Single and multi-family residential central all-air HVAC system operational characteristics in cooling-dominated climate

Kristen Sara Cetin, Atila Novoselac

Department of Civil, Architectural and Environmental Engineering, University of Texas at Austin, USA

A R T I C L E   I N F O

Article history:
Received 5 December 2014
Received in revised form 6 February 2015
Accepted 17 March 2015
Available online 27 March 2015

Keywords:
Runtime fraction
Duty cycle
Central air conditioning
Single family homes
Multi-family homes

A B S T R A C T

189 conditioned residential single-family and multi-family homes in the cooling-dominated climate of Texas were instrumented with home energy management systems (HEMS) to collect sub-metered data on HVAC operations. This study analyses the HVAC operation from these homes over a 1-year period to determine the duty cycles of the HVAC systems. This includes annual, monthly, and hourly HVAC ON-OFF operation patterns. Regression analysis was used to determine the relationship to HVAC energy use and whole-home energy use, and the influence of building and occupant characteristics. HVAC runtimes are found to be approximately 20% per year, but vary, depending on the season and time of day. Daily and monthly runtime fractions are lowest (10%) at average outdoor temperatures of 15 °C, and increase with increasing or decreasing temperature. Hourly runtime peaks at 7 pm in the cooling season, while in the heating and transition seasons, it peaks at 7 am. The number of occupants and the indoor cooling set point temperature were found to most strongly influence the HVAC runtime. The results are formatted to be used in various building and indoor air quality applications where the studied phenomena are influenced by HVAC operation.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

In the United States people spend 68% of their time in residential buildings [1] and 90% of their time indoors [2]. Therefore, there is a need for residential buildings and their systems to provide a comfortable and healthy indoor environment. This is often accomplished through the use of heating, ventilation, and air conditioning (HVAC) systems, particularly in the summer (cooling) and winter (heating) seasons. Nearly 87% of homes in the United States use air conditioning, including 89% of single family homes, and 84% of multi-family homes [3]. In more extreme hot climates such as Texas, air conditioning penetration is nearly 100%. Air conditioning penetration is lower in many other parts of the world, but is predicted to grow worldwide by 72% between 2000 and 2100, particularly in the face of predicted climate change [4]. Nearly all homes in the U.S. (97%) [3] also use central heating. Worldwide, the use of central heating is also predicted to increase by 34% by 2100. Since HVAC systems impact energy use, thermal comfort and indoor air quality, it is important to understand how and when these systems operate. However, there is limited information available on the operational characteristics, and specifically on runtimes of these HVAC systems, particularly in the United States.

A residential centralized all-air HVAC system typical of U.S. homes cycles ON and OFF to maintain a temperature set by a central thermostat. Of homes that utilize HVAC system in the U.S., 80% of single family homes (53 million housing units), and 60% of multi-family homes (13 million housing units) utilize this type of system [3]. Of the homes located in hot and humid climates, as defined by the Building America climate guidelines [5], 82% (15 million housing units) utilize central all-air HVAC, the highest percent penetration of all climate zones in the United States. HVAC use is greatest in the summer (cooling season) and winter (heating season) months, or when indoor and outdoor temperatures have the greatest temperature differential. This runtime fraction, also called duty cycle, or the percent of time the HVAC system is ON, affects both the energy demand on the electric grid, and the other duties of HVAC systems including dehumidification, filtration and, in some cases ventilation [6].

Impact of runtime fraction on energy systems: HVAC use has a large impact on both overall electricity use, and peak demand on the electric grid [7]. Of the 22% of energy use and 38% of electricity use attributed to residential buildings in the U.S. [8], HVAC systems make up over 52% of this energy use, and 31% of this electricity use [9]. These percentages are greater in the more extreme climate regions. In hot climates such as Texas, HVAC use accounts for...
over 56% of electricity use of residential buildings in the summer months [10]. Higher runtime fractions of HVAC systems also equate to greater demand on the electric grid. In the summer (cooling season), particularly in warm climates, in the afternoon and evening hours when residential HVAC use is highest across all homes, a greater duty cycle equates to greater loads on the electric grid.

The reason for this is a greater percentage of air conditioning units that are running simultaneously. With the development of demand response programs, dynamic and time-of-use pricing, introduced to reduce load on the electric grid during peak use times [11], it is crucial to understand existing runtime fractions of homes. This will enable better prediction of the effects these programs will have on peak electricity demand and better forecasting of energy demand and use trends.

