Airflow Patterns of Semi-open Shopping Malls in Bangkok

Songpol Atthakorn

Faculty of Architecture, Rangsit University, Pathum Thani, Thailand
E-mail: Songpol@alum.mit.edu

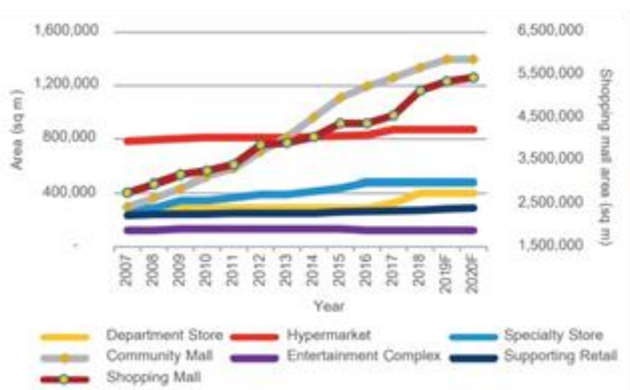
Abstract

Since semi-open shopping malls are a trendy sustainable commercial building type in Bangkok over the few past decades, this research reveals the airflow patterns and qualities of natural ventilation inside the malls. The main benefit of providing natural ventilation is to comfort the customers inside the shopping mall with less energy consumption. It is important to learn how the semi-open malls could have good natural ventilation. The aim of the research is to investigate the airflow qualities inside the mall atriums by Computational Fluid Dynamics (CFD) simulation. Firstly, the 8 case studies are analyzed to reveal the airflow patterns and evaluated. The visual images of airflow patterns could answer how well these semi-open malls perform. Secondly, the semi-open mall architectures and airflow patterns are identified and characterized into basic typology in order to understand the rules of thumb. Then, the alternative modifications of a low-performing case study are experimentally explored to improve airflow qualities. The results are reported as airflow patterns and qualities of each case studies responding to the wind direction. The research suggests that wind-driven ventilation through the mall atrium is the key to success in sustainable malls. The mall should provide either horizontal direct-cross or angle-flow ventilation by having proper building orientation and opening positions. The vertical airflow caused by the interaction of the lower wall inlet with the upper roof outlet openings is also a successful solution in the semi-open shopping malls. In summary, the simulation study of airflow patterns is an important design strategy to develop better natural ventilation for energy saving shopping malls.

Keywords: *Airflow pattern, ventilation, semi-open shopping mall, atrium, typology, CFD*

1. Introduction

According to the greatly increased number of shopping malls in Bangkok in the past decade, community malls are the most popular retail supply to open in the Bangkok Metropolitan Region. Over 3 million square meters of community malls have been opened in Bangkok since 2007 (Colliers International, 2017) (Figure 1). While the large-enclosed regional malls having been increasing their air-conditioning areas and consume lots of energy, as much as a small province in Thailand (Mekong Eye, 2016) (Figure 1). The smaller community malls have been developed their sustainable concepts to save energy consumption. Beside the open malls, the "semi-open community malls" were created by the aims of more protecting the heat from the sun, bringing the natural light and providing the fresh air ventilation into their open-air atrium. The ecological trend creates such an attractive natural-lifestyle environment to the community malls. This research will reveal the qualities of airflow patterns of semi-open community malls in Bangkok.



Proceedings of RSU Research Conference (2019)

Figure 1 The retail supply markets in Bangkok and super-regional mall's energy use
Source: (Colliers International, 2017; Mekong Eye, 2016)

The semi-open mall is created to comfort public shopping spaces inside the mall without air conditioning. While the enclosed mall is a fully air-conditioned shopping plaza with indoor public facilities and the open mall is an open-air arcade with more outdoor public facilities. The semi-open mall is an open-air shopping atrium where most public facilities are covered by a long-span roof.

The semi-open shopping mall is now a trendy commercial building type in Bangkok. In the past 10 years, the semi-open community malls in Bangkok have been opened as many as 46 buildings. Over a decade, the proportional number of semi-open community malls have been increasing compared to other types of malls each year. Most community malls were opened in 2014-2016 when the various typologies of semi-open malls were dramatically developed and opened to the public (Figure 2).

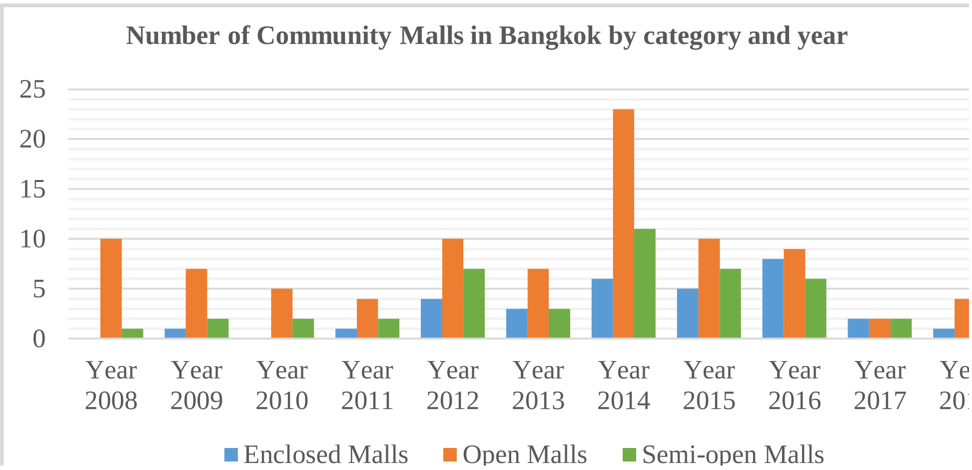


Figure 2 Number of community malls in Bangkok, classified by types
Source: (Anuntapornpanich, 2010; Groatong, 2015) with additions by the author

In the contemporary period, the first semi-open mall is "The Old Siam Shopping Plaza" which opened in 1993. At first, it was built by the ecology concept linked to the long history of the old town market "Ming Muang Market" demolished in 1978. At the opening time, the newly opened shopping mall which consists of hundreds of retail shops and 3 large multi-purposed atriums had no air-conditioning system. The mall intended to provide a lot of openings to bring the natural wind to the 3 story-high atriums under the long-span roofs with natural sunlight. Unfortunately, the original natural ventilation concept didn't work well since the giant building was too wide to get enough ventilation from the small wall openings and the roof openings were blocked by the 4^{th}-floor housing. In 1998, the air-conditioning system was installed to the classic atrium mall in order to have the same standard as other new enclosed shopping malls. It was disappointing that the ecology concept for natural ventilation hadn't been developed enough at that time. However, the first historical semi-open community mall still represents the senses of Thai-classic culture which harmonize with the old town environment (The Old Siam, 2018) (Figure 3).

