

Article

Assessment of Natural Ventilation Potential for Residential Buildings across Different Climate Zones in Australia

Zijing Tan ¹ and Xiang Deng ^{2,*}

¹ School of Civil Engineering, Chang'an University, Xi'an 710064, China; tanzijing01@163.com

² Sustainable Buildings Research Centre, University of Wollongong, Wollongong, NSW 2500, Australia

* Correspondence: xd902@uowmail.edu.au; Tel.: +61-4-1548-4106

Received: 3 September 2017; Accepted: 16 September 2017; Published: 20 September 2017

Abstract: In this study, the natural ventilation potential of residential buildings was numerically investigated based on a typical single-story house in the three most populous climate zones in Australia. Simulations using the commercial simulation software TRNSYS (Transient System Simulation Tool) were performed for all seasons in three representative cities, i.e., Darwin for the hot humid summer and warm winter zone, Sydney for the mild temperate zone, and Melbourne for the cool temperate zone. A natural ventilation control strategy was generated by the rule-based decision-tree method based on the local climates. Natural ventilation hour (NVH) and satisfied natural ventilation hour (SNVH) were employed to evaluate the potential of natural ventilation in each city considering local climate and local indoor thermal comfort requirements, respectively. The numerical results revealed that natural ventilation potential was related to the local climate. The greatest natural ventilation potential for the case study building was observed in Darwin with an annual 4141 SNVH out of 4728 NVH, while the least natural ventilation potential was found in the Melbourne case. Moreover, summer and transition seasons (spring and autumn) were found to be the optimal periods to sustain indoor thermal comfort by utilising natural ventilation in Sydney and Melbourne. By contrast, natural ventilation was found applicable over the whole year in Darwin. In addition, the indoor operative temperature results demonstrated that indoor thermal comfort can be maintained only by utilising natural ventilation for all cases during the whole year, except for the non-natural ventilation periods in summer in Darwin and winter in Melbourne. These findings could improve the understanding of natural ventilation potential in different climates, and are beneficial for the climate-conscious design of residential buildings in Australia.

Keywords: natural ventilation; residential building; climate zone; thermal comfort; natural ventilation hour

1. Introduction

Rapid urbanisation has led to a significant increase in building energy usage, which accounts for nearly one third of the total primary energy consumption worldwide [1]. As a key solution to the efficient operation of buildings, natural ventilation plays a significant role in maintaining an acceptable indoor environment [2,3]. The benefits of natural ventilation include, but are not limited to, improved indoor thermal comfort, reductions in occupant illness associated with indoor environmental quality (IEQ), and increased work productivity with low energy consumption and greenhouse gas (GHG) emissions [4–6].

Natural ventilation potential was defined to evaluate the possibility of ensuring an acceptable indoor air quality and thermal comfort naturally [7]. Determined by both the indoor and outdoor environment, natural ventilation potential can be influenced by local climate, urban form and building

characteristics (geometrical and thermal) [8,9]. An early preliminary study conducted by Teitel and Tanny [10] investigated the impact of building structure and window height on the natural ventilation of greenhouses, and revealed that the effect of natural ventilation (e.g., air change rate) increased with the height of the window opening and the wind speed. Fordham [11] indicated that the heat effect due to building thermal capacity should not be ignored in the design of natural ventilation. Meanwhile, the influence of internal heat gain on natural ventilation performance has also been intensively studied, and heat source geometries [12–14] and transient characters [15,16] have been proven to be the most significant factors influencing ventilation rate and airflow pattern. In the last few decades, the effect of the urban environment on natural ventilation potential has become of increasing concern. Ghiaus et al. [17] conducted a series of field measurements and quantified the effect of urban phenomena on natural ventilation. Han et al. [18] compared the thermal comfort performance in urban and rural residential buildings in a naturally ventilated environment, and claimed that high-density urban settings could reduce the cooling effect of natural ventilation. Hang et al. [19] adopted a CFD model to investigate the effect of semi-open street roofs on the natural ventilation of urban canopy layers.

Since building detail and urban configuration are known factors, natural ventilation potential depends greatly on the suitability of local climate [20]. In recent years, the natural ventilation potential in different climate zones has been investigated around the world. Wang and Greenberg [21] evaluated the thermal comfort and energy performance of three major cities with different climates in the US to identify the available natural ventilation time through the EnergyPlus simulation. Su et al. [22] analysed thermal comfort conditions in Shanghai, located in the hot summer and cold winter district of China, in a naturally ventilated residential building and found natural ventilation was not inappropriate in winter and transition seasons. Calautit et al. [23] investigated using CFD simulation the indoor air change rate of a traditional row house using a wind tower in the hot and arid Middle East. Artmann et al. [24] studied the potential of night-time ventilation in commercial buildings all over Europe, with the results showing that northern Europe had the most potential for passive cooling during night time, while in southern Europe night-time ventilation could only be used as an auxiliary cooling method.

Although numerous studies have been conducted to detail thermal-comfort-related natural ventilation over the world, there has been little research related to natural ventilation feasibility evaluation across different climate zones in Australia. It is, therefore, necessary to evaluate the suitability of natural ventilation across the diverse climates of this country. This study presents a computational methodology for the analysis of the climate suitability of natural ventilation for residential buildings in three Australian climates. A typical multi-zone residential building model with a rule-based window control strategy was adopted as the research platform. This research can contribute to a more sophisticated approach to understanding natural ventilation potential across different climate zones, and hence to achieving the free cooling predesign purpose.

2. Research Methodology

2.1. Climate Zones in Australia

Because Australia is not subject to the movements of frigid polar air from the South Pole due to its separation by the Antarctic Ocean, the climate is generally temperate: most of the country receives more than 3000 h of sunshine a year. The temperature difference between summer and winter can be relatively small compared to the northern continents. Nevertheless, having a vast interior, many areas are characterised by particular climate conditions. Based on a set of definitions relating to summer and winter temperature and humidity conditions, eight key zones across Australia from north to south are categorised as hot humid summer and warm winter, warm humid summer and mild winter, hot dry summer and warm winter, hot dry summer and cool winter, warm temperate, mild temperate, cool temperate and alpine (Figure 1) [25].

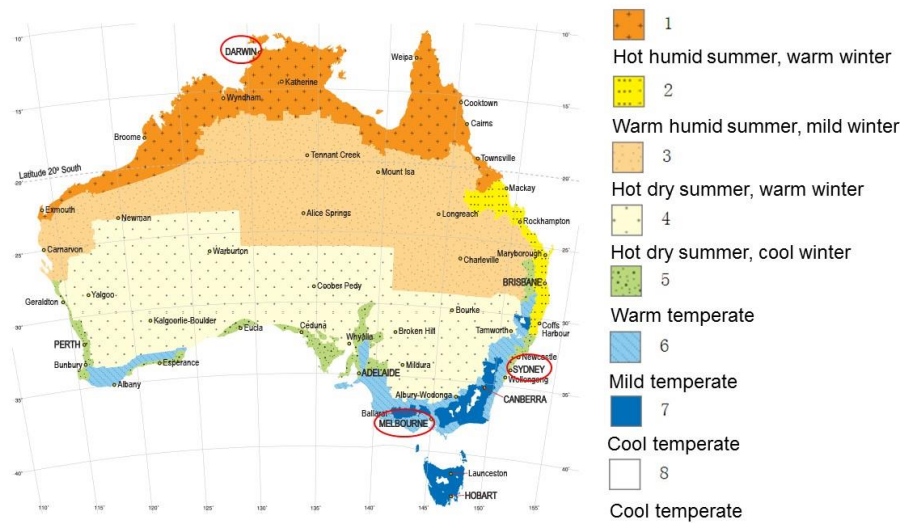


Figure 1. Australian climate zones [25]. Reproduced with permission from Australian Bureau of Statistics, Year Book Australia, 2012; published by ABS Canberra: Canberra, Australia, 2012.

