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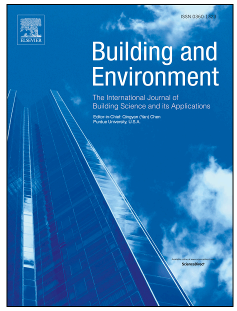

Evaluation of thermal comfort and building form attributes in different semi-outdoor environments in a high-density tropical setting

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Abstract

In highly dense tropical cities, a semi-outdoor space (SOS) is frequently used as a social space within tall building forms where people can interact and connect. Thermal comfort in SOSs within tall buildings, however, may vary depending on the type and form attributes that define it. This study classifies 63 SOSs in four tall buildings of Singapore into five types based on literature review: *perimeter buffers*, *sky terraces*, *horizontal breezeways*, *breezeway atria* and *vertical breezeways*. Findings suggest that the five SOS types perform differently in terms of thermal comfort (based on PMV*), environmental parameters (air temperature, mean radiant temperature, relative humidity, and air velocity), and building form attributes (*height-to-depth ratio*, *open space ratio*, and *green plot ratio*). Of these five, *vertical breezeways* and *horizontal breezeways* are the

most thermally comfortable for all activities during a typically warm hour. It is postulated that higher thermal comfort levels in these SOS types are linked to form attributes that enhance air velocity. This study examines the pros and cons of each SOS type in terms of thermal comfort in their role as communal spaces in tall buildings situated within a highly dense tropical city.

Keywords:

veranda; sky terrace; sky garden; horizontal breezeway; breezeway atria; vertical breezeway

1. Introduction

Buildings in warm-humid tropical climates, whether contemporary or vernacular, frequently include semi-outdoor spaces (SOSs) as architectural features that mediate between the outdoors and the indoors, providing effective shading and rain protection [1,2]. However, incorporating them into tall buildings in highly dense and compact built environments of tropical climates like Singapore may potentially have also environmental, social, and financial benefits such as: reducing urban heat island effect and air pollutants where greenery is incorporated [3–5]; compensating the lack of green areas in cities, by increasing vegetation [6–8]; promoting wind permeability by encouraging building porosity [9–12]; creating value enhancement of real estate [13,14]; providing ecosystem services and greater human-nature interaction within a community [15]; pushing the limits of passive design and reducing energy use in buildings [16–20]; and promoting new public space for social interaction and recreation with microclimates suitable for human activities as a replacement of indoor air-conditioned (AC) spaces [21–25].

Greenery and communal semi-outdoor environments are promoted in tall buildings through Singapore's LUSH (Landscape for Urban Spaces and High-Rise) program and Hong Kong's Green and Innovate Buildings Incentive scheme, with exemptions from gross floor area calculation especially if SOSs such as *balconies* and *sky terraces/sky gardens* are included [26–31]. However, more types of SOS, each with a different thermal comfort performance, exist in tall building forms in dense tropical contexts such as Singapore.

2. Literature review on semi-outdoor space types in tall buildings

2.1. *Types of semi-outdoor space*

Five types of SOS have been identified in tropical high-rise building literature: *perimeter buffers*, *sky terraces*, *horizontal breezeways*, *breezeway atria* and *vertical breezeways* (see **Figure 1**).

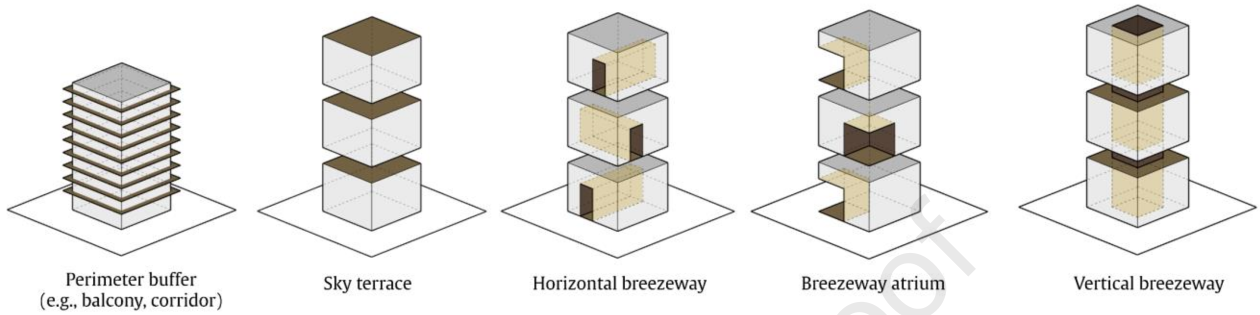

Figure 1. Schematic diagrams of types of SOS found in literature.

2.1.1. Perimeter buffers

This type of SOS includes spaces such as *balconies* and *corridors*. It is commonly found in contemporary multistorey buildings [1], on the perimeter, next to outer envelope and with limited depth. When referring to a public space, it is referred to as a *corridor*, and it is defined as a long and narrow architectural feature that serves as a space for circulation [24]. Also, this type of SOS can affect indoor thermal comfort due to its ability to keep rooms away from solar radiation (due to the 'overhang effect') and to transform airflow patterns (see **Figure 2**) [32]. Building codes regulate balcony design in both residential and non-residential buildings in Singapore and Hong Kong. It must have a minimum width of 1.5 meters measured from the external building wall, a continuous perimeter opening of at least 40%, and cannot be enclosed with walls or glass panels because it is meant to be a SOS; however, screens (i.e., green screens, louvred screens) can be included to allow for natural ventilation [28,29,31].

Figure 2. *Perimeter buffer* type (PB). Left: School of the Arts (SO) building. Right: Kampung Admiralty (KA) building.

2.1.2. Sky terraces

Also known in literature as *verandas in the sky*, *sky verandahs*, *terraces*, *forecourts*, *sky gardens* (if *sky terraces* provide greenery) or *sky court*. The *sky terrace* type is a vertically distributed semi-outdoor social space that often cuts across the depth of buildings to provide cross-ventilation. Often, it is a private or communal spaces with greenery, where it might be called *sky garden*. Incentive schemes in Singapore and Hong Kong define a *sky terrace/sky garden* as a communal, covered and lushly landscaped SOS (with a garden area occupying at least 15% of the floor plate area) provided at the intermediate storeys of a building, with a minimum depth of 4.5-5 meters, and a minimum perimeter openness of 40% (see **Figure 3**) [26–29].

Figure 3. *Sky terrace* type (ST). Left: Skyville@Dawson (SV) building. Right: OASIA Hotel Downtown (OA) building.

2.1.3. Breezeway atria

In the recent decades hotels, office buildings and shopping malls have exploited the *atrium* concept extensively [33]. *Atria* are typically large, tall and enclosed air-conditioned or naturally ventilated spaces within a building with at least one transparent façade or a glazed roof that provide daylight into the space, usually designed in tropical contexts as indoor environments where natural ventilation is controlled via exhaust ventilation strategies (inlet and outlet openings) that remove stagnant warm air through stack effect [34–39]. However, a *breezeway atrium* (see **Figure 4**) is the reinvention of an air-conditioned, enclosed *atrium*. It is a large volume space that is open to outdoors on one or two sides, incorporated not only on ground floor but also on higher floors. As proposed by WOHA, this type of SOS is a communal semi-open space with a large vertical volume that can rise up to multiple levels creating a ‘shared’ precinct within a tropical tower and facilitating constant cross-ventilation and natural light [40].

Figure 4. *Breezeway atria* type (BAT). Left & right: School of the Arts (SO) building. Middle: Kampung Admiralty (KA) building.

2.1.4.Horizontal breezeways and vertical breezeways

The *horizontal breezeway* and *vertical breezeway* types are pathways for accelerated air movement that work also as social spaces. When the SOS is a 'no-dead-end' space that intends to provide lighting and ventilation in spaces deep inside large buildings it is called a *horizontal breezeway* (see **Figure 5**), channelling prevailing winds and maximising daylight penetration, as proposed by WOHA [40].

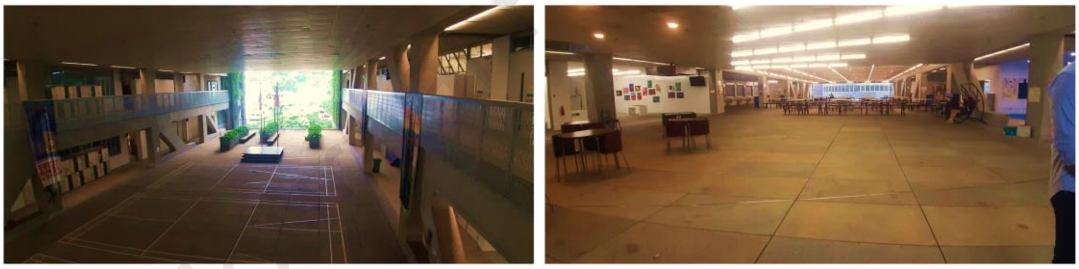

Figure 5. *Horizontal breezeway* type (HB). Left & right: School of the Arts (SO) building.

The *vertical breezeway* can be defined as a semi-open space located within a continuous internal void that rises from ground to the roof and intends to stimulate vertical air displacement through a heat stack effect (see **Figure 6**), as proposed by WOHA [40].

