Assessment of natural ventilation potentials on free-form architecture design using CFD simulations: a Learning Hub building in Singapore

https://escholarship.org/uc/item/0wb1k6xf

Szu Cheng, CHIEN

2013-09-09

ASSESSMENT OF NATURAL VENTILATION POTENTIALS ON FREE-FORM ARCHITECTURE DESIGN USING CFD SIMULATIONS: A LEARNING HUB BUILDING IN SINGAPORE

Wu Xiaoying[1], Chien Szu-Cheng[2], and Li Hua[3]
[1]Energy Research Institute @ NTU (ERI@N), Singapore
[2]Berkeley Education Alliance for Research in Singapore (BEARS) Center
[3]Nanyang Technological University, Singapore

ABSTRACT

This research focuses on an effort to demonstrate a case study of CFD approach to natural ventilation evaluation in freeform architecture design in Tropics. We first constructed the CFD models based on three building design configurations and then compared. Thereby, the complicated building geometry together with the CFD modelling issues (domain setting and model simplification) was investigated. Subsequently, steady state, k-ε turbulence model and incompressible flow of a constant property fluid was considered. Furthermore, climate information (wind directions, temperature, and solar heat gain), urban context (surrounding building masses and distribution), and time and season-based changes were collected and evaluated. CFD simulation was performed along with the whole design process iteratively to optimize the natural ventilation as well as the architecture design. The result of this study is expected to serve as a solid basis for the CFD application to optimize the natural ventilation and create innovate ventilation strategies, and hence to achieve sustainability in building designs without compromising the novel architecture design potentials.

INTRODUCTION

In the past decades, air-conditioning systems were predominately conducted in Singapore. However, the increased focus on climate change and sustainability has encouraged people to reconsider the deployment of natural ventilation in buildings in terms of energy efficiency. Furthermore, Computational Fluid Dynamics (CFD) simulation has been increasingly employed for predicting building airflows and testing natural ventilation strategies [1-3]. On the other hand, in recent years, new possibilities have emerged to allow the architects and structure engineers to further explore novel architecture forms and design based on advancements in AEC (architecture, engineering, and construction). Therefore, the evaluation and prediction of building performance with CFD in design phase will be a great challenge.

The present study focuses on an effort to demonstrate a case study of CFD approach to natural ventilation evaluation in freeform architecture design in a challenging climate zone, namely the hot-humid climate in Singapore. We first investigated the CFD modelling issues (e.g. domain setting and model simplification) to better construct the CFD model in terms of the complicated geometry. Subsequently, steady, k-ε turbulence model and incompressible flow of a constant property fluid were considered. Furthermore, climate information (wind directions, temperature, and solar heat gain), urban context (surrounding building masses and distribution), and season-based changes were collected and evaluated. CFD simulation was performed along with the whole design process iteratively to optimize the natural ventilation as well as the architecture design. The result of this study is expected to serve as a solid basis for the CFD application to optimize the natural ventilation and create innovate ventilation strategies, and hence to achieve sustainability in building designs without compromising the novel architecture design potentials.

In this paper, level 1, 2, 3 … 9 are named as L1, L2, L3… L9. North wind, northeast wind, south wind and southeast wind are named as N-Wind, NE-Wind, S-Wind and SE-Wind. Point a, b, c and d are named as P-a, P-b, P-c and P-d.

APPROACH

Case Study: Learning Hub in NTU Campus

The case study project is Learning Hub, an educational facility designed and built for Nanyang Technological University (NTU) in Singapore as shown in Figure 1 [4]. The building design was completed in Oct 2012 with CFD evaluation started from March to October 2012. Currently it is under construction.

This hub has 9 stories with total height 34.2 meters, and each level has 3.8 meters height. It is designed with a structure without conventional corridors. As a flower like layout, it is made up with several “petals” (involving 55 tutorial rooms), atrium and 3 staircase blocks, as shown in Figure 3. In L1, there are only

Proceedings of the SB 13 Singapore — Realising Sustainability in the Tropics

ISBN: 978-981-07-7377-9

petals in the north, south and west side. From L2 to L6, there are 13 petals. In L7, L8 and L9, there are 10, 6 and 4 petals respectively.

