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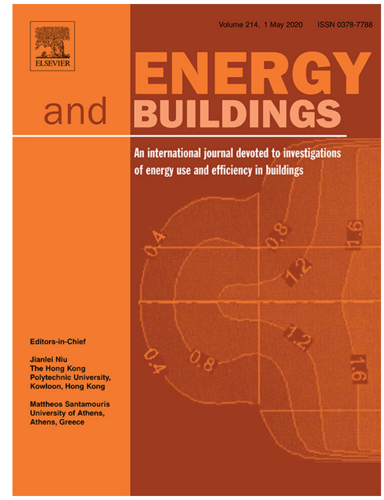

Porosity, openness, and exposure: Identification of underlying factors associated with semi-outdoor spaces' thermal performance and clustering in tropical high-density Singapore

Juan Gamero-Salinas, Nirmal Kishnani, Ana Sánchez-Ostiz, Aurora Monge-Barrio, Edgar Benitez

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Authors: Gamero-Salinas, Juan [a]; Kishnani, Nirmal [c]; Sánchez-Ostiz, Ana [d]; Monge-Barrio, Aurora [e]; Benitez, Edgar [b]

Emails: Corresponding author [a]: jgamero@unav.es / Co-author [b]: ebenitezs@unav.es / Co-author [c]: akintk@nus.edu.sg / Co-author [d]:aostiz@unav.es / Co-author [e]:amongeb@unav.es

Affiliation:

[a b] University of Navarra (UNAV). Institute of Data Science and Artificial Intelligence, University Campus, 31008 Pamplona, Spain

[a b] University of Navarra (UNAV). TECNUN School of Engineering, Manuel Lardizábal 13, 20018 San Sebastián, Spain

[c] Department of Architecture, College of Design and Engineering, National University of Singapore (NUS), 8 Architecture Drive SDE4 #04-03 Singapore 117 356

[d e] School of Architecture. Department of Construction, Building Services and Structures. University of Navarra (UNAV), Calle Universidad, 31009, Pamplona, Navarra, Spain; (+34) 948425600

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Abstract

The lack of green open spaces undermines the environmental and social quality of tropical highly-dense cities (i.e. raises urban temperatures, limits social interaction). The goal of this study, which focused on environmental aspects, was to identify underlying factors (i.e. *hypothetical constructs*) in semi-outdoor spaces within building forms that explain their microclimatic behaviour, thermal comfort levels, and clustering. Sixty-three semi-outdoor spaces in four high/mid-rise building forms of Singapore were studied using microclimatic data collected from field measurements and analysed via inferential statistical methods (e.g., exploratory factor analysis, multivariate regression analysis, and hierarchical clustering analysis). Findings demonstrate: (1) that spatial attributes (i.e. *height, depth, void, solid, total frontage, open frontage, area, volume, perimeter, sky view factor, green plot ratio*) are manifestations of three underlying factors: *volume porosity* (VP), *perimeter openness* (PO) and *exposure to sky* (ES); (2) that VP and PO are significantly associated with air velocity and predicted thermal comfort; and (3) that *vertical breezeways* appear to be the most thermally comfortable cluster due to high

VP and low PO. This study sheds new light on the spatial nature of semi-outdoor spaces, which designers can consider in order to enhance wind movement for promoting thermally comfortable semi-outdoor environments in highly-dense Singapore.

Keywords: semi-outdoor space; microclimate; thermal comfort; volume porosity; perimeter openness; exposure to sky

1. Introduction

A semi-outdoor space is a common architectural design feature of warm-humid tropical buildings. It is defined as an 'in-between' (transitional) space that, in the absence of mechanical cooling systems, mediates between indoor and outdoor environments through man-made structures that protect against outdoor environmental conditions (i.e., rainfall and undesired radiation) [1,2]. Typically, a semi-outdoor space is attached to, or embedded within, an architectural form. In traditional, low-rise buildings, it may be a *veranda* on a building's perimeter or *courtyard* around which spaces are organised [3,4]. In modern, high-rise developments, semi-outdoor spaces take the form of *balconies, atria*, *courts, decks* and *terraces* which affect the form of the building to varying degrees [5–10]. There have been calls to design buildings in ways that mitigate the urban heat island (UHI) effect and extreme temperatures due to global warming [11,12]. According to the Cooling Singapore project, the semi-outdoor space appears to be a potential UHI design measure to address socio-environmental outcomes; however, it receives little attention [13], despite Singaporeans preferring to spend more time in outdoor-like environments rather than indoors [14]. The need for semi-outdoor spaces in tall, urban structures was initially argued as envelope-affixed spaces that improve a building's environmental performance [15–17]. Their positive outcomes on comfort and energy use were subsequently supported by onsite measurements of bioclimatic buildings [18]. Since then, additional studies have been conducted to investigate the performance provided by the semi-outdoor space as a design strategy, which are discussed in a summarised way in Subsection 1.1.

1.1. State-of-the-art on the environmental and social performance of semi-outdoor spaces

In tropical buildings the semi-outdoor space serves two purposes: (a) an *environmental* one, as it acts as a buffer between indoor and outdoor conditions, improving human comfort and, where an interior relies on climate-control systems, it tempers energy demand; and (b) a *social* one, as it acts as a social space, often bridging private and public realms. Current knowledge on semi-outdoor spaces is based more on the environmental performance of semi-outdoor spaces than on their social one.

1.1.1. Environmental performance of semi-outdoor spaces

According to field measurement studies and computational fluid dynamics (CFD) simulations studies shown in Table 1, most in tropical and subtropical locations, *thermal comfort in semi-outdoor environments is particularly linked to wind and solar radiation*. Moreover, *many studies link the microclimatic and thermal comfort performance of semi-outdoors environment to spatial attributes.* For instance, (1) greater *height-to-depth* ratio in semi-outdoor spaces increases wind sensation, wind speed and thermal comfort [19,20]; (2) higher amounts of *void-to-solid ratio* in semi-outdoor spaces induces more wind movement, however increases the mean radiant temperature [19,20]; and (3) more *GnPR* or *vegetation* lowers the ambient air temperature and mean radiant temperature; however, it reduces wind speeds [21–26]. *Other studies suggest that thermal comfort in semi-outdoor spaces varies depending on the type of semi-outdoor space and their attached spatial attributes.* For instance, the most thermally comfortable semi-outdoor spaces identified in some studies (e.g. *sky courts*, *vertical breezeways*) are linked to more wind movement due to spatial attributes that funnel wind [27,28]; however, other studies suggest they are more reliant on solar radiation (e.g. *forecourt/veranda*) due to spatial attributes that provide shade [7,8]. *Multiple thermal comfort indices have been used in the literature for assessing thermal comfort in semi-outdoor environments.* Fanger's PMV index is commonly used in field measurement and simulation studies for assessing thermal comfort in semi-outdoor environments [5,7,8,23,24,29,30]. Other studies use Gagge's SET* and PMV* indices [20,28,31–35], as well as the Physiological Equivalent Temperature (PET) [35–42], because these indices are based on the two-node model of the human thermal regulation system and thus better suited for semi-outdoor environments [37,43–45]. Additional indices have been proposed for assessing thermal comfort in semi-outdoor spaces: (1) the Universal Thermal Climate Index (UTCI) [46], and (2) the OUT_SET* [2,47].

Reference	Location (KG)	Building/Site	Semi-outdoor space type	Spatial attribute	Methodology	Performance metrics
[5–8]	Singapore	Bedok Court Condominium Block 295, Jurong West Block 510	forecourts/verandas, corridors	depth, vegetation	In-situ measurements & surveys	T_a, solar radiation, T_{globe}, V_a, RH, Fanger's PMV, TSV
[19]	Singapore	National University of Singapore (NUS) campus	corridors, halls, atria	depth, height, void, area, void-to-solid ratio, orientation	In-situ measurements & surveys	T_a, RH, V_a, TSV, HSV, WSV
[20,21,28]	Singapore	School of the Arts (SOTA), OASIA Hotel Downtown, Kampung Admiralty, Skyville@Dawson	perimeter buffer (corridor, balconies), sky terrace (sky garden), breezeway atria, horizontal breezeway, vertical breezeway	height-to-depth ratio, frontage, perimeter, void-to-solid ratio, green plot ratio, area, height from ground level, orientation, volume	In-situ measurements & surveys	T_a, T_{mrt}, V_a, RH, Gagge's PMV*, Gagge's SET*
[48,49]	Singapore	.	Hawker's centre	-	In-situ measurements & surveys	V_a, RH, T_a, TCV
[36]	Singapore	Asia Towers	covered/shaded plaza (AsiaSquare)	SVF, vegetation, orientation		T_a, T_{mrt}, PET
[29]	Hong Kong	-	sky garden	-	CFD	V_a, Fanger's PMV
[22–25]	Hong Kong	-	sky garden, sky court	depth, width, height, height from ground level (elevation), vegetation (i.e. hedge, tree)	CFD	V_a, T_a, Fanger's PMV
[27]	Penang, Malaysia	Suntech	sky court, balconies	height, vegetation, water presence	In-situ measurements & surveys	T_a, V_a, RH, TSV, HSV, WSV
[39]	Penang, Malaysia	Universiti Sains Malaysia campus	-	-	In-situ measurements & surveys	T_a, T_{mrt}, V_a, RH, TSV, PET

[30]	Shenzhen, China	Shenzhen Institute of Building Research (iBR)	terraces	-	In-situ measurements & surveys	T_a, RH, V_a, T_{mrt}, TSV, HSV, WSV, TCV, Fanger's PMV
[33]	Shenzhen, China	Apartment block	piloti	-	In-situ measurements & CFD	T_a, T_{mrt}, V_a, RH, Gagge's SET*, TSV
[31]	Guangzhou, China	South China University of Technology campus	pilotis	height	In-situ measurements & surveys	Gagge's SET*
[32]	Wuhan, China	-	piloti	-	In-situ measurements & surveys	T_a, T_{mrt}, V_a, RH, Gagge's SET*, TSV
[34]	Brisbane, Australia	36-storey residential building	balconies	depth	In-situ measurements & CFD	V_a, Gagge's SET*
[35]	Strasbourg, France	Gare de Strasbourg	hall	-	CFD	Gagge's SET*, PET
[38]	Kuala Lumpur & Shah Alam, Malaysia	Universiti Teknologi Malaysia campus buildings & UniversitiTeknologi Mara campus	-	SVF	In-situ measurements & surveys	TSV, WSV, HSV, PET
[40]	Parma, Italy	-	semi-outdoor space enclosed by a semi-transparent pitched roof	width, height, view factor	CFD	PET
[42]	Chiang Mai, Thailand	-	-	SVF	In-situ measurements, surveys & CFD	TSV, PET
[50]	Qeshm, Iran	-	terraces	depth	CFD	V_a
[51]	Brazil	-	veranda	depth, height, orientation	CFD	solar radiation
[52]	London, Manchester and Glasgow, UK	-	unheated sheltered transitional space	-	CFD	PET

Table 1. Literature review on semi-outdoor spaces' microclimate performance. *Note: see Nomenclature table for acronyms and abbreviations.*

1.1.2. Social performance of semi-outdoor spaces

The extent to which the SOS succeeds as a social space depends on the degree to which it creates a microclimate that is perceived by its users to be thermally comfortable (socio-environmental approach). To the best of the authors' knowledge only the following studies, also shown in Table 1, examine the latter. A measurement- and survey-based study in a Singaporean high-rise residential building demonstrates that semi-outdoor space types such as *forecourts/verandas* promote social cohesion among neighbours by creating thermally comfortable environments [5–8]. A post-occupancy measurement- and survey-based study comparing two high-rise residential developments in Singapore demonstrates that the presence of thermally comfortable semi-outdoor spaces (i.e., *sky terraces* and *vertical breezeways*) encourages more interaction among neighbours, as well as less energy use by cooling [21].

1.2. Research gap and questions

Despite a growing awareness of the role of building form in facilitating performance (environmental, social or both), the act of form-making is largely intuitive and lacks guidelines that designers can use to create a thermally comfortable semi-outdoor microclimate. Thermal comfort is defined in this study as the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation [53]. Few studies have been conducted explicitly on the relationship between form-related spatial attributes and thermal comfort/microclimate outcomes of semi-outdoor spaces [19,20,28], assuming that semi-outdoor spaces can be understood by their observed spatial attributes (e.g. *height, depth, GnPR, void, perimeter, ...*). However, more research is needed to uncover the hidden/unobserved nature of semi-outdoor spaces' spatial attributes that contributes to the promotion of thermally comfortable semi-outdoor microclimates. Statistical methods applied to social science research (e.g. psychology) can assist in inferring these underlying factors that are not directly observable. In statistics, an underlying factor, also known as a *hypothetical construct* (or *latent variable* or *factor*), is a variable that is unobserved – at least not directly – and can be measured by multiple observed/manifest variables, rather than by a single variable [54,55]. When these various observed/manifest features are bound together by some commonality, they form and give meaning to the *hypothetical construct*, which can then be used to explain a phenomenon [56,57]. Because this study takes an exploratory approach, *hypothetical constructs* will be referred to simply as "underlying factors" throughout the text.

Research seeking underlying factors in outdoor and semi-outdoor environments, to the best of the author's knowledge, has focused primarily on the following areas: (1) thermal comfort perceptions in outdoor environments (e.g. streets, parks) [58–60], and (2) environmental satisfaction and cognitive performance in tropical semi-outdoor spaces [61]. However, there is still a scientific gap in understanding the factors underlying form-related spatial features of semi-outdoor spaces and how they relate to microclimate, thermal comfort, and clustering in a high-density tropical setting. Based on this, the following research questions are posed:

- RQ1: To what extent are the spatial attributes that characterise semi-outdoor spaces manifestations of underlying factors, and what type of underlying factor*s* might these be?
- RQ2: To what extent are these underlying factors associated with semi-outdoor spaces' microclimate performance?
- RQ3: To what extent do these underlying factors provide evidence as to how semi-outdoor spaces can be grouped, and what relationship do these underlying factors have with how thermally comfortable these clusters are?

2. Methodology

The following sections explain how data was collected, processed, and analysed.

2.1. Data collection

Figure 1 shows four buildings in Singapore's tropical city-state (1.3º N, 103.8º E), designed by WOHA Architects [62], selected as case studies for answering posed research questions: School of the Arts (SO), OASIA Hotel Downtown (OA), Kampung Admiralty (KA), and Skyville@Dawson (SV), all of which are prototypes experimenting with the building form, creating semi-outdoor spaces intended to be communal spaces where people can enjoy wind airflows, shade, and nature [9,10]. SO is a 10-storey high school project made up of three long rectangular blocks separated by semi-outdoor spaces intended to channel wind and green facades intended to reduce noise. OA is a 27-storey hotel project wrapped in a double skin green facade that introduces elevated semi-outdoor spaces at various levels. KA is 10-storey mixed-use building project consisting of a semi-outdoor public plaza at ground level, covered by a rooftop community park overlooking apartments for the elderly. SV is a 47-storey high-rise public housing project made up of three north-south oriented towers connected horizontally by semi-outdoor 'sky villages' that favour horizontal and vertical air flows. SO and OA are located in mixed-use urban sites within Singapore's Central Business District (CBD) with a mix of commercial, residential, office, and hospitality uses; whereas KA and SV are in residential areas, in Woodlands and Queenstown, respectively [62].

Figure 1. From left to right: School of the Arts (SO), OASIA Hotel Downtown (OA), Kampung Admiralty (KA) and Skyville@Dawson (SV).

Within these four buildings, sixty-three (n=63) semi-outdoor spaces were identified. A previous study labelled them as follows based on spatial characteristics, environmental design intention, and social functions [28]: 13 as *perimeter buffers*, 20 *as sky terraces, 8 as breezeway atria, 8 as horizontal breezeways, and 16 as vertical breezeways (*see Figure 2 - Figure 7*).* In summary*, perimeter buffers* (e.g. balconies, corridors) are semi-outdoor spaces with limited depth adjacent to the outer envelope that provide shade to indoors; *sky terraces* (e.g. sky gardens, sky verandas) are semi-outdoor social spaces (e.g. lounge area in OA; study/playground areas in SV) that cut across the depth of buildings to provide cross-ventilation; *breezeway atria* are semi-outdoor communal spaces (e.g. shaded plaza in KA; pool deck, lounge and lawn in OA) with a large vertical volume that can rise to multiple levels, allowing for constant cross-ventilation; *horizontal breezeways* are deep semi-outdoor social spaces (e.g. canteen/playground/study areas in SO) within a 'no-dead-end' horizontal wind channelling pathway; and *vertical breezeways* are semi-outdoor social spaces (e.g. community planters and viewing decks in SV) located within a continuous internal void rising from the ground to the roof, with the goal of stimulating vertical air displacement via a heat stack effect.

