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# Connecting Theory and Practice:

## *An Overview of the Natural Ventilation Standards and Design Strategies for Non-Residential Buildings in Singapore*

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**Key words**: Natural ventilation, Green Mark Standard, Design Strategy, Singapore, Tropics

**Abstract**: With increasing environmental damage, passive architectural design strategies, particularly natural ventilation strategies, are essential techniques for architectural design to protect the environment. In order to improve human comfort and the health of the living environment, spaces for human activities are no longer bounded primarily by closed, indoor artificial spaces and have extended to open, semi-indoor naturally ventilated spaces. Singapore, located in the tropics, has a unique climate where the attention of the Singapore government to natural ventilation indicators in green building decision making, and application of natural ventilation tropical architecture, can be seen. This paper analyses the development of evaluation contents related to natural ventilation in the Singapore green building standard – Green Mark, studies typical naturally ventilated buildings and then proposes effective design strategies. The relationship between standards and cases are finally discussed to explore the differences from theory to practice, with a view to using suitable approaches and methods to encourage natural ventilation design, thus promoting the green building movement and achieving sustainability.

## 1. INTRODUCTION

In the face of limited living space and resources, as well as the growing demand for space in general, high density, highly efficient, and orderly space utilization is an inevitable and effective method of human survival and development. In the high-density city, architectural superposition makes full use of the vertical space, compact urban function, and efficient public transportation systems. The multipurpose use of land makes everyday life convenient but, leads to large, clustered crowds of people, poor quality of living, and ecological destruction. Up to now, it is an indisputable fact that the development of major Asian countries or territories such as Macao, Singapore and Hong Kong has become increasingly intensive. According to Statistics Singapore (2018), the population density of Singapore was 7,796 people per km$^2$ in 2017, ranking third in the world, and having increased more than three times since 1961.

Although relative energy consumption will become less with an increase in population density, the problems of urban high-density development are detrimental and cannot be ignored. Firstly, the ecology is seriously damaged; low environmental urban and building ventilation quality leads to stagnant air pollution, frequent smog and the spread of disease. Secondly, a high concentration of buildings and energy consumption from human activities generate massive heat, forming remarkable Urban Heat Island (UHI) effects. This is due to the growing need for the heating and cooling of indoor spaces, the use of hot water in buildings, and, in some cases, is due to the presence of fuel-intensive industries (United Nations, 2010). Affected by UHI effects, the energy conversion efficiency of Heating, Ventilation and Air Conditioning (HVAC) becomes lower in a hot environment and higher in a cold environment. Therefore, the existence of UHI effects is amplified in Singapore and other tropical areas where there are increases in the annual building energy consumption. Energy consumption increases UHI effects, and UHI effects further increase energy consumption, forming a vicious circle that should be controlled and resolved. Aside from this, a large volume, wide ground coverage and high density of buildings lead to less contact with nature. Spaces with HVAC impose negative effects on human ability to adapt to the thermal environment. 'Sick building syndrome', from residents disregarding nature, encompasses the negative physical and mental symptoms caused by a long-term stay in the indoor environment (Mushtaha, 2017; Rostron, 2005). These problems are contrary to the concepts of sustainability and wellbeing.

Researchers have expressed specific concern about architectural design in order to conserve energy, improve air quality and relieve global warming. Taleb (2014) stated that a residential building applying passive cooling strategies could decrease its total annual energy consumption by up to 23.6% in Dubai. Agrawal (1989) propounded that at least 2.35% of the world energy consumption could be avoided by using proper passive design concepts (as cited in Hamdan, Yamin, and Hafez (2012)). Specifically, energy consumption can be counteracted by utilizing passive cooling strategies which, according to Kamal (2012), include non-mechanical methods like natural ventilation, air cooling, and shade provision to maintain a comfortable indoor environment, and constitute a key factor in mitigating the impact of buildings on the natural environment. In addition, with the improvement of quality of life, more and more people are paying attention to their health. People gradually realize the disadvantages of living in a closed, indoor and air-conditioned environment, and thus yearn for a semi-open or open space close to nature. Furthermore, facilitated by information technology such as the Internet, spaces for intensive and prolonged stays are no longer bounded primarily by interior spaces and have extended to semi-outdoor and outdoor spaces. One's person becomes an active regulator of the natural environment, rather than a passive receiver of the artificial environment. Passive architectural design strategies, especially natural ventilation strategies, are not only key methods to protect the natural environment, but also an effective means to improve the health of users.