**Impact of runtime fraction on the indoor environment:** Regarding the indoor environment, the HVAC system operation directly influences building indoor temperatures, relative humidity (RH), ventilation and recirculation rates, air speeds, and building pressure relative to the outdoor environment. Without heating and cooling, the indoor unit central fan may also provide whole-home air recirculation or ventilation. Air recirculation facilitates air movement and mixing. Most all-air residential HVAC systems only recirculate the indoor air (no fresh air is added), and ideally the return air volume (m$^3$/s) is equal to the supply air volume. In this case the HVAC system does not change the indoor-to-outdoor pressure. However, even small differences in supply and return air flow rates caused by leaks in supply or return ducts cause that pressure are positively or negatively pressurized affecting the ventilation rate by infiltration. Thus frequency and duration of HVAC system operation may also have a significant impact on ventilation rates in buildings. In newer homes with a tighter building envelope, a forced ventilation system may be installed which provides additional fresh air indoors by adhering to a minimum ventilation rate, as discussed in ASHRAE Standard 62.2 [12]. This is accomplished either through the use of an exhaust ventilation system which depressurizes a home by pushing indoor air outdoors through a vent, or a supply ventilation system which pressurizes a home through the intake of fresh air into the home. Often these ventilation systems are tied to the operation of the main HVAC system and the intensity of this mechanical ventilation depends on the frequency and duration of HVAC system operation.

Air movement, pressure, temperature and RH resulting from HVAC operation also have implications in particulate matter concentrations and indoor chemistry. This includes devices in a home to aid in the removal of pollutants, such as filters installed in the HVAC indoor unit that remove pollutants from the indoor air such as particles and ozone [13–16]. Their effectiveness in removing pollutants depends on the air flow rate, and how much air is flowing through these filters. HVAC operation also affects indoor air flow rates and mixing conditions, which can result in changes in deposition of indoor surfaces [17–19] and occupants [20,21], and the formation of secondary pollutants [22,23]. Passive removal materials (PRMs) [24–27] and stand-alone air filter effectiveness [23] are also affected by air speed and indoor air mixing from HVAC operation schedules. Indoor concentrations of particulate matter, ozone, secondary organic aerosols and other byproducts have been linked to human health, as discussed in [28–30], thus additional study and analysis on HVAC runtime characteristics is needed to realistically evaluate the dynamics of pollutant concentration and human exposure.

Considering the efforts to improve energy efficiency and reduce peak power consumption, while providing indoor environmental control, researchers use runtime fraction information for various analyses. However, there is very limited information available on runtime characteristics of central all-air HVAC systems. Previous studies that have required HVAC runtime fractions for assessment of indoor pollutant level and human exposure, have assumed or estimated these values, or used energy modeling to determine them [27,31–34]. Several small-scale studies have also been conducted on residential buildings to determine runtime fractions. Previous field studies include the study of 37 homes in North Carolina, 17 homes in Florida, and 17 homes and light commercial buildings in Texas [35–38]. These previous studies have collected data on runtime fractions of a small number of homes, and most for a time period of less than a year. There are also no known studies to date that provide runtime characteristics of multi-family housing. As discussed by El Orch et al. [39] additional information is needed to better characterize runtime fractions in residential buildings. This is particularly important for the hot and humid climate zone which has the greatest percent use of this type of HVAC system in residential buildings.

This research aims to identify annual, monthly, daily and hourly seasonal operation trends from data analysis of HVAC energy monitoring data from 189 homes in a hot and humid, cooling-dominated climate. This includes determining the air conditioning and heating runtime fractions of conditioned residential buildings, including single family and multi-family homes with heat pumps and with air conditioners/gas-fired furnaces. The results are divided into sections by time interval frequency including annual, monthly and seasonally hourly runtime data. A second section covers runtime fractions of indoor fan-only operation. The third section identifies trends in HVAC runtime fractions as a function of outdoor temperature to extend the use of this data beyond the hot and humid climate where this study was conducted. This work highlights the importance of the time-varying and outdoor temperature-varying runtime fractions and the implications this has on the indoor environment.

### 2. Methodology

The operation of the air conditioning and heating systems was monitored for 189 households in Austin, TX between September 2013 and August 2014. Of the monitored homes, 161 are single family homes, and 28 are multi-family apartments. In all cases the homes utilized a centralized HVAC system, including an outdoor condenser/compressor unit, and an indoor air handling unit. The HVAC is controlled by a thermostat which can be set to heating or cooling mode by the occupant. The results of a survey of a portion of the participating households ($n = 128$) describe the general characteristics of the single family homes (Table 1). Average data for the participating multi-family home properties is also provided in Table 1. The majority of the single family homes studied (86%) are heated using gas heat, while all multi-family homes utilize heat pumps, with the on major differentiating factor between heat pumps and air conditioning/gas heat being the type of heat used. The age of the HVAC system is known for only a limited number of homes ($n = 12$). However, assuming a new HVAC system was installed and has not yet been replaced in homes with known dates of construction built in the last 10 years, the average age of these HVAC systems is 6.9 years. The average indoor cooling and heating set point temperatures of the single family homes have a standard deviation of 1.8°C and 1.7°C respectively across the reporting homes ($n = 103$), with the average maximum setback of 1.8°C higher and 2.0°C lower, respectively, 28% and 29%, respectively, reported a constant set point temperatures in the cooling (summer) and heating (winter) seasons. Indoor set point temperatures were not available for the studied multi-family homes.