Figure 6. *Vertical Breezeway* type (VB). Skyville@Dawson (SV) building.

2.2. *Research gap and objectives*

Designers need a better understanding of the pros and cons of incorporating SOSs in tall buildings in terms of thermal comfort, however few studies exist on whether the thermal comfort levels vary depending on types of SOS exist and the form attributes that characterise them. There are no studies on *breezeway atria* and *horizontal breezeways*, and few on *sky terraces*, *perimeter buffers (e.g., balconies)*, and *vertical breezeways*, according to the classification shown in Section 2.1: Types of semi-outdoor space.

Research on *perimeter buffers* focus on their impact on indoors. *Balconies* may increase or reduce indoor air movement and energy consumption depending if they are re-entrant or protrusive [41–44], with positive effects on indoors if single-sided ventilation is the only option [45–47]. They provide effective shading from solar radiation, particularly on upper floors [48]; but in hot climates, if *balconies* are closed with glazing, cooling loads and thermal discomfort may increase [49,50].

Thermal comfort provided by *perimeter buffers* and *sky terraces* as social spaces has been also investigated. A study conducted in a high-rise office building in Penang, Malaysia, has compared *sky courts*, *balconies*, and *roof top gardens* in terms of thermal comfort, and has found that *sky courts*, due to their double height and the combination of water and vegetation features, may be the most thermally comfortable space [51]. According to some measurement-based studies conducted in high-rise residential buildings of Singapore, semi-outdoor spaces such as *forecourts* or *sky verandahs* are more thermally comfortable environments than *balconies* very likely due to higher solar shading, despite lower air velocity [22–25]. A measurement-based study conducted in a high-rise office building in Shenzhen shows that people can feel warmer within semi-open *terraces* when compared to indoor air-conditioned offices, however, they feel more comfortable in the terrace rather than inside the office [52]. Wind speeds are amplified on *sky gardens*, according to research, and thermal comfort can be achieved in summer with a predicted mean vote (PMV) of less than +0.5 [53,54]. Unacclimatized *sky courts* in temperate climates can work as effective thermal buffer zones and reduce energy consumption in buildings during summer conditions [55–59].

Thermal comfort in *vertical breezeways* and its impact on indoors has been also researched. According to a study conducted in high-rise residential buildings in Singapore, *vertical breezeways* serve as a semi-outdoor buffer space that mediates between the outdoors and the indoors, reducing energy consumption and promoting thermally comfortable spaces and social interaction among neighbours [16].

Few studies exist on the form attributes that explain thermal comfort in semi-outdoor environments. In Singapore's tropical context, SOSs in high-rise buildings can provide thermally comfortable environments for typical social activities through building form parameters (e.g., *height-to-depth ratio, open space ratio, green plot ratio*) that help enhance air movement and reduce the mean radiant temperature [21]. A measurement and survey-based study in SOSs of a university campus of Singapore shows that thermal comfort in semi-outdoor environments is linked to spatial attributes that affect shading and ventilation, for instance, the higher the *height* or *height-to-depth ratio* of the semi-outdoor space the higher the overall thermal comfort satisfaction [60].

Are there differences between SOS types in terms of thermal comfort? Which attributes of these SOSs are linked to higher thermal comfort levels? These research questions are addressed with the following approach: (1) classification of SOSs based on literature review; (2) based on measurements, evaluation of the differences between types of SOS in terms of thermal comfort, environmental parameters (air temperature, mean radiant temperature, air velocity and relative humidity) and building form attributes; (3) discussion on which form attributes explain findings.

3. Methodology

The methodology of this study is summarised in **Figure 7**. As shown in **Section 2** this study identifies, through literature review, the types of SOS that can be found in tall buildings of a tropical highly dense city.

Later, as shown in **Subsection 3.1.**, 63 SOSs that were measured in four buildings of Singapore [21] are classified into five types of SOS identified in literature review. **Subsection 3.2.** explains how measurements of the environmental factors that affect thermal comfort - air temperature (T_a), mean radiant temperature (T_{mrt}), relative humidity (RH), and air velocity (V_a) - were performed, as well as what building form attributes may explain the environmental factors and thermal comfort. **Subsection 3.3** explains how thermal comfort in SOSs was estimated and what statistical methods were used to compare SOS types in terms of thermal comfort, environmental factors, and building form attributes.

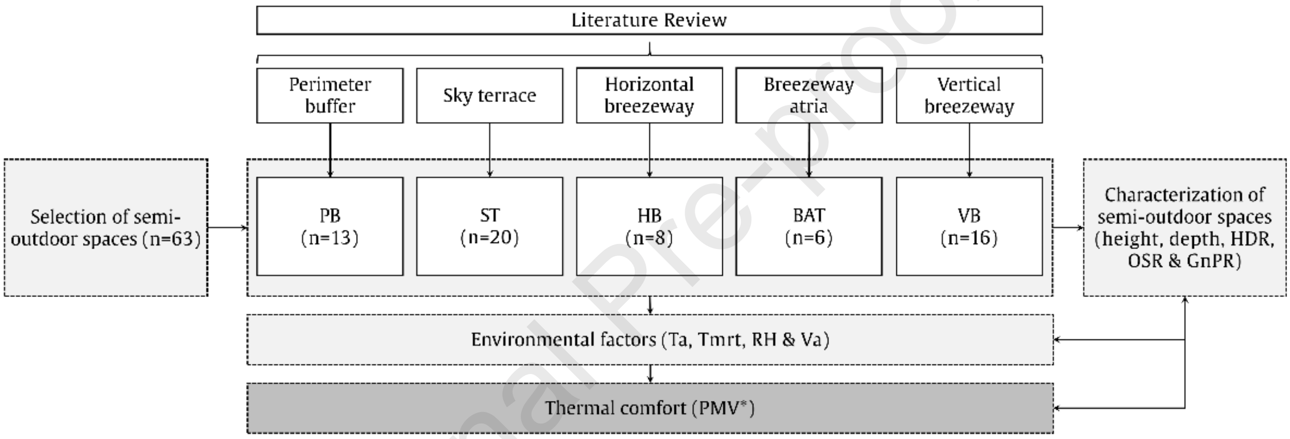

Figure 7. Methodology of the study.

3.1. Selection of semi-outdoor spaces

Four buildings in Singapore (1.3º N, 103.8º E) were used as case studies to evaluate environmentally these 63 SOSs, later classified by types. These buildings are: School of the Arts (SO), OASIA Hotel Downtown (OA), Kampung Admiralty (KA) and Skyville@Dawson (SV), designed by WOHA. In summary, SO building is a 10-storey high school project in Singapore's Central Business District (CBD) area surrounded by medium-rise buildings, composed of three long rectangular blocks separated by semi-open spaces (*horizontal breezeways*) that are intended to channel wind and green facades that are intended to reduce noise; OA building is a 27-storey hotel project surrounded by hotel and mixed-use (commercial, office, and residential) high-rise developments, wrapped in a double skin green facade that introduces elevated semi-open spaces (*breezeway atria and sky terraces*) throughout different levels, also in the CBD area; KA is a mixed-use project within a compact site in Woodlands, adjacent to a train station in medium-rise public housing area, composed of a sheltered and shaded public plaza at ground level (*breezeway atria*), covered by a rooftop 'community park' overlooked by apartments for the elderly; and SV building is a 47-storey public housing project in Queenstown, composed of 3 north-south oriented towers linked horizontally by 'sky villages' (*sky terraces and vertical breezeways*) that favour horizontal and vertical air flows, surrounded by medium and high-rise residential developments [61].

In these buildings, the architects experiment with the building form by introducing SOSs to create social spaces that benefit from enhanced airflows, shade, and greenery [40]. These buildings were selected as they have all five SOS types, including the three proposed by WOHA (i.e., *horizontal breezeways, breezeway atria* and v*ertical breezeways)*. As shown in **Figure 8**, from all 63 measured SOSs, 20.6% of them (n=13) were classified as a *perimeter buffer* (PB). SOSs classified within the PB type comply with the definition provided by incentive schemes in Singapore and Hong Kong [28,29,31]. As shown in **Figure 9**, 31.7% measured SOSs (n=20) were classified as *sky terraces* (ST), which comply with the definition given by incentives in Singapore and Hong Kong [26–29]. As shown in **Figure 10**, 12.7% of measured SOSs (n=8) were classified as *horizontal breezeways* (HB) based on literature [40]. As shown in **Figure 11,** 9.5% of measured SOSs (n=6) were classified as *breezeway atria* (BAT) and comply with the characteristics of *atria* shown in aforementioned literature [34–40]. As shown in **Figure 12**, and based on literature [40], 25.4% of measured SOSs (n=16) where classified as a *vertical breezeway* (VB).