## 2. NATURAL VENTILATION PRINCIPLES IN BUILDINGS AND APPLICATIONS IN ARCHITECTURAL DESIGN

Natural ventilation in buildings is due to the pressure gradient between two openings. Wind velocity has a close relationship with inside/outside temperature difference, winds, a building's peripheral environment, spatial form and layout. In fluid mechanics, if the two sides of the hole of an outer wall present an air pressure difference $\triangle p$, there will be air flow through the hole by overcoming resistance equal to $\triangle p$, which is the physical mechanism of natural ventilation. For its working principle, natural ventilation is defined as pressure acting, which primarily includes wind force and stack effect (IHVE, 1971).

## 2.1 Wind-driven ventilation

Wind force, also called wind-driven ventilation, depends on the pressure difference between wind flows around the building. The wind velocity forms positive pressure areas on the windward face of a building, while there is negative pressure on the leeward face. If there are any openings on this building, fresh air will infiltrate through the opening on the windward face and exit from one on the leeward face to balance the pressures, completing an air exchange, i.e. cross-ventilation, between internal and external environments.

There are several crucial factors for capturing wind and considering ventilation in architectural design by adopting the principle of wind effect. Ayo, Mohd-Ghazali, and Mansor (2015) indicated that the direction of ambient wind, distance between buildings, and a buildings' height ratio all play a role in outdoor ventilation. They also emphasized the need to consider wind flow and direction in the planning of urban cities. In addition, Zaki, Hagishima, and Tanimoto (2012) illustrated that the overall pressure due to buildings sharply decreases as building coverage increases from 4% to 40% of the surrounding area. Wind-driven ventilation design needs to be considered in urban planning, in which the configuration of building layout is a very important factor. After that, the creation of an external environment, such as microclimate, landscape, waterscape and so on, is another crucial factor before designing for buildings themselves. Architects have discussed the wind-driven ventilation design from different perspectives of building design strategy, such as building shape, building orientation, building form and dimensions, or window and opening typologies of the building envelope (Dursun & Yavas, 2015; Gan, 2000; von Grabe, Svoboda, & Bäumler, 2014; Shetabivash, 2015; Thomas & Garnham, 2007; Yuan, 2007). Prevailing wind and cross ventilation have always been the focus of architects, so a lot of research has taken place on the boundaries between prevailing wind and cross ventilation, and windward faces.

It is worth mentioning that wind-driven ventilation is so easily influenced by wind direction that the corresponding measures need to be adopted to regulate indoor airflow in architectural design. Common means include double-skin façade, shuttered window, and so on. On the one hand, summer is the best time for adopting wind pressure ventilation. Air cryogenic treatments, however, should be taken before infiltrating into a room when the outdoor temperature is too high. On the other hand, controlling overventilation to reduce unwanted heat loss should be considered in winter. Over winter, heating elements should pre-warm the cold intake air. Wind-driven ventilation strategies apply to the tropical country Singapore, which is well reflected in its local green building standard – the Green Mark.

## 2.2 Buoyancy-driven ventilation

Stack effect is commonly named buoyancy-driven ventilation. It is the vertical air movement through building envelopes, openings, chimneys and flues. Warm air, gained from computers and equipment, rises and then is exhausted out of the upper parts of the building because it is lighter than cooler air which is sucked into the lower portion.

For buoyancy-driven ventilation to work properly, the most important variable is temperature difference, followed by variations in height, as demonstrated in *Formula 1* (Thomas, 2006) and *Table 1* (CIBSE, 2006):

$$\Delta p = 3462h\left(\frac{1}{t_{ext}+273}-\frac{1}{t_{in}+273}\right)Pa \quad (1)$$

Where $\Delta p$ is pressure arising, $h$ is vertical distance between inlet and outlet openings, $t_{ext}$ is outdoor temperature and $t_{in}$ is indoor temperature. The formula shows that vertical distance and an indoor/outdoor temperature difference is proportional to pressure arising. Environments with high vertical distance and temperature difference should take advantage of buoyancy-driven ventilation.

*Table 1*. Pressure differences due to buoyancy-driven ventilation

| Temperature difference, $(\theta_i-\theta_o)$/K | Pressure difference (/Pa) for stated vertical height difference (/m) | | | | |
|---|---|---|---|---|---|
| | 5 | 10 | 20 | 50 | 100 |
| -10 | 2.2 | 4.3 | 8.6 | 22 | 43 |
| 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | -2.2 | -4.3 | -8.6 | -22 | -43 |
| 20 | -4.3 | -8.6 | -17 | -43 | -83 |

Note: Minus sign indicates a reduction in pressure with height, i.e. flow upwards within the building.

