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Passive and Biophilic Design: Assessment of the Semi-Open Educational Atrium Buildings in the Tropics

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ABSTRACT

The contemporary semi-open educational atrium buildings in Southeast Asia are among the most provocative sustainable buildings in tropical architecture. Since the qualities of natural environments inside atriums promote well-being and academic performance, passive and biophilic design strategies are applied to optimize the thermal and visual performances of the buildings. This research aims to assess four selected case studies in Bangkok in order to discover how the atrium elements affect the qualities of the inside natural environmental conditions, and recommend guidelines for semi-open atrium design. The most important natural environment indices are air temperature, radiation, humidity, airspeed, daylight, green area, view in and view out. The research methodology is as follows: Firstly, assess the natural environmental conditions of the case study atriums on-site during summer. Secondly, analyze the thermal and visual performances of the semi-open atriums. Then, find the linkages between the atrium element designs and the qualities of natural environmental conditions. Lastly, recommend passive and biophilic design guidelines for semi-open atriums. The on-site assessment results indicate that all case study atriums perform well above average, although each case study uncovered both pros and cons. The research results showed that: 1) The amount of heat gain and daylight factor depend mostly on the percentage of roof opening (skylight) and the sizes and proportions of the atriums. 2) Relative humidity inside the buildings is reduced by natural ventilation during the daytime. 3) The most effective air velocity is from cross ventilation. 4) Quality of views depends on the openness of the atrium on the ground floor. 5) Biophilic quality depends mainly on the amount of indoor green area. At the end of the research, design recommendations for semi-open educational atrium buildings in the tropics are provided.

Keywords: semi-open atrium, educational building, natural environment, passive design, biophilic design

INTRODUCTION

Recently, passive and biophilic design strategies have been intensively used in educational buildings in the tropics. These contemporary designs focus on providing thermal and visual comfort in semi-outdoor biophilic spaces integrated into buildings. The recent educational atrium buildings in Southeast Asia have developed sustainable spaces with more connections to nature, with semi-open atriums that provide natural environments within the educational facilities, including fresh air, daylight, natural ventilation, green features, and views that can promote well-being and enhanced academic performance. Examples of outstanding architectures include the Lasalle College of the Arts building in Singapore, the University of Reading Malaysia building in Malaysia, and the Thai Health Promotion Center in Thailand, as shown in Figure 1.

Figure 1

Examples of semi-open educational atrium buildings in Southeast Asia

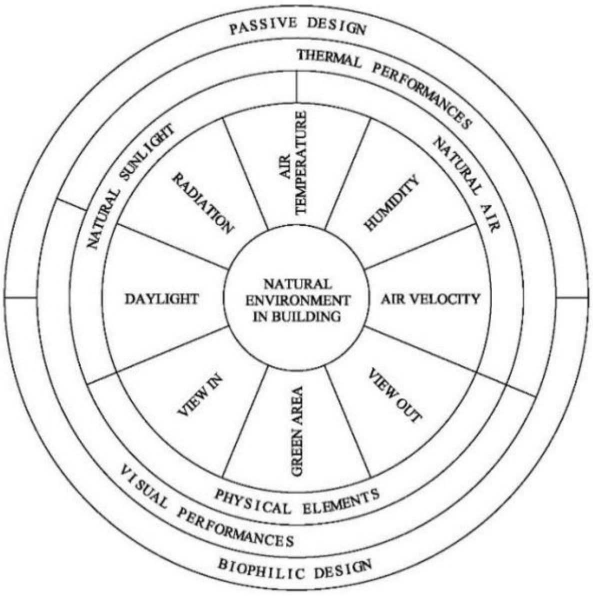
Note. The atrium views of the buildings from left to right: The Lasalle College of the Arts building in Singapore from Buildings in the Lasalle College of the Arts, by The Lasalle College of the Arts, 2021 (https://www.edwiseinternational.com/study-abroad/study-in-Singapore/LASALLE-College-of-the-Arts.aspx). Copyright 2021 by The Lasalle College of the Arts. The University of Reading Malaysia building in Malaysia from University of Reading Malaysia, by Indesignlive.HK, 2021 (https://www.indesignlive.hk/tag/university-of-reading-malaysia). Copyright 2021 by Indesignlive.HK. The Thai Health Promotion Center in Thailand from Duet Diary, by Duet Diary, 2021 (http://www.duetdiary.com/thaihealth). Copyright 2021 by Duet Diary.

The benefits of the semi-open atriums in educational buildings are as follows: Firstly, the academic atrium is a multi-function public space that may serve as a reception and group activity space, relaxing and study space, passage and transition space, exhibition and event space, and green space. The public place helps enhance the quality of academic life by promoting public activities and social interactions. Secondly, the non-air-conditioned atrium helps saving energy and promote environmental friendliness. Since public spaces and circulation in an educational building comprise about 30-50% of the total building area, elimination of air-conditioning and electrical-lighting in these areas can eliminate a great deal of energy consumption. Thirdly, these natural environments inside the atriums help promote thermal satisfaction. A well-ventilated natural atrium in the tropics can provide cooler air temperature at the atrium floor (Baharvand et al., 2013). The semi-outdoor learning spaces with high ceilings that are well-connected to natural environments can increase user satisfaction with thermal perceptions in the tropics (Tao et al., 2019). Fourthly, green features inside the atriums help improve indoor environmental qualities. Living plants can improve indoor air quality and cool down the air temperature (Han, 2019). Greenery in academic buildings also creates a positive effect on the health and general well-being of users, improves students' performance and their ability to concentrate, and enhances the social climate (Hiemstra et al., 2019). Lastly, the atrium provides spaciousness and views. The openness of atrium space with higher viewing volume and viewing area can promote students' relaxation and participation in atrium activities (Wu et al., 2020). Therefore, the multidisciplinary functions of the semi-open atrium are valuable for educational buildings in the tropics.

To provide thermal and visual comfort in educational atrium buildings, passive and biophilic designs are important design techniques that create adequate natural environments in sustainable spaces. While passive design is more concerned with the climate and thermal performance of a building, biophilic design focuses more on connections to nature and visual performance. According to the thermal comfort theory, the important environmental factors that provide thermal comfort include air temperature, radiation, humidity, and air speed (American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE], 2020). Biophilic theory also says that the important element factors are fresh air, sunlight, green features, spaces, and views (Kellert et al., 2013). The correlation between passive and biophilic design and natural environments in a building can be drawn into a relationship diagram as shown in Figure 2.

Figure 2

Relationship Diagram of Passive & Biophilic Design and Natural Environment in Building



Note. This diagram, drawn by the author, shows the relationships of theories, performances, resources, and the 8 factors of natural environments in a building.