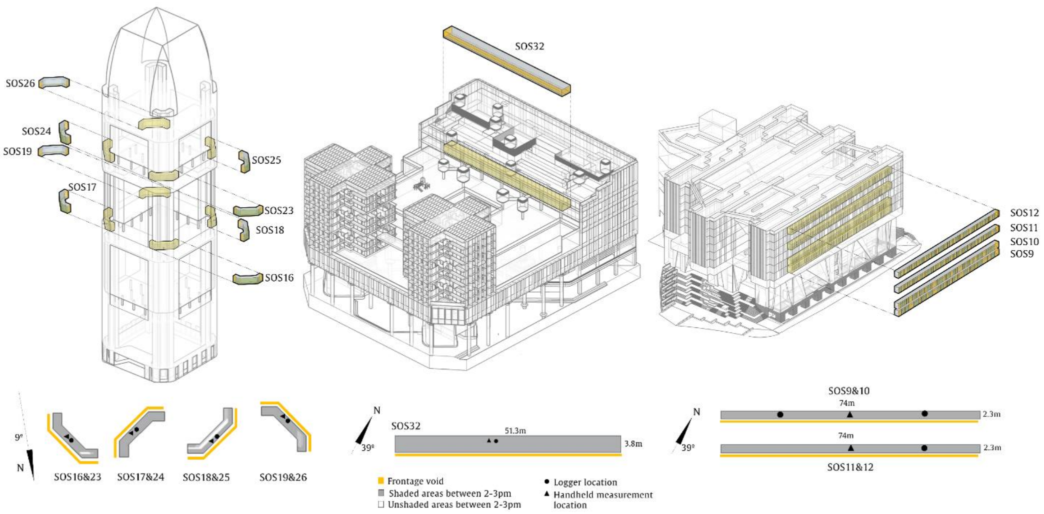

Figure 8. Above: semi-outdoor spaces classified within the *perimeter buffer* type (PB), where yellow colour indicates voids. Below: dimensions of SOSs, measurement locations and shading conditions (2-3pm - OA: June 26, KA: July 09 & SO: June 10).

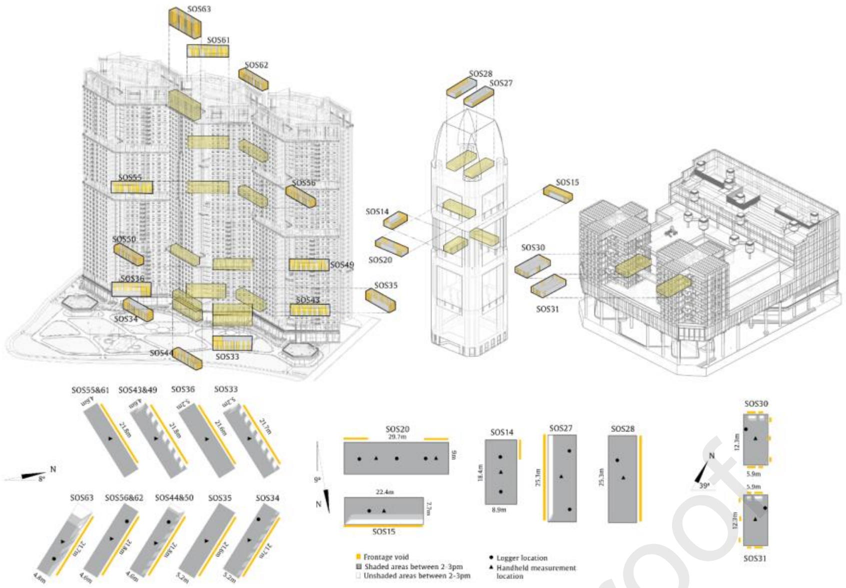

Figure 9. Above: semi-outdoor spaces classified within the *sky terrace* type (ST), where yellow colour indicates voids. Below: dimensions of SOSs, measurement locations and shading conditions (2-3pm - SV: July 24, OA: June 26 & KA: July 09).

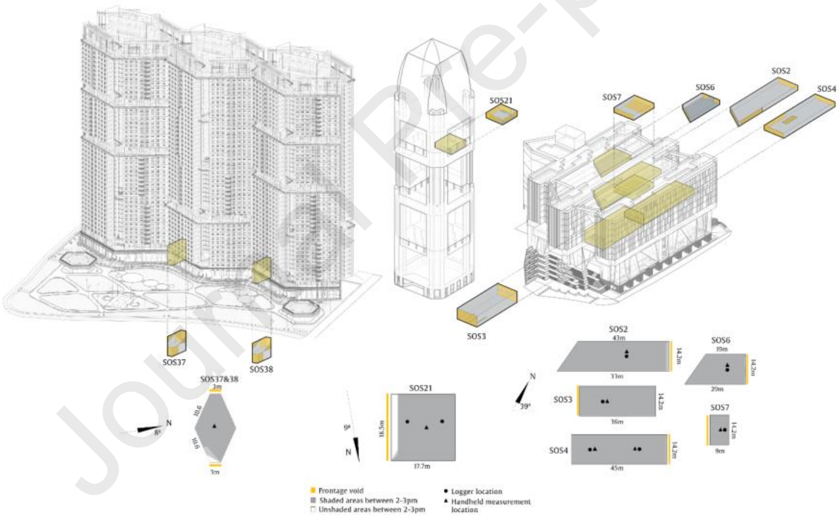

Figure 10. Above: semi-outdoor spaces classified within the *horizontal breezeway* type (HB), where yellow colour indicates voids. Below: dimensions of SOSs, measurement locations and shading conditions (2-3pm - SV: July 24, OA: June 26 & SO: June 10).

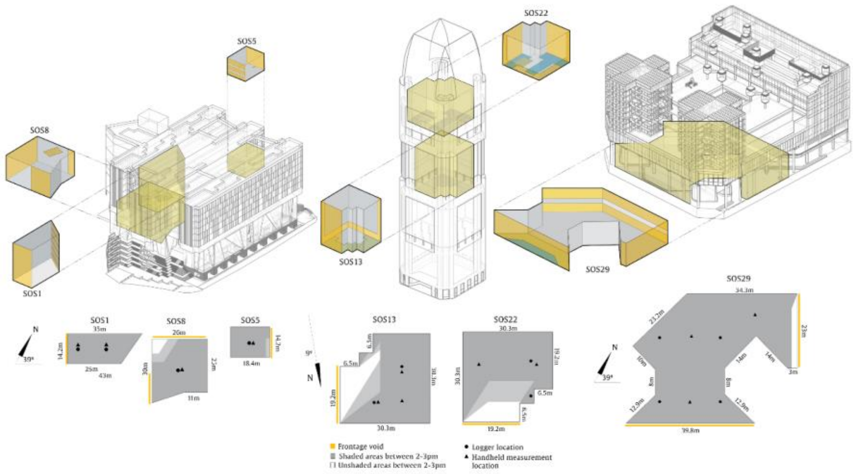

Figure 11. Above: semi-outdoor spaces classified within the *breezeway atria* type (BAT), where yellow colour indicates voids. Below: dimensions of SOSs, measurement locations and shading conditions (2-3pm - SO: June 10, OA: June 26 & KA: July 09).

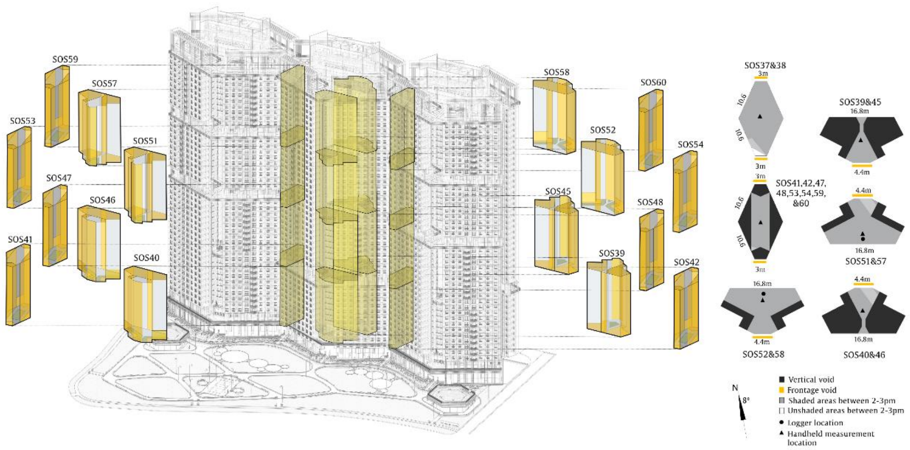

Figure 12. Left: semi-outdoor spaces classified within the *vertical breezeway* type (VB), where yellow colour indicates voids. Below: dimensions of SOSs, measurement locations and shading conditions (2-3pm - SV: July 24).

3.2. Measurements

This study was developed during the southwest monsoon season (June – September) [62]. Measurements of air temperature (T_a), relative humidity (RH), globe temperature (T_{globe}) and air velocity (V_a) were taken in each SOS within the following periods: SO building (June 10 – 17, 2019), OA building (June 26 – July 02, 2019), KA building (July 09 – 16, 2019), and SV building (July 24 – 30, 2019). Different periods were studied due to the fact that few measurement equipment was available for studying all 63 SOSs at the same time.