As can be seen from *Table 1*, no matter how high the vertical difference is, the pressure difference is zero while the temperature difference is 0. Pressure difference increases with vertical height while temperature difference is not 0. In architectural design, architects usually use solar heat gain and internal heating to create naturally occurring buoyancy-driven ventilation. A common method for this is using glass façades to absorb solar radiation. Raising the height of the chimney is another way to develop the efficiency of thermal force ventilation. Buoyancy-driven ventilation can create relatively stable air flow without considering pressure and direction of the wind, which has potential in xerothermic, temperate, and hot-summer and cold-winter regions.

In addition, a neutral pressure plane is a related key concept of thermal force. No pressure difference exists in such a neutral pressure plane or neutral pressure zone. Only when an opening is located under a neutral pressure plane is there fresh air infiltrated into the building. On the contrary, the upper hot air can discharge from the openings above a neutral plane. It is because of the existence of neutral pressure zones that buoyancy-driven ventilation, in some cases, only realizes the advantages of natural ventilation from a room below. Space above will face the harm of dirty air (exhaust) recharge. Therefore, in the design process, the architect will generally set a ventilating shaft above the roof to raise the height of the air outlet and the neutral plane, thus strengthening the chimney ventilation effect.

Buoyancy-driven ventilation has always been studied by using numerical simulations such as computational fluid dynamic (CFD) methods. The research hotspots on buoyancy-driven natural ventilation mainly consist of four aspects. Firstly, the most central issue is about the principle of buoyancy-driven ventilation, i.e. the temperature difference between the indoors and outdoors, or between inlets or outlets. The essential related factors include vent shape and horizontal position of heat source, inseparable in this issue (Yang et al., 2015; Andersen, 2016). Secondly, a large number of engineering scholars have developed simulations or numerical models in order to depict buoyancy-driven flow much more accurately (Bangalee, Miau, & Lin, 2013). Thirdly, atria have been a hot topic regarding space in buildings for discussing buoyancy-driven ventilation. When considering the space itself, research can be roughly divided into two branches of thought, which are regarding the thermal comfort of occupants or the height ratio of such space (Hussain & Oosthuizen, 2013; Gong & Hang, 2018). Last but not least, building components have sometimes been the subject of discussion, but once mentioned, they involve innovation. For example, Hussain and Oosthuizen (2013) proposed that hot water circulation against chimney walls, heated by solar collectors during the daytime, was useful in inducing night ventilation airflows. Another innovative example regards double-skin façade devices (Mei et al., 2018). The contribution or innovation of this research was to consider two factors, high density and climate, which corresponded to high-rise buildings and tropical regions. It seems that buoyancy-driven ventilation also has potential in the tropics.

## 3. GREEN BUILDING STANDARDS FOR NATURAL VENTILATION IN SINGAPORE

Nowadays, there are many different green building standards all over the world. Although most standards have the same considerations – site, energy, water, resources, indoor environmental quality and innovation (Reed et al., 2011), the specific assessment indicators are variable to reflect different local characteristics, such as climate, culture or policy. Therefore, the weightings for criteria in each country are also different.

According to Ting (2012), green building is not a new phenomenon in temperate countries. Almost all the green building standards were concentrated in temperate climate zones before 2005. They include BREEAM, LEED, and CASBEE. The Singapore BCA Green Mark was launched in 2005, which was the first green building standard designed for the tropics. Buildings are awarded a BCA Green Mark Platinum, Gold$^{Plus}$, Gold or Certified (removed in 2015) rating depending on the scores achieved. Certified buildings are valid for three years. After that, they are required to be re-assessed under the existing building rating criteria to maintain their Green Mark status.

The BCA Green Mark for Non-Residential Buildings (GM NRB) has several versions. The GM NRB v3.0 was launched on 31 January 2008, then updated to GM NRB v4.0 on 1 December 2010, and finally improved to GM NRB 2015 on 31 August 2016 (BCA, 2008, 2013, 2015). This research will compare all versions where they have comparable contents; a separate analysis of GM NRB 2015 will be performed because the GM NRB 2015 has a very different evaluation system to the previous versions.

## 3.1 Comparison based on categories

According to *Table 2*, the old versions of GM NRB include the same categories – energy, water, resources, indoor environmental quality, and innovation – as most green building standards, but lack the assessment of the site. They put more emphasis on the category “Energy Efficiency”, accounting for more than 60%. In this category, GM NRB divides the assessment into two branches, "Air-Conditioned Areas" and "Non-Air-Conditioned Areas". They have the same 42-point value in GM NRB v3.0, but in GM NRB v4.0, there is an increase from 42 points to 55 points for “Non-Air-Conditioned Areas”, demonstrating the Singapore government's encouragement for the naturally ventilated environment. Generally, stakeholders tend to choose “Air-Conditioned Areas” rather than “Non-Air-Conditioned Areas” as the target of scoring. Such bias has not changed in the context of the increasing emphasis on natural ventilation. For instance, both the Stephen Riady Centre certified by GM NRB v3.0 and Learning Hub – The Hive certified by GM NRB v4.0 received full points for “Air-Conditioned Areas” and no points for “Non-Air-Conditioned Areas”, although they are known for excellent natural ventilation design in the discipline of architecture. Thus, the status of “Air-Conditioned Areas” and “Non-Air-Conditioned Areas” are not equal in green building assessment. Their relationship is not parallel, but overlapping. The Green Mark has a long way to go in this regard.

