the building design, while meeting the other design targets. Simplified simulation software programs such as CoolVent (Menchaca-B and Glicksman 2008) allow architects and engineers to predict the effects of natural ventilation. This knowledge is useful in determining which natural ventilation strategy—single-side ventilation, cross ventilation or stack ventilation—should be employed to meet the design target for ventilation. However, there is no consensus on how to actually develop this design target. One common method is to implement an optimization analysis to determine the optimal air exchange rate in terms of energy savings, occupant satisfactions and minimized cost. This optimization analysis, however, requires significant effort that often prevents architects and engineers from implementing it. Furthermore, the building information at this early design stage is often insufficient to carry out the sophisticated energy simulations necessary for the optimization analysis. As a result, the various targets, e.g., air exchange rate, are often based on the architects' experience or through case research. This makes it difficult to verify their accuracy. The air exchange rate determined by the architect might be too small to achieve the effects as intended or too large to be cost-effective. Therefore, the links between air exchange rates and the effects of natural ventilation obtained through monitoring existing buildings can provide useful information for determining early stage building design targets.

In this study, the operational frequency of a cooling system throughout the year is used to estimate the effect of natural ventilation. Architects can easily understand this effect on natural ventilation and incorporate it into their design. For example, we can separate buildings into two categories based on this estimate. In the first category, i.e., where an enhancement in air exchange rate reduces the operational frequency of the cooling system (Figure1), it is expected that significant improvement in building ventilation can be achieved through natural ventilation. In this case, natural ventilation itself can reduce energy consumption and improve the satisfaction of the occupants by reducing the operational frequency of the cooling system. In this context, while mixed-mode ventilation that enables a combination of natural ventilation and mechanical cooling systems might improve the effect, architects can plan natural ventilation strategies without mixed-mode operation to avoid the complexity and the increment of budget related to the operation. In the second category, where it is difficult to reduce the operational frequency of a cooling system by natural ventilation only (Figure2), architects should incorporate "mixed-mode ventilation" to achieve energy savings while considering the cost-effectiveness of the introduction of facilities related to the operation of natural ventilation. It is thus useful to investigate the link between the air exchange rate and the operational frequency of cooling to provide information during the early stages of building design. This helps architects to categorize the building and determine which natural ventilation strategy is needed to achieve the largest effect from natural ventilation. In this paper, we present a method for determining the link between the natural ventilation air exchange rate and the operational frequency of the cooling system to achieve comfort with only natural ventilation. As a first step of this study, we use a database based on building performance simulations with a basic building model to identify the general law of the relationship between air exchange rate and operational frequency. In future studies, the feasibility of this general law will be cross-referenced with existing building databases.

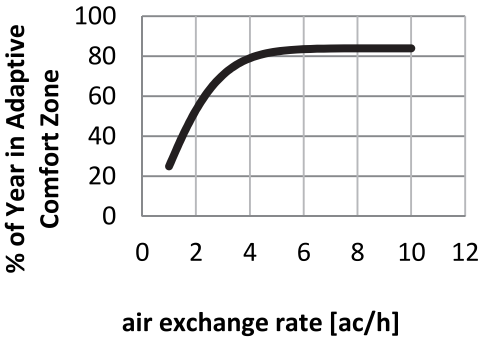


Figure 1. *Image of the link between air exchange rate and operational frequency in Category I. Even a small amount of air exchange, 1-2 ac/h, can effectively increase the % of year using NV alone.*

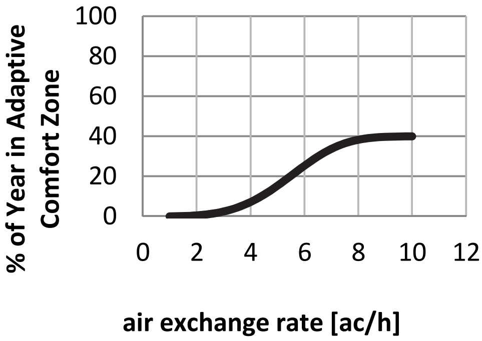


Figure 2. *Image of the link between air exchange rate and operational frequency in Category II. A small amount of air exchange, 1-2 ac/h, cannot effectively increase the % of year using NV alone.*

RESEARCH APPROACH

The overall goal of this study is to provide a data mining methodology that streamlines a building database from a pile of inordinate data to useful design information that can assist architects in creating rational design targets. In this paper, we focus on the methodology for naturally ventilated building design.

