

Study on Integrated Design Workflow for Natural Ventilated Tropical Office Building Using CFD

Hyeong-III Kim*

National University of Singapore, 4 Architecture Drive, Singapore 117566

Abstract

In this study, the integration of natural ventilation techniques is proposed as a solution to the problems of tall office buildings in tropic. Issues such as the over reliance on active systems as well as urban heat island effect, developed with the evolution of these glass box buildings. It is an issue that requires a paradigm shift in perspectives when it comes to designing for sustainability.

This proposed methodology presents the application of CFD, which was predominantly an engineering tool, for modelling wind environmental conditions around a variety of building configurations. Using the software CRADLE by scStream, the simulations of the iterations can be illustrated through visual interpretations of air temperature, surface temperature, pressure difference, and wind velocity around a single building or flow between multiple buildings. Building forms will be optimized in more aerodynamic, in which CFD acted as a quantitative tool to justify how wind was able to flow through and around the form without losing much speed, or being deflected in opposing directions. These were hence the transformation techniques used in "sculpting" an optimized form for the proposed NV office tower block.

Keywords: Tall building; Sustainable building design; Natural ventilation; CFD

Introduction

In countries like Singapore, the climate is characterized as tropical, to mean the climatic conditions are harsh with abundant rainfall, high humidity and relatively high air temperatures throughout the year. Simply replicating the devised solution may not work, where the harsher conditions would demand excessive loads on the active systems.

In this study, the integration of natural ventilation techniques is proposed as a solution to the problems of office environment. It was accepted that natural ventilation with a good design is logical and applicable to many types of buildings from low-rise dwellings to high-tech office buildings.

The integration of natural ventilation in office environments aims to provide answers to issues associated with heating, cooling, air quality, noise, health problems (eg Sick Building Syndrome), and requirements for routine maintenance and energy consumption of active systems.

This approach of integrating natural ventilation to office buildings will be mainly a "reintroduction" of vernacular knowledge in the current context with the help of modern technologies.

Integrating natural ventilation techniques into initial building design process may demand more time and expenses during the design stage, but the eventual reduction in energy demands and cost of purchasing and maintaining mechanical equipments, as well as better worker efficiency would pay off as a more healthy and sustainable office building compared to the typical ones that seals itself from the environment.

Background: Development of Office Buildings

Emergence of sealed office buildings: The oil crisis of 1973 was the turning point in the development of contemporary office buildings. Energy policies of western countries were regulated to reduce global energy consumption mainly used for heating and air-conditioning. Buildings began to be sealed up to reduce the volume of occupied space,

to achieve lesser volume of heated air provided to the occupants. The main objective was to reduce the fuel bill by reducing heat loss through ventilation [1].

According to O'Sullivan (1988), introduction of sealed office building concept creates more general problems on top of the decreased level of indoor air quality [2]. He states that approaching the problem of energy consumption from the point of reducing the amount of fresh air available to each person changes the norms; so, instead of traditional levels, minimum becomes the norm.

This situation is highly associated and a result of the use of air-conditioning systems. This is a problem that will be repeated by the designers and practitioners who rely on the sealed office building concept.

The construction, operations, and maintenance of tall buildings consume enormous quantities of resources and generate bigger amounts of waste than conventional building. They are enough reason that tall building design should look for sustainable approach from the very early design stage, Kim [3].

Air-conditioning systems for offices: During the 1950s and the 1960s, light and transparent buildings, achieved by curtain walling became very popular. Moreover air-conditioning in this type of buildings was so integrated that it was impossible for buildings to operate without it. This phenomenon was a result of the introduction of new all-air systems (VAV Variable Air Volume) in the late 1960s. This system was able to "provide air conditioning from the window

*Corresponding author: Hyeong-III Kim, National University of Singapore, 4 Architecture Drive, Singapore 117566; Tel: +65-6601 2549; E-mail: akikhi@nus.edu.sg

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wall to the core, independent of depth and only supplemented by heating at the perimeter”.

The disadvantages of VAV system however, were the size of the air handling plants and ducts. They were occupying twice the floor space and VAV needed ceiling voids 30% deeper. This was creating undesirable situations especially for high-rise buildings. Solution to the problem was installing air handling plants at each floor supplied with only the minimum rate of fresh air by other means.