*Table 2.* Comparison of categories, scores, and weightings in GM NRB

| | GM NRB v3.0 | | GM NRB v3.0 | | GM NRB 2015 | |
|---|---|---|---|---|---|---|
| Old Categories | Scores (Weighting) | | Scores (Weighting) | | New Categories | Scores (Weighting) |
| Energy Efficiency | Air-Con Areas 42 (26.25%) | Non-Air-Con Areas 42 (26.25%) | Air-Con Areas 42 (22.11%) | Non-Air-Con Areas 55 (28.95%) | Climatic Responsive Design | 30 (21.43%) |
| | All Areas 57 (35.63%) | | All Areas 61 (32.11%) | | Building Energy Performance | 30 (21.43%) |
| Water Efficiency | 14 (8.75%) | | 17 (8.95%) | | Resource Stewardship | 30 (21.43%) |
| Environmental Protection | 32 (20.00%) | | 42 (22.11%) | | | |
| Indoor Environmental Quality (IAQ) | 8 (5.00%) | | 8 (4.21%) | | Smart and Healthy Building | 30 (21.43%) |
| Other Green Features | 7 (4.38%) | | 7 (3.68%) | | Advance Green Effort | 20 (14.28%) |

Note: “Air-Con Areas” and “Non-Air-Con Areas” are abbreviations of “Air-Conditioned Areas” and “Non-Air-Conditioned Areas”.

A significant change occurs in GM NRB 2015. The old category “Energy Efficiency” is split into two new categories – “Climatic Responsive Design” and “Building Energy Performance”. “Climatic Responsive Design” contains new site-related indicators such as the analysis of the wind environment, as well as all the passive architectural design indicators extracted from the previous version. In short, the original overlapping relationship between “Air-Conditioned Areas” and “Non-Air-Conditioned Areas” is replaced by a parallel relationship. In addition, “Water Efficiency” and “Environmental Protection” of the previous version are combined into “Resource Stewardship” in the new version. The first three new categories, “Climatic Responsive Design”, “Building Energy Performance” and

“Resource Stewardship” have lower weightings than the older version, with a total reduction of 27.83%. Correspondingly, the weightings of “Smart and Healthy Building” and “Advanced Green Efforts” rise sharply. “Smart and Healthy Building” adds new indicators about human wellbeing and smart control. “Advanced Green Efforts” provides green buildings with more space to innovate and enhance. The adjustments and updates in GM NRB 2015 reflect the local government's incentives for passive architectural design and the emphasis on the human experience.

## 3.2 Comparison of ventilation and comfort

*Table 3* calculates the scores and weightings of ventilation indicators that are distributed in the sub-categories "Natural Ventilation", "Building Envelope", "Ventilation in Common Area", "Ventilation in Carparks" and "Indoor Air Quality Management" of the previous version. From GM NRB v3.0 to GM NRB v4.0, a 13-point increase in the previous analysis for “Non-Air-Conditioned Areas” can be seen in *Table 3*. For a more detailed breakdown, this includes an increase of 7 points for “Natural Ventilation”, and 6 points for “Building Envelope”. No new indicators are generated, only the scores of the original indicators are increased. “Natural Ventilation” increases the scores of all indicators significantly, such as the architectural design indicator “Building Layout” (2-point increase) and technical indicator “Ventilation Simulation” (5-point increase), while “Building Envelope” separately improves “percentage of west-facing façade areas over total façade areas" (5-point increase) and "thermal transmittance (U-value) of external west facing walls" (1-point increase). Both "Ventilation in Common Area" and "Ventilation in Carparks" propose a requirement with aspects of natural ventilation and mechanical ventilation. The scoring of natural ventilation in the common area is three times that of mechanical ventilation, while natural ventilation in a car park can get full points.