Also, it allows the students enter from all directions around into a large central space which links all the separate "petals" together. The classrooms are stacked into each "petal" tower and build up gradually. Gardens, shaded terraces, and pergolas are on selected upper levels and rooftops, as shown in Figure 1. All the rooms are air-conditioned. On the other hand, the public spaces (e.g. the corridors and atrium area) are designed to be naturally ventilated.

Figure 1 Impression drawing of Learning Hub [4]

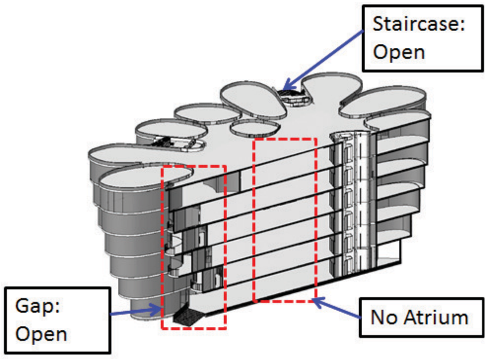
The main objective is to explore the effect of atrium design on the natural ventilation performance of Learning Hub. Thereby, four wind directions and seasonal changes are considered. We mainly focus on the following questions: i) Atrium and openings are considered as a good design to facilitate the natural ventilation in structured buildings. However, how good can the atrium design and openings help to improve the natural ventilation in such freeform architecture? and, ii) what are the implications of such freeform architecture design in Tropics in terms of natural ventilation? Thus, three cases were studied and then compared, namely Base Case, Variant I, and Variant II.

These three simulation cases are illustrated in Figure 2 and descripted in Table 1. The difference between Base Case and Variant II is that there is an atrium in Variant II but no atrium in Base Case. As illustrated in Figure 3, there are 3 staircases and 10 gaps in this building. The difference between Variant II and I is that, the gaps between blocks and staircases are closed in Variant I, but 50% meshed in Variant II. In another words, there is C-Ventialtion in Variant II but not in Variant I from L2 to L6.

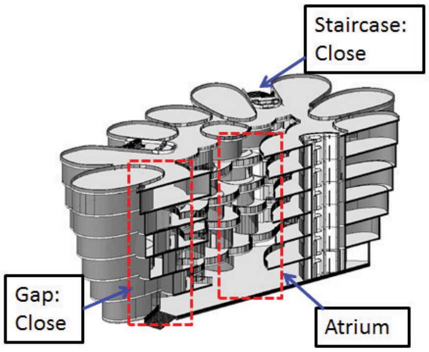
All the simulation cases are shown in Table 1, which include two design models and four wind directions N-Wind, NE-Wind, S-Wind and SE-Wind.

In order to measure the performance of natural ventilation within atrium, two parameters are used here, which are:

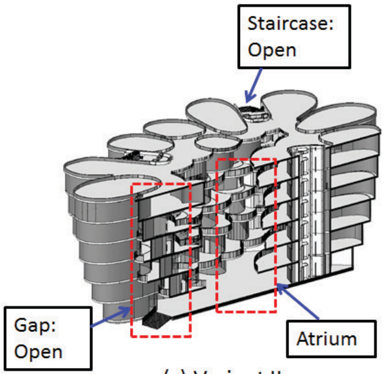
- Volume weighted average velocity magnitude within the atrium. It is based on the volume of whole atrium from ground level up to level 9. The total height of the atrium is 34.2 meters.
- Velocity magnitude of 4 points on each level. The 4 points are indicated in Figure 3 as P-a, P-b, P-c and P-d. in the following paper. P-a is the centre point of atrium area where there is no people activates. P-b, P-c and P-d are located in the corridor area where lots of human activities happen.



(a) Base



(b) Variant I



(c) Variant II

Figure 2 Cross section view of 3 models: (a) Base, (b) Variant I and (c) Variant II.