3.2.1.Environmental factors

Outdoor air temperature (T_{out}) measurements were taken for each building, sheltered from direct sun. Statistical tests were performed to analyse if outdoor conditions were significantly different throughout the different measurement periods, as explained in **Section 3.3.2** and **Section 4.**

T_a and RH measurements were taken with calibrated HOBO loggers (temperature accuracy: ±0.35°C; RH accuracy: ±2.5% from 10-90% RH), Madgetech RH Temp loggers and VelociCalc handheld air meter. Globe temperature (T_{globe}) and air velocity handheld measurements were taken using a TESTO 0.15 meters globe temperature thermometer with a type K thermocouple and a VelociCalc air velocity meter, respectively. Loggers took data every 10 minutes for the mentioned periods, later transformed into hourly data. Handheld measurements were taken every hour between 10am and 4pm in one day (in SO, OA & KA building) or two days (in SV building) of each mentioned period. T_{mrt} was calculated following ISO 7726 forced convection equation [63]. For security reasons (in SV and KA buildings) and privacy reasons (in OA and SO buildings) the dataloggers were placed in locations hidden from the general public, approximately 1.5 meter above the ground depending on the fixed furniture or walls available in the semi outdoor space, sheltered from direct solar radiation.

3.2.2. Building form attributes

A previous study has found that SOSs can be characterized by the building form attributes of *open space ratio (OSR)*, and *height-to-depth ratio (HDR)*, which can influence significantly on thermal comfort and the environmental factors that affect thermal comfort. For instance, *HDR* affects PMV*, T_{mrt}, V_a and RH; *OSR* affects PMV* and V_a; and *GnPR* affects T_{mrt} and RH [21]. Within the green incentives of Singapore and Hong Kong the *OSR* form attribute is explicitly mentioned as one aspect to consider for establishing if building designs qualify for gross floor area (GFA) exemption; *HDR* and *GnPR* are implicitly mentioned. From an environmental performance position, this study delves into characterizing SOSs by types, based on the building form attributes of *HDR*, *OSR* and *GnPR* (see **Table 1** and **Figure 13**), implicitly and explicitly mentioned already in green incentive schemes of Singapore and Hong Kong. These building form attributes were calculated using a simplified model of all 63 SOSs, based on floor and section plans and on in-situ observations.

Attributes	Definition	Formula
Height-to-depth ratio (HDR)	It measures the ratio between *height* and *depth* of the semi-outdoor space [21,60].	HDR = height/depth
Open space ratio (OSR)	It measures in meters the ratio between the *perimeter openness* (only frontage exposed to outdoor conditions) of the SOS and the total perimeter of the SOS. The *perimeter openness* adjacent to a SOS is not computed [21].	OSR = frontage/perimeter
Green plot ratio (GnPR)	It measures the ratio between the total *Leaf Area Index* (LAI) to the total area of the space (m^2) [64], where LAI is a common biological parameter defined as the single-side leaf area per unit ground area. LAI ratios specified for grassland (1:1), shrubs (1:3) and trees (1:6) were used as reference values [65].	GnPR = LAI/SOS area

Table 1. Influential building form attributes on thermal comfort of semi-outdoor spaces.

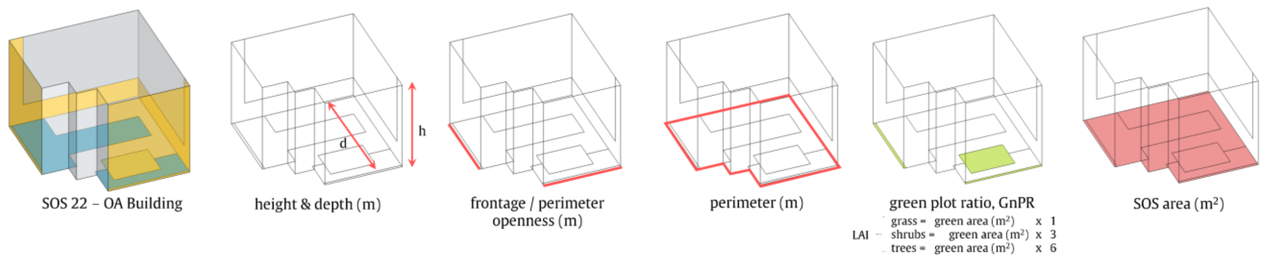

Figure 13. Measured building form attributes (SOS22 in OA building used as example).

3.3. Data analysis

The typically warm hour of 2pm (between 2-3pm), time at which all SOSs are shaded (as shown from **Figure 8** to **Figure 12**), was used as the reference time to assess how SOS types are different in terms of the thermal comfort, environmental factors (T_a, T_{mrt}, RH and V_a) and building form attributes (*HDR*, *OSR* and *GnPR)*. This method of selecting a typical warm hour is also used in other studies [21,66,67]. A typical T_a, T_{mrt} and RH value was calculated for each individual SOS averaging all 2pm readings. Rainy days were discarded from the analysis since in those conditions all environmental factors are modified. Also, a typical air velocity value was calculated for each SOS averaging the wind velocities measured from 10am – 4pm for 1 day (in SO, OA and KA building) or 2 days (in SV building). For SV building, both horizontal and vertical air velocities were taken considering that SOSs in this building are within a *vertical breezeway*. As shown in **Figure 12**, vertical air movement was calculated in the following spaces: SOS39, SOS41 and SOS42 at 3rd Floor; SOS45, SOS47 and SOS48 at 14th Floor; SOS51, SOS53 and SOS54 at 25th Floor; and SOS57, SOS59 and SOS60 at 36th Floor.

3.3.1. Thermal comfort estimation in semi-outdoor spaces

In order to assess the degree of thermal comfort in studied SOSs Gagge's thermal comfort index (called PMV*) was used since it is a better index, in contrast to Fanger's PMV, for measuring thermal stress of environments, such as semi-outdoor ones, due to heat loads and to the physiological heat strain caused by changing humidity of the environment and by changing vapor permeability properties of clothing worn [68]. PMV*, developed by Gagge, was considered to be the most appropriate index for assessing thermal comfort in SOSs, although it is scarcely mentioned in literature [21,43,69]. It is the counterpart of SET* thermal index, which is based on the two-node model of human thermal regulation and is one of the most common indices for evaluating thermal comfort in semi-outdoor environments [21,47,78,70–77]. PMV* is considered one of the most advanced heat budget models since it improves the latent heat fluxes of Fanger's PMV [69]. Although Fanger's PMV has been used for estimating thermal comfort on semi-outdoor environments [52], it was not used since it was developed for indoor environments. The thermal comfort indices of OUT_SET*, PET and

UTCI were not used either since they were developed for assessing heat stress in outdoor urban environments, although they have also been used for semi-outdoor environments within buildings [79–83].

PMV* was calculated using *calcPMVStar* functions (*comf* package) with R software. [84]. Measured thermal comfort parameters of T_a, T_{mrt}, V_a and RH were introduced in the function. A CLO value of 0.3 was considered for all calculations, considering it as the typical clothing value in outdoor and semi-outdoor urban spaces of Singapore [85,86]. Three PMV* calculations were performed for each SOS only differing in MET values for slight activities (1 MET for people sitting; 1.5 METs for people standing; and 2 METs for people slow walking at 0.9m/s), considering that the metabolic activity values in SOSs may be higher than the typical sedentary behaviour on indoors [87].

Also, ASHRAE 55-2017 PMV-PPD method [88], with Gagge's thermal index of PMV*, was used in order to calculate the percentage of SOSs within each type that have a good thermal comfort performance (PMV* between -0.5 and +0.5).

3.3.2. *Statistical analysis*

Since measurements were performed in different periods for each building, T_{out} readings of each building were analysed statistically to find if in overall they differ significantly or not from each other. Since the sample was small (6 -7 days of measurements) Kruskal-Wallis non-parametric test was performed, using *kruskal.test* function with R software, for comparing the T_{out} 2pm readings of all four buildings shown in **Appendix Section**.

To determine whether SOS types differ in terms of thermal comfort (based on PMV*), environmental factors that affect thermal comfort (T_a, T_{mrt}, RH, and V_a), and building form attributes (*OSR*, *HDR* and *GnPR*) the Kruskal-Wallis test was performed with R software's *kruskal.test* function. Post hoc tests were used to determine the specifics of the differences between each group. The Kruskal-Wallis test was followed by (i) the Mann-Whitney non-parametric test with Bonferroni p-value adjustment method, which was performed with R software using the *pairwise.wilcox.test* function; and by (ii) Dunn's non-parametric test with Benjamini-Hochberg p-value adjustment method using the *dunnTest* function within the *FSA* package.

4. Results

In terms of thermal comfort (using PMV* thermal index), environmental factors (T_{mrt}, RH and V_a), and building form attributes (*HDR*, *OSR* and *GnPR)*, all 5 types of SOS are different. Readings of T_{out} at 2pm in all four buildings were found not to be significantly different between each building when performing Kruskal-Wallis test (Kruskal-Wallis chi-squared = 5.940; df = 3; p =.115), although measured in different periods.

4.1. Semi-outdoor space types and thermal comfort

Results of SOSs falling within ASHRAE thermal comfort range (PMV* between -0.5 and +0.5) are shown in **Figure 14**. Estimations show that none of the SOSs classified as *perimeter buffers* (PB) provide for any activity type an environment within that thermal comfort range. In contrast, 75.0% of SOSs classified as *vertical breezeways* (VB) fall within that thermal comfort range, assuming a metabolic activity of 1 MET, 56.3% for 1.5 METs, and 6.3% for 2 METS. For 1.5 METS *sky terraces* (ST), *horizontal breezeways* (HB) and *breezeway atria* (BAT) also have SOSs within the specified thermal comfort range, 20.0%, 50.0% and 16.7%, respectively. Besides *vertical breezeways* (VB), 5.0% of SOSs classified as *sky terraces* (ST) fall also within the thermal comfort range for 1.5 METs.