Twenty-two of the homes utilize timed whole-home ventilation systems, all of which are single family homes. All homes studied pay for their utility bills. The electricity and gas utilities utilize a tiered rate structure that increase in price by total cumulative use
per month, but rates do not vary by time of day or week. The single family homes are newer properties on average, as compared to the multi-family homes, and are more than twice as large in area. Despite a large home size, however, the number of occupants in the single family and multi-family homes is similar. For the surveyed homes, the average number of weekdays that someone is home during work day hours is 3.22 days.

A home energy management system (HEMS) was used to collect energy consumption data in each household including whole-home electricity (kWh) and individual circuit electricity (kWh) at 1-min intervals. The HEMS data was found to provide good agreement with utility meter data; more details on the data collection methodology are discussed in [40,41]. Following the methodology in [41], the data was quality controlled to remove spikes and to check for missing data. All of the 189 homes contained 90% or more of the data available over the studied 1-year time period. HVAC energy use data collection began for some homes as early as January 2012; thus, missing data was filled using the same day and time from a previous year, following the same methodology of other researchers utilizing energy data (e.g. [42]).

Two types of central HVAC systems are used in the studied homes, distinguished by the heating energy source: including (1) heat pumps and (2) air conditioning with gas furnace heating. This is important to note because type of HVAC system in use determines the methodology used to determine the runtime fraction. The type of HVAC system heat source, however, should not affect the resulting runtime fraction.

The energy data from two circuits, including the indoor air handling unit and the outdoor condenser/compressor unit, were used to determine the HVAC operational characteristics discussed in this paper. In homes with heat pump units, both the indoor and outdoor units are in use together throughout the year, in both the heating and cooling modes (Fig. 1a). For homes utilizing a gas furnace, both the indoor and outdoor units are in use in cooling mode, but only the indoor unit is used in heating mode (Fig. 1b) since the gas furnace is used as the heat source and does not create an electricity signal. This distinction in energy signal distinguishes the two system types. As a part of the occupant survey, occupants also reported their type of HVAC system. For quality control, this data-driven determination of HVAC system type confirmed with the occupant-reported HVAC system type.

To determine the runtime fraction for each home, the energy signal (illustrated in Fig. 1) must be divided to determine when the HVAC system is ON and when it is OFF. A threshold value of 0.05 kW is used, where above 0.05 kW indicates the system is ON, and below is OFF. Since both indoor and outdoor units often draw a small amount of power while “OFF” and not in use, the threshold value must be above zero. A parametric analysis of the effect of the threshold value found that a threshold value between 0.04 and 0.05 kW had the least effect on the runtime fraction values across all homes, including 0.2% change in the median, and 2% for the mean.

To determine when a system is ON or OFF, two energy signals were utilized for each HVAC system, including the indoor and outdoor units. For the heat pump systems, the outdoor unit signal is utilized to define when the HVAC system is ON or OFF. The indoor system may also be used, however, the difference between the power draw (kW) when the HVAC system is OFF and ON is approximately four times higher for the outdoor unit (2 kW) than the indoor unit (0.5 kW) showing a more clear distinction between the ON and OFF system states using the outdoor unit. For the gas furnace systems, since the outdoor unit is not the source of heat in the heating season, the indoor unit data is used. The outdoor unit signal was used for cooling season months (March–November) where the average monthly temperature was above 18.3 °C (65 °F). The indoor

<table>
<thead>
<tr>
<th>Type of home</th>
<th>HVAC system</th>
<th>Mechanical ventilation</th>
<th>Heating</th>
<th>Cooling</th>
<th>Home age (years)</th>
<th>Area (m²)</th>
<th>Ceiling height (m)</th>
<th>Occupants (#)</th>
<th>Cooling set point (°C)</th>
<th>Heating set point (°C)</th>
<th>Week-days at home</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single family</td>
<td>Furnace</td>
<td>Yes (n = 103)</td>
<td>Gas</td>
<td>Electric</td>
<td>8</td>
<td>197</td>
<td>3</td>
<td>2.6</td>
<td>25.2</td>
<td>20.0</td>
<td>3.22</td>
</tr>
<tr>
<td>(n = 161)</td>
<td>Heat pump</td>
<td>No (n = 136)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multi-facily</td>
<td>Heat pump</td>
<td>No (n = 28)</td>
<td>Electric</td>
<td>Electric</td>
<td>37</td>
<td>78</td>
<td>2.7</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Data from results of online survey of the participating household residents in 2013.
* Data provided by the apartment complex management.

![Fig. 1](image_url) Energy signal for a residential building HVAC system, including the indoor air handling unit, and outdoor condenser/compressor unit. (a) Indoor and outdoor unit ON at the same time, indicating, in winter (heating season), the system is a heat pump; in summer, both heat pump, and air conditioner/gas-furnace units show this same signal. (b) Indoor unit is ON and outdoor unit is OFF, indicating, in winter, the system is using a non-electric source of heat (gas furnace); in summer (cooling season) and transition months, indicating the indoor unit only is ON.
unit was used for the heating season (December–February), where the average monthly temperatures was below 18.3 °C (65 °F).

