INTRODUCTION

Weather normalization attempts to compare energy conservation management trends of buildings by eliminating the variety of weather conditions. The Energy performance of buildings™ directive utilizes normalization and weather correction procedures.\(^1\) The goal of weather normalization is to be able to compare the buildings™ consumptions independent from their weather zone and location. For example, it should enable us to compare the energy performance of a house in a colder climate, such as in Toronto, with a house in a warmer climate, such as in Florida, extracting the effects of weather-related factors.

Degree-Day method is the most popular approach for weather normalization. This approach utilizes the difference between a base temperature and the average daily outdoor temperature for a given period. Ratio base method is one of the easiest way of calculation and implementation of the Degree-Day method. However, it can easily lead to inaccurate, misleading results. A linear regression analysis is an improvement version...
of ratio-based normalization technique. This method correlates historical energy use data with degree-days. The analysis in ref.2 is an example of this technique for analysis of energy for residential buildings. The ENERGY STAR Portfolio Manager program uses a multiple regression as extension of the linear regression method.3 The building size, operation, and weather are the independent variables in this method. We will discuss more about this popular method in the next section.

Climate Severity Index method4 is another method of weather normalization. The method was developed to take into account temperature, solar radiation, and wind speed. Although the method uses an index related to the building energy consumption for different region, the accuracy and reliability of climate severity index method are questionable. In addition, this method requires building auditing to obtain many parameters, and was proposed for cold climates only. Another weather normalization method is Modified Utilization Factor method, which uses a ratio of the maximum demand to the rated capacity of a power plant. This is a complicated calculation when normalizing space cooling. Lack of a central set-point temperature is a limitation of the Modified Utilization Factor method.5,6 Simulation-based Weather Normalization method7 incorporates building modeling in its weather normalization formula. Nevertheless, detailed information of the building is required in this modeling that in real applications is not available. However, their level of success varies in different climate zones, and the temperature is the only weather factor which is considered. In ref.8 an analytical method is presented for weather-normalization and used to evaluate the normalized energy consumption in several office buildings.

Motivated by various shortcomings of the existing weather normalization methods, we have proposed a new weather normalization method in this paper. Other than temperature, we take into account other weather factors such as wind speed, humidity, and solar radiation. In addition, we include the building parameters’ dependent factors in the proposed method. We considered all of these parameters with proposed linear and nonlinear models for building energy consumption; consequently, a novel criterion based on that modeling is proposed for weather normalization, denoted by “Structure Dependent Weather Normalization.”

Several methods have studied the problem of load and energy forecasting by using regression analysis and neural network.9-11 A model to predict heat demand based on temperature and historical data of natural gas consumption is developed in ref.12 This model predicts the expected heat demand 1 day in advance. In ref.13 machine learning techniques are used to model electricity and natural gas consumption for every property in New York City using the physical, spatial, and energy use attributes of a subset derived from 23 000 buildings. The proposed method learns and models the behavior of a building in energy usage habits and energy loss. Consequently, a novel Structure Dependent model is proposed for long- and short-term load and energy forecasting. The main differences between our models and the above works are: (a) almost all of above works only consider temperature as the only weather parameter in modeling, but our work not only considers weather temperature but also considers wind speed, humidity and solar radiation in the model, and (b) other important factors in weather normalization are building parameters such as building size, window size, construction joints, and the effect of flues that are ignored in the existing approaches and are considered in our proposed method.

In the linear model, we use a Multiple Linear Regression that is linear with the unknown parameters used for energy consumption calculation. The most common form of linear regression is the Least Squares Fitting, which provides a solution to the problem of finding the best fitting straight line through a set of points. Multiple linear regression models the relationship between weather parameters and energy reading meter by fitting a linear equation to energy reading values. The building-based parameters are effects or regression coefficients. The statistical estimation and inference in the multiple linear regression focus on the building-based parameters. These parameters are interpreted as the partial derivatives of the dependent variable with respect to the various independent variables. In the nonlinear case, we use Nonlinear Multiple Regression (NMR). This model is implemented based on the neural network. Multilayer perceptron feed-forward fully connected neural network with a sigmoid activation function that is used to model the behavior of a buildings’ energy usage.

