use and ventilation rates. To investigate the parameters affecting the performance of these systems, a 31-house field study of distribution-system performance based on diagnostic measurements was performed in California, and an integrated airflow and thermal simulation tool was developed. The results of the field study, a brief description of the simulation tool, and the results of the first applications of the simulation tool are presented. The

field-study measurements generally agreed with the findings in earlier studies, provided field experience with new diagnostic tools, and provided system/house characterization data for use in simulation codes and in the development of retrofit protocols. Some highlights of the field results include: (1) building envelopes appear to be approximately 30% tighter for California houses built after 1979; (2) duct system tightness showed no apparent improvement in the post-1979 houses; (3) distribution-fan operation added an average of 0.45 ACH to the average measured air change rate of 0.24 ACH, and (4) an average of 20% of the furnace heating effect was measured to be lost due to duct conduction losses alone. The stimulation tool developed is based upon DOE-2 for the thermal simulations, MOVECOMP, an airflow network simulation model, for the duct/house leakage and flow interactions, and a combined heat and mass transfer model of the duct performance. The first complete set of simulations performed for a new ranch house in Sacramento CA indicated that steady-state duct-system efficiencies vary over a large range with outside temperature, ranging from 50 to 95% (decreasing with increasing outside temperature for cooling and decreasing outside temperature for heating). The simulations also indicated that the location of the return duct can have a large influence on duct-system efficiency during the cooling season.

Mountain, D, T Strack, and J Sager. “Advanced Residential Load Reduction Pilot Project – A Field Trial of Centrally Zoned Forced Air Systems,” July 15, 2016. https://www.nrcan.gc.ca/maps-tools-publications/publications/energy-publications/publications/advanced-residential-load-reduction-pilot-project-field-trial-centrally-zoned-forced-air-systems/18807.

No abstract available for this reference.

Redfern, Andrew, Michael Koplow, and Paul Wright. “Design Architecture for Multi-Zone HVAC Control Systems from Existing Single-Zone Systems Using Wireless Sensor Networks.” In Smart Structures, Devices, and Systems III, 6414:64140Y. International Society for Optics and Photonics, 2007. https://doi.org/10.1117/12.695963.

Most residential heating, ventilating, and air-conditioning (HVAC) systems utilize a single zone for conditioning air throughout the entire house. While inexpensive, these systems lead to wide temperature distributions and inefficient cooling due to the difference in thermal loads in different rooms. The end result is additional cost to the end user because the house is over conditioned. To reduce the total amount of energy used in a home and to increase occupant comfort there is a need for a better control system using multiple temperature zones. Typical multi-zone systems are costly and require extensive infrastructure to function. Recent advances in wireless sensor networks (WSNs) have enabled a low-cost drop-in wireless vent register control system. The register control system is controlled by a master controller unit, which collects sensor data from a distributed wireless sensor network. Each sensor node samples local settings (occupancy, light, humidity and temperature) and reports the data back to the master control unit. The master control unit compiles the incoming data and then actuates the vent resisters to control the airflow throughout the house. The control system also utilizes a smart thermostat with a movable set point to enable the user to define their given comfort levels. The new system can reduce the run time of the HVAC system and thus decreasing the amount of energy used and increasing the comfort of the home occupations.

Sager, J, and M Armstrong. “An Assessment of Peak Demand Reductions and Energy Savings of a High Velocity Centrally Zoned Combination System at the Canadian Centre for Housing Technology,” July 18, 2016. https://www.nrcan.gc.ca/maps-tools-publications/publications/energy-publications/publications/assessment-peak-demand-reductions-and-energy-savings-high-velocity-centrally-zoned-combination/18809.

No abstract available for this reference.

Sager, Jeremy, and M Armstrong. “Performance Assessment of a High Velocity Zoned Combination System at the Canadian Centre for Housing Technology,” July 18, 2016. https://www.nrcan.gc.ca/maps-tools-publications/publications/energy-publications/publications/performance-assessment-high-velocity-zoned-combination-system-canadian-centre-housing-technology/18811.

No abstract available for this reference.

Watts, W., M. Koplow, A. Redfern, and P. Wright. “Application of Multizone HVAC Control Using Wireless Sensor Networks and Actuating Vent Registers,” 2007. https://oaktrust.library.tamu.edu/handle/1969.1/6214.

Most residential heating, ventilating, and air conditioning (HVAC) systems are designed to treat the home as a single zone. Single zone control consists of one thermostat, in a central area of the house that controls the HVAC operation. In a single-zone system, all of the vent registers are open, distributing air into all areas of the house at once. Single zone control leads to wasted energy for two reasons - all rooms being conditioned when they are not occupied, and conditioning occupied rooms, without maintaining them at the comfortable temperature for the occupants. Improved control of residential cooling and heating can be attained with a variable HVAC fan, duct, and vent system.