Since the majority of Australia’s population lives in coastal instead of central areas (dry and desert regions), three coastal cities, Darwin, Sydney and Melbourne, were selected to represent the three most populous climate zones. Darwin is the capital of the Northern Territory located in the hot humid summer, warm winter zone with a tropical climate. The coldest month’s average air temperature is 20 °C. The hottest monthly average air temperature is 32 °C. Sydney is the capital of the State of New South Wales, located in the mild temperate zone with a humid subtropical monsoon climate. The coldest month’s average air temperature is 17.2 °C. The hottest monthly average air temperature is 36.4 °C. Melbourne is the capital of the State of Victoria, located in the cool temperate zone with a temperate marine climate. The climate details of the three cities are illustrated in Table 1.

Table 1. Climatic characteristics of the representative cities [25].

City	Climate Zone	Annual Temperature (°C)		Average Annual Relative Humidity (%)	Average Annual Wind Speed (m/s)
		Average High	Average Low		
Darwin	Tropical	32.0	23.2	53.4	4.3
Sydney	Warm temperate	22.5	14.5	56.2	3.1
Melbourne	Mild temperature	20.4	11.4	51.8	2.9

2.2. Residential Building Model

Description of the Case Study Building

The AS/NZS building code published by Standards Australia [26] specifies universal material requirements for thermal insulation of residential buildings in different climate zones in Australia. Given this, building models with the same envelope conditions could be employed for potential natural ventilation analysis in different climate zones. A multi-zone single-story house model based on a typical residential building was adopted.

It consists of five main parts: a master bedroom at the northeast corner, a study/guest bedroom at the southeast corner, an open-plan living room connected with the dining room and kitchen, a laundry space, and a shower space (Figure 2). Both the external envelope and internal enclosure are insulated by glasswool. Two types of windows are used in this house, including three top-hung clerestories on the south wall of the living room, and six side-hung windows in the rest of the walls. All windows are equipped with low-e double argon-filled glazing. This building is located in a flat yard with no significant wind obstructions.



Figure 2. Case study building.

2.3. Simulation Approach

The commercial simulation software TRNSYS (Transient System Simulation Tool) combined with COMIS (Conjunction of Multi-zone Infiltration Specialists) was used for the indoor airflow and thermal modelling of the case study building, as well as for the natural ventilation control strategy proposed in the following section of this study. The control strategy was programmed in MATLAB and integrated within the simulation platform through the TRNSYS component Type 22. The schematic of the airflow-thermal modelling in TRNSYS is presented in Figure 3.

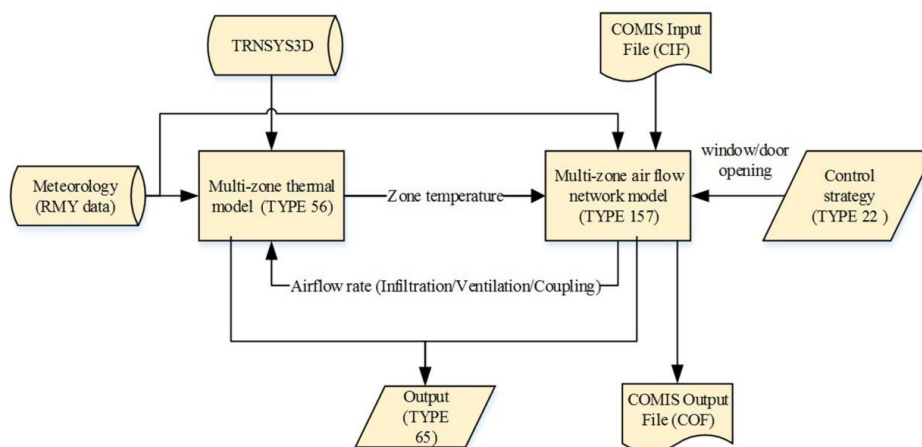


Figure 3. Integration of COMIS into TRNSYS simulation.

To translate the physical layout of the house into a building model with a node-based airflow network (Component Type 56), several assumptions were made as follows:

- The cracks for closed windows and doors were set as 1 mm based on the estimated crack dimensions of the house;
- Zones were defined by rooms of the house and each zone was assumed to have a uniform air temperature distribution and pressure distribution;
- The door between the laundry and the living room was assumed to be closed. The laundry and shower spaces were not considered in the airflow network for the multi-zone ventilation calculation but were modelled in thermal simulations;
- Internal doors that connect the bedroom and the guest room to the living room were assumed to be normally open.

Although actual local temperature and velocity distributions might be non-uniform and even contribute to thermal comfortability divergence in a room, this study was mostly concerned with the flow rate and ventilation efficiency over a whole residential building. As a highly efficient and widely used ventilation model, the multi-zone airflow network was adopted in the current simulation.

The airflow network of the case study building (Component Type 157) is shown in Figure 4. The components of external openings were highlighted in red. As there were three clerestory windows in the living room, the buoyancy effect was taken into account by introducing a virtual horizontal opening component, highlighted in green.

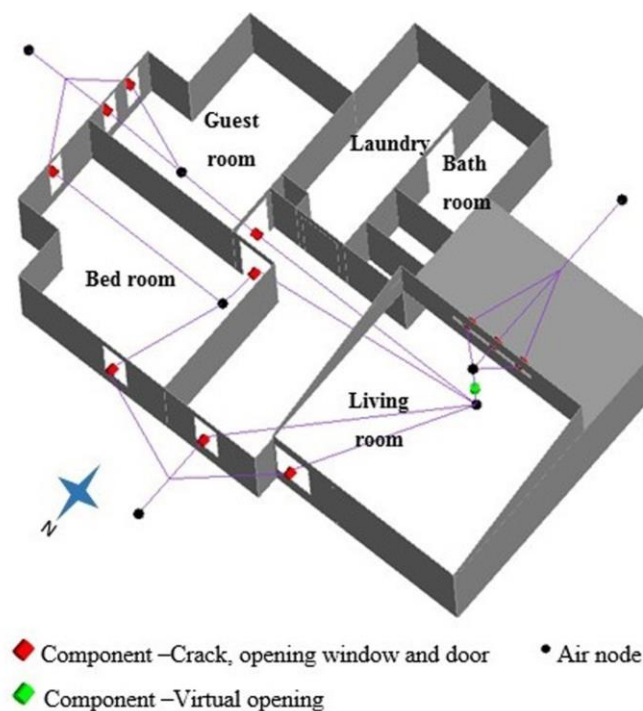


Figure 4. Schematic of the airflow nodal network.