Figure 3 Ming Muang market in the past and the recent The Old Siam shopping plaza with the atrium
Source: (The Old Siam, 2018)

The semi-open community malls in Bangkok consist of the main open-air atrium which is surrounded and enclosed by shopping walkways and retail shops and covered by a wide-span roof. The largest opening is normally the main entrance or the windward side and the smaller openings are normally the spaces between retail shops or walkways connected to other functions. Generally, these openings are designed for both visual attraction and ventilation flow. Good ventilation helps to reduce the heat collection in the building and makes people feel cooler. A multi-story atrium provides the lifting space for the hotter air and it is blown away at the roof openings. Then the cooler air from the wall openings replaces the lower space of the atriums where the multi-purpose plaza is full of activities. An example of the concept of "Green Lifestyle Mall" could clearly represent the main proposals of the semi-open community mall (MGR Online, 2013) (Figure 4).

Figure 4 The concept of "Green Lifestyle Mall" by screening sunlight and having natural ventilation
Source: (MGR Online, 2013)

The literature reviews explain the benefits and the needs of natural ventilation in the open atrium. The airflow patterns are depending on forms, spaces, and openings of semi-open community malls. The qualities of the airflow patterns can be evaluated from the airspeed and air distribution at activity spaces. The building design guidelines recommend how to get better natural ventilation inside the mall atriums.

Chartered Institution of Building Service Engineers (CIBSE) listed general benefits of natural ventilation compared with mechanical air-conditioning. The uses of natural ventilation in public buildings help lower initial, running and maintenance costs, lower energy consumption and carbon emission. The natural sunlight and open-air ventilation in public spaces promote a healthier environment (CIBSE, 2005).

The book “Designing spaces for natural ventilation” guides how to accomplish the uses of natural ventilation. The best way to reduce energy consumption is to design for human comfort by exploiting natural forces around the building site. Natural ventilation brings fresh air into buildings and gives thermal comfort to occupants. As wind blows across a building, natural ventilation by the wind-driven and buoyancy-driven forces moves cooler fresh air into the building and eliminates the warmer air to the outside building. Besides, buildings are considered more spaciously beautiful since there are no air-conditioning mechanical installation but more transparency for daylight and free flow spaces for ventilation (Passe and Battaglia, 2015).

Norbert Lechner recommended several passive cooling techniques for sustainable design of a building in a hot and humid climate. Besides the protection of radiation heat from the sun, one of the most important design strategies is to increase the natural ventilation performance of a building which helps eliminate the waste heat from the human body by evaporative heat transfer. Good natural ventilation could provide a wider range of comfort zone to occupants that makes people feel cooler (Lechner, 2015).

When there is calm or light wind, the atrium of a mall could circulate the air by stack ventilation through the vertical space. As warm air rises, it exits through the higher-level openings at the top of the space. The large difference in height between the low-level entry of fresh air and the exit of warm air through the atrium creates a large buoyancy effect that draws air through the building. The upward airflow and circulation create a cooler, more comfortable indoor environment (Construction Canada, 2017).

When there is enough wind, the atrium of a mall could create both cross and upward ventilation by the wind-driven ventilation. Wind-driven ventilation can be classified as horizontal and vertical ventilation. Airflow ventilation depends on wind behavior interacting with building envelopes and openings. Wind-induced force could create more effective upward airflow inside atriums than buoyancy force when proper lower inlets and upper outlets are provided to the wind direction. A well-designed atrium should perform well in both buoyancy and wind-driven ventilation (Gan, 2010).

In this research, the study of the wind pattern concentrates only on wind-driven ventilation analysis. The airflow rate of an inlet can be measured by the area of opening and efficiency of the wind speed. The airflow rate is important because it dictates the rate at which stale air can be replaced by fresh air. The airflow rate due to the wind can be calculated by the following equation (ASHRAE, 2017);

$$Q = CvAU \qquad \text{(Equation 1)}$$

Where Q = airflow rate, m^3/s

Cv = effectiveness of openings (Cv is assumed to be 0.5 to 0.6 for perpendicular winds and 0.25 to 0.35 for diagonal winds)

A = free area of inlet openings, m^2

U = wind speed, m/s

In order to get a better airflow rate, openings for inlet and outlet wind should be in the right positions according to the ASHRAE recommendations (ASHRAE, 2017) as follows:

Air intakes should be placed in exterior high-pressure regions, and air reliefs should be placed in exterior low-pressure regions. Air intakes should face directly into the prevailing wind. If they are not advantageously placed, the flow will be less than that predicted by Equation (1). If intakes are unusually well placed, the flow will be slightly more.

Air relief on a wall for horizontal airflow is desirably placed on the following locations:

1. On the leeward side of the building directly opposite the intake, for cross ventilation
2. On a side perpendicular to the windward face, where low-pressure areas occur, for angle ventilation, if the opposite direction of the windward face is unavailable.

Air relief on a roof for vertical upward airflow is desirably placed on the following locations:

1. On the roof, in the low-pressure area caused by flow separation

2. On a dormer at the leeward side

Natural Ventilation Guidelines suggests that in hot and humid climates, air velocities should be maximized as well as air distribution in the occupied zones of rooms. Opening characteristics and opening locations in a building should be well considered (ASHRAE, 2017).

The selected considerations which apply for this research are as follows:

1. Building orientation should be shaped to expose maximum openings to wind directions.
2. Openings positions should be located in opposing pressure zones. Two openings on opposite sides of a space increase ventilation flow. Effective cross ventilation is to be considered.
3. Air distribution depends on the air relief location relative to the intake's airstream. Openings on perpendicular sides of the building force air to change direction and provide ventilation to a greater area.
4. For single-sided openings, two separated openings make better airflow through an atrium.
5. Vertical airflow between different levels of openings should have the same direction as the stack effect. Upward wind in an atriums helps evacuate the hotter air through a roof opening.
6. Greatest airflow between two openings is obtained by having openings of nearly equal areas. If an inlet of an atrium is smaller than the outlet, it creates higher velocity. If an outlet is smaller than the inlet, it creates lower velocity but having more uniform speed with better air distribution through the atrium.
7. Horizontally separated openings in an atrium are generally better than vertically separated openings. Because there are more chances to catch the wind from more directions and create horizontal cross ventilation which is more effective.

These natural ventilation design considerations are selected to be the hypotheses of this research. This research will find out how case studies perform relating to the local wind and airflow behavior. In order to reveal the airflow patterns, the tool used for analysis is the computer simulation software, Computational Fluid Dynamics (CFD). The simulations will result in the speeds and directions of the air movements through the models. The results of airflows will be evaluated in terms of ventilation qualities.