Existing single zone systems are expensive to retrofit with the above-mentioned features. Current techniques require replacing major components in the HVAC system which are both costly and time consuming, invading the user's home. An alternative to the extensive retrofit is detailed in this work.

The experiments in this paper implement an automated vent louver system to solve two problems in heating homes: the problem of temperature stratification between floors and zonification between rooms, and the energy wasted to heat in unoccupied areas of the home.

This paper considers the application of replacing the standard vents in each room with wireless controlled louvered vents. These vents allow for simpler, more cost-effective retrofits which are also less invasive tithe end user's home. The experiments in this paper implement an automated vent louver system to reduce the energy wasted to heat unoccupied areas of the home.

This test house in these experiments was a two-story home. Wireless sensor-actuator networks were used to automate the test of closing off vent registers while maintaining the appropriate temperature set point in a control zone. A control zone consists of the house area where the vents are fully open. Controlling the vent registers allowed for reduced zonification between

rooms on the same floor, and reduced stratification between the upstairs and downstairs. Energy savings were shown when vents were closed to heat the control zones containing the bedroom, of the office.

Zhou, Wen, and Dean C. Mountain. "The Benefits of Combining Utility-Controlled Demand Response with Residential Zoned Cooling." Energy Efficiency 7, no. 6 (December 1, 2014): 1067–99. https://doi.org/10.1007/s12053-014-9265-7.

This paper evaluates the effectiveness of combining direct load control with a residential zoned-cooling technology in meeting the objectives of reducing peak demand and maintaining home comfort level. In contrast, the traditional approach has been for utilities to smooth summer peak cooling loads, by controlling the cooling load of the whole house. While accounting for weather, dwelling characteristics and demographics, with detailed field data, we are able to develop empirical models to evaluate the benefits of utility control of cooling loads for a residential zoned cooling system during summer peak-demand periods and to compare with non-zoned systems. A zoned house allows for an upper floor cooling interruption without affecting the comfort on the main floor. An upper floor interruption for a full 4 h during the day leads to an average peak air conditioning change of −0.52 kW, approximately 1.6 times the reduction from the curtailment of cooling by cycling the air conditioning serving the whole house.

Metzger, Cheryn E., Siddharth Goyal, and Michael C. Baechler. 2017. "Review of Residential Comfort Control Products and Opportunities." PNNL-27141. Pacific Northwest National Lab. (PNNL), Richland, WA (United States). https://doi.org/10.2172/1417446.

This paper begins by discussing the interaction of each major component in advanced sensor and control applications related to HVAC equipment. The paper also looks at the applications of these components to commissioning, maintenance and operations of the HVAC equipment in residential buildings. A summary of state-of-the-art product features is also provided. These products are categorized through their primary application type (commissioning/maintenance or operation) and the features are categorized by component type (sensors, data storage, human-in-the-loop, communication, and controls). A common theme that emerges from this study is the importance of the ability for various product categories to be connected to each other. There are many manufacturers of sensors and many manufacturers of controls, but the power to automate any commissioning, maintenance or operation application, requires connectivity.

Haile, James, and David Springer. 2017. "Laboratory House Test of Smart Damper Control Systems to Provide Zoning." ETCC. July 31, 2017. https://www.etcc-ca.com/reports/laboratory-house-test-smart-damper-control-systems-provide-zoning.

The technology to be evaluated is an automated, smart, internet connected zone control system for residential HVAC. This first phase of a two phase project will complete lab tests to verify that the zone control system can regulate comfort while not degrading overall system efficiency, while also complying with Title 24 HVAC equipment acceptance rules. Based on initial findings, a

potential Phase II project will involve field testing with a sample size to identify statistically significant energy savings in a variety of climate zones.

Appendix B: Manufacturer Multizone Equipment

We identified seven major manufacturers that have multizone packages for their furnaces, heat pumps and air conditioners: Armstrong, Carrier, Lennox, Mitsubishi, Rheem, Trane, and York. Daikin is the only major manufacturer that we evaluated that did not have a multizone package, but there is a third-party manufacturer that has a package that interfaces with Daikin equipment. All of the manufacturers offer the multizone package for both furnaces and heat pumps except Mitsubishi which only has heat pumps. Most of the furnaces and heat pumps have variable capacity, but some have only two stages. All of the air handlers have ECMs for their fans. The packages use wired damper controls and all except Lennox have a smart phone application for system control. Four of the systems can accommodate up to four zones, the Rheem EcoNet can control up to three, York up to eight, and Mitsubishi up to 16. All of the manufacturers have Wi-Fi linked applications except Lennox. Key information for the systems is shown in Table 21.