The paper is organized in the following manner. In Section 2, the concept of weather normalization is presented by reviewing the Degree-day method, and consequently our motivation is elaborated. In Section 3, our new energy consumption model denoted by “Structure Dependent Energy Usage/Loss” is formulated and modeled, and in Section 4, Structure Dependent Weather Normalization as a new method for normalization is provided. The results and simulations are in Section 5, and the paper is concludes in Section 6.

2 | WEATHER NORMALIZATION AND OUR MOTIVATION

Degree-Day method is the most popular approach for weather normalization, due to its simplicity, fast calculation and implementation, and since it does not require any pre-energy auditing. In this section, we briefly review the Degree-Day method to set the stage for analyzing the question for weather normalization.

Consider a simple scenario of comparing energy consumption of a building for two consequent years. A building has energy usage of 200 000 kWh in year 2014, and 150 000 kWh in year 2015. Weather normalization of
these energy usages requires you to take the effect of variation in temperature out of the comparison. The building uses less energy in 2015, and 2015 was warmer than 2014. If the behavior of the building in energy usage is similar in both years, we expect to have almost the same “normalized” energy consumption for the building. However, if the consumption behavior of the occupants is not the same for these 2 years, this fact should be captured by the normalized energy consumption regardless of the weather effect.

2.1 Degree-Day method

Here we briefly discuss the Degree-Day method and the plan that attempt to answer to the above question. Heating degree days (HDD), and cooling degree days (CDD) are defined as two main types of degree day as follows:

\[
\text{HDD} = T_{\text{Base}} - T_{\text{out}} \\
\text{HDD} = 0 \quad \text{if} \quad T_{\text{out}} > T_{\text{Base}}
\]

\[
\text{CDD} = T_{\text{out}} - T_{\text{Base}} \\
\text{CDD} = 0 \quad \text{if} \quad T_{\text{out}} < T_{\text{Base}}
\]

where \( T_{\text{Base}} \) is base temperature or set-point, and \( T_{\text{out}} \) is the outside temperature. For example: if \( T_{\text{Base}} = 18^\circ \text{C} \), and \( T_{\text{out}} = 15^\circ \text{C} \) for 10 days, HDD would be 30 heating degree days over that period (3 degrees * 10 days = 30 degree days), and over that period CDD = 0.

The following equation shows the basic form of Degree-Day weather normalization (Ratio-Base):

\[
\text{EUI}^{\text{Normalized}} = \frac{\text{EUI}_{\text{ReadingMeter}}}{\text{HDD} + \text{CDD}} \times (\text{HDD} + \text{CDD})_{\text{average-year}}.
\]

**FIGURE 1** Inaccuracy in weather normalization of electrical and natural gas consumption for Building B
where \((HDD + CDD)_{\text{average-year}}\) is the “average year” degree-day value over couple of years for each month and season, and \(\text{EUI}_{\text{ReadingMeter}}\) is reading meter of energy usage intensity. The time periods for normalization, energy usage reading and degree-days \((HDD\) and \(CDD)\) are the same and can be 1 day, 1 month, 1 year, and so on.

Going back to our example, the calculated degree-days for 2014 is 2000 degree days, for 2015 is 1000 heating and cooling degree days, and the average value for 10 years is 2000 heating and cooling degree days. The normalized energy consumption for 2014 is 200 000 kWh and for 2015 is 300 000 kWh. The normalized value above concludes that energy efficiency was actually worse in 2015 than in 2014.

### 2.2 Drawbacks of available weather normalization methods

Rewriting equation (3), we have \(\text{EUI}_{\text{ReadingMeter}} \times (HDD + CDD)_{\text{average-year}} = \text{EUI}_{\text{Normalized}} \times (HDD + CDD)\) which considers that the weather-independent consumption of the building is linearly proportional to the meter reading. This assumption needs verification and in general is not true.

**FIGURE 2** Climate parameters for building A in Fiscal Year 2013-2014. Temperature, Wind Speed, Relative Humidity, Solar Radiation