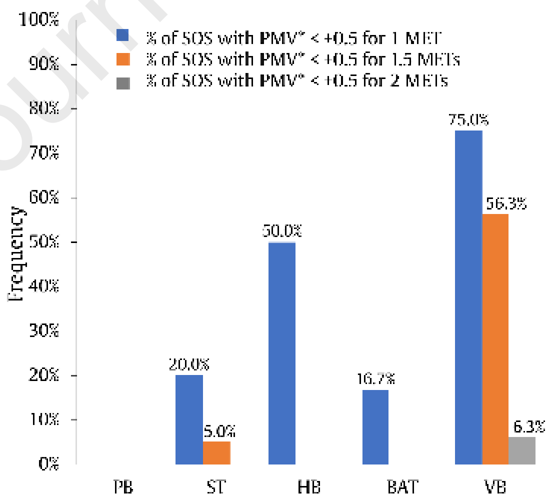

Figure 14. Percentage of SOSs within each type falling within ASHRAE thermal comfort range (PMV* between -0.5 and +0.5).

When using the Kruskal-Wallis test, the median values of all SOS types differ significantly in terms of PMV* (see **Table 2)** for all three studied activity type (1, 1.5 and 2 METs) (see Model 1, 2 and 3). In terms of thermal comfort (PMV*), post hoc tests (see **Appendix Section, Table A. 2**) show that there is a significant difference in median values between the *vertical breezeways* (VB) and the *perimeter buffer*s (PB), *the sky terraces* (ST) and the *breezeway atria* (HB).

Except for Model 4a (T_a as response variable), SOS types differ significantly (see **Table 2)** when performing Kruskal-Wallis test for all other environmental factor (T_{mrt}, V_a and RH). In terms of only T_{mrt}, RH and V_a, post hoc tests (see **Appendix Section, Table A. 3**) show that there is a significant difference in median values between the *vertical breezeways* (VB) and *perimeter buffers*, between *vertical breezeways* (VB) and *breezeway atria* (BAT); in terms of only T_{mrt} and RH, between *perimeter buffers* (PB) and *sky terraces* (ST).

Model	Response variables	p-value (*p*)
Thermal comfort		
Model 1	PMV*, 1 MET	$p < .001$
Model 2	PMV*, 1.5 METs	$p < .001$
Model 3	PMV*, 2 METs	$p < .001$
Environmental factors		
Model 4a	T_a	$p = .483$
Model 4b	T_{mrt}	$p < .001$
Model 4c	RH	$p < .001$
Model 4d	V_a	$p < .001$

Table 2. Summary of the Kruskal-Wallis models having PMV* thermal comfort index and environmental factors as the response variable.

The degree of thermal comfort (PMV*) on each SOS type are shown in **Figure 15a** and **Table 3**. SOSs classified as *vertical breezeways* (VB) have the lowest median PMV* value for all activity types: +0.13 (1 MET), +0.42 (1.5 METs) and +0.71 (2 METs); and SOSs classified as *breezeway atria* (BAT) have the highest median PMV* value for all activity types: +0.98 (1 MET), +1.28 (1.5 METs) and +1.66 (2 METs).

Environmental factors of each SOS type are shown in **Figure 15b** and **Table 3**. SOSs within the *perimeter buffer* (PB) type experienced the lowest median T_a and T_{mrt} values: 29.41ºC and 30.73ºC, respectively. The *horizontal breezeway* (HB) and *breezeway atrium* (BAT) types experienced the highest median RH values: 75.94% and 75.87%, respectively. SOSs classified as *breezeway atria* (BAT) and *perimeter buffers* (PB) experienced the lowest V_a values: 0.50m/s. SOSs classified within the *vertical breezeway* (VB) type experienced the highest median T_{mrt} value: 33.81ºC; followed by those classified as *sky terraces* (ST): 32.68ºC. Those SOSs classified as *vertical breezeways* (VB) experienced the lowest RH median value: 65.53%; and the highest median V_a value: 1.55 m/s.

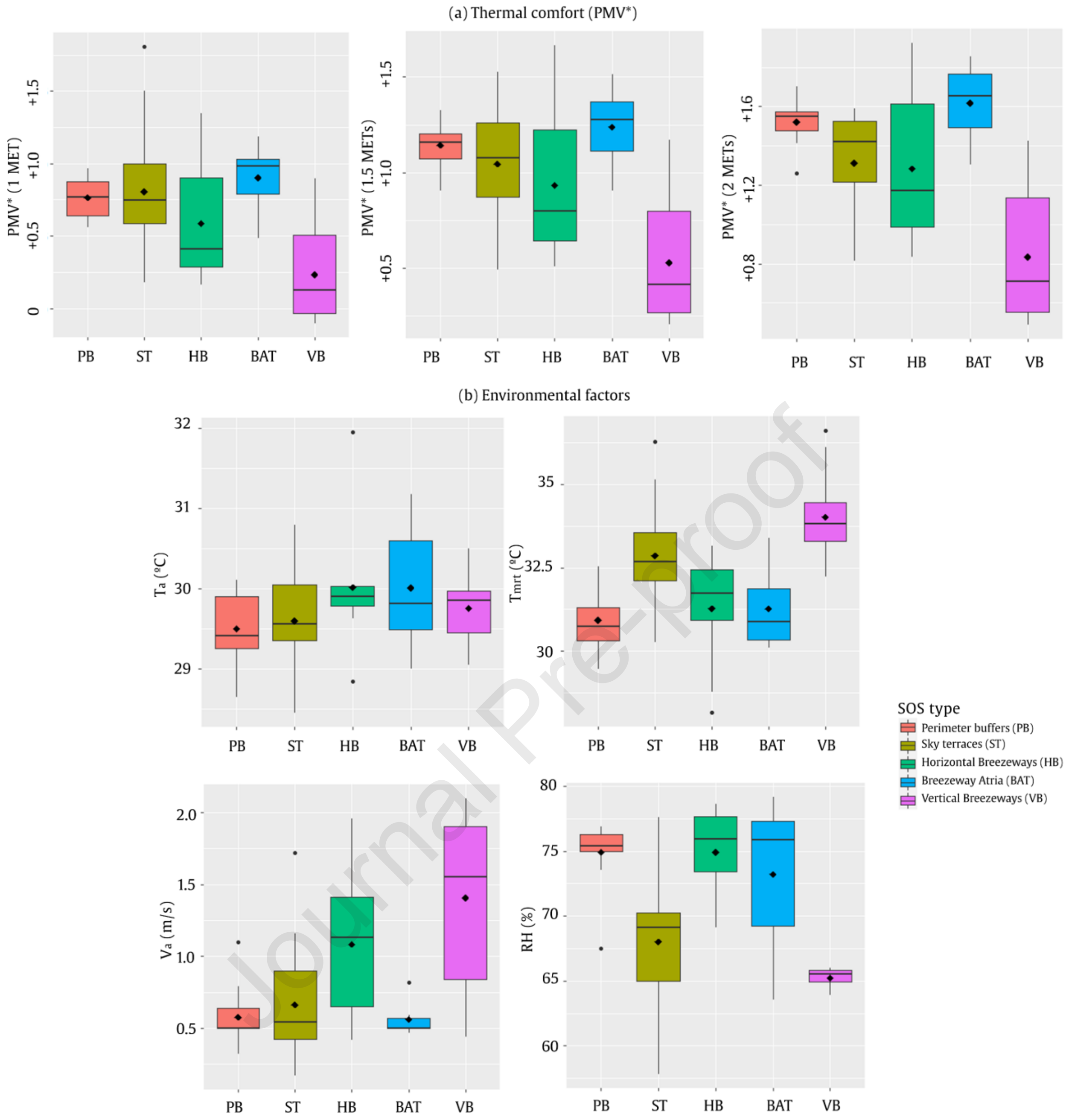

Figure 15. Boxplots showing medians and means for each SOS type in terms of: (a) estimated thermal comfort level (PMV* for 1 MET, 1.5 METs and 2 METs), and (b) measured environmental factors (T_a, T_{mrt}, RH and V_a).

	PB (n=13)	ST (n=20)	HB (n=8)	BAT (n=6)	VB (n=16)
Thermal comfort					
PMV*, 1 MET	+0.77 (+0.77)	+0.75 (+0.81)	+0.41 (+0.59)	+0.98 (+0.90)	+0.13 (+0.23)
PMV*, 1.5 METs	+1.16 (+1.14)	+1.08 (+1.05)	+0.80 (+0.93)	+1.28 (+1.24)	+0.42 (+0.53)
PMV*, 2 METs	+1.55 (+1.52)	+1.42 (+1.31)	+1.17 (+1.28)	+1.66 (+1.62)	+0.71 (+0.83)
Environmental factors					
T_a (ºC)	29.41 (29.50)	29.55 (29.60)	29.90 (30.02)	29.81 (30.01)	29.85 (29.75)
T_{mrt} (ºC)	30.73 (30.92)	32.68 (32.86)	31.73 (31.27)	30.88 (31.27)	33.81 (34.02)
RH (%)	75.42 (74.90)	69.13 (68.02)	75.94 (74.91)	75.87 (73.21)	65.53 (65.23)
V_a (m/s) - horizontal	0.50 (0.58)	0.54 (0.66)	1.13 (1.08)	0.50 (0.56)	1.55 (1.41)
V_a (m/s) - vertical	-	-	-	-	0.40 (0.40)

Table 3. Medians (means in parenthesis) of estimated thermal comfort (PMV*) and measured environmental factors for each SOS type.