From that period till today, air conditioning for tall office buildings has become almost a prerequisite to design. Air conditioning had two major effects on office buildings: one, offices were subsequently designed without considering the passive means of providing comfort conditions, second, introduction of new materials and building techniques are based on the idea that air conditioning is the primary element to provide conditions of comfort.

Natural Ventilation Techniques for Office Buildings

Arnold (1999) said, “the skyscraper ‘as we know it’ evolved without the benefit of air conditioning, classic buildings such as the Woolworth and Chrysler reach unprecedented heights by relying on nature to provide lighting and ventilation” [4]. Natural ventilation is proposed as a solution to the problems arising from the sealed office building concept, to provide passive means of comfort conditions of an office space.

Ventilation strategies would be to understand how air is introduced into a building, and how it is extracted out of it. The different strategies used to ventilate high-rise buildings can be classified into three main categories:

The atrium naturally ventilates balconies and corridors which surround it on each floor. Along with the feasibility of the stack effect, the aerofoil shape louvers were designed using Computer Fluid Dynamics (CFD) to ensure high wind speeds would not affect the blinds, and exhaust air would not re-enter the cavity above.

Land stated that Environmental factors and/or the structural concept may shape building form and skin [5]. Wind can have many positive attributes in an architectural environment such as providing a comfortable and healthy indoor environment and that can also save energy, by means of passive cooling or natural ventilation [6].

Airflow within the facade cavity helps maintain a constant average temperature in the building, reducing the reliance on HVAC systems. 1 Bligh Street is an example of how using wind simulation tools during

the design process have allowed an effective use of natural ventilation for a stack-ventilated office building.

Designing for NV Office Buildings

Tropical climate of Singapore: Tropical climates are characterized by relatively high air temperatures, high humidity levels, high precipitation, and high solar radiation. The high humidity of 80% or higher means that this climate can be one of the most challenging to adopt natural ventilation strategies in, especially for office buildings. Two important strategies can be utilized when designing in this climate; protection from solar radiation and ventilation with a high air change rate to remove unwanted humidity (Figure 1).

A high air change rate can also broaden the human comfort zone, as air movement over the skin creates a cooling sensation, known as “psychological cooling”.

In this climate, the natural ventilation strategy will likely have a major impact on the form of the tower. Narrow floor plates are useful to ensure adequate cross-ventilation across space. High floor-to-ceiling heights can be utilized to keep warmer air stratified upwards, away from the occupants, and also increase natural ventilation through stack effect.

Certain design strategies can be adopted when designing for natural ventilation. From a typical square plan tower block, slicing the block at an angle of prevailing wind directions would encourage great wind flow in and around the building. Sculpting of the mass will be elaborated in the later part on the use of CFD simulations to validate the various transformation strategies.

By sculpting the outside form and skin of the building, vertical cavities can be formed, which capture wind from the prevailing directions that accelerate through surfaces of the building. However, that higher air change rates can cause problems of discomfort and troublesome movement of paper documents, especially in office environments, Figure 1.

Design considerations: The proposed naturally ventilated office building is sited at Singapore’s Central Business District (CBD), in view of how office buildings more often than not appear in highly efficient business clusters in cities around the world. Singapore suffers from a phenomenon called Urban Heat Island effect, it is caused by a high density of built up areas relative to forested areas on the island. This effect is accentuated in the densely built up areas of the CBD, where air temperature in the region is highest at 28.4°C, and it is a result of

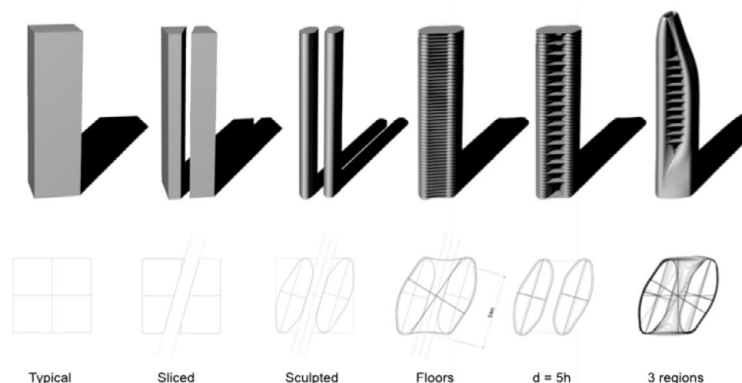


Figure 1: Massing studies concerning ventilation strategies.

the general decrease in wind velocity and high heat exhausted from excessive amounts of mechanical systems that gets trapped [7].