Table 1
Matrix of 3 simulation cases

	Base Case	**Variant I**	**Variant II**
Atrium	No	Yes	Yes
Gaps	Open	Close	Open
Staircases	Open	Close	Open

CFD Model Description

The computational model is illustrated in Figure 4. The domain is a cubic with dimension 1000 m × 1000 m × 500 m. The Learning Hub model and its surrounding buildings are located in the centre of the domain.

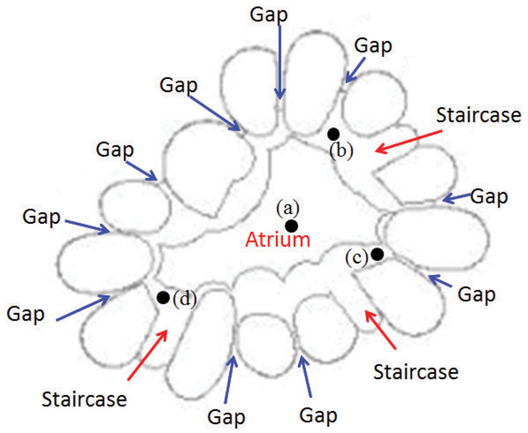


Figure 3 An example of positions of atrium, gaps and staircases together with four selected measured points in computational model (level 5).

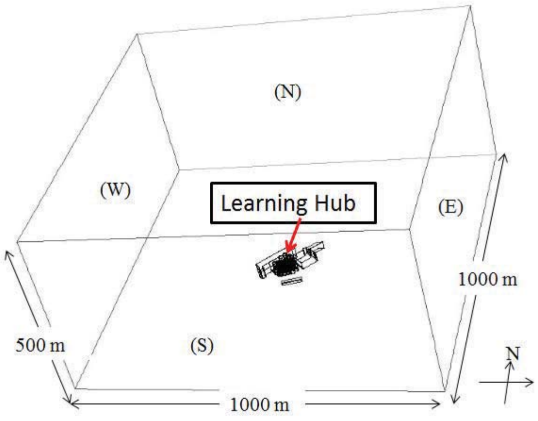


Figure 4 Geometry of the computational domain.

Figure 3 is the top view of the Learning Hub computational model. In order to build up the simulation model, following assumptions are made.

1) The ground is assumed to be a flat surface;
2) The height differences between Learning Hub and surrounding buildings are considered.
3) The envelope of staircases is assumed to be a porous face with 50% porosity for Base Case and Variant II.

Turbulent Model

The turbulence models were divided into two groups: large-eddy simulations (LES), and turbulent transport model (Reynolds averaged Navier-Stocke equation modelling, RANS). Generally, LES model provides much more information about the flow field and the dispersion process than the RANS approach which directly gives only the mean field and provides only statistical estimates for the turbulent transport. This has been proven in many areas [5-7]. However, LES requires finer grid distribution which will increase the computing time dramatically. RANS models are the two-equation turbulence models, k-ε and k-ω models in which k represent the turbulent kinetic energy, ε is the turbulent dissipation rate and ω is specific dissipation rate. The k-ε models can be separated into standard model, renormalization group theory (RNG) model and realizable model. RNG model performs better than standard k-ε model near wall surfaces [8]. Also, RNG model provides reasonable accuracy compared to large-eddy simulation (LES) that is more computational intensive but with higher accuracy. In order to make the results as accurate as possible and save computational time at the same time, RNG k- ε model is used in this paper.

Radiation Model

In order to calculate the solar heat gains, the position of the sun in the sky, solar intensity, and the thermal radiation exchange between each building envelope element and the surroundings, must be calculated [9]. Fluent offers the Solar Ray Tracing model which helps to calculate the direction of solar radiation. The time selected was 13:00 on 21st June, which represented the peak solar load time in Singapore. In order to calculate the thermal radiation exchange, the Discrete Ordinates model was used. The radiation model was only used in Case II, where the buoyancy effect was included.