4.2. Semi-outdoor space types and building form attributes

SOS types are significantly different also when performing Kruskal-Wallis test for each building form attribute (*OSR*, *HDR* and *GnPR*), as shown in **Table 4.** Post hoc tests (see **Appendix Section, Table A. 4**) show that: (i) in terms of *OSR*, the *vertical breezeway* (VB) differs significantly from all SOS types except with the *horizontal breezeway* (HB); and (ii) in terms of *HDR*, the *vertical breezeway* (VB) differs significantly from all SOS types except with the *perimeter buffer* (PB). More significant differences are thoroughly discussed in the **Discussion Section.** The current study investigates thermal comfort on SOS types while controlling for the parameters of *height from ground level* (*HFG*) and *orientation* (see **Appendix Section, Table A. 5** and **Fig. A. 1**).

Model	Response variables	p-value (*p*)
Model 5a	OSR	p <.001
Model 5b	HDR	p <.001
Model 5c	GnPR	p <.001

Table 4. Summary of the Kruskal-Wallis models having building form attributes as response variable.

Building form attributes of each SOS type are shown in shown in **Figure 16** and **Table 5.** SOSs classified within the *vertical breezeway* (VB) type have the lowest median *OSR* value: 0.11; followed by *horizontal breezeways*: 0.13. SOSs considered as *vertical breezeways* (VB) also have the highest median *HDR* value: 2.10.

SOSs classified within the *perimeter buffer* (PB) type have the highest median *GnPR* value: 3.54; as well the highest median *OSR* value: 0.49. SOSs classified within the *horizontal breezeway* (HB) type have the lowest median *HDR* value: 0.24.

	PB (n=13)	ST (n=20)	HB (n=8)	BAT (n=6)	VB (n=16)
OSR	0.49 (0.49)	0.29 (0.31)	0.13 (0.16)	0.28 (0.26)	0.11 (0.11)
HDR	1.75 (1.44)	1.04 (0.92)	0.24 (0.21)	0.70 (0.71)	2.10 (2.10)
Height (m)	3.50 (3.27)	4.80 (4.95)	4.00 (4.50)	19.10 (20.22)	30.80 (30.80)
Depth (m)	2.00 (2.45)	5.20 (5.81)	21.65 (27.29)	30.15 (29.50)	15.55 (15.55)
GnPR	3.54 (2.50)	0.00 (0.04)	0.00 (0.13)	0.30 (1.02)	1.28 (1.23)

Table 5. Medians (means in parenthesis) of building form attributes for each SOS type.

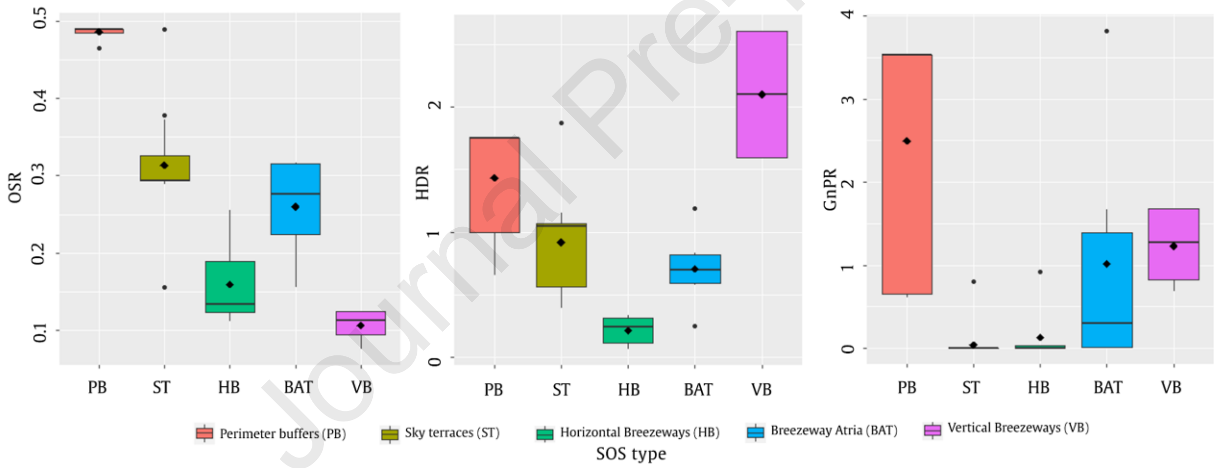

Figure 16. Boxplots showing medians and means for each SOS type in terms of building form attributes (*OSR*, *HDR* and *GnPR*).

5. Discussion

According to the findings of this study, estimated thermal comfort (based on PMV*) and measured environmental parameters (T_a, T_{mrt}, RH and V_a) differ depending on the type of semi-outdoor space (SOS): *perimeter buffers* (PB), *sky terraces* (ST), *horizontal breezeways* (HB), *breezeway atria* (BAT) and *vertical breezeways* (VB). The latter is the most likely due to the form attributes. The study confirms previous research findings that *HDR* and *OSR* are parameters that define thermal comfort (based on PMV* and SET*) in semi-outdoor spaces [21], and it provides new insights into how these parameters, along with *GnPR*, shape the microclimate of these spaces when classified by types.

5.1. Thermal comfort according to semi-outdoor space types

Few studies have compared different types of SOS within tall buildings in highly dense tropical contexts in terms of thermal comfort and environmental benefits [22–24,51]; but, these studies do not cover all of the different types of semi-outdoor space that may exist in tall buildings nor do they attempt to characterise them by building form attributes. Although in overall all SOS types are significantly different in terms of thermal comfort (PMV*), only the *vertical breezeway* (VB) type differs significantly from all other SOS types (except for the *horizontal breezeway* type). The latter is very likely as a result of the significant differences, particularly in *HDR* and *OSR*.

5.1.1. Perimeter buffers

The low air velocity performance in the *perimeter buffer* (PB) type may explain why it is also low in terms of thermal comfort performance. The PB type has a significantly lower performance in terms of thermal comfort (PMV*) than the VB type (e.g., for 1 MET - MW: $p < .001$, D: $p = .001$). The low performance of the PB type in terms of SOSs falling within the ASHRAE thermal comfort range (using PMV*) is most likely due to its *OSR* value of 0.49, which is significantly higher than the *OSR* value of the VB type of 0.11 and means that nearly half of its perimeter is exposed to outdoor conditions (e.g., more solar incidence). Because higher *OSR* values are also associated with lower air movement [21], the latter appears to explain the low performance of the PB type in terms of air velocity, with a median V_a value of 0.50 m/s, significantly lower than the median V_a value of the VB type of 1.55 m/s; for instance, this is approximately 1 m/s lower than the VB type. Low air velocities in the PB type may be also related to the greenery systems (i.e., double skin façade, planter boxes), which can interfere with air movement [20,21]. The PB type is distinguished from the other SOS types by having the highest *GnPR* median value: 1.28, which may explain why it also has the lowest median T_{mrt} value of 30.73ºC and one of the highest median RH values: 75.4%; for instance, this is approximately 3ºC lower than VB type, approximately 2ºC lower than the ST type, and approximately 10% RH lower than the VB type.

5.1.2. Sky terraces

The *sky terrace* (ST) type is very likely the third most thermally comfortable SOS type, as it also has the third highest V_a value. The ST type has a significantly lower performance in terms of thermal comfort (PMV*) than the VB type (e.g., for 1 MET - MW: $p < .001$, D: $p = .001$). The latter is most likely due to its *OSR* value of 0.29, which is significantly higher than the VB type's median *OSR* value of 0.11. Because higher *OSR* values are associated with lower air movement [21], the latter appears to explain the ST type's low performance, which is 1.01 m/s lower than the VB type. In addition, the ST type, along with the PB and BAT types, is among the SOS types with the highest median *OSR* values, which may explain their low median V_a values and why these three types of SOS are the least thermally comfortable ones. In terms of air velocity, these three SOS types are not significantly different. Additionally, the ST type has a significantly lower *HDR* value than the VB type. The lower the *HDR* value the lower the air velocity, but the higher the shading [21]. The latter may explain also why the ST type has a marginally significantly lower T_{mrt} value than that of the VB type, this is, 1.13ºC lower than the VB type, despite the median *GnPR* of the VB type is significantly higher. Previous research in Singapore has shown that *forecourts* (ST type) are more thermally comfortable than *balconies* (PB type). The current findings confirm that the ST type performs slightly better than the PB type, very likely due to its median *depth* of 5.20m that double that of the ST type and its median V_a of 0.54m/s; however, in this study both are not significantly different in terms of thermal comfort (e.g., for 1 MET - MW: $p = 1$, D: $p < .805$).