From Figure 2, it can be seen that the thermal and visual performances of a building are influenced by the incoming natural sunlight, air, and the physical environments. The 8 nature environments that affect perceptions of users in the building are air temperature, radiation, humidity, air velocity, daylight, view in, view out, and green area. The thermal and visual performances depend on the qualities of these natural environments. The educational atrium buildings are studied in order to understand how well the sustainable spaces perform, and how the building elements affect the qualities of natural environments in the atriums.

As part of coping with heat islands in a tropical city, a semi-open atrium of a building should provide acceptable thermal comfort. Air temperature, radiation, humidity, and air velocity are the environmental factors for human thermal comfort. The temperature at the atrium floor is technically colder than the rest of the atrium since the hotter air rises to the upper layer of the atrium due to buoyancy effects. While the heat from the building facades is protected by the surrounding multi-story classrooms and shaded openings, the radiation heat from the atrium roof is focused. Temperature and radiation inside the atrium should be reduced as much as possible since the average climate in a tropical city during the day is beyond the comfort zone limit. Humidity in areas of human occupancy should be within a range of 30-60%RH for optimal occupant wellness. Moreover, in this range, the environment provides human comfort, while growth of bacteria and chemical organisms is minimized (American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE], 2016).

Natural ventilation is an essential factor for thermal comfort in a tropical semi-open space. The human skin can sense air movement at an airspeed of more than 0.2 m/s. Air moving past the skin creates convection and evaporation effects that help cool down the human body. An open-air space in a tropical climate should have natural ventilation with an airspeed of 0.2-2 m/s. Air velocity of 0.2-1 m/s can affect perception of coolness of about 1-3.30°C (Lechner, 2015). However, air velocity inside a room depends on the characteristics of the room openings, and the percentage of wind velocity is an overall indicator of the natural ventilation performance of a room (Givoni, 1998).

Daylighting is a key for a semi-outdoor space used for multi-purpose activities. Daylight Factor (DF) is an index defined as the percentage ratio of indoor to outdoor daylight illuminance. The TREES standard recommends that a newly constructed building should provide daylight in most parts of the building with a DF of at least 1.5% (Thai Rating of Energy and Environmental

Sustainability [TREES], 2021). According to the Illuminating Engineering Society of North America (IESNA), a room with a DF of <2% is poorly lit, meaning that electric lighting is needed for most of the day. A room with a DF of ≥2-5% can be considered daylit, but may require some additional electric lighting during the day. A strongly daylit atrium with a DF of ≥5% is full of daylight and needs no electric lighting, while an atrium with a DF of 5-10% creates a lively semi-outdoor atmosphere (Tregenza & Wilson, 2011). A semi-outdoor garden is preferable in an atrium, and plants usually need daylight for ≥10 hours a day at 250-2000 lux for survival, depending on the species. Under 5000-lux standard overcast sky, plants need a DF of 5-40% to sustain life (Baker, 2013). However, the atrium should avoid direct or high contrast sunlight since it may cause a glare effect, visual fatigue, and an overheated environment.

The openness of a semi-open atrium supports the quality of public space, visual comfort, and connection to outdoor nature. The Green Star standard clarifies that, for a daylit atrium view, the atrium must be at least 8-m wide and 2-storeys high, with a daylight factor of at least 3% for 90% of the atrium floor area (Green Star, 2019). The EN 17037 standard sets the criteria for the view out as follows: the view opening should provide a view that is perceived to be clear, undistorted, and neutrally colored. The utilized area should also have a total horizontal sight angle through an opening higher than a minimum value of 14° and ≥28°, or ≥54° for medium and high qualities. The distances to the outside view should be at least 6 m and ≥20 m, or ≥50 m for medium and high qualities. Moreover, a minimum number of view layers of sky, landscape (urban or nature), or ground are required (European Committee for Standardization [CEN], 2018). The quality levels of view in and view out are prescribed sequentially in Table 2 and Table 3.

With the biophilic design trend, indoor green areas are promoted in buildings. In Singapore, the Urban Redevelopment Authority (URA) has encouraged developers to arrange more open spaces and green areas in various parts of buildings, including roofs, terraces, and semi-outdoor spaces. Landscape areas with planter boxes, sky terraces, or covered ground gardens are incentive options that can allow a building developer to get a bonus of more buildable area (Urban Redevelopment Authority [URA], 2020). In Malaysia, the Green Building Index (2019) encourages the provision of indoor greenscape with native/adaptive plants covering at least 1% or 3% of the floor space for GBI credits of 1 or 2 points, respectively. The WELL building standard recommends that the internal green area of an office building should be at least 1% of the floor area, and/or the green wall area should be greater than 2% of the floor area (International WELL Building Institute [WELL], 2020). In summary, greenery in buildings has become a substantial element in the design of public buildings.

In Bangkok, there are several examples of alternative designs of semi-open educational atrium buildings, and recent contemporary designs of this building type feature a variety of environmental themes inside the atriums. From the literature review, assumptions about the qualities that are desirable in natural environments depend mainly on the design elements of semi-open atriums such as dimensions, openings, skylights, and internal green areas.

These come to the research questions about the building performances as follows: 1) How well do the atriums perform in the hot and humid climate? 2) What are the design considerations to provide desirable qualities of the natural environments in the semi-open atriums?

Therefore, the research aims to find the keys to architectural designs that promote the desirable qualities of the natural environments in the atriums. The research objectives are as follows: 1) to assess the natural environmental conditions of case studies of educational atriums in Bangkok, 2) to discover how the atrium elements affect the qualities of the natural environmental conditions, and 3) to suggest the passive and biophilic design considerations for semi-open educational atrium buildings in the tropics.

MATERIALS AND METHODS

Materials in the research are the 4 case studies of the semi-atrium education buildings and the tools used for on-site testing of the natural environments in the case studies. Methods are the process of collecting and analyzing the data.

Case Studies

Since the research aims to assess some semi-open educational atrium buildings in Bangkok, four contemporary case studies were selected for study in this research. The case studies are similar in building type (mid-atrium), total percentage of all-level openings (about 25%), and location (near Northern suburb of Bangkok); however, the case study atriums are different in shape, scale, elements and openings. The case studies are as follows:

Case study #1 is the Flagship Building, Silpakorn University, City Campus (FB SUCC). The classroom building is interesting in its composition of multiple layers of transparent materials. The main atrium openings are on the ground level, and the upper openings are on the east and west of the atrium. The atrium size is slender and the skylight is small.

Case study #2 is the Faculty of Learning Sciences and Education, Thammasat University (LSED TU). The multi-purpose building was designed to integrate nature into the medium-sized atrium, which consists of indoor trees, water features, and natural materials. The atrium space is open mainly to the south and is well lit by a large area of the skylight.

Case study #3 is the Digital Multimedia Complex, Rangsit University (DMC RSU). The creative atmosphere of the large multi-purpose atrium is surfaced with modern-bright materials. The openings are mainly on the upper floor and the skylight. The half-oval shape of the atrium has a great amount of volume with more enclosed on the ground floor.