Since the wind pressure coefficients of the openings in the case study building were required for wind-induced ventilation calculation, CFD simulation was conducted as one of the prime sources [27] (simulation results were shown in Appendix A Table A1). The reference meteorological year (RMY) data of the three selected cities was selected for the performance evaluation. The internal heat gains from occupants and equipment activities were set as the recommended value referred to in the ASHRAE handbook [28] (Appendix A Table A2).

2.4. Model Validation

The current numerical approach was validated against a field measurement in the case study building located in the Sydney area. Indoor air temperature, as a joint result of the airflow and thermal transfer process, was measured and collected hourly in each room over eight consecutive days (27 July 2015–3 August 2015) during the daytime. During the measurements, three window conditions, i.e., fully open, half open (50% open) and fully closed, were performed. The temperature data was continuously tested for three days under each scenario. As a main functional area of the residential building, the master bedroom was selected for the validation. Indoor temperatures predicted by numerical and measurement methods are compared in Figure 5.

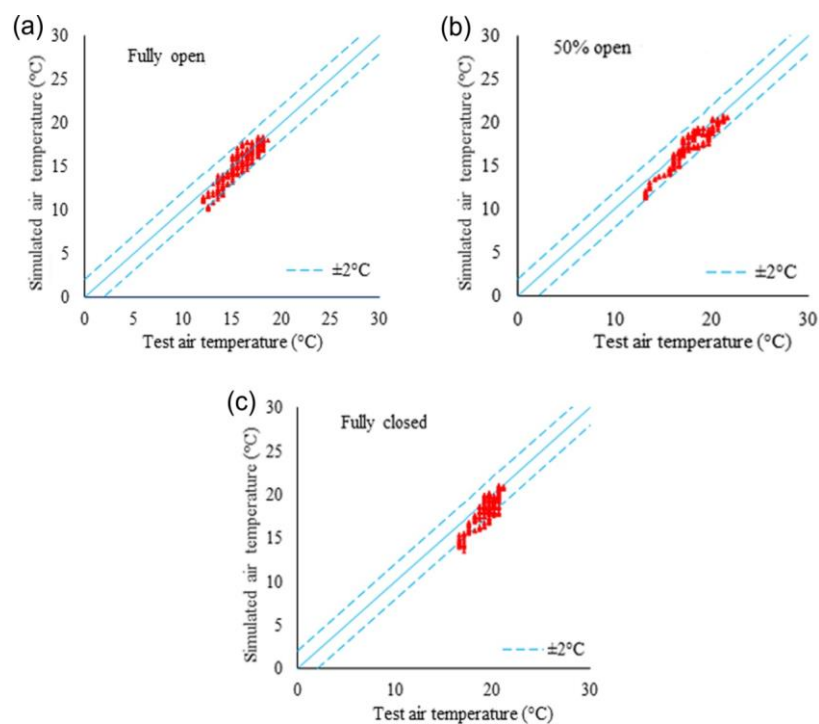


Figure 5. Comparison of indoor air temperatures of the master bedroom between numerical simulated methods and measured data under three window conditions: (a) fully open; (b) half open; (c) fully closed.

In general, the numerical prediction of the indoor temperature under all window conditions agreed well with that of the field measurement data. The deviations of the simulated data points from the bisector (e.g., the test points) mostly fell within $\pm 2^\circ\text{C}$. Only slightly divergence were observed for the fully closed condition. These could be attributed to the diversity of numerous factors influencing indoor thermal conditions (e.g., instantaneous meteorological conditions, surrounding obstacles, ground roughness, etc.). In the numerical model, the ambient wind condition was assumed to be constant in half an hour, and obstacles around the building were neglected. The value divergence was of the same level as previous studies [29–31], where the error band for the predicted indoor temperature based on the TRNSYS was shown to be about $\pm 2^\circ\text{C}$.

Overall, the reasonable level of agreement found in these comparisons demonstrate that the proposed numerical approach is capable of predicting the indoor thermal environment and airflow with fair accuracy.

2.5. Natural Ventilation Control Strategy

2.5.1. Decision-Tree Model

Actual thermal comfort is dependent on environmental factors, such as air temperature, air velocity, relative humidity and the uniformity of conditions and personal factors such as clothing and metabolic heat. However, it is very complex to assess indoor thermal comfort by considering all these variables (see predicted mean vote), and a simpler measure can be more useful in practice. In practice, operative temperature derived from air temperature, mean radiant temperature and air speed is widely used as a reasonable indicator of thermal comfort. Operative temperature is defined as:

$$T_o = \left(T_r + \left(T_a \times \sqrt{10v} \right) \right) / \left(1 + \sqrt{10v} \right) \quad (1)$$

where T_a is the air temperature; T_r is the mean radiant temperature; and v is the air speed. In this study, the indoor operative temperature was selected as the indoor thermal comfort index for natural ventilation control.

In this paper, the decision-tree induction method was used to generate a rule-based window control algorithm in order to determine whether natural ventilation could be used under local climate conditions. For a decision-tree model, a reversed tree-like structure is built with several nodes and branches. Each internal node and leaf node represents a test condition with an attribute and a classification prediction, respectively. Meanwhile, the outcomes of the test are presented by branches [32]. The process to generate the decision-tree model employed in this study is presented in Figure 6.

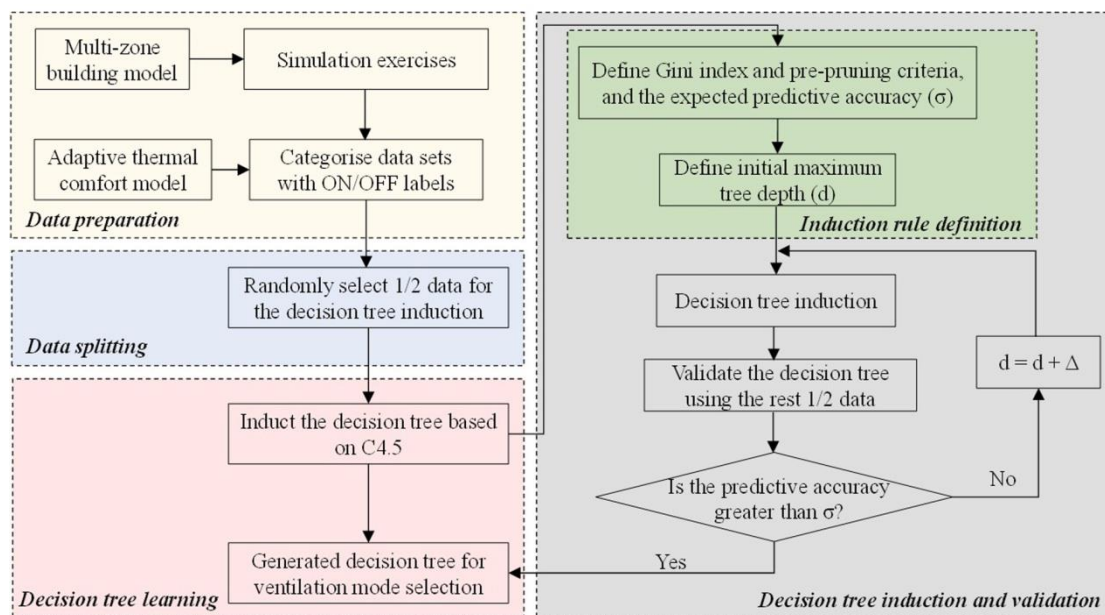


Figure 6. Illustration of the decision-tree generation process.