2. Objectives

The research objective is to study the ventilation patterns of semi-open community malls in Bangkok. The purposes of this research are as follows:

1. To analyze the airflow patterns inside the atriums of the case studies by computer simulation
2. To identify the basic typology of semi-open atrium malls and wind-driven ventilation
3. To evaluate the alternative modification of a case study to improve airflow qualities

3. Materials and Methods

The population in this research was 50 semi-open community malls in Bangkok. The characteristics of a mall consist of typical elements including: a multi-story atrium space, an open-air shopping plaza with a multi-purpose area and alongside walkways surrounded by retail shops and a main tenant anchor store, a wide span roof over the atrium with skylight and openings at wall and roof levels. The locations of the population and the selected samples are shown in Figure 5.

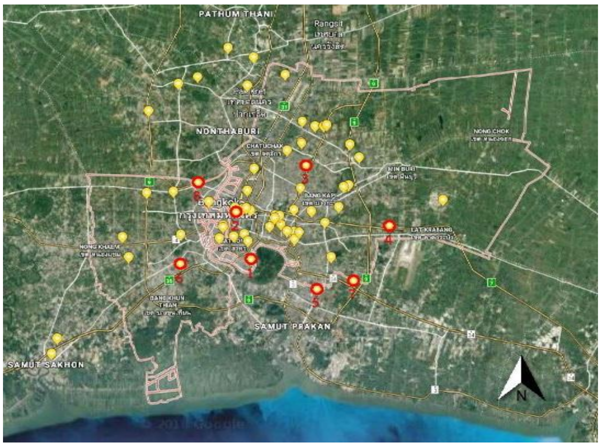


Figure 5 Locations of semi-open malls (yellow dot) in Bangkok (pink borderline) and the 8 case studies (red circle)

The samples in this research are the 8 case studies of the semi-open community malls. The chosen case studies have the variation of sizes and forms of their atriums. The names of the case studies and their dimensions are shown in Table 1.

Table 1 Case study names and dimensions

Case Studies Project No./Name	Cross-Section Area (m^2)	Atrium Width (m)	Atrium Length (m)	Atrium Height (m)	Atrium Area (m^2)	Atrium Volume (m^3)	Number Opening Side/s	Wall Opening Length (m) (%)	Roof Opening Height (m) (%)
1. INT-Intersection Rama 3	684	12	85	14	1,146	16,044	2	31 (16%)	2 (14%)
2. I'm Park Chula	999	12	130	18	1,799	32,382	4	97 (34%)	1 (5%)
3. Central Festival Eastville	1,170	20	140	15	1,782	26,730	2	28 (9%)	5 (33%)
4. Jas Urban Srinakarin	1,332	24	60	16	1,760	28,160	1	20 (12%)	2 (12%)
5. The Nine Rama 9	1,415	24	140	17	3,150	50,400	4	92 (28%)	1 (6%)
6. The Bright Rama 2	2,664	30	64	22	2,023	44,506	3	47 (24%)	2 (9%)
7. Mega Foodwalk Bangna	2,669	30	110	22	2,775	61,050	3	54 (19%)	5 (23%)
8. The Sense Pinklao	3,340	40	60	24	1,924	36,072	3	38 (23%)	3 (12%)
Average	1,784	24	109	18.5	2,045	36,918	2.75	51 (21%)	2.6 (14%)

The wind conditions in Bangkok that influence the ventilation pattern inside the mall atriums can be seen by the wind rose diagrams from the Thai Meteorological Department. The average wind direction and speed year-round in 10 years period from 2008-2017 and the average in summer (February 15th to May 15th) are shown in Figure 7. The major wind direction is from the South South West (SSW) and the most wind speed is in between 5.40-8.86 km/h (1.5-2.5 m/s) (Thai Meteorological Department, 2018).

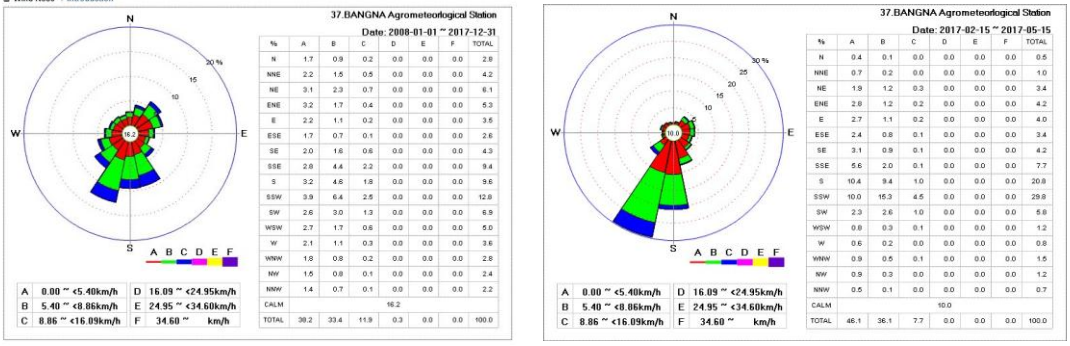


Figure 7 Wind Rose diagrams for Bangkok: average year round (Left) and average in summer (Right) (Thai Meteorological Department, 2018)

The methodology of this research is to study the relationships of the airflow behaviors inside the atriums of semi-open shopping malls. Firstly, the case studies were analyzed by computer simulations to observe the airflow patterns in terms of performance and suitability. Pros and Cons from the results will be detected and reported. Secondly, the basic typology of the semi-open malls will be identified. The best orientation to the wind direction for the typical formations of the malls will be analyzed. Thirdly, the typology of the wind characteristics in the basics type of the malls was summarized as rules of thumb. Then, the knowledge of wind-driven ventilation was experimentally used to improve ventilation efficiency of a low-performing mall. Several alternatives of modification were evaluated in order to get the best result of airflow improvement in the mall. In summary, the research process consists of the analysis part by gathering data, testing, identifying, classifying and evaluating and the synthesis part by identifying problems, alternative designing, implementing and evaluating.

The tool used in this research is computational fluid dynamic (CFD) simulation software. The inputs are the mall models and the outputs are the results of airflow patterns which could be evaluated.