5.1.3. Horizontal breezeways

The *horizontal breezeway* (HB) type's deep spatial configuration is very likely to aid in the creation of a funnel effect. Findings suggest that the HB type is very likely the second most thermally comfortable SOS type, as it also has the second highest V_a value. The HB type has a median *OSR* value of 0.13, the second lowest of all SOS types, which may explain (i) why it has a median V_a value of 1.13m/s, the second highest air velocity value of all SOS types, and (ii) why it is the second most performative type of SOS in terms of thermal comfort after the VB type. This performance is very likely associated with the *OSR* attribute as a previous research shows that the lower the *OSR* the higher the V_a, as well as a funnel effect [21]. The median *OSR* and V_a values of the HB type are not significantly different from that of the VB type, the most thermally comfortable SOS type. Similarly, the median PMV* value of the HB type is not significantly different from that of the VB type (e.g., for 1 MET - MW: p = .526, D: p = .152), except for PMV* 2 METs. The HB type's median *HDR* value is significantly lower than that of the VB type. The latter very likely explains why SOSs classified within the HB type have the highest median RH value: 75.94%, and the third lowest median T_{mrt} values: 31.73ºC, due to (i) its median *depth* value of 21.65m, the second deepest value of all SOS types, and (ii) its median *HDR* value of 0.24, the lowest of all SOS types. Given that T_{mrt} and RH covariate [21], a higher *depth* value and a lower *HDR* may result in lower solar incidence and higher humidity levels in the space. The HB type has a significantly lower T_{mrt} value and a significantly higher RH value than the VB type; this is, 2.08ºC lower and 10.41% RH higher. The influence of greenery in the thermal comfort of the HB type may be considered negligible.

5.1.4. Breezeway atria

Due to limited air flow movement, SOSs classified within the BAT type are very likely to be the least performative in terms of median PMV* values. Findings suggest that air velocity is increased, particularly in the HB and VB types, due to their median *OSR* values of 0.13 and 0.11, respectively. The latter implies that the median *OSR* value of 0.28 in the BAT type may be less effective in promoting wind movement. The BAT type has a significantly lower performance in terms of thermal comfort (PMV*) than the VB type (e.g., for 1 MET - MW: p = .008, D: p < .001). The latter is very likely explained by the fact that the BAT type is significantly different than the VB type in terms of *OSR* and V_a, where the air velocity in the BAT type is significantly 1.05m/s lower than that in the VB type. Additionally, the BAT type is the deepest SOS type with the second highest median *GnPR* value of 1.28, which may explain why it has the second lowest median T_{mrt} value of 30.88ºC and the second highest median RH value of 75.87%, very likely due to increased shading from solar radiation and a higher greenery presence. Additionally, the BAT type provides a semi-outdoor environment where the median *height* value is almost equal to the median *depth* value. For instance, the ST type has a median *HDR* value of 1.04. However, the BAT type has a median *HDR* value of 0.70 (*height*: 19.1, *depth*: 30.15), very close to 1, and not significantly different to that of the ST type, which may explain why the median V_a values of the ST type and the BAT type are not significantly different. Previous research has shown that the higher the

HDR value the higher the air velocity [21]; however, when both *height* and *depth* are equal (*HDR* = 1) air velocity may not be enhanced. Both types are also not significantly different in terms of OSR.

5.1.5. Vertical breezeways

Findings suggest that the degree of thermal comfort attained in the VB type is due to high levels of horizontal V_a values despite having high levels of T_{mrt}. Because the lower *OSR*, the higher V_a [21], the VB type is most likely the most thermally comfortable type of SOS due to its *OSR* value of 0.11, the lowest from all SOS types, which may explain also why the VB type has the highest median V_a value of 1.55m/s. Together with the *OSR* attribute, the *HDR* attribute also helps explain the high air velocity performance. The VB type also has the highest median *HDR* value from all SOS types, of 2.10. The latter could explain not only why this type of SOS has the highest median V_a value, but also why it has the highest median T_{mrt} value of 33.81ºC and the lowest median RH value of 65.53ºC, because the higher the *HDR*, the higher V_a, but also the higher T_{mrt} and the lower RH [21]. Also, the VB type differs significantly from all other SOS types (except from the PB type) in terms of *HDR*. Nonetheless, the VB type differs significantly from the PB type in terms of thermal comfort, T_{mrt}, and V_a, implying that the *OSR* attribute, rather than the *HDR* attribute, may be more important in defining thermal comfort because it aids in wind flow channelling. Significant differences in thermal comfort between the VB type and all other SOS types are also very likely explained by the architectural design of the VB type that seeks to displace heat through vertical cooling airflows, with a median vertical median V_a value of 0.40m/s, as shown in **Table 3**.

5.2. Further research and limitations

Further research should not only examine the degree of association that exists between studied building form attributes and thermal comfort of each type of SOS but should also attempt to demonstrate a cause-effect relationship using inferential statistical tests; however, a larger sample size than that shown in this study is required. For instance, it is very likely that the influence of *GnPR* on the environmental and thermal comfort performance of each type of SOS is more related to the sample size, given that only 36 of the 63 measured SOSs (57.1%) incorporated greenery. If thermally comfortable social spaces are to be promoted in highly dense tropical contexts, future research should carefully examine the optimal *HDR* and *OSR* values for each of the semi-outdoor space types, considering results indicating that they are related to air velocity values, particularly in the *horizontal breezeway* (HB) and *vertical breezeway* (VB) types. In order to do so, future research should employ a parametrization-based research methodology that controls each of the influential attributes in order to identify the optimal values that promote thermal comfort in each semi-outdoor space type. In Singapore and Hong Kong, for example, incentive schemes require semi-outdoor spaces such as *sky terraces* to have a minimum perimeter openness of 40% [26,27,29]; however, in this study the *OSR* value appears to be optimum in air velocity enhancement from values less than 0.13 (13%), having as a result a median V_a value of 1.13 m/s in *horizontal breezeways* (HB), for instance.

Additionally, further research should consider the impact of urban density on providing thermal comfort in semi-outdoor environments, as this parameter was not studied in this study and may affect the thermal performance of SOSs, particularly due to surrounding buildings blocking wind flows [89], especially in KA and OA buildings.

Given that thermal comfort was estimated using Gagge's thermal comfort index (PMV*), additional studies with post-occupancy surveys are needed to validate the results, as thermal comfort in this study is based on in-situ measurements data. Future research should look into how indoor environments may benefit and how cooling energy consumption (when needed) may decrease with these types of SOS using building energy simulations and computational fluid dynamics (CFD) simulations, taking into account a study that shows that semi-outdoor environments can reduce energy use in Singapore's tropical context [16].

Aside from Singapore, future research should look at other highly dense tropical cities as case studies (e.g., Bangkok, Jakarta, and Kuala Lumpur) to see if the thermal conditions of semi-outdoor environments are equally comfortable for people. This research work focuses on assessing thermal comfort; however, further research should look into the construction costs of incorporating the SOS types shown in this study, as doing so may be burdensome, though a Hong Kong study suggests that the costs of incorporating *sky gardens* with intensive or extensive greenery is not so high when compared to the high construction costs of high-rise buildings [8].

6. Conclusions

63 semi-outdoor spaces (SOSs) were measured in four tall buildings of the highly dense tropical city of Singapore and were classified into five types (based on literature review): *perimeter buffers* (PB), *sky terraces* (ST), *horizontal breezeways* (HB), *breezeway atria* (BAT) and *vertical breezeways* (VB). These five types of semi-outdoor space were then compared in terms of thermal comfort (based on PMV*), environmental parameters (T_a, T_{mrt}, RH and V_a), and building form attributes (*HDR, OSR, and GnPR*). This study shows that it is very likely that building form attributes determine the degree of thermal comfort that can be achieved on them, mainly due to air velocity enhancement promoted by the *HDR* and *OSR* form attributes. The findings of this study are the following:

- The PB type, BAT type and ST type are the least thermally comfortable types of SOS, most likely due to low air velocities. (i) None of the SOSs classified within the PB type provide for any activity type (1, 1.5 and 2 METs) an environment within the ASHRAE thermal comfort range (PMV* between -0.5 and +0.5), very likely due to a high *OSR* value. (ii) The BAT type has the highest median PMV* value for all activity types: +0.98 (1 MET), +1.28 (1.5 METs) and +1.66 (2 METs), very likely due to a high *OSR* value and a *HDR* value closer to 1. (iii) The ST type has the third lowest median PMV* value for all activity types: +0.75 (1 MET), +1.08 (1.5 METs) and +0.80 (2 METs), very likely due to a high *OSR* value.
- The VB type and HB type are the most thermally comfortable types of SOS, most likely due to high air velocities. (i) The VB type has the lowest median PMV* value for all activity types: +0.13 (1 MET), +0.42 (1.5 METs) and +0.71 (2 METs). 75.0% of SOSs fall within the ASHRAE thermal comfort range (PMV* between -0.5 and +0.5), assuming a metabolic activity of 1 MET. The latter is very likely due to a low *OSR* value and a high *HDR* value. (ii) The HB type has the second lowest median PMV* value for all activity types: +0.41 (1 MET), +0.80 (1.5 METs) and +1.17 (2 METs). 50.0% of SOSs fall within the ASHRAE thermal comfort range (PMV* between -0.5 and +0.5), assuming a metabolic activity of 1 MET. The latter is very likely due to low *OSR* and *HDR* values.