*Table 3.* Comparison of sub-categories, scores, and weightings for ventilation in GM NRB

| | GM NRB v3.0 | GM NRB v3.0 | GM NRB 2015 | |
|---|---|---|---|---|
| Old Sub-categories/ Indicators | Scores (Weighting) | Scores (Weighting) | New Sub-categories/ Indicators | Scores (Weighting) |
| Natural Ventilation | 13 (8.13%) | 20 (10.53%) | Ventilation Performance | 4 (2.86%) |
| Building Envelope | 29 (18.13%) | 35 (18.42%) | Tropical Façade Performance | 3 (2.14%) |
| | | | Internal Spatial Organisation (NV+MV) | 1 (0.71%) |
| Ventilation in Common Area (NV+MV) | 5 (3.13%) | 5 (2.63%) | | 2 (1.43%) |
| Ventilation in Carparks (NV+MV) | 5 (3.13%) | 4 (2.11%) | Carpark System Efficiency (MV) | 2 (1.43%) |
| Indoor Air Quality Manajement (MV) | - | - | Indoor Air Quality Outdoor Air (NV+MV) | 3 (2.14%) |
| Total | 52 (32.5%) | 64 (33.68%) | Total | 15 (10.71%) |

Note: “NV” and “MV” are the abbreviations of “Natural Ventilation” and “Mechanical Ventilation”.

*Table 4.* Comparison of scores for thermal comfort in GM NRB

| | GM NRB v3.0 | GM NRB v3.0 | GM NRB 2015 |
|---|---|---|---|
| Non-Air-Conditioned Areas | - | - | 4 Points |
| Air-Conditioned Areas | 2 points | 1 Point | Prerequisite |

For GM NRB 2015, the update can be elaborated on from four aspects. Firstly, “Natural Ventilation” is renamed to "Ventilation Performance" which involves a new requirement of thermal comfort simulation, air quality simulation, and a W-H[1] ratio of naturally ventilated space. This new sub-category takes single sided ventilation, cross ventilation, design for spatial scale, thermal comfort and human health into consideration, and is the first time that the Singapore government has proposed an assessment of thermal comfort for natural ventilation areas (*Table 4*). As Green Mark pays more attention to health and comfort, the thermal comfort assessment of air-conditioned areas also changes from an indicator to a pre-requisite (*Table 4*). Secondly, the most notable update to "Tropical Façade Performance" in GM NRB 2015 is that it evaluates all façades rather than only the west façade in the previous version. A subtle note associated with space design in the previous version’s sub-category “Building Envelope” is that it has been upgraded to a new indicator within a new sub-category “Internal Spatial Organisation”, emphasizing the application of passive architectural design. Thirdly, the scoring ratio of natural ventilation to mechanical ventilation in the common area rises from 3 to 4. The car park no longer has an assessment of natural ventilation and now has the sub-category "Carpark System Efficiency", to provide a more comprehensive and detailed assessment of mechanical ventilation and lighting systems. Finally, a new indicator "Outdoor Air" is introduced into the sub-category "Indoor Air Quality", where naturally ventilated spaces receive full points.

## 3.3 Discussion

To sum up, the categories of GM NRB are becoming more comprehensive and balanced, keeping pace with the global green and healthy building movement. Naturally ventilated space has always been the focus of research and evolution by the Singapore Building and Construction Authority (BCA). The new category "Climatic Responsive Design" of GM NRB 2015 clearly illustrates the locals' respect for passive architectural design in the tropics. Naturally ventilated areas also gain equal status with air-conditioned areas. In addition to the building layout and building ventilation simulation, the newly added site wind environment analysis, single side and cross ventilation strategies, spatial dimension design, human health assessment for the naturally ventilated environment, and so on, cover most natural ventilation strategies related to wind-driven ventilation principles. The Singapore Green Mark is a green building standard that respects the climate and environment, encourages passive design strategies, emphasizes local characteristics, and pursues human health and well-being.

[1] W is the limiting depth for effective ventilation. H is the floor-to-ceiling height.

# 4. APPLICATION OF NATURAL VENTILATION STRATEGIES IN SINGAPORE

The Singapore Green Mark is increasingly concerned with climate responsive design. The core of it is to coordinate the relationship between people, the physical indoor environment, building, site, and climate, which is the work of the architects. Therefore, how to achieve proper ventilation and human comfort is the key issue for architects to think about in terms of climate responsive design. In practice, there are diverse design strategies to meet the requirements of green building standards or even to go beyond the standards.

Natural ventilation strategies can be traced back to traditional houses in tropical areas such as Malaysia, Indonesia, and Vietnam. The common strategies contain large roof eaves for sun shading, openings at body level, open interior space and stilted house/pilotis (Ngoh, 2015). These traditional strategies are still widely used today, but their applied forms are slightly different due to urbanization.

## 4.1 National Library Building

Ken Yeang is an advocate of eco-design aesthetics, focusing on the sustainability of tropical urban architecture. From 1975 to the present, he has built a variety of climate-responsive and ecological buildings in the tropics, such as the National Library of Singapore. It is one of the first buildings to achieve the highest GM NRB Platinum Award (*Figure 1*).