Case study #4 is the operation building, Faculty of Economics, Kasetsart University (ECON KU). The educational building is full of plants, and is known as the place of the secret garden. The atrium size is the largest and the highest among the case studies, while multi-directional openings are scattered all over the 6-storey-high atrium.

The exterior and atrium views of the case study buildings are shown in Figure 3, and the comparative dimensions of the case study atriums are detailed in Table 1.

Research Tools

In this research, there are 8 natural environmental conditions to be assessed in each case study. The 8 environments are divided into 5 invisible environments and 3 visible environments. The 5 invisible environments are air temperature, radiation, humidity, air speed, and daylight, while the 3 visible environments are view in, view out, and internal green area. The instruments used for on-site testing are an air thermometer, globe thermometer, hygrometer, anemometer, and lux meter, while the 3 visible elements can be analyzed through computer-generated drawings of the case study buildings. Basic surveying, measuring, drawing, and computing tools are also used in the research.

The details of the portable instruments used for testing the invisible natural environmental conditions are as follows:

1. Heat stress meters are the combined instruments of an air thermometer, globe thermometer, and hygrometer. The heat stress meter used in the research is the EXTECH model HT30. The 3-in-1 tool considers the effects of temperature, humidity, and direct or radiant sunlight, and can measure an air temperature range of 0-50°C to the accuracy of ±1°C, a relative humidity range of 1-99%RH to the accuracy of ±1°C, and a globe temperature range of 0-80°C to an accuracy of ±2°C.

2. A hot-wire anemometer is used for measuring airspeed. The selected tool is the TENMARS model TM-4002, which can measure airspeed in the range of 0.1-40 m/s at the scale of 0.01 m/s to an accuracy of ±3%.

3. A lux meter is used for measuring daylight illumination. The selected lux meter is the TENMARS model TM-720, which meets the standard of JISC 1609: 1993 and CNS 5119. With silicon photodiode and filter, the lux meter can measure both indoor and outdoor light at the illuminance range of 0-400,000 lux to an accuracy of ±3%.

Figure 3

Pictures of the exterior and atrium views of the 4 case study buildings

Note. The exterior and atrium views of the 4 case study buildings and existing environments; Case study #1 FB SUCC, Case study #2 LSED TU, Case study #3 DMC RSU, and Case study #4 ECON KU.

Table 1

Dimensions of the case study atriums

Case Studies	**Length** ***L*** ***(m)***	**Width** ***W*** ***(m)***	**Height** ***H*** ***(m)***	**Area** ***LxW*** ***(m²)***	**Volume** ***LxWxH*** ***(m³)***	**Proportion** ***L:W:H*** ***(approx.)***	**Openings to Walls Ratio *(%)***	**Skylight to Roof Ratio *(%)***
1) FB SUCC	26	5.50	40	143	3,060	5:1:4	25	28
2) LSED TU	32.50	11.50	17	374	6,354	5:2:3	24	75
3) DMC RSU	39	17	15	663	9,945	5:2:2	25	33
4) ECON KU	40	18	24	720	17,280	5:2:3	24	35

Note. Dimensions of the case study atriums are compared to get a sense of the scale and proportions of the atrium elements.

Data Collection

The research aims to assess the natural environmental conditions inside and outside of the case study atriums. The research data collected on-site are the primary data.

The primary data refer to the on-site testing results, including air temperature (T), radiation (GT), humidity (RH), air velocity (V), Illuminance (E), green areas, opening sizes, and distance to views. The methods of testing invisible elements of the natural environmental conditions are as follows:

1. The independent variables are the architectural elements of the 4 case study atriums.

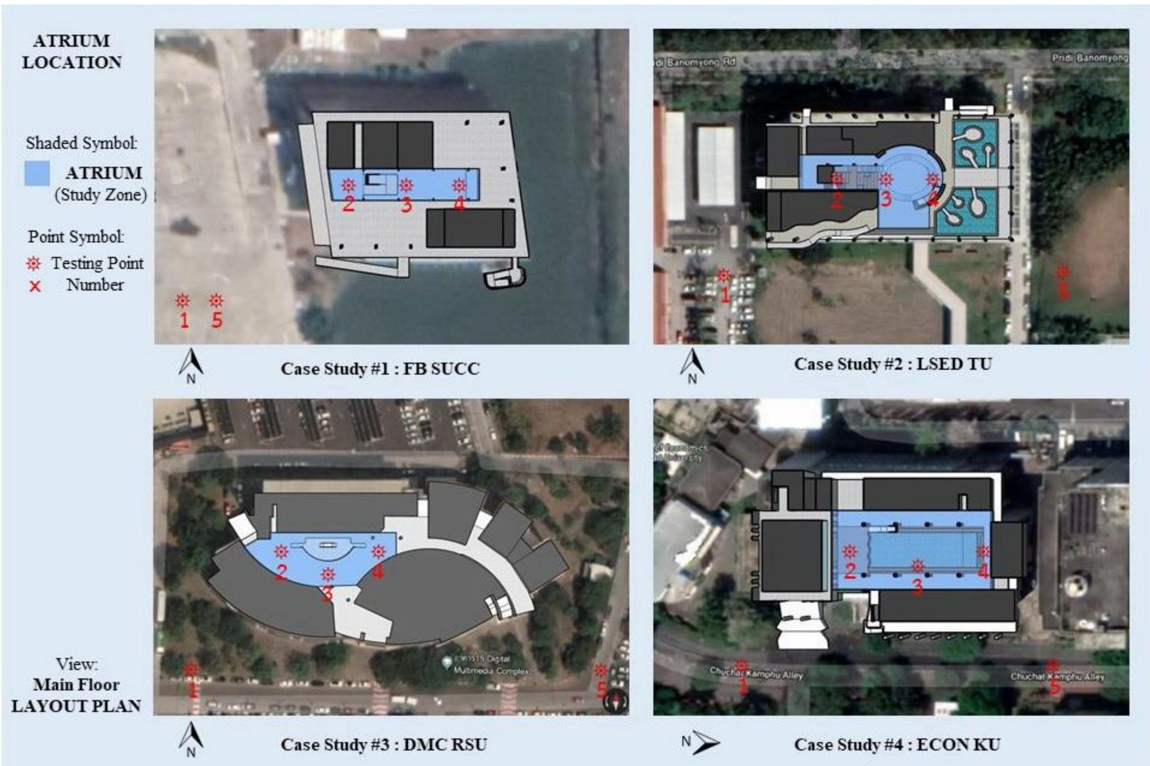
2. The dependent variables are the effects of natural environmental conditions, which are: air temperature (T), radiation (GT), humidity (RH), air velocity (V), and illuminance (E). The dimensions of visible elements include green areas, atrium-level opening sizes, and distance to views. The results are average values of the internal and external conditions that will later converted to secondary data.