Wind Data in Singapore

In Singapore, there are four prevailing winds: N-Wind, NE-Wind, S-Wind and SE-Wind. The average wind speed are 2 m/s, 2.9 m/s, 2.8 m/s and 3.2 m/s accordingly. According to the statistics by National Environmental Authority of Singapore [10], N-Wind and NE-Wind prevail from December to March, and S-Wind and SE-Wind prevail from May to September; in the months of April, October and November, the wind directions are various. In this paper, we assumed that, in April, October and November the time are evenly shared by all four prevailing winds; N-Wind and NE-Wind evenly share the time from December to March; and the same assumption was applied to S-Wind and SE-Wind. Therefore, the frequencies for N/NE wind and S/SE wind in a year are 22.9% and 27.1%.

Boundary Conditions

External climate affects the ventilation profiles inside the building, especially when it is natural ventilation. For wind driven ventilation, the most important weather factor is the wind condition including the wind direction, speed and frequency. For buoyancy driven ventilation, the outdoor air temperature, solar radiation and other heat sources inside the building are important weather data. In this model, solar radiation is the only heat source for buoyancy driven ventilation.

The faces (N), (E), (S) and (W) indicated in Figure 4 are north face, east face, south face and west face for the cubic domain. Except these four faces, the top face and bottom face represents the sky and the ground, which were set as symmetry and wall in the boundary condition accordingly. The boundary conditions for faces (N), (E), (S) and (W) varied accordingly, as shown in Table 2. Inside the domain, all the boundaries except the staircases and gaps in between "petals" were modelled as no-slip wall boundaries with zero heat flux. The staircases and gaps in between "petals" were modelled as porous jump boundaries with 50% porosity. Fluent offers kinds of calculations for inertial resistance coefficient. In the present work, a solid plate with holes model is used [11]. The thickness of the surface was assumed to be 0.1 m and C_2 calculated is 31.24 /m.

Table 2
Boundaries conditions for four wind scenarios.

Faces	N-Wind	NE-Wind	S-Wind	SE-Wind
(N)	Velocity inlet	Velocity inlet	Pressure Outlet	Pressure Outlet
(E)	Pressure Outlet	Velocity inlet	Pressure Outlet	Velocity inlet
(S)	Pressure Outlet	Pressure Outlet	Velocity inlet	Velocity inlet
(w)	Pressure Outlet	Pressure Outlet	Pressure Outlet	Pressure Outlet

RESULTS AND DISCUSSIONS

The types of natural ventilation driving forces are summarized in Table 3. In Base Case, wind-driven ventilation which is also cross ventilation dominates; in Variant II, there are two driving forces, wind and buoyancy effect, which is hybrid ventilation; in Variant I, buoyancy driven ventilation dominates from L2 to L6 and hybrid ventilation dominates the other levels. Figure 5 is an example of velocity contours in nine levels.

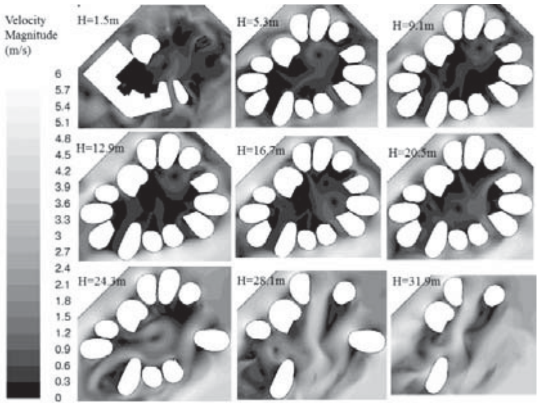


Figure 5 Velocity contours in 9 levels for Base Case NE-Wind.

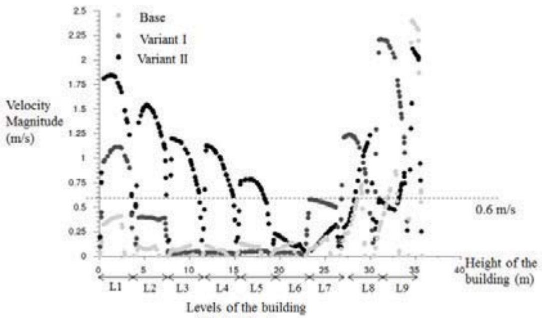
Effect of wind directions on atrium natural ventilation

As shown in Table 3, for all 3 cases, when the wind blows from southeast, the volume-weighted average velocity within the atrium has the highest value, followed by northeast wind, south wind and north wind. This matches the sequence of input where the southeast wind has the highest average wind speed 3.2 m/s, followed by northeast wind 2.9 m/s, south wind 2.8 m/s and north wind has the lowest average wind speed 2 m/s.

