Consideration of Envelope Airtightness in Modelling Commercial Building Energy Consumption

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ABSTRACT

As strategies for improving building envelope and HVAC equipment efficiencies are increasingly used to reduce building energy use, a greater percentage of energy loss will occur through building envelope leakage. Although the energy impacts of unintended infiltration on a building's energy use can be significant, current energy simulation software and design methods are generally not able to accurately account for envelope infiltration and the impacts of improved airtightness. The airflow analyses capabilities of several energy simulation software are summarized, including whether the program calculates airflow rates or considers them to be inputs. The bases of these airflow rate estimation approaches are evaluated for their physical soundness and accuracy. A new strategy to more accurately incorporate airflow calculations into energy software is also proposed, which is based on relationships between building infiltration rates calculated using detailed multizone airflow models and building characteristics, weather conditions, and building envelope airtightness.

KEYWORDS

Commercial buildings, energy, envelope airtightness, indoor air quality, infiltration

1. INTRODUCTION

Heating, ventilating, and air conditioning (HVAC) systems in buildings are designed to maintain acceptable thermal comfort and indoor air quality (IAQ). However, the operating cost of HVAC systems is often a large percentage of the total energy cost of buildings, which constitutes 40 % of the primary energy consumed in the U.S. (DOE 2010). Due to the current emphasis on reducing energy consumption and greenhouse gas emissions, the use of energy simulation software has increased to investigate different design options and their impacts on building energy use. However, current energy simulation software and design methods are generally not able to accurately account for envelope infiltration. Also, since commercial building envelopes are much leakier than typically assumed (Emmerich and Persily 2011), and this leakage results in a significant energy penalty (Emmerich et al. 2007), one design option to reduce building energy use is improving building envelope airtightness. The limited ability of energy simulation software to account for infiltration means that the impacts of improved airtightness on energy may not be fully captured.

Ng and Persily (2011) conducted a detailed comparison of the airflow capabilities within 12 of the energy simulation software tools surveyed by Crawley et al. (2005), which is summarized in Section 1.1 of this paper. As described below, multizone airflow modelling can be implemented in some of these programs but this approach is seldom used due to their actual or perceived complexity. Most energy simulation programs include empirical formulas to estimate building infiltration rates. However, those formulas were developed for low-rise, residential buildings and generally are not applicable in mechanically ventilated commercial buildings. A new strategy to more accurately incorporate calculations of infiltration rates into energy modelling of commercials buildings is proposed in Section 2. This strategy is based on relationships between the building infiltration rates calculated using multizone airflow models, building characteristics, weather conditions, and envelope airtightness values. The airflow rates calculated using detailed multizone airflow modelling are compared to the infiltration rates calculated by EnergyPlus using the proposed strategy in Section 3.

1.1. Comparing airflow capabilities of energy simulation software

Table 1 summarizes the airflow capabilities of five widely used energy simulation software reported by Glazer (2010). A "Y" in Table 1 indicates that the energy simulation software has the simulation capability listed on the left-hand side. An "O" indicates that the capability is optional, but may not be commonly employed. An "X" indicates that the capability is not available. All of the energy simulation software in Table 1 can account for constant infiltration rates that are not affected by changes in indoor and outdoor conditions. In some models, infiltration can be adjusted to reflect wind and stack effects. However, these adjustments for wind and stack effect are based on empirical equations for infiltration developed for low-rise residential buildings (ASHRAE 2005; Coblenz and Achenbach 1963; Sherman and Grimsrud 1980; Walker and Wilson 1998) and are not generally applicable to taller buildings or buildings with natural or mechanical ventilation systems. The effect of wind on external pressures, and thus on infiltration, can be calculated using the optional multizone airflow (pressure) network capability in EnergyPlus, DesignBuilder, or TRNSYS. When the multizone airflow network capability is utilized, the user has the option to input wind pressure coefficients or allow the software to generate them.