The data used for the decision-tree induction and validation was first generated based on the hourly simulation with the multi-zone building model under different window opening percentages (i.e., 25%, 50%, 75% and 100%). Then, the simulated indoor operative temperatures under different window and weather conditions (including ambient air temperature, relative humidity, solar radiation, wind speed and wind direction) were prepared as the data sets for decision-tree induction and validation. Based on these data sets, the applicability of natural ventilation under different window

and weather conditions was assessed by an adaptive thermal comfort model (the 80% thermal comfort band) developed by De Dear [33]. The equation is given below [34]:

$$T_{\text{up}} = 0.31T_{\text{out}} + 17.8 + \frac{1}{2}\Delta T_{80\%} \quad (2)$$

$$T_{\text{low}} = 0.31T_{\text{out}} + 17.8 - \frac{1}{2}\Delta T_{80\%} \quad (3)$$

where T_{up} and T_{low} represent the upper and lower thresholds of temperature varied by month, T_{out} is the monthly average outdoor temperature, and $\Delta T_{80\%}$ is the mean comfort zone temperature band for 80% acceptability.

If indoor operative temperature was within the 80% acceptable indoor operative temperature thresholds [35], it was considered that natural ventilation could be used for this particular condition and the specific data set was then labelled as “ON”. Otherwise, the data set would be labelled as “OFF”. Half of the labelled data was randomly selected as the training data for the decision-tree induction using the C4.5 algorithm [36]. C4.5 inducts the decision tree based on the concept of Shannon entropy in order to measure the unpredictability or the impurity of the information content [37]. The impurity of the attribute partition decreases with the decrease of Shannon entropy. If a set of training data was allocated to a node S , and the probability distribution of the target attributes was $D_i = (D_1, D_2 \dots D_n)$, Shannon entropy for the training data carried by this distribution is defined as Equation (4).

$$\text{Entropy}(D, S) = - \sum_{i=1}^n (D_i \times \log_2(D_i)) \quad (4)$$

In the decision-tree induction, rules including the Gini index, pre-pruning criteria, and the minimal expected predictive accuracy were defined first. In order to balance the decision-tree scale and splitting accuracy (i.e., the ratio between the correctly labelled training datasets and all the training datasets), the Gini index was used to measure the impurity of a node [38]. Meanwhile, pre-pruning criteria including the minimal gain, minimal leaf size and minimal size were adopted to avoid overfitting of the decision tree. As it represented the expected ratio between the correctly labelled testing data sets and all the testing data sets, the expected predictive accuracy was related to the data quality. Thus, a reasonable expected predictive accuracy was selected through trial and error, set as 0.93. The details of induction rule settings were given in the Appendix A (Table A3).

On account of the defined Gini index, pre-pruning criteria, and the expected predictive accuracy, an initial maximum tree depth can be assigned for decision-tree induction and validation. To control the size of the decision tree, the depth should start with a relatively small value. The values for the tree induction were used according to [39].

If the predictive accuracy of the decision tree validated by the testing data was larger than the minimum expected value, the decision-tree learning process would be terminated. Then, the generated decision tree would be used for ventilation control. Otherwise, a new tree would be generated by increasing the maximum tree depth so as to improve the predictive accuracy.

2.5.2. Natural Ventilation Strategy Based on the Decision-Tree Model

The decision tree for the case study building was introduced by the open source data mining software RapidMiner. A total of 3000 hourly data sets for each of the four window opening conditions (i.e., 25%, 50%, 75% and 100%) were obtained during the whole RMY for decision-tree generation and validation.

A final decision-tree model for the case study building in Sydney is depicted in Figure 7. The decision tree consisted of 55 nodes, among which 27 yellow rectangular nodes presented the categorical parameters, and 12 blue and 16 red ovals at the bottom denoted the classification results. The outdoor air temperature nodes accounted for 1/3 of the total internal (i.e., a node between input

and output) nodes, indicating that the outdoor air temperature was one of the most critical parameters for natural ventilation. By using this decision tree, each data record was assigned to a leaf node that was associated with a specific window condition, and a window opening prediction could be made. In addition, no internal node related to the window opening percentage was found in this decision tree, implying that window opening percentage had less influence on ventilation mode selection when compared to the outdoor climate.

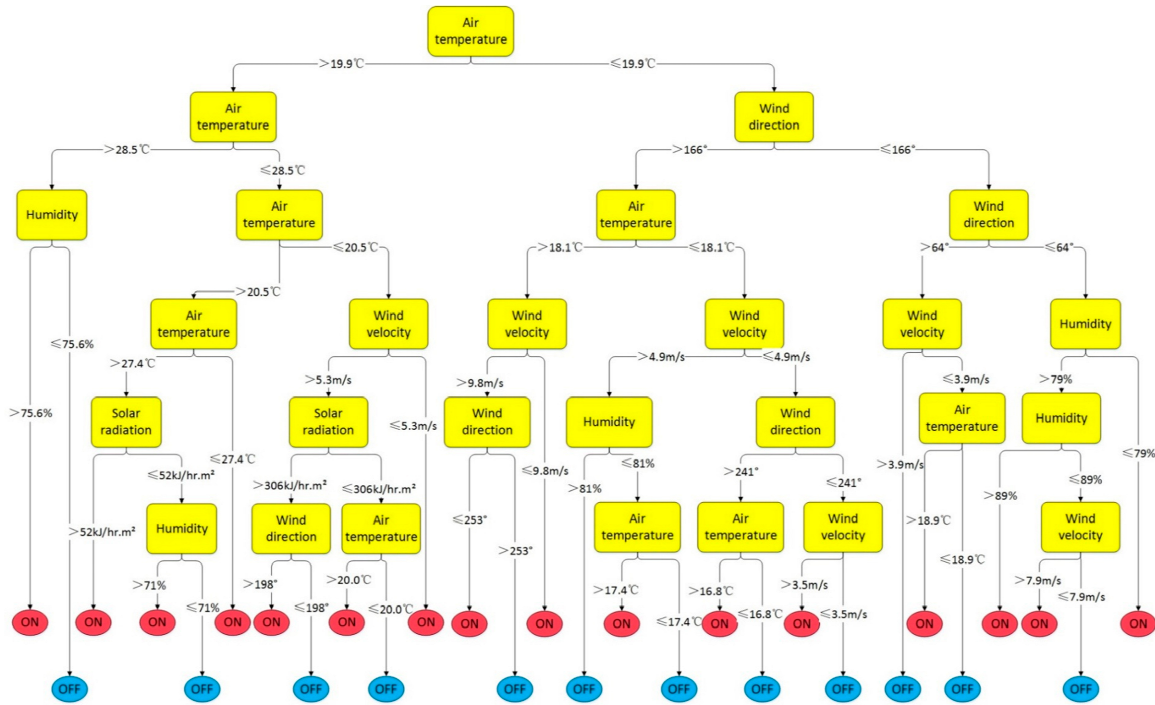


Figure 7. The generated decision tree for ventilation mode selection in Sydney.