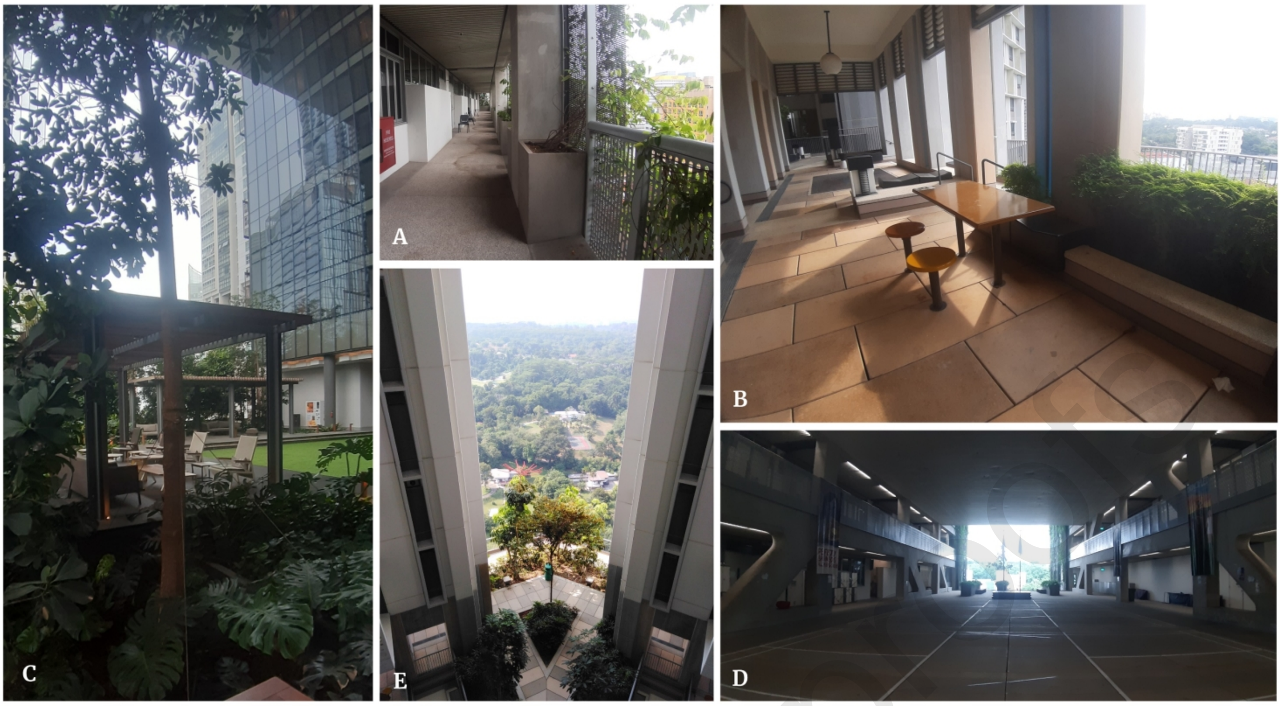

Figure 2. Semi-outdoor space labelling according to a previous study: A (*perimeter buffer*, e.g. SOS11 in SO); B (*sky terrace*, e.g. SOS49 in SV); C (*breezeway atrium*, e.g. SOS 13 in OA); D (*horizontal breezeway*, e.g. SOS3 in SO); and E (*vertical breezeway*, e.g. SOS51 in SV).

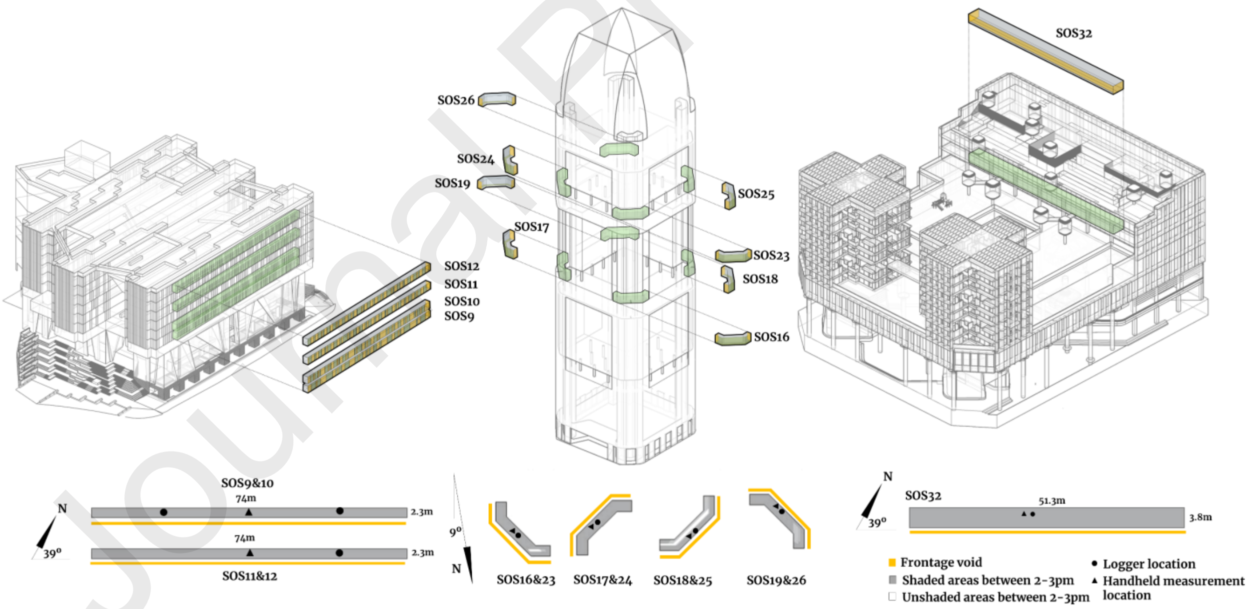

Figure 3. Above: semi-outdoor spaces (SOS) labelled previously as *perimeter buffers,* where yellow colour indicates voids. Below: dimensions, measurement locations and shading conditions between 2 and 3pm (Reference days: SO: June 10; OA: June 26; & KA: July 09).

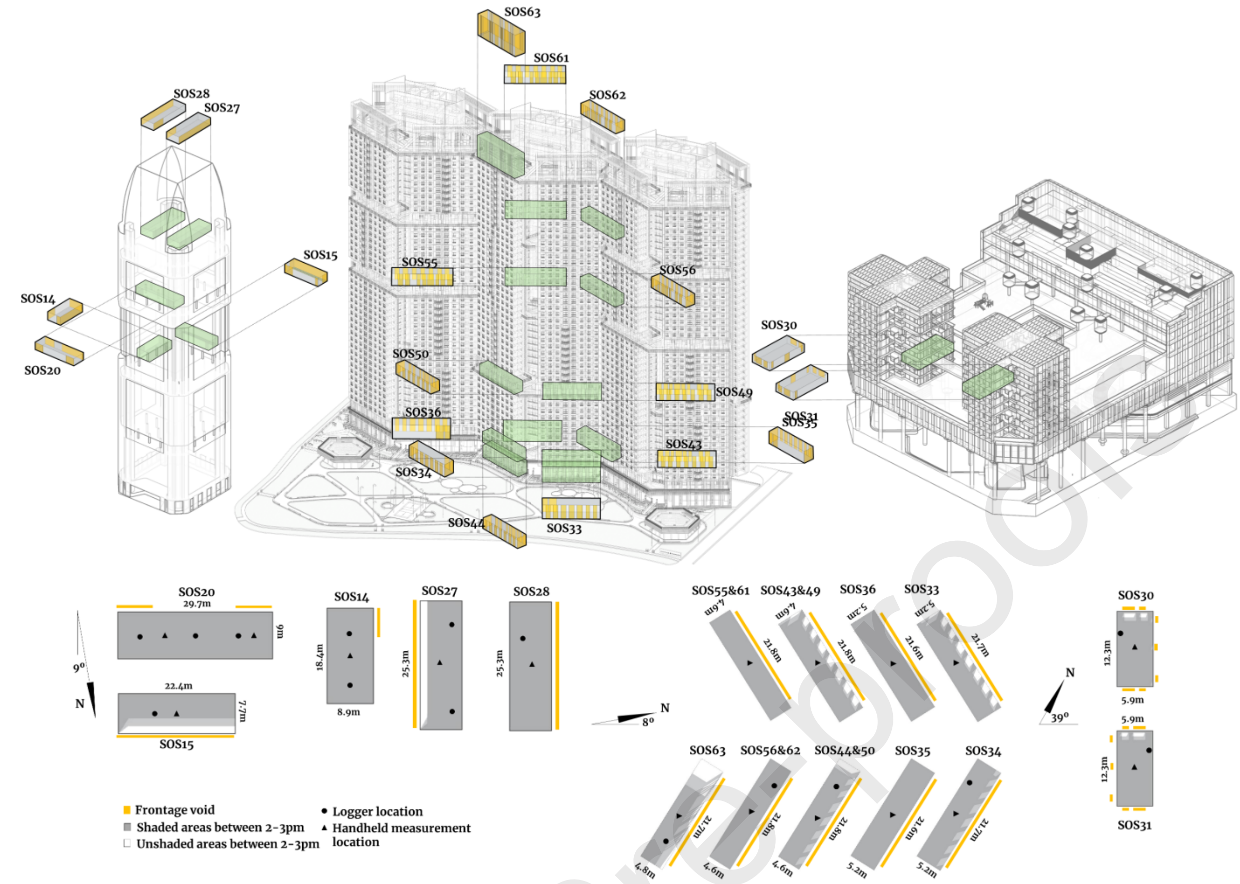

Figure 4. Above: semi-outdoor spaces (SOS) labelled previously as *sky terraces*, where yellow colour indicates voids. Below: dimensions, measurement locations and shading conditions between 2 and 3pm (Reference days: OA: June 26; SV: July 24; & KA: July 09).

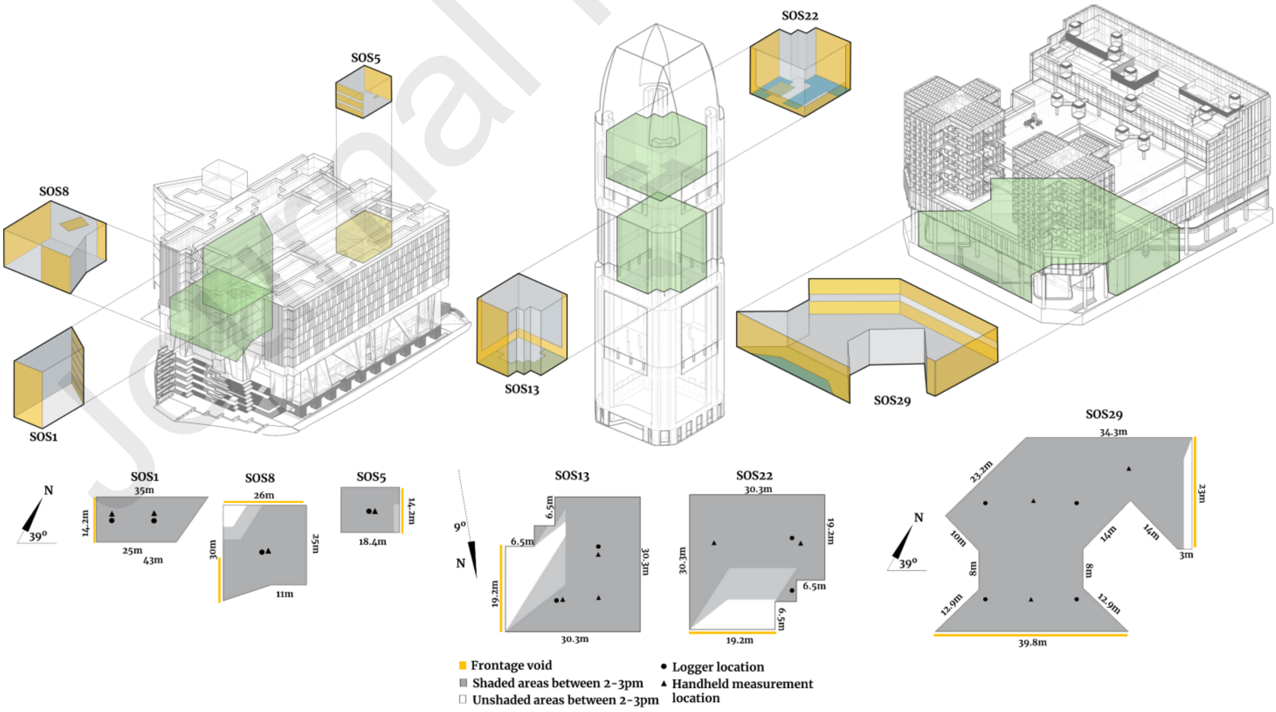

Figure 5. Above: semi-outdoor spaces (SOS) labelled previously as *breezeway atria,* where yellow colour indicates voids. Below: dimensions, measurement locations and shading conditions between 2 and 3pm (Reference days: SO: June 10; OA: June 26; & KA: July 09).

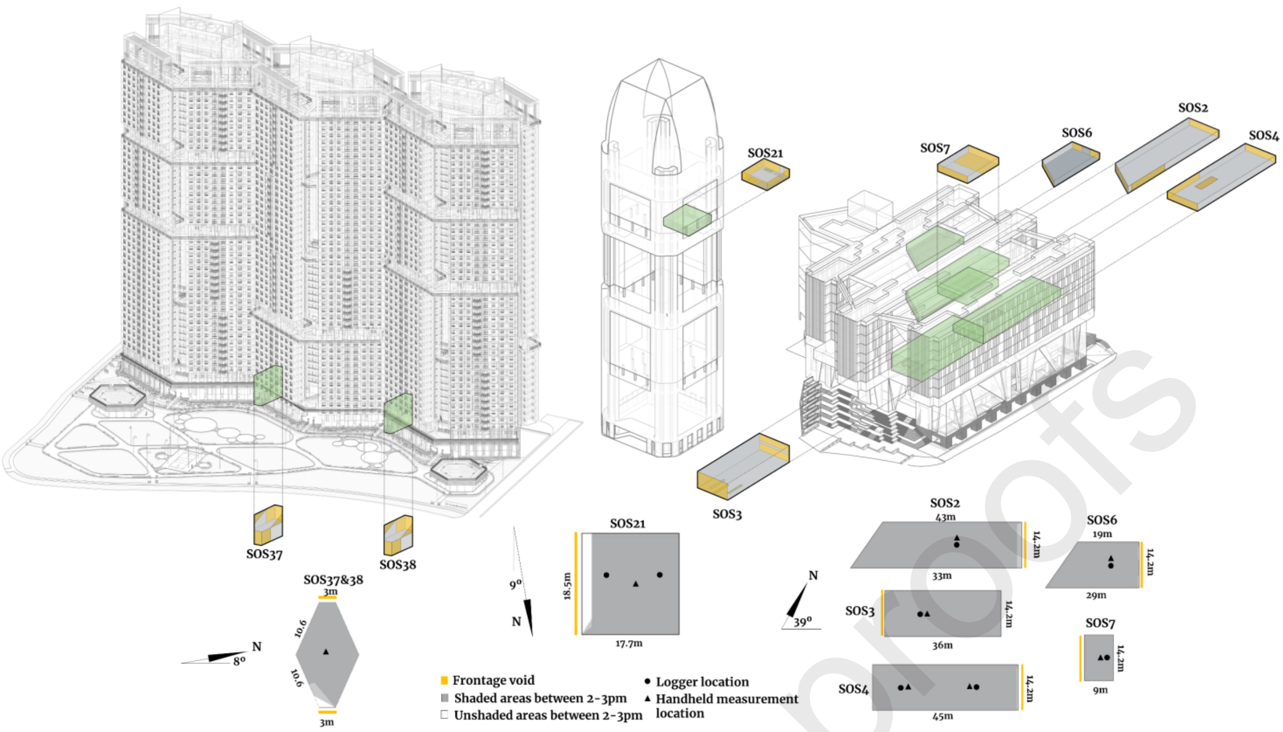

Figure 6. Above: semi-outdoor spaces (SOS) labelled previously as *horizontal breezeways*, where yellow colour indicates voids. Below: dimensions, measurement locations and shading conditions between 2 and 3pm (Reference days: SV: July 24; OA: June 26; & SO: June 10).

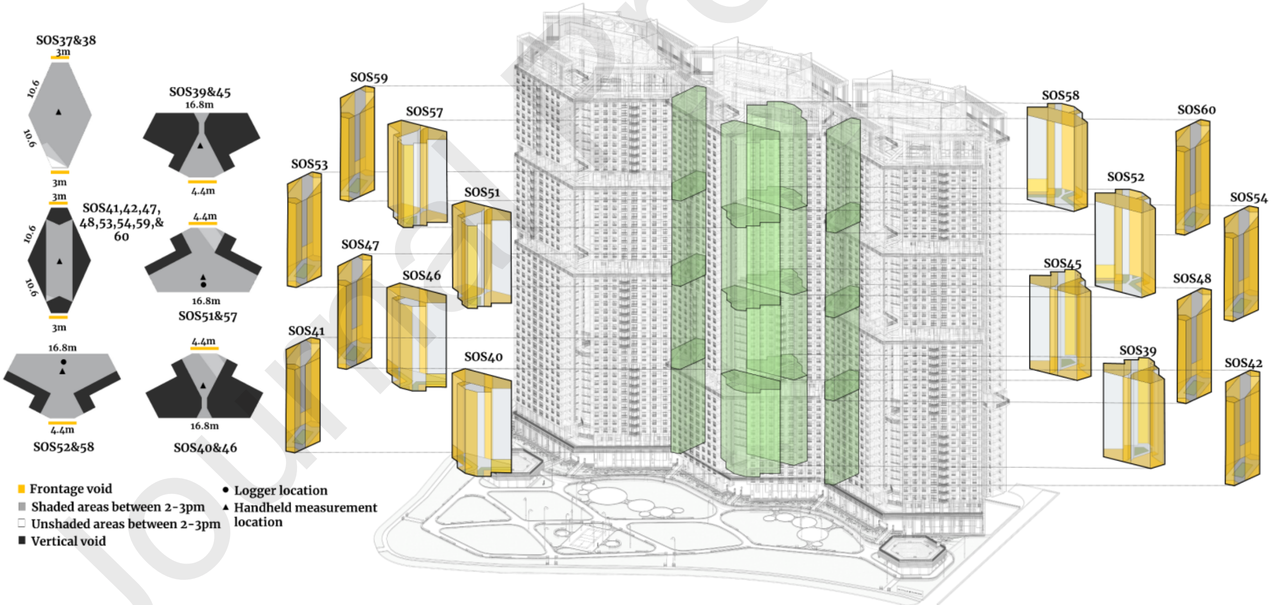

Figure 7. Right: semi-outdoor spaces (SOS) labelled previously as *vertical breezeways*, where yellow colour indicates voids. Left: dimensions, measurement locations and shading conditions between 2 and 3pm (Reference day: SV: July 24).