If social interaction is to be encouraged in tropical, highly dense contexts, it is critical from a thermal comfort standpoint that SOSs with the highest thermal comfort and environmental performance are encouraged in building regulations and designs, particularly those types of SOSs such as *vertical breezeways* (VB) and *horizontal breezeways* (HB), and *sky terraces* (ST). These last three types of SOS are used by people as spaces where to interact with friends and family, study, rest or enjoy from city views. However, although these SOS types have better thermal comfort performance, from a design standpoint, all of the studied communal SOS types may have other functions and indoor benefits that outweigh the thermal comfort aspect. For example, *perimeter buffers* (PB) (i.e., *balconies, corridors*) are spaces commonly incorporated into high-rise buildings that can be used as thermal buffers (second skin) to cool internal spaces, as well as maintenance pathways for green facades; and *breezeway atria* (BAT) function as sheltered meeting spaces to foster community and social cohesion.

This study can help designers understand the pros and cons that each type of SOS has when incorporating them as semi-open communal spaces for social gathering, especially considering that the goal of these four building designs is to deal with thermal comfort and social engagement in tropical high-density contexts prone to heat up by the urban heat island effect and climate change.

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Appendix

Building	SO	OA	KA	SV
Period of study *	June 10 – 17, 2019	June 26 – July 02, 2019	July 09 – 16, 2019	July 24 – 30, 2019
Mean T_{out} 2pm (ºC)	30.86	30.55	32.40	30.69
Day 1	30.90	28.21	-	-
Day 2	32.42	31.18	32.83	30.45
Day 3	-	31.49	32.99	30.57
Day 4	29.94	-	32.41	30.90
Day 5	30.66	29.42	34.12	30.39
Day 6	30.38	31.46	34.12	31.03
Day 7	30.80	31.55	27.91	30.80
Day 8	30.90	NA	-	NA

* Blank values (-) correspond to rainy days not included in the comparison. NA corresponds to days not analysed

Table A. 1. Raw data of outdoor ambient air temperature (T_{out}) at 2pm for each building.

	PMV* (1 MET)	PMV* (1.5 METs)	PMV* (2 METs)
Combination	Δ (MW/D)	Δ (MW/D)	Δ (MW/D)
PB - ST	0.02 (1.000/0.805)	0.08 (1.000/0.520)	0.13 (0.055/0.076)
PB - HB	0.36 (1.000/0.347)	0.36 (1.000/0.275)	0.38 (1.000/0.155)
ST - HB	0.34 (1.000/0.363)	0.28 (1.000/0.533)	0.25 (1.000/0.961)
PB - BAT	0.21 (1.000/0.521)	0.12 (1.000/0.513)	0.11 (1.000/0.567)
ST - BAT	0.23 (1.000/0.423)	0.20 (1.000/0.315)	0.24 (0.087/0.052)
HB - BAT	0.57 (1.000/0.175)	0.48 (1.000/0.186)	0.49 (1.000/0.086)
PB - VB	0.64 (< 0.001/0.001)	0.74 (< 0.001/< 0.001)	0.84 (< 0.001/< 0.001)
ST - VB	0.62 (< 0.001/0.001)	0.66 (< 0.001/< 0.001)	0.71 (< 0.001/0.004)
HB - VB	0.28 (0.523/0.152)	0.38 (0.230/0.073)	0.46 (0.159/0.027)
BAT - VB	0.85 (0.008/< 0.001)	0.86 (0.002/< 0.001)	0.95 (< 0.001/< 0.001)

Table A. 2. P-values for Mann-Whitney (MW) and Dunn's (D) tests and the difference (Δ) between estimated thermal comfort (PMV*) medians.

	T_a (ºC)	T_{mrt} (ºC)	RH (%)	V_a (m/s)
Combination	Δ (MW/D)	Δ (MW/D)	Δ (MW/D)	Δ (MW/D)
PB - ST	0.14 (1.000/0.708)	1.95 (0.002/0.002)	6.29 (0.005/0.007)	0.04 (1.000/0.855)
PB - HB	0.49 (1.000/1.000)	1.00 (1.000/0.445)	0.52 (1.000/0.823)	0.63 (0.155/0.081)
ST - HB	0.35 (1.000/0.581)	0.95 (0.419/0.093)	6.81 (0.053/0.011)	0.59 (0.633/0.102)
PB - BAT	0.40 (1.000/0.777)	0.15 (1.000/0.689)	0.45 (1.000/0.723)	0.00 (1.000/0.963)
ST - BAT	0.26 (1.000/0.715)	1.80 (0.160/0.067)	6.74 (0.995/0.103)	0.04 (1.000/0.798)
HB - BAT	0.09 (1.000/0.920)	0.85 (1.000/0.764)	0.07 (1.000/0.685)	0.63 (0.601/0.114)
PB - VB	0.44 (1.000/0.890)	3.08 (< 0.001/< 0.001)	9.89 (< 0.001/< 0.001)	1.05 (0.002/0.002)
ST - VB	0.30 (1.000/0.885)	1.13 (0.099/0.057)	3.60 (0.157/0.079)	1.01 (0.003/< 0.001)
HB - VB	0.05 (1.000/0.658)	2.08 (0.001/0.002)	10.41 (< 0.001/< 0.001)	0.42 (1.000/0.430)
BAT - VB	0.04 (1.000/0.785)	2.93 (0.015/0.001)	10.34 (0.188/0.006)	1.05 (0.035/0.009)

Table A. 3. P-values for Mann-Whitney (MW) and Dunn's (D) tests and the difference (Δ) between the medians of the measured environmental factors.

	HDR	OSR	GnPR
Combination	Δ (MW/D)	Δ (MW/D)	Δ (MW/D)
PB - ST	0.71 (0.344/0.055)	0.20 (< 0.001/0.014)	3.54 (< 0.001/< 0.001)
PB - HB	1.51 (0.001/< 0.001)	0.36 (0.001/< 0.001)	3.54 (0.003/< 0.001)
ST - HB	0.80 (< 0.001/0.011)	0.16 (< 0.001/0.016)	0.00 (1.000/0.551)
PB - BAT	1.05 (0.039/0.041)	0.21 (0.004/0.018)	3.24 (0.616/0.084)
ST - BAT	0.34 (1.000/0.423)	0.01 (1.000/0.524)	0.30 (0.013/0.069)
HB - BAT	0.46 (0.117/0.157)	0.15 (0.236/0.164)	0.30 (1.000/0.218)
PB - VB	0.35 (0.733/0.124)	0.38 (< 0.001/< 0.001)	2.26 (1.000/0.525)
ST - VB	1.06 (< 0.001/< 0.001)	0.18 (< 0.001/< 0.001)	1.28 (< 0.001/< 0.001)
HB - VB	1.86 (< 0.001/< 0.001)	0.02 (0.117/0.306)	1.28 (0.005/0.002)
BAT - VB	1.40 (0.002/< 0.001)	0.17 (0.003/0.018)	0.98 (0.741/0.207)

Table A. 4. P-values of Mann-Whitney (MW) and Dunn's (D) tests and the difference (Δ) the medians of the building form attributes.

Response variables	p-value (p)
Height from ground level (HFG)	p = .202
Orientation	p = .816

Table A. 5. Summary of the Kruskal-Wallis models having *HFG* and *orientation* as response variable.

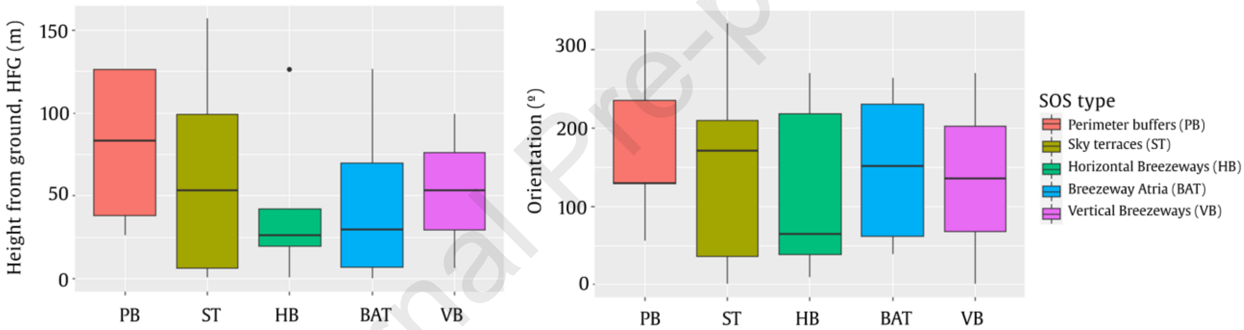

Fig. A. 1. Boxplots showing medians for each SOS type in terms of *HFG* and *orientation.*

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Highlights

- 5 types of semi-outdoor space were evaluated in tall buildings of Singapore
- *Vertical* and *horizontal breezeways* achieve the highest levels of thermal comfort
- *Perimeter buffers* and *breezeway atria* achieve the lowest levels of thermal comfort
- Thermal comfort is linked to building form attributes that enhance air velocity

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: