Natural Ventilation Applications in Hot-humid Climate: A Preliminary Design for the College of Design at NTUST

Ming-Tse Lin	Hao-Yang Wei	Yi-Jiun Lin	Ho-fu Wu	Po-Hung Liu
Associated Architect	Associate Professor	Assistant Professor	Professor	Associated Architect
Bio-Architecture Formosana Firm	Department of Architecture, NTUST	Department of Mechanical Engineering, NTUST	Department of Architecture, Cal Poly Pomona	Bio-Architecture Formosana Firm
Taipei, Taiwan	Taipei, Taiwan.	Taipei, Taiwan.	Pomona, CA, U.S.A	Taipei, Taiwan

ABSTRACT

In Taiwan's humid environment, the application of natural ventilation is an essential passive strategy for high performance buildings. However, conventional architectural design tools are rarely capable of analyzing the unpredictable air currents in an urban environment. Thus, the integration of a natural ventilation strategy in the conventional design process remains uncommon and difficult to implement.

This paper discusses the incorporation of various ventilation design strategies in an early stage of architectural design using simple simulation software (Ecotect and WinAir4) to evaluate the benefits of natural ventilation in building design. The preliminary design of the new College of Design at the National Taiwan University of Science and Technology (NTUST) in Taipei, Taiwan, is used as a vehicle to demonstrate this integrated design process.

INTRODUCTION

Natural ventilation is an appropriate technology to create a comfortable architectural environment, especially in a hot, humid climate such as that of Taiwan. However, the air currents of urban wind fields are unpredictable and whimsical. The conventional architectural design process does not employ any capable tools to facilitate this environmental factor. Architects and designers lack appropriate tools to consider natural ventilation in design; thus, the integration of natural ventilation as a design strategy in the design process remains awkward. In addition, with increased awareness of the impact of climate change and greenhouse emissions, the effective usage of natural ventilation will likely become a crucial element in reducing the energy consumption of buildings.

In improving the effectiveness of using natural ventilation for comfort, several factors have a strong impact on ventilation design schemes, namely objective analysis of the climatic profile, urban blocks and wind effects, and ventilation routes. These factors not only affect building geometry but also the layout of spaces and the design of openings. In order to demonstrate how to improve ventilation objectively, we use a preliminary design of the new College of Design at NTUST as a case study.

This paper will show that collective ventilation strategies and simple simulation tools can be applied during the preliminary stage to analyze climatic characteristics, initial design effectiveness, and design performance. This paper also summarizes the overall impact of urban environmental factors, potential ventilation strategies, and the effective ventilation routes for subsequent stages of design.

Figure 1. Weather Classified in Taipei (Weather Tool)

APPLICATYION OF CLIMATE ANALYSIS

In order to understand the actual climate situation in Taipei, we used the TMY2 (Typical Meteorological Year, version 2) weather data for simulations. Since the weather data, which was measured at the airport, could not represent the microclimatic conditions in the city, the weather data was modified with data on wind direction and velocity collected at the weather station on the National Taiwan University campus. This modified set of weather data was the basis for this paper.

Square-One's Weather Tool, UCLA's Climate Consultant 4, and WRPLOT were used for climatic analysis. Figures 1 to 3 show the weather profile; it is clear that in Taipei, the weather is hot, humid, and outside the comfort zone.

From the weather profile, it is impossible for designers to achieve the desired physical environment without implementing specific strategies. To this end, we used weather analysis programs, involving psychometric charts, to obtain further information about design strategies. Suitable design strategies for hot-humid climate areas were referenced from literature by Givoni B. and Szokolay S. V. The Comfort Zone setting was set to dry-bulb temperature, 18℃(64℉) to 27℃ (80℉), and relative humidity up to 80％(Givoni B. 1998). The Natural Ventilative Cooling Zone was set to a range of a minimum velocity of 0.1m/s (20fpm) to a maximum velocity of 2.0m/s (400fpm), with a maximum relative humidity of 90% (Szokolay S. V. 2004). In the hot and humid climate like Taiwan, comfort situation is not easy to meet ASHRAE Standard 55, which defines comfort as temperature between 22 to 25℃ (72-78℉) and RH between 30 to 60%, but we can try to add airflow around body, thus with 1.5 to 2.0 m/s (300 to 400fpm) of air speed, therefore one can take as much as 30℃ (85℉) and still feel comfort. Figures 4 to 6 show the results of analysis in Weather Tool and Climate Consultant 4. The results show that natural ventilation is very effective in Taipei City, especially in the mild seasons of spring and autumn.

Table 1 shows that a Natural Ventilation design strategy provides an improvement of 23%, corresponding to 2,013 hours in annual time.

To effectively integrating a passive natural ventilation strategy in Taipei, we have derived useful information from the wind-rose. Figures 7 and 8 show that the wind blows from the northeast about 72% of the time. Figure 9 shows prevailing wind directions for the four seasons, which is very useful for the initial settings in CFD analysis.

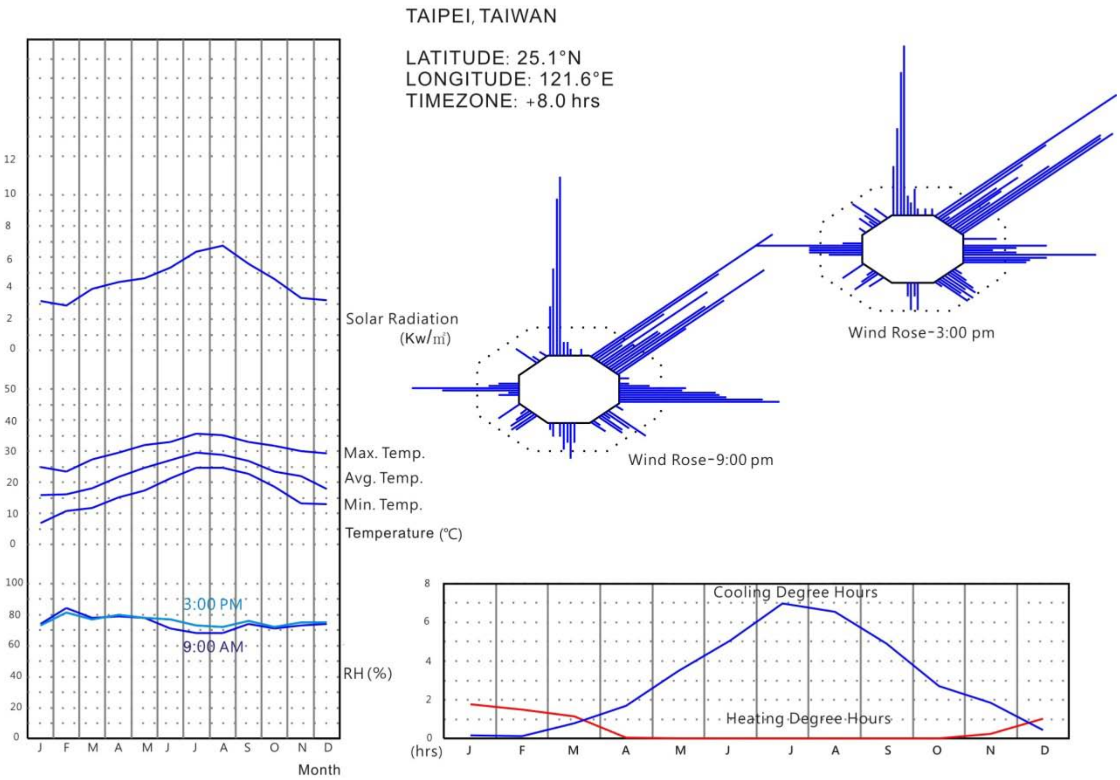


Figure 2. Monthly Weather Data (Weather Tool)

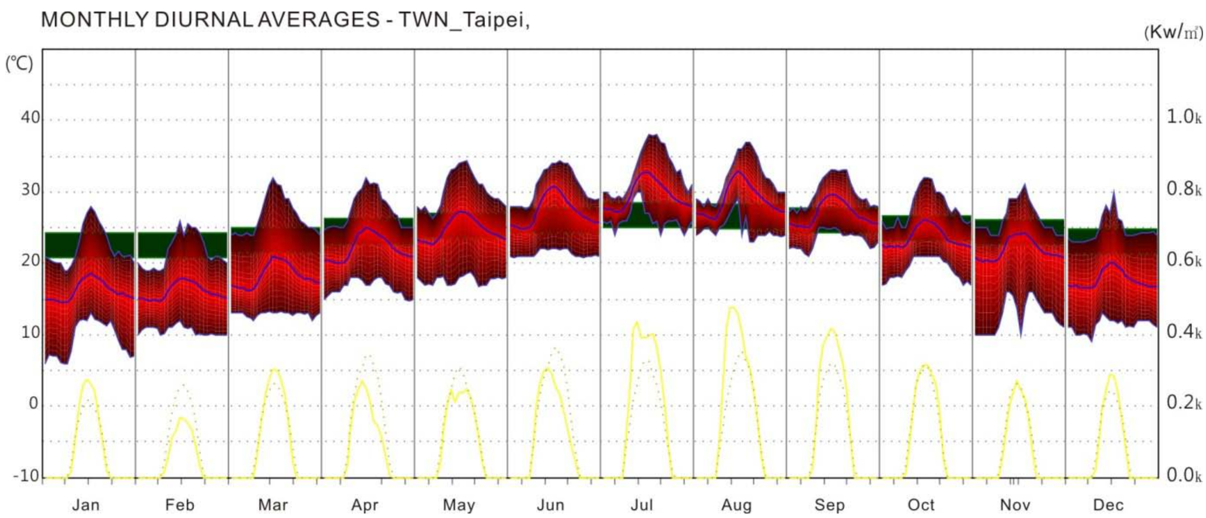


Figure 3. Monthly Diurnal Weather Averages (Weather Tool)