*Figure 1.* National Library Building and its atrium

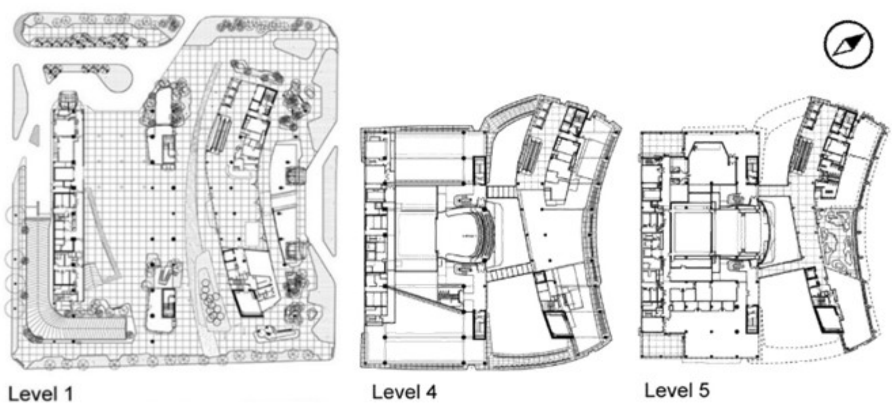


*Figure 2.* Floor plan of the National Library Building

The National Library Building in Singapore is designed with the best possible building orientation and configuration to achieve natural ventilation and daylighting and to buffer against direct solar heat at the same time (BCA, 2005). There is an event plaza, the huge semi-open atrium between two blocks on the first storey, covered by a ventilating louvered canopy over the entire built form. The eastern and western openings of this space are wide, while space is narrow in the middle, shaped like a funnel in order to facilitate cross ventilation (*Figure 2*). Louver devices installed at the openings prevent both sunlight and rain. Furthermore, the hot air from the building can be drawn up into the highest public space between the two blocks, forming effective buoyancy-driven natural ventilation.

This project provides a didactic diagram for the application of natural ventilation principles in tropical regions, particularly the tropical compact city – Singapore. In the tropics, the design of wind-driven ventilation is not limited to small-scale openings such as windows, but includes large-scale building openings, which may be several floors in height. However, no matter how different the opening design is from other climate zones, the natural ventilation principles to be followed do not change. They are the principles associated with prevailing wind and cross ventilation, which are also the main criteria of the sub-categories of "Natural Ventilation" in Green Mark assessment. The design of buoyancy-driven ventilation is usually integrated with wind-driven ventilation in the atrium. The main content of such design is the "canopy" above the atrium, especially the openings of the "canopy". The most basic theories of natural ventilation are cleverly incorporated into this building.

## 4.2 Star Vista

*Figure 2.* Star Vista and its indoor public space

Since the announcement of the first version of Green Mark in 2005, Singapore has stepped into the green building movement under the guidance of specific standards. The Star Vista is the next famous Green Mark certified building after the National Library Building because it is the first commercial building whose public space relies on natural ventilation (*Figure 3*). Its entire design process was centred around the concept of natural ventilation strategies. The building orientation and form follow the principle of reducing east-west exposure to decrease the heat. The north-south inward streets connect the public space to accelerate indoor natural air flow. The overhanging theatre acts as a "canopy" to provide shelter for the public space beneath (*Figure 4*).

The thermal environment of naturally ventilated spaces in Star Vista was measured by Hot-Wire Anemometer TES 1341 (*Figure 5*). This anemometer measured the thermal parameters such as relative humidity, air temperature, dew point temperature, wet bulb temperature, heat index, humidex, and wind speed. Three instruments were set to a 10-second recording interval and a

10-minute test time. They simultaneously recorded data in three naturally ventilated spaces (*Figure 6*).

