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

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A R T I C L E I N F O

A B S T R A C T

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.

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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.

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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

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 are 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].

1.1.2. Social performance of semi-outdoor spaces

The extent to which the semi-outdoor space 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 [52]. 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

Table 1

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

Reference	Location	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
[41]	London, Manchester and Glasgow, UK	–	unheated sheltered transitional space	–	CFD	PET

measured by multiple observed/manifest variables, rather than by a single variable [53,54]. 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 [55,56]. 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) [57–59], and (2) environmental satisfaction and cognitive performance in tropical semi-outdoor spaces [60]. However, there is still a scientific gap in understanding the factors underlying form-related spa-

tial features of semi-outdoor spaces and how they relate to micro-climate, 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 factors 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

Fig. 1 shows four buildings in Singapore's tropical city-state (1.3° N, 103.8° E), designed by WOHA Architects [61], 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 [61].

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 Fig. 2 - Fig. 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.

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 [62]. Different periods were measured due to insufficient measurement equipment to study all 63 semi-outdoor spaces at the same time.

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 Figs. 3–7. For privacy and security, loggers were placed in locations hidden from the general public, approximately 1.5 m 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} [63].

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

Fig. 1. From left to right: School of the Arts (SO), OASIA Hotel Downtown (OA), Kampung Admiralty (KA) and Skyville@Dawson (SV).
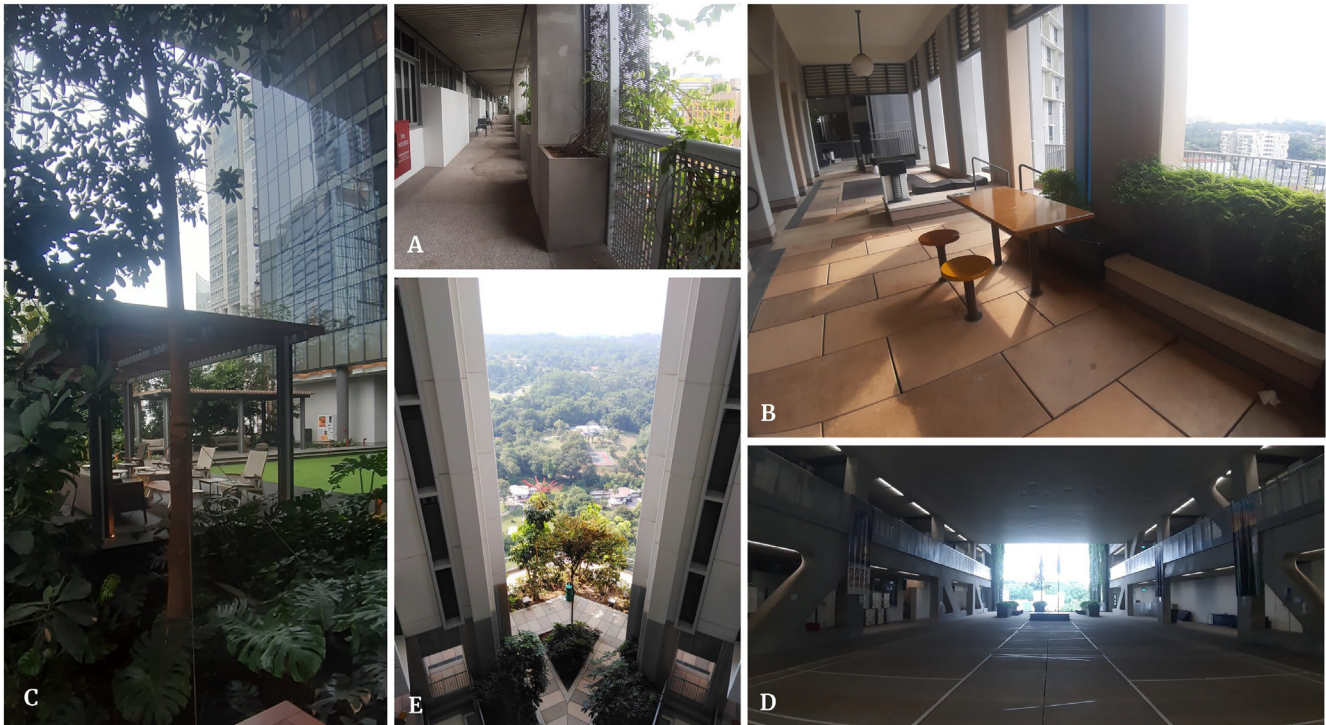
Fig. 2. Semi-outdoor space labelling according to a previous study: A (*perimeter buffer*, e.g. SOS11 in SO); B (*sky terrace*, e.g. SOS49 in SV); C (*breezeway atrium*, e.g. SOS 13 in OA); D (*horizontal breezeway*, e.g. SOS3 in SO); and E (*vertical breezeway*, e.g. SOS51 in SV).

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

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 min (all days)	Every 10 min (all days)	Every 10 min (all days)	Every 10 min (all days)
V_a & T_{globe} readings	Every hour between 10 a.m. and 4p.m. (in 1 day)	Every hour between 10 a.m. and 4p.m. (in 1 day)	Every hour between 10 a.m. and 4p.m. (in 1 day)	Every hour between 10 a.m. and 4p.m. (in 2 days)

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

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

Sketchup digital models [64] based on each building's floor and section plans, as well as on in-situ observations during the measurements campaign.