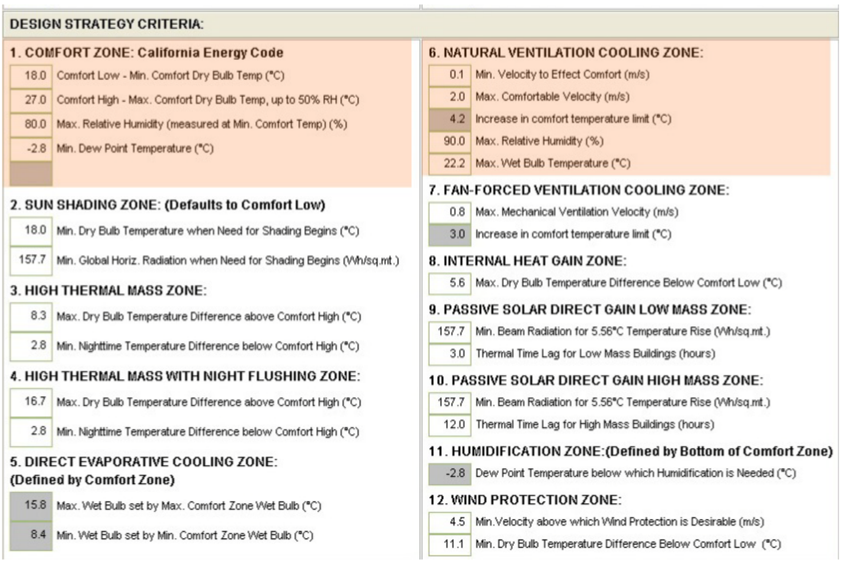


Figure 4. Design strategy criteria setting (Climate Consultant 4)

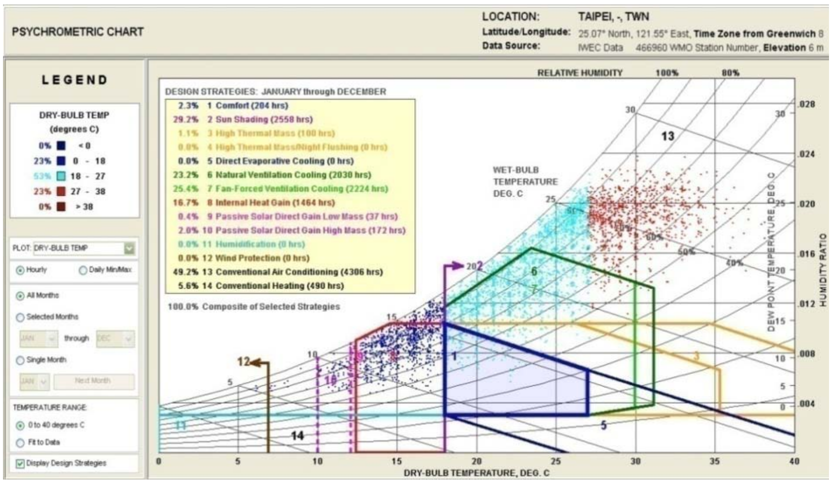


Figure 5. Design Strategies analysis in Taipei City (Climate Consultant 4)

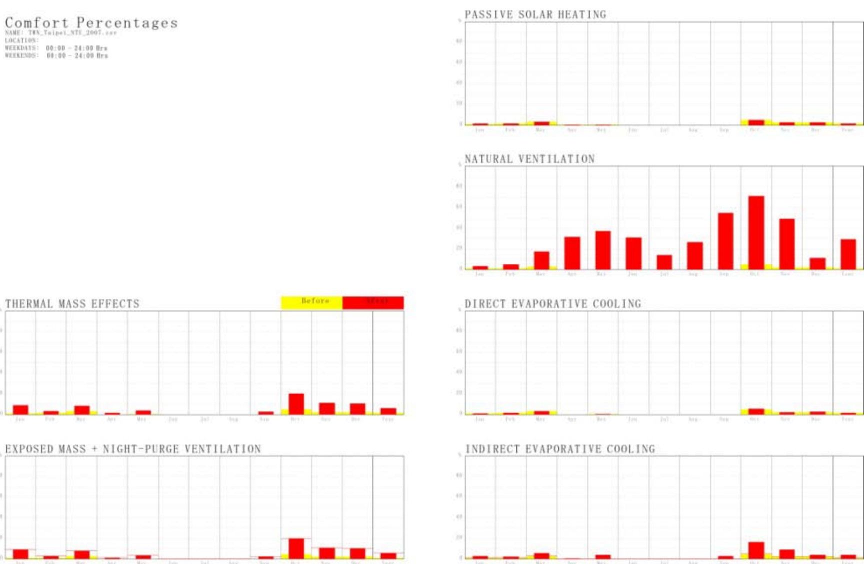


Figure 6. Comfort Percentages Analysis in Taipei City (Weather Tool)