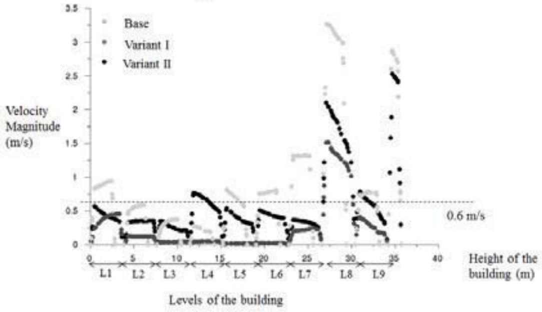
Table 3
Volume-weighted average velocity of 3 cases.

Speed (m/s)	Base Case	Variant I	Variant II
N-Wind	1.14	1.61	1.63
NE-Wind	2.14	1.86	1.91
S-Wing	1.75	1.73	1.91
SE-Wind	2.22	1.86	2.13
Average in a year	1.83	1.77	1.91

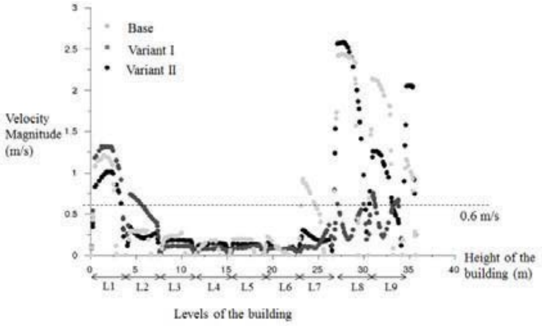
The effect of wind directions in various locations is summarized in Table 4. Inside the Table 4, the black dot means that in certain wind direction, the wind speed in certain location is larger than 0.6 m/s, which is one requirement for human comfort [12] in Singapore.



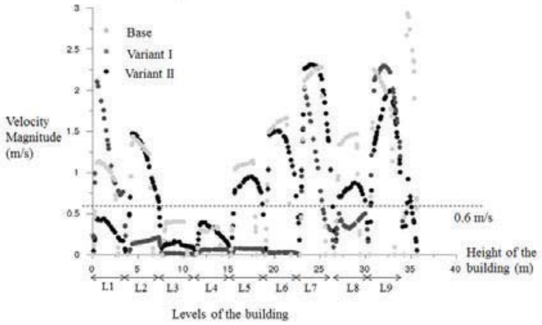
(a) N-Wind



(b) NE-Wind



(c) S-Wind



(d) SE-Wind

Figure 6 Velocity magnitude plot on Line-a for (a) N-Wind, (b) NE-Wind, (c) S-Wind and (d) SE-Wind.

As mentioned above, P-a is located in the centre of atrium, and P-b, P-c and P-d are located in different corners where are corridors. From the Table 4, we can see that, in all 3 cases, the performance of natural ventilation from level 2 to level 6 is the worst compared with the other levels, where almost no wind scenario could match the human comfort standard in the corridor. The performance of cross ventilation becomes better from level 7 and above. The main reason is that some blocks are removed from level 7 and above, which is shown in Figure 5 clearly. This enhance the cross ventilation. Level 1 is the ground floor and lots of people activities happen here. For both two cases, either N/NE wind or S/SE wind helps to reach the human comfort level in P-a, P-b and P-c. P-d locates in the deep corner and no cross ventilation could happen here.

All the wind directions do not exist all the time in a year but are seasonal. From December to March, N/NE wind dominates; and from May to September, S/SE wind dominates. Therefore, even though the average wind speed at certain point can be larger than 0.6 m/s for certain wind scenario, this can only happen in certain month not whole year.