2.2. Data processing

The typically warm hour of 2p.m. (between 2 and 3p.m.) was used as the reference time for assessing semi-outdoor spaces' microclimate performance (see Fig. 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 Fig. 3 – Fig. 7). After 3p.m., the solar angle decreases, and semi-outdoor spaces facing west receive more direct solar radiation than semi-outdoor spaces facing other directions. Before 2p.m., T_{out} has not reached daily maximum values (between 2p.m. and 5p.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 [20,70,71]. Previous research has shown through statistical analysis that T_{out} at 2p.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
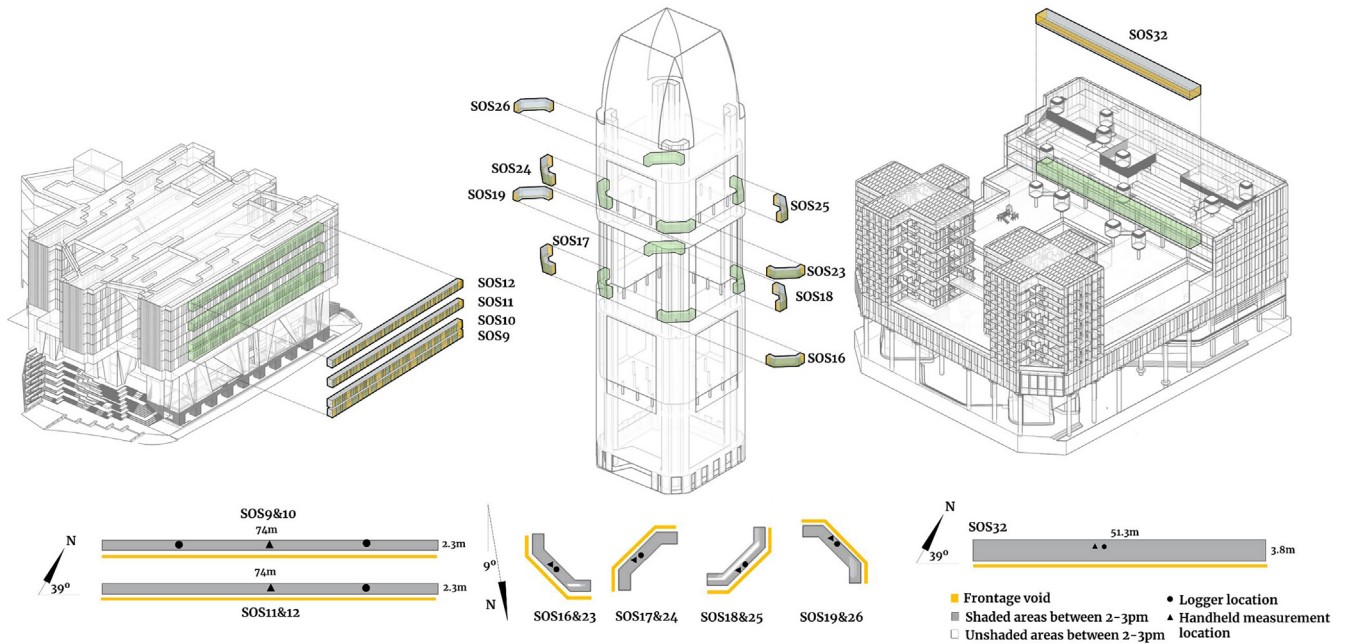
Fig. 3. Above: semi-outdoor spaces (SOS) labelled previously as *perimeter buffers*, where yellow colour indicates voids. Below: dimensions, measurement locations and shading conditions between 2 and 3 pm (Reference days: SO: June 10; OA: June 26; & KA: July 09). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
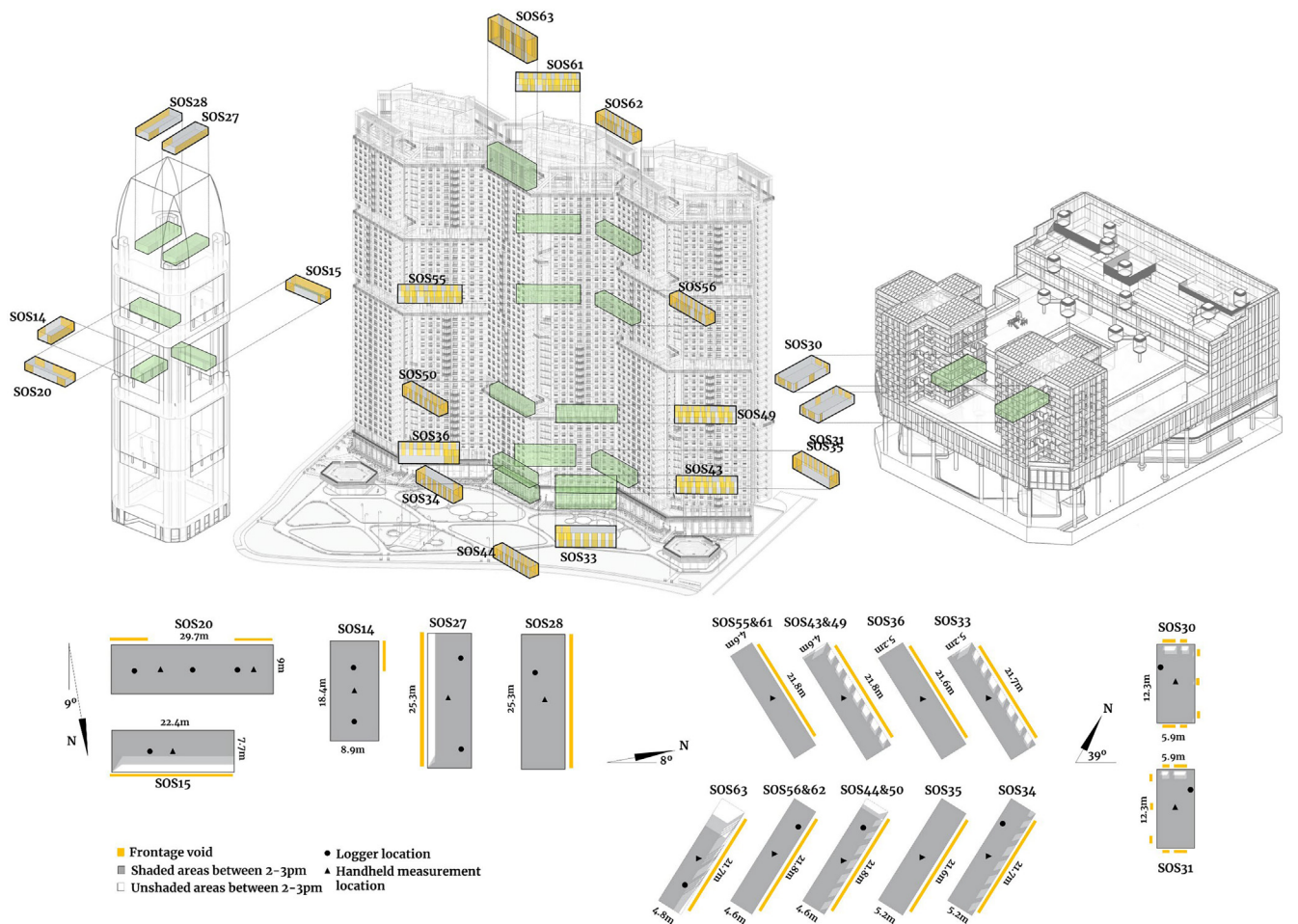