For systems that utilize both electric heating and cooling, including heat pumps, when the indoor unit is ON (>0.05 kW) and the outdoor unit is OFF (<0.05 kW), this indicates the use of the indoor fan without heating or air conditioning. This method is also used to identify indoor fan-only operation in the summer (cooling) season in homes with gas heating systems.

The annual, monthly and hourly runtime fraction are calculated using all available data from the 189 homes, and are the sum of all times where a system is ON over each time interval. Both mean and median values are reported, as well as standard deviation, where the distributions are normally distributed. Cumulative energy use (kWh) information on the indoor and outdoor units was also collected. Outdoor temperature data for Austin, TX was obtained from the National Climatic Data Center, US Climate Data Network quality controlled data sets [43]. The monthly, daily and hourly temperatures used represent the average temperature for the given time period and are computed as the average of the high and low temperature for the given time period.

3. Results

The results are divided into three sections including, yearly, monthly, and hourly runtime fractions, as well as runtime fraction compared to outdoor temperature. These results are further subdivided by type of HVAC system, and by whether the home is a single family home or a multi-family home.

3.1. Annual runtime fractions

The mean annual runtime fraction of all systems, including both heat pump and gas furnace systems, and all homes, including single-family and multi-family houses is approximately 20% (12 min/h), with a standard deviation of 2.8–4.1% (1.7–2.5 min/h) depending on the home and system type. Table 2 shows the mean, median and standard deviation of the annual runtime fraction (%). The studied multi-family homes have a 2.5% lower average annual runtime fraction with a 1.3% larger standard deviation than single family homes. Heat pump and gas-furnace homes have a minimal difference of 0.2% in annual average runtime fraction. The median annual values for runtime fractions are lower than the mean values in all cases, ranging from 14.1 to 16.4% of time. Fig. 2 shows a histogram of all homes annual runtime fraction, which peaks in frequency between 15 and 20%.

3.2. Monthly/daily heating and air conditioning runtime fractions

Runtime fractions were determined for each month monitored from September 2013 to August 2014. Fig. 3 shows the mean values for the runtime fractions (center horizontal line of the box plot) for single family (a) and multi-family (b) homes, as well as for homes with the heat pump (c) and gas furnace (d) systems. The upper and lower ends of the box plots represent the 25% and 75% percentile of homes, and the vertical dotted lines show 2.7 times the standard deviation (99.3% of data).

Table 2
Annual runtime fractions (%) of subsets of 189 homes in Austin, TX.

<table>
<thead>
<tr>
<th>Type (# of homes)</th>
<th>Mean</th>
<th>Median</th>
<th>Std. Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single family (n=161)</td>
<td>21.0</td>
<td>14.1</td>
<td>2.4</td>
</tr>
<tr>
<td>Multi-family (n=28)</td>
<td>21.3</td>
<td>16.4</td>
<td>3.1</td>
</tr>
<tr>
<td>Heat pump (n=50)</td>
<td>18.5</td>
<td>15.2</td>
<td>4.1</td>
</tr>
<tr>
<td>Gas-fired furnace (n=139)</td>
<td>21.1</td>
<td>14.5</td>
<td>2.8</td>
</tr>
</tbody>
</table>

The four subsets of data have similar runtime fraction patterns. Monthly runtime fractions are highest during the months of the peak of the cooling (summer) season, in all cases. Mean monthly runtime values range from 33.9 to 39.5% and median, from 35.4 to 41.1% in August. In addition the peak summer season also has the greatest variation in runtime fraction among the studied homes. The heating (winter) season represents the second highest runtime fractions of the four seasons, with runtimes peaking in December–February. Mean monthly runtime values range from 6.8 to 17.4% and median, from 9.6 to 19.6% in January. The multi-family units show the lowest heating runtime fraction of the four subsets of data.

The lowest runtime fractions of the HVAC systems are in the spring and fall seasons, which is the transition between the heating and cooling seasons. During this time, unlike the cooling and heating seasons, the outdoor temperatures are often within the thermal comfort zone of occupants. Of these months, including March–May and October–November, the monthly runtime fractions are lowest in March and November, ranging from 6.6 to 9.8% mean, and 8.4 to 10.7% median. These transitions periods in the seasons also have the least variation in value among the homes studied.

3.3. Hourly heating and air conditioning runtime fractions

Average hourly runtime fractions (Fig. 4) were computed for all homes following the same methodology. The months of January, August, and March are used to show the heating, cooling, and transition seasons respectively. During the peak cooling season the hourly runtime fraction is on average the lowest at 9:00 am (21%), and highest at 7:00 pm (46%). During the peak heating season, the runtime fraction is greatest in the early morning at 7:00 am (25%), and lowest at 4 pm (14%). The transition season (March) is similar in shape to the heating season, but lower in value (10–16%). Hourly runtime fractions vary significantly across all homes. The average standard deviation for the heating, cooling, and transition seasons are 31%, 37% and 28% respectively. Since an hour time increment is shorter than daily or monthly intervals of study, the chances that the HVAC runs nearly 100% or 0% of the time are higher.