3. Results and Discussion

3.1. Natural Ventilation Hour

The natural ventilation hour (NVH) [1] was employed as an indicator to measure the natural ventilation potential for the case study building at each location. It is defined as the number of hours in a typical year (8760 h) or a typical season (2190 h) during which outdoor weather conditions are suitable for utilising natural ventilation. The NVH of the studied residential building in the three representative cities were simulated by the proposed TRNSYS simulation approach. The results for spring, summer, autumn and winter at the three locations were presented in Table 2, respectively.

Table 2. Natural ventilation potential under different seasons.

City	Natural Ventilation Hour				
	Spring	Summer	Autumn	Winter	Total
Darwin	1010.5	996	1109.5	1612	4728
Sydney	915	1898.5	1240.5	125.5	4179.5
Melbourne	352.5	1150	571	41.5	2115

As expected, the building located in Darwin in the hot humid summer and warm winter zone showed the greatest potential for utilising natural ventilation, with the NVH number of 4728. While, the least natural ventilation potential with 2115 NVH was observed at Melbourne in the cool temperate zone. Additionally, the seasonal NVH results showed that summer and transition seasons (spring and autumn) were the optimal periods for utilising natural ventilation, while not being

applicable in winter in Sydney and Melbourne. By contrast, roughly similar NVHs (about 1000 of 2190 h) were observed in Darwin for summer and transition seasons, while a higher NVH was found in winter. This can be attributed to Darwin's tropical climate, with remarkably similar outdoor weather conditions during summer and transition seasons, yet more temperate conditions in winter [40].

The seasonal and annual NVH results of the three cities shown above demonstrated that the potential of utilising natural ventilation was significantly altered by local climate. Natural ventilation was applicable for more than half the year in the hot humid summer and warm winter zone and mild temperate zone, while only for a quarter of the year in the cool temperate zone.

3.2. Satisfied Natural Ventilation Hour

Since maintaining indoor thermal comfort without consuming industrial energy is the most significant advantage of natural ventilation, the potential for utilising natural ventilation meeting indoor thermal comfort requirements should be a significant concern. To quantify this potential, an index named the satisfied natural ventilation hour (SNVH) is proposed in this study. It is defined as the number of hours in a typical year (8760 h) or a typical season (2190 h) when indoor operative temperature under natural ventilation conditions could meet the thermal comfort requirements (i.e., within the 80% acceptable thermal comfort band). As both outdoor weather and building conditions (geometry, thermal performance) are considered in the definition, SNVH measures the maximum number of hours when the outdoor weather is favourable for the natural ventilation of a specific building based on indoor thermal comfort requirements. The SNVH numbers of the studied residential building in the three representative cities were calculated based on the proposed TRNSYS simulation.

Statistical data of SNVH during four seasons is presented in Table 3. Similar seasonal results were obtained for the SNVH and the formentioned NVH. The maximum SNVH value for the whole year occurred in Darwin, while the minimum value was observed in Melbourne. This demonstrates that the residential building located in Darwin, the hot humid summer and warm winter zone, has the greatest natural ventilation potential for maintaining thermal comfort. Due to the contribution of the hot humid summer and warm winter climate, the average air temperature of Darwin is about 20 °C in winter. Such pleasantly cool outdoor conditions improve the applicability of natural ventilation for maintaining indoor thermal comfort in Darwin. A relatively higher SNVH number was found in Darwin in winter. Significant seasonal difference for SNVH was found in Sydney and Melbourne. The greatest value of SNVH occurred in summer, while it was quite small and negligible in winter. However, the SNVH value for Melbourne during all seasons was dramatically lower than that of the other two cities. In addition, the annual SNVH to NVH ratio was calculated and is shown in the last column in Table 3. As a quantitative index representing the correlation between SNVH and NVH, the ratio was found to be 88% for Darwin, 84% for Sydney and 85% for Melbourne. In this study, the natural ventilation control strategy was constructed via the rule-based decision-tree prediction model based on outdoor climate data. These results implied that, in spite of the fact that natural ventilation potential for maintaining thermal comfort was significantly influenced by outdoor climate (embodied by the ANVH to NVH ratio), the effect of building characteristics such as layout, internal heat gain and the thermal performance of the envelope on indoor thermal comfort could not be underestimated when using natural ventilation. The factor of building characteristics should be considered in the rule-based decision-tree prediction model in future studies to further improve predictive accuracy.

Table 3. Thermal comfort potential during different seasons.

City	Satisfied Natural Ventilation Hours					SNVH _{total} /NVH _{total} (%)
	Spring	Summer	Autumn	Winter	Total	
Darwin	862	875	977.5	1426.5	4141	88
Sydney	787.5	1561.5	1036	125.5	3510.5	84
Melbourne	322.5	913.5	522.5	41.5	1800	85

3.3. Thermal Comfort Level or Indoor Operative Temperature

As mentioned, summer is the best season for utilising natural ventilation in all the three cities. To quantify the performance of indoor operative temperature during summer, hourly averaged data for the hottest month (January) was plotted for the three cities (Figure 8).

As revealed in the analysis of the decision-tree generation, outdoor temperature was the essential factor influencing indoor operative temperature when utilising natural ventilation. This result was confirmed by the temperature profiles shown in Figure 8. For all three cases, the fluctuations of outdoor air temperature and average indoor operative temperature were nearly consistent all the time, and the peak and trough values of average indoor operative temperature appeared simultaneously during natural ventilation.

Although consistent variation was found in average indoor operative temperature and outdoor air temperature, there were distinctive natural ventilation performances during January for the three cities. For Darwin and Melbourne cases (Figure 8a,c), natural ventilation was utilised with relatively regular time intervals during the whole month, resulting in virtually equal hours of natural ventilation and non-ventilation. By contrast, the natural ventilation schedule of Sydney was irregular in January, with a long and continuous ventilation period (Figure 8b). Thus, the natural ventilation time during January for the Sydney case was observed to be much longer than that for the Darwin and Melbourne cases.

The indoor operative temperature for the Darwin case was higher than the upper thermal comfort threshold during most non-natural ventilation periods (Figure 8a). However, this was maintained in the thermal comfort band for the Sydney and Melbourne cases (Figure 8b,c). Although outdoor temperature during most non-natural ventilation periods was dramatically lower than the thermal comfort threshold for the Melbourne case, the indoor operative temperature remained in the comfort band (Figure 8c). This can be attributed to the coupling effect of outdoor conditions and internal heat gain during natural ventilation and non-ventilation periods. For the Darwin case, the hot summer climate with discomforting outdoor conditions and internal heat gain were all disadvantages when it came to indoor thermal comfort. However, due to the heating effect of the internal heat source, the indoor operative temperature could be kept in the thermal comfort band with much lower outdoor temperatures during the non-ventilation periods in Melbourne.