3. The control variable is the testing method used in all case studies. Each case study atrium is assessed on-site, hourly from 9:00-18:00 on specific summer days (March 20-23, 2020). The testing positions consist of the 3 testing points inside the atriums and the 2 testing points outside the buildings. All measurements are taken at the height of 1.20 meters from the ground, and the equipment is protected from direct sunlight. The testing sequence moves from testing point #1 to #5. The total assessments comprise 45 tests per day per case study (9 tests at each of 5 testing points). However, the testing processes of all case studies should be executed on consecutive days that have very similar climate conditions. The atrium locations and the testing points of the case studies are shown in Figure 4.

In summary, the primary data are the averages or totals of testing results of each case study. The internal testing results are the average of testing points nos. 2, 3, and 4, and the external testing results are the sum of testing points nos.1 and 5.

Figure 4

The atrium locations and the testing points of the case studies



Note. The overhead views of the 4 case study buildings show the atrium study zones (blue shaded areas) and the location of the testing points that are sequentially numbered (red marks).

Data Analysis

The data analysis in this study involved transforming the collected data into secondary data used to analyze performance of the case study atriums.

The secondary data refers to the natural environmental indices generated from the primary data by computation and analysis. The invisible condition indices are values that compare internal conditions to external conditions, including temperature difference (ΔT), globe temperature difference (ΔGT), relative humidity difference (ΔRH), percentage of air velocity (ΔV), and daylight factor (DF). The green-area-ratio index is the percentage of total internal green areas to total atrium area that is referenced to the WELL's biophilia standard; the view-in index is the quality of atrium views that is referenced to the Green Star's visual comfort standard, and the view-out index is the visibility and quality of the outside views that is referenced to CIE's EN 17037 Standard.

The calculations of the secondary data that provide comparative indices of the internal environment to the external climate and the assessment criteria are as follows.

1. 'Air temperature difference' (ΔT; °C) is calculated by the following formula:

$$\Delta T = Internal\ T - External\ T \quad \textbf{(1)}$$

The higher the differential result of ΔT, the better the quality of the air temperature is. Internal T should be as low as possible.

2. 'Globe temperature difference' (ΔGT; °C) is calculated by the following formula:

$$\Delta GT = Internal\ GT - External\ GT \quad \textbf{(2)}$$

The higher the differential result of ΔGT, the better the quality of the radiation is. Internal GT should be as low as possible. However, direct sunlight must be excluded.

3. 'Relative humidity difference' (ΔRH; %) is calculated by the following formula:

$$\Delta RH = Internal\ RH - External\ RH \quad \textbf{(3)}$$

The fewer different results of ΔRH, the better quality of the humidity is. Since outdoor relative humidity during the daytime is drier than indoor. Internal RH in the tropics should be as low as possible. However, the average internal RH should be between 40% and 60%.

4. 'Percentage of wind velocity' (% of V) is calculated by the following formula:

$$Percentage\ of\ wind\ velocity\ (\%) = \frac{Internal\ V}{External\ V} \times 100 \quad \textbf{(4)}$$

where V is air velocity in m/s. The higher the result of % of V, the better the quality of the airspeed is. V should be at least 0.2 m/s.

5. 'Daylight factor' (DF; %) is calculated by the following formula:

$$DF\ (\%) = \frac{Internal\ E}{External\ E} \times 100 \quad \textbf{(5)}$$

where E is illuminance in lux. The higher the result of % of DF, the better the quality of the daylight is. DF should be 2-10%.

6. 'View in' is a visual assessment of views inside an atrium space of a building. Based on the Green Star standard (Green Star, 2019), the criteria for view in are given in Table 2.

7. 'View out' is a visual assessment of the view outwards from an internal space. Based on the EN 17037 standard (CEN, 2018), the criteria for view out are given in Table 3.

8. 'Internal green area ratio' is an assessment of internal green features in an atrium. Referring to the WELL standard (WELL, 2020), the ratio is calculated by the following formula and then compared to criteria given in Table 4.

$$Internal\ green\ area\ ratio\ (\%) = \frac{Internal\ green\ area\ (m^2)}{Atrium\ area\ (m^2)} \times 100 \quad \textbf{(6)}$$

Table 2

Assessment criteria for view in

Standard Certification	⊗ **Below Standard**		✓ **Meets the Standard**		
Quality Score (5-point scale)	***1 (very poor)***	***2 (poor)***	***3 (moderate)***	***4 (good)***	***5 (very good)***
Atrium width (m)	<4 m	<8 m	≥8 m	≥12 m	≥16 m
Daylight factor (%)	<3%		≥3%		
Atrium view angle (°)	<14°		≥14°		

Note. An atrium that provides inside views must have enough size and daylight.

Table 3

Assessment criteria for view out

Standard Certification	⊗ **Below Standard**		✓ **Meets the Standard**		
Quality Score (5-point scale)	***1 (very poor)***	***2 (poor)***	***3 (moderate)***	***4 (good)***	***5 (very good)***
Color symbol	● ***Red Dot***	● ***Orange Dot***	● ***Yellow Dot***	● ***Lime Dot***	● ***Green Dot***
View out quality	No views	Little views	Some views	Moderate views	Lots of views
View angle (degree)	0°	<14°	≥14°, <28°	≥28°, <54°	≥54°
View distance (m)	-	-	≥6 m	≥20 m	≥50 m
View levels: - Sky - Landscape - Ground	-	-	At least landscape layer is included	Landscape layer and another layer are included	All layers are included in the same view opening

Note. Assessment points located on every two-meter horizontal grid at the height of 1.2 meters. Qualities of view out depend on view angle, view distance, and view level.

Table 4

Assessment criteria for Internal green area ratio

Standard Certification	⊗ **Below Standard**		✓ **Meets the Standard**		
Quality Score (5-point scale)	***1 (very poor)***	***2 (poor)***	***3 (moderate)***	***4 (good)***	***5 (very good)***
Internal green area ratio (% of the floor area)	0%	<1%	≥1%	≥3%	≥10%

Note. The more internal green area ratio, the better the quality of the biophilic environment.

The natural environmental conditions of the case studies are to be analyzed step by step as follows: Firstly, average and compare the results to understand the overall qualities of the case study atriums. Secondly, evaluate the pros and cons of each case study atrium to learn how the buildings perform. Then, identify the relationships between atrium elements and the outcome conditions to understand how the atrium elements affect the environments. Lastly, summarize the discovery and develop passive and biophilic design recommendations for educational atrium buildings in the tropics.

RESULTS AND DISCUSSION

The results and discussion are divided into 4 stages, including test results, performance analysis, atrium characteristics and performances, and semi-open atrium design recommendations.

Test Results

The natural environments inside and outside the case study atriums were tested in a nearby location with a quite similar summer climate. The on-site tests were executed during 4 consecutive days (March 20-23, 2020). Each case study atrium was tested within a day during 8:00-18:00 hr. Each of the case study atriums (#1 to #4) was tested sequentially from Day 1 to Day 4. The test and assessment results of the 8 natural environments in the case studies are presented with discussion below.