3.4. Indoor fan-only operation runtime

Of the 189 homes studied, 22 showed indoor fan-only operation, all of which are single family homes. Fig. 5 shows the runtime fractions for the studied homes with indoor fan-only ventilation.

Fig. 3. Monthly runtime fractions (%) of residential HVAC systems, including, (a) single family homes, (b) multi-family homes, (c) homes with heat pumps, and (d) homes with gas-fired furnaces. Note: Month 1 corresponds to January, and Month 12 to December.

Fig. 4. Average hourly runtime fractions (%) for January (heating season), August (cooling season), and March (transition season) across all homes studied (n = 189).

for the summer months, and those without it for all months of the year. Only the summer months are shown for the indoor fan-only ventilation homes since only three of the 22 homes utilized heat pumps, and thus for a large majority of these homes, the winter (heating season) runtimes of the indoor unit for ventilation and for heat cannot be distinguished using the electricity signal only.

On average, the median runtime value is 3.1% of the time (1.9 min/h) for homes with indoor fan-only ventilation. For homes that do not show this pattern, the median value for runtime averaged just under 1.0% (0.6 min/h). Mean values are 8.4% (5.4 min/h), and 2.3% (1.4 min/h) respectively. In both cases, the runtime fraction of when only the indoor unit is ON is consistent across all months studied. The nearly three times larger indoor fan-only runtime fraction in homes with timed fan–only ventilation is expected since these homes should be running the indoor fan regularly per ASHRAE 62.2 guidelines [12].
3.5. **Relationship to outdoor temperature**

Monthly and daily outdoor temperatures (°C) are compared to the runtime fraction (%) of the monitored home's HVAC systems (Fig. 6). The minimum daily and monthly HVAC runtime fractions occur when the monthly and daily outdoor temperatures are 14–15 °C (57–59 °F), and are 12% and 8% on average, respectively. The highest runtime fractions occur at the extreme high and low monthly and daily average outdoor temperatures. At outdoor temperatures of 30 °C, the average monthly and daily runtime fractions are 46% and 45% respectively.

A third-order polynomial function is fit to the monthly and daily runtime fractions, showing the relationship of runtime fractions to outdoor temperature. This is determined since year-to-year daily and monthly outdoor temperatures vary, both within the same location and climate zone, and when considering other climate zones. Understanding this relationship between the outdoor temperature and runtime fraction allows for consideration in applying these results to other climate zones with overlapping temperature ranges. This polynomial function is applicable between the ranges of the temperatures observed when developing the curve (−5 to 30 °C for daily averages, and 5–29 °C for monthly averages). Table 3 shows the coefficients of the polynomial function $P$, where $p_0$ to $p_3$ are coefficients of the polynomial function in Eq. (1). The $R^2$ value listed in Table 3 indicates the high variability of the runtime fractions across homes.

\[ y(t) = p_0 + p_1 t + p_2 t^2 + p_3 t^3 \quad (1) \]

### Table 3

<table>
<thead>
<tr>
<th></th>
<th>$p_3$</th>
<th>$p_2$</th>
<th>$p_1$</th>
<th>$p_0$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monthly</td>
<td>−7.5e−6</td>
<td>1.9e−3</td>
<td>−0.052</td>
<td>0.49</td>
<td>0.32</td>
</tr>
<tr>
<td>Daily</td>
<td>1.1e−5</td>
<td>8.0e−4</td>
<td>−0.029</td>
<td>0.30</td>
<td>0.31</td>
</tr>
</tbody>
</table>

3.6. **HVAC and whole-home energy use**

The HVAC energy use (kWh) and whole-home energy use (kWh) are compared to the monthly, daily and annual runtime fractions (Fig. 7). HVAC energy use has a stronger correlation to the annual, monthly and daily runtime fractions than the whole-home energy use. Monthly energy use also has a stronger correlation to runtime fraction than does annual and daily values.

4. **Discussion**

Historically due to lack of detailed, longer-term datasets, most models, particularly those utilized for indoor environmental research, have assumed a single value for the runtime fraction for an entire year. Previous work's assumed annual runtime fractions range from 16.7% [31,36] to 25% [27,44]. Small scale studies of runtime fractions have found duty cycles between 9 and 34% [35,39]. The study previously conducted in Austin, TX found a median runtime of 20.6% [37]. This study finds a median runtime fraction of 14.1–16.4%, and an average runtime fraction of 18.5–21.1%.