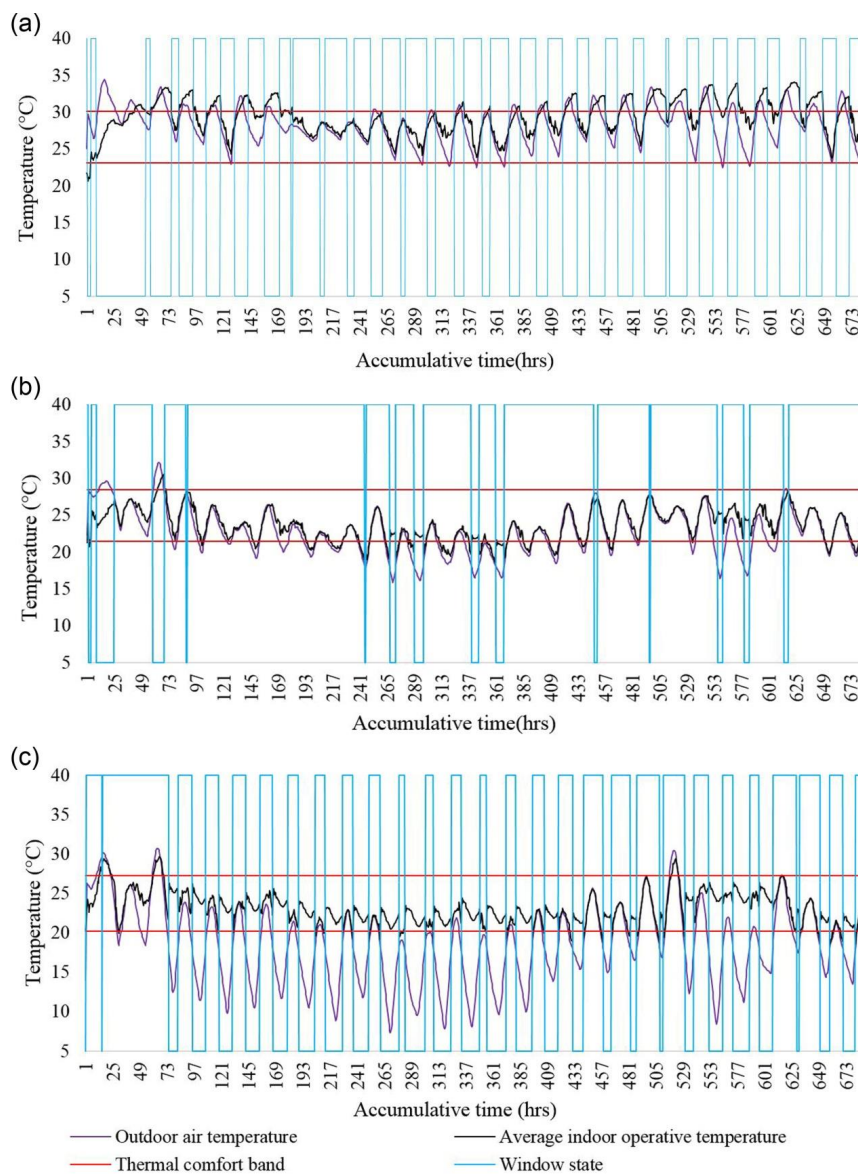


Figure 8. Indoor operative temperature variation during January in: (a) Darwin; (b) Sydney; and (c) Melbourne.

The indoor operative temperature results in January shown above implied that an air-conditioning system should be used in summer during non-ventilation periods in Darwin, while indoor thermal comfort requirements can be met only by utilising natural ventilation in Sydney and Melbourne.

Further qualitative analysis was also conducted to evaluate the average indoor operative temperature during winter for the three cases. The hourly outdoor temperature, indoor operative temperature, and thermal comfort band, were plotted against window opening conditions in Figure 9. In general, the fluctuation tendency of the indoor operative temperature was in keeping with that of the outdoor temperature for all the three cases. However, the thermal comfort level during July was found to be significantly different across Darwin, Sydney and Melbourne. Due to the warm winter climate, natural ventilation was applicable during the whole month in Darwin. Consequently, a regular ventilation schedule was adopted during July with longer natural ventilation hours than non-natural ventilation hours (Figure 9a). By contrast, during July the cold winter climate in Sydney and Melbourne reduced the suitability of natural ventilation. Thus, the natural ventilation hours were nearly zero for both the Sydney and Melbourne cases (Figure 9b,c). In summary, the average indoor

operative temperature that was observed remained in the thermal comfort band during most periods in Darwin and Sydney, although the natural ventilation periods for Sydney could almost be ignored; while the indoor operative temperature was found to be frequently lower than the lower thermal comfort threshold during the whole month for the Melbourne case. These results indicate that indoor thermal comfort could be achieved during winter with reasonable ventilation control in Darwin and Sydney, but the heating system would be needed for improving thermal comfort in Melbourne.