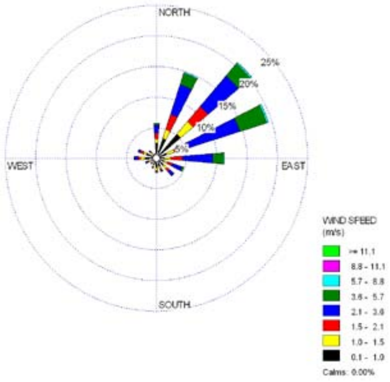


Figure 7. Annual Wind-Rose

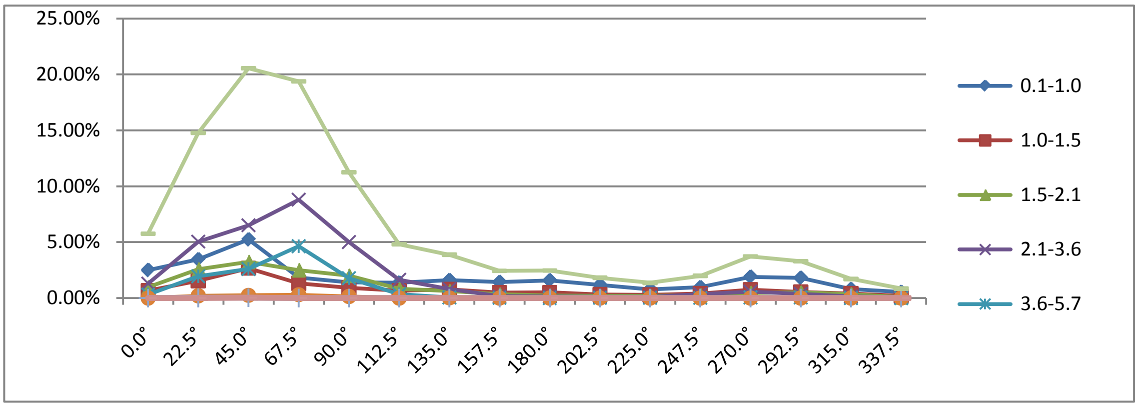


Figure 8. Annual Wind Direction and Velocity Analysis

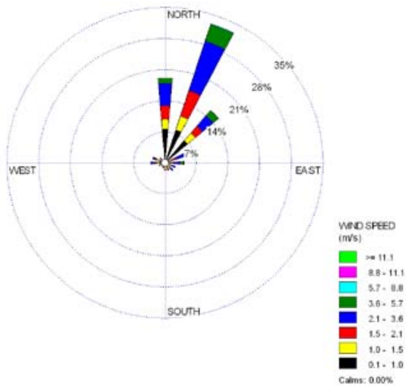


Figure9. Spring Time

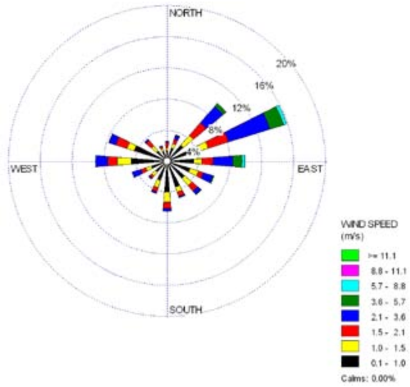


Figure 10. Summer Time

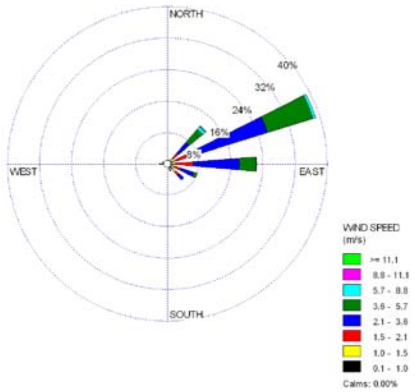


Figure 11. Autumn Time

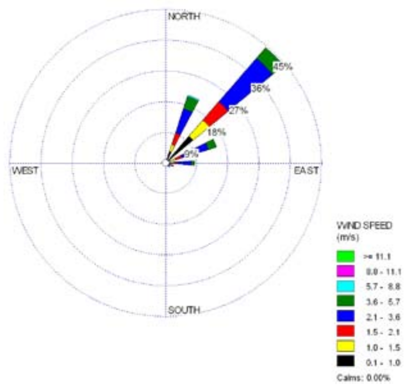


Figure 12. Winter Time

Figures 9, 10, 11, 12. Wind Rose Analyses of Each Season in Taipei

Table1. Design Strategies and comfort percentage analysis for Taipei City

Classification	Design Strategies	Percentage (%)	Time (hrs)
Passive Design Strategies	Sun Shading	29.2	2558
	High Thermal Mass	1.1	100
	Natural Ventilation Cooling	23.2	2013
	Fan-Force Ventilation Cooling	25.4	2205
	Internal Heat Gain	16.7	1464
	Passive Solar Direct Gain Low Mass	0.4	37
	Passive Solar Direct Gain High Mass	2.0	172
Active Design Strategies	Conventional Air Conditioning	49.2	4306
	Conventional Heating	5.6	490

Table2. Natural Ventilation Design Strategies Category

Scale	Category	Strategy
Climate	Climate as a context	Wind Rose, air flow movement
	Evaluation of weather	Comfort
Urban	Ventilation in urban space	1.Street as ventilation corridor 2.Wind effect and building shape
	Ventilation in street space	1. Seasonal ventilation 2. Compact organizations in urban area 3. Ventilation in the street
Building	Outdoor space	1. Distributed layout of buildings 2. Plants adjust air flow 3. Green plants boundary
	Atrium	1.Atrium space 2.Ventilated and airless atrium
	Indoor space	1. Permeable buildings 2.Windward space 3.Cross ventilation 4.Openning performance of air change 5.Stack ventilation 6. Night cooled mass

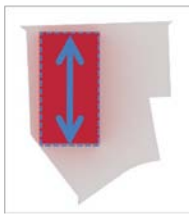
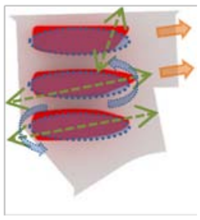
THE COLLECTIVE VENTILATION STRATEGIES

In order to focus on ventilation design in a humid climate, this study cites the principals of ventilation design from G. Z. Brown, B. Givoni, and Hsien-te Lin. Table 2 shows the natural ventilation strategies categorized into three physical scales; climate, urban, and building. These categorized strategies are useful and provide rapid focus for preliminary ventilation design.

SCHEMATIC DESIGN PHASE

Before applying CFD analysis, it is necessary to define several models to represent the building in the normal and improved conditions for the initial design of a new building. Table 3 shows two schemes, the comparable and experimental models, separately. The experimental model adopted collective strategies and added a few considerations corresponding to local prevailing wind trends in the climate situation of the building. Oppositely, the comparable model is a rectangular mass with no added ventilation strategies. Based on these settings of model geometry, we can easily identify the effective and normal schematic options.

Table3. Development Scheme

Scheme	Perspective View	Plan View	Development Description
Scheme One (Comparable)			1. Normal geometry does not apply any ventilation strategies. 2. Deeper space is less effective for ventilation and beneficial for urban wind effects. 3. North-south axis is prone to excess solar radiation.
Scheme Two (Experimental)			1. Separated elliptical geometry reduces exposure to solar radiation. 2. The atrium allows wind to pass through the building. 3. Streamlined shape can reduce the generation of vortices. 4. The building axis is matched to the prevailing wind direction to conduct air flow into the building. 5. Building geometry is twisted to allow more daylight into the atrium and to stretch the geometry in the prevailing wind direction to increase air flow.

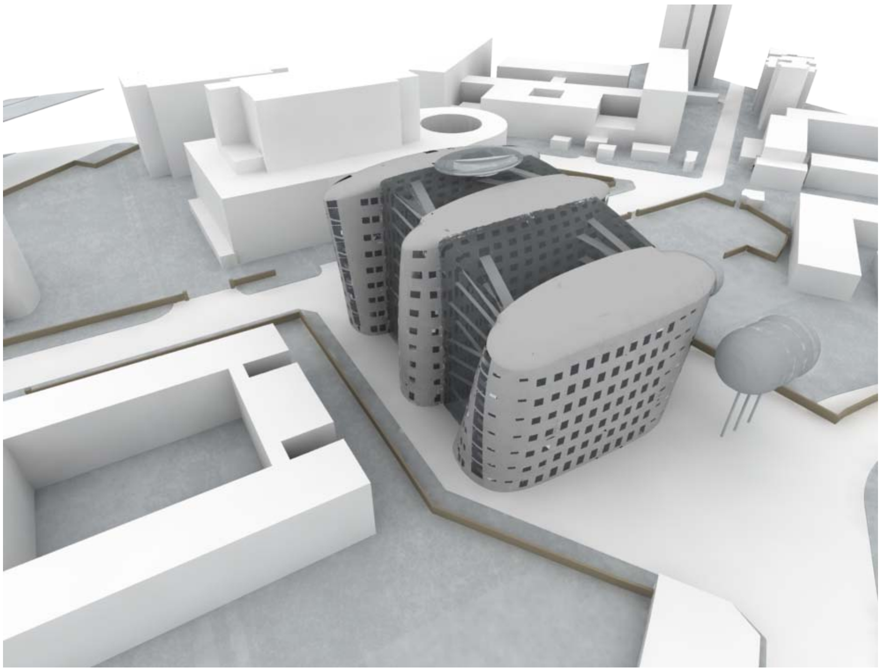


Figure13. Perspective of Scheme Two Model

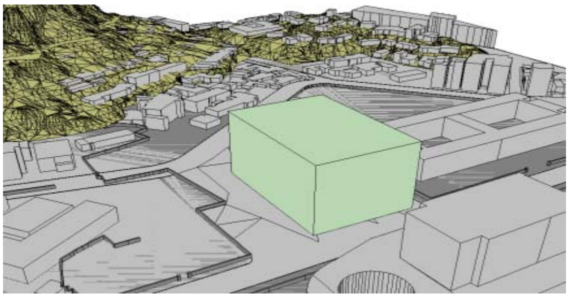


Figure14. Comparative Model

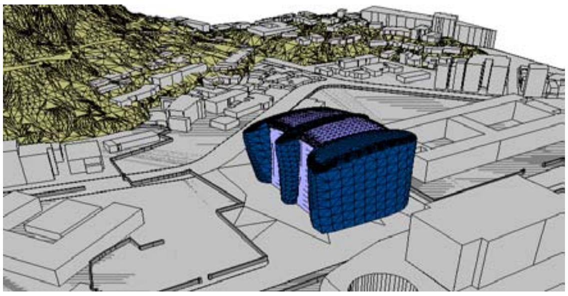


Figure15. Experimental Model

Figures 14,15. Model settings of CFD simulation

SIMPLIFIED CFD SIMULATION ASSESSMENT

Several aspects of architectural ventilation design should be considered systematically. These include strategies of fluid movement of geometric and ventilation design as basic principles of ventilation design. But these principles are not easy to present in terms of quantitative availability, performance, and comparability. Therefore, we employed an application that uses rudimentary CFD software, such as Eco-Tect and Win-Air 4, to simulate and evaluate the natural ventilation effect for each alternative. Visible simulative analysis graphics were generated to evaluate the urban winds and to calculate pressure coefficients and pressure gradients. The ventilation potentials for each alternative were quantitatively investigated for the reference in making design decisions. The implications of these findings will be discussed in more detail in the following sections of this paper.

Three specific aspects were identified for the simulation experimentation. They were:

- Graphic urban wind environment assessment,
- Quantitative simulation of interior ventilation potential,
- Quantitative simulation of optimizing interior ventilation routes.

We discuss each of these items in the sections that follow.

Graphic Urban Wind Environment Assessment

Since the air currents of urban wind fields are hard to predict in architectural design, a design scheme that does not integrate wind issues could suffer from the effects of wind and result in a negative effect on wind comfort (G.Z. Brown and Mark Dekay 2000). For this reason, we discuss the possibility of using simple and graphic simulation software in the initial stage of designing auxiliary natural ventilation in order to extend the controllable design scope for architects. Observations from the simulations can be integrated into the initial design scheme.