Therefore, having the proposed naturally ventilated office building sited in the CBD aims to better improve the quality of air movement in the area, and hopes to set an example of how office buildings in the tropics should be.

Designing a tower block in CBD, the issues to consider can be broken down into three regions based on altitude. The lower region of the tower, marked at 0 to 50 meters above ground, entail issues such as noise and air pollution caused by vehicular traffic at street level. Also, lower wind speeds causing higher humidity build up can create a rather uncomfortable environment for occupants.

The middle and higher region of the tower faces relatively similar issues, and these at regions 50 meters and above from street level. These regions enjoy better wind speeds, thus lower humidity levels and better air quality; also, there is usually adequate day-lighting with lesser overshadowing by neighbouring blocks at these levels.

The minute differences in temperature between optimal internal temperatures for human comfort also call for concern when it comes to designing with the natural environment. For this reason, solar heat gain on the building facade needs to be carefully controlled.

Although shading devices are important to be used, they should be carefully placed so as not to block wind and ventilation access. Although day and night temperatures typically do not vary greatly, night time ventilation can still be strategically applied to remove some daytime heat gain.

Spatial configuration: Since the introduction of vertically stacked office buildings in the 1900s, spatial layouts have evolved in many ways. It began with a Taylorist fashion, which involved large open plans which a supervisor requires to have permanent view of the labour intensive clerical work of the period.

Today, the problem that O'Sullivan theorized in 1988 with regards to the advent of sealed up office buildings has taken truth. The situation when associating with air-conditioning system is that the solution to reduce the energy demands of the system will inherently be to minimize everything. In the case of the current typical office plan, service cores have to be kept compact, the less floor area used for circulation the better, working cubicles are kept as tightly clustered as possible. This situation is a problem caused by the use of air-conditioning system in the universal sealed up office buildings (Figure 2).

The proposed spatial configuration of an office floor plan is illustrated by the zonal diagram above, (Figure 2). Service cores will still be kept as one package, but will be designed to be naturally and mechanically ventilated. To do so, the lift lobby will be opened up 10 meters wide to allow for wind to naturally flow through, adjacently, services such as toilets and pantry spaces can be aligned along the wind

channel to achieve naturally ventilation with better air quality.

Unlike the transient spaces of service and circulation spaces, the operational spaces will still be zoned as air-conditioned spaces, to reduce the risk of unpredictable weather conditions throughout the year. The meeting rooms and semi-formal breakout spaces however, will be classified as contingency zones, to mean these spaces are only occasionally occupied throughout the day, hence, need not be air-conditioned all day.

Hence, a standalone system along with operable monsoon windows allows the interchangeable use of methods to cool the room to a comfortable level.

Design Methodology

Computational fluid dynamics for architecture: The design of natural ventilation in buildings is often performed by means of computational fluid dynamics (CFD) techniques, whose application is gaining popularity [8].

Understanding the airflow patterns around buildings is of importance for designing sustainable naturally ventilated buildings. Before Computational Fluid Dynamic (CFD) softwares, designing for ventilation required the use of scale models and structures to be tested in wind tunnels of salt baths techniques, it was consuming both in terms of time and effort. Advancements in CFD have provided new approaches to quantify building airflow.

This proposed methodology presents the application of CFD, which was predominantly an engineering tool, for modelling wind environmental conditions around a variety of building configurations, Figure 3. Using the software CRADLE by scStream, the simulations of the iterations can be illustrated through visual interpretations of air temperature, surface temperature, pressure difference, and wind velocity around a single building or flow between multiple buildings (Figure 3).

With CFD, when design for natural ventilation in architecture, designers can better predict airflow patterns, indoor air velocities, indoor temperature distribution and ventilation rates associated with different combinations of natural ventilation techniques with the environment. This quantitative data is functional from the urban scale of design to schematic design to detailed design in architecture.

Urban ventilation: On the urban scale, CFD is able to predict airflow patterns through a city with a mix of low to high-rise buildings. Understanding airflow in the urban scale, ensures that heat gain as well as pollution accumulation can be minimized and to generate good cross ventilation for greater human comfort of urban dwellers. CFD can be used to evaluate the effects of heat gain from materials, air-conditioning condensers and building geometry in the urban environment, (Figure 4).