Fig. 4. Above: semi-outdoor spaces (SOS) labelled previously as *sky terraces*, where yellow colour indicates voids. Below: dimensions, measurement locations and shading conditions between 2 and 3 pm (Reference days: OA: June 26; SV: July 24; & KA: July 09). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
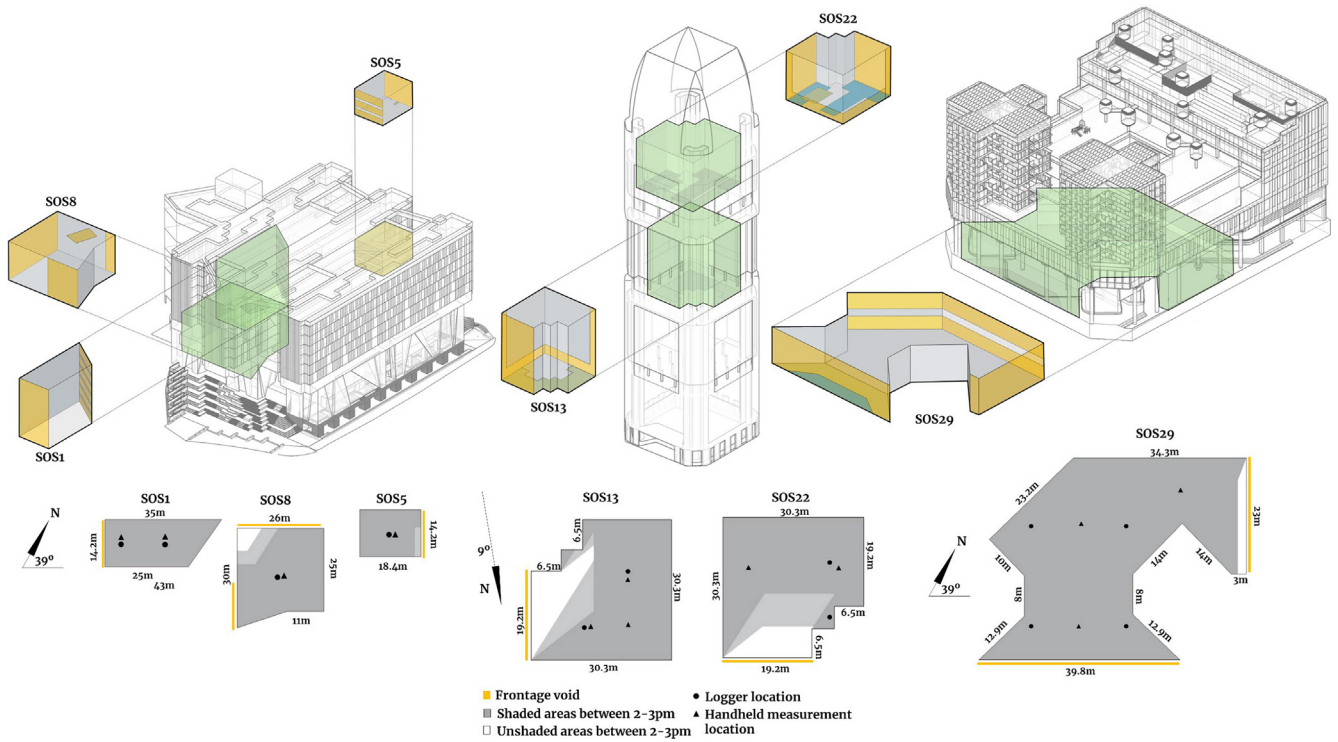
Fig. 5. Above: semi-outdoor spaces (SOS) labelled previously as *breezeway atria,* where yellow colour indicates voids. Below: dimensions, measurement locations and shading conditions between 2 and 3 pm (Reference days: SO: June 10; OA: June 26; & KA: July 09). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
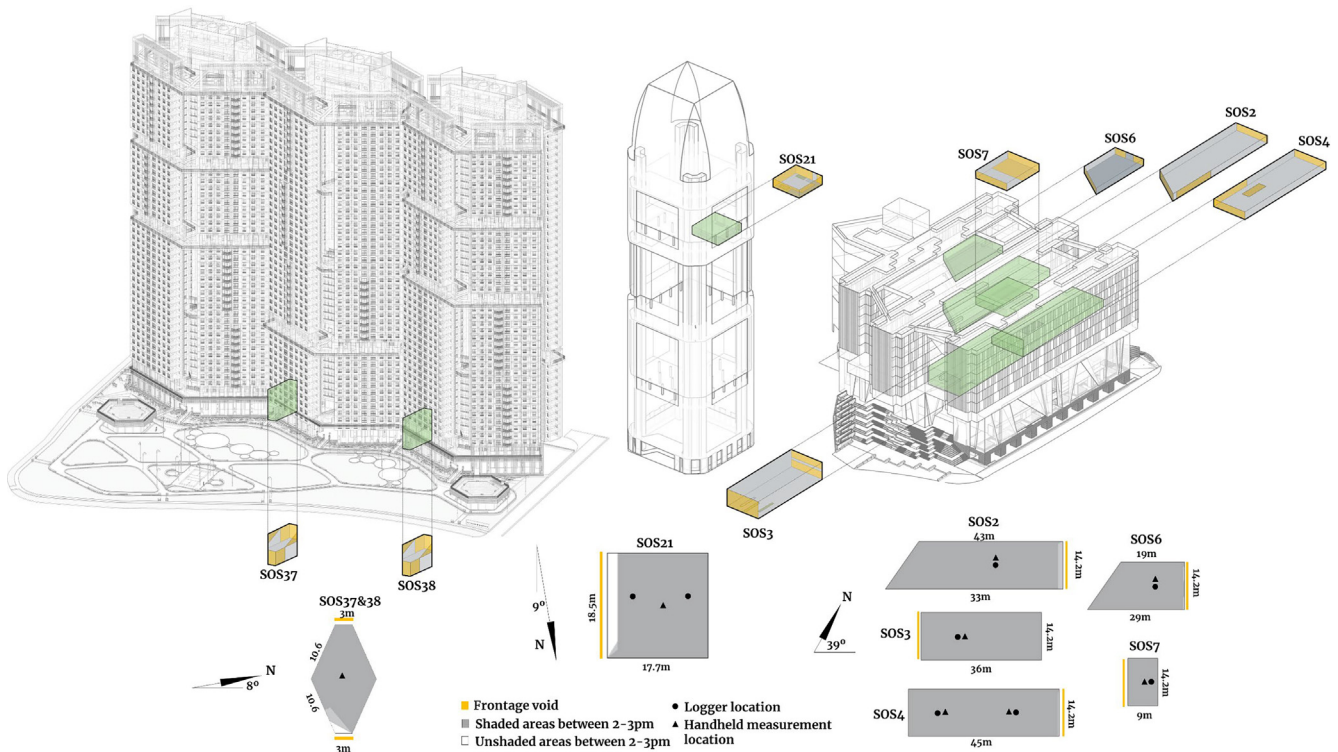

Fig. 6. Above: semi-outdoor spaces (SOS) labelled previously as *horizontal breezeways*, where yellow colour indicates voids. Below: dimensions, measurement locations and shading conditions between 2 and 3 pm (Reference days: SV: July 24; OA: June 26; & SO: June 10). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
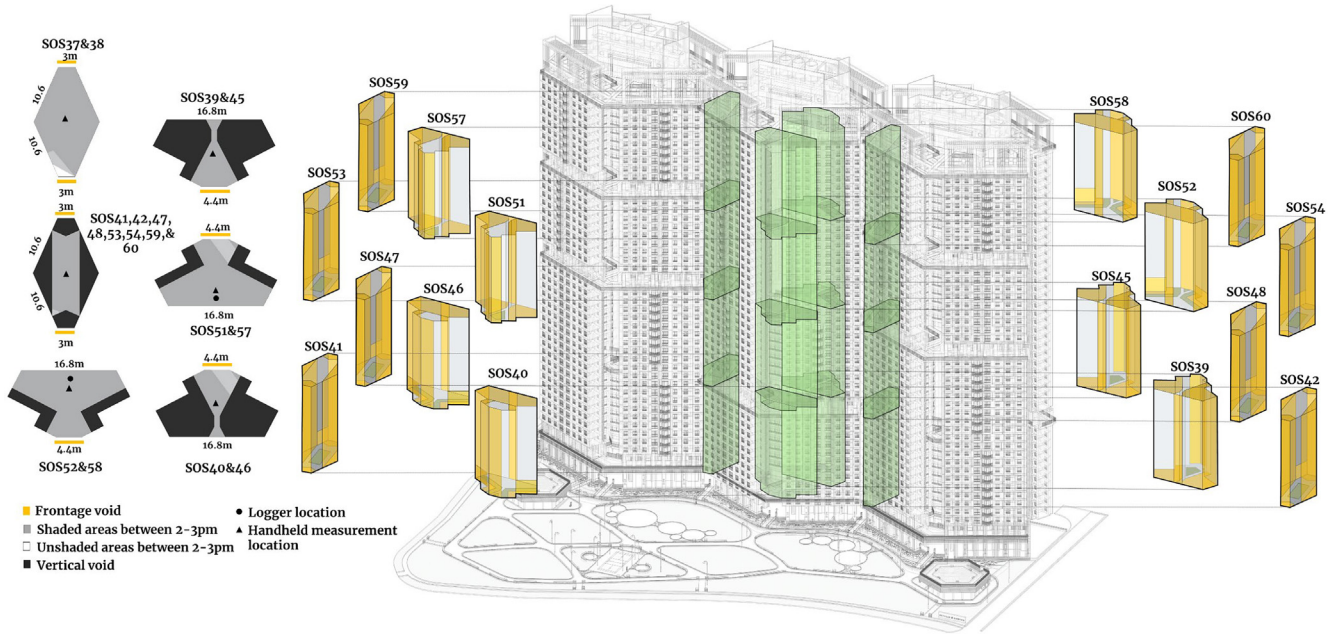
Fig. 7. Right: semi-outdoor spaces (SOS) labelled previously as *vertical breezeway*s, where yellow colour indicates voids. Left: dimensions, measurement locations and shading conditions between 2 and 3 pm (Reference day: SV: July 24). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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

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	m²	Vertical openings the *volume* of the semi-outdoor space [19].
Solid	m²	Opaque vertical surfaces (i.e. walls, columns, fenestration) the *volume* of the semi-outdoor space has [19].
Area	m²	Total amount of surface area in the semi-outdoor space that is sheltered.
Volume	m³	*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 [65], 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 [65], 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 [66]. It was calculated using the Sketchup *Sky View Analysis* plugin [67].
Green plot ratio (GnPR)	%	Ratio between the total Leaf Area Index (LAI) to the total area of the space (m²) [68], 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 [69].
Height from ground (HFG)	m	Distance of the semi-outdoor space from ground/street level.
Orientation	°	Cardinal point the semi-outdoor space is facing, in relation to the north up to south (0-180°).

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.