**FIGURE 3** Buildings with different weather conditions and parameters
(we will show a more precise relationship between these two numbers in this paper). Secondly, even if we linearly link these two numbers, it is not clear why the coefficient has to be degree days. Note that these numbers only show the effect of temperature, ignoring the other weather factors, such as wind speed, humidity, and solar radiation which have become something we need to consider due to the world climate’s change issues. Lastly, although having the average behavior of the temperature as a normalization factor represents the average behavior of location, it is not clear why it should be used in normalization as a simple proportional gain. Figure 1 shows the Degree-Day method (Ratio Base) result for building B.1 The building consumes both electricity and gas. In this building the heating system uses gas while the cooling system uses electricity. As the figures show the normalized values of gas and gas + electricity almost follows the reading meters while the behavior of normalized electricity is different. For electricity (the middle graph) we show the normalized version using CDD or HDD + CDD. As the figure shows the degree day method is sensitive to this prior on the fact that electricity is only used as a cooling method. In addition the normalized based on CDD only peaks at October due to the fact that the average of CDD over past 10 years is a small nonzero number while the CDD of October of 2014 itself (in denominator) is zero. In fact degree day provides infinity for this value and in graph we show it with a larger number compare to September and November. This shows sensitivity of the method to calculate temp related values. In addition note that for the cold months both average of CDD and the months CDD are zero we have no other choice but to replace this zero over zero with a zero display in the figure. And the normalized version based on HDD + CDD peaks at June due to high consumption of electrical energy for cooling system.

Note that other normalization methods have similar shortcomings. These methods ignore either weather factors or building parameters effects. On the other hand, the methods that include some of these building parameters’ require detail information of the building and preenergy auditing, and some of them require complicated computation analysis. Many factors are included in this weather normalization method that assumes a linear relationship with energy consumption without validating such assumptions.

After thorough study, our analysis indicates that in order to have a rational weather normalization criterion, we need to first model the energy consumption as a function of key related factors. In the following section, we provide our energy consumption modeling, and describe some of the key related factors.

3 | STRUCTURE DEPENDENT ENERGY USAGE/LOSS

In this section, we concentrate on energy consumption modeling of a building. We first describe some of the important energy consumption factors. Next, we formulate our model, denoted by “Structure Dependent Energy Usage/Loss SDE U/L”. Modeling that structure in linear and nonlinear settings is then provided. The forecasting ability of the proposed model is then illustrated. We use the energy consumptions for school A and B and weather data for fiscal years 2013 and 2014 in all models and calculations.

3.1 | Key factors in energy consumption modeling

Here we describe three main energy consumption factors in the modeling procedure.

3.1.1 | Weather factors

We use building A’s information to illustrate important climate parameters in weather normalization. Figure 2 shows the climate parameters for building A in 2014. The Pearson correlation coefficients of energy consumption of this building with the considered climate parameters temperature, wind speed, humidity, and solar radiation are 0.9742, 0.31, 0.42, and 0.75, respectively. The energy consumption has a high correlation with temperature, sun radiation, wind speed, and humidity, respectively. This simple yet important observation for several buildings motivated us to consider these weather factors in our energy consumption modeling.

3.1.2 | Building factors

Characteristics of the building play an important role in its energy consumption. For example, the three building shown in Figure 3 can be located next to each other with completely same weather factors. However, the shape of these buildings, window size and orientation, isolation, building size, and so on can differentiate between the energy consumption of these buildings. Considering the building parameters in energy consumption modeling should be an essential component of any accurate model.

3.1.3 | Occupant (metabolic) factors

Each individual using a building contributes in energy consumption. In addition, the habits of occupants in using the energy consuming appliances can be another factor.

3.2 | Structure dependent energy usage/loss formulation

In steady-state, the heat balance equation in a building is defined as:
\( Q_{\text{HeatLoss/Gain}} = Q_{\text{SpaceHeating/Cooling}} + Q_{\text{Appliance}} + Q_{\text{Metabolic}} + Q_{\text{Solar}}, \) \( (4) \)

where \( Q_{\text{SpaceHeating/Cooling}} \) is generated heat/cool by heating/cooling system, \( Q_{\text{Appliance}} \) is the generated heat by building appliances, \( Q_{\text{Metabolic}} \) is the heat capacity of the residence, and \( Q_{\text{Solar}} \) is sun heat energy captured by reflection and absorption.

The building Energy Usage Intensity (EUI) is defined as follows:

\[ EUI = EUI_{\text{Baseline}} + K.(Q_{\text{HeatLoss/Gain}} - Q_{\text{Metabolic}} - Q_{\text{Solar}}). \] \( (5) \)

The heat loss/gain is a function of various parameters. These parameters can be considered in a function, denoted by \( g_{bl}(\cdot) \). The subscription \( bl \) per each building models the specific building and occupancy factors.

\[ K.(Q_{\text{HeatLoss/Gain}} - Q_{\text{Metabolic}} - Q_{\text{Solar}}) = g_{bl}(T,W,R,H,P), \] \( (6) \)

where parameters \( T, W, R, \) and \( H \) directly effects weather conditions, \( T \) is temperature, \( W \) is wind speed, \( R \) is solar radiation, and \( H \) is humidity percent. Parameter \( P \) includes the occupant dependent effect on building energy consumption. For example, if additional information about buildings’ occupant is available, it can be included in the \( P \) parameter.