Table 1: Summary of airflow and IAQ capabilities of selected energy simulation software.

	eQuest	EnergyPlus	TRNSYS	DesignBuilder	Ecotect Analysis
Infiltration					
Constant	Y	Y	Y	Y	Y
Account for wind and stack effects	Y	Y	O	X	Y
Multizone airflow (pressure network model)	X	O	O	O	X
Wind pressure coefficients					
Input	X	O	X	O	X
Calculated by software	X	O	O	X	X

For energy simulation software that is able to simulate airflow using multizone airflow models (EnergyPlus, TRNSYS, and DesignBuilder), the capabilities are often limited and can be difficult for users to employ. The AIRFLOW NETWORK model in EnergyPlus is an earlier version of the National Institute of Standards and Technology's (NIST) multizone airflow and contaminant transport model CONTAM (Walton and Dols 2013) with restrictions such as only a single forced air system with a constant volume supply air fan. DesignBuilder implements limited capabilities of the EnergyPlus AIRFLOW NETWORK model. McDowell et al. (2003) describe a limited coupling of the multizone airflow model, CONTAM, with the transient system simulation program TRNSYS. More recently, NIST has updated the TRNSYS/CONTAM coupling to include the full multizone airflow and IAQ capabilities of CONTAM (available at http://www.bfrl.nist.gov/IAQanalysis/software/).

Gowri et al. (2009) proposed a method to account for infiltration in commercial buildings that was developed using a square medium office building and a building envelope airtightness value, such as one obtained by a pressurization test. Assuming a constant indoor-outdoor pressure difference of 4 Pa, Gowri calculated an infiltration rate to be input into EnergyPlus, using an approach that accounts for wind but not temperature effects on infiltration. In EnergyPlus, this leakage rate is then multiplied by a wind speed adjustment and a factor of 0.25 when the HVAC system is on and 1.0 when the HVAC system is off. The method proposed by Gowri is limited because it does not account for temperature effects on infiltration, which can be important, particularly in taller buildings and colder climates. It was also developed using a square building for which the wind pressure profile will be much different than for a non-square building. Overall, the method greatly simplifies the interaction of building envelope airtightness, weather, system operation and infiltration.

The ways in which infiltration are currently accounted for in energy simulations are not typically based on well-developed airflow theory relating building envelope airtightness, HVAC system operation, and weather (Walton 1989). In those few energy simulation programs where airflow can be more accurately modeled, the features are often cumbersome to employ and therefore are not widely used. A new strategy to more accurately, but relatively simply, incorporate physically-based infiltration calculations into energy software is proposed in the next section. The proposed strategy is based on relationships developed between infiltration rates calculated by multizone airflow modelling, building characteristics, system operation, weather conditions, and building envelope airtightness. The strategy is described for implementation in EnergyPlus but is applicable to a variety of energy simulation software.

2. METHODS

The equation used to calculate infiltration in EnergyPlus is:

$$\text{Infiltration} = I_{\text{design}}\,[A + B|\Delta T| + C \cdot W_s + D \cdot W_s^2] \qquad (1)$$

where I_{design} is defined by EnergyPlus as the "design infiltration rate", which is the flow through the building envelope under design conditions. Its units are $m^3/s{\bullet}m^2$. *A, B, C,* and *D* are constants, $|\Delta T|$ is the absolute indoor-outdoor temperature difference in °C, and W_s is the wind speed in m/s. Values for *A, B, C,* and *D* are recommended in the EnergyPlus user manual (DOE 2012), but these are based on empirical data for low-rise residential buildings. In the approach described in this paper, the authors used multizone airflow model infiltration data from several commercial building models to solve Equation (1) for *A, B, C,* and *D*. In this discussion, infiltration includes the outdoor air entering through unintentional building envelope leakage only. It does not include any outdoor air entering the building through mechanical ventilation systems.

2.1. Correlating infiltration to weather (finding *A, B, C,* and *D*)

The multizone airflow modeling software, CONTAM (Walton and Dols 2013), was used to simulate the airflow in seven commercial reference buildings (DOE 2011) using weather data for Chicago. The buildings were: Full Service Restaurant, Hospital, Large Office, Medium Office, Primary School, Stand Alone Retail, and Small Hotel. Details on the building models can be found in Ng et al. (2012) and Ng et al. (2013). CONTAM-calculated infiltration rates for each building were then regressed against $|\Delta T|$ and W_s using Equation (1) to determine *A, B, C,* and *D* for each of the seven buildings. It was assumed that $A = 0$ when the HVAC system was off because when $|\Delta T|$ and W_s are zero, the system-off infiltration rate should be zero. A building envelope airtightness of 5.27 cm^2/m^2 at a reference pressure of 4 Pa was used in the CONTAM building models. This leakage area value was based on consideration of airtightness data in U.S. commercial buildings (Emmerich and Persily 2005). In Equations (1) and (2), the units of I_{design} are $m^3/s{\bullet}m^2$, thus the airtightness value at 4 Pa of 5.27 cm^2/m^2 used in CONTAM was converted to an EnergyPlus building envelope leakage value of 0.00137 $m^3/s{\bullet}m^2$.