2.2.1. Microclimatic variables in semi-outdoor environments

T_a and RH readings taken every 10 min were converted to hourly data. A 6-day average of T_a and RH at 2p.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 2p.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 2p.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 4p.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. − 4p.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 [72]. 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
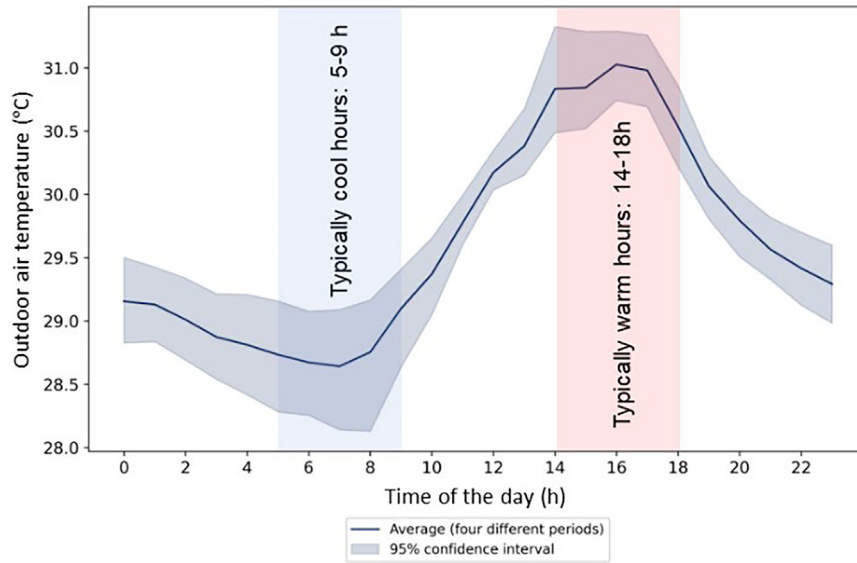
Fig. 8. Average T_{out} for each hour of every day monitored during the four different periods outlined in Table 2.

(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 [73]. Gagge's SET* and PMV* were calculated using *calcSET( )* and *calcPMVStar( )* functions within the *comf* 0.1.11 package in R [74]. The PET thermal comfort index was calculated using the *pet_steady( )* function within the *pythermalcomfort* 2.5.1 package in Python [75]. Thermal comfort was estimated using microclimatic variables (i.e. T_a, T_{mrt}, V_a and RH at 2p.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 [48,76]. 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 0.9 m/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. Fig. 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 Mendeley Data [107] and GitHub (https://github.com/jgamerosalinas/Supplementary-Materials.git). Supplementary data

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 [77]. 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 [78]. KMO and Bartlett's test were calculated in R software using the *psych* package's *KMO( )* and *cortest.bartlett( )* functions [79], 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 for factor analysis using the Maximum Likelihood estimation (MLE) method [80,81]. The MLE method is an inferential method that provides the estimates of the parameters that most likely produce the aforementioned correlation matrix [81].

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 [82]. Values below the borderline are probably spurious [83]. Parallel Analysis was performed in R software using the *fa.parallel( )* function within the *psych* package [79].

2.3.1.4. Rotating and interpreting the factor pattern matrix. Following the determination of the number of underlying factors, a rotated
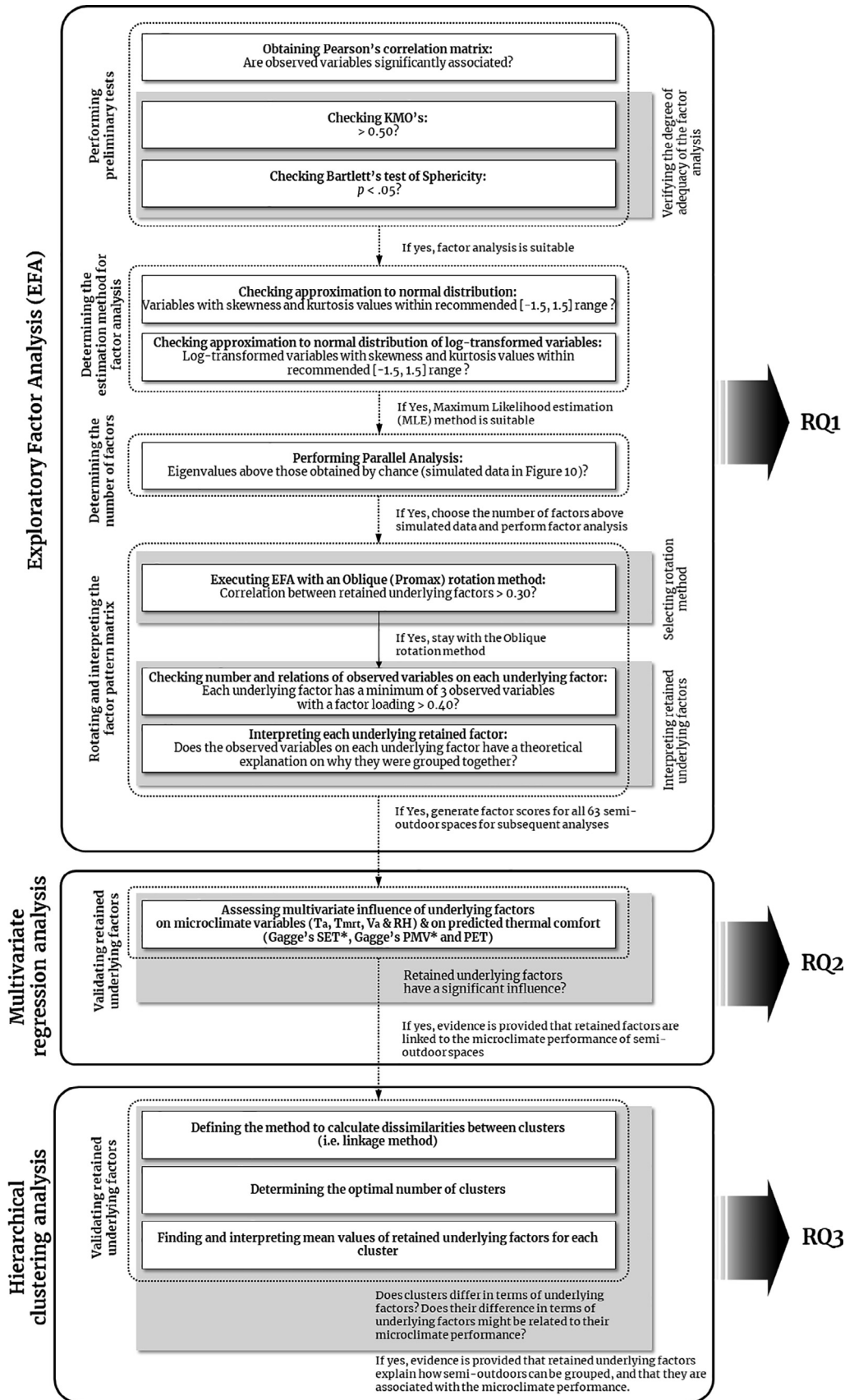
Exploratory Factor Analysis (EFA)

Performing preliminary tests

Obtaining Pearson's correlation matrix:
Are observed variables significantly associated?

Checking KMO's:
> 0.50?

Checking Bartlett's test of Sphericity:
$p < .05$?

Verifying the degree of adequacy of the factor analysis

If yes, factor analysis is suitable

Determining the estimation method for factor analysis

Checking approximation to normal distribution:
Variables with skewness and kurtosis values within recommended [–1.5, 1.5] range?

Checking approximation to normal distribution of log-transformed variables:
Log-transformed variables with skewness and kurtosis values within recommended [–1.5, 1.5] range?

If Yes, Maximum Likelihood estimation (MLE) method is suitable

Determining the number of factors

Performing Parallel Analysis:
Eigenvalues above those obtained by chance (simulated data in Figure 10)?

If Yes, choose the number of factors above simulated data and perform factor analysis

Rotating and interpreting the factor pattern matrix

Executing EFA with an Oblique (Promax) rotation method:
Correlation between retained underlying factors > 0.30?