The links between the operational frequencies and the air exchange rates observed in existing buildings, however, cannot be directly used to create a design target for a new building. It is helpful to draw an approximate curve to describe the features of the link between these two parameters. These features can be used to categorize naturally ventilated buildings. The categorization helps architects consider to what extent their building project demands improvement in the air exchange rate to achieve the largest effects of natural ventilation.

In this study, a general form of the approximation formula was investigated first. Moreover, there are typically differences in the design conditions that affect this approximation formula. Adjustments must be made to account for variations such as climate condition, internal heat, building orientation, window to floor area percentage and thermal mass. This study also seeks to establish a methodology based on the sensitivity analyses of the various conditions that affect natural ventilation to guide the adjustments.

BASIC BUILDING MODEL FOR THE CASE STUDIES

A basic office building model is established. An approximation formula is investigated based on the simulation results using this simple office model. In this formula, the operational frequency of the cooling system is selected as the objective variable. The air exchange rate is the primary explanatory variable. Other variables, such as the amount of internal heat, the window area and the floor area all affect the natural ventilation. Thus, these variables will be used to adjust the parameter in the formula in future studies. Ultimately, this study should include the air change rate fluctuations due to pressure effects of wind. In addition, the increment in % of year in comfort zone achieved by night cooling should also be discussed.

The basic building model is a three-story office building model. The area of each floor is 25 x 25 m^2 and the floor height is 3.5 m, including the plenum space. Figure 3 shows a rendering of the building. Table 1 lists the building conditions. Figure 4 shows the activity schedule. The basic building model has same size windows on each wall.

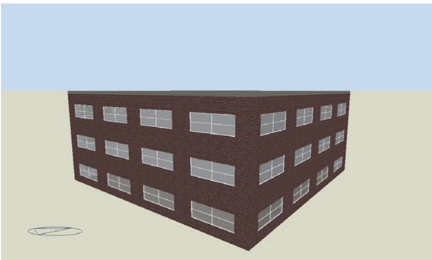


Figure 3. *Rendering of the basic building.*

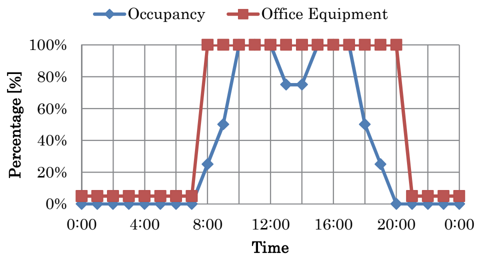


Figure 4. *Schedule for the internal heat load.*

Table 1. *Characteristics of the basic building model.*

U-value	Outer wall: 0.25W/m^{2}K(Concrete Block and Brickwork), Ground Floor: 0.15W/m^{2}K, Roof: 0.15W/m^{2}K, Window: 1.96W/m^{2}K (Double Glazing)
Window Dimensions	Window to Wall Percentage : 30 % Window Height : 1.5 m Window Spacing : 5.0 m Sill Height : 0.8 m
Internal heat	Human:0.1 person/m^2, 123 W/person Office equiment 12 W/m^2
Lighting	3.3W/m^2-100lux Target illuminance: 400 lx

SIMULATION CONDITIONS

The object variable is the operational frequency of the cooling system. The primary explanatory variable is the air exchange rate. The air exchange rate ranges from 1 ac/h to 8 ac/h. A rate of 1 ac/h is used as the minimum value for outdoor air because it is the minimum amount of fresh air for the occupants. The simulation calculates the temperature without artificial control in a naturally ventilated building. The natural ventilation rate is defined as the zone volume multiplied by the air exchange rate. The periods during which the indoor thermal environment is higher than the acceptable temperature in a naturally ventilated building are regarded as periods that require cooling operations. The operational frequency of the cooling system is calculated during normal business hours, 8:00 to 18:00, over the course of the year. The operative temperature is used to represent the indoor thermal environment. The adaptive comfort zone is defined as the acceptable temperature range around the optimum comfort temperature T_{comf} in a naturally ventilated building and specified as ±3.5 for 80% general acceptability (de Dear and Brager 2002).