2.1.1. Measurements of microclimatic variables

As shown in Table 2, measurements of air temperature (T_a), relative humidity (RH), globe temperature (T_{globe}), and air velocity (V_a) were taken during the southwest monsoon season (June–September), with south-easterly and southerly prevailing winds and common short duration showers/thunderstorms in the afternoon [63]. Different periods were measured due to insufficient measurement equipment to study all 63 semi-outdoor spaces at the same time.

Building project	School of the Arts	OASIA Hotel Downtown	Kampung Admiralty	Skyville@Dawson
Period of measurement	June 10 - 17, 2019	June 26 - July 02, 2019	July 09 - 16, 2019	July 24 - 30, 2019
T_a & RH readings	Every 10 minutes (all days)	Every 10 minutes (all days)	Every 10 minutes (all days)	Every 10 minutes (all days)
V_a & T_{globe} readings	Every hour between 10 a.m. and 4 p.m. (in 1 day)	Every hour between 10 a.m. and 4 p.m. (in 1 day)	Every hour between 10 a.m. and 4 p.m. (in 1 day)	Every hour between 10 a.m. and 4 p.m. (in 2 days)

Table 2. Microclimatic variable measurement periods and methods for all four buildings.

As shown in Table 3, T_a and RH were collected using calibrated loggers, while T_{globe} and V_a were collected using handheld instruments due to property managers' restriction on placing larger equipment. Approximate measurement points of loggers and handheld instruments are shown in Figure 3 - Figure 7. For privacy and security, loggers were placed in locations hidden from the general public, approximately 1.5 meters from the floor, depending on the fixed furniture or walls available in the semi-outdoor space, sheltered from direct solar radiation. Also, outdoor air temperature (T_{out}) measurements were taken for each building, sheltered from direct solar incidence. The ISO 7726 forced convection equation was used to calculate T_{mrt} [64].

Instrument	Manufacturer	Microclimatic variable	Accuracy
U12 logger	HOBO	T_a & RH	T_a ± 0.35°C from 0° to 50°C RH ±2.50% from 10%RH to 90%RH
RHTemp	Madgetech	T_a & RH	T_a ± 0.50 °C from 0 °C to 55 °C RH ±3.00 % from 25% RH to 75% RH
VelociCalc	TSI	V_a	±3.00% of reading or ±0.015 m/s
Globe thermometer (Ø :150 mm, TC type K, emissivity: 0,95)	Testo	T_{globe}	EN 60584-1, Class 1 accuracy

Table 3. Specifications of instruments used for measuring microclimatic variables (T_a, T_{globe}, V_a and RH).

2.1.2. Measurements of spatial attributes

Thirteen spatial attributes were identified in the literature that could be manifestations of underlying factors in semi-outdoor spaces. As shown in Table 4, identified spatial attributes have been found to influence the microclimate performance of semi-outdoor spaces as well as the degree of thermal comfort that can be achieved in them. The values of each spatial attribute were calculated for each of the 63 semi-outdoor spaces using simplified Sketchup digital models [65] based on each building's floor and section plans, as well as on in-situ observations during the measurements campaign.

Variable	Unit	Definition
Height	m	Distance of the semi-outdoor space from base to top [19].
Depth	m	Distance of the semi-outdoor space perpendicular from the outermost building contour [19].
Void	m^2	Vertical openings the *volume* of the semi-outdoor space [19].
Solid	m^2	Opaque vertical surfaces (i.e. walls, columns, fenestration) the *volume* of the semi-outdoor space has [19].
Area	m^2	Total amount of surface area in the semi-outdoor space that is sheltered.
Volume	m^3	*Area* of the semi-outdoor space multiplied by its *height*.
Perimeter	m	Outermost boundary line that encloses the semi-outdoor space [19].
Open frontage	m	Adapted from a previous study [66], part of the perimeter in the semi-outdoor space exposed to outdoor conditions not including opaque elements in the façade.
Total frontage	m	Adapted from a previous study [66], part of the perimeter in the semi-outdoor space exposed to outdoor conditions including opaque elements (e.g. walls, columns, screens) in outermost building contour.
Sky view factor (SVF)	%	Ratio of visible sky at the centre point of the semi-outdoor space [67] . It was calculated using the Sketchup *Sky View Analysis* plugin [68].
Green plot ratio (GnPR)	%	Ratio between the total Leaf Area Index (LAI) to the total area of the space (m^2) [69], 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 [70].
Height from ground (HFG)	m	Distance of the semi-outdoor space from ground/street level.
Orientation	º	Cardinal point the semi-outdoor space is facing, in relation to the north up to south (0-180º).

Table 4. Spatial attributes that affect the microclimate performance of semi-outdoor spaces according to the literature review.

2.2. Data Processing

The typically warm hour of 2 p.m. (between 2-3 p.m.) was used as the reference time for assessing semi-outdoor spaces' microclimate performance (see Figure 8). At this moment of the day all semi-outdoor spaces in all four building are relatively shaded, and the influence of solar radiation may be ruled out (see Figure 3 – Figure 7). After 3 p.m., the solar angle decreases, and semi-outdoor spaces facing west receive more direct solar radiation than semi-outdoor spaces facing other directions. Before 2 p.m., T_{out} has not reached daily maximum values (between 2 p.m. and 5 p.m.), thus semi-outdoor spaces would not be tested in one of the warmest conditions of the day. This method of selecting a typical warm hour is also used in other studies [20,71,72]. Previous research has shown through statistical analysis that T_{out} at 2 p.m. is not significantly different between buildings despite measurements were performed at different periods [20] (see Table S1 in Appendix A: Supplementary data), validating the comparison between semi-outdoor spaces measured in different periods. Table S2 in Appendix A: Supplementary data shows the T_{out} values for each building for all days used for analysis. For each period rainy days were discarded in order to assess only days of high outdoor air temperature and high solar radiation.

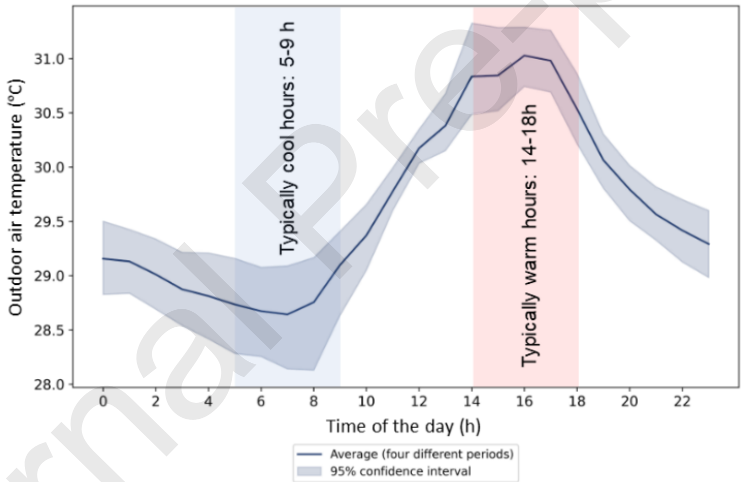

Figure 8. Average T_{out} for each hour of every day monitored during the four different periods outlined in Table 2.

2.2.1. Microclimatic variables in semi-outdoor environments

T_a and RH readings taken every 10 minutes were converted to hourly data. A 6-day average of T_a and RH at 2 p.m. was calculated for each semi-outdoor space in OA, KA, and SV, and a 7-day average for each in SO.

The T_{mrt} reading at 2 p.m. was selected for semi-outdoor spaces in SO, OA, and KA considering that handheld measurements were taken for only one day in these buildings; and a 2-day average of T_{mrt} at 2 p.m. for semi-outdoor spaces in SV was calculated considering that handheld measurements were taken for two days in this building. Similarly, a 'typical' V_a value was calculated by averaging the one-day (for semi-outdoor spaces in the SO, OA, and KA) and two-day (for semi-outdoor spaces in the SV) wind velocities readings between 10 a.m. and 4 p.m. Unlike T_a, T_{mrt}, and RH, V_a fluctuates constantly over time; thus, the methodological decision of representing V_a as an average of 10 a.m. - 4 p.m. readings was made to capture wind's intrinsic nature of high variability over time.

2.2.2. Predicted thermal comfort levels in semi-outdoor environments

Three thermal comfort indices were used to assess the degree of thermal comfort in semi-outdoor spaces. First, Gagge's SET* thermal comfort index, which is defined as the equivalent dry bulb temperature of an isothermal environment at 50% of RH in which a subject would have the same heat stress (skin temperature) and thermo-regulatory strain (skin wettedness) as in the actual environment while wearing clothing standardised for the activity concerned [43,44]. While the SET* thermal comfort index provides a tool to evaluate a semi-outdoor environment, it does not give the designer a comfort scale [73]. Therefore, and second, Gagge's PMV* thermal comfort index was used to provide designers with a comfort scale for Gagge's SET*, which calculates Fanger's PMV based on Gagge's two-node model of the human regulation system, with the exception that DRY is calculated using SET* rather than the operative temperature. Third, the Physiological Equivalent Temperature (PET) thermal index was used. It is also based on Gagge's two-node model from which SET* was derived [37], which is defined as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed [74]. Gagge's SET* and PMV* were calculated using *calcSET()* and *calcPMVStar()* functions within the *comf* 0.1.11 package in R [75]. The PET thermal comfort index was calculated using the *pet_steady()* function within the *pythermalcomfort* 2.5.1 package in Python [76]. Thermal comfort was estimated using microclimatic variables (i.e. T_a, T_{mrt}, V_a and RH at 2 p.m., previously explained in Subsection 2.2.1) as inputs in the functions. A clothing insulation value of 0.3 clo was considered for all calculations, as the typical clothing value in outdoor and semi-outdoor urban spaces of Singapore [48,77]. Three calculations were performed per thermal comfort index, differing only in metabolic activity rate (MET) values for slight activities (1 MET for people sitting; 1.5 MET for people standing; and 2 MET for people slow walking at 0.9m/s). The latter because metabolic activity values in semi-outdoor spaces may be higher than typical sedentary behaviour indoors [1].

2.3. Data Analysis

In this study, three inferential statistical methods were used to answer each of the three research questions posed in Sub section 1.2: (1) Exploratory Factor Analysis (EFA), (2) multivariate regression analysis, and (3) hierarchical clustering analysis. Figure 9 depicts the steps taken by each statistical method to answer each research question. In addition, the R code used to perform the statistical data analysis is provided in Appendix A: Supplementary data.

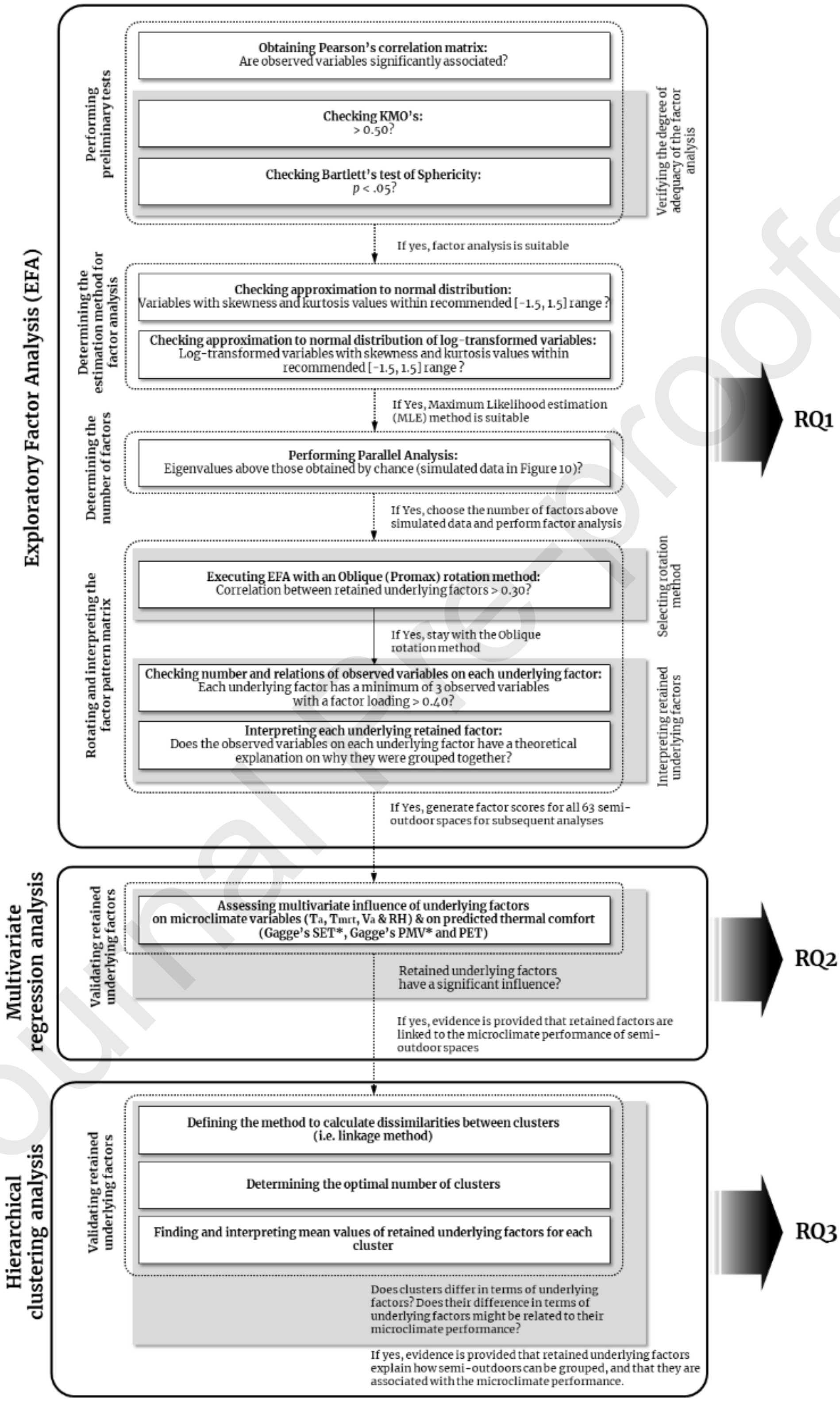

Figure 9. Methodology illustrating the different inferential statistical methods used in the current study to answer research questions.

2.3.1. Exploratory Factor Analysis

An Exploratory Factor analysis (EFA) was performed to determine: (i) the number and kind of underlying factors influencing a set of spatial attributes, (ii) the strength of the relationship between each underlying factor and their corresponding spatial attribute, and (iii) the factor scores to be used for subsequent analyses (i.e. multivariate regression analysis and hierarchical clustering analysis).

2.3.1.1. Performing preliminary tests

A correlation matrix with Pearson's correlation coefficients was used to analyse correlations between spatial attributes as a preliminary step for EFA.

The Kaiser-Meyer-Olkin's Measure of Sampling Adequacy (KMO) test and Bartlett's Test of Sphericity were then used to verify whether the variable dataset was suitable for factor analysis. On the one hand, the KMO's test determines whether the data is suitable for factor analysis by using an index that ranges from 0 to 1 and represents the proportion of variance that can be explained by the underlying factors. If the KMO value is greater than 0.50, it is assumed that the data is factorable [78]. On the other hand, the Bartlett's Test of Sphericity provides an alternative measure of whether a matrix is factorable by testing the null hypothesis that the correlation matrix is an identity matrix. If the null hypothesis is rejected ($p < 0.05$), it means that spatial attributes are related and that the set of variables is factorable [79]. KMO and Bartlett's test were calculated in R software using the *psych* package's *KMO()* and *cortest.bartlett()* functions [80], respectively.

2.3.1.2. Determining the estimation method for factor analysis

Variables in the dataset with kurtosis and skewness values outside the recommended range [-1.5, 1.5] were log-transformed to produce data that is relatively normally distributed and thus suitable using a Maximum Likelihood estimation (MLE) method for factor analysis [81,82]. The MLE method is an inferential method that provides the estimates of the parameters that most likely produce the aforementioned correlation matrix [82].