4.1. **Comparison to previous studies**

The annual runtime fraction found in this study is lower than the previous study in Austin, TX, and within the range of assumed
values and findings of previous literature. There are many possible reasons for these differences. The current study utilizes measurements from a larger number of homes over a continuous, uninterrupted period of time, rather than intermittent or shorter periods of time [35,37,39], thus it is not necessarily expected that the annual runtime values would equate to those found in the previous studies. Compared to the previous study in Austin, TX [37], this study utilizes data collected over a year-long period (8760 h), rather than 100–212 h for the cooling period only. The predicted runtime fraction (Eq. (1), Table 3) for daily and monthly runtime at the same average outdoor temperature as the previous study (27.9 °C) is approximately 35% for the current study, which is higher than

Fig. 7. HVAC (left column) and whole-home (right column) energy use (kWh) compared to the annual, monthly and daily runtime fractions of the studied homes.
what was found in Stephens et al. [37]. Stephens et al. [37] also included light commercial, non-residential buildings, which have different HVAC demands, while the current study does not. Previous studies have also concentrated on single family homes, or single family and light commercial buildings, rather than multifamily and single family homes. The single family homes studied have a higher runtime fraction as compared to the multi-family homes but not as high as those in previous studies.

4.2. Influencing factors on runtime fraction

The observed runtime fractions show significant variation. Regression analysis was conducted on the annual runtime fraction of single family homes to determine the significance of the effect of influencing factors where data was available (n = 103). These include building age, estimated building volume, number of occupants, type of HVAC system, and average cooling and heating set point temperatures, and were found to explain some of the variation in the annual runtime fraction data ($R^2 = 0.33$). Combined with annual HVAC energy use values (kWh), the coefficient of determination is nearly doubled ($R^2 = 0.64$). There are many possible additional influencing factors. Discussion on the influence of these factors and the results of the regression analysis are discussed as follows.

Temperature and climatic conditions: Perhaps the most logical influence on the overall runtime fraction and runtime fraction temporal patterns is the outdoor climatic conditions. Since the purpose of an HVAC system is to maintain desired indoor climatic conditions despite changes in the outdoor conditions, when the difference in indoor and outdoor temperature increases, the runtime fraction should also increase since the HVAC must work longer to heat or cool the interior space. This pattern is observed in Fig. 6, when compared to both daily and monthly average outdoor temperatures, with considerable variation among the homes studied, which may be due to a variety of influences discussed in this section.

The lowest runtime fractions occur at approximately 15 °C. When the outdoor temperature is close to the desired indoor set point temperature, the HVAC runtime should be low since the difference in indoor and outdoor temperatures are low. As observed in Fig. 3, low runtime fractions occur during the spring and fall seasons (transition seasons). During transition months, when outdoor conditions are closer to the thermal comfort zone conditions, as defined by ASHRAE 55, the HVAC is needed less to maintain a desired indoor temperature. Building occupants may also open windows or doors rather than use the HVAC. 15 °C is lower than the thermal comfort zone range of temperatures for conditioned spaces of approximately 21 °C and 28 °C operative temperature (average of air temperature and mean radiant temperature). However the interior temperature of the home is likely different than the exterior. According to the adaptive thermal comfort model used for naturally ventilated spaces, at an outdoor monthly temperature of 15 °C, and acceptable indoor operative temperature is between 20 and 25 °C.

Building age: The age of the homes studied may affect the runtime fraction. According to data from the U.S. Residential Energy Consumption Survey [3], the average energy use (kWh/year) of residential air conditioning and heating systems decreases, the older the age of the home, meaning either the power draw (kW) or runtime fraction (%) of the HVAC system decreases. Stephens et al. [37] found that runtime fraction increased with the increasing age of the home. Because only shorter periods of time during the cooling season were used, it [37] did not capture the annual behavior of the system. However, it is expected this trend would be similar for the heating season. Comparing the annual runtime fraction (%) to the age of the homes in this study for those homes with available information, the runtime fraction decreases slightly with the increasing age of the home. However a strong correlation between the age and annual runtime fraction ($R^2 = 0.05$) was not observed, and regression analysis indicated this factor was not statistically significant ($p > 0.05$). The age of a home does not capture any energy efficiency retrofits or other modifications to a home that may have been performed that may affect runtime fraction, thus this may explain part of the lack of strong correlation between home age and runtime fraction.

Air exchange rate: The air exchange rate (ACH) of the studied homes can also affect the operation of the HVAC system. A higher air exchange rate means more unconditioned air infiltrates into the home through the building envelope, including the walls, floors, and ceilings, while conditioned or heated interior air escapes through the envelope or ductwork. In the summer (cooling) and winter (heating) months, with additional unconditioned air to heat or cool to maintain the desired indoor set point temperature, the HVAC systems needs to be ON for a longer period of time to make up for the lost heating or cooling load from the unconditioned infiltration. A more leaky construction with more unconditioned air can also mean higher humidity inside a home, particularly in humid climates. While humidity will not affect the behavior of the thermostat and HVAC runtime directly, it may make occupants more uncomfortable at higher temperatures. This may cause them to turn down the thermostat, causing the HVAC to run longer. During the transition months in which outdoor temperature is within the thermal comfort zone the increased ACH may become beneficial. For example, with suitable ambient condition, the HVAC system will be off and occupants may open the windows to allow for natural ventilation. In this case, the ACH would have a small effect on HVAC use.