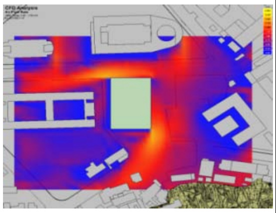
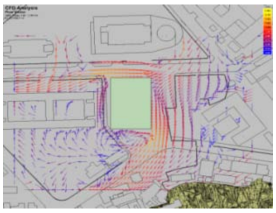
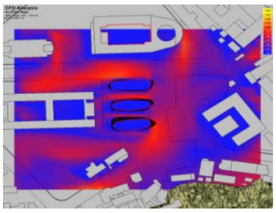
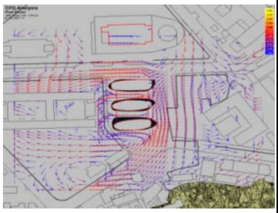
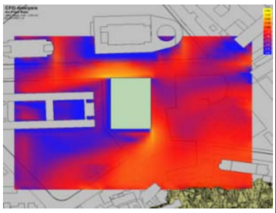
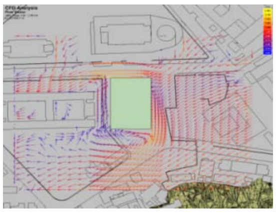
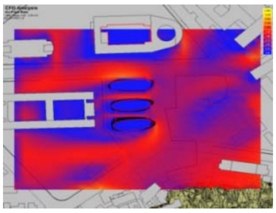
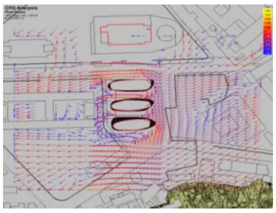
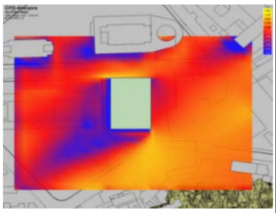
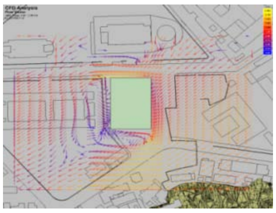
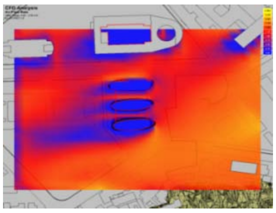
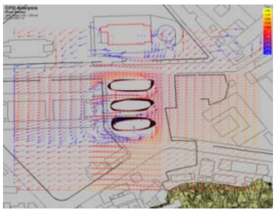
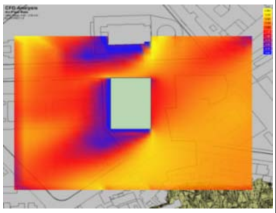
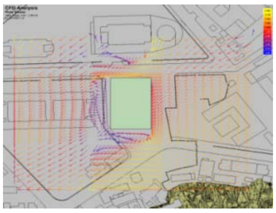
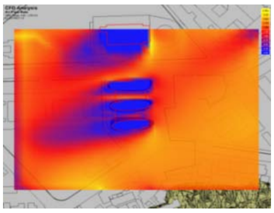
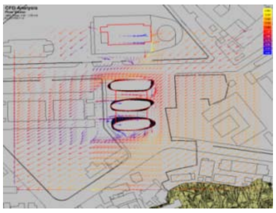
To assess the effects of a wind field, we set several boundary conditions in the experimental simulation. Figures 14 and 15 present the model settings, as noted above. The comparative model represents the regular mass, while the experimental model integrates ventilation design strategies and adjacent urban conditions. The simulation also adopts a prevailing wind direction of northeast (45˚) and a wind velocity of 5m/s.

Table 4 presents the graphic CFD analysis of the comparative and experimental models. The graphic simulation results can assist the designer in making objective design decisions. The simulation is summarized as follows:

1. Wind pressure balance in environmental wind field: Creating a wind corridor in a building with an atrium, as in the experimental model, balances the urban wind pressure and reduces the wind shadow on the leeward side, thus reducing the intensity of turbulence.

2. A streamline form, such as elliptical geometry with the long axis parallel to the wind direction, can offer greater wind velocity and significantly reduce unwanted urban wind effects.

Table4. Wind Velocity and Vector Analysis

	Comparative Model		Experimental Model	
Elevation	Wind Velocity analysis	Wind Vector	Wind Velocity	Wind Vector
3M				
10M				
20M				
30M				

<u>Quantitative simulation of interior ventilation potential</u>

This section develops an interior ventilation evaluation method for wind pressure coefficients and gradients. This method uses simple CFD simulation results to estimate the possible ventilation design of the building.

The Pressure coefficient is a convenient way to present pressure data in dimensionless form and is thus widely adopted in fluid mechanics (Robert W. Fox and Alan T. McDonald, 1992). The Pressure Gradient is a physical quantity that describes in which direction and at what rate the pressure changes the most rapidly around a particular location. The pressure gradient is a dimensional quantity expressed in units of pressure per unit length. The SI unit is Pascals per meter (Pa/m) (5).

Table 5 shows the CFD simulation. We set wind directions of 0°, 45°, and 90° due to the wind direction in the first quadrant. But these graphic simulations only display trends between different model types and wind directions. We assess the indoor ventilation efficiency and potential by comparing the pressure coefficient and pressure gradient through CFD analysis. Table 6 shows the analysis zoning of the evaluation of wind pressure coefficients and gradients.

Tables 7 and 8 show the wind pressure coefficients and gradients separately for various wind direction settings in the comparative and experimental models. For clearer analysis, wind routes are assigned to this analysis in Table 8. It is easier to evaluate the interior beneficial potential through comparing the two models. The summary of this simulation is as follows:

1. A separated streamline geometry provides better cross-ventilation and resolves disproportionate ventilation in the interior space as compared to a single rectangular geometric building condition.
2. A separated streamline geometry entails independent wind pressure effects beneficial to cross ventilation caused by wind inertia effects.
3. The usefulness of sideward negative wind pressure in exhausting air from the interior by the pinch effect in the atrium is demonstrated.
4. A shorter wind route improves the effectiveness of ventilation, as shown by the pressure gradient analysis.

Table6. Analysis Grid Settings of Comparative Model and Experimental Model

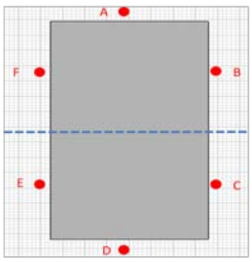
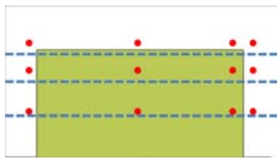
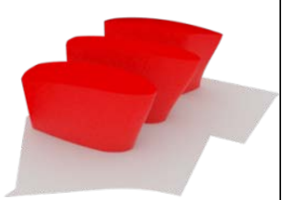
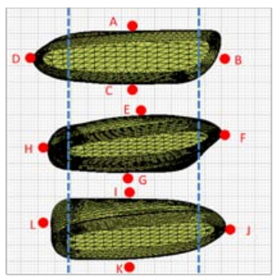
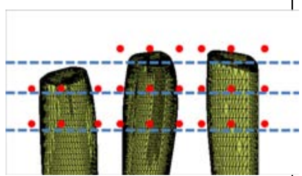
Model Type	Wind direction and Velocity Setting	Horizontal analysis zone setting	Vertical analysis zone setting
 Type-A (Comparative Model)	1. North Wind Direction (0°,↓, 5m/s) 2. Northeast Wind Direction (45°,↙, 5m/s) 3. East Wind Direction (90°,←, 5m/s)		 15M、27M、34M
 Type-B (Experimental Model)			 15M、27M、34M

Table5. CFD Analysis of Comparative and Experimental Model in Wind Direction 0°, 45°, 90°.