2.3.1.3. Determining the number of underlying factors

The Parallel Analysis was performed in order to determine the number of underlying factors to extract in the EFA, which selects the number of underlying factors with eigenvalues above those obtained by chance [83]. Values below the borderline are probably spurious [84]. Parallel Analysis was performed in R software using the *fa.parallel()* function within the *psych* package [80].

2.3.1.4. Rotating and interpreting the factor pattern matrix

Following the determination of the number of underlying factors, a rotated factor pattern matrix is recommended. When more than one underlying factor is retained a factor rotation method is suggested to facilitate the interpretation of the factor pattern matrix, this is, what factor appears to be measured by underlying factor 1, what factor appears to be measured by underlying factor 2, and so on [85]. Because almost all phenomena studied in many fields of science are somewhat interrelated, an oblique rotation was preferred rather than an orthogonal one [82]. In this study, the oblique *Promax* rotation was used.

The factor pattern matrix is made up of rows that represent the observed/manifest variables (i.e. spatial attributes) under consideration and columns that represent the retained underlying factors, with the entries in the matrix representing the factor loadings [86]. The factor loadings are used to determine the strength of the relationship between each underlying factor and its corresponding spatial attributes. The factor loading, which is 'large' if it exceeds the absolute value of 0.40, is used to investigate the strength of the relationship between underlying factors and spatial attributes. As a rule of thumb, a minimum number of three variables should be retained for each underlying factor. In this study, EFA was performed in R software using the *fa()* function within the *psych* package [80].

The Bartlett's estimation method was used as an argument in the *fa()* function to generate the factor scores for subsequent analyses. The factor scores are dimensionless estimates of each retained underlying factor for each of the 63 Semi-outdoor spaces.

2.3.2. Multivariate regression analysis

Once the factor scores were generated multivariate regression analysis was performed to validate the underlying factors generated by the EFA. The validation consisted in assessing the multivariate influence of the underlying factors on the microclimatic variables (i.e. T_a, T_{mrt}, Va, and RH) and the predicted thermal comfort of semi-outdoor spaces, based on the PMV* index. The *lm()* function in R software [87] was used to accomplish this, with underlying factors considered as independent variables and T_a, T_{mrt}, Va, and RH and PMV* (for all activity types: 1, 1.5, and 2 MET) as dependent variables. Both standardised and unstandardised coefficients are reported to assess the effect of each underlying factor on the degree of thermal comfort. Standardized coefficients were calculated in R software using *lm.beta()* package [88]. In order to assess collinearity in the multivariate regression models, the condition index (CI) was calculated in R software using the *collin.diag()* function within the *misty* package [89].

2.3.3. Hierarchical clustering analysis

Once the factor scores were generated hierarchical clustering was performed to see if the retained underlying factors can cluster semi-outdoor spaces by type and if such clustering provides evidence on how environmentally performative Semi-outdoor spaces are based on clusters. Clustering is an unsupervised statistical technique that groups items based on distance-based similarities by using unlabelled input data. Three main steps were followed: (i) defining the method to calculate dissimilarities between clusters (i.e linkage method); (ii) determining the optimal number of clusters; and (iii) and finding and interpreting mean values for each cluster. Commonly, scaling of data is necessary before performing hierarchical clustering analysis, however, factor scores generated by Bartlett's method are already standardised and share the same scale (i.e. mean value of 0 and standard deviation of 1).

2.3.3.1. Defining the linkage method

In order to perform hierarchical clustering and produce a dendrogram the *agnes()* function within the *cluster* package in R software was used [90]. Ward's minimum variance method was chosen as an argument over other linkage methods (i.e. average linkage, single linkage, complete linkage) when performing the hierarchical clustering analysis because it produces the highest agglomerative coefficients (closer to 1).

2.3.3.2. Determining the number of clusters and generating mean values of underlying factors per cluster

One limitation of the hierarchical clustering method is that it does not tell the number of existing clusters within the hierarchical tree. The optimal number of clusters was calculated in R software using the *NbClust* package and the *NbClust()* function, which provides 30 indices for determining the number of clusters and proposes the best clustering scheme from the different results obtained by varying all combinations of number of clusters, distance measures, and clustering methods [91]. The number of clusters was calculated based on the 'majority rule', a reliable method for selecting the best number of clusters [91]. Once the optimal number of clusters is established, the hierarchical tree generated by the *agnes()* function is cut at a given height using in R software the *dendextend* package's *cutree()* function [92], to identify in which cluster each SOS was assigned. Once assigned, mean values of retained underlying factors, spatial attributes, microclimatic variables and predicted thermal comfort per cluster are created using the *aggregate()* function in R software.

3. Results

Results are organised around the three research questions posed in Sub section 1.2.

3.1. RQ1: To what extent are the spatial attributes that characterise semi-outdoor spaces manifestations of underlying factors, and what type of underlying factors might these be?

Results of the exploratory factor analysis (EFA) show that the spatial attributes of semi-outdoor spaces manifest underlying factors.

Preliminary tests of the Exploratory Factor Analysis (EFA) show that conducting factor analysis; that is, uncovering underlying factors, is plausible. Pearson's correlation matrix, the KMO and the Bartlett's test of Sphericity all reveal relationships between observed/manifest variables (i.e. spatial attributes). Pearson's correlation coefficients of spatial attributes are shown in Table 5 and Fig. A 1, however, are explained later in the text as part of EFA's factor pattern matrix. The KMO value is 0.64, above the threshold of acceptability. The Bartlett's test of Sphericity rejects the null hypothesis that the correlation matrix is an identity matrix ($p < .001$, df = 64, approx. Chi-squared = 1003.01).

Variable	Mean	Std.	Kurt.	Skew.	Void	Height	Solid	Volume	Total frontage	Open frontage	Perimeter	SVF	GnPR	Depth	Area	HFG	Orientation
Void (m^2)	394.6	402.2	1.4	1.4	1												
Height (m)	12.6	12.1	-1.3	0.8	0.87*	1											
Solid (m^2)	426.7	519.0	-1.0	0.3	0.74*	0.73*	1										
Volume (m^3)	3090.9	4913.2	-0.9	0.0	0.84*	0.61*	0.87*	1									
Total frontage (m)	21.6	18.8	-1.0	0.1	-0.11	-0.42*	-0.1	0.05	1								
Open frontage (m)	14.6	13.5	0.0	-0.8	0.14	-0.22	0.15	0.35*	0.83*	1							
Perimeter (m)	203.2	36.6	-0.1	0.8	0.22	-0.08	0.3*	0.4*	0.73*	0.83*	1						
SVF (%)	17.9	11.8	-0.2	0.6	-0.1	-0.1	-0.08	-0.07	0.25	-0.12	-0.21	1					
GnPR (%)	1.0	1.2	0.1	1.2	0.23	0.17	0.06	0.18	-0.12	-0.3*	-0.24	0.62*	1				
Depth (m)	12.6	11.2	1.3	1.4	0.5*	0.35*	0.49*	0.57*	-0.16	0.2	0.45*	-0.54*	-0.16	1			
Area (m^2)	216.3	234.2	0.3	0.0	0.46*	0.13	0.52*	0.71*	0.27*	0.62*	0.73*	-0.36*	-0.15	0.80*	1		
HFG (m)	57.5	45.3	-1.0	0.4	-0.03	-0.05	-0.09	-0.02	-0.08	-0.18	-0.23	0.45*	0.40*	-0.24	-0.15	1	
Orientation (º)	90.9	56.4	-1.3	-0.1	-0.03	-0.01	0.03	-0.02	0.09	0.07	0.09	-0.05	-0.01	-0.11	-0.05	0.02	1

Table 5. Descriptive statistics (mean, standard deviation, kurtosis, skewness and coefficient of variation) and Pearson's correlation matrix of spatial attributes. *Note: * indicates p-values< 0.05*

Spatial attributes of *perimeter, total frontage, open frontage, volume, area* and *solid*, had kurtosis and skewness values outside of the recommended range [-1.5, 1.5] for EFA, and were log normalised, in order to use the MLE method. Figure 10 shows the results of the Parallel Analysis which indicated that the number of underlying factors to be retained for the EFA should be three (n = 3), the latter because only three underlying factors yielded eigenvalues greater than those obtained by chance (i.e. simulated data).

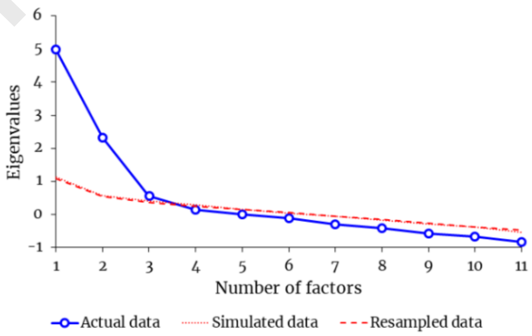

Figure 10. Parallel Analysis results showing eigenvalues per number of underlying factors.

EFA results yielded a factor pattern matrix, shown in Table 6, with observed/manifest variables (i.e. spatial attributes) that are manifestations of the three underlying factors retained by the EFA. On the one hand, according to the factor pattern matrix these three underlying factors explained 82% of the overall variance in retained observed/manifest variables used for characterising/describing semi-outdoor spaces. On the other hand, the factor pattern matrix showed the factor loadings of each of the three underlying factors retained in the EFA. Except for *HFG* and *orientation*, which were excluded from the analysis, results showed large factor loadings (> |0.40|). Underlying factor 1 had large factor loadings on *void, height, solid* and *volume*; underlying factor 2 on *open frontage, total frontage,* and *perimeter;* and underlying factor 3 on *SVF, GnPR, area,* and *depth.* The retained underlying factors were named based on an interpretation of their observed/manifest variables identified by the EFA. Underlying factor 1 was named *volume porosity* (VP) because it appears to explain the porosity of the semi-outdoor volume. Underlying factor 2 was named *perimeter openness* (PO) because it appears to explain the openness of the semi-outdoor perimeter. Underlying factor 3 was named *exposure to sky* (ES), because it appears to explain how exposed to the sky, unsheltered and shallow the semi-outdoor space is.

Observed/manifest variable	Volume porosity (VP)	Perimeter openness (PO)	Exposure to sky (ES)
Void	1.04	-	-
Height	1.04	-	-
Solid	0.89	-	-
Volume	0.85	-	-
Total frontage	-	1.02	0.43
Open frontage	-	0.76	-
Perimeter	-	0.73	-
Sky view factor	-	-	0.89
Green plot ratio	-	-	0.66
Depth	-	-	-0.64
Area	-	-	-0.58
Variance explained (%)	0.37	0.22	0.23
Cumulative variance (%)	0.37	0.60	0.82

Table 6. Factor pattern matrix showing: (i) factor loadings for each retained underlying factor [>|0.4|]; (ii) and the variance explained by each underlying factor.

A summary of all EFA results is depicted in Figure 11. First, results show a positive correlation between VP and all its observed/manifest variables; in other words, that a larger VP is associated with larger *void, height, solid* and *volume.* Results also show a positive correlation between observed/manifest variables, for instance, as the *height* of a semi-outdoor space increases the *void, solid* and *volume* also increases. Second, results show a positive correlation between PO and all its observed/manifest variables, this is, that a larger PO is associated with larger *total frontage, open frontage* and *perimeter*. Results also show a positive correlation between observed/manifest variables, for instance, as the *perimeter* of a semi-outdoor space increases the *total frontage* and *open frontage* also increases. And third, results show a positive correlation between ES and the observed/manifest variables of *SVF* and *GnPR,* this is, that a greater ES is associated with greater *SVF* and *GnPR*; and a negative correlation between ES and the observed/manifest variables of *area* and *depth*, in other words, that a lower ES is associated with larger *area* and *depth.* Results also show that as the *area* and *depth* of a semi-outdoor space increase, the *SVF* and *GnPR* decrease. In overall, results show a 'moderate' negative correlation between ES and VP (r = -0.48), a moderate negative correlation between ES and PO (r = -0.44), and a low positive correlation between VP and PO (r = 0.12).

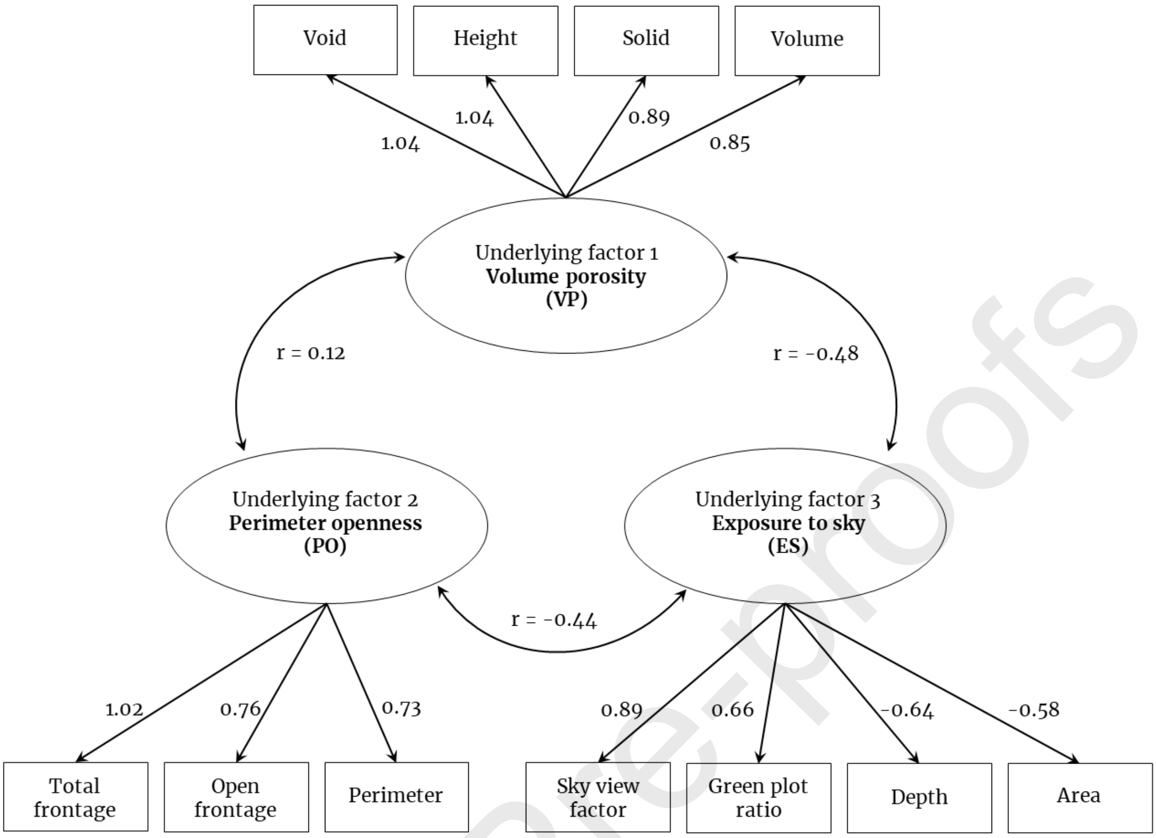

Figure 11. Graphical summary of results obtained from the Exploratory Factor Analysis (EFA). Note: straight lines are factor loadings shown in Table 6, curved lines are correlations (r), rectangles are observed/manifest variables (i.e. spatial attributes) and ovals are the retained underlying factors.

3.2. RQ2: To what extent are these underlying factors associated with semi-outdoor spaces' microclimate performance?

Table S2-S4 and Figure S2-S3 in Appendix A: Supplementary data summarize descriptive statistics of microclimate and thermal comfort performance in semi-outdoor spaces at 2 p.m. T_a at 2 p.m. in semi-outdoor spaces was significantly lower than T_{out}. T_a values in semi-outdoor spaces ranged between 28.5ºC and 32.0ºC, RH values between 57.8% and 79.2%, and V_a values between 0.2 and 2.1 m/s. T_{mrt} and T_a had a mean temperature difference of 2.7ºC. T_a and T_{mrt} were negatively and significantly correlated with RH. Predicted thermal comfort ranged between "slightly cool" (-1) and "slightly warm" (+1) thresholds for SET* and PMV*, and between "slight stress" and "moderate stress" thresholds for PET, as also shown in Fig. A 2 and Fig. A 3.

Results of the multivariate regressions analysis indicate a statistically significant association between the underlying factors retained by the EFA and the microclimate performance measured via microclimatic variables (i.e. T_a, T_{mrt}, V_a and RH) and predicted thermal comfort indices (i.e. Gagge's SET*, Gagge's PMV* and PET). Table 7, Table 8 and Table 9 summarise such results. Table S5 – Table S17 in Appendix A: Supplementary data contain the full results of all multivariate regressions. Results indicate no evidence of multicollinearity issues on any multivariate regression model.