The independent variables are the 8 exact models of the case studies and the 4 basic-type models which variables are as follow;

1. Number of opening directions; 1, 2, 3 or 4 sizes
2. Sizes of openings; small (minor opening) or large (major opening)
3. Actions of openings; none, inlet or outlet
4. Level of openings; wall (lower level) or roof (upper level)

The controlled variables are the setting up of the simulation software as follow;

1. Incoming wind speed; the major wind speed is 2 m/s (according to the local wind)
2. Exact Wind direction; the major wind direction is from South South West (SSW)
3. Alternative wind direction; direct wind to the major opening or minor opening

The dependent variables are the results from the simulation analysis as follow;

1. Horizontal airflow direction; none, cross, reversed, angled or eddy (turbulence)
2. Vertical airflow direction; none, cross, reversed, downward, upward or eddy
3. Airflow speed level; none, low, medium, high or very high
4. Airflow distribution level; none, low, medium, high or very high

The drawings of the 8 case studies are drawn by 2D drafting software from the site survey and internet data. The case studies are drawn in plans and sections with the gray highlights of the study areas (Figure 6). Next, the case studies drawing are made from the 3D mock-up models for the computer simulation. Then, the models will simulate airflow patterns in both plan and section. The simulations are assumed that there are no surrounding buildings and the wind blows consistently without effects from the heat.

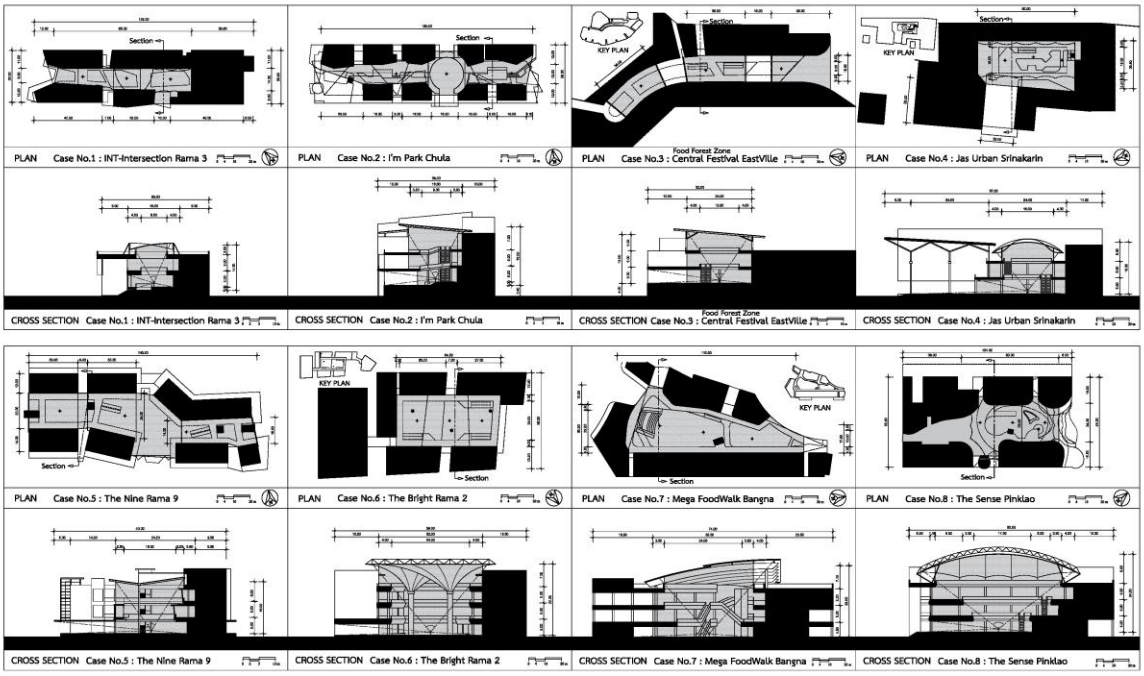


Figure 6 Drawings of the 8 case studies show solids enclosures (Dark) and the atrium volumes (Gray)

The results of airflow patterns will show as follows:

1. Direction indicated by the thicker side of a line as arrowhead and slimmer as an arrow tail.
2. Volume indicated by density, length, and spacing of arrows
3. Speed indicated by the color of arrows as displayed in wind speed index

Later after analyzed, the case studies were classified by the typical organizing plans and the number of opening directions. By this classification, most of the population could also be identified into a few basic types. The simplified typology of the semi-open community malls and airflow patterns are shown in the result and discussion part.

4. Results and Discussion

4.1 Analysis of the case studies

After the 8 case studies were analyzed by computational fluid dynamics (CFD), the results are shown in horizontal and vertical airflow patterns. The qualities of airflow patterns inside the mall atriums are evaluated in terms of airflow speed, airflow volume, and airflow distribution.

4.1.1 Horizontal airflow patterns

The horizontal airflow patterns of the 8 case studies are shown respectively by the wind simulation results in plans (Figure 7). The incoming local wind is from the South South West (SSW) direction at wind speed 2 m/s. Each case study responds to the wind differently according to the forms, spaces, and openings. The patterns are described individually by the following case study numbers;

1. Case study No.1 (INT-Intersection Rama 3): The major wind comes from the side of the mall and passes through most of the atrium from the 2 minor openings and turn sharply to the front of the building where the main opening is located. This causes medium airflow speed and high level of wind distribution.

2. Case study No.2 (I’m Park Chula): The wind easily passes through the slim atrium which comes from by a lot of openings toward the wind direction. The airflow pattern inside the atrium contains various speed caused by the openings and the solid walls. Therefore the wind distribution is not

very good because the wind cannot pass through all parts of the atrium. However, the four-side openings of the mall catch the wind very well.

3. Case study No.3 (Central Festival Eastville, Food Forest Zone): Although the long plaza with a few openings creates a tunnel-like mall, the orientation of the mall is good enough to catch the major wind. The small low-pressure outlet openings help to suck the air in some part of the atrium. The airflow and air distribution of the mall are in medium levels.

4. Case study No.4 (Jas Urban Srinakarin): This is a critical case since the mall has only a large front opening. The cave-like atrium is located deep inside the building. The orientation is worst facing the West and not applicable to the local wind. As the result, there is almost none of the airflow and air distribution in the mall atrium.

5. Case study No.5 (The Nine Rama 9): The four-direction openings of the mall, just like case No.1, generate the speed of wind through the opposite direction of the openings while some parts of the atrium do not have that much ventilation. Nonetheless, the airflow speed and distribution are at a high level.

6. Case study No.6 (The Bright Rama 2): The front wide opening of the mall is not in the same direction of the major wind. The ventilation inside the atrium gets only a small volume of the wind and generates two eddy-wind patterns. The wrong orientation causes the medium level of airflow speed and air distribution.

7. Case study No.7 (Mega Foodwalk Bangna): This case study is considered one of the best-designed malls for natural ventilation. Since the mall orientation and the large openings on both sides respond to the major wind very well. The airflow pattern inside the large atrium is excellent. Both airflow speed and distribution are at a very high level.