$$T_{comf} = 0.31 \text{ x } T_{a,out} + 17.8 \tag{1}$$

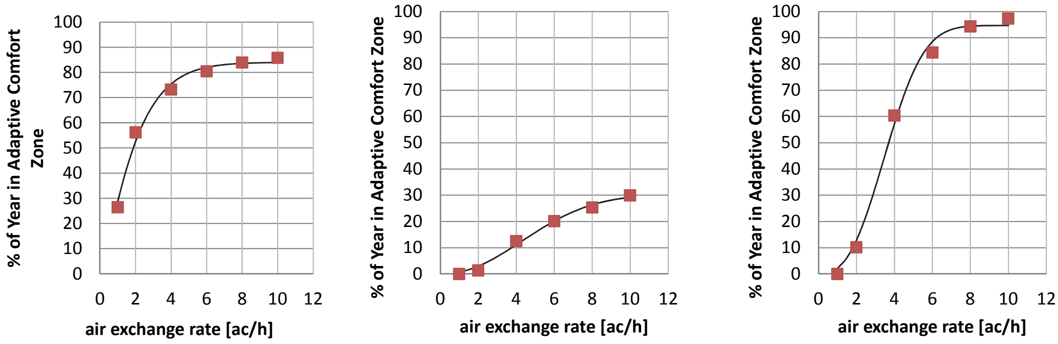
where $T_{a,out}$ is the monthly average of the daily average outdoor dry bulb temperatures (Levitt et al. 2013).

We assume that the operational frequency of the cooling system is equal to the cumulative probability of the period when the indoor operative temperature is above the adaptive comfort zone. The simulation is performed using a software; Design Builder. This software calculates the internal operative temperature as the mean of the internal air and mean radiant temperature (MRT). The MRT of the zone is calculated by assuming that the person is in the center of the zone, with no weighting for any particular surface.

RESULTS AND DISCUSSIONS

Figure 5 shows the link between the air exchange rate and the percentage of year in the adaptive comfort zone. In this study, we focus on the operation frequency of the cooling system. Therefore, heating is assumed and the period when the indoor operative temperature is below the adaptive comfort zone is also factored into the percentage of year in the zone. In other words, only the period when the indoor operative temperature is above the adaptive comfort zone is assumed to be out of the zone. The denominator for the probability is the accumulated business hours throughout the year.

Figure 5 shows the approximation curves for this analysis. The approximation curve *F'(x)* (Eq. 2) is based on the cumulative distribution function *F(x)* (Eq. 3). The cumulative distribution function is used because the percentage of year should range between 0% and 100%. In addition, the multiplier α, which ranges from 0 to 1, is used to plot the approximation curve because the outdoor air is not suitable for natural ventilation in some periods and the percentage of year cannot reach 100% even if there is a huge amount of air exchange. A Weibull distribution is used as a trial for the probability function (Eq. 4). The Weibull parameter is popular in the field of civil engineering because it can be used to describe the wind speed distribution. Therefore, we assume that this distribution is also valid for phenomena related to natural climate fluctuation.



a) Boston (0.84, 1.22, 2.03)   b) Miami (0.30, 2.15, 5.77)   c) Los Angeles (0.95, 2.66, 4.11)

Figure 5. *Simulation results and the respective approximation curves. Values in the parentheses show parameters α, k and λ, respectively. The data points are the calculated cases shown with a best fit distribution*

$$F'(x) = \alpha F(x) \tag{2}$$

$$F(x) = \int_0^x f(u)du \tag{3}$$

$$f(x;k,\lambda) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} \exp\left\{-\left(\frac{x}{\lambda}\right)^k\right\} \tag{4}$$

In the equation above, *f(x)* is the probability distribution, *α* is the multiplier, *k* is the shape parameter and *λ* is the scale parameter.
Parameters *α, k* and *λ,* are calculated by the least squares method. The approximation curves fit well with the simulation results in all cases. Using these curves, the naturally ventilated buildings can be categorized as follows:

Category I (e.g., Fig 5a)**:** In this category, buildings have capabilities to significantly increase the percentage of year that the indoor thermal environment is in the adaptive comfort zone, even with a small amount of air exchange rate, e.g., 1-2 ac/h. Although mixed-mode ventilation is recommended to achieve more effect from natural ventilation, the introduction of simple natural ventilation facilities alone, such as operable windows, can save energy and improve occupant satisfaction. It is worth considering natural ventilation strategies even though only a small improvement in air exchange rate can be expected.
Category I' (special cases in Category I): The buildings have capabilities to eliminate the cooling systems when the air exchange rate is high, e.g., 8 ac/h. It is worth considering "affirmative" natural ventilation strategies, such as solar chimneys, to increase the amount of air exchange rate as much as possible.
Category II (e.g., Fig 5b)**:** In this category, it may be difficult to increase the percentage of year that the indoor thermal environment is in the adaptive comfort zone using only natural ventilation, with a small amount of air exchange rate, e.g., 1-2 ac/h. Mixed mode ventilation

is necessary to achieve energy savings by natural ventilation in these cases.