Previous studies of over 70,000 U.S. homes have found that the age of a home is a significant predictor of the air exchange rate (ACH) of a home [45], with older homes having a higher ACH, or more “leaky” construction, and newer homes having a lower ACH, or “tighter” construction. However, as discussed, older homes may also be retrofitted to reduce the ACH of the home using weatherization techniques. Without testing for the ACH in each of the studied homes, a definitive answer of the ACH cannot be provided, however, as shown in Thornburg et al. [38], ACH and runtime fraction do have a positive but weak ($R^2 = 0.35$) correlation. A similar trend may occur in the homes in this study.

Building envelope characteristics: The thermal performance of the building envelope of a residential building can also be an important influence. Newer homes are built with greater amounts of insulation than older homes. Less insulation allows more heat exchange to occur between the exterior and interior of the home, thus with a less insulation, the HVAC system must be on longer to maintain the desired set point. As applicable building codes have become more stringent with time in the U.S., the R-values of the walls and fenestration has improved. Retrofits, including added insulation, will reduce the heat loss from interior to exterior of the home. The insulation value of the studied homes is not definitively know, however assuming the homes were built to code this, this may also influence the runtime fraction.

The volume of the building (m$^3$) also has an influence on the runtime as a larger space requires more air to be conditioned for a desired set of indoor conditions. The regression analysis did not show a statistically significant influence estimated building volume, determined by the reported building area (m$^2$) multiplied by ceiling height (m), on the annual runtime fraction.

External wall surface exposure: The single family homes studied are, on average 8 years old, while the multi-family homes are, on average, 37 years old. However the runtime fractions are also lower for the older multi-family homes, despite likely lower R-value walls. In considering the building envelope for single family versus multi-family homes, while single family homes have all sides of the
home exposed to exterior conditions, multi-family homes have a smaller number of exterior walls, and thus a larger number of interior walls that interface with other conditioned housing units. This may explain part of the lower runtime fraction values found for the multi-family homes since the HVAC system requires less use to make up for cooling and heating losses to the exterior.

**Building thermal mass:** Building thermal mass influences how much heat is absorbed and stored in a building and can have a positive or negative effect on reducing building HVAC energy use and runtime. In hot climates with large temperature swings below and above the indoor set point, a large thermal mass can reduce HVAC use by introducing a thermal lag or time delay in the flow of heat from the exterior to the interior; when the outdoor temperatures increase over the set point temperature this allows the indoors to stay cooler longer without the need for mechanical conditioning. In cold climates in which the set point temperature inside is always warmer than outside, heat flow is always flowing from interior to exterior. In this case thermal mass will not have a significant effect. In the hot and humid climate in which this study is conducted, the thermal mass of the homes studied likely has an influence on the HVAC runtime.

**HVAC system characteristics:** Several other influences on runtime fraction include, for system characteristics, under or oversized HVAC systems [46–48], indoor evaporator fan speeds [49], and the presence of one or more faults or system inefficiencies [50,51]. An undersized system requires longer runtimes to meet the desired interior conditions since the cooling or heating capacity is lower than needed. Conversely an oversized system often results in short cycling, where the HVAC turns ON and OFF frequently, but for short periods of time. Indoor evaporator fan speeds change the amount of air flowing over the cooling coil and thus affect the sensible and latent cooling and heating capacities. The studied systems, however, utilize constant speed evaporator fans, thus this should not affect runtime fractions in the studied homes. Faults in an HVAC system, such as evaporator or condenser flow rate reductions, and low or high refrigerant charge, can cause degradation in system capacity, which requires the system to run longer to meet the same needs of a properly functioning system.

The age of the HVAC systems studied may also have an effect on the runtime fraction, particularly since such faults or inefficiencies may be more common in older systems. While the studied systems were all single-stage systems, the use of newer systems such as variable speed or multi-stage systems, or in the case of multi-family units, variable refrigerant flow (VRF) systems, would also impact runtime fraction since the rate of cooling is variable. As manufacturers use a variety of techniques to improve efficiency of residential HVAC systems, this must be considered in the use of this research.

The age and size of the studied HVAC systems were reported for only some of the systems in the studied homes and the systems were not tested for faults. However, considering most of the single family homes studied were built within the last 15 years, it is assumed that the age of the HVAC systems in these homes is the same age of the home. In the regression analysis, the age of the home was the third most influencing factor of those studied.

**Internal loads and occupant behavior:** Internal loads including occupants, plug loads, and appliances can also affect HVAC operations. Higher internal loads can increase HVAC runtime in the summer, and reduce it in the winter. The thermostat set point temperature set by the occupants, the deadband range, and location of the thermostat and return registers determines whether the thermostat tells the system to be ON or OFF. This also includes human behavior such as the opening and closing of doors and windows. The regression analysis indicated that the number of occupants had a significant influence on the annual runtime fraction of the HVAC system ($p = 0.04$). This analysis also indicated that the indoor cooling set point temperature (summer) is influential on the runtime fraction ($p = 0.05$).