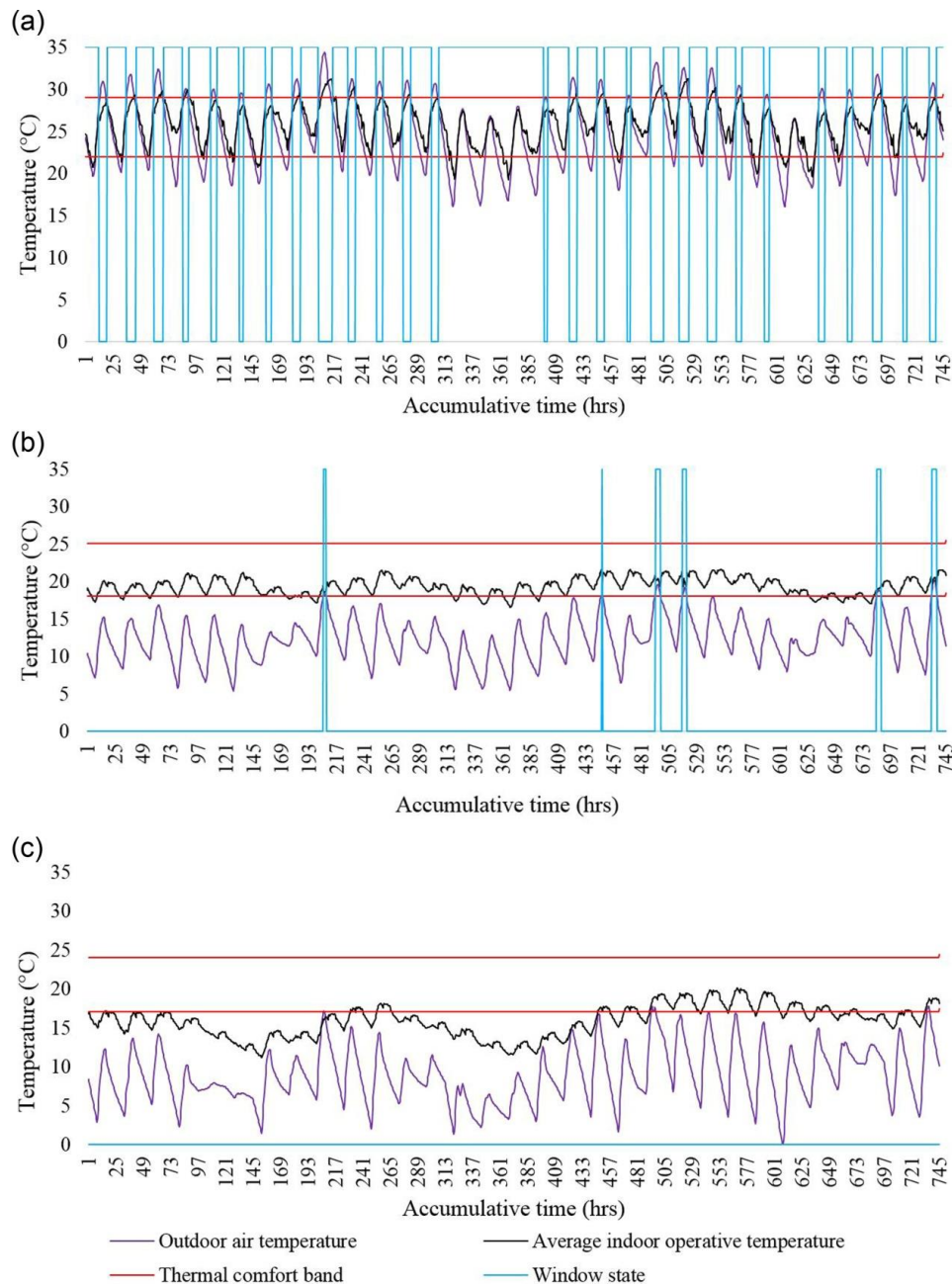


Figure 9. Indoor operative temperature variation during July in: (a) Darwin; (b) Sydney; and (c) Melbourne.

4. Conclusions

The natural ventilation potential of residential buildings located in three different Australian climate zones (hot humid summer and warm winter zone, mild temperate zone, and cool temperate zone) were investigated for a typical single-story house model. Three events were modelled in the

representative cities of Darwin, Sydney and Melbourne. Numerical simulations considering a natural ventilation strategy based on an approach combined with TRNSYS and COMIS were conducted for all the seasons. A rule-based decision-tree model was generated to modulate the window state for natural ventilation. Through a comparison of the numerical results with onsite experimental data, the accuracy of the proposed simulation approach was validated. The conclusions yielded from this study are summarised as follows:

The greatest natural ventilation potential was observed in Darwin (hot humid summer, warm winter zone) with the largest annual NVH and SNVH numbers 4728 and 4141, respectively; while, the least natural ventilation potential was found for the Melbourne case in the cool temperate zone. Natural ventilation was applicable during the whole year in Darwin, while summer and transition seasons (spring and autumn) were found to be the optimal periods in Sydney and Melbourne for utilising this. The potential for utilising natural ventilation to maintain indoor thermal comfort was altered by both local climate and building conditions. The indoor operative temperature was higher than the upper thermal comfort threshold during most non-natural ventilation periods in January in the case of Darwin, but out of the lower thermal comfort band for most of the time during July for Melbourne. This indicates that, except for non-natural ventilation periods in summer in Darwin and winter in Melbourne, indoor thermal comfort requirements can be met only by utilising natural ventilation in all the three cities over the whole year.

The potential for utilising natural ventilation for residential buildings in Australia is significantly altered by climate. As the current study considered only the three most populous climate zones with three representative cities, further research is needed to investigate the variation of natural ventilation potential across the whole of Australia. Despite existing limitations, the findings and simulation approach presented in this study can assist architects and policy makers in quantifying the potential for utilising natural ventilation under the three most representative climates; and can be used as a reference guideline for the natural ventilation design of residential buildings in Australia.

Acknowledgments: The financial support of the Fundamental Research Funds for the Central Universities (Project ID: 310828171006) is gratefully acknowledged. The contribution of Dr. Zhenjun Ma on simulation design is gratefully acknowledged.

Author Contributions: X.D. and Z.T. conceived and designed the experiments; X.D. performed the experiments; Z.T. and X.D. analyzed the data; Z.T. and X.D. wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Pressure coefficient in the openings of the case study building.

Angle	Facade-E1	Facade-E2	Facade-E3	Facade-E4	Facade-N1	Facade-N2	Facade-N3	Facade-N4	Facade-S1	Facade-S2	Facade-S3	Facade-S4	Facade-S5	Facade-S6	Facade-S7	Facade-W1
0	-0.333	-0.437	-0.47	-0.797	0.817	0.864	0.835	0.827	-0.34	-0.339	-0.312	-0.243	-0.24	-0.258	-0.329	-0.353
45	-0.629	0.085	0.127	0.404	0.527	0.449	0.08	0.432	-0.434	-0.696	-1.371	-0.278	-0.476	-0.636	-0.642	-0.263
90	-0.15	0.942	0.956	0.946	-0.608	-0.403	-0.197	-0.136	-0.115	-0.137	-0.178	-0.22	-0.282	-0.251	-0.614	-0.102
135	0.792	0.327	0.328	0.151	-0.45	-0.388	-0.329	-0.333	-0.046	0.161	0.538	0.183	0.399	-0.009	0.739	-0.267
180	0.196	-0.664	-0.718	-0.402	-0.314	-0.209	-0.301	-0.307	0.289	0.345	0.17	0.769	0.933	0.555	0.661	-0.435
225	-0.429	-0.402	-0.395	-0.404	-0.338	-0.349	-0.354	-0.306	0.224	0.365	0.053	0.85	0.858	0.958	-0.278	0.161
270	-0.181	-0.092	-0.098	-0.08	-0.122	-0.176	-0.493	-0.674	-0.577	-0.523	-0.487	-0.51	-0.482	0.18	-0.190	0.357
315	-0.216	-0.291	-0.303	-0.274	0.25	0.287	0.797	0.712	-0.47	-0.47	-0.453	-0.38	-0.395	-0.432	-0.195	0.151

Table A2. Occupant activity and equipment usage.

	Heat Gain	Schedule
Occupant 1	60 w	23:00–08:00 in the master room; 08:00–17:00 in the study room; and 17:00–23:00 in the living room
Occupant 2	60 w	23:00–08:00 in the master room and 17:00–23:00 in the living room
Light	4 w/m ²	18:00–23:00 in all rooms
Computer	90 w	09:00–17:00 in the study room
TV	120 w	19:00–23:00 in the living room
Fridge	60 w	24 h in the living room
Oven	1500 w	08:00–08:30, 12:30–13:00 and 18:00–18:30 in the living room
Washing machine	300 w	09:00–10:00 in the laundry

Table A3. Induction rules setting.

Minimal Gain	Minimal Leaf Size	Minimal Size for Splitting	Initial Maximum Tree Depth
10%	4	2	3