Air Temperature

The results of hourly air temperature tests inside the case study atriums were variable. Since the average external air temperature of all the testing days were quite similar, the results of internal air temperature are compared in the same chart in order to differentiate the performances of each case study, as shown in Figure 5 (Left). The average outdoor air temperatures of the 4 testing days were a bit different at 32.56, 32.57, 32.76, and 32.79 °C, respectively, and the inside air temperatures of each day are referenced to these outside temperatures. The average air temperature differences comparing inside to outside (ΔT) of the case studies are provided in Figure 5 (Right).

As can be seen from Figure 5 (Left), the air temperatures inside all the case study atriums were rather high in the summer. The temperature during the day varied from 29 to 34 °C. The outside hot air blowing through the South and Southwest openings increased the internal temperature gradually from morning to mid-afternoon. The temperatures in most case studies increased rapidly during 11:00-13:00 time period, and then steadily decreased after that, except in case study #1, where the temperature increased slightly at 16:00. While the heat comes into the atriums in case studies #2, #3, and #4 mainly from overhead large skylights, in case study #1, a little heat comes from the small skylight, but comes strongly later from the large opening to the West. However, case studies #1 and #4 performed well in average air temperature difference, as can be seen in Figure 5 (Right). Interestingly, case study #4 provided the coolest environment. The relatively high ceiling and the abundant green area could be the cause of the lower air temperature in that atrium.

The results show that the heat inside the atriums comes directly from the convection of the incoming air. The air temperature inside the buildings could be reduced by separating the hot air layer by having higher atrium ceilings, ventilating the upper hotter air, and increased planting.

Radiation

The test results of hourly globe temperature tests inside the case study atriums were variable, as shown in Figure 6 (Left). The average outdoor globe temperatures of the 4 testing days varied between 40.77 and 42.18 °C, and the average globe temperature differences (inside to outside) (ΔGT) of the case studies are given in Figure 6 (Right).

As can be seen in Figure 6 (Left), the hourly globe temperatures inside the case study atriums were much different. There were obvious levels of radiation rising inside the atriums of case studies #2, #3, and #4 from 10:00 to 14:00 hr. On the other hand, the radiation inside case study #1 increased more gradually and reached its peak at 16:00-17:00 hr. This made the average globe temperature difference in case study #1 the highest, as shown in Figure 6 (Right).

Radiation in an atrium comes from solar heat that is transferred to the inside atrium surfaces. Therefore, the skylights should be minimized, the openings should be shaded, and the envelopes should be insulated.

Humidity

The hourly test results of relative humidity inside the case study atriums were variable, as shown in Figure 7 (Left). The average outside humidity during the day varies from 54.18 to 55.45 %RH. The average humidity differences (inside to outside) (ΔGT) of the case studies are shown in Figure 7 (Right).

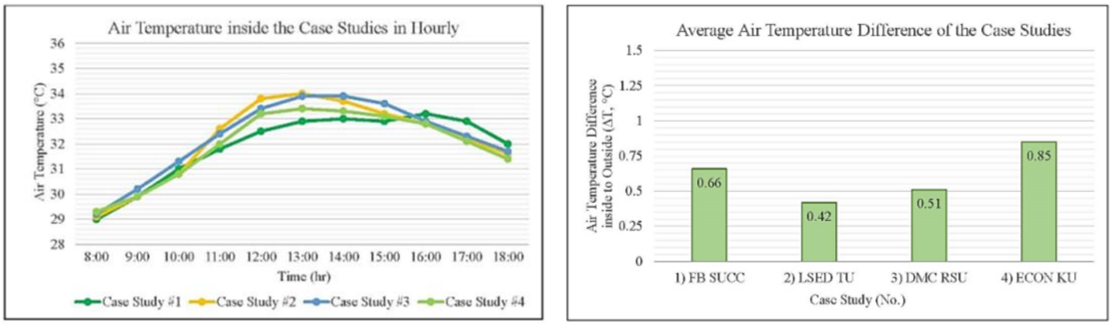
From Figure 7 (Left), all case study atriums are in the preferable humidity range of 0-60%RH from about 11:00 to 18:00 hr. Case study #1 was best able to reduce humidity before 11:00 hr., and the humidity dropped to the lowest point at 45%RH fastest in case study #2. Meanwhile, case study #4 had the highest humidity through most of the day, as shown in Figure 7 (Right).

The large openings were found in the atrium of case study #1, bringing drier air from outside into the atrium and lowering the inside humidity in the morning. Having a larger ratio of skylight to roof area and lower height to width proportion of the atrium, the skylight of case study #3 helped dry the inside air, resulting in low humidity. On the other hand, plants and wet ground inside case study #4 promoted high humidity. Overall, the average relative humidity of all case studies was in the comfort zone in most hours of the day.

The results imply two reasons for the humidity reduction in atriums. Firstly, natural ventilation helps blend the internal air with external air and dehumidify the indoor air since the outside humidity is lower than the inside air during the daytime. Secondly, the radiated heat from the atrium skylight helps dry the indoor air. In other words, the buoyancy and evaporation effects help remove the hot air and the vapor through the upper ventilation louvers.

Figure 5

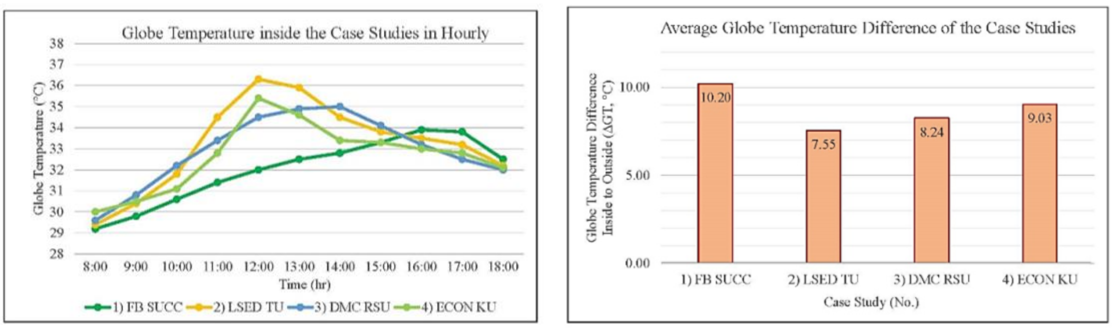
Hourly Air Temperature readings and Average Air Temperature Differences



Note. Left: Hourly air temperature readings from inside the case study atriums. Right: Average air