Selecting rotation method

If Yes, stay with the Oblique rotation method

Checking number and relations of observed variables on each underlying factor:
Each underlying factor has a minimum of 3 observed variables with a factor loading > 0.40?

Interpreting each underlying retained factor:
Does the observed variables on each underlying factor have a theoretical explanation on why they were grouped together?

Interpreting retained underlying factors

If Yes, generate factor scores for all 63 semi-outdoor spaces for subsequent analyses

RQ1

Multivariate regression analysis

Validating retained underlying factors

Assessing multivariate influence of underlying factors
on microclimate variables (Ta, Tmrt, Va & RH) & on predicted thermal comfort
(Gagge's SET*, Gagge's PMV* and PET)

Retained underlying factors have a significant influence?

If yes, evidence is provided that retained factors are linked to the microclimate performance of semi-outdoor spaces

RQ2

Hierarchical clustering analysis

Validating retained underlying factors

Defining the method to calculate dissimilarities between clusters
(i.e. linkage method)

Determining the optimal number of clusters

Finding and interpreting mean values of retained underlying factors for each cluster

Does clusters differ in terms of underlying factors? Does their difference in terms of underlying factors might be related to their microclimate performance?

If yes, evidence is provided that retained underlying factors explain how semi-outdoors can be grouped, and that they are associated with the microclimate performance.

RQ3

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

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 [84]. Because almost all phenomena studied in many fields of science are somewhat interrelated, an oblique rotation was preferred rather than an orthogonal one [81]. 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 [85]. 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 [79].

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}, V_a, and RH) and the predicted thermal comfort of semi-outdoor spaces, based on the SET*, PMV*, and PET thermal indices. The *lm()* function in R software [86] was used to accomplish this, with underlying factors considered as independent variables, and T_a, T_{mrt}, V_a, RH, SET*, PMV* and PET (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 the *lm.beta()* package [87]. 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 [88].

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 [89]. 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 [90]. The number of clusters was calculated based on the 'majority rule', a reliable method for selecting the best number of clusters [90]. 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 [91], to identify in which cluster each semi-outdoor space 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 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. A1, 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 ($p < 0.001$, df = 64, approx. Chi-squared = 1003.01).

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. Fig. 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).

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

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.*

Variable	Mean	Std.	Kurt.	Skew.	Void	Height	Solid	Volume	Total frontage	Open frontage	Perimeter	SVF	GnPR	Depth	Area	HFG	Orientation
Void (m²)	394.6	402.2	1.4	1.4	1												
Height (m)	12.6	12.1	−1.3	0.8	0.87*	1											
Solid (m²)	426.7	519.0	−1.0	0.3	0.74*	0.73*	1										
Volume (m³)	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 (m²)	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 (°)	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
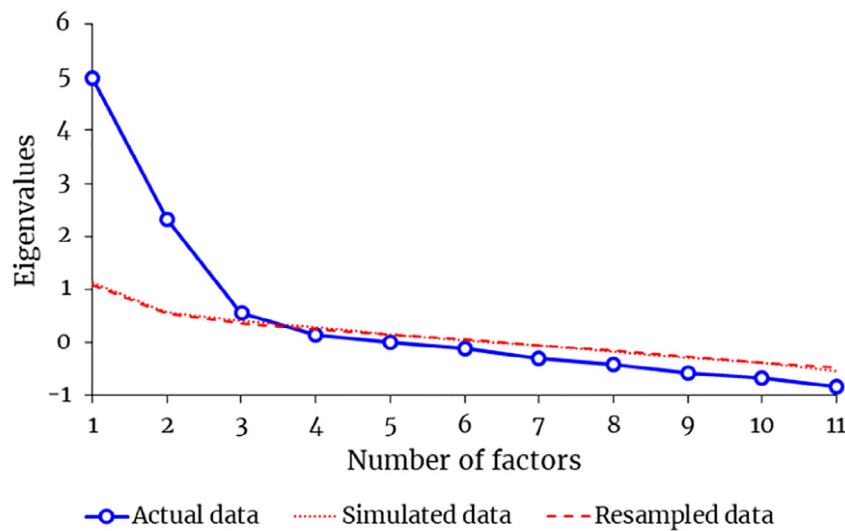
Fig. 10. Parallel Analysis results showing eigenvalues per number of underlying factors.

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.

A summary of all EFA results is depicted in Fig. 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

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.

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

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).

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 2p.m. T_a at 2p.m. in semi-outdoor spaces was significantly lower than T_{out}. T_a values in semi-outdoor spaces ranged between 28.5 °C and 32.0 °C, 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 2.7 °C. 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. A2 and Fig. A3.

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.

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
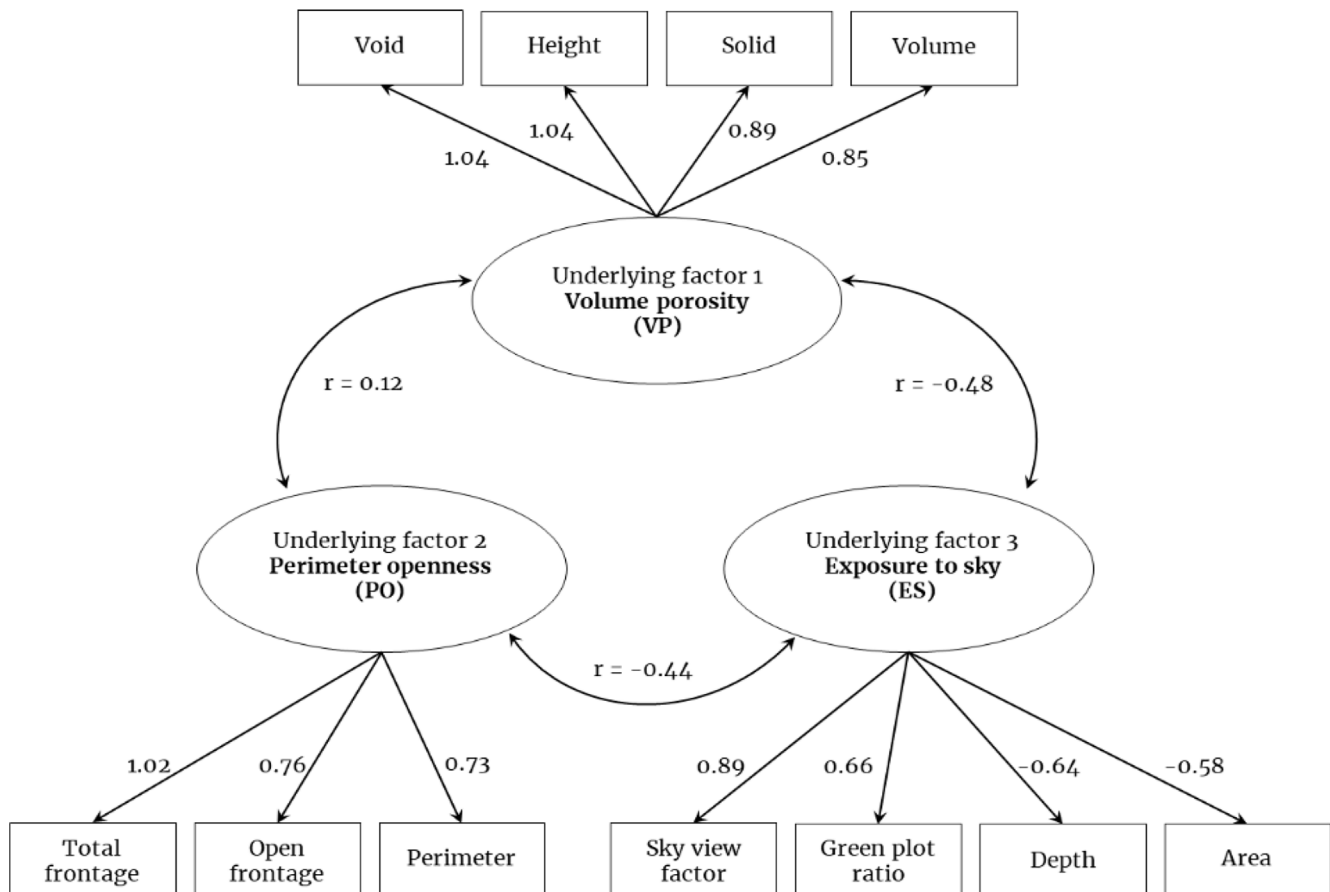

Fig. 11. Graphical summary of results obtained from the Exploratory Factor Analysis (EFA). Note: straight lines are factor loadings shown in Table 6, curved lines are correlations (r), rectangles are observed/manifest variables (i.e. spatial attributes) and ovals are the retained underlying factors.