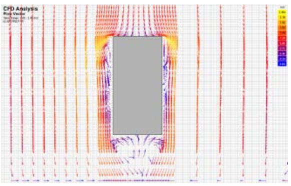
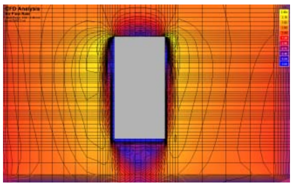
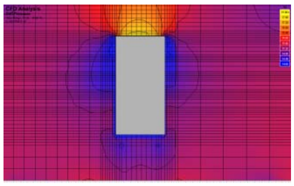
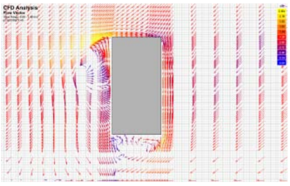
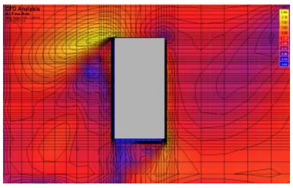
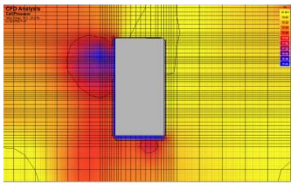
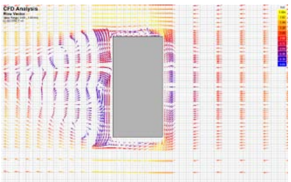
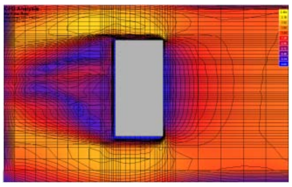
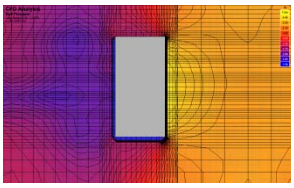
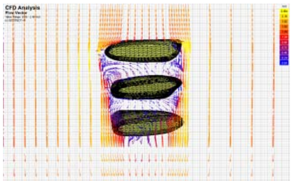
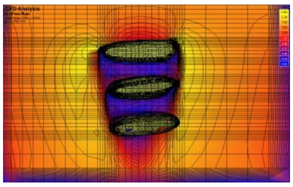
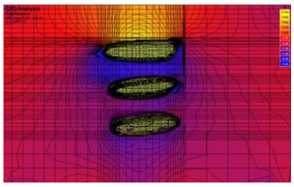
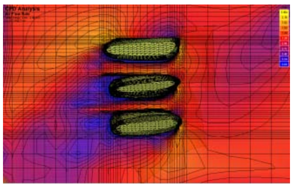
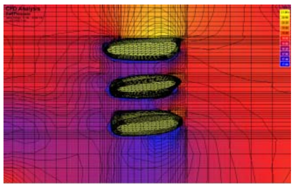
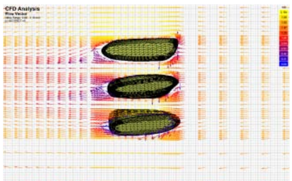
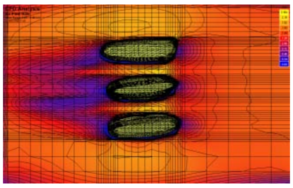
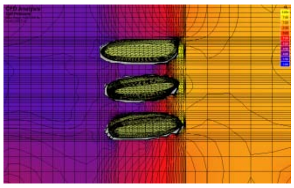
Model Type	Elevation	Wind Vector Chart	Wind Velocity Chart	Wind Pressure Chart
Comparative Model	North Wind (0°)			
	Northeast Wind (45°)			
	East Wind (90°)			
Experimental Model	North Wind (0°)			
	Northeast Wind (45°)			
	East Wind (90°)			

Table7. Pressure Coefficient Chart for Comparative and Experimental Models with Wind Directions of 0°, 45°, and 90°.

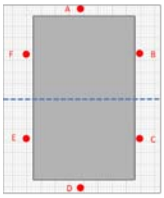
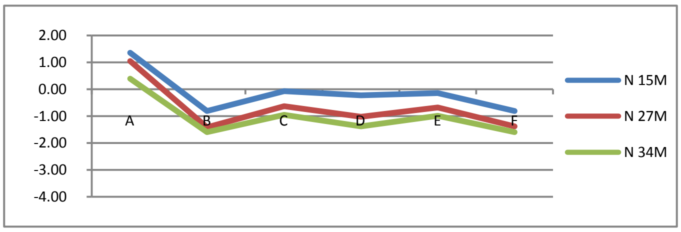
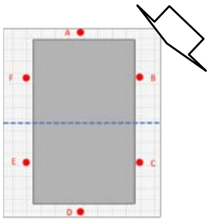
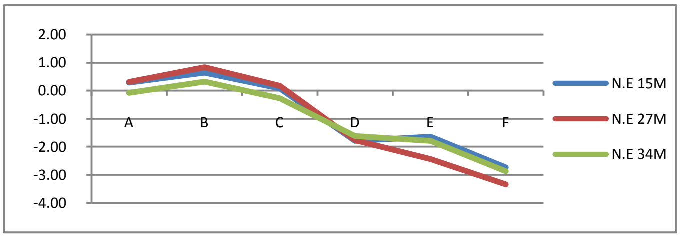
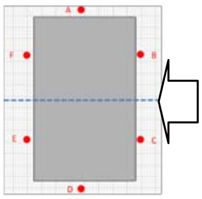
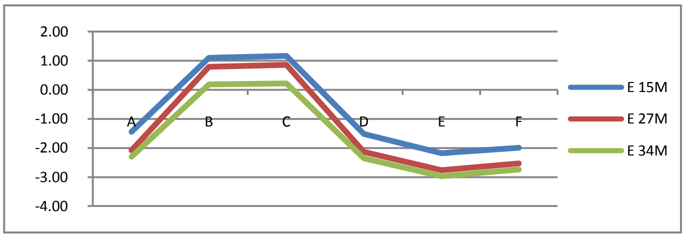
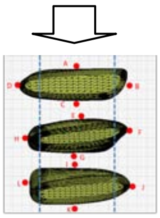
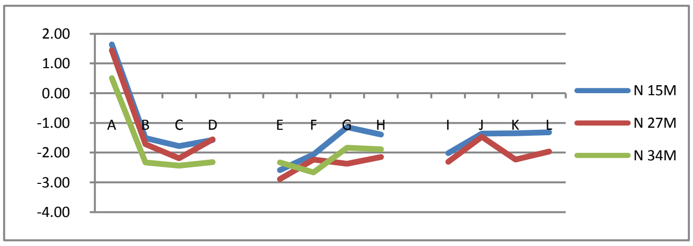
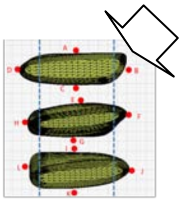
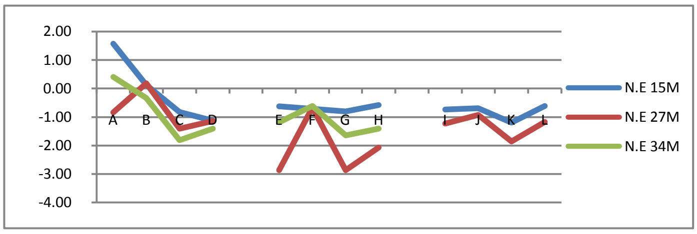
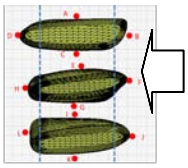
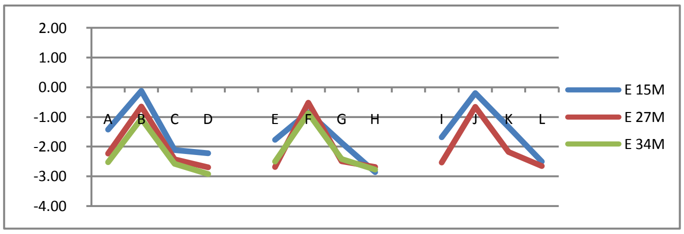
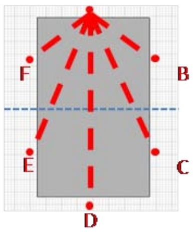
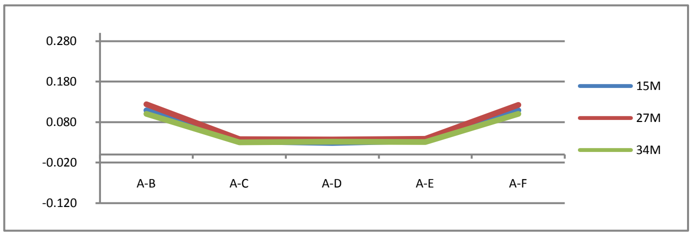
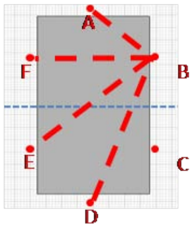
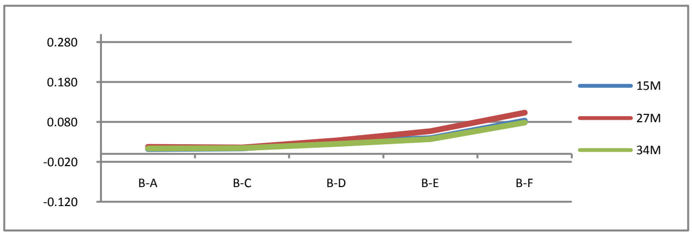
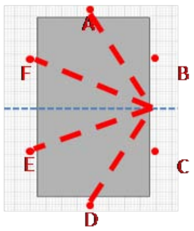
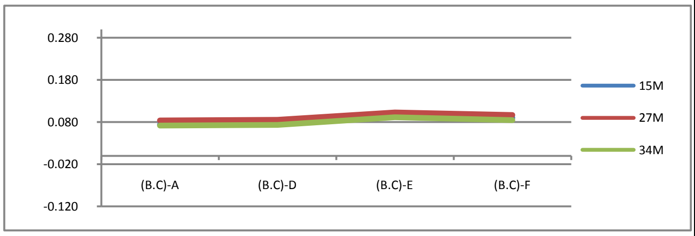
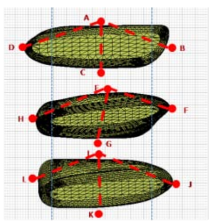
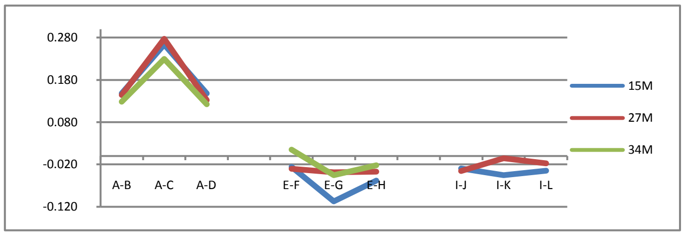
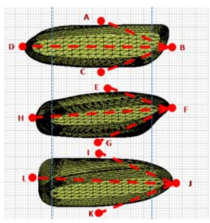
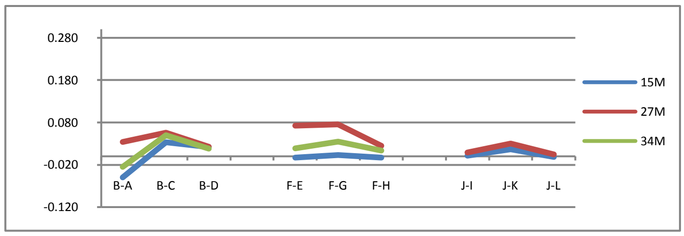
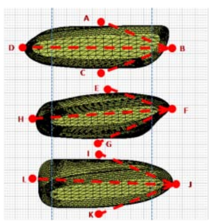
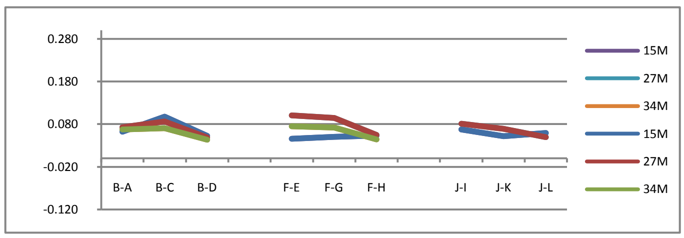
<table>
<tr><th>Model Type</th><th>Wind direction setting</th><th>Analysis zone</th><th>Pressure Coefficient Chart</th></tr>
<tr><td rowspan="3">Comparative Model</td><td>North Wind (0°)</td><td></td><td></td></tr>
<tr><td>Northeast Wind (45°)</td><td></td><td></td></tr>
<tr><td>East Wind (90°)</td><td></td><td></td></tr>
<tr><td rowspan="3">Experimental Model</td><td>North Wind (0°)</td><td></td><td></td></tr>
<tr><td>Northeast Wind (45°)</td><td></td><td></td></tr>
<tr><td>East Wind (90°)</td><td></td><td></td></tr>
</table>