Since wind pressure is a function of the square of wind speed (Walton and Dols 2013), the CONTAM infiltration rates were also regressed against weather using Equation (2), where *C* in Equation (1) is equal to 0.

$$\text{Infiltration} = I_{design}\,[A + B|\Delta T| + D{\cdot}W_s^2] \qquad (2)$$

It was found that the calculated infiltration rates using Equation (1) and (2) were similar, thus Equation (2) was used to simplify the subsequent analyses.

Each individual building's values for *A, B,* and *D* were regressed against the building characteristics of the seven buildings, assuming $I_{design} = 0.00137$ $m^3/s{\bullet}m^2$. The characteristics considered were: building height (*H* in m), exterior surface area to volume ratio (*SV* in m^2/m^3), and net system flow (i.e., supply air minus return air minus mechanical exhaust air) normalized by exterior surface area (F_n in $m^3/s{\bullet}m^2$). The values for each of the seven buildings considered are listed in Table 2.

Table 2: Summary of building characteristics of seven simulated buildings.

	Full Service Restaurant	**Hospital**	**Large Office**	**Medium Office**	**Primary School**	**Small Hotel**	**Stand Alone Retail**
H **(m)**	4.7	23.8	50.4	12	4	11.6	6.1
SV **(m^2/m^3)**	0.17	0.11	0.09	0.18	0.34	0.23	0.24
F_n ($m^3/s{\bullet}m^2$) × 10^{-3}	-2.6	1.0	1.3	0.56	0.02	0.50	0.21

The following relationships between the constants (*A*, *B*, and *D*) in Equation (2) and the building characteristics (*H*, *SV*, and F_n) were considered:

$$A = M_A \cdot H + N_A \cdot SV + P_A \cdot F_n \quad (3)$$
$$B = M_B \cdot H + N_B \cdot SV + P_B \cdot F_n \quad (4)$$
$$D = M_D \cdot H + N_D \cdot SV + P_D \cdot F_n \quad (5)$$

where *M*, *N*, and *P* are constants, and their subscripts distinguish between *A*, *B*, and *D*. The values of *A*, *B,* and *D* were estimated for each building by regressing the system-on and system-off infiltration rates using Equation (2) for each building. Given these values and the building characteristics (*H*, *SV*, and F_n) of the seven buildings in Table 2, *M*, *N*, and *P* were estimated through regression using Equations (3) through (5). Equations (6) through (11) show the values for *M*, *N*, and *P* for system-on and system-off conditions. The idea behind the proposed approach is to use the equations to estimate values of *A*, *B*, and *D* for another building. As stated above, $A = 0$ and the net system flow is zero ($F_n = 0$) when the system is off.

$$A_{on} = 0.0001 \cdot H + 0.0933 \cdot SV + -47 \cdot F_n \quad (6)$$
$$B_{on} = 0.0002 \cdot H + 0.0245 \cdot SV + -5 \cdot F_n \quad (7)$$
$$D_{on} = 0.0008 \cdot H + 0.1312 \cdot SV + -28 \cdot F_n \quad (8)$$

$$A_{off} = 0 \quad (9)$$
$$B_{off} = 0.0002 \cdot H + 0.0430 \cdot SV \quad (10)$$
$$D_{off} = -0.00002 \cdot H + 0.2110 \cdot SV \quad (11)$$

Since Equations (6) through (11) were developed assuming an $I_{design} = 0.00137$ m^3/s•m^2, other I_{design} values, 0.000304 m^3/s•m^2 and 0.0054 m^3/s•m^2, were also simulated in CONTAM and EnergyPlus without changing the values of *A*, *B*, and *D*. This was done to assess the ability of a single set of *A*, *B*, and *D* values to predict infiltration over a range of building envelope leakage.

3. RESULTS

Using Equations (6) through (11), *A*, *B*, and *D* were calculated for each of the seven buildings as shown in Table 3 and input into EnergyPlus. Hourly infiltration results were then compared between a complete building multizone airflow model using CONTAM and the empirical formula within EnergyPlus. The mean of the CONTAM and EnergyPlus infiltration rates are listed in Table 4, along with the standard error and coefficient of determination, R^2, of the EnergyPlus infiltration rates compared with the CONTAM rates. Some R^2 values in Table 4 are negative because the relationships between infiltration, $|\Delta T|$, and W_s are not linear. The system-on and system-off standard errors and R^2 of the EnergyPlus infiltration rates listed in Table 4 indicate that CONTAM infiltration rates are predicted best for the Stand Alone Retail building. This case is shown in Figure 1, where the CONTAM vs. EnergyPlus infiltration rates fall close to a line of perfect agreement.