Figure 6

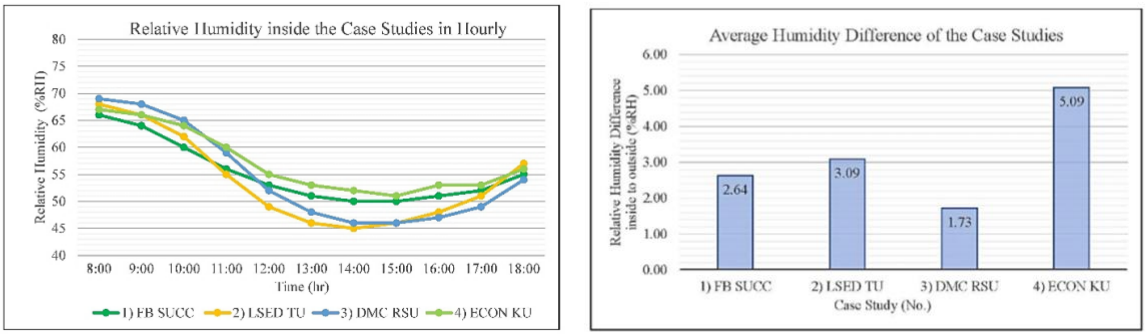
Hourly Globe Temperature results and Average Globe Temperature Differences



Note. Left: Hourly globe temperature readings from inside the case study atriums. Right: Average globe temperature differences (inside to outside) of the case studies.

Figure 7

Hourly Relative Humidity and Average Humidity Difference



Note. Left: Hourly Relative humidity inside the case study atriums. Right: Average humidity difference (inside to outside) of the case studies.

Airspeed

The hourly test results of air velocity inside the case study atriums were much different, as shown in Figure 8 (Left). On the testing dates, a lot of wind was coming from the Southwest at the daily average wind speed of 2.60-3.03 m/s. The average air velocity differences (inside to outside) (% of V) of the case studies are shown in Figure 8 (Right).

From Figure 8 (Left), the air velocities inside the case study atriums were much different and inconsistent. Due to the unstable wind speeds, the graphics of hourly air velocity readings show as serrated lines. The average percentages of air velocity differences of the case studies show that case study #1 is the best, while case study #3 is the worst, as can be seen in Figure 8 (Right).

The amount of air velocity depends on the quality of cross-natural ventilation. The inlet openings should open toward the wind direction, with the outlet openings on opposite or perpendicular sides (American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE], 2017). Noticeably, the floor-level openings provided much more effective wind toward the activity areas than did the upper-level openings.

Daylight

The hourly test results of daylight illuminance inside the case study atriums was varied, as shown in Figure 9 (Left). On the testing dates, there were partly cloudy skies. The average outdoor illuminance on each testing day was between 57,851-68,475 lux. The average daylight factors (DF) of the case studies are shown in Figure 9 (Right).

As shown in Figure 9 (Left), the daylight illuminance curve of case studies #2, #3, and #4 are reversed-U shapes due to the higher percentages of skylight area, while the curve line of case study #1 is very different because of this atrium having the lowest percentage of skylight area and large horizontal openings, especially in the West.

From Figure 9 (Right), case study #2 provided the highest average daylight factor (DF) at 8.86%, following by case studies #3 and #4, with average DFs of 8.07% and 4.89%, respectively. Case study #1 has the lowest average DF of 2.53%.

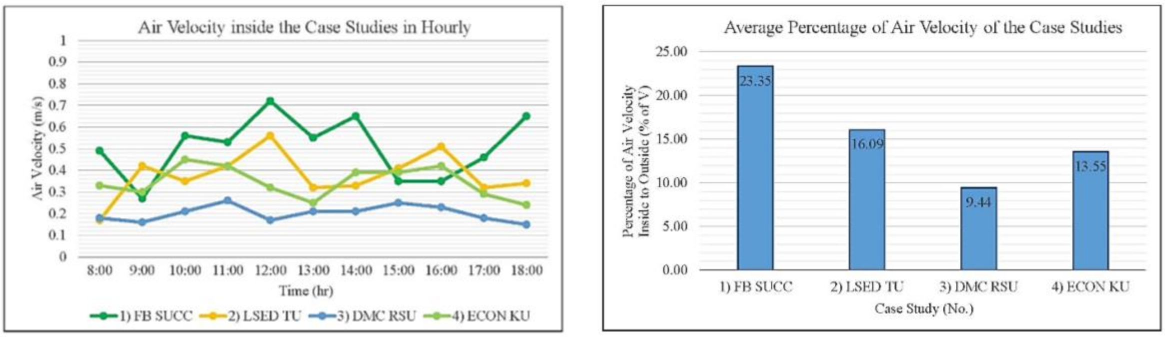
The results demonstrate that the amount of daylight inside the atriums depended mostly on the percentage of the skylight openings and the depth of the atrium wells. Daylighting from 10:00 to 14:00 should be intensively controlled. The average daylight factor for semi-outdoor spaces should be about 6% since the average of all case studies is at 6.09%.

View In

The atrium width, daylight factor, and atrium view angle define the qualities of spaces and internal views of the case studies. The assessment of views inside the case study atriums is shown in Table 5.

Figure 8

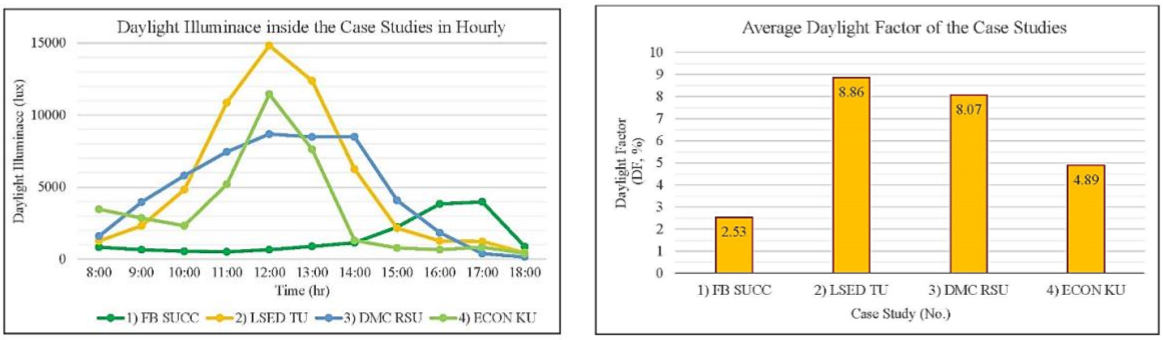
Hourly Air Velocity readings and Average Percentage of Air Velocity



Note. Left: Hourly air velocity readings inside the case study atriums. Right: Average percentage differences of air velocity (inside to outside) of the case studies.

Figure 9

Daylight Illuminance in Hourly and Average Daylight Factor



Note. Left: Hourly daylight illuminance inside the case study atriums. Right: Average daylight factors of the case studies.