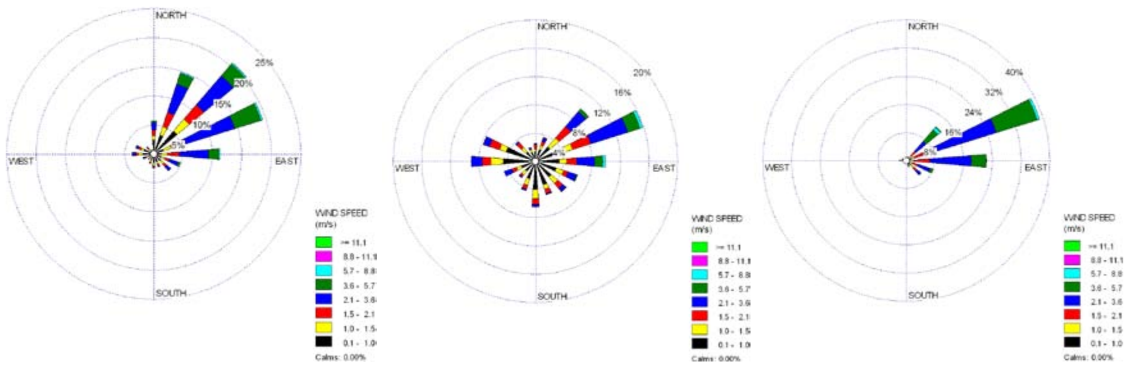
Table8. Pressure Gradient Chart for Comparative and Experimental Models with Wind Directions of 0°, 45°, and 90°.

Model Type	Wind direction setting	Wind Route	Wind Pressure Gradient Chart
Comparative Model	North Wind (0°)		
	Northeast Wind (45°)		
	East Wind (90°)		
Experimental Model	North Wind (0°)		
	Northeast Wind (45°)		
	East Wind (90°)		

Quantitative simulation of optimizing interior ventilation routes

Although the quantitative simulation with the two model types in above section allows estimation of the interior ventilation potential, we conducted an additional study on optimizing interior ventilation routes in a single model. In this section, we reference the previous wind analysis and utilize the prevailing and secondary wind directions as the initial settings of the CFD simulation. Figure 16 shows the wind directions of 45° and 67.5°, which represent annual, summer, and autumn patterns. The wind blowing in these directions both increase ventilation comfort and occupy longer periods.

Table 9 shows the graphic CFD simulation and similar trends of wind flow because similar wind directions are utilized. We conduct further analysis with quantitative calculating, such as wind pressure coefficients and gradients, which not only resolves the unclear estimation in the graphic simulation but also provides more details of the indoor ventilation potential. Table10 shows the analysis zoning of the evaluation of the experimental model. This facilitates the average potential of wind pressure of each calculated zone.



(1) Annual Wind-Rose (2) Summer Wind-Rose (3) Autumn Wind-Rose

Figure 16. Wind Rose of Gongguan District, Taipei

Table10. Analysis Grid Setting in Experimental Model

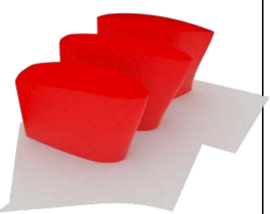
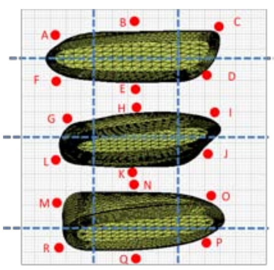
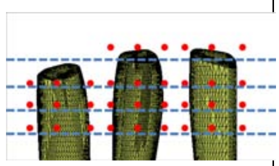
Model Type	Wind direction and Velocity Setting	Horizontal analysis zone setting	Vertical analysis zone setting
 (Experimental Model)	1. Northeast Wind Direction (67.5°,↙, 5m/s) 2. Northeast Wind Direction (45°,↙, 5m/s)		 9M、18M、27M、34M

Table9. CFD Simulation in Experimental Model in Wind Directions of 0°, 45°, and 90°

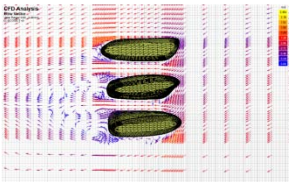
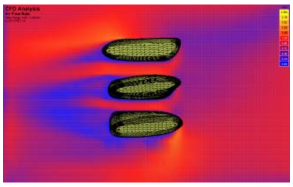
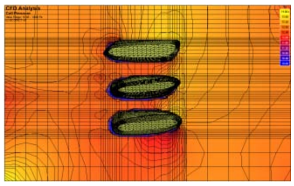
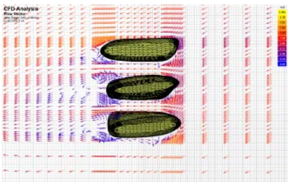
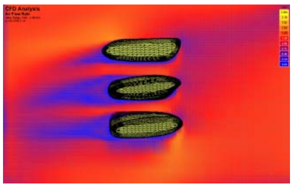
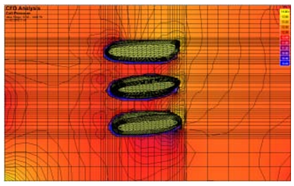
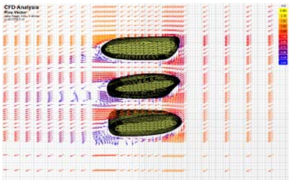
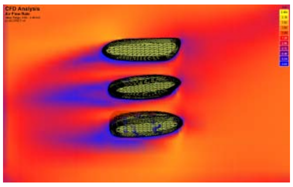
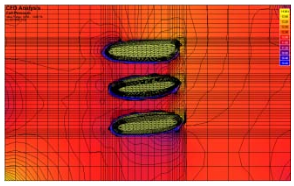
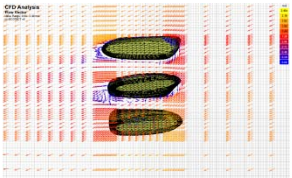
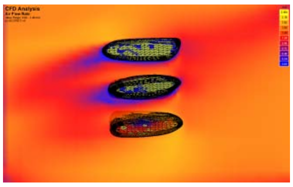
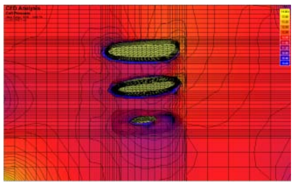
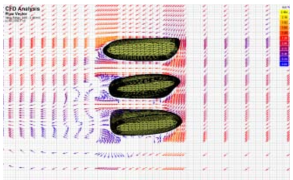
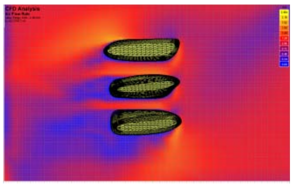
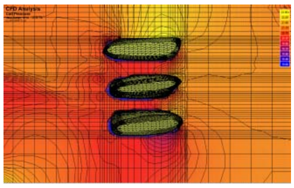
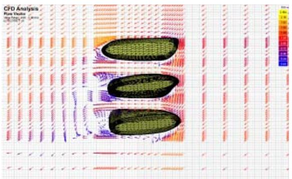
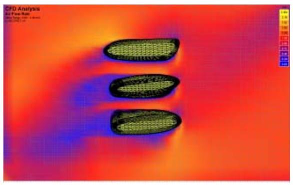
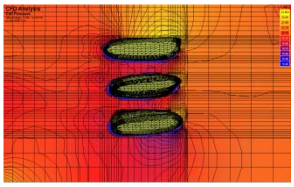
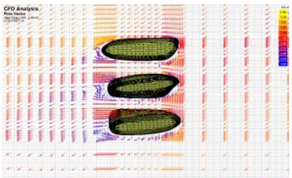
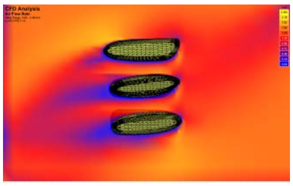
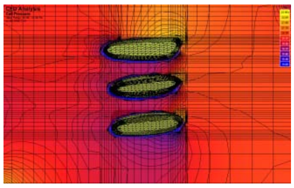
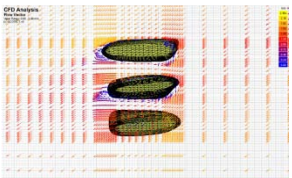
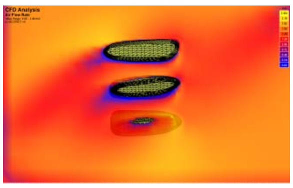
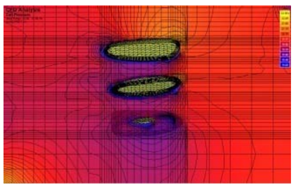
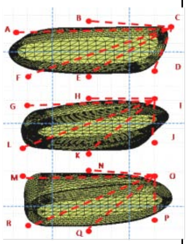
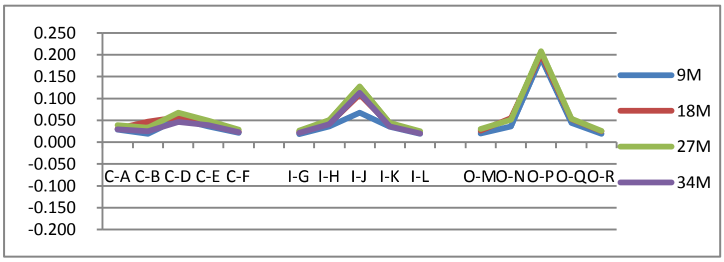
Wind Direction	Elevation	Wind Vector Chart	Wind Velocity Chart	Wind Pressure Chart
67.5°	9M			
	18M			
	27M			
	34M			
45°	9M			
	18M			
	27M			
	34M			