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 Fig. 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. Fig. 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. A4 and Fig. A5 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*

Table 9
Standardised (outside parenthesis) and unstandardized coefficients (inside parenthesis) of multivariate regression analysis having PET thermal comfort index as dependent variable. Note: * p-value < 0.05.

	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)

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. A2 and Fig. A3 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.

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 Fig. 11). In other words, a highly *porous* semi-outdoor space is not the same as a highly *open* or a highly *exposed* semi-outdoor space according to findings (see Fig. 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
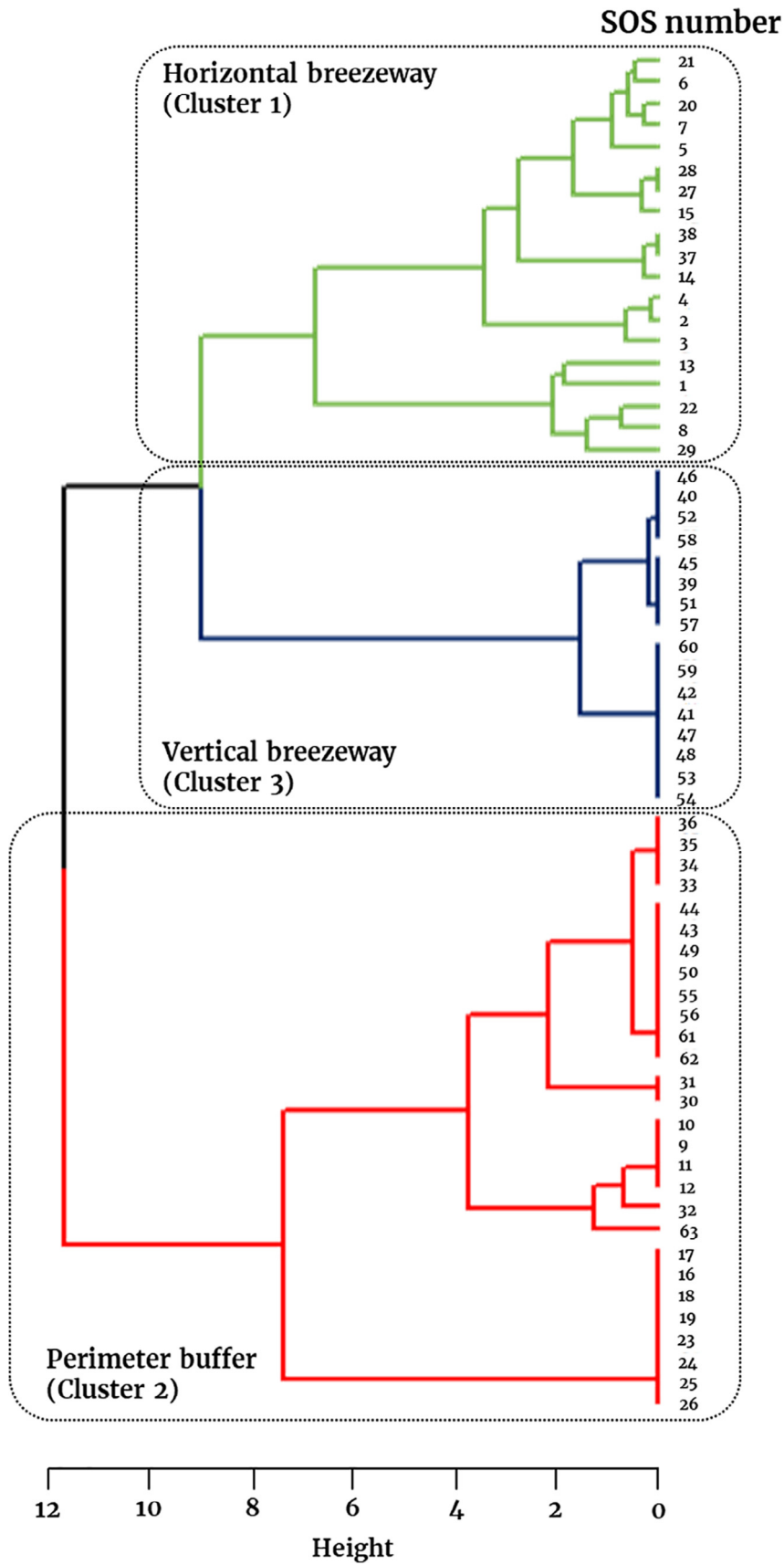
Table 7
Standardised (outside parenthesis) and unstandardized coefficients (inside parenthesis) of multivariate regression analysis having microclimatic variables (T_a, T_{mrt}, V_a and RH) as dependent variables. Note: * p-value < 0.05.

	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 8
Standardised (outside parenthesis) and unstandardized coefficients (inside parenthesis) of multivariate regression having Gagge's SET* and PMV* thermal comfort indices as dependent variables. Note: * p-value < 0.05.

	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)

Fig. 12. Dendrogram showing identified clusters: *horizontal breezeway* (cluster 1), *perimeter buffer* (cluster 2) and *vertical breezeway* (cluster 3).
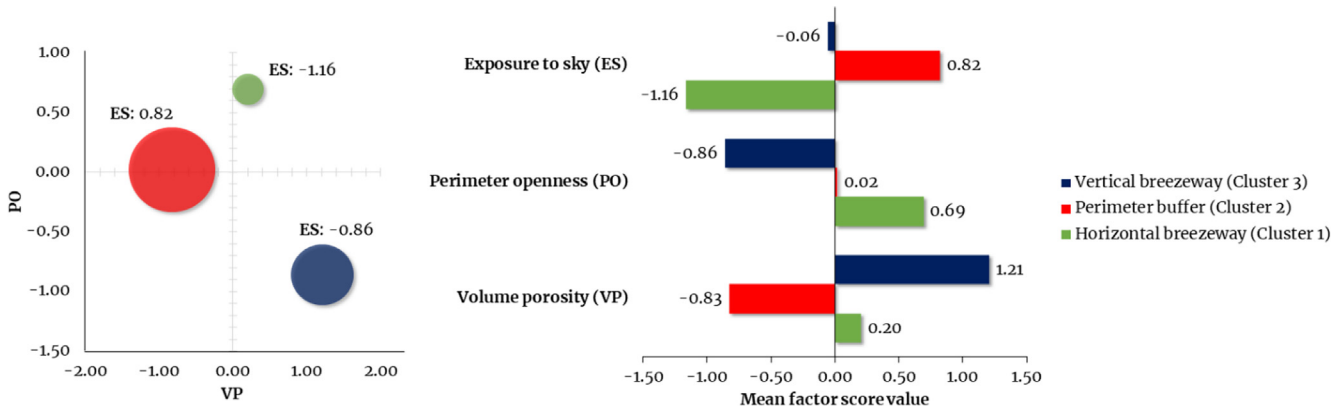
Fig. 13. Bubble chart (left) and bar graph (right) showing mean factor scores of each cluster in terms of underlying factors retained by the Exploratory Factor Analysis (EFA).