Including our parametric modeling (7) in energy consumption equation (6), the energy reading value is obtained as follows:

\[ EUI_{\text{ReadingMeter}} = EUI_{\text{Baseline}} + g_{bl}(T,W,R,H,P). \] \( (7) \)

### 3.3 Structure dependent energy usage/loss modeling

Before, exploring the linear and nonlinear models, we will have a brief discussion on the calculation of \( EUI_{\text{Baseline}} \). If it is possible to have the exact building consumption for a time interval that the cooling/heating system is off, and outside temperature is the set-point temperature, this is ideally providing the base load energy usage. However, in practical applications this value may not be available. Linear regression analysis is used to calculate the baseload. The regression line for energy meter reading over available historic data against degree days over a period of time is obtained, and then the baseload is the intercept of regression line as follows:

\[ EUI_{\text{Baseline}} \approx a \quad \text{where} \quad EUI_{\text{ReadingMeter}} = a + \beta \times \text{Degree Days}. \] \( (8) \)

### 3.3.1 Linear model

In linear modeling, \( SDE \ U/L \) is as follows:

\[ g_{bl}(T,W,R,H,P) = a + bT + cR + dW + eH + eP, \] \( (11) \)

where linear building coefficients \( a, b, c, d, \) and \( e \) are linearly modeled with their corresponding weather effects. While \( a \) parameter is the constant term and \( e \) is a coefficient population parameter.

\( a, b, c, \) and \( d \) are buildings structure dependent parameters.\(^4\) While parameter \( a \) represents the building mass and insulation; parameter \( b \) represents the window size and orientation, and the nature of the glass/blind materials used in the windows. Also parameter \( c \) represents gaps and cracks around windows and doors, construction joints, the effect of flues, ventilators, and other designed or fortuitous openings. It has been shown that the \( a \) parameter is directly related to temperature \( T \) while the \( b \) parameter is related to solar radiation parameter, and building parameter \( c \) is related to wind speed parameter.\(^4\) \( P \) can be as general as the number of occupants or can be detailed vector of more information of the occupants. In linear model, the optimal \( \hat{a}, \hat{b}, \hat{c}, \hat{d}, \) and \( \hat{e} \) are obtained as follows:

\[ \hat{a}, \hat{b}, \hat{c}, \hat{d}, \hat{e} = \operatorname{arg min}_{a,b,c,d,e} ||EUI_{\text{ReadingMeter}} - EUI_{\text{Min}} - g_{bl}(T,W,R,H,P)||. \] \( (12) \)

Therefore, we can rewrite the energy consumption in (10) as follows:

\[ EUI_{\text{ReadingMeter}} = EUI_{\text{Min}} + g_{bl}(T,W,R,H,P). \] \( (10) \)

The rest of this section, concentrates on modeling \( g_{bl}(\cdot) \) function. We model \( g_{bl}(\cdot) \) by using a the linear regression in the linear case, and by using neural network in the nonlinear case. Using the building’s available energy meter reading, models can learn the behavior of a building in energy usage/loss, and this can be used to forecast a building’s energy usage/loss.
3.3.2 | Nonlinear model

In the nonlinear case, \( SDE_{U/L} \) is modeled by using a neural network. Multilayer perceptron feed forward fully connected neural network with a sigmoid activation function that is used to model the behavior of a building’s in energy usage. The training is done using the back propagation algorithm with options for resilient gradient descent, and momentum back propagation. In this network, there are 5 nodes in input, 1 node in output, 2 hidden layers and 7 nodes in those hidden layers are considered. Figure 4 shows the topology of this network. Similar to the linear modeling, if any of the input elements such as \( P \) (occupants information) is not available that node is removed. The data for 5 years (weather, energy consumption, and occupant number) are feed to the network as training set, RMSE less than \( 10^{-10} \) is considered as termination of training, and learning rate would be 0.2. The activation function uses bipolar sigmoidal function.