Table 11 shows the wind pressure in the same model when inlet wind comes from various specific wind directions. The distributions of wind pressure can be distinguished due to the analysis of the quantitative pressure coefficient. The greatest pressure occurs on the northeast side of each mass, including zones C, I and O, and the second-highest pressure level occurs on the north side of each mass, including zones B, H and N. We conjecture that the northeast and north sides can be potential inlets to each mass. Based on this assumption, we can have analyze the interior pressure gradient by adding the distance of each route when setting the northeast and north zones in each mass as the inlet openings. Therefore, we separate two evaluation conditions, type-c and type-d, due to the positions of inlet openings and ventilation routes.

Table12. Pressure Gradient Chart

<table>
<tr><th>Condition Type</th><th>W.D.</th><th>Analysis zone</th><th>Wind Pressure Gradient Chart</th></tr>
<tr><td rowspan="2">Type-C</td><td>67.5°</td><td></td><td>
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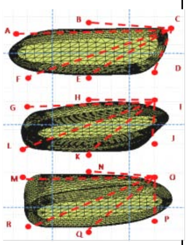
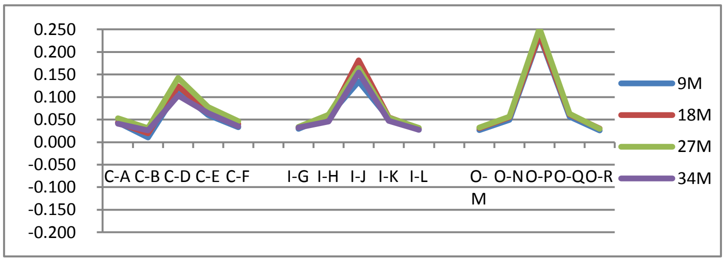
<tr><td>45°</td><td></td><td>
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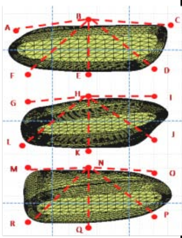
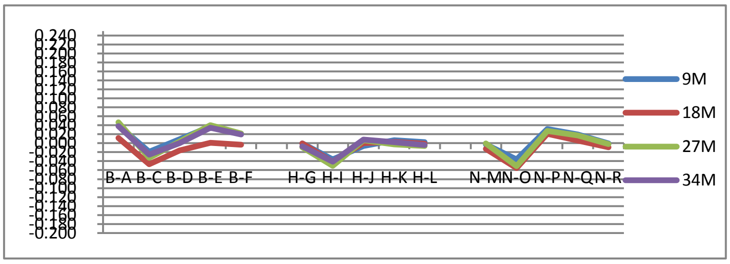
<tr><td rowspan="2">Type-D</td><td>67.5°</td><td></td><td>
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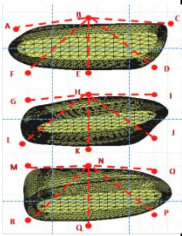
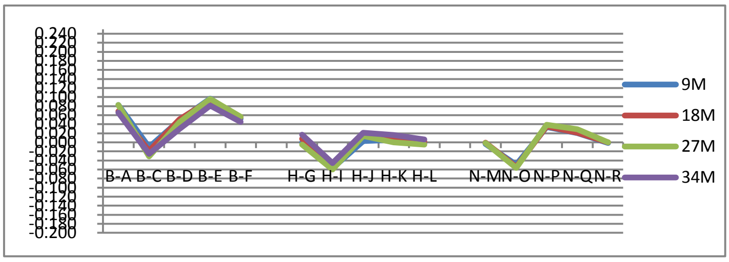
<tr><td>45°</td><td></td><td>
</td></tr>
</table>

Table11. Pressure Coefficient Analysis in Experimental Model with Wind Directions of 67.5° and 45°.

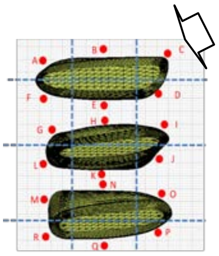
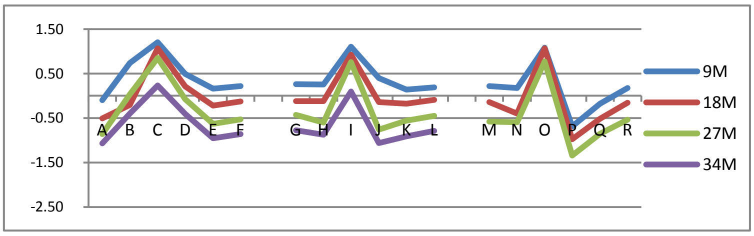
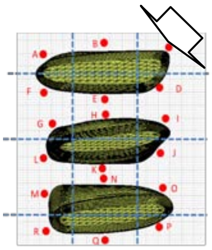
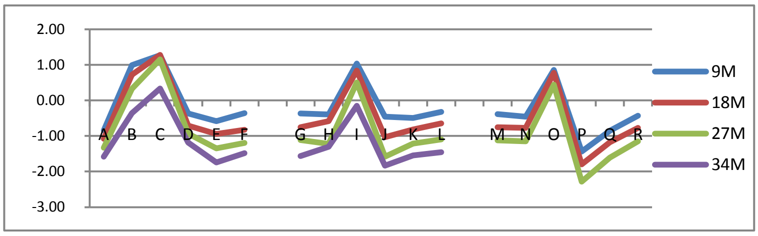
W.D	Analysis zone	Pressure Coefficient Chart
67.5°		
45°		

Table 12 presents the results of this simulation, which help us to identify the performance of cross ventilation. Obviously, the wind pressure gradient is influenced by shorter routes and higher pressure differences. Figures 17 and 18 are simplified diagrams showing the rough ventilation potentials in the two conditions. According to the gradient analysis, the potential routes can be prioritized as the best, better, and normal three levels.