8. Case study No.8 (The Sense Pinklao): Although the inlet is small, the rear opening direction toward the incoming wind is good. The large outlet in front of the building and other small openings at the side of the building work together well in order to get airflow speed and distribution. The airflow qualities are at a high level.

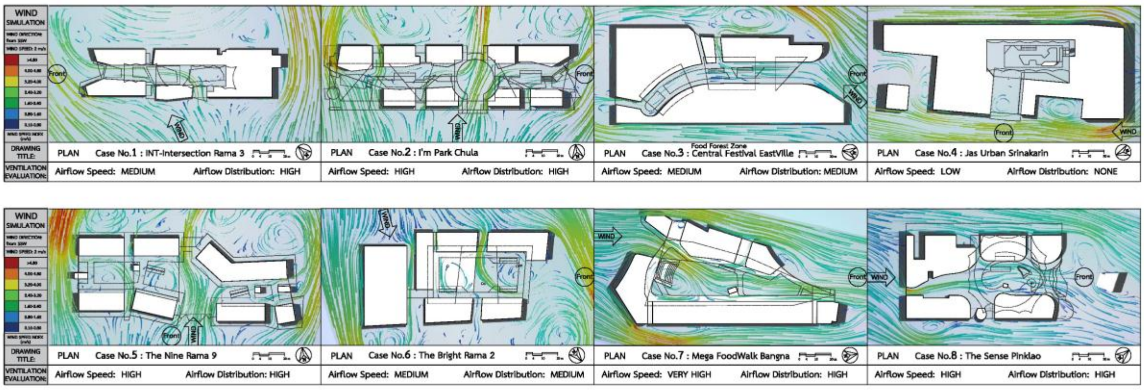


Figure 7 Horizontal airflow pattern of the 8 case studies

From the analysis, Cross ventilation driven by the natural wind is the most effective ventilation. When the 2 openings are in opposite direction along the wind, the airflow speed is from high to a very high level (Case No.2, 5, 7 and 8). When an outlet opening is in the perpendicular angle to the inlet opening, the airflow speed is in medium to high level and also creates medium to high level of airflow distribution in the atrium (Case No.1, 3 and 6). A building with more opening sides could get more chances to catch the wind in various directions and have airflow qualities from medium to a very high level (Every case accept No.4). A building with an only one-sided opening couldn't make any airflow inside the atrium (Case No.4). When the longitudinal axis of an atrium is oriented along the wind direction, the atrium building with 2 openings at both ends performs best in airflow efficiency (Case No.7 and 8).

4.1.2 Vertical airflow patterns

The vertical airflow patterns of the 8 case studies are shown respectively by the wind simulation results in cross sections (Figure 8). The incoming local wind is from the South South West (SSW) direction at wind speed 2 m/s. Each case study responds to the wind differently according to the forms, spaces, and openings. The patterns are described individually by the following case study numbers;

1. Case study No.1 (INT-Intersection Rama 3): The upward ventilation from the lower opening passes diagonally through the atrium to the roof opening in 45˚. The slim side of the atrium tracks the airflow passing in high speed. The airflow volume, speed, and distribution are at a high level.
2. Case study No.2 (I'm Park Chula): Although the opening at the windward side is very wide, the roof openings are too small to create cross ventilation. Like the single-sided opening space, the atrium has low air movement.
3. Case study No.3 (Central Festival Eastville, Food Forest Zone): The separation level of the openings at the windward side together with the wide roof opening especially at the leeward side of the mall creates a very high level of airflow qualities. The atrium is just like a pavilion in the wind field.
4. Case study No.4 (Jas Urban Srinakarin): The mall has a small outlet since the roof opening at the leeward side is blocked by the solid mass. The wind from the large opening at the entrance could not easily pass through the atrium roof. The airflow quality is low since the atrium could be more considered as a one-sided opening building.
5. Case study No.5 (The Nine Rama 9): This case study has the effect of the single-sided opening in cross-section. The leeward side is enclosed by 4-story solid mass and the attached roof. Wind from the large opening side could not get into the atrium caused by the inside high-pressure zone.
6. Case study No.6 (The Bright Rama 2): The airflow pattern shows vertical air movement from the lower inlet toward the roof outlet. The wind speed and distribution inside the atrium is at a medium level.
7. Case study No.7 (Mega Foodwalk Bangna): The upper-level openings bring strong wind passing through the upper space of the atrium to the large opening at the leeward side of the roof. But there is not much air movement at the ground level where the multi-purpose plaza is located. This air pocket effect makes a low level of air distribution in the atrium.
8. Case study No.8 (The Sense Pinklao): The large volume of atriums with a small outlet opening generates moderate airspeed. The ground level opening catches the wind blowing well at the activity level and the wind passes diagonally through the upper step corridors. This makes air distribution quality in the atrium at a high level.

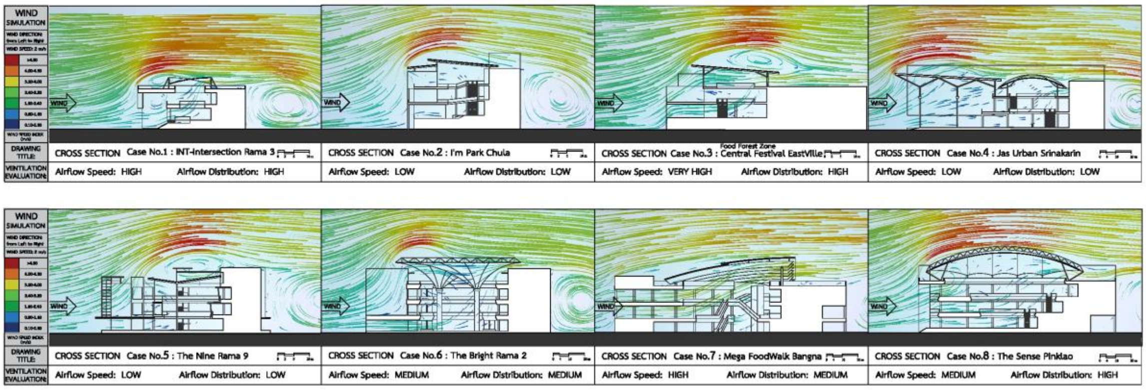


Figure 8 Vertical airflow pattern of the 8 case studies

From Figure 8, the airflow patterns tell the wind behaviors that respond to the forms and spaces of the case studies. The proportions of an inlet to outlet opening affect the airflow speed. When inlet and outlet are quite the same sizes, the airflow speed is high and the airflow distribution is medium to high (Case

No.1, 3 and 7). On the other hand, when there is a larger inlet with a smaller outlet, the airflow speed is medium and the airflow distribution is medium to high (Case No.6 and 8). And when there is a very large inlet with a very small or none of an outlet or obstructed by a solid mass above a roof, there is low air movement (Case No.2, 4 and 5). The airflow patterns analysis reveals that some case studies need improvement of proper inlet and outlet locations and sizes in order to get better cross ventilation. The airflow qualities of the case studies are rated, compared, and ranked (Table 2).