Table 21. Major Manufacturer multizone equipment

Heat Type	Model	Cooling Capacity (kBtu/h)	Heating Capacity (kBtu/h)	Modulation	SEER	HSPF or AFUE
Armstrong Air Comfort Sync						
Furnace	A802V		52 - 105	VS		80
	A962V		42 - 106	VS		96
	A97MV		64 - 127	VS		97
HP	4SHP16LS	24 - 60	15.1 - 39.9	2 Stage	16	8.5
	4SHP20LX	24 - 60	15.1 - 39.9	VS	20	10
Carrier Infinity SYSTXCCUIZ01-V						
Furnace	59MN7		60 - 120			98.5
	59TN6		60 - 120	2 Stage		96.7
	58TN0A		44 - 66	2 Stage		80
HP	25VNA4	24 - 60		5 Stage	24	13
	25VNA8	24 - 60	15.5 - 35.2	5 Stage	19	11
	25HNB6	24 - 60	15.3 - 36	2 Stage	17.5	9.5
	25HNB6**C	24 - 60	15.3 - 36	2 Stage	17.5	9.5
Lennox Harmony III and LZP-4						
Furnace	SLP99V		22-64; 45-128			99
	SLP98V		22-64; 45-129	VS		98.7
	SL297NV		26- 40; 52 - 80	VS		97.5
	SL280V		43-66; 86-132	VS		80
	EL296V		29-44; 72-110	VS		96

Heat Type	Model	Cooling Capacity (kBtu/h)	Heating Capacity (kBtu/h)	Modulation	SEER	HSPF or AFUE
	ML296V		29-44; 72-110	VS		96
HP	XP20	21.6 - 58	21.4 - 55	VS	20	10
	EL18XPV	18 - 60	16.7 - 61	VS	18	10.4
	XP16	23.6 - 59.5	21 - 61.5	2 Stage	17	9.5
Mitsubishi M series Controls						
HP	MXZ-3C24NA	12.6- 25.5	14		18	9.5
	MXZ-3C30NA	12.6 - 27.4	15.1	VS	17.6	10.1
	MXZ-4C36NA	12.6 - 34.8	20.3	VS	17.6	10.4
	MXZ-5C42NA	12.6 - 43	23	VS	17.5	9.7
	MXZ-8C48NA	15.5 - 48	36.6	VS	16.8	10.8
	MXZ-8C60NA	30 - 60	58	VS	17.40	10.5
Rheem EcoNet						
Furnace	R97V		60 - 115	VS		97
	R98V		60 - 115	VS		98
	R96V		40 - 115	VS		96
	R802V		75 - 125	2 Stage		80
HP	RP20	24 - 60	22.8 - 47	VS	20	11.5
	RP17	24 - 60	15.6 - 41.5	VS	18.5	9.5
Trane ComfortLink II						
Furnace	XC95m		60-120	VS		95
HP	XV20i	24 - 60		750 Stage	21	10
	XV18	23.8 - 54		700 Stage	18	9.5
	XV19	23.8 - 58.6		750 Stage	19.5	12
York HX3 Communicating zoning system						
HP	YZV SERIES	24 - 54	22.4 - 48	VS	20	11
Furnace	YPLC SERIES		60 - 120	VS		80
	YP9C SERIES		60 - 120	VS		97.5 - 98.0

We identified six third-party manufacturers that provide zoning equipment: ECOJAY, Emee Zoning, EWC Control, Flair, Honeywell, and Keenhome Systems. Key information for the systems is shown in Table 22.

Table 22. Third-party manufacturer multizone equipment

Model	# Zones	Control Functions	# Stages
EWC Control			
NCM series	3	T-stat and/or Timer/OAS	Furnace – 2 Heat & 1 Cool HP – 2 Heat & 1 Cool
UZC series	4	T-stat and/or Timer/OAS	Furnace– 2 Heat & 2 Cool HP – 4 Heat & 2 Cool
BM PLUS series	3	T-stat and/or Timer/OAS	Furnace– 2 Heat & 2 Cool HP – 3 Heat & 2 Cool
Honeywell			
HZ432	4	VS Fan Control	Furnace- 1 Heat & 1 Cool, 2 Heat & 2 Cool with (AC) HP- 1 or 2 Stage + Aux Elec back up
HZ322K	3	VS Fan Control	Furnace- 1 Heat & 1 Cool, 2 Heat & 2 Cool with (AC) HP- 1 Heat & 1 Cool + Aux Elec back up, 2 Heat & 2 Cool
HZ311	3	VS Fan Control	Furnace- 1 Heat & 1 Cool
HZ211	2	VS Fan Control	HP- 1 Heat & 1 Cool + Aux Elec back up
Ecojay			
SmartZone-4X	4	-	Furnace – 2 Heat & 3 Cool HP – 2 Heat & 3 Cool
SmartZone-2X	2	-	Furnace – 2 Heat & 3 Cool HP – 2 Heat & 3 Cool
Keen home Systems			
Ecovent	10	-	Compatible with All Units