	T_a	T_{mrt}	V_a	RH
	R^2 = 0.096	R^2 = 0.231 *	R^2 = 0.351 *	R^2 = 0.273 *
VP	0.225 (0.135)	0.513 (0.910) *	0.422 (0.222) *	-0.543 (-3.000) *
PO	0.207 (0.125)	-0.135 (-0.240)	-0.412 (-0.217) *	0.120 (0.663)
ES	0.022 (0.013)	0.177 (0.313)	-0.193 (-0.101)	-0.349 (-1.924) *

Table 7. Standardised (outside parenthesis) and unstandardized coefficients (inside parenthesis) of multivariate regression analysis having microclimatic variables (T_a, T_{mrt}, V_a and RH) as independent variables. Note: * p-value < .05

	SET* (1 MET)	SET* (1.5 MET)	SET* (2 MET)	PMV* (1 MET)	PMV* (1.5 MET)	PMV* (2 MET)
	R^2 = 0.197 *	R^2 = 0.300 *	R^2 = 0.352 *	R^2 = 0.296 *	R^2 = 0.350 *	R^2 = 0.376 *
VP	-0.237 (-0.262)	-0.365 (-0.488) *	-0.379 (-0.538) *	-0.399 (-0.166) *	-0.452 (-0.172) *	-0.439 (-0.166) *
PO	0.411 (0.454) *	0.449 (0.600) *	0.490 (0.696) *	0.420 (0.175) *	0.438 (0.170) *	0.473 (0.178) *
ES	0.089 (0.098)	0.094 (0.125)	0.156 (0.221)	0.006 (0.002)	0.030 (0.011)	0.096 (0.036)

Table 8. Standardised (outside parenthesis) and unstandardized coefficients (inside parenthesis) of multivariate regression having Gagge's SET* and PMV* thermal comfort indices as independent variables. *Note: * p-value < .05*

	PET (1 MET)	PET (1.5 MET)	PET (2 MET)
	R^2 = 0.298 *	R^2 = 0.302 *	R^2 = 0.303 *
VP	-0.321 (-0.269) *	-0.346 (-0.331) *	-0.363 (-0.393) *
PO	0.481 (0.403) *	0.471 (0.451) *	0.461 (0.497) *
ES	-0.005 (-0.004)	0.001 (0.011)	0.024 (0.026)

Table 9. Standardised (outside parenthesis) and unstandardized coefficients (inside parenthesis) of multivariate regression analysis having PET thermal comfort index as independent variable. *Note: * p-value < .05*

On the one hand, multivariate regressions show that (1) the higher the VP the higher the T_{mrt} and V_a and the lower RH; (2) the lower the PO the higher V_a; (3) the lower the ES the higher the RH; and (4) the higher the VP and the lower the PO, the lower the SET*, PMV* and PET values.

On the other hand, standardised coefficients in multivariate regressions demonstrate: (1) that VP has the strongest effect on T_{mrt} and RH; (2) that VP and PO have a similar effect on V_a; (3) that PO has the strongest effect on SET*, PMV* and PET values; and (4) that no cause-effect relation exists between ES and thermal comfort indices.

3.3. RQ3: To what extent do these underlying factors provide evidence as to how semi-outdoor spaces can be grouped, and what relationship do these underlying factors have with how thermally comfortable these clusters are?

Results of the hierarchical clustering analysis, illustrated in Figure 12, show that the optimal number of clustering semi-outdoor spaces is three (n=3). The clusters were interpreted and named based on a previously proposed five-type classification [28]. Cluster 1 was named *horizontal breezeway* (HB) because it includes no-dead-end' semi-outdoor spaces that intends to channel winds deep inside buildings. Cluster 2 was named *perimeter buffer* (PB) because it includes semi-outdoor spaces such as *balconies* or *corridors* on the building perimeter, next to the outer building envelope and with limited depth. Cluster 3 was named *vertical breezeway* (VB) because it includes semi-outdoor spaces located within continuous internal voids that rise from ground to the roof intending to stimulate vertical air displacement through a heat stack effect. Figure 13 and Figure S1 in Appendix A: Supplementary data depict how the three resulting clusters gravitate toward a retained underlying factor. *Horizontal breezeways*, for example, gravitate toward positive PO values and negative ES values; *perimeter buffers* gravitate toward positive ES and negative VP values; and *vertical breezeways* gravitate toward positive VP values and negative PO values. Table 10 shows the mean values for each cluster regarding retained underlying factors (i.e VP, PO and ES), spatial attributes, microclimatic variables (i.e. T_a, T_{mrt}, V_a and RH) and predicted thermal comfort (i.e. Gagge's SET*, Gagge's PMV* and PET). Fig. A 4 and Fig. A 5 depict conceptual representations of all three clusters generated by the hierarchical clustering analysis in relation to the underlying factors and their corresponding observed variables (i.e. spatial attributes). Regarding retained underlying factors, *horizontal breezeways* stand out as having the lowest ES and the highest PO mean value; *perimeter buffers* stand out as having the highest ES mean value and the lowest VP mean value; and *vertical breezeways* stand out as having the highest VP mean value and the lowest PO mean value. Regarding spatial attributes, *horizontal breezeways* stand out as having the highest *volume, open frontage, perimeter, depth* and *area* mean values and the lowest *SVF* and *GnPR* mean values; *perimeter buffers* stand out as having the highest *total frontage* and *SVF* mean values and the lowest *void, height, solid, volume, depth* and *area* mean values; and *vertical breezeways* stand out as having the highest *void, height, solid* and *GnPR* mean values and the lowest *total frontage, open frontage* and *perimeter* mean values. Regarding the microclimate and predicted thermal comfort, *horizontal breezeways* stand out as having the highest RH, Gagge's SET*, Gagge's PMV* and PET mean values and the lowest T_{mrt} value; and *perimeter buffers* stand out as having the lowest V_a mean value; and *vertical breezeways* stand out as having the highest T_a, T_{mrt} and V_a mean values and the lowest RH and Gagge's SET*, Gagge's PMV* and PET mean values. Fig. A 2 and Fig. A 3 show that *vertical breezeways* experience higher levels of thermal comfort than *horizontal breezeways* and *perimeter buffers* in terms of Gagge's PMV* and PET thermal indices.

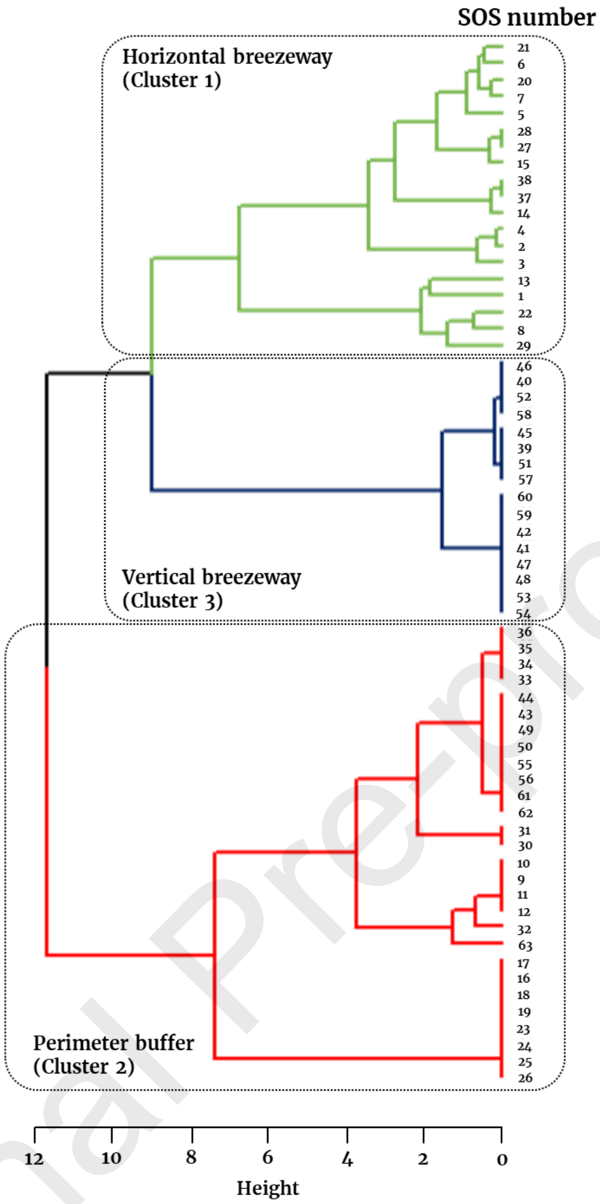

Figure 12. Dendrogram showing identified clusters: *horizontal breezeway* (cluster 1), *perimeter buffer* (cluster 2) and *vertical breezeway* (cluster 3).

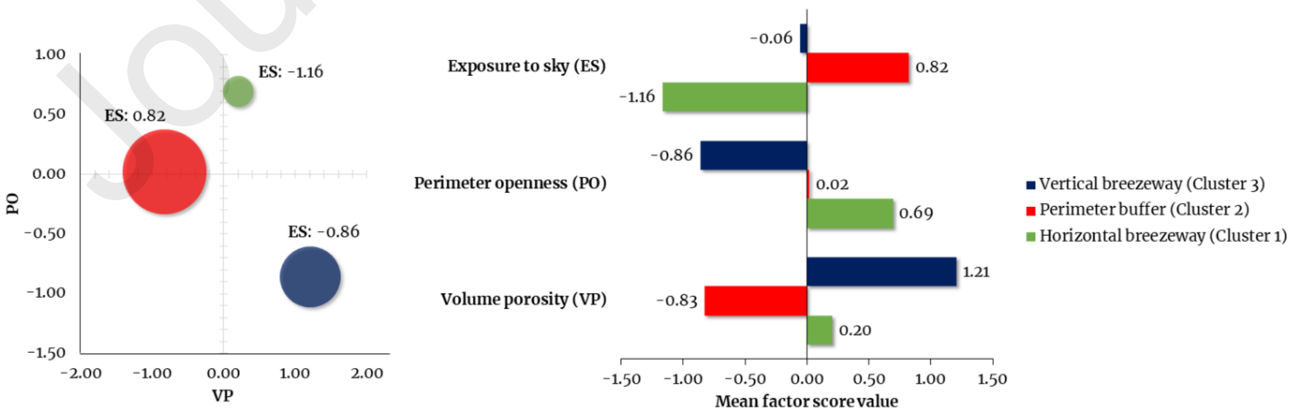

Figure 13. Bubble chart (left) and bar graph (right) showing mean factor scores of each cluster in terms of underlying factors retained by the Exploratory Factor Analysis (EFA).

Variables	Horizontal breezeway (Cluster 1)	Perimeter buffer (Cluster 2)	Vertical breezeway (Cluster 3)
# semi-outdoor spaces	19	28	16
Volume porosity, VP	0.20	-0.83	1.21
Perimeter openness, PO	0.69	0.02	-0.86
Exposure to sky, ES	-1.16	0.82	-0.06
Void (m^2)	408.14	135.41	832.20
Height(m)	9.49	4.23	30.80
Solid (m^2)	592.30	111.53	781.77
Volume (m^3)	5478.08	398.87	4967.19
Total frontage (m)	21.20	31.19	5.20
Open frontage (m)	20.99	15.56	5.20
Perimeter (m)	89.24	62.45	54.43
Sky view factor (%)	11.02	23.91	15.62
Green plot ratio (%)	0.42	1.16	1.23
Depth (m)	23.02	3.79	15.55
Area (m^2)	443.96	93.23	161.27
T_a (ºC)	29.73	29.68	29.76
T_{mrt} (ºC)	31.63	32.00	34.02
V_a (m/s)	0.73	0.66	1.41
RH (%)	74.31	70.03	65.24
SET* 1 MET (ºC)	26.93	26.54	25.64
SET* 1.5 MET (ºC)	28.69	28.35	26.77
SET* 2 MET (ºC)	30.14	29.94	28.00
PMV* 1 MET	+ 0.88	+0.70	+0.23
PMV* 1.5 MET	+1.15	+1.03	+0.53
PMV* 2 MET	+1.45	+1.37	+0.83
PET* 1 MET (ºC)	30.35	29.88	29.04
PET* 1.5 MET (ºC)	31.20	30.73	29.71
PET* 2 MET (ºC)	32.05	31.57	30.37

Table 10 Mean values of microclimatic variables, predicted thermal comfort, spatial attributes and underlying factors for each cluster.

4. Discussion

The current study demonstrate that semi-outdoor spaces can be characterised by underlying factors (i.e. VP, PO, and ES), and that each underlying factor in conceptually unique, and therefore not interchangeable, as they each relate to different spatial attributes of the semi-outdoor space (see Table 6 and Figure 11). In other words, a highly *porous* semi-outdoor space is not the same as a highly o*pen* or a highly *exposed* semi-outdoor space according to findings (see Figure 13). Nonetheless, based on the oblique rotation, all three underlying factors are assumed to be related. Results indicate that the greater the VP the greater the PO*;* however, the greater the VP and the PO the lower the ES. Such correlations between underlying factors demonstrate that as semi-outdoor spaces become more *porous* (i.e. greater *volume, height, solid* and *void*), they also become more *open* (i.e. greater *perimeter, open frontage,* and *total frontage*); however, semi-outdoor spaces become less *exposed to sky*, because as *depth* and surface *area* increase, and in consequence, *SVF* decreases.

It should be also noted that this is the first study of its kind to use EFA to show how spatial attributes in semi-outdoor environments relate to underlying factors (i.e. *volume porosity, perimeter openness*, and *exposure to sky)*; however, to some extent, such names have already been used in the literature. The most visible examples are Singapore and Hong Kong incentive schemes that promote greenery and communal spaces in tall buildings and exempt semi-outdoor spaces like *balconies* and *sky gardens* from gross floor area calculations by specifying a minimum *perimeter openness* [93–97]. Some studies have linked the concept of *openness* to microclimate performance [19,98]. Other studies, in both outdoor and semi-outdoor environments, have used the term *building/facade porosity* or *urban porosity* as a concept linked to wind flow promotion and UHI mitigation [13,99–101]. Multiple studies have linked the *exposure to sky* of semi-outdoor environments to only the *SVF* [36,38,40,42], but this study shows that particularly in semi-outdoor environments the underlying factor of *exposure to sky* can be explained by multiple observed/manifest variables (i.e. *SVF*, *GnPR, area* and *depth).*

4.1. Association between underlying factors and microclimate performance and clustering

The current study demonstrate that retained underlying factors (i.e. VP, PO, and ES) are related to the microclimate performance (i.e. T_a, T_{mrt}, V_a, RH, Gagge's SET*, Gagge's PMV* and PET) and clustering of semi-outdoor spaces (i.e. *vertical breezeway, horizontal breezeway, perimeter buffer*)

4.1.1. Microclimate performance

Pearson's correlation coefficients in Sub section 3.1 and standardised coefficients of VP in multivariate regressions in Sub section 3.2 demonstrate the impact of VP, PO and ES on semi-outdoor spaces' microclimate performance. As follows, performance is discussed in terms of the retained underlying factors and their practical implications for architects designing buildings in highly dense tropical environments such as Singapore:

- First, positive correlations shown in the factor pattern matrix between VP and their manifest spatial attributes demonstrate that as semi-outdoor spaces grow taller, more voluminous, and with more voided and solid vertical surfaces, they become *more porous*. Taller and more voluminous semi-outdoor spaces with more voided/solid vertical surfaces is linked with higher values of T_{mrt} and V_a, and lower values of RH, Gagge's SET*, Gagge's PMV* and PET.
- Second, positive correlations between PO and the spatial attributes in the factor pattern matrix demonstrate that as semi-outdoor spaces have more *perimeter* and *frontage* (whether total or partial), they are *more open*. Semi-outdoor spaces with lower *frontage* (whether total or partial) and *perimeter* is linked with higher values of V_a and lower values of Gagge's SET*, Gagge's PMV* and PET.
- Third, correlations between ES and some spatial attributes demonstrate that as semi-outdoor spaces have more *SVF* and *GnPR*, they are *more exposed to the sky* (positive correlation), and that as they have more *area* and *depth* they are *less exposed to the sky* (negative correlation). Shallower semi-outdoor spaces with higher *SVF* and less *area* experienced lower humidity values. Pearson's correlation coefficients shown in Fig. A 1 as well as Figure S2 in Appendix A: Supplementary data, link the latter with higher T_a and higher T_{mrt} values. Previous research has found a negative correlation between *SVF* and *GnPR* [71,72,77], but the positive correlation found in this study is due to the fact that as the *exposure to sky* increases, so does the amount of greenery that the semi-outdoor space can accommodate.

- Finally, while *HFG* and *orientation* were not identified by EFA as manifestations of underlying factors of semi-outdoor spaces, previous research has shown that *HFG* has a significant influence on T_a and T_{mrt} of semi-outdoor spaces [20], and *orientation* on V_a [19].

The performance of underlying factors is particularly related to V_a, and less to T_{mrt}, which in turn, is associated with the time of study (i.e. 2 p.m.), when most semi-outdoor spaces are shaded (see Figure 3 - Figure 7). These associations explain why ES is the least important from all three underlying factors in creating microclimate and thermal comfort performance. Multivariate regressions and Pearson's correlation matrix in Fig. A 1 show that the microclimatic variable with the greatest association with Gagge's SET*, Gagge's PMV* and PET is V_a. Considering the latter, both VP and PO have a similarly significant influence on the predicted thermal comfort, because both VP and PO have a similarly significant influence on V_a. Instead, ES has no effect on Gagge's SET*, Gagge's PMV*, or PET, because it has no effect on V_a despite having a significant effect on RH. The importance that V_a has on providing thermally comfortable environments explains why semi-outdoor spaces with higher VP have more thermally comfortable environments despite its positive association with T_{mrt}. Pearson's correlation matrix in Fig. A 1 also shows that T_{mrt} and V_a are positively correlated, this is, that semi-outdoor spaces with higher V_a values experience also higher T_{mrt} value, and viceversa. The latter explains, on the one hand, why semi-outdoor spaces are able to achieve thermally comfortable environments despite having high T_{mrt} values, and on the other hand, why T_{mrt} is negatively correlated with Gagge's SET*, Gagge's PMV* and PET. In outdoor environments solar radiation has a higher effect on changing subject's thermal sensation than air movement [102]. Nonetheless, in semi-outdoor spaces T_{mrt} may have a lower importance than it has in outdoor environments, and instead, V_a may have a higher importance. According to the literature, this is because semi-outdoor spaces receive low levels of solar radiation when shaded [47–49], and wind can always provide a cooler feeling for people even when the intensity of solar radiation is high [7].