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

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 (°C)	29.73	29.68	29.76
T_{mrt} (°C)	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 (°C)	26.93	26.54	25.64
SET* 1.5 MET (°C)	28.69	28.35	26.77
SET* 2 MET (°C)	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 (°C)	30.35	29.88	29.04
PET* 1.5 MET (°C)	31.20	30.73	29.71
PET* 2 MET (°C)	32.05	31.57	30.37

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 [92–96]. Some studies have linked the concept of *openness* to microclimate performance [19,97]. 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 [13,98–100]. 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* [70,71,76], 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. 2p.m.), when most semi-outdoor spaces are shaded (see Fig. 3 - Fig. 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 [101]. 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. Fig. 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. 2p.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 [81,102,103], 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 [103]. 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 [12,70,104–106]; 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.

Data availability

We have shared our code in GitHub (https://github.com/jgameros-alinas/Supplementary-Materials.git) and Mendeley Data (http://dx.doi.org/10.17632/9wyjpnwghk.5). We have also shared our data for conducting the Exploratory Factor Analysis (EFA) in Table 5.

Declaration of Competing Interest

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.

Acknowledgements

Appendix A Supplementary data

Supplementary material related to this article can be found at Mendeley Data [107] and Github repository (https://github.com/jgamerosalinas/Supplementary-Materials.git).
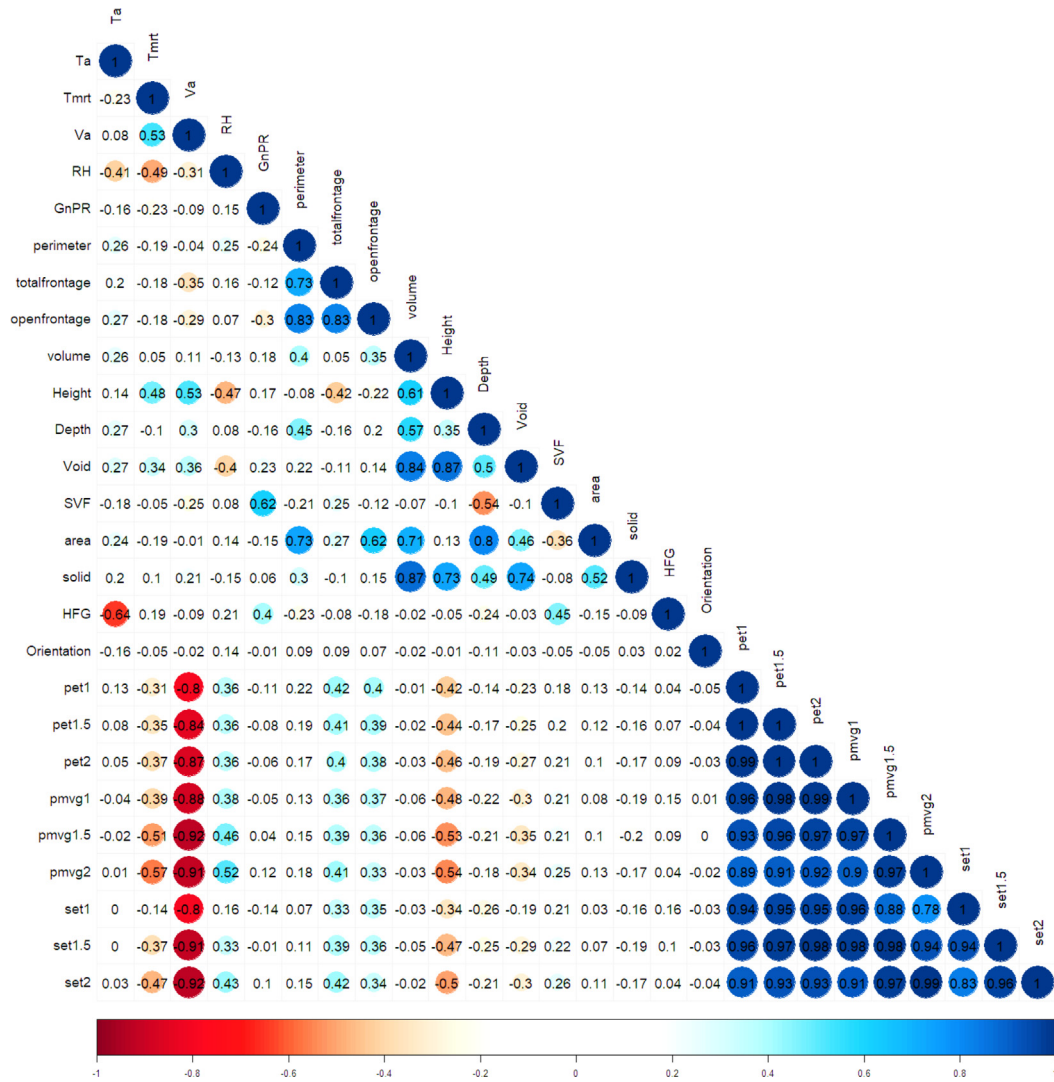
Fig. A1. Correlogram showing Pearson's correlation coefficients for spatial attributes, microclimatic variables and thermal comfort indices.
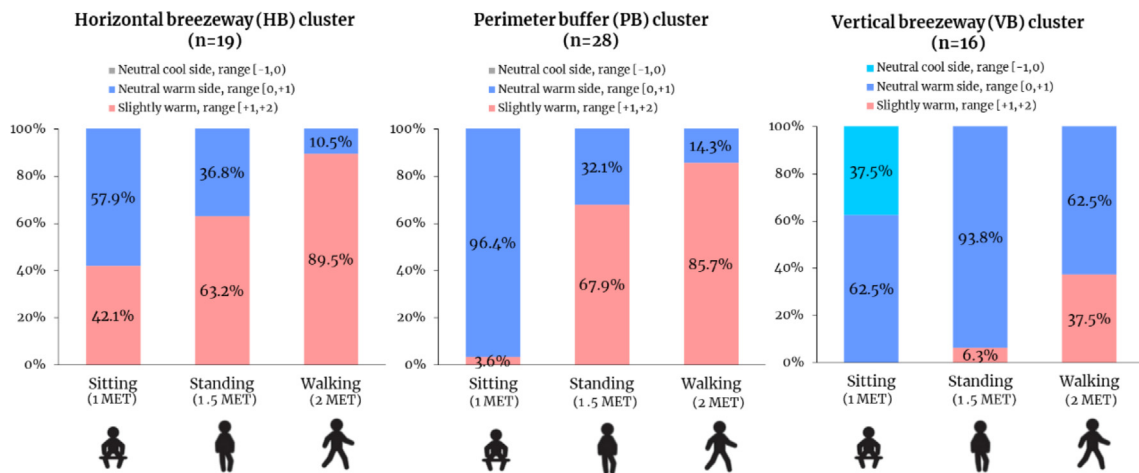

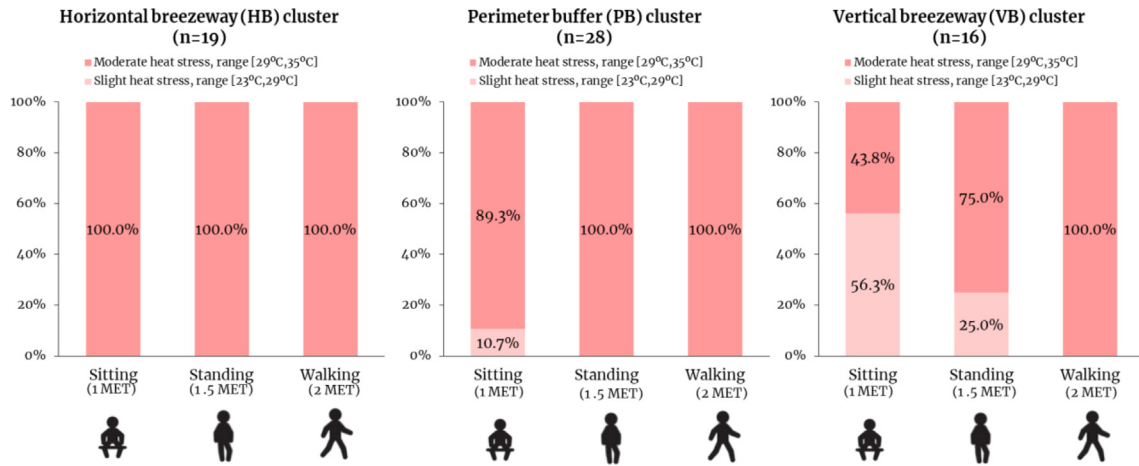**Fig. A2.** Thermal comfort levels achieved on each cluster based on Gagge's PMV* thermal index.