3.3.3 | Forecasting model

Structure Dependent Energy Usage/Loss learns and models the behavior of a building’s energy usage habits and energy loss. After finding weight coefficients in the nonlinear \( SDE_{U/L} \), they can be used in the forecasting model. This function can forecast the energy consumption of building. The equation in the equation (10) is rewritten as follows:

\[
\text{EUI}_{\text{ReadingMeter}}(t+1) = \text{EUI}_{\text{ReadingMeter}}^{*} + g_b(T(t+1), W(t+1), R(t+1), H(t+1), P(t+1))
\]

where \( \text{EUI}_{\text{ReadingMeter}}(t+1) \) is EUI in month \( t + 1 \), \( \text{EUI}_{\text{ReadingMeter}}^{*} \) is average of \( \text{EUI}_{\text{Min Year}} \) in time before \( t + 1 \), and \( g_b(\cdot) \) is the function which is modeled by the nonlinear method. \( T(t+1), W(t+1), R(t+1), H(t+1), \) and \( P(t+1) \) are temperature, wind speed, sun radiation, humidity, and occupant information in month \( t + 1 \), respectively.

4 | STRUCTURE DEPENDENT WEATHER NORMALIZATION METHOD

Before presenting our normalization method, we discuss and challenge the definition of weather normalization. One of the purposes of the weather normalization approach is to compare the consumption of different buildings by extracting the weather-related effects. For example Figure 5 depicts 3 temperature-related scenarios. If 3 buildings have the same structures and consumption habits and the inside temperature of all of them is set to one number (18°C), as the figure shows different outside temperatures imposes different consumption values. While for the left building shows the minimum energy meter reading, the other two

| Variable | \( df \) | Parameter estimate | \( t \) Value | \( Pr > |t| \) | Standardized estimate | Tolerance | Variance inflation |
|----------|--------|--------------------|-------------|----------------|----------------------|-----------|-------------------|
| Intercept | 1      | 117.130            | 2.57        | 0.0153         | 0                    | 0.0       | 2.87              |
| Temp     | 1      | -4746.030          | -15.56      | <0.0001        | -0.98436             | 0.347     | 2.87              |
| Wind     | 1      | -1911.37           | -1.73       | 0.0934         | -0.076               | 0.710     | 1.40              |
| Humidity | 1      | 241.74             | 0.52        | 0.6084         | 0.0297               | 0.421     | 2.37              |
| Radiation| 1      | -371.15            | -0.17       | 0.86           | -0.0128              | 0.238     | 4.19              |

Note: In a practical scenario where no information on \( P \) is available, \( e \) has to be set to zero.
buildings will show higher energy meter readings. The weather normalization method aims to compare the energy consumption of these buildings regardless of the outside temperature. In this explained scenario, the method should provide the same normalized value for these three buildings, as the structures are identical and the behavior of the occupants has been the same. On a related case, if despite the same structure, the occupants of the building have drastically different consumption behaviors, the normalized EUI should depict this difference. In our view, the better the EUI is modeled, the more accurate normalization. For example, in linear modeling of two buildings, comparison of obtained coefficients \( \hat{a}, \hat{b}, \hat{c}, \hat{d}, \) and \( \hat{e} \) is equivalent to normalizing the consumption. To have more tangible comparison values, however, we can feed our EUI models with desired scenarios to compare the buildings. For example, if we want to compare the consumption of buildings regardless of the temperature effects, the temperature normalized consumption can be obtained using our SDE U/L models setting the temperature to the set-point.

\[
\text{EUI}_{\text{温度修正}} = \text{EUI}_{\text{Baseline}} + g_b(T = \text{set point}, W, R, H, P) \tag{14}
\]

Another scenario can be comparison of energy consumption of a building in 2 consequent years. If it is assumed that the building structure has been changed in 2 years, the above normalized value depicts different occupants’ behavior for the 2 years. The following corollary relates the existing normalization method to our proposed normalization method.

Corollary 1 The degree-day method (linear regression method)\(^2\) is a special case of our SDE U/L method for weather normalization, when \( b, c, d, \) and \( e \) are set to zero in linear SDE U/L, and \( R, W, H, \) and \( P \) are totally ignored.

\[
\text{Linear regression Method} \equiv \text{EUI}_{\text{Baseline}} + g_b(T = \text{set point}, 0, 0, 0, 0) \tag{15}
\]

\[
\equiv \alpha + \alpha T, \tag{16}
\]

where \( \alpha = \text{intercept, the nonweather-sensitive component}; \ a = \text{consumption slope, the weather-sensitive component.} \)

Note that our new view on consumption normalization can not only depict weather on a related energy consumption, but can also provide insight for improving building conditions. For example, consider two buildings that are in different climate zones, but have identical building structures and the same occupant energy consumptions. If the involved values of \( W \) and \( H \) are the same, but the \( R \) values are very different, using the \( T \) normalized value in (14) provides a higher value for the building with more solar radiation. If we want to compare the two buildings under the exact same weather conditions, we need to replace the value of \( H, \ W, \) and \( R \) with the same values for the both buildings; each value can be replaced with the average value of 2 buildings. Consequently, in our latter scenario we put the same value of \( R \) for the 2 buildings and our weather normalized EUI correctly, which will be the same value for the both buildings. However, if we compare the temperature normalization with the 2 different radiations, these will give us

**FIGURE 6** The energy consumption of building A and the estimated energy consumption using the proposed linear model.
additional insight on the effects of radiation in energy consumption on such buildings. This information can be used by building facility to employ methods for efficient use of radiation, resulting in less energy consumption. The same analysis can be done by varying the values of wind speed and humidity in the normalization procedure.
5 | SIMULATION AND RESULTS

In this section, the proposed methods for modeling (Sections 3.3.1 and 3.3.2), forecasting (13) and normalization (14) of energy consumption are simulated, evaluated and compare with Degree-Day method.

For this normalization the base temperature is set to 18°C, and energy meter reading is the summation of electric and gas energy consumption. As no additional information about occupant behavior is available, “e” coefficient for $P$ parameter in (7) is set to zero.

In the simulations two buildings have been randomly selected from the Ontario Ministry of Education’s Utility Consumption Database to illustrate advantages the proposed approach. This dataset contains 5 years (2011-2015) of energy consumption reading meter (monthly usage for electricity and gas) for both schools. The hourly weather data (2011-2015) is aggregated and join with energy data to make the training and testing dataset.

5.1 | Weather normalization results

Table 1 summarizes the linear SDE U/L model parameters for building A, and third column of this table shows the estimated values of $\alpha$, $a$, $b$, $c$, and $d$, respectively by using (12).
VIF (Variance Inflation Factor) for a model shows there is not any multicollinearity between model parameters. The available energy consumption of building A and or estimated values using the linear model (as explain in Section 3.3.1) are provided in Figure 6. As the figure shows the linear modeling provides the good estimate of the true values of energy consumption. Reading meter using nonlinear SDE U/L model (as explain in Section 3.3.2) are provided in Figure 7. As the figure shows the nonlinear modeling provides an accurate estimate of the true values of energy consumption.

Figures 8 and 9 show the normalized EUI for building A in 2 Fiscal Years (2012-13 and 2013-14) using a linear and nonlinear model, respectively. As the figures show while the Degree-Day method seems to be scale version of reading meter, our SDE U/L methods provides the much more accurate normalized version of EUI, as independent as possible to the monthly changes of weather conditions. While both linear and nonlinear SDE U/L method extract the effects of the weather, the more accurate modeling the nonlinear approach results in normalized version which depicts the occupant behavior more accurately. Also, the fact that over warmer seasons there is less of normalized energy consumption reveals the cooling system (if any) has more efficient than heating system. Reading meters and Normalized values in two Fiscal Years (2012-2013 and 2013-2014) using a linear and nonlinear SDE U/L model are shown in Figure 10. It is Note that it is known that Fiscal Years 2013-2014 was colder than Fiscal Years 2012-2013. This fact has also been reflected in average monthly reading meters these years as shown in last column set of these figures. Our results in the first and second columns set this figure shows that the population in this building has behaved almost identical from Fiscal Years 2012-2013 to Fiscal Years 2013-2014, and had a more energy efficient
behavior as time progressed. Comparison of these averaging over linear and nonlinear SDE U/L shows similar behavior of these two methods in this respect.

### 5.2 SDE U/L method robustness and efficiency

Here we revisit Building B that was introduced in example in Section 2.2. Figure 11 shows the weather normalization for this building using SDE U/L model. As the figure shows unlike degree day method, the proposed method is robust and does not produce unexplained huge values. The proposed normalized version attempts to capture the building consumption due to all elements other than the weather dependent behavior. Note that the degree day method provides different normalization results for electricity consumption of this building as it was discussed before (considering CDD or CDD + HDD). However, the proposed method can adaptively model the building behavior and it shows almost a weather independent EUI that is the result of electricity consumption of the building users for purposes other than cooling the building during warm weathers.