### 4.3. Application for other climates

While the monthly, daily, and hourly runtime fractions will be specific to the climatic region of the studied homes, they have important implications for use in indoor environmental models, thus an effort is made in this research to allow for the extension of the use of this data for other locations. The correlation between outdoor temperature and runtime fraction is developed to also be applied for use in other climate regions with overlapping outdoor temperature ranges. Using the curves shown in Fig. 6 of runtime fraction vs outdoor temperature, this correlation of temperature vs. runtime fraction could be applied to TMY (typical meteorological year) data for a given location of study. This could be used to determine the runtime fraction of HVAC systems in buildings in other geographic locations.

### 5. Limitations and future work

It is important to note that there are many factors that affect the runtime fraction of an HVAC system, including the HVAC system characteristics, the building it services, and the climatic conditions in which the building is located. These factors introduce uncertainties into runtime fractions across homes. It is also important to note that the studied central all-air HVAC system is the most commonly used HVAC system type in the U.S., however there are other types of heating and air conditioning systems used throughout the U.S. and world beyond the studied system that are not covered in this analysis.

The runtime fraction of an HVAC system is highly dependent on the seasonal conditions, including outdoor temperature and RH. In the cooling-dominated climate of Texas, the summer season is long, and the winter season is short. Other milder climates may see lower annual runtime fractions than those found here, as the outdoor conditions that correlate with low-runtime fractions of HVAC occur more often. This is a geographic limitation of the presented dataset of homes. The correlation between temperature and runtime fraction shown in Fig. 6 also contains a higher level of uncertainty and should be noted if used to apply to other locations.

This study also includes 1 year of data. Additional data may be helpful in providing additional insights, however 1 year of data captures the full range of seasonal conditions and temperatures that are typical of the region’s weather. Additional data may provide a slightly larger range of performance by outdoor temperature, however this study provides a significantly larger dataset in terms of time of monitoring, as compared to previous studies.

The dataset also includes a limited set of homes ($n = 189$). These homes’ physical characteristics and their occupants’ characteristics are not necessarily representative of all U.S. homes or homes in other countries, but are a strong improvement from previously presented data.

As discussed, runtime fractions assumptions are typically constant values. More detailed information on HVAC operational characteristics such as this allows for a more detailed modeling based on this variable. For example, in calculations of ozone indoors, ozone is typically present in higher concentrations in the summer months. Using a constant value for runtime fraction may thus underestimate the ozone concentrations indoors since a lower value for runtime would be assumed in the summer months rather than the seasonal values. Similarly in looking at the hourly profiles of runtime fraction, a constant value for runtime would not capture the changes in runtime throughout different hours of the day.
6. Conclusions and future work

This study has conducted analysis on the characteristics of the operation of HVAC systems for 189 homes in Austin, TX for a 1 year period. The results of this study are intended to build the dataset of information on central all-air HVAC operations to aid in improving indoor air models. The following conclusions can be drawn from this work:

(a) The average annual HVAC runtime for both single family and multi-family homes is approximately 20% (12 min/h). However, while this average value is consistent with previous research, assuming a single value for annual runtime fraction is misleading, as the runtime fraction varies, on average between 7% and 40% with the seasons.

(b) The HVAC runtime fraction of the studied homes in the peak heating season and peak cooling season are approximately 1.5 and 4 times greater, respectively, than in the transition spring/fall seasons. Summer runtime fractions average 34–40% across all homes in the peak summer month, and winter runtime fractions average 7–17%, depending on the home and system type. Transition period runtime fractions range from 7 to 10%.

(c) The hourly profile of HVAC runtime fraction in the cooling and heating season are different; in the cooling season the runtime fraction is highest in the evening (7:00 pm), and lowest in the morning (9:00 am); there is a 21% runtime fraction difference between the highest and lowest hourly average across all homes. The hourly profile of HVAC runtime fraction in the heating season, however, peaks in the morning (7:00 am), is lowest in the afternoon (4:00 pm), and varies by 11% runtime fraction across all homes. The transition season runtime fractions are the most consistent across all hours of the day, averaging between 10 and 16% per hour.

(d) Monthly and daily HVAC runtime fractions are lowest where the outdoor temperatures are at approximately 15°C; the farther above and below this range the outdoor temperatures get, the greater the runtime fraction of the heating or cooling system.

(e) Indoors fan-only operation averages between 1 and 3% by month. This value is consistent across all months of the year. When comparing homes with regular timed indoor fan-only operation, the indoor fan is ON, on average 3.1% of the time, approximately three times more than those that do not.

(f) There is considerable variation in the runtime fractions of the studied homes, which is due to a variety of influencing factors. These factors must be taken into consideration when using the results of this study.

Acknowledgements

This work was supported by the National Science Foundation IGERT Grant no. DGE-0966298. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. Residential energy data and building information is provided in coordination with the Pecan Street Research Institute and Foundation Communities.

References