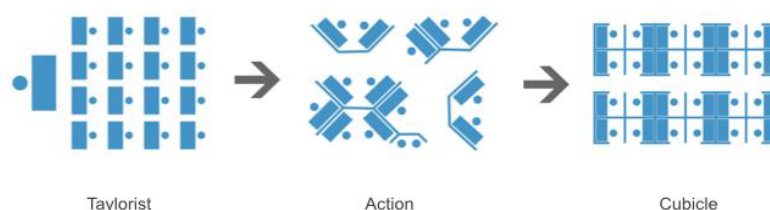


Figure 2: Spatial Configuration.



Figure 3: Integrated Design Process.

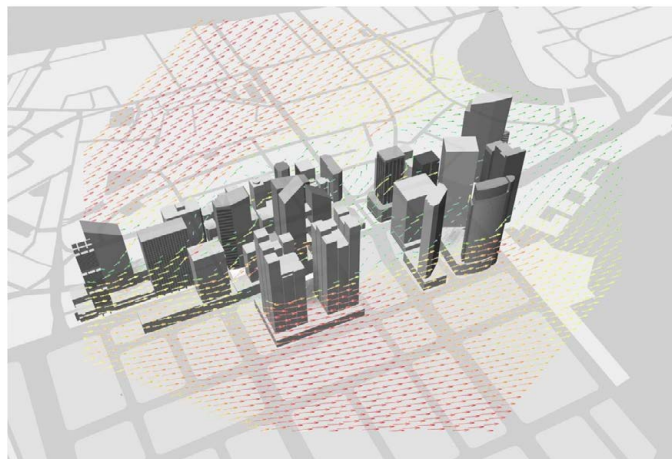


Figure 4: CFD of Singapore CBD.

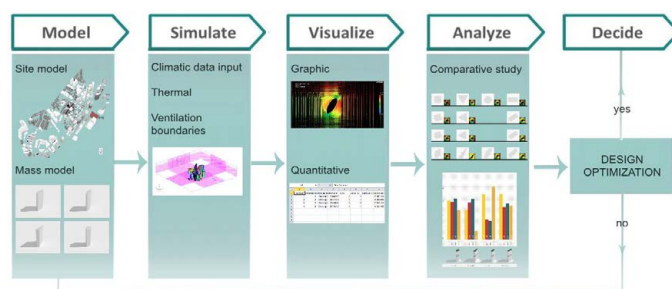


Figure 5: Integrated Work Flow.

Strategies can be used in the tropical context to accelerate airflow at pedestrian level by creating “air tunnels” which acts as funnels that encourages increased airflow for the comforts of pedestrians. Being site responsive is also vital when design new developments, and ensuring that the development does not obstruct or direct wind away from low lying NV spaces, such as food centers, can be simulated using CFD.

Optimized form generation: With scStream’s function of the “multi-block”, data from the urban simulation can be carried forward to be used when designing at a single block scale. With this capability, results can be more accurate without the need to manually re-enter the micro-climatic data of a single block. Hence, at the schematic design level, an integrated workflow is introduced to better illustrate the methodology to NV optimized form generation using CFD simulations tool, (Figure 5).

First, a 3D model of the site has to be modelled and input into the software, and using the relevant wizards, input climatic data, such as prevailing wind direction, average wind speeds, and air temperature, to set a premise for the simulation to work on, Figure 6. After the first block (urban scale) has been set, a secondary more concise block and

be created within, in that block, the various iterations that have been modeled will be simulated at higher resolutions for a more accurate representation.

After all the iterations have been set in separate files, the solver can be launched for the simulation to begin. With the multi-block tool, the entire simulation can be done just once and not separately at different building scales (Figure 6).

Once the simulation is complete, the post processor will be launched. Using the post processor, a choice of visualization tools can be chosen to best represent the data computed. For the comparative study, a 2D representation of wind velocities as well as an excel read out of point data was used, (Figure 7).

In each transformation of rotating, curving the edges, and skewing the form, the form becomes more and more aerodynamic, in which CFD acted as a quantitative tool to justify how wind was able to flow through and around the form without losing much speed, or being deflected in opposing directions. These were hence the transformation techniques used in “sculpting” an optimized form for the proposed NV office tower block.