Table 5

View-In Assessment of the Case Studies

View-In Assessment	Case Studies				Average
	1) FB SUCC	***2) LSED TU***	***3) DMC RSU***	***4) ECON KU***	
Atrium Width (m)	5.50	11.50	17.00	18.00	13.00
Daylight Factor (%)	2.53	8.86	7.33	4.89	5.90
Atrium View Angle (°)	<14°	≥14°	≥14°	≥14°	
Quality Score (5-point scale)	2 (poor)	4 (good)	5 (very good)	5 (very good)	4.00

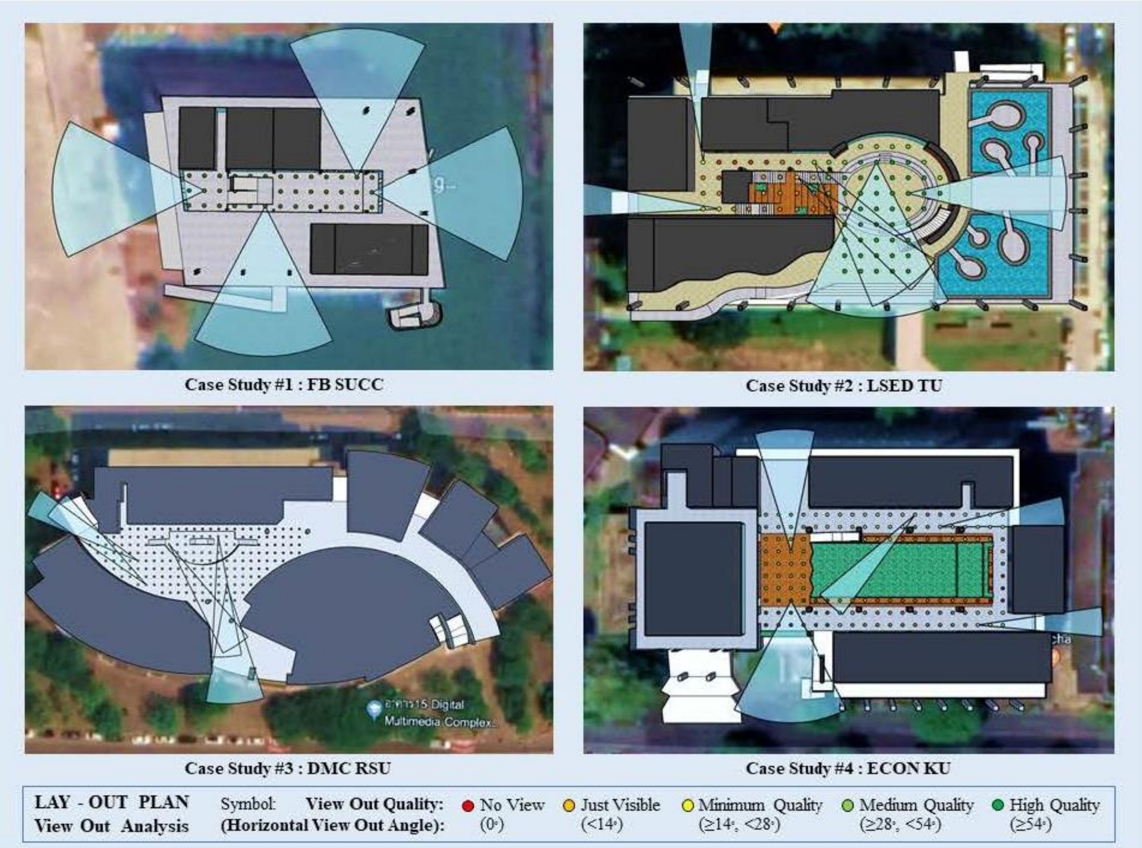
Note. Quality Scores are graded according to the view-in criteria from Table 2.

View Out

The view-out qualities in the case studies were analyzed as illustrated in Figure 10. The view-out assessment results are shown in Table 6.
The view-out analysis and assessment detailed in Figure 10 and Table 6 show the view-out qualities of the case studies. Case studies #2 and #4 are more open to the outside views than case study #3. Although case study #1 seems to have large openings, the views are blocked and distorted by the multi-colored glass screens around the atrium. Therefore, the percentage of total opening widths to the atrium parameter and visibility to distant views are the keys to the view-out qualities.

Figure 10

View-Out Analysis of the Case Studies



Note. Quality level of each test position in every 2x2 m grid is shown as the color of dot. 75% of the color of dots in an atrium determine the overall quality of the atrium's view out.

Table 6

View-Out Assessment of the Case Studies

View-Out Assessment	Case Studies				Average
	1) FB SUCC	***2) LSED TU***	***3) DMC RSU***	***4) ECON KU***	
View Angle of ≥75% (°)	≥54°	≥28°	<14°	≥14°	
View Distance (m)	≥50 m	≥50 m	-	≥6 m	
View Layers (1, 2, 3)	Distorted	2, 3	-	1, 2	
Quality Score (5-point scale)	2 (poor)	4 (good)	2 (poor)	3 (moderate)	2.75

Note. Quality Scores are graded according to the view-out criteria in Table 3.

Internal Green Area

The percentage of internal green areas of the case studies are displayed in Table 7.
The results shown in Table 7 demonstrate that the greater the percentage of internal green area, the better the score of the case study. Clearly, case study #4 has the best score due to the abundant green area of 51.50% inside the atrium. Case study #2 also presents as a semi-outdoor green space by having total all-level green areas of 7.55%. On the other hand, there are few plant pots inside case study #1, and no green areas at all in case study #3. Of course, the scores of case studies #1 and #3 could easily be upgraded by adding more green features to the atriums.

Performance Analysis

The natural environmental results of the case studies were converted into performance scores. While the qualities of invisible environments were scored by comparative methods from best to worst, the qualities of visible environments were scored by set criteria. The comparative analysis of the case studies identifies the pros and cons of each of the case studies. The overall scores are intended to measure the overall performance of the case studies, while the average scores indicate the average performances of the case studies.

The performances of the case studies are divided into thermal and visual performances. The thermal performances include air temperature, radiation, humidity, and air velocity, while the visual performances include daylight, view in, view out, and internal green area. The performance scores of the case studies are shown in Table 8.

From Table 8, the sub total performance scores of the 4 case studies offer insight to the relative overall rankings of the different atrium designs. Case study #1 has the best thermal performance while having the worst visual performance. Case study #2 has the worst thermal performance while having the best visual performance. Case study #3 performs moderately in both thermal and visual performances. Case study #4 performs the best overall.

Since the performance scores highlight the pros and cons, the case study atriums could easily be modified to upgrade their thermal and visual performances. For example, the addition of internal green features in case studies #1 and #3 for at least 1% of the atrium floor area could dramatically increase their performance scores. Also, if case study #2 optimized the skylight areas and lowered the radiation heat from the roof, the total performance score would be perfect. Therefore, the performance analysis can be helpful in identifying important design considerations for maximizing comfort.