4.1.2. Clustering

The hierarchical clustering analysis demonstrate that only three clusters (i.e. *vertical breezeways, horizontal breezeways, perimeter buffers*) exist when considering only the spatial characteristics of semi-outdoor spaces manifested by the factor scores of VP, PO and ES. Figure 12 depicts the three main branches of the dendrogram, which correspond to the three yielded clusters, with sub branches only indicating small and natural variations within each main branch that are not attributed to another cluster. However, if the scope of the study were expanded and social aspects (e.g., function of the space, number of people visiting the space) were included, it is possible that more clusters would exist, as indicated by a previous study that proposed a five-type classification of semi-outdoor spaces based on both their spatial characteristics, social functions and design intentions [28]. Nonetheless, the three-group clustering yielded by the hierarchical clustering analysis is complementary to the previously proposed five-type classification of semi-outdoor spaces; thus, the current study's clustering approach validates the previous study's architectural/design approach. Given that the social function and design intentions of semi-outdoor spaces were not considered and that only factor scores of retained underlying factors (i.e. VP, PO, ES) were used as input, hierarchical clustering analysis downsized the *horizontal breezeway* and *breezeway atrium* types of the previous five-type classification into one unique cluster (i.e. Cluster 1), and the *perimeter buffer* and *sky terrace* types into another unique cluster (i.e. Cluster 2).

Table 10 and Fig. A 2-Fig. A 3 indicate that the most thermally comfortable semi-outdoor spaces are those grouped within the *vertical breezeway* cluster. For all activity types, the *vertical breezeway* cluster had the lowest Gagge's PMV* and PET* values, as well as a mean Gagge's PMV* value that was always within the neutral/comfortable range [-1, +1]. High levels of thermal comfort in *vertical breezeways* are associated with high VP values (i.e. high *height, solid, void* and *volume*) and low PO values (i.e. low *total/open frontage* and *perimeter*), both of which are associated with high V_a values despite also being associated with high T_{mrt} values. Although a previous study found that the vertical wind velocity in this group was 0.40 m/s [28], the combined effect of horizontal (i.e. wind-driven) and vertical (i.e., buoyancy-driven/stack effect) movement may also explain why this cluster provides the most thermally comfortable semi-outdoor environments. In contrast, the *horizontal breezeway* cluster and the *perimeter buffer* cluster are the least thermally comfortable ones. Both had the highest Gagge's PMV* and PET* values, as well as a mean Gagge's PMV* value that was less than +1 (neutral/comfortable) for 1 MET and greater than +1 (slightly warm) for 1.5 & 2 MET. Results demonstrate that the low thermal comfort levels in *perimeter buffers* are associated with low VP values (i.e. low *height, solid, void* and *volume*) and that the low thermal comfort levels in *horizontal breezeways* are associated with high PO values (i.e. high *total/open frontage* and *perimeter*). Both low VP and high PO values are associated to low V_a values according to multivariate regressions.

4.2. Design recommendations

In light of the findings, the following design recommendations are made in order to promote thermally comfortable semi-outdoor microclimates at a typically hot hour (e.g. 2 p.m.) in a highly-dense tropical setting such as Singapore:

- Because of their *height*, narrow *open/total frontage*, and large amount of *void*, linked to higher VP with lower PO, semi-outdoor spaces within the *vertical breezeway* cluster encourage higher levels of wind movement and thermal comfort. In contrast to *the perimeter buffer* and *horizontal breezeway* cluster, the void in the *vertical breezeway* cluster faces not only outdoor conditions but also an inner (semi-outdoor) void (see Fig. A 4), making it more porous to wind.

- Cross-ventilation is used in the most thermally comfortable semi-outdoor spaces within the *perimeter buffer* cluster. The most thermally comfortable ones within the *horizontal breezeway* cluster have a deeper *depth* and a narrow *open/total frontage*, which increases wind movement due to a funnel effect.

4.3. Limitations of the study and further research recommendations

An Exploratory Factor Analysis (EFA) was used to assess the underlying factorial structure of semi-outdoor spaces' spatial attributes; however, current literature recommendations suggest using a Confirmatory Factor Analysis (CFA) to confirm that theory built by EFA. CFA was not performed because the sample of semi-outdoor spaces (n=63) was too small to divide into two subsamples as suggested by the literature [82,103,104], one for EFA and another for CFA. Future research should attempt to validate the consistency of VP, PO, and ES using CFA, as well as assess the cause-effect relationship between such underlying factors and microclimate performance using Structural Equation Modelling (SEM), since SEM allows to model more accurately causal mechanisms when compared to multivariate regressions [104]. Additionally, future research should also juxtapose environmental outcomes to social outcomes to see if the same underlying factors and clusters apply, or if new ones emerge, as a result of recognizing the nature and types of social interactions in semi-outdoor spaces.

Urban density features (e.g. urban land use, mean building height) might be also affecting temperatures, solar radiation, wind, humidity and predicted thermal comfort values in semi-outdoor spaces [12,71,105–107]; however, the current study focused only on form-related intrinsic attributes of semi-outdoor spaces. In line with the latter, future research should delve in identifying the impact of such urban features. Future research should also look into which underlying factors *HFG* and *orientation* belong to.

The current study, for instance, relied on estimates of thermal comfort; however, future research should look for onsite occupant responses/surveys to validate the current study's findings about the relationship between such three underlying factors and microclimate performance and clustering.

5. Conclusions

The current study has identified three underlying factors - *volume porosity* (VP)*, perimeter openness* (PO) and *exposure to sky* (ES) - associated with semi-outdoor spaces' microclimate performance and clustering in tropical high-density Singapore. Exploratory Factor Analysis (EFA) uncovered the underlying nature of a large set of spatial attributes (i.e. *height, depth, void, solid, total frontage, open frontage, area, volume, perimeter, sky view factor, green plot ratio*) that describe semi-outdoor spaces, which are manifestations of such underlying factors. All the latter was based on a measurement campaign of 63 semi-outdoor spaces in four Singapore high/mid-rise building forms in terms of microclimatic variables (i.e. T_a, T_{mrt}, V_a, and RH), as well as predicted thermal comfort levels based on the Gagge's SET*, Gagge's PMV* index and PET (for 1, 1.5 & 2 MET) derived from the measurement campaign data. The analyses have further shown the following:

- the three underlying factors explain 82% of the variance of all 11 form/spatial attributes;
- such underlying factors have a significant impact on the predicted thermal comfort, particularly VP and PO, which in turn have a significant impact especially on V_a. Higher levels of thermal comfort in semi-outdoor spaces are linked to higher VP and lower PO since both increase V_a;
- such underlying factors point to differentiated performance of semi-outdoor spaces. *Vertical breezeways* appear to be the most thermally comfortable, with high VP and low PO values. *Perimeter buffers* and *horizontal breezeways* appear to be the least thermally comfortable clusters: *perimeter buffers* with low VP and high PO values, and *horizontal breezeways* with high PO values.
- At a typically warm hour, semi-outdoor spaces have thermal comfort levels that range between "slightly cool" (-1) and "slightly warm" (+1) for SET* and PMV*, and between "slight stress" and "moderate stress" for PET.

This study, in particular, sheds new light on the spatial nature of semi-outdoor spaces, which designers can consider when seeking to promote thermally comfortable semi-outdoor environments in highly-dense tropical contexts such as Singapore. It may also assist designers in defining what it means to design *porous, open,* and *exposed* semi-outdoor environments, as well as the implications for microclimate and thermal comfort.

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Appendix A: Supplementary data

Supplementary material related to this article can be found at Mendeley Data [108] and Github repository (https://github.com/jgamerosalinas/Supplementary-Materials.git)

Nomenclature	
Acronyms	
EFA	Exploratory Factor Analysis
TSV	Thermal Sensation Vote
HSV	Humidity Sensation Vote
WSV	Wind Sensation Vote
TCV	Thermal Comfort Vote
SET*	Gagge's Standard Effective Temperature
PMV*	Gagge's Predicted Mean Vote
PMV	Fanger's Predicted Mean Vote
CFD	Computational Fluid Dynamics
SVF	Sky View Factor
GnPR	Green Plot Ratio
HFG	Height from ground level
OUT_SET*	Outdoor Standard Effective Temperature
PET	Physiological Equivalent Temperature
UTCI	Universal Thermal Climate Index
CBD	Central Business District
LAI	Leaf area index
MLE	Maximum Likelihood estimation
Abbreviations	
T_a	Ambient air temperature
T_{mrt}	Mean radiant temperature
V_a	Air velocity
RH	Relative humidity
T_{globe}	Black globe temperature
T_{out}	Outdoor air temperature
SO	School of the Arts
OA	OASIA Hotel Downtown
KA	Kampung Admiralty
SV	Skyville@Dawson
VP	Volume porosity
PO	Perimeter openness
ES	Exposure to sky

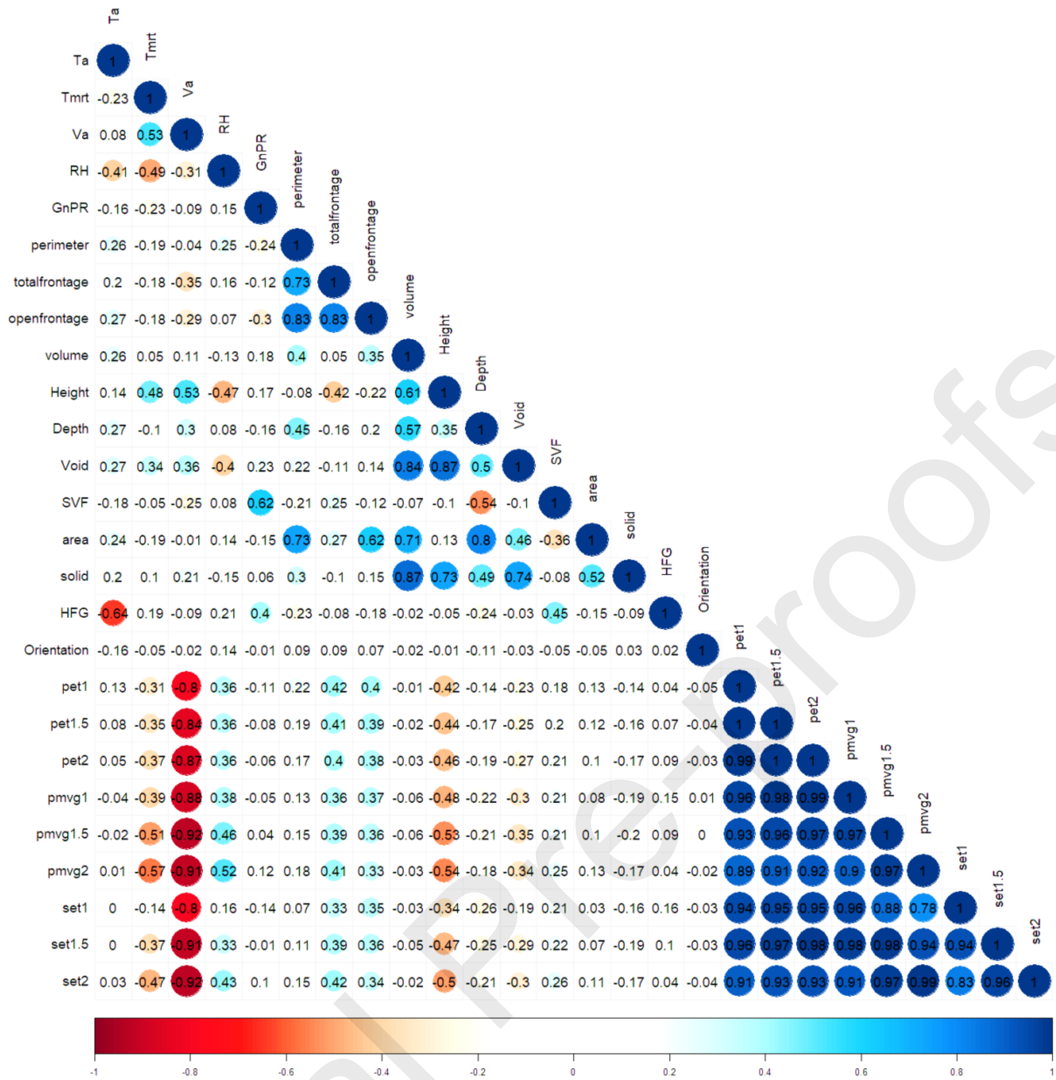

Fig. A 1. Correlogram showing Pearson's correlation coefficients for spatial attributes, microclimatic variables and thermal comfort indices.

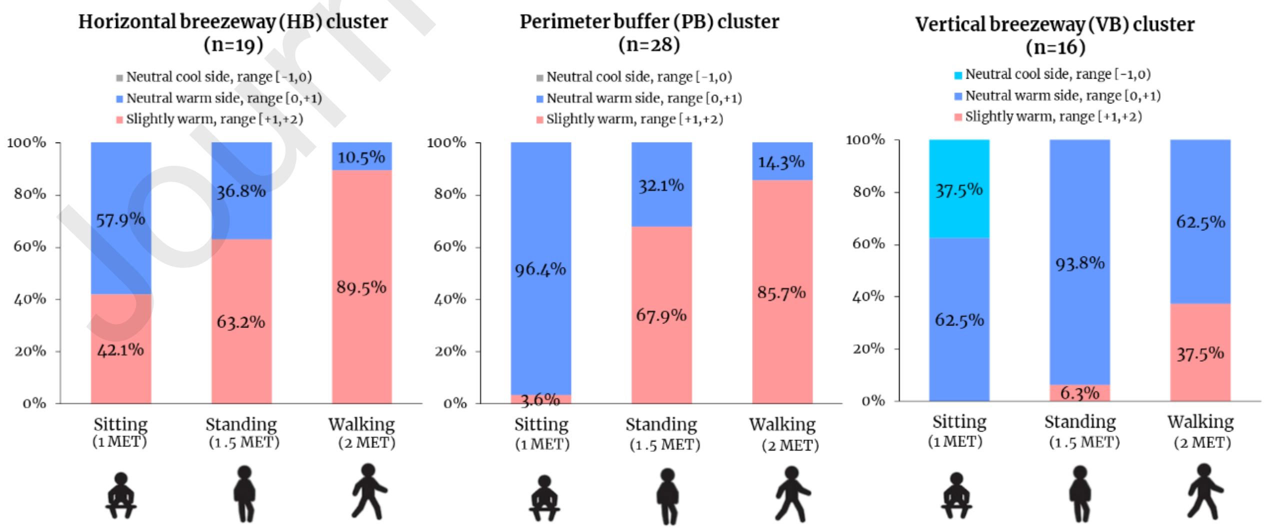

Fig. A 2. Thermal comfort levels achieved on each cluster based on Gagge's PMV* thermal index.

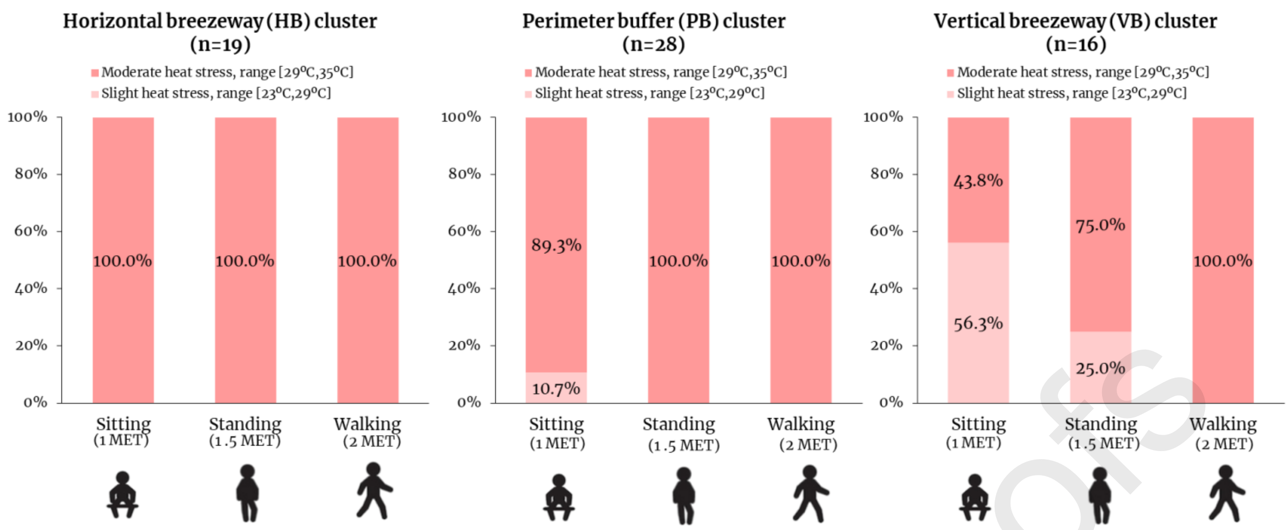

Fig. A 3. Thermal comfort levels achieved on each cluster based on PET thermal index.