Table 2 Case study airflow qualities by the exact wind direction

Case Studies Project No./Name	Horizontal Airflow Speed Rating	Horizontal Airflow Distribution Rating	Vertical Airflow Speed Rating	Vertical Airflow Distribution Rating	Overall Qualities Rating Value	Performance Ranking No.
1. INT-Intersection Rama 3	Medium	High	High	High	2.75	Tie 2nd
2. I'm Park Chula	High	High	Low	Low	2.50	Tie 3rd
3. Central Festival Eastville	Medium	Medium	High	High	2.50	Tie 3rd
4. Jas Urban Srinakarin	Low	None	Low	Low	0.75	5th
5. The Nine Rama 9	High	High	Low	Low	2.50	Tie 3rd
6. The Bright Rama 2	Medium	Medium	Medium	Medium	2.00	4th
7. Mega Foodwalk Bangna	Very high	High	High	Medium	3.00	**1st**
8. The Sense Pinklao	High	High	Medium	High	2.75	Tie 2nd
Average	2.50	2.375	2.00	2.00	2.34	-

Remarks: Rating value equivalent; Very high = 4, High = 3, Medium = 2, Low = 1, or None = 0

From Table 2, the performance rating and ranking tell the overall qualities of airflow patterns compared among the case studies. The airflow qualities of the case studies are rated from 1-5. The best overall qualities rating goes for the case study No.7 at rating value of 3.00. The case study No.1 and 8 are tied at the second rankings at rating value of 2.75. The 3 tied 3rd rankings are the case study No.2, 3 and 5 at rating value of 2.50. The 4th ranking is the case study No.6 at rating value of 2.00. The worst ranking is the case study No.4 at rating value of 0.75.

In theory, all of the case studies could be developed to perform better by adjusting the independent variations. In this research, case study No.4 is selected to develop by modification of opening positions. The results of the case study modification are shown later in heading 4.4.

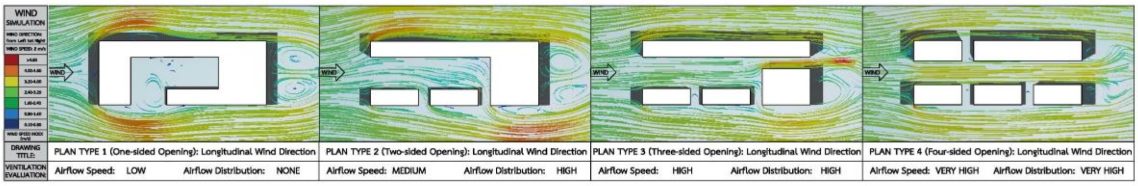
4.2 Mall typology and the airflow pattern

4.2.1 Mall typology in plan

The case studies are classified by the typical organizing plans and the number of opening directions. By this classification, most of the population could also be identified into a few basic types. The analysis of the typology of the semi-open community malls shows clearly responds to the airflow patterns.

According to the horizontal wind analysis of the 8 case studies, the openings can be simplified into 4 types of openings from 1 to 4. The atriums enclosed by the retail shops and anchor stores can also be simplified into 4 organization types as well. These opening and enclosure types could be characterized into 4 building types as follow (Figure 9):

1. Plan type 1 (Single-sided opening type) represents case study No.4.
2. Plan type 2 (Two-sided opening type) represents case studies No.1 and 3.
3. Plan type 3 (Three-sided opening type) represents case studies No.6, 7 and 8.
4. Plan type 4 (Four-sided opening type) represents case studies No.2 and 5.



Type 1 Type 2 Type 3 Type 4

Figure 9 Typology of semi-open malls in plan

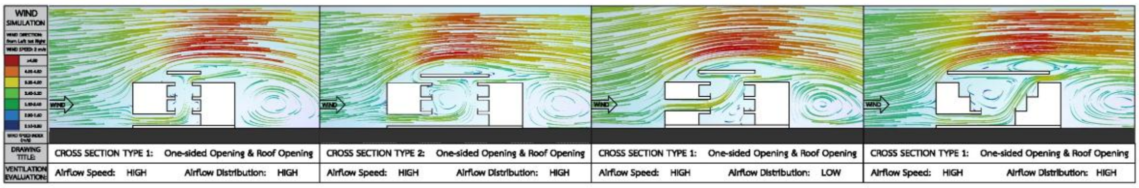
Being tested in several directions by wind simulation, all semi-open mall types could get the best wind airflow patterns by the straight wind direction to the main front opening or toward the longitudinal axis of the atriums (Figure 9). In type 4, wind direction from both the front and back sides in type 4 creates the same airflow patterns at a very high level of airflow speed and distribution (Type 4). The second best is the reversed wind direction at the back opening (Type 3). The third is the wind direction toward the side openings (Type 2, 3 and 4). The worst wind direction is the wind toward the solid mass from the back or side (Type 1, 2 and 3). Plan type 1 performs worst among the 4 types at all wind directions (Type 1).

This analysis tells that the longitudinal axis of mall atrium should be oriented along the wind direction and should have openings at both ends. The more number of opening sides, there are more chances to get better airflow pattern from various wind directions.

4.2.2 Mall typology in cross-section

The vertical airflow patterns are the results of cross ventilation between the lower wall openings and the roof openings by the wind-driven ventilation inside the mall atriums. All roof openings are assumed to be good outlets while the inlet positions and the atrium proportions vary. The basic typology of semi-open malls can be classified into 4 types as follow (Figure 10);

1. Cross section type 1 (Shallow atrium) represents the atrium height higher than the width.
2. Cross section type 2 (Wide atrium) represents the atrium width wider than the height.
3. Cross section type 3 (Middle-level wall opening) represents case studies No.7.
4. Cross section type 4 (V-shape atrium) represents case studies No.8.