Table 3: Summary of *A*, *B*, and *D* of the seven simulated buildings.

	Full Service Restaurant	Hospital	Large Office	Medium Office	Primary School	Small Hotel	Stand Alone Retail
***A* on**	0.1424	-0.0349	-0.0466	-0.0082	0.0310	-0.0008	0.0137
***B* on**	0.0186	0.0014	0.0040	0.0036	0.0088	0.0050	0.0059
***D* on**	0.1004	0.0049	0.0160	0.0177	0.0468	0.0256	0.0311
***A* off**	0	NA	0	0	0	NA	0
***B* off**	0.0086	NA	0.0155	0.0106	0.0154	NA	0.0119
***D* off**	0.0427	NA	0.0175	0.0437	0.0710	NA	0.0515

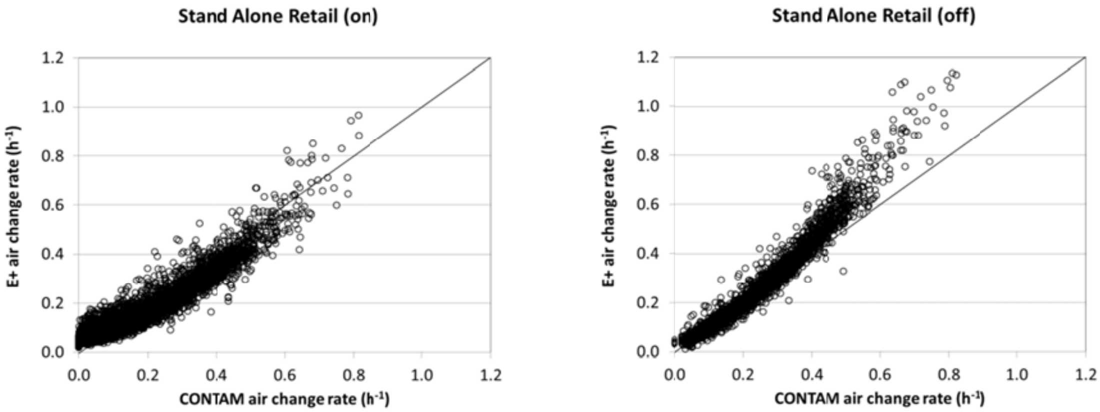
Note: The Hospital and Small Hotel HVAC systems are always scheduled to be on.

Table 4 shows that the Full Service Restaurant, with the system off, has the lowest R^2 value of the seven buildings, though its standard error relative to CONTAM is comparable with the other buildings. Figure 2(a) shows that for the Full Service Restaurant with the system on, the CONTAM and EnergyPlus infiltration rates are in good agreement. However, for the system off (Figure 2(b)), the EnergyPlus infiltration rates are lower than the CONTAM rates. This is likely a reflection of the limitation of the proposed approach or perhaps due to the presence of an attic space in this building.

Table 4: Comparison of CONTAM and EnergyPlus infiltration results.

	Restaurant	Hospital	Large Office	Medium Office	School	Hotel	Retail
System on							
CONTAM mean infiltration rate (h^{-1})	0.53	0.02	0.03	0.11	0.25	0.26	0.23
EnergyPlus mean infiltration rate (h^{-1})	0.46	0.01	0.08	0.11	0.34	0.19	0.21
Standard error of EnergyPlus rates (h^{-1}) (% of CONTAM mean)	0.09 (17)	0.02 (130)	0.02 (68)	0.04 (36)	0.07 (26)	0.06 (24)	0.05 (20)
Coefficient of determination, R^2	0.80	-0.23	-1.74	0.83	0.31	0.61	0.83
System off							
CONTAM mean infiltration rate (h^{-1})	0.50	NA	0.14	0.27	0.29	NA	0.26
EnergyPlus mean infiltration rate (h^{-1})	0.15	NA	0.13	0.23	0.44	NA	0.29
Standard error of EnergyPlus rates (h^{-1}) (% of CONTAM mean)	0.08 (15)	NA	0.02 (16)	0.06 (23)	0.15 (18)	NA	0.03 (13)
Coefficient of determination, R^2	-1.47	NA	0.81	0.57	-0.90	NA	0.78