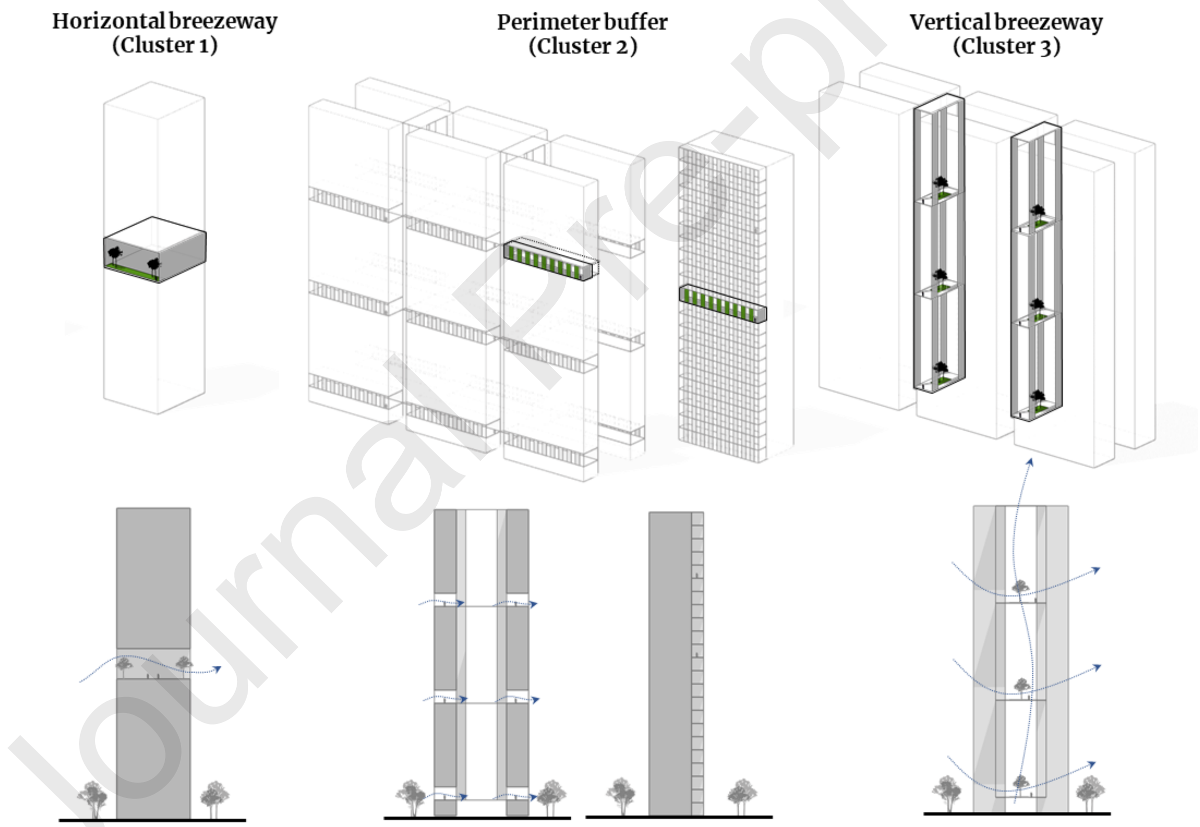

Fig. A 4. Conceptual representation of clusters in relation to how they are attached or embedded to building forms. Note: 3D models of buildings are 'to scale'.

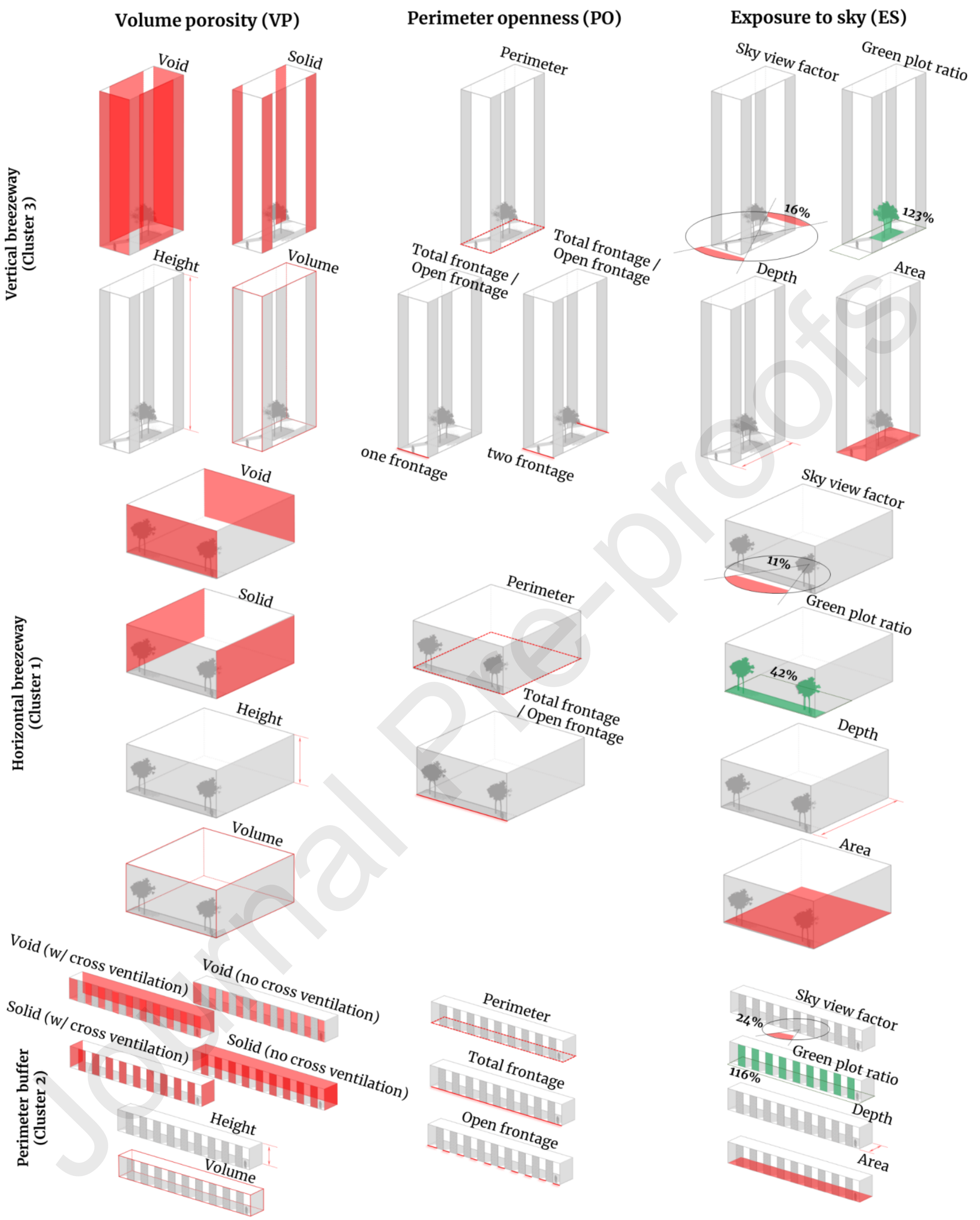

Fig. A 5. Conceptual representation of clusters generated by the hierarchical clustering analysis (*height, depth* and *total frontage* values in Table 10 were used as reference values for modelling). *Note: 3D models of clusters are 'to scale'.*

References

[1] C. Chun, A. Kwok, A. Tamura, Thermal comfort in transitional spaces—basic concepts: literature review and trial measurement, Building and Environment. 39 (2004) 1187–1192. https://doi.org/10.1016/j.buildenv.2004.02.003.

[2] J. Spagnolo, R. de Dear, A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia, Building and Environment. 38 (2003) 721–738. https://doi.org/10.1016/S0360-1323(02)00209-3.

[3] L.J. Yuan, A comparison of the traditional Malay house and the modern housing-estate house, United Nations University, 1981.

[4] V.F. Chen, The Encyclopedia of Malaysia, Volume 5: Architecture, Didier Millet Pte Ltd, 2007.

[5] J.-H. Bay, Sustainable community and environment in tropical Singapore high-rise housing: the case of Bedok Court condominium, Architectural Research Quarterly. 8 (2004) 333–343. https://doi.org/10.1017/S135913550400034X.

[6] J.-H. Bay, A balcony is not a verandah. Illusions in greening designs for high-rise high-density tropical living, in: III Encuentro de Arquitectura, Urbanismo y Paisajismo Tropical, Costa Rica, Instituto de Arquitectura Tropical, San José, Costa Rica, 2004.

[7] Q. Liang, Tropical Semi-Open Entrance Space: Solar and Wind Effects on Thermal Comfort (Master thesis), National University of Singapore, 2005. http://scholarbank.nus.edu.sg/handle/10635/16965 (accessed October 29, 2020).

[8] J.-H. Bay, N. Wang, Q. Liang, P. Kong, Socio-Environmental Dimensions in Tropical Semi-open Spaces of High-rise Housing in Singapore, in: J.-H. Bay, B.-L. Ong (Eds.), Tropical Sustainable Architecture: Social and Environmental Dimensions, 1st ed., Architectural Press, Elsevier, Oxford, 2006: pp. 59–82.

[9] P. Bingham-Hall, WOHA, Garden City Mega City: rethinking cities for the age of global warming, Pesaro Publishing Singapore, 2016.

[10] M.S. Wong, R. Hassell, A. Yeo, Garden City, Megacity: Rethinking Cities For the Age of Global Warming, CTBUH Journal. (2016) 46–51. https://global.ctbuh.org/resources/papers/download/3010-garden-city-megacity-rethinking-cities-for-the-age-of-global-warming.pdf.

[11] Edward. Ng, Designing High-Density Cities: For Social and Environmental Sustainability, 1st ed., Routledge, 2009. https://doi.org/10.4324/9781849774444.

[12] N.H. Wong, Y. Chen, Tropical Urban Heat Islands, Routledge, London, 2008. https://doi.org/10.4324/9780203931295.

[13] L. Ruefenacht, J.A. Acero, Strategies for Cooling Singapore A catalogue of 80+ measures to mitigate urban heat island and improve outdoor thermal comfort, Cooling Singapore (CS), 2017. https://doi.org/10.3929/ethz-b-000258216.

[14] N. Borzino, S. Chng, M.O. Mughal, R. Schubert, Willingness to Pay for Urban Heat Island Mitigation: A Case Study of Singapore, (2020) 1–26. https://doi.org/10.3390/cli8070082.

[15] K. Yeang, A. Balfour, I. Richards, Bioclimatic skyscrapers: Hamzah & Yeang, Ellipsis, London, 1994.

[16] Ken. Yeang, The skyscraper bioclimatically considered: a design primer, Academy Editions, London, 1996.

[17] R. Powell, K.S. Tay, A.K.S. Lim, Line, edge & shade: the search for a design language in tropical Asia : Tay Kheng Soon & Akitek Tenggara, Page One Publisher, Singapore, 1997.

[18] N. Kishnani, Climate, buildings and occupant expectations: a comfort-based model for the design and operation of office buildings in hot humid conditions (PhD Thesis), Curtin University, 2002. http://hdl.handle.net/20.500.11937/2325.

[19] Y. Tao, S.S.Y. Lau, Z. Gou, J. Zhang, A. Tablada, An investigation of semi-outdoor learning spaces in the tropics: Spatial settings, thermal environments and user perceptions, Indoor and Built Environment. 28 (2019) 1368–1382. https://doi.org/10.1177/1420326X19841115.

[20] J. Gamero-Salinas, N. Kishnani, A. Monge-Barrio, J. López-Fidalgo, A. Sánchez-Ostiz, The influence of building form variables on the environmental performance of semi-outdoor spaces. A study in mid-rise and high-rise buildings of Singapore, Energy and Buildings. 230 (2021) 110544. https://doi.org/10.1016/j.enbuild.2020.110544.

[21] J.C. Gamero-Salinas, N. Kishnani, A. Monge-Barrio, B. Gandhi, M. Bilgi, A. Sánchez-Ostiz, The Influence Of Building Form On Energy Use, Thermal Comfort And Social Interaction. A Post-occupancy Comparison Of Two High-rise Residential Buildings In Singapore, in: Proceedings of 35th PLEA International Conference: Planning Post Carbon Cities. A Coruña, 1-3 September 2020. PLEA 2020 Conference, A Coruña, Spain, 2020.

[22] M. Mohammadi, P.W. Tien, J. Kaiser Calautit, Influence of Wind Buffers on the Aero-Thermal Performance of Skygardens, Fluids. 5 (2020) 160. https://doi.org/10.3390/fluids5030160.

[23] P.W. Tien, M. Mohammadi, J.K. Calautit, Providing comfortable environment in sykgardens within high-rise buildings: Analysis of the impact of vegetation on wind and thermal comfort, Journal of Sustainable Development of Energy, Water and Environment Systems. (2020). https://doi.org/10.13044/j.sdewes.d8.0353.

[24] P.W. Tien, J.K. Calautit, Numerical analysis of the wind and thermal comfort in courtyards "skycourts" in high rise buildings, Journal of Building Engineering. 24 (2019). https://doi.org/10.1016/j.jobe.2019.100735.

[25] M. Mohammadi, J.K. Calautit, Numerical Investigation of the Wind and Thermal Conditions in Sky Gardens in High-Rise Buildings, Energies (Basel). 12 (2019) 1380. https://doi.org/10.3390/en12071380.

[26] A.R. Mohammadi, M.M. Tahir, I.M.S. Usman, N.A.G. Abdullah, A.I. Che-Ani, The Effect of Balcony to Enhance the Natural Ventilation of Terrace Houses in the Tropical Climate of Malaysia, in: 6th WSEAS International Conference on REMOTE SENSING (REMOTE '10), 4-6 October 2010, Iwate Prefectural University, Japan, 2010. http://ir.unimas.my/id/eprint/31159 (accessed October 28, 2020).

[27] N. Taib, A. Abdullah, S.F. Syed Fadzil, F.S. Yeok, An Assessment of Thermal Comfort and Users' Perceptions of Landscape Gardens in a High-Rise Office Building, Journal of Sustainable Development. 3 (2010) 153–164. https://doi.org/10.5539/jsd.v3n4p153.

[28] J. Gamero-Salinas, N. Kishnani, A. Monge-Barrio, J. López-Fidalgo, A. Sánchez-Ostiz, Evaluation of thermal comfort and building form attributes in different semi-outdoor environments in a high-density tropical setting, Building and Environment. 205 (2021) 108255. https://doi.org/10.1016/J.BUILDENV.2021.108255.

[29] J. Niu, Some significant environmental issues in high-rise residential building design in urban areas, Energy and Buildings. 36 (2004) 1259–1263. https://doi.org/10.1016/j.enbuild.2003.07.005.

[30] B. Cao, M. Luo, M. Li, Y. Zhu, Thermal comfort in semi-outdoor spaces within an office building in Shenzhen: A case study in a hot climate region of China, Indoor and Built Environment. 27 (2018) 1431–1444. https://doi.org/10.1177/1420326X17728152.

[31] T. Xi, Q. Li, A. Mochida, Q. Meng, Study on the outdoor thermal environment and thermal comfort around campus clusters in subtropical urban areas, Building and Environment. 52 (2012) 162–170. https://doi.org/10.1016/j.buildenv.2011.11.006.

[32] Z. Zhou, H. Chen, Q. Deng, A. Mochida, A Field Study of Thermal Comfort in Outdoor and Semi-outdoor Environments in a Humid Subtropical Climate City, Journal of Asian Architecture and Building Engineering. 12 (2013) 73–79. https://doi.org/10.3130/jaabe.12.73.

[33] H. Chen, R. Ooka, K. Harayama, S. Kato, X. Li, Study on outdoor thermal environment of apartment block in Shenzhen, China with coupled simulation of convection, radiation and conduction, Energy and Buildings. 36 (2004) 1247–1258. https://doi.org/10.1016/j.enbuild.2003.07.003.

[34] S. Omrani, V. Garcia-Hansen, B.R. Capra, R. Drogemuller, On the effect of provision of balconies on natural ventilation and thermal comfort in high-rise residential buildings, Building and Environment. 123 (2017) 504–516. https://doi.org/10.1016/j.buildenv.2017.07.016.

[35] F. Devys-Peyre, E. Walther, C. Inard, B. Soulier, Modélisation du confort thermique dans les espaces semi-ouverts, in: Conférence IBPSA France, Reims, 2020. https://lhypercube.arep.fr/.

[36] J.A. Acero, L.A. Ruefenacht, E.J.Y. Koh, Y.S. Tan, L.K. Norford, Measuring and comparing thermal comfort in outdoor and semi-outdoor spaces in tropical Singapore, Urban Climate. 42 (2022) 101122. https://doi.org/10.1016/J.UCLIM.2022.101122.