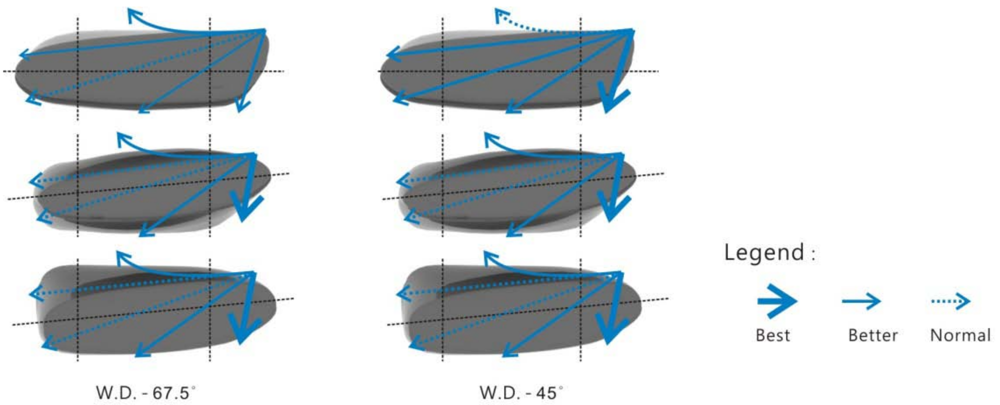


Figure 17. Ventilation Potential of Type-C

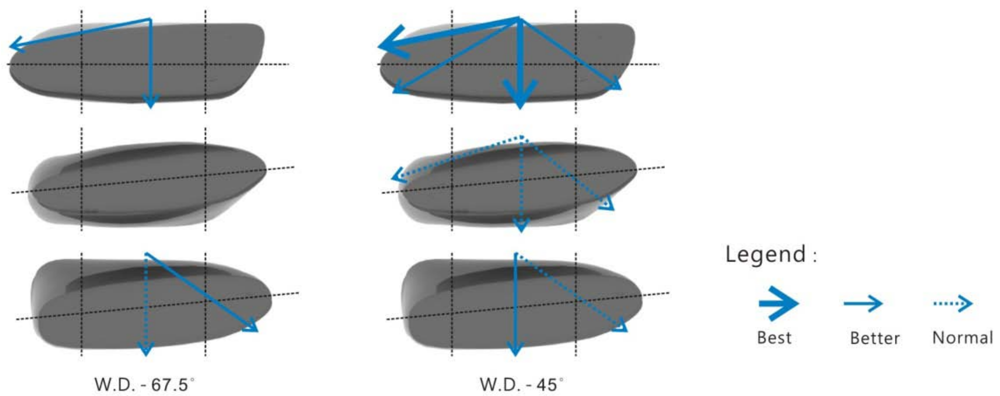


Figure 18. Ventilation Potential of Type-D

For purposes of architectural design, the results of the analysis above can function not only as a quantitative chart but as a straight design guide. We can further extend the ventilation design implications. They are:

- Ventilation space division,
- Ventilation modes, and
- Improvement of wind corridors.

Ventilation space division: According to the pressure gradient distribution, the space can be separated into several compartments that contain various ventilation tasks, such as the inlet space to receive wind, and the main space and the negative pressure space to exhaust air. The functional compartments are shown in Fig. 19.

Ventilation modes: By combining the wind pressure gradient analysis and the ventilation space division, it is good to design flexible ventilation modes for different seasons. These flexible ventilation modes are shown in Figs. 20 to 22.

Improvement of wind corridor: Considering the ventilation space divisions and modes, the space can be modified by adding wind corridors to improve ventilation. This is illustrated in Figs. 23 to 25. Placing ventilation corridors inside the building both creates more public space and improves airflow, according to the wind pressure gradient analysis. Thus, we can definitely present a higher number of alternative solutions to improve indoor ventilation.

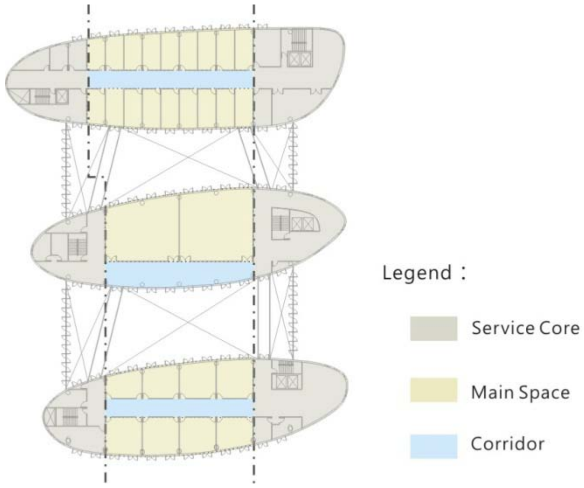
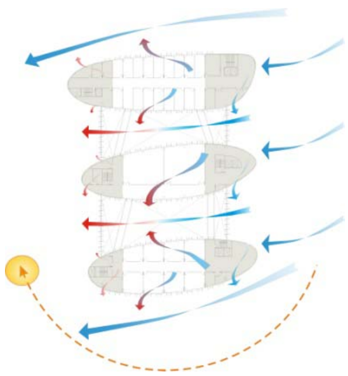
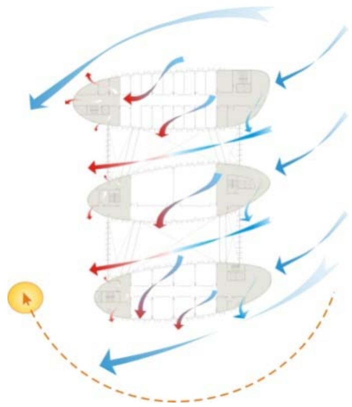


Figure 19. Diagram of Compartments of Ventilation





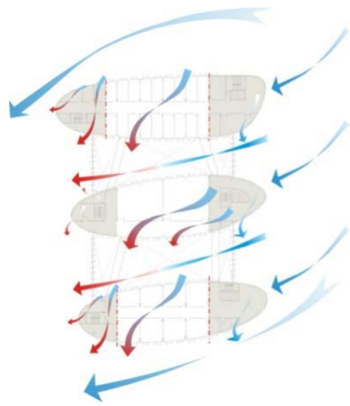


Figure 20. W.D.-67.5°

Figure 21. W.D.-45°(A)

Figure 22. W.D.-45°(B)

Figure 20 to 22. Diagrams of Ventilation Mode

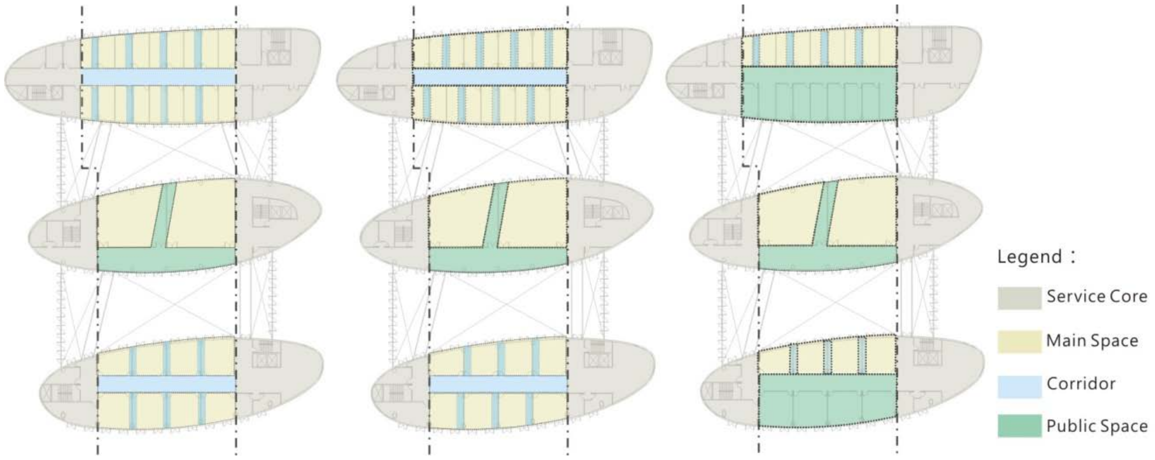


Figure 23. Improvement One Figure 24. Improvement Two Figure 25. Improvement Three

Figure 23 to 25. Diagrams of Improvements of Wind Corridors

CONCLUSIONS

As described above, the results show that the aforementioned procedure of ventilation design, the collected ventilation strategies, and rudimentary simulation software at the preliminary stage are applicable to the climatic analysis of architectural design, evaluation of initial design, design development, and simulation investigation. The procedure provides a large amount of graphic and quantitative information to assist in objective decision-making in ventilation design. Building project planned with this model in an early stage can both balance the pressure of urban wind fields and maximize the wind effects to improve the wind fields of the urban environment. In addition, streamlined mass groups can also improve the potentials for interior ventilation. This study has successfully developed an interior ventilation evaluation method using pressure gradients. This method can assist the application of rudimentary CFD simulation to identify the best ventilation routes for buildings. It also summarizes functional influencing factors of an urban wind environment, ventilation potentials, and ventilation routes. The conclusions are:

- Creating atrium as a wind corridor can balance the urban wind pressure and reduce the wind shadow on the leeward side.
- Adjusting the orientation of a building's long axis parallel to the prevailing wind direction can produce greater wind velocity and significantly reduce the unwanted gustiness of urban wind.
- Providing a streamline geometry is better for cross ventilation and can resolve disproportionate ventilation in the interior space as compared to a single rectangular geometric building shape.
- With analysis of the distribution of wind pressure and gradients, the design can be easily understood with the profile of ventilation performance.
- It is good to combine the wind pressure gradient analysis and the ventilation space divisions with flexible ventilation modes for different seasons.

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