Effect of atrium design on atrium natural ventilation

The Base Case is without atrium case and Variant II is the one with atrium, and all the other designs for both cases are the same. By comparing Base case and Variant II, it is shown in Table 3 that, for N-Wind and S-Wind, the volume-weighted average wind velocity of atrium is increased by 43.0% and 9.1% accordingly, after adding the atrium. However, the volume-weighted average wind velocity of atrium is decreased by 10.7% and 4.1% for NE-Wind and SE-Wind. For north monsoon which include north wind and northeast wind, the average wind velocity in atrium is increased by 7.9%, after adding the atrium. Similarly, for the south monsoon, the average wind velocity is increased by 2%. In a year, the time percentage for north and south monsoon is 22.9% and 27.1%. Therefore, the average wind velocity in the atrium is 1.83 and 1.91 m/s, for Base Case and Variant II. Therefore, in a year, the volume-weighted average velocity in atrium is increased by 4.4% by adding the atrium, in such a freeform architecture design.

The difference between Variant I and II is that the staircases and gaps between blocks are closed for Variant I and open for Variant II. In another word, from level 2 to level 6, it is hybrid ventilation in Variant II and only wind driven ventilation in Variant I. By comparing these two cases, the volume-weighted average wind velocity of atrium is increased by 1.24%, 2.69%, 10.4% and 14.52% for N-Wind, NE-Wind, S-Wind and SE-Wind separately. In a year, the volume-weighted average velocity in atrium is increased by 7.91% by adding openings in the building.

From Table 4, in Base Case, there are 24 black dots under N/NE-Wind and 29 black dots under S/SE-Wind; in Variant I, there are 21 and 23 black dots under N/NE-Wind and S/SE-Wind; in Variant II, there are 21 and 39 black dots under N/NE-Wind and S/SE-Wind accordingly. Therefore, the comfortable time percentage in a year for Base Case, Variant I and II are 37.10%, 30.67% and 42.72%. This means that the comfortable time in a year is increased by 5.62% by adding atrium, and 12.04% by adding openings in this building. The detailed calculation is shown in Table 5.

The velocity magnitudes at P-a for all 3 cases and four wind scenarios are shown in Figure 6. From Figure 6, we can see that, the velocity magnitude increases and then decreases within a level, which forms a parabola pattern. For all three cases and 4 wind directions, the velocity magnitude from level 2 to level 6 is the lowest compared with the other levels. For N-Wind, there is a big difference in velocity magnitude between Variant II and Base Case; for other wind directions, the velocity magnitude of Base Case and Variant II is very similar. Variant II has higher velocity magnitude than Variant I in almost all scenarios, except S/SE-Wind Level 1.

CONCLUSION

In this research effort, we have investigated the natural ventilation performance towards optimal freeform architecture design. We demonstrated the process and generated a set of CFD models on the basis of wind directions, tropical climate and building heights. The following main conclusions are drawn from this study: in such a freeform architecture design, 1) the volume-weighted average velocity of atrium is increased by 4.4% by adding atrium; 2) the percentage of comfortable time calculated based on air velocity on an annual basis is increased by 5.61% by adding the atrium; 3) the volume-weighted average velocity of atrium is increased by 7.91% by adding openings and using naturally ventilated staircases; 4) the percentage of comfortable time calculated based on the air velocity on annual basis is increased by 12.04% by adding openings and using naturally ventilated staircases. In the future, long-term monitored data collection and analysis will be further investigated. Further thermal comfort analysis will be carried out.

ACKNOWLEDGMENTS

This research is supported in part by grants from Office of Development & Facilities Management and Energy Research Institute, Nanyang Technological University. Also, it is partially funded by the Republic of Singapore's National Research Foundation through a grant to the Berkeley Education Alliance for Research in Singapore (BEARS) for the Singapore-Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST) Program. BEARS has been established by the University of California, Berkeley as a centre for intellectual excellence in research and education in Singapore.