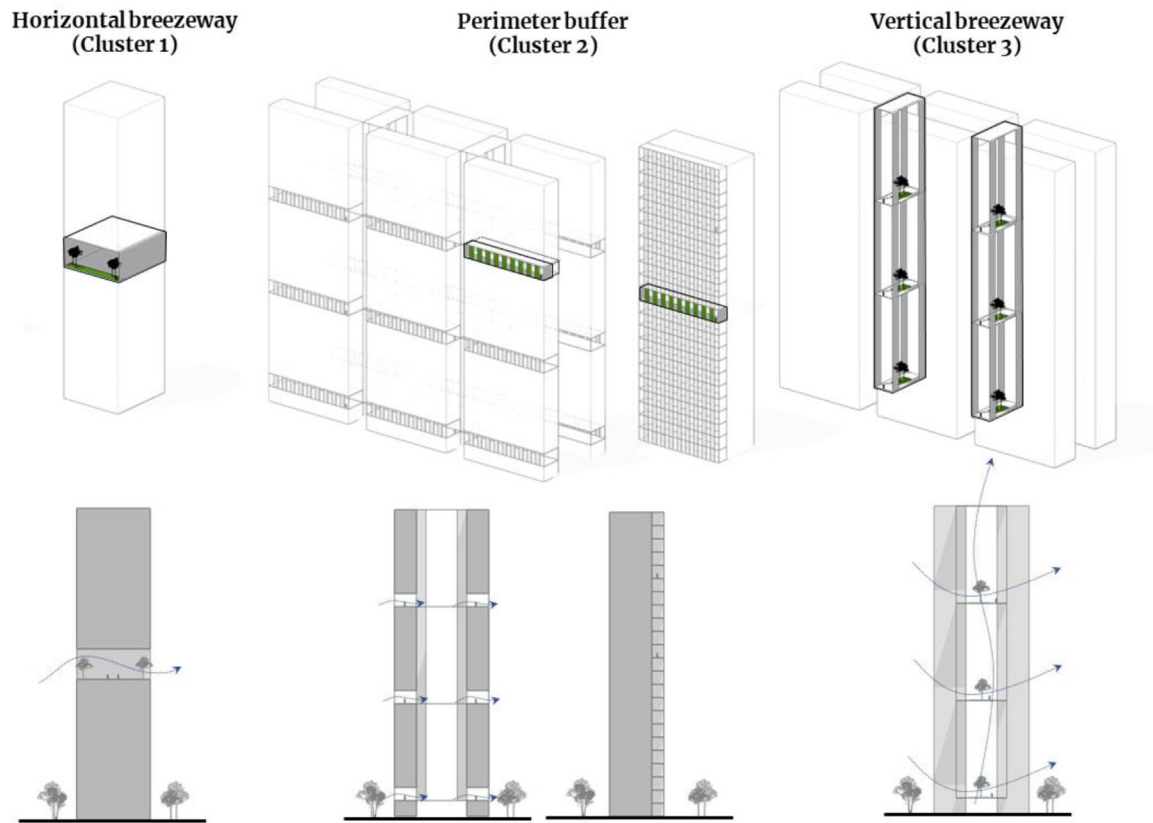**Fig. A3.** Thermal comfort levels achieved on each cluster based on PET thermal index.

Fig. A4. Conceptual representation of clusters in relation to how they are attached or embedded to building forms. Note: 3D models of buildings are 'to scale'.
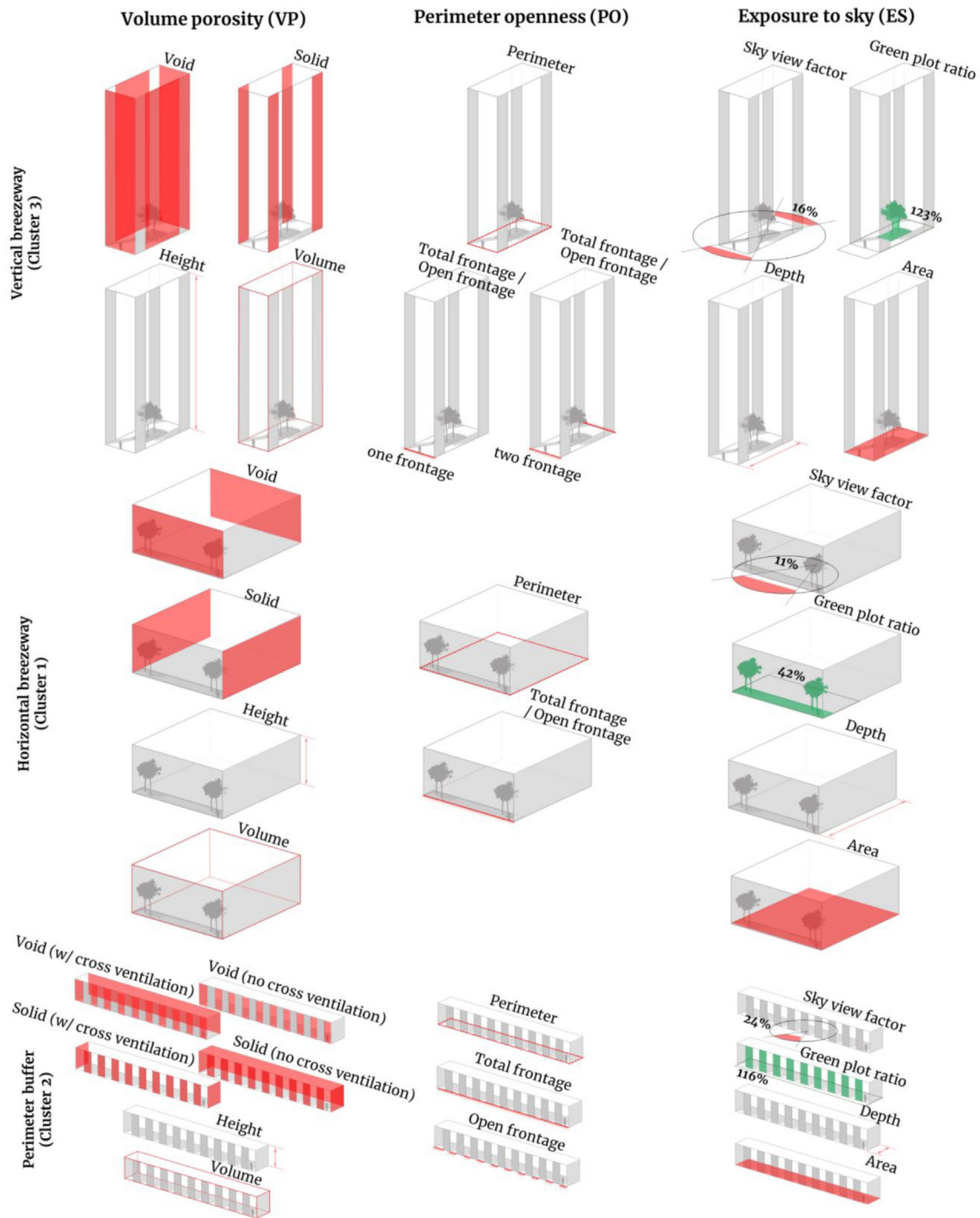
Fig. A5. Conceptual representation of clusters generated by the hierarchical clustering analysis (height, depth and total frontage values in Table 10 were used as reference values for modelling). Note: 3D models of clusters are 'to scale'.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2022.112339.

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