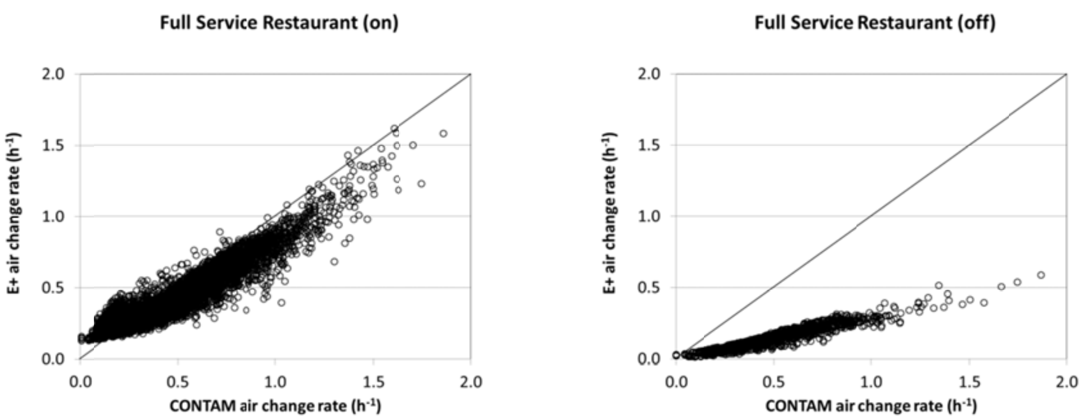
Note: The Hospital and Small Hotel HVAC systems are always scheduled to be on. The standard error of EnergyPlus rates and R^2 values were based on the regression between EnergyPlus and CONTAM results.



(a) (b)

Figure 1: EnergyPlus vs. CONTAM infiltration rates for Stand Alone Retail (a) system-on and (b) system-off

The Hospital has the largest standard error relative to CONTAM, though the mean infiltration rates are the lowest among the other buildings. Figure 3 shows that for the Hospital, the EnergyPlus infiltration rates are lower than the CONTAM rates. The Large Office, with the system on, has the lowest R^2 value of the seven buildings, and its standard error relative to CONTAM is second highest among the other buildings. In general, buildings with the lowest infiltration rates, the Hospital and two offices, also have the highest standard error in relation to the CONTAM mean rate. However, since the infiltration rates are relatively low for these three buildings, the low absolute errors are also low.



(a) (b)

Figure 2: EnergyPlus vs. CONTAM infiltration rates for Full Service Restaurant (a) system-on and (b) system-off

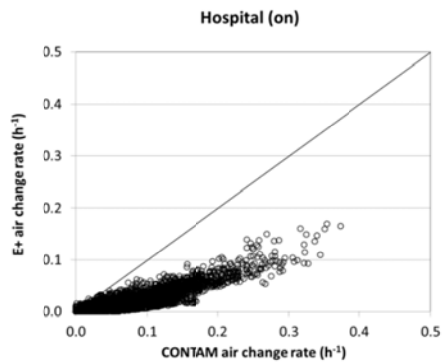
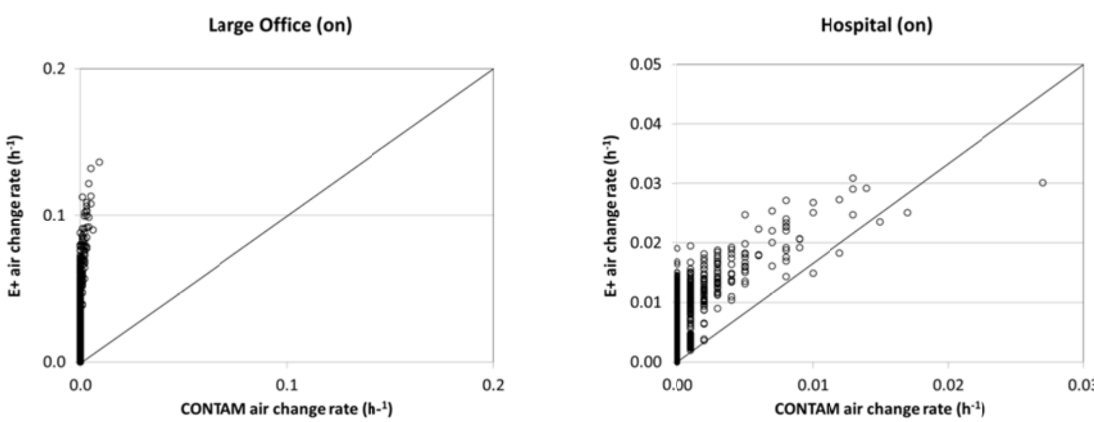