Table 7

Internal Green Area Assessment of the Case Studies

Internal Green Area Assessment	**Case Studies**				**Average**
	1) FB SUCC	***2) LSED TU***	***3) DMC RSU***	***4) ECON KU***	
Internal Green Area (m^2)	1 m^2	25 m^2	0 m^2	412 m^2	109.50 m^2
Atrium Floor Area (m^2)	143 m^2	331 m^2	900 m^2	800 m^2	543.50 m^2
Percentage of Green Area (%)	0.7%	7.55%	0%	51.50%	14.94%
Quality Score (5-point scale)	2 (poor)	4 (good)	1 (very poor)	5 (very good)	3.00

Note. Quality Score are graded according to the internal green area criteria in Table 4.

Table 8

Performance Scores Summary of the Case Studies

Performance Scores	**Case Studies' Scores**				**Average Score**
	1) FB SUCC	***2) LSED TU***	***3) DMC RSU***	***4) ECON KU***	
Thermal Performances					
1. Air Temperature	4	2	3	5	3.50
2. Radiation	5	2	3	4	3.50
3. Humidity	4	3	5	2	3.50
4. Air Velocity	5	4	2	3	3.50
Sub Total Score	18	11	13	14	14
Visual Performances					
5. Daylight	2	5	4	3	3.50
6. View In	2	4	5	5	4.00
7. View Out	2	4	2	3	2.75
8. Internal Green Area	2	4	1	5	3.00
Sub Total Score	8	17	12	16	13.25
Performance Summary					
Grand Total Score	26	28	25	30	27.25
Overall Score (5-point scale)	3.25	3.50	3.12	3.75	3.40
Overall Quality Ranking (#)	3rd	2nd	4th	1st	

Note. Scoring Scale (5-point scale): 1 = very poor or none (very light gray), 2 = poor or the 4th (light gray), 3 = moderate or the 3rd (gray), 4 = good or the 2nd (dark gray), 5 = very good or the best (very dark gray).

Atrium Elements and Performances

The relationships between atrium element characteristics and the natural environmental conditions are detected and summarized as follows:

1. The air temperature, and levels of radiation and daylight depend mostly on the percentage of roof openings (skylight) and the proportion of the height to width of the atriums.

2. The indoor humidity is reliant on the quality of natural ventilation, the evaporation effect in the atriums, and the amount of green area.

3. The inside air velocity depends on the opening ratio toward the wind and the relationships between inlet and outlet openings.

4. Quality of view in depends on the atrium size and sufficient daylight, while the quality of view out depends on the sizes and directions of openings toward the outside views.

5. Internal green areas impact the visual perception of nature and reduces air temperature, but increases humidity.

Semi-open Atrium Design Recommendations

Based on the results of the case studies and the minimum standards identified from the literature review, the design recommendations for the semi-open atrium in the tropics are as follows:

1. The atrium space should be ≥8 m in width, and the proportion of height to width ≥1:1.

2. The atrium roof and skylights should be well insulated to protect against heat transfer, and ventilation louvres under the roof should be provided.

3. The atrium should provide an average daylight factor (DF) of ≥3% or a minimum illuminance (E) of ≥300 lux, and the DF for semi-outdoor spaces should be at about 6%

4. The semi-open atrium should provide good natural ventilation passing through the floor level of the atrium, with an average air velocity percentage ≥15% of the outside wind, and the average internal airspeed (V) should be at about 0.20-0.60 m/s.

5. The atrium should provide internal green areas or other biophilic features ≥1% of the total atrium area, and ≥15% of the total atrium area for the effective green atmosphere.

6. The atrium should be clearly and widely open to distant views of surrounding nature or pleasant spaces.

CONCLUSION

The research focuses on balancing both passive and biophilic theories to determine the appropriate assessment criteria of the natural environmental performances for semi-open atriums in educational buildings in the tropics since the natural environments inside these buildings can provide comfort and connection with nature that promote well-being and academic performance. The research aimed to study how well sustainable spaces perform, and determine how to provide good natural environments inside the atriums. The 8 natural environments, including air temperature, radiation, humidity, air velocity, daylight, view in, view out, and green features, are the keys to the thermal and visual performance of the buildings. Accordingly, the research achieved all the stated purposes as follows: Firstly, the natural environments inside the 4 case study atriums were assessed. Secondly, the atrium elements that affect the qualities of the inside natural environmental conditions were revealed. Lastly, semi-open atrium design guidelines for educational buildings were recommended.

The on-site testing results demonstrate that all case study atriums perform well above average, while each one has both pros and cons. The average performance measurements of the case studies during the summer, as shown in Table 8, are as follows: air temperature difference to outside (ΔT) = -0.61°C, globe temperature difference (ΔGT) = -8.75°C, relative humidity difference (ΔRH) = +3.14%, percentage of wind velocity (% of V) = 15.61%, daylight factor (DF) = 6.09%, internal green area ratio = 14.94%, view in score (5-point scale) = 4.00, and view out score (5-point scale) = 2.75. The total performance scores (5-point scale) of the case studies are as follows: case study #1 = 3.25, case study #2 = 3.50, case study #3 = 3.12, case study #4 = 3.75, and the average total performance score is 3.40.

From the analysis of the relationships between the atrium characteristics and the performance results, the research found that the design keys that promote qualities of the natural environments in the atriums are as follows: 1) Amount of heat gain and daylight factor depend mostly on the percentage of roof opening (skylight) and the sizes and proportions of the atriums. 2) Relative humidity inside the buildings is reduced by natural ventilation during the daytime. 3) The most effective air velocity is achieved from cross ventilation. 4) Quality of views depends on the openness of the atrium on the ground floor. 5) Biophilic quality depends mainly on the amount of indoor green areas.

Although these findings are in agreement with previous theories of passive and biophilic design, the ways in which the strategies can be applied holistically in atrium building designs to optimize the qualities of 8 natural environments is more important. These findings are the focus points that affect the qualities of atrium environments.

In summary, the research accomplished the on-site testing of the natural environments in the case study atriums. The analysis measured the overall performances, and highlighted the pros and cons of each case study atrium design. The research also found the main components of the atriums that affect the semi-outdoor natural environments that confirm the theories of passive and biophilic design. Moreover, the study also developed the architectural design recommendations detailed in Section 3.4.

Still, there were some limitations on the precision of the research. Although the on-site assessments involved the collection of samples in real climatic situations during the day, the testing results were limited to certain areas of the building, and on only one day of the year. The measurements of the 4 case studies could not be taken on the same day due to limitations of the numbers of tools and researchers. However, the weather conditions on the 4 testing days were, luckily, quite similar. Future research should be more comprehensive by using computer simulation for more precise and extensive results.

The author hopes that the research will help architects, architectural students, educational organizations, and others to provide superior natural environments in their architectural designs of the semi-open atriums in the tropics.

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