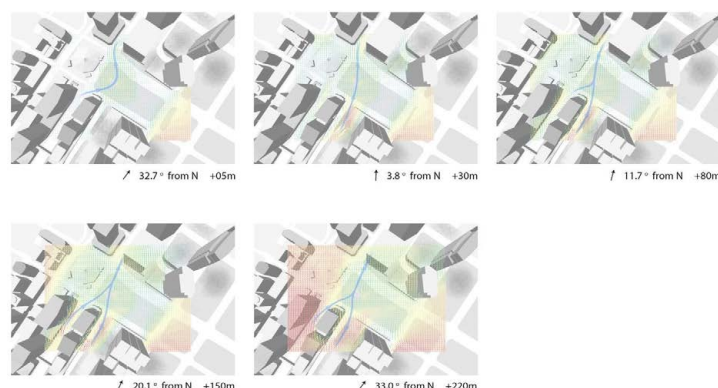


Figure 6: Urban ventilation study by altitude.

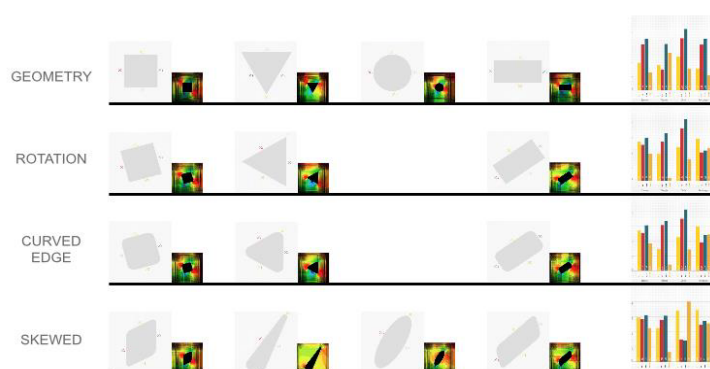


Figure 7: Preliminary Analysis of Form and Wind.

Subsequently, when designing with the environment, it is insufficient to simply rely on average data which are determined at a global scale. Hence, at the building scale, the environment involves the consideration of immediate adjacent surroundings. In the figures above, a site specific representation of the wind velocities at various altitudes were exported from the results of the CFD simulation. The arrows formed are able to illustrate the change in wind pattern relative to the urban fabric at varying heights of the site. This valuable data is a relevant reflection on form generation of the tower that is very much specific to its site.

Detailed design tool: When designing for natural ventilation, strategies used are either, single-side ventilation, cross ventilation, or stack ventilation. The designer may for example illustrate in his drawings that the passive strategy of his building would utilize stack ventilation to naturally cool the spaces. However, if not designed properly, if the actual built naturally ventilated atrium does not have any temperature, density, and pressure differences between the interior and exterior space, the stack effect would not work, and the atrium would end up being a void space with uncomfortable stale air trapped in the building, which in turn may require mechanical systems to create a circulation (Figure 8).

The Figure 8 is a compilation of ventilation techniques and its applicability in the context of the tropical climate of Singapore. The variance in technique would cause differences in the eventual buildable floor area as well as the percentage of it that can remain naturally ventilated. Hence, the comparative study has to encompass building

feasibility together with the possibility of natural ventilation. In the first instance of using stack ventilation, similar to that in the case study of 1 Bligh Street, the technique remains consistent except the weather data is set in Singapore. The result from the simulation shows how it is less applicable here due to the lack of air movement in the central atriums, factually caused by the marginal difference in pressure between the lower and higher regions.

In the instances utilizing single side ventilation technique, floor to floor height has to be generous for winds to reach depths close to the core. Compared to stack ventilation towers, single side ventilated towers have a greater percentage of naturally ventilated areas, however, due to the requirement of a building core, at certain times of the day, there will always be vortex shedding regions with low wind speeds. The use of cross ventilation may achieve the highest level air change rate among the techniques.

However, the requirements to achieve cross ventilation demand aerodynamics as well as immense openings, these factors cause relative reduction in floor area as well as higher floor to floor height

Hence, for the proposed natural ventilated office tower, a combined strategy of single and cross ventilation technique is used. Relative to the respective zones, cross ventilation is used to ventilate the area of the lift lobby, whereas a combination of cross and single side ventilation is used to ventilated work spaces so as to not compromise on buildable floor area. After modelling out the tower, the CFD simulation was able to justify the feasibility of the cross-ventilated strategy to naturally cool