Figure 3: EnergyPlus vs. CONTAM infiltration rates for Hospital system-on

CONTAM and EnergyPlus were also used to estimate infiltration rates with I_{design} = 0.000304 $m^3/s{\bullet}m^2$ and 0.0054 $m^3/s{\bullet}m^2$, which were respectively two times lower and two times higher than the I_{design} used to develop Equations (6) through (11). For the Stand Alone Retail and Full Service Restaurant, the change in I_{design} did not affect the general trends of the EnergyPlus predictions relative to the infiltration rates predicted by CONTAM. For the Hospital, the higher I_{design} values resulted in similar results to those shown in Figure 3, for which EnergyPlus underestimated the CONTAM results. For the Hospital, the lower I_{design} value resulted in the EnergyPlus results overestimating the CONTAM results as shown in Figure 4. This was also the case for the Large Office, for the lower I_{design} value and the system on.

Thus, using a specific I_{design} to develop relationships between infiltration, weather conditions, system operation, and building characteristics generally resulted in good agreement between CONTAM and EnergyPlus in most buildings for other leakage values. The buildings for which the change in I_{design} made the largest impact were those where the system pressurization tended to overcome any infiltration due to a very tight building envelope, which in this study were the Hospital and Large Office. For these two buildings, using a lower I_{design}, EnergyPlus results overestimated the CONTAM results as shown in Figure 4.



(a) (b)

Figure 4: EnergyPlus vs. CONTAM infiltration rates for (a) Large Office system-on and (b) Hospital system-on, low I_{design} value (0.000304 $m^3/s/m^2$)

4. DISCUSSION

Though modellers can account for infiltration and improved envelope airtightness with current energy simulation software, the simplified approaches employed result in the effects of weather, system operation, and envelope leakage on infiltration being either ignored or not well accounted for. Oftentimes, zero or a constant/scheduled infiltration rate is input into energy simulation software due to lack of understanding of how to more accurately account for infiltration. Currently, infiltration equations in energy simulation software and guidance for input variables are based largely on research for low-rise, residential buildings. However, the interaction of weather, system operation, and envelope leakage in determining infiltration rates is fundamentally related to pressure, and these physics are not typically or easily modeled in current energy simulation software. Multizone airflow modelling is the correct way to calculate infiltration, however, the current means of doing so in energy simulation programs are limited and cumbersome to implement.

The proposed strategy to incorporate the effects of weather, system operation, and envelope leakage on infiltration has been shown to be in good agreement with CONTAM simulations of several buildings of different sizes, system operation, and building envelope airtightness. The proposed strategy was also tested on buildings that were not among the seven used in developing the strategy, and those results will be reported in the future.

5. FUTURE WORK

The proposed strategy for incorporating the effects of building envelope leakage, weather, and system operation on infiltration was shown to be comparable to multizone airflow calculations for most of the buildings considered. The strategy also has potential for predicting infiltration in other buildings, but additional study is needed in more buildings as well as other weather and operating conditions. In addition, further understanding and guidance on how to use the proposed strategy over a range of building envelope leakage values needs to be developed. Additional work could also involve relatively straightforward modifications to energy simulation software in order to implement the proposed strategy with better accuracy. The energy impacts of improving building envelope airtightness can then be evaluated more easily and more reliably.

6. CONCLUSIONS

Due to an increased emphasis on energy consumption and greenhouse gas emissions, the potential savings from energy efficiency measures are often analyzed using energy simulation software. However, the impact of implementing some of these measures is oftentimes incomplete because building envelope infiltration is not properly accounted for. This study summarizes the airflow analyses capabilities of widely used energy simulation software (eQuest, EnergyPlus, TRNSYS, DesignBuilder, and Ecotect Analysis). Many of the airflow models implemented in these software tools are inappropriate for large buildings or are limited in simulation capabilities. The proposed strategy, based on the relationship between building envelope airtightness, building characteristics, weather, and system operation, has been shown to be applicable in a variety of buildings and the results are comparable to performing multizone calculations.

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