Type 1 Type 2 Type 3 Type 4

Figure 10 Typology of semi-open malls in cross section

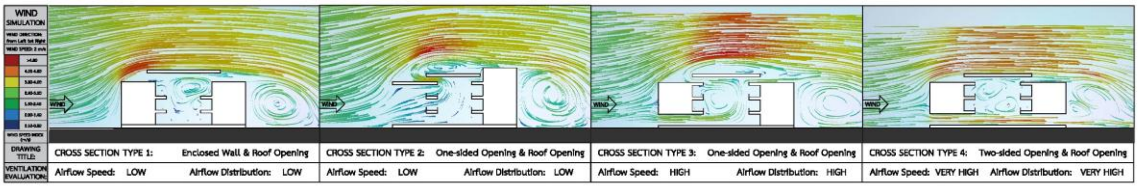
From Figure 10, the ventilation in the shallow atrium (Type 1) has one-way vertical airflow while the wide atrium (Type 2) has an eddy effect in the atrium. The inlet in the upper level generates the strong wind in the upper part of the atrium space but the low wind at the atrium floor (Type 3). The V-shape atrium creates strong diagonal wind with an eddy effect which promotes good air distribution (Type 4).

This analysis shows that wind-driven ventilation could make effective vertical airflow patterns. Vertical airflow helps removing hot air toward roof outlets. Wall-opening inlets at windward side works well together with the roof-opening outlets at the leeward side. The ground floor-level inlets make the most effective ventilation since most activities are at floor level.

4.3 Typology of ventilation in the mall atriums

4.3.1 Ventilation in cross-section

The analysis of ventilation in various types of building forms and openings shows the airflow patterns of ventilation. Typology of ventilation in cross-section is shown below (Figure 11).



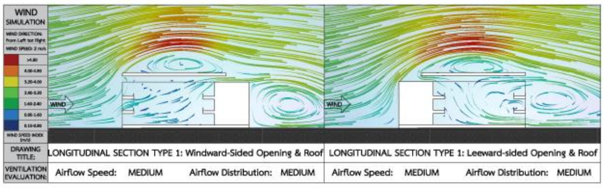
Type 1 Roof Type 2 Single-sided Type 3 Horizontal & vertical Type 4 Cross

Figure 11 Typology of ventilation in cross section

From Figure 11, the 4 ventilation types are evaluated. The qualities of airflow patterns are evaluated by the results of airflow speed and distribution in the activity area. Cross ventilation is the most effective ventilation (Type 4). The second best ventilation is the working together of horizontal and vertical ventilation (Type 3). The third best is single-sided ventilation created from separated openings at one side (Type 2). And the worst ventilation is the ventilation from the roof openings alone (Type1).

4.3.2 Ventilation in longitudinal section

Most of the semi-open malls have a single-sided opening in the longitudinal section since the far end of a mall atrium is the location of an anchor store and shops. This analysis tells how the mall atriums get ventilated along the longitudinal length (Figure 12).



1. Direct ventilation 2. Reversed ventilation

Figure 12 Typology of ventilation in longitudinal section

From Figure 12, the longitudinal section of an atrium consists of a large single-sided wall opening with a small roof opening. The section is tested in two opposite directions to the wind. The analysis of ventilation in the mall atrium shows 2 kinds of ventilation. First, direct ventilation is the ventilation from the outside wind direction. And second, reversed ventilation is the ventilation from the turbulence wind from the leeward side. The low pressure in the atrium sucks the wind from the higher pressure at leeward side. Although these two effects have different airflow patterns, the airflow qualities are quite the same.

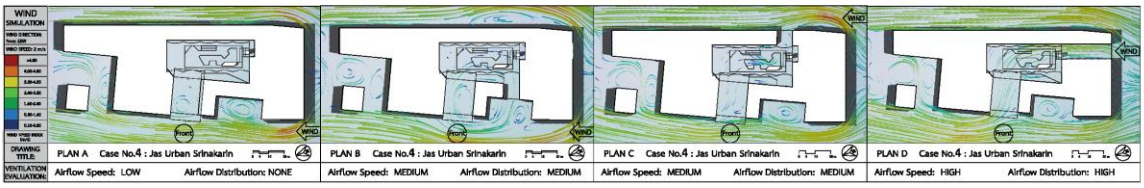
4.4 Results of the case study modification

In order to study how to improve the natural ventilation inside an atrium, a case study which has low airflow qualities are experimented by modifications. The modifications are suggested from the basic knowledge of typical openings related to the airflow qualities in the last part. This is an exercise to test the hypotheses. The success of the modifications would confirm the hypotheses.

The selected mall to modify is the case study No.4 Jas Urban Srinakarin. The still air inside the atrium of the mall caused by the enclosed building form since the mall has only one opening side in both horizontal and vertical views.

4.4.1 Modification in plan

The ideas of adding more openings are the concept of the modification in the plan (Figure 13). There are 3 modifying options of adding more opening in 3 different directions. The first option is to develop the single-sided opening by adding another separating opening (Option 1). The second option is to create cross ventilation by adding an opening at the opposite side of the main opening (Option 2). The third option is to open the enclosed atrium at the windward side by creating a long corridor to the south opening in order to get the angle cross ventilation (Option3). The test results of the modified models in the plan are compared with the existing mall is shown below (Figure 13).



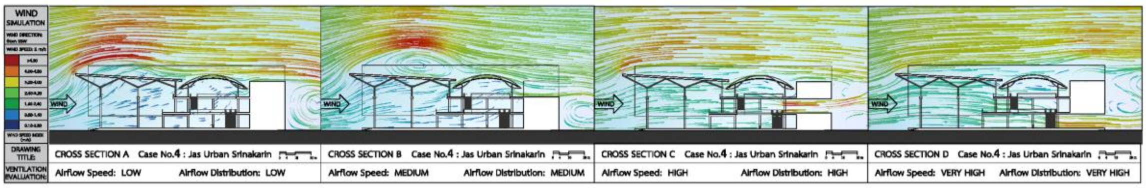
1. Existing mall 2. Modifying option 1 3. Modifying option 2 4. Modifying option 3

Figure 13 The airflow patterns before and after modifications in plan

From the results of the airflow pattern, the airflow qualities can be evaluated (Figure 13). The modifying option 3 performs best since the inlet is opened directly to the wind direction and the angle airflow through the atrium distributes the cross ventilation to all over the atrium areas in high level (Option 3). While modifying option 1 and 2 are not opened toward the wind, but the airflow qualities are in medium level (Option 1 and 2). Therefore all 3 modifying options improve better ventilation from a low level to medium and high level.

4.4.2 Modification in cross section

Since the existing roof opening outlets could not create enough airflow, there are 3 modifying options in cross-section (Figure 14). In order to get cross ventilation, there are 3 modifying options of adding an opening at the opposite direction to the main existing opening at 3 different levels. The first option is to clear the obstructing mass on the rooftop. The implementations are done by clearing the mechanical room at the rooftop to be a clear opening at the leeward side (Option 1) in order to get cross ventilation through the mall atrium. The second option is to add an opening at the second level (Option 2). The third option is to open the enclosed atrium at the atrium floor level (Option 3). The test results of the modified models in cross sections compared with the existing mall is shown below (Figure 14).