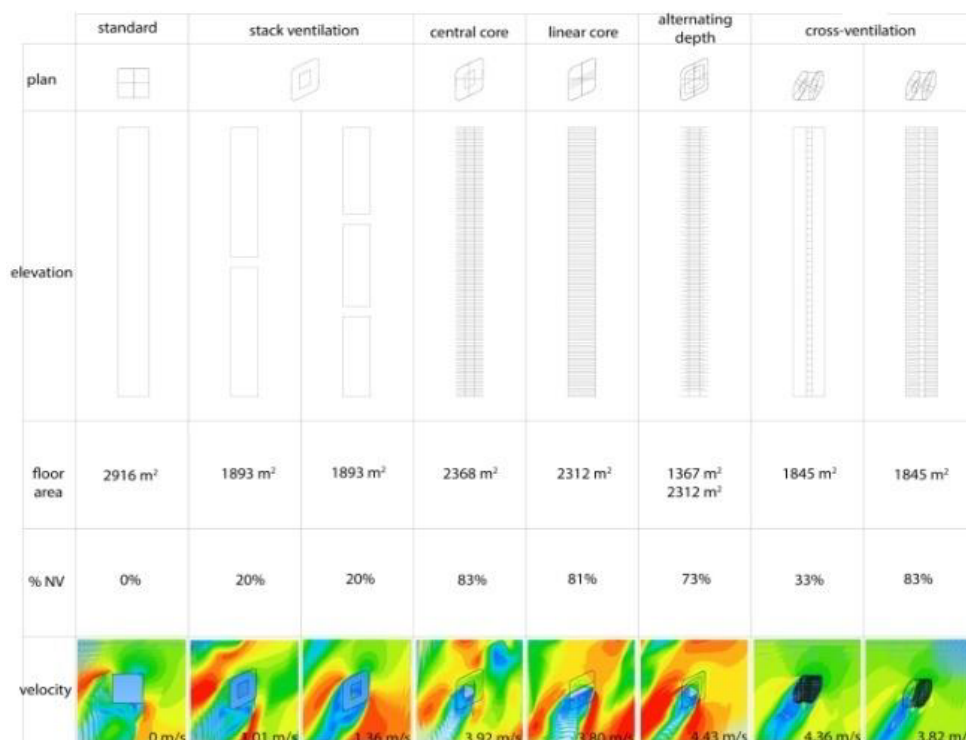


Figure 8: CFD Analysis; Wind.

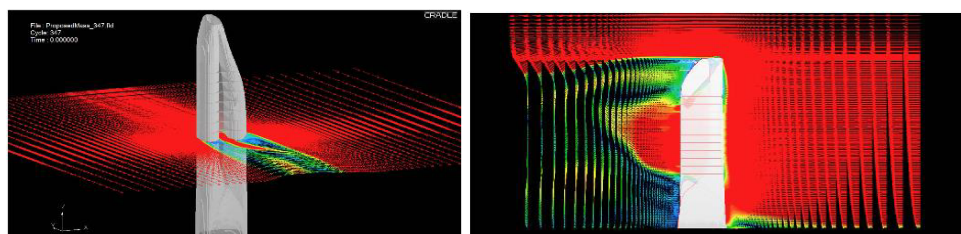


Figure 9: CFD Analysis; Results.

the space. In the Figure 9, it is apparent that the cavity of the tower encourages airflow through the space and even at accelerated air change rates (Figure 9).

Conclusions

The intention of this research serves to question the constructs of the typical office buildings present in metropolitan cities like Singapore. These clusters of buildings often take on the typology of “glass boxes”, which are generic plug and play models, aimed at creating standard indoor environments, exclusive from its surroundings.

Formally, the design relies on calculated steps to break away from the typical glass box typology into one that tries to relate to surrounding climatic conditions. With the emphasis on wind as a passive means to ventilate the indoor environment, the CFD software scStream was used to set up premises in which the design is to work with to create both form and space that enables effective introduction and extraction of wind.

As elaborated in the earlier chapter, the formal transformation begins with the manipulation of simple geometries. These

manipulations serve to better the connection of form to the cityscape in terms of understanding prevailing wind patterns to better facilitate air movement in and around buildings in the city.

Subsequently, the choice of feasible ventilation techniques were tested, the result would effectively embody the second set of premise in which the form could work with.

For instance, in simulating forms that abide to using stack ventilation techniques, it is found that the negligible difference in pressure and temperature in Singapore’s tropical climate negates the possibility to provide for passive means of comfort with this method of ventilation. The third consideration is ultimately more site specific; it considers the relation of wind patterns as well as shadow studies that are a cause of the height and shape of adjacent buildings.

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