REFERENCES

1. Liu P.C., Lin, H.T. & Chou, J.H. 2009. Evaluation of buoyancy-driven ventilation in atrium buildings using computational fluid dynamics and reduced-scale air model, Building and Environment 44 1970-1979.
2. Cook, M.J., Ji, Y. & Hun, G.R. 2003. CFD modelling of natural ventilation: combined wind and buoyancy forces, International Journal of Ventilation 1, 169-180.
3. Zhai, Z. & Chen, Q. 2006. Sensitivity analysis and application guides for integrated building energy and CFD simulation, Energy and Buildings 38 (9) 1060-1068.
4. Nanyang Technological University website, [Online], Available: http://www.ntu.edu.sg/Pages/home.aspx [14 May 2013].
5. Shuzo, M., Akashi, M., & Yoshihiko, H. (1990). Examing the k-ε model by means of a wind tunnel test and large-eddy simulation of the turbulence structure around a cube. Wind Engineering and Industrial Aerodynamics, 35, 87-100.
6. Bu, Z. & Kato, S. (2010). Numerical simulation of wind-driven natural ventilation in basement and attached areaway space in single detached dwelling. In The Fifth International Symposium on Computational Wind Engineering Conference.
7. Nielsen, P.V. (1998). The selection of turbulence models for prediction of room airflow. ASHRAE Transactions, 104(1B), 1119-1127.
8. Evola, G. & Popov, V. (2006). Computational analysis of wind driven natural ventilation in buildings. Energy and Buildings. 38(5), 491 - 501.
9. Shafqat, H. and Patrick, H.O. 2012. Numerical investigations of buoyancy-driven natural ventilation in a simple atrium building and its effect on the thermal comfort conditions. Applied Thermal Engineering 40 358-372.
10. Singapore National Environment Agency, (2009). Weather Wise Singapore, Singapore.
11. Porous media conditions, [Online], Available: https://www.sharcnet.ca/Software/Fluent13/help/flu_ug/flu_ug_sec_bc_porous_media.html.
12. Building Construction Authority. (2010). BCA Green Mark: Certification Standard for New Buildings. Singapore.

Table 4
Statistics of wind directions where human comfort based on air speed is matched.

		P-a				**P-b**				**P-c**				**P-d**			
		N	NE	S	SE	N	NE	S	SE	N	NE	S	SE	N	NE	S	SE
Base	L1	●		●		●	●		●	●		●	●				
	L2	●			●												
	L3	●															●
	L4	●	●														●
	L5	●			●												
	L6				●		●		●								
	L7				●		●		●		●	●	●			●	●
	L8	●	●	●	●	●		●	●	●	●		●	●	●		●
	L9	●	●	●	●	●		●	●	●		●	●	●	●		●
Variant I	L1	●		●	●	●	●		●		●		●	●			
	L2																
	L3																
	L4																
	L5																
	L6																
	L7				●		●		●		●	●	●			●	●
	L8	●	●			●	●	●	●	●	●	●	●	●	●	●	●
	L9	●			●	●		●	●	●	●	●	●	●	●	●	●
Variant II	L1		●	●	●			●	●	●			●				
	L2				●				●								
	L3						●										●
	L4						●										●
	L5		●		●								●				●
	L6		●		●		●		●								●
	L7		●	●	●			●	●		●	●	●		●	●	●
	L8		●	●	●	●		●	●	●	●	●	●		●	●	●
	L9	●	●	●	●	●		●	●	●	●	●	●		●	●	●

Table 5
Comfortable time percentage calculation in a year based on air velocity at 4 points.

Wind Directions	**Parameters**	**Base Case**	**Variant I**	**Variant II**
N/ NE	No. of black dots	24	21	21
	Possibility of black dots (%)	33.33	29.17	29.17
	Possibility N/NE in a year (%)	45.8		
S/ SE	No. of black dots	29	23	39
	Possibility of black dots (%)	40.28	31.94	54.17
	Possibility of S/SE in a year (%)	54.2		
Comfortable time percentage in a year (%)		37.10	30.67	42.72