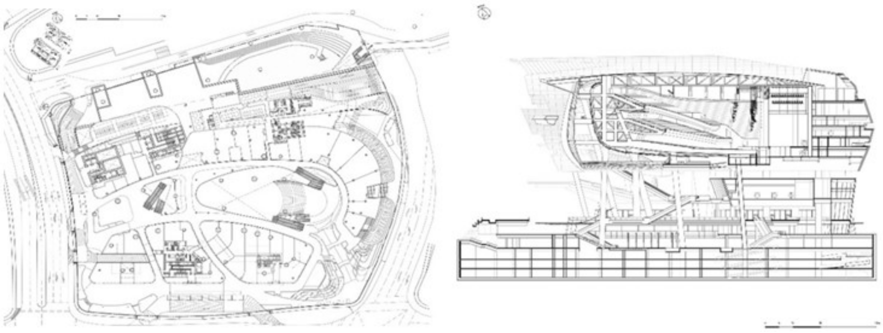

*Figure 3.* First-floor plan and cross-section of Star Vista

*Figure 4.* Hot-Wire Anemometer TES 1341

The weather on the day of the test was sunny. The prevailing wind direction was south so that the openings facing the south direction were selected. These were point A in a narrow inward street that formed the curved wind corridor and point C in a very spacious opening or open space. Although both openings had the same facing direction, their differing size contributed to totally different wind speeds. The wind speed of the small opening was generally high (up to 1.3m/s), while that of the large opening was close to 0 m/s. The third point of thermal measurement was point B located in the central space under the "canopy". The wind speed stayed within the range 0-0.3m/s, which was suitable for people sitting still. Although all these spaces were naturally ventilated, design methods with different natural ventilation strategies resulted in different wind sensations, which determined the types of human activities that could be conducted in comfort. The Star Vista transcends the traditional retail model. The feeling of openness and nature creates a new urban lifestyle.

Compared with the National Library Building, Star Vista pays more attention to the wind-driven ventilation strategy and seeks to create more complex and varied public spaces, incorporating more architectural innovations beyond the basic strategies. In addition to the building shape, building orientation, building form and dimensions that must be considered, the windward face, opening, and indoor wind corridor are the focus of the project's natural ventilation design. Its design team developed a ventilation simulation model that was uniquely suited to this project to support the innovative natural ventilation design. Irregular passages, corridors, and spaces were inconvenient for evaluation following the previous version of the Green Mark. However, the latest version provided a thermal comfort assessment for natural ventilation space, making it possible to assess the natural ventilation design of such irregular objects.

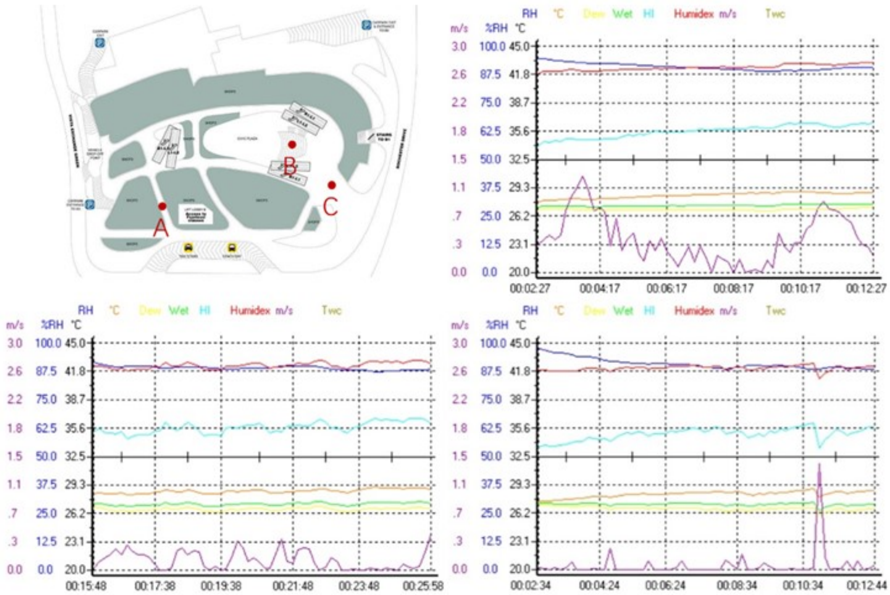


*Figure 5*. Thermal measurements at point A (upper-right table), B (lower-left table) and C (lower-right table) in Star Vista

## 4.3 Marina One

*Figure 6*. Marina One and its atrium

*Figure 7*. Floor plan of Marina One

*Figure 8*. Section of Marina One

In addition to educational facilities and commercial buildings, city complexes are the most important part of a high density city. The latest and most famous complex, located in the heart of downtown Singapore, is Marina One which was completed in December 2018 (*Figure 7*). It consists of four high-rise buildings that enclose a large, naturally ventilated interior atrium (*Figure 8*). The atrium allows cool air to pass through the building's large multi-story transitional space (*Figure 9*). This atrium is a five-meter high space that is named the “Green Heart” by designers. The “Green Heart” is the core concept of this project.

The word "Green" refers to the creation of lush greenery in the garden with high biodiversity. The garden comprises over 350 species of tropical flora, including 700 trees. In the central area of the garden are spectacular waterfall features (*Figure 10*). The integrated landscape and waterscape mimic a green valley, which serves as an evaporative-cooling device to cool the wind in the naturally ventilated atrium as well as in the surrounding buildings.