References

1. Chen, Y.; Tong, Z.; Malkawi, A. Investigating natural ventilation potentials across the globe: Regional and climatic variations. *Build. Environ.* **2017**, *122*, 386–396. [[CrossRef](#)]
2. Haase, M.; Amato, A. An investigation of the potential for natural ventilation and building orientation to achieve thermal comfort in warm and humid climates. *Sol. Energy* **2009**, *83*, 389–399.
3. Chenari, B.; Carrilho, J.D.; Silva, M.G.D. Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: A review. *Renew. Sustain. Energy Rev.* **2016**, *59*, 1426–1447.
4. Jomehzadeh, F.; Nejat, P.; Calautit, J.K.; Yusof, M.B.M.; Zaki, S.A. A review on windcatcher for passive cooling and natural ventilation in buildings, Part 1: Indoor air quality and thermal comfort assessment. *Renew. Sustain. Energy Rev.* **2017**, *70*, 736–756. [[CrossRef](#)]
5. Stabile, L.; Dell’Isola, M.; Russi, A.; Massimo, A.; Buonanno, G. The effect of natural ventilation strategy on indoor air quality in schools. *Sci. Total Environ.* **2017**, *595*, 894. [[CrossRef](#)] [[PubMed](#)]
6. Dimitroulopoulou, C. Ventilation in European dwellings: A review. *Build. Environ.* **2012**, *47*, 109–125. [[CrossRef](#)]
7. Ghiaus, C.; Allard, F.; Wilson, M. *Natural Ventilation in the Urban Environment Assessment and Design*; Earthscan: London, UK, 2005.
8. Luo, Z.; Zhao, J.; Gao, J.; He, L. Estimating natural-ventilation potential considering both thermal comfort and IAQ issues. *Build. Environ.* **2007**, *42*, 2289–2298. [[CrossRef](#)]
9. Yang, L.; Zhang, G.; Li, Y.; Chen, Y. Investigating potential of natural driving forces for ventilation in four major cities in China. *Build. Environ.* **2005**, *40*, 738–746. [[CrossRef](#)]
10. Teitel, M.; Tanny, J. Natural ventilation of greenhouses: Experiments and model. *Agric. For. Meteorol.* **1999**, *96*, 59–70. [[CrossRef](#)]
11. Fordham, M. Natural ventilation. *Renew. Energy* **2000**, *19*, 17–37.
12. Kaye, N.B.; Hunt, G.R. Heat source modelling and natural ventilation efficiency. *Build. Environ.* **2007**, *42*, 1624–1631. [[CrossRef](#)]
13. Chen, Z.D.; Li, Y.; Mahoney, J. Natural ventilation in an enclosure induced by a heat source distributed uniformly over a vertical wall. *Build. Environ.* **2001**, *36*, 493–501. [[CrossRef](#)]
14. El-Agouz, S.A. The effect of internal heat source and opening locations on environmental natural ventilation. *Energy Build.* **2008**, *40*, 409–418. [[CrossRef](#)]
15. Bolster, D.; Maillard, A.; Linden, P. The response of natural displacement ventilation to time-varying heat sources. *Energy Build.* **2008**, *40*, 2099–2110. [[CrossRef](#)]
16. Coomaraswamy, I.A. *Natural Ventilation of Buildings: Time-Dependent Phenomena*; University of Cambridge: Cambridge, UK, 2011.
17. Ghiaus, C.; Allard, F.; Santamouris, M.; Georgakis, C.; Nicol, F. Urban environment influence on natural ventilation potential. *Build. Environ.* **2006**, *41*, 395–406. [[CrossRef](#)]
18. Han, J.; Yang, W.; Zhou, J.; Zhang, G.; Zhang, Q.; Moschandreas, D.J. A comparative analysis of urban and rural residential thermal comfort under natural ventilation environment. *Energy Build.* **2009**, *41*, 139–145. [[CrossRef](#)]
19. Hang, J.; Luo, Z.; Sanberg, M.; Gong, J. Natural ventilation assessment in typical open and semi-open urban environments under various wind directions. *Build. Environ.* **2013**, *70*, 318–333. [[CrossRef](#)]
20. Kolokotroni, M.; Giannitsaris, I.; Watkins, R. The effect of the London urban heat island on building summer cooling demand and night ventilation strategies. *Sol. Energy* **2006**, *80*, 383–392. [[CrossRef](#)]
21. Wang, L.; Greenberg, S. Window operation and impacts on building energy consumption. *Energy Build.* **2015**, *92*, 313–321. [[CrossRef](#)]
22. Su, X.; Zhang, X.; Gao, J. Evaluation method of natural ventilation system based on thermal comfort in China. *Energy Build.* **2009**, *41*, 67–70. [[CrossRef](#)]
23. Calautit, J.K.; Hughes, B.R.; Ghani, S.A. A numerical investigation into the feasibility of integrating green building technologies into row houses in the Middle East. *Archit. Sci. Rev.* **2013**, *56*, 279–296. [[CrossRef](#)]
24. Artmann, N.; Manz, H.; Heiselberg, P. Climatic potential for passive cooling of buildings by night-time ventilation in Europe. *Appl. Energy* **2007**, *84*, 187–201. [[CrossRef](#)]
25. Australian Bureau of Statistics. *Year Book Australia, 2012*; ABS Canberra: Canberra, Australia, 2012.

26. BD-058, AS/NZS 4859.1:2009 *Materials for the Thermal Insulation of Buildings—General Criteria and Technical Provisions*; SAI Global: Sydney, Australia, 2009.
27. Montazeri, H.; Blocken, B. CFD simulation of wind-induced pressure coefficients on buildings with and without balconies: Validation and sensitivity analysis. *Build. Environ.* **2013**, *60*, 137–149. [[CrossRef](#)]
28. ASHRAE. *Applications (SI)*; ASHRAE Inc.: Atlanta, GA, USA, 2011.
29. Mei, L.; Infield, D.; Eicker, U.; Fux, V. Thermal modelling of a building with an integrated ventilated PV façade. *Energy and Build.* **2003**, *35*, 605–617. [[CrossRef](#)]
30. Lu, S.; Zhao, Y.; Fang, K.; Li, Y.; Sun, P. Establishment and experimental verification of TRNSYS model for PCM floor coupled with solar water heating system. *Energy Build.* **2017**, *140*, 245–260. [[CrossRef](#)]
31. Aparicio-Fernández, C.; Vivancos, J.L.; Ferrer-Gisbert, P.; Royo-Pastor, R. Energy performance of a ventilated façade by simulation with experimental validation. *Appl. Therm. Eng.* **2014**, *66*, 563–570. [[CrossRef](#)]
32. Han, J.; Kamber, M.; Pei, J. *Data Mining: Concepts and Techniques: Concepts and Techniques*; Elsevier: Amsterdam, The Netherlands, 2011.
33. Deuble, M.P.; de Dear, R.J. Mixed-mode buildings: A double standard in occupants' comfort expectations. *Build. Environ.* **2012**, *54*, 53–60. [[CrossRef](#)]
34. Tong, Z.; Chen, Y.; Malkawi, A. Estimating natural ventilation potential for high-rise buildings considering boundary layer meteorology. *Appl. Energy* **2017**, *193*, 276–286. [[CrossRef](#)]
35. ASHRAE. *Thermal Environmental Conditions for Human Occupancy*; Standard 55-2013; ASHRAE: Atlanta, GA, USA, 2013.
36. Pang-Ning, T.; Steinbach, M.; Kumar, V. *Introduction to Data Mining*; Library of Congress: Washington, DC, USA, 2006.
37. Yu, Z.; Haghghat, F.; Fung, B.C.M.; Yoshino, H. A decision tree method for building energy demand modeling. *Energy Build.* **2010**, *42*, 1637–1646. [[CrossRef](#)]
38. Rokach, L.; Maimon, O. *Data Mining with Decision Trees: Theory and Applications*; World Scientific: Singapore, 2014.
39. Shri, A.; Shri, A.; Sandhu, P.S.; Gupta, V.; Anand, S. Prediction of reusability of object oriented software systems using clustering approach. *World Acad. Sci. Eng. Technol.* **2010**, *43*, 853–856.
40. Sturman, A.P.; Tapper, N.J. *Weather and Climate of Australia and New Zealand*; Oxford University Press: Oxford, UK, 2006.



© 2017 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).