[37] E. Walther, Q. Goestchel, The P.E.T. comfort index: Questioning the model, Building and Environment. (2018). https://doi.org/10.1016/j.buildenv.2018.03.054.

[38] N.E. Othman, S.A. Zaki, H.B. Rijal, N.H. Ahmad, A.A. Razak, Field study of pedestrians' comfort temperatures under outdoor and semi-outdoor conditions in Malaysian university campuses, International Journal of Biometeorology. 65 (2021) 453–477. https://doi.org/10.1007/S00484-020-02035-3/TABLES/7.

[39] M.S. Oual, A.A. Tabassi, A.S. Hassan, Thermal Comfort in Semi-Outdoor Studying Spaces: A case study of Universiti Sains Malaysia, IOP Conference Series: Materials Science and Engineering. 401 (2018) 012022. https://doi.org/10.1088/1757-899X/401/1/012022.

[40] G. Pagliarini, S. Rainieri, Thermal environment characterisation of a glass-covered semi-outdoor space subjected to natural climate mitigation, Energy and Buildings. 43 (2011) 1609–1617. https://doi.org/10.1016/j.enbuild.2011.03.044.

[41] C. Kwon, K. Lee, Outdoor Thermal Comfort in a Transitional Space of Canopy in Schools in the UK, Sustainability. 9 (2017) 1753. https://doi.org/10.3390/su9101753.

[42] M. Srivanit, S. Auttarat, The Summer Thermal Environment and Human Comfort of Shaded Outdoor and Semi-Outdoor Spaces to Living in the Urban Area of Chiang Mai City, Journal of Architectural/Planning Research and Studies (JARS). 12 (2015) 53–72. https://so02.tci-thaijo.org/index.php/jars/article/view/53106 (accessed June 13, 2022).

[43] A.P. Gagge, A.P. Fobelets, L.G. Berglund, A standard predictive index of human response to the thermal environment, ASHRAE Transactions. 92 (1986) 709–731.

[44] A.P. Gagge, J.A. Stolwijk, Y. Nishi, An effective temperature scale based on a simple model of human physiological regulatory response, ASHRAE Transactions. 77 Part I (1971) 247–262.

[45] G. Jendritzky, R. de Dear, G. Havenith, UTCI—Why another thermal index?, International Journal of Biometeorology. 56 (2012) 421–428. https://doi.org/10.1007/s00484-011-0513-7.

[46] P. Gugel-Quiroga, Assessing the use of UTCI in semi-outdoor spaces. A case study in Hyderabad, India, in: Proceedings of 35th PLEA International Conference: Planning Post Carbon Cities. A Coruña, 1-3 September 2020. PLEA 2020 Conference, 2020.

[47] R. de Dear, J. Spagnolo, Thermal comfort in outdoor and semi-outdoor environments, in: Elsevier Ergonomics Book Series, 2005: pp. 269–276. https://doi.org/10.1016/S1572-347X(05)80044-8.

[48] J.F. Song, N.H. Wong, K. Huang, Ventilation comfort chart for semi-outdoor spaces in the tropics, in: 7th International Symposium on Heating, Ventilating and Air Conditioning - Proceedings of ISHVAC 2011, ScholarBank@NUS Repository, 2011. https://scholarbank.nus.edu.sg/handle/10635/114095.

[49] J.F. Song, Thermal comfort for semi-outdoor spaces in the tropics (PhD Thesis), National University of Singapore (NUS), 2007. http://scholarbank.nus.edu.sg/handle/10635/49060 (accessed September 4, 2020).

[50] P. Saadatjoo, M. Mahdavinejad, G. Zhang, A study on terraced apartments and their natural ventilation performance in hot and humid regions, Building Simulation. 11 (2018) 359–372. https://doi.org/10.1007/s12273-017-0407-7.

[51] G.V. Maragno, H.C. Roura, Impacts of form-design in shading transitional spaces: The Brazilian veranda, in: P. Hájek, J. Tywoniak, A. Lupíšek, J. Růžička, K. Sojková (Eds.), CESB 2010 Prague: Central Europe towards Sustainable Building: "From Theory to Practice," Department of Building Structures and CIDEAS Research Centre, Faculty of Civil Engineering, Czech Technical University, Prague, 2010.

[52] C. Kwon, K. Lee, Outdoor Thermal Comfort in a Transitional Space of Canopy in Schools in the UK, Sustainability. 9 (2017) 1753. https://doi.org/10.3390/su9101753.

[53] ASHRAE, ANSI/ASHRAE Standard 55-2020. Thermal Environmental Conditions for Human Occupancy, Atlanta, GA, 2020.

[54] M.W. Watkins, Exploratory Factor Analysis: A Guide to Best Practice, Journal of Black Psychology. 44 (2018) 219–246. https://doi.org/10.1177/0095798418771807.

[55] M. Allen, Latent Variables, The SAGE Encyclopedia of Communication Research Methods. Vols. 1-4 (2017). https://doi.org/10.4135/9781483381411.

[56] H.E. Reas, E.K. Verdi, T.M. Erickson, Hypothetical Constructs, Encyclopedia of Personality and Individual Differences. (2020) 2119–2124. https://doi.org/10.1007/978-3-319-24612-3_679.

[57] P. Lavrakas, Construct, Encyclopedia of Survey Research Methods. Vols. 1-0 (2008). https://doi.org/10.4135/9781412963947.n91.

[58] S.Y. Chan, C.K. Chau, T.M. Leung, On the study of thermal comfort and perceptions of environmental features in urban parks: A structural equation modeling approach, Building and Environment. 122 (2017) 171–183. https://doi.org/10.1016/J.BUILDENV.2017.06.014.

[59] F. Vazin, Investigating the Role of Environmental Comfort on Citizens' Behavior in an Urban Street: A Case Study of Khosravi Street, Mashhad, Creative City Design. 3 (2020) 141–154. http://crcd.sinaweb.net/article_681222.html (accessed January 26, 2022).

[60] C.F. Wu, Y.F. Hsieh, S.J. Ou, Thermal Adaptation Methods of Urban Plaza Users in Asia's Hot-Humid Regions: A Taiwan Case Study, International Journal of Environmental Research and Public Health. 12 (2015) 13560–13586. https://doi.org/10.3390/IJERPH121013560.

[61] K. Mihara, S. Chen, T. Hasama, C.L. Tan, J.K.W. Lee, N.H. Wong, Environmental satisfaction, mood and cognitive performance in semi-outdoor space in the tropics, Building and Environment. 216 (2022) 109051. https://doi.org/10.1016/J.BUILDENV.2022.109051.

[62] WOHA Architects, WOHA, (1994). https://www.woha.net/# (accessed March 11, 2020).

[63] Meteorological Service Singapore (MSS), Climate of Singapore, (2020). http://www.weather.gov.sg/ (accessed May 25, 2020).

[64] ISO, ISO 7726:1998 - Ergonomics of the thermal environment - Instruments for measuring physical quantities, 1998.

[65] Trimble Inc., SketchUp: 3D Design Software, Modeling on the Web, (2022). https://www.sketchup.com/ (accessed February 3, 2022).

[66] M. Berghauser Pont, P. Haupt, The Spacemate: Density and the typomorphology of the urban fabric, in: F. van Hoeven, H. Rosemann (Eds.), Urbanism Laboratory for Cities and Regions. Progress of Research Issues in Urbanism 2007, IOS Press, Delft, 2007: pp. 11–26.

[67] T.R. Oke, Street design and urban canopy layer climate, Energy and Buildings. 11 (1988) 103–113. https://doi.org/10.1016/0378-7788(88)90026-6.

[68] Sky View Analysis | SketchUp Extension Warehouse, (2021). https://extensions.sketchup.com/ (accessed January 18, 2022).

[69] B.L. Ong, Green plot ratio: an ecological measure for architecture and urban planning, Landscape and Urban Planning. 63 (2003) 197–211. https://doi.org/10.1016/S0169-2046(02)00191-3.

[70] J.M.O. Scurlock, G.P. Asner, S.T. Gower, Global Leaf Area Index from Field Measurements, 1932-2000, Oak Ridge, Tennessee, U.S.A. (2001). https://doi.org/10.3334/ORNLDAAC/584.

[71] S.K. Jusuf, W.N. Hien, Development of empirical models for an estate level air temperature prediction in Singapore, in: Proceedings of 2nd International Conference on Countermeasures to Urban Heat Islands, Berkeley, California, USA, 2009.

[72] S.K. Jusuf, Development of Estate Level Climate Related Impact Assessment Framework and Air Temperature Prediction Within Urban Climatic Mapping Method in Singapore (PhD Thesis), National University of Singapore (NUS), 2009. http://scholarbank.nus.edu.sg/handle/10635/17383.

[73] M. Bogdan, E. Walther, Comfort modelling in semi-outdoor spaces, The REHVA European HVAC Journal. 54 (2017) 23–25.

[74] P. Höppe, The physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment, International Journal of Biometeorology. 43 (1999) 71–75. https://doi.org/10.1007/s004840050118.

[75] M. Schweiker, comf: An R Package for Thermal Comfort Studies, The R Journal. 8 (2016) 341–351.

[76] F. Tartarini, S. Schiavon, pythermalcomfort: A Python package for thermal comfort research, SoftwareX. 12 (2020) 100578. https://doi.org/10.1016/J.SOFTX.2020.100578.

[77] W. Yang, N.H. Wong, S.K. Jusuf, Thermal comfort in outdoor urban spaces in Singapore, Building and Environment. 59 (2013) 426–435. https://doi.org/10.1016/j.buildenv.2012.09.008.

[78] H.F. Kaiser, An Index of Factorial Simplicity, Psychometrika. 39 (1974) 31–36.

[79] M.S. Bartlett, The Effect of Standardization on a chi square Approximation in Factor Analysis, Biometrika. 38 (1951) 337–344. https://doi.org/10.1093/BIOMET/38.3-4.337.

[80] W. Revelle, psych: Procedures for Psychological, Psychometric, and Personality Research, Evanston, Illinois, 2021. https://CRAN.R-project.org/package=psych. (accessed December 13, 2021).

[81] C.G. Forero, A. Maydeu-Olivares, D. Gallardo-Pujol, Factor Analysis with Ordinal Indicators: A Monte Carlo Study Comparing DWLS and ULS Estimation, Structural Equation Modeling. 16 (2009) 625–641. https://doi.org/10.1080/10705510903203573.

[82] S. Lloret-Segura, A. Ferreres-Traver, A. Hernández-Baeza Inés Tomás-Marco, S. Lloret Segura, El análisis factorial exploratorio de los ítems: una guía práctica, revisada y actualizada, 30 (2014) 1151–1169. https://doi.org/10.6018/analesps.30.3.199361.

[83] J.L. Horn, A Rationale and Test for the Number of Factors in Factor Analysis, Psychometrica. 30 (1965) 179–185.

[84] S.B. Franklin, D.J. Gibson, P.A. Robertson, J.T. Pohlmann, J.S. Fralish, Parallel Analysis: a method for determining significant principal components, Journal of Vegetation Science. 6 (1995) 99–106. https://doi.org/10.2307/3236261.

[85] L.L. Thurstone, Multiple Factor Analysis, The University Chicago Press. (1947) 406–427.

[86] L. Hatcher, N. O'Rourke, Step-by-Step Approach to Using SAS for Factor Analysis and Structural Equation Modeling, Second Edition, SAS Institute, 2013.

[87] R Core Team, R: A language and environment for statistical computing., (2013). http://www.R-project.org/ (accessed December 16, 2021).

[88] S. Behrendt, lm.beta: Add Standardized Regression Coefficients to lm-Objects, (2014). https://cran.r-project.org/web/packages/lm.beta/index.html (accessed December 16, 2021).

[89] T. Yanagida, misty: Miscellaneous Functions , (2021). https://cran.r-project.org/web/packages/misty/index.html (accessed December 16, 2021).

[90] Maechler M, Rousseeuw P, Struyf A, Hubert M, Hornik K, cluster: Cluster Analysis Basics and Extensions, 2021. https://CRAN.R-project.org/package=cluster (accessed December 16, 2021).

[91] M. Charrad, N. Ghazzali, V. Boiteau, A. Niknafs, NbClust: An R Package for Determining the Relevant Number of Clusters in a Data Set, Journal of Statistical Software. 61 (2014) 1–36. https://doi.org/10.18637/jss.v061.i06.

[92] T. Galili, dendextend: an R package for visualizing, adjusting and comparing trees of hierarchical clustering, Bioinformatics. 31 (2015) 3718–3720. https://doi.org/10.1093/BIOINFORMATICS/BTV428.

[93] HKSAR, Joint Practice Note No. 1: Green and Innovate Buildings, 2019. https://www.pland.gov.hk/pland_en/tech_doc/joint_pn/jpn1_e.pdf.

[94] HKSAR, Joint Practice Note No. 2: Second Package of Incentives to Promote Green and Innovative Buildings, 2011. https://www.pland.gov.hk/pland_en/tech_doc/joint_pn/jpn2_e.pdf (accessed November 13, 2020).

[95] URA, Sky Terraces, Residential Handbooks for Flats and Condominiums. (2020). https://www.ura.gov.sg/Corporate/Guidelines/Development-Control/gross-floor-area/GFA/SkyTerraces (accessed October 15, 2020).

[96] URA, Circular to professional institutes: Refinements to gross floor area (GFA) rules to facilitate more efficient calculation of GFA, 2019. https://www.corenet.gov.sg/media/2268613/dc19-11.pdf.

[97] URA, Balconies, Private Enclosed Spaces, Private Roof Terraces and Indoor Recreation Spaces, Residential Handbooks for Flats and Condominiums. (2020). https://www.ura.gov.sg/Corporate/Guidelines/Development-Control/Residential/Flats-Condominiums/~/link.aspx?_id=073E26836E5A406892CF59BA9A501130&_z=z (accessed October 28, 2020).

[98] R. Wei, D. Song, N.H. Wong, M. Martin, Impact of Urban Morphology Parameters on Microclimate, Procedia Engineering. 169 (2016) 142–149. https://doi.org/10.1016/J.PROENG.2016.10.017.

[99] C. Yuan, E. Ng, Building porosity for better urban ventilation in high-density cities – A computational parametric study, Building and Environment. 50 (2012) 176–189. https://doi.org/10.1016/j.buildenv.2011.10.023.

[100] S. Cui, P. Stabat, D. Marchio, Numerical simulation of wind-driven natural ventilation: Effects of loggia and facade porosity on air change rate, Building and Environment. 106 (2016) 131–142. https://doi.org/10.1016/j.buildenv.2016.03.021.

[101] M. Tuczek, K. Degirmenci, K.C. Desouza, R.T. Watson, T. Yigitcanlar, M.H. Breitner, Mitigating urban heat with optimal distribution of vegetation and buildings, Urban Climate. 44 (2022) 101208. https://doi.org/10.1016/J.UCLIM.2022.101208.

[102] R.-L. Hwang, T.-P. Lin, Thermal Comfort Requirements for Occupants of Semi-Outdoor and Outdoor Environments in Hot-Humid Regions, Architectural Science Review. 50 (2007) 357–364. https://doi.org/10.3763/asre.2007.5043.

[103] T. Brown, Confirmatory Factor Analysis for Applied Research, 2nd ed., Guilford Press, 2015.

[104] J.C. Anderson, D.W. Gerbing, Structural Equation Modeling in Practice: A Review and Recommended Two-Step Approach, Psychological Bulletin. 103 (1988) 411–423.

[105] V. Ok, M. Aygün, The Variations of Wind Speeds with Building Density in Urban Areas, Architectural Science Review. 38 (1995) 87–95. https://doi.org/10.1080/00038628.1995.9696783.

[106] N.H. Wong, S.K. Jusuf, N.I. Syafii, Y. Chen, N. Hajadi, H. Sathyanarayanan, Y.V. Manickavasagam, Evaluation of the impact of the surrounding urban morphology on building energy consumption, Solar Energy. 85 (2011) 57–71. https://doi.org/10.1016/j.solener.2010.11.002.

[107] C.K. Heng, L.C. Malone-Lee, J. Zhang, Relationship between density, urban form and environmental performance, in: J.-H. Bay, S. Lehmann (Eds.), Growing Compact: Urban Form, Density and Sustainability, Routledge, London, 2017: pp. 271–286. https://doi.org/10.4324/9781315563831.

[108] J. Gamero-Salinas, N. Kishnani, A. Sánchez-Ostiz, A. Monge-Barrio, E. Benitez, Porosity, openness, and exposure: Identification of underlying factors associated with semi-outdoor spaces' thermal performance and clustering in tropical high-density Singapore: Supplementary Materials, Mendeley Data, V5. (2022). https://doi.org/10.17632/9wyjpnwghk.5.

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:

Highlights

- 63 semi-outdoor spaces are characterised in terms of underlying factors (i.e. *hypothetical constructs)*.
- Exploratory Factor Analysis (EFA) analyses 11 spatial attributes of semi-outdoor spaces.
- EFA reveals 3 underlying factors: *volume porosity, perimeter openness* & *exposure to sky*
- Such underlying factors are linked to the microclimate and predicted thermal comfort.
- Such underlying factors are associated with how semi-outdoor environments are clustered.