The word "Heart" means that the atrium tends to give life to the unique shape of the high-rise buildings. Marina One has an atrium open to the sky so that rain can irrigate its plantings. The high-rise and enclosed design features replace the function of a "canopy" to cast vertical shadows over the atrium. The organic shape of the buildings' iconic louvers forms a three-dimensional oasis. Openings between the buildings and louvers directly infiltrate wind into the atrium (*Figure 10*). In addition, the compact layout design allows for a large number of social spaces on the different open terraces facing the "Green Heart". The design provides living spaces close to nature, the usable area of which is 125 percent of the original site surface area.

In addition, the elevator and stair core are naturally ventilated and pushed to the edge of the east part of the building to block solar heat gain and allow wind to infiltrate. The "Green Heart" provides an oxygen-enriched environment to promote freshly cooled air circulation which is partly allowed to flow indoors. The permeable external walls of buildings provide cross ventilation (*Figure 10*).

*Figure 9.* Louvers, waterscape and permeable external walls of Marina One

In summary, the unique shape, generous landscape, waterscape and passive building design make the project itself an environmental filter. It facilitates comfortable natural ventilation and generates an agreeable microclimate, thus shaping a high-quality living environment in Singapore. This project makes an innovative contribution to the discourse on high-density cities, especially in tropical regions, in the context of enormous challenges such as increasing population and climate change. Inspired by the ideas of Green Mark, Marina One innovates its own green design strategies of high-rise and high-density buildings, which goes beyond the existing or conventional green design.

## 4.4 Discussion

Natural ventilation strategies of the tropics, in accordance with the purpose of climate responsive design, show a unique pattern – "protect" and "direct". The building self-shading strategies such as building form, canopy design (e.g. roof, vertical shading blade, louver, and other sunshade components), pilotis, non-thermally critical non-air-conditioned spaces exposed to eastern and western walls (e.g. lift cores, staircases, toilets, electrical plant rooms, etc.), and the cooling strategies such as waterscape and landscape can be regarded as "protect" assets. Building orientation towards prevailing wind directions, windward face, openings, north-south wind gallery, semi-open public space, and permeable external wall can be considered as "direct" assets. "Protect" and "direct" are inseparable and indispensable. Their strategies are complementary.

## 5. CONCLUSION

In the rapid development context of high-density cities, ecological destruction, global warming, energy consumption, human disease, and other increasingly serious problems evoke the responsibility of architects to regain passive design approaches. Natural ventilation, as a passive cooling strategy, is a key climate control means that is widely accepted and adopted by contemporary designers in response to mainstream green and health-related ambitions. Different climate zones have different natural ventilation strategies. The tropical high-density city Singapore commonly applies wind-driven ventilation strategies, which can be clearly seen in the local green building standard – Green Mark.

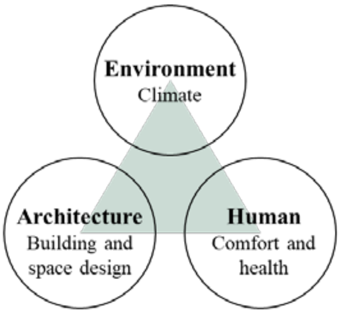


*Figure 10.* Three-dimensional relationship of "environment (climate) – architecture (building and space design) – human (comfort and health)"

Throughout Green Mark's ten-year development, the Singapore Building and Construction Authority (BCA) has always put emphasis on the revolution of natural ventilation assessment. The category "Climatic Responsive Design" was established in the latest version to propose a new scheme for evaluating the passive design based on natural ventilation strategies. The Green Mark shows Singapore's interpretation of green design as a three-dimensional relationship of "environment (climate) – architecture (building and space design) – human (comfort and health)" (*Figure 11*). The actual applications of tropical natural ventilation strategies were in the coupling mode of "protect" and "direct" features.

For the difference between natural ventilation theories and natural ventilation practices, the types of natural ventilation applications are far more varied than allowed for in the natural ventilation indicators of standards. The establishment of theories lags behind, while the practice often contains infinite possibilities that stimulate the creativity of architects so that they can break through theoretical limits and pursue innovation. In short, practice goes beyond theory, which is actually a natural phenomenon rather than a problem. The existence of the final category "innovation" in each green building standard indicates that theory takes the diversity of practice into account. However, if the standard is not designed properly, "innovation" will be useless, so that stakeholders will focus on the easy-to-score indicators, thus weakening the architect's enthusiasm for creation. At this time, the phenomenon becomes a problem that hinders green building development. Although the status of natural ventilation indicators has risen since 2015, they only cover part of actual applications. There are no specific innovation indicators that evaluate the architect's innovative design. Green building standards must carefully simplify the passive design strategies to indicators and avail themselves for the creation of architects in the actual design process, otherwise, it will change from a driving force to a hindrance, which is not conducive to the green building movement and sustainable development.

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