Category II' (e.g., Fig 5c; special cases in Category II)**:** The buildings have capabilities to eliminate the cooling systems when the air exchange rate is high, e.g., 8 ac/h. It is worth considering "affirmative" natural ventilation strategies with full examinations to obtain a large improvement in the air exchange rate.

This categorization is useful for identifying natural ventilation strategies during early stage building design. If the necessary parameters can be obtained at the early design stage, the architects can set more realistic target values for air exchange rate using natural ventilation strategies.

To check the influences of other variables, simulations using different values in the internal heat gain were carried out. Figure 6 shows the simulation results shown with a best fit distribution. Figure 7 shows the linear relationship between the amount of internal heat gain and each parameter (α, k and λ). These data imply that the parameters can be explained by variables other than the air exchange rate and that the approximation curves can be adjusted using those variables. Although further investigation with other variables, such as window to wall ratio and thermal mass, is necessary, it would appear that the cumulative distribution function based on the Weibull distribution is adequate to explain the link between the air exchange rate and the operation frequencies of the cooling system. In addition, identifying the building design conditions at the early design stage is helpful for creating a reasonable design strategy for natural ventilation.

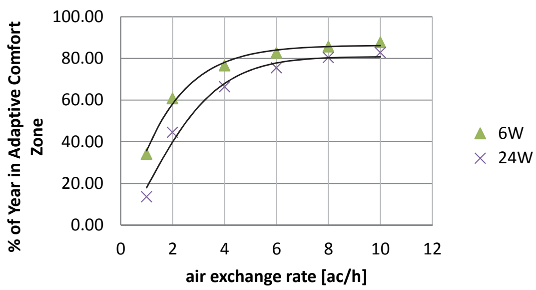


Figure 6. *Simulation results with the variation in internal heat gain.*

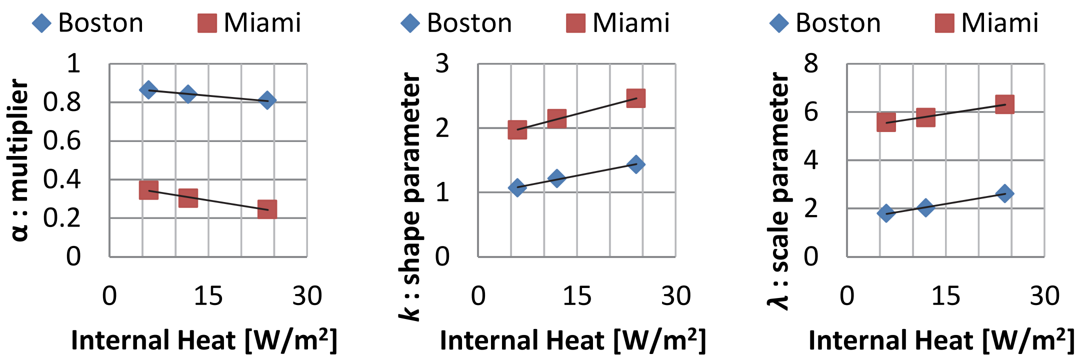


Figure 7. *Links between the amount of internal heat gain and each parameter.*

CONCLUSIONS

The goal of this study was to establish a methodology for data mining of existing building designs and monitoring data. It is expected that the knowledge gained in this study can be used by architects to define building categories in their projects based on the link between the air exchange rate and operation frequencies of the cooling system for similar locations and building designs. This categorization is helpful for implementing natural ventilation strategies, such as introduction of mixed-mode ventilation and solar chimneys.

Throughout this case study, it was shown that the operational frequency of the cooling system can be described with an approximation curve based on the Weibull distribution using the air exchange rate as the design value. In addition, the effects of other design variables, e.g., internal heat gain in this case study, were verified. Although the amount of internal heat generation affects the system, this influence can be attenuated to the approximation curve by adjusting its parameters. The parameters in the approximation curve have linear relationships with the amount of internal heat generation. The approximation curves can be adjusted by the amount of heat generation, even in a design project with different internal heat conditions.

In future work, we will perform sensitivity analyses using other design variables such as outdoor climate, thermal mass, window to wall ratio and window properties, with varying orientations and materials. We will also search for explanatory variables that can be used to further adjust the parameters of the approximation curves. Finally, we will search for conditions that can group data samples to obtain higher accuracy approximation curves.

ACKNOWLEDGEMENTS

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