Energy Usage Intensity and normalized values for building A in January and February of 2013 and 2014 using the linear and nonlinear SDE U/L model and Degree-Day method are shown in Figures 12 and 13, respectively. Note that it is known that January and February of 2014 were colder than January and February of 2013 (Figure 14). This fact has also been reflected in average monthly reading meters of this month as shown in the last column set of these figures. Both methods show identical results for energy conservation in January of 2013 and 2014. The behavior of the building (such as number of occupants and number of active days) in January of each year is the same of behavior of the building in February of that year. From Figure 14 we have (a) February of 2013 is about 4°C colder than January of 2013, while February of 2014 is about 2°C warmer than January of 2014, (b) the average of wind speed in January and February of 2013 is the same, but January of 2014 is windier than February of 2014 is the same, but January of 2014 is windier than February of 2014, (c) percentage of humidity in January and February of 2013 are the same, but February of 2014 is more humid than January of 2014, and (d) the increase percent and value of solar radiation
in 2014 is more than that in 2013. As the averaging results in Figures 12 and 13 show, the Degree-day method fails to consider effect of these weather parameters. Considering only the temperature, the degree-day method shows that normalized EUI of February is less than that of January for both years. On the other hand considering the above mentioned for other involved elements, the $SDE_{U/L}$ model normalized results show that while there is a decrease from January to February for 2013, there is an increase from January to February of 2014 in the normalized values.
The building A is closed in the summer, the results show the Degree Day method could not consider internal heat gain due to people behavior and equipment in different seasons, while the proposed method considered the people behavior and occupant factors. Based on simulation results, we could summarize the main differences between our models and the other existing methods: (a) almost all of existing methods do not
consider all weather parameters in the modeling, but our work considers wind speed, humidity and solar radiation in the model, (b) other important factors in weather normalization are building parameters such as building size, window size, construction joints, and the effect of flues are ignored in the existing approaches and are considered in our proposed method, (c) the habits of occupants in using the energy and the number of occupants are considered in our method, and (d) the proposed method is the only method which consider weather parameters, building factors, and occupant factors all in one model.

5.3 | Effects of wind, solar radiation and humidity

Here we provide the effects of wind, sun radiation and humidity in the weather normalization process. For these simulations behavior of building A in 2014 is considered. Figure 15 shows the effects of only temperature and humidity. Figure 16 shows the effects of only temperature and sun radiation. Figure 17 shows the effects of only temperature and wind speed. It shows how elimination of any these factors changes the weather normalization behavior. These figures also show how SDE U/L weather normalization considers the effects of these weather conditions. For example, in Figure 15, anytime humidity increases, the normalization procedure reverses react.

5.4 | Energy usage forecasting

Figure 18 shows the forecasted EUI for building A in Fiscal Year 2014-2015 using the nonlinear SDE U/L model. Learning of SDE U/L is done from data in Fiscal Years 2012-2013 and 2013-2014, and weather conditions parameters (air temperature, wind speed, humidity, and sun radiation) are forecasted from the closest weather station. Note that Root Mean Square Error (RMSE) of this forecasting method is <2.5%.

6 | CONCLUSION

Some weather normalization methods assume the heat loss/gain in buildings is linearly proportional to the indoor and outdoor temperature difference. Consequently, this naive calculation cannot trace the fluctuations in weather conditions, and are not dependent on the building parameters; therefore, these methods are not able to normalize the energy usage with high confidence. We have modeled the behavior of a building and its energy usage habits using a linear and nonlinear model. This structure dependent model can not only be used for weather normalization, but also it can be used for forecasting the energy usage and loss. Our simulation results have shown the flexibility and advantages of a structure dependent weather normalization method over the Degree-Day method (the most popular method).

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ENDNOTES

1. Ontario Ministry of Education’s Utility Consumption Database, electricity and natural gas meter readings. (Location: Latitude = 44.2583399, Longitude = −80.4533254).
2. Ontario Ministry of Education’s Utility Consumption Database, electricity and natural gas meter readings. (location: Latitude = 43.7257545, Longitude = −79.643965).
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