1. Existing mall 2. Modifying option 1 3. Modifying option 2 4. Modifying option 3

Figure 14 The airflow patterns before and after modifications in cross section

The cross-sectional modifications reveal the qualities of airflow inside the atrium (Figure 14). The modifying option 3 performs best since the cross ventilation passes though activity level, 0-2 meters high from floor level, of the atrium in very high level (Option 3). The second best is modifying option 2 where the outlet is in the middle of the height of the atrium (Option 2). Although option 1 responds in medium quality level, the free flow horizontal and vertical airflow through roof opening improves overall ventilation (Option 1). These results of the modifications make better cross ventilation which comforts most functional areas. The airflow patterns are successfully improved by the simulation process of modification.

5. Conclusion

The study of ventilation patterns by analyzing the 8 case studies revealed the airflow behaviors through the various forms and spaces of the semi-open community malls. By reviewing the literature, the researcher could understand the relevant issues of ventilation in buildings. The research methodology was aimed to discover the airflow patterns of the malls and understand the effects of the wind. The airflow characteristics were simulated by computational fluid dynamics software, CFD. The qualities of airflow patterns were evaluated in terms of speed and distribution which comfort the usable spaces of the malls.

The typology of semi-open community malls was simplified into 4 types in plan and 4 types in cross-section. The typology of wind-driven ventilation provides the basic knowledge of ventilation produced by forces of the natural wind. These images show as rules of thumb of natural ventilation behaviors in atriums. The main opening at the windward side is the most important and the second opening side could be whether at the leeward side or at the perpendicular side to the windward side. The interaction of the lower wall inlet with the upper roof outlet openings could well generate both horizontal and vertical airflow inside the semi-open malls. Architects and designers could apply this typology to their works.

The modification analysis helps to understand the problems and test the knowledge of airflow in semi-open malls. The evaluation process helps decision making in choosing the best alternative for modification options. This achieving experiment could confirm the hypotheses.

This research has revealed the invisible and untouchable airflow inside the semi-open community malls. Providing natural ventilation for shopping mall atriums is a contemporary trend in commercial architecture. Sustainable malls help in saving costs and making the world greener. The challenging design techniques by computational fluid dynamics simulation create a better environment for the malls. This research provides understandable images for most general readers to easily sense the ventilation flow.

Hopefully, this research could benefit those people who deal with or study about semi-outdoor commercial spaces in a hot and humid climate. The target groups are educators, architects, developers, mall managers, and others. The further research, such as: stack ventilation by buoyancy effect, natural lighting effects from a skylight and thermal comforts in semi-open malls would be recommended.

6. Acknowledgements

The researcher would like to express great appreciation to the following organizations and people who are valuable and contribute to this research;

Firstly, Rangsit Research Institute (RRI) partially supports the research fund. Faculty of Architecture, Rangsit University also supported the research lab and office. The organizers of the RSU International Research Conference on Science and Technology, Social Sciences, and Humanities 2019 (RSUSSH 2019) and the staffs of the Session G3 Architecture and Design for all Perspectives.

Secondly, the organizations and owners of the shopping malls are used as references and case studies in this research. The case studies are including: The Old Siam Shopping Plaza, Porto Chino Rama 2, INT-Intersection Rama 3, I'm Park Chula, Central Festival Eastville, Jas Urban Srinakarin, The Nine Rama 9, Maga Foodwalk Bangna, and The Sense Pinklao. The Autodesk Flow Design software organizer supported the computational fluid dynamic software.

Last but not least, the respectful supervisors and the research team. Asst. Prof. Dr. Narupol Chaiyot and Asst. Prof. Dr. Wilaiporn Nakapan encouraged this research paper. Mrs. Nattinee Atthakorn was the research assistance. The research staff helped in collecting information and operating tools.

7. References

Anuntapornpanich, K. (2010). *Development of community mall in Bangkok and greater metropolitan area.* A thesis for the degree of Master of Architecture. Thammasat University.

ASHRAE. (2017). *Natural ventilation. 2017 ASHRAE Handbook-Fundamentals (SI)*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Georgia. 16.13-16.15.

CIBSE. (2005). Natural Ventilation in Non-Domestic Buildings – a guide for designers, developers and owners: The Benefits. *Good Practice Guide* 237. England: The Chartered Institution of Building Services Engineers, London. 3-6.

Colliers International. (2017). *Market report: Bangkok Retail Market "Retail business is still continuing to grow in 2018, but there is resistance from the slower recovery of purchasing power".* Retrieved December 15, 2018, from http://www.colliers.com/-/media/files/apac/thailand/market-reports/q2-2018/bangkok-retail-2q-2018_eng.pdf

Construction Canada. (2017). *Atriums: Ideal for dual-purpose natural ventilation systems*. Retrieved from https://www.constructioncanada.net/atriums-ideal-for-dual-purpose-natural-ventilation-systems/

Gan, G. (2010). Interaction between wind and buoyancy effects in natural ventilation of buildings. *The Open Construction and Building Technology Journal*, *4*, 134-145.

Groatong, K. (2015). *Consumer behavior and marketing factors affecting the decision to use shopping center services in Bangkok metropolis: A comparative case study between shopping mall and community mall*. A thesis for the degree of Master of Economics in Business Economics. Kasetsart University.

Lechner, N. (2015). *Heating, cooling, lighting: sustainable design methods for architects*. 4th edition. New Jersey: John Wiley & Sons.

Mekong Eye. (2016). *Gigawatts for mega-spenders: infographic shows Bangkok's luxury malls use more energy than some provinces*. Retrieved December 15, 2018, from https://www.mekongeye.com/2016/09/05/gigawatts-for-gigaspenders-infographic-shows-bangkoks-luxury-malls-use-more-energy-than-some-provinces/

MGR Online. (2013). *"Porto Chino" Green Lifestyle Mall: The continuing development of energy-saving Architecture*. Retrieved January 3, 2018, from https://mgronline.com/greeninnovation/detail/9560000100296

Passe, U. and Battaglia, F. (2015). *Designing space for natural ventilation: An architect's guide*. New York: Taylor & Francis.

Thai Meteorological Department. (2018). *Wind rose map*. Retrieved December 15, 2018, from http://www.aws-observation.tmd.go.th/web/aws/aws_windroses.asp

The Old Siam. (2018). *History of The Old Siam shopping plaza*. Retrieved, December 15, 2018, from http://www.theoldsiam.co.th/index.php?lang_id=EN#