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Analysing impacts of urban morphological variables and density on outdoor microclimate for tropical cities: A review and a framework proposal for future research directions

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ABSTRACT

Modifying urban morphology, defined as mass, density, and orientation of building stock in cities, are well-known heat mitigation strategies addressing urban heat islands (UHI) at various scales and consequent thermal discomfort. However, varying morphological aspects may have divergent effects on Outdoor Thermal Comfort (OTC) in cities. Unlike UHI, which is derived from urban-rural temperature differences, OTC can be quantified by thermal comfort indices considering the objective assessment of microclimatic variables including air temperature (T_a), relative humidity (RH), mean radiant temperature (T_{MRT}), and wind speed (V_a), as well as a subjective assessment of individual perception. In Singapore and other tropical cities, thermally uncomfortable conditions prevail year-round due to higher T_a and RH coupled with high solar irradiance from its equatorial location. To better understand the relationship between density related morphological variables, microclimate conditions and OTC in Singapore, we first conduct a systematic literature review to identify existing research gaps and uncertainties. We subsequently analyse prominent building bylaws and urban planning codes of Singapore to understand the potential comfort implications of existing urban morphological norms. Finally, we propose a methodological framework on how to address the gaps and uncertainties in mainstream urban design and urban planning process keeping into consideration microclimatic, comfort and socio-economic variables.

1. Introduction

The combined processes of urbanisation have led to significant changes to physical near-surface climates. In particular, the alterations of surface energy balance via the construction of physical urban infrastructure are major factors in cities having significantly different climates than their rural surroundings, such as having warmer temperatures attributed to the Urban Heat Island (UHI) effect [1]. These altered climates have, in many tropical and subtropical cities, driven detrimental impacts onto urban residents such as increased heat stress and thermal discomfort [2]. Apart from increased temperatures, humid and low-wind conditions are also factors that increase thermal discomfort in low-latitude cities year-round [3].

The mass, density, and orientation of building stock in cities - categorised by urban morphology - are important physical factors in significantly altering urban climates [4]. Manipulation of urban morphology is well understood in reducing UHI intensities [5]. However, altering these factors can also have different effects on Outdoor Thermal Comfort (OTC), in which exposure to radiant heat, wind speeds and atmospheric moisture can be more significant in affecting individual perception and sensation to OTC relative to air temperatures [6,7] especially for tropical and subtropical climates. Recent studies explored the impact of urban morphology or related variables on climatic conditions of outdoor spaces in subtropical climate categories. Zheng et al., (2021) [8] investigated appropriate spatial domains of surrounding building regions for predicting wind flow characteristics around a specific building considering variations in layouts (e.g., heights, densities, and arrangements) in the humid continental climate city of Dalian, China. Liu et al., (2021) [9] considered seven cities in four thermal

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List of abbreviations and acronyms

Abbreviation/Acronym	
AH	Anthropogenic Heat
BD	Building Density
BH	Building Height
BCA	Building Construction Authority
CBD	Central Business District
CFD	Computational Fluid Dynamics
DDES	Delayed Detached Eddy Simulation
FAD	Floor Area Density
FAI	Frontal Area Index
FAR	Floor Area Ratio
FnAR	Frontal Area Ratio
GCR	Ground Cover Ratio
GnPR	Green Plot Ratio
GSC	Gross Site Coverage
HDB	Housing Development Board
HDR	Height-to-depth Ratio
HFG	Height from ground level
H/W	Height to aspect ratio
ITCZ	Intertropical Convergence Zone
LAD	Leaf area density
LCZ	Local Climate Zone
LES	Large Eddy Simulation
LCP	Least Cost Path
MEMI	Munich Energy Model for Individuals
NEV	Net Escape Velocity
OMVR	Overall Mean Wind Velocity
OSPR	Perimeter-based Open Space Ratio
OSR	Open Space Ratio
OSRA	Area-based Open Space Ratio
OTC	Outdoor Thermal Comfort
OTCA	Outdoor Thermal Comfort Autonomy
OUD	Open Urban Design
PALM	Parallelized LES Model
PET	Physiological Equivalent Temperature
RH	Relative Humidity
SBF	Sea Breeze Front
SGP30	Singapore Green Plan
SET	Standard Effective Temperature
SLR	Systematic Literature Review
SOS	Semi-outdoor Spaces
SUHI	Surface Urban Heat Island
SVF	Sky View Factor
T_a	Air Temperature
T_{mrt}	Mean Radiant Temperature
TSI	Thermal Stress Indicator
UBL	Urban Boundary Layer
UCL	Urban Canopy Layer
UHI	Urban Heat Island
UN	United Nations
URA	Urban Redevelopment Authority
UTCI	Universal Thermal Climate Index
V_a	Air Velocity
VCP	Ventilation Corridor Planning
VE	Ventilation Efficiency
VF	Visitation Frequency
VM	Velocity Magnitude
VSR	Void-to-solid ratio
λF	Frontal area density

climate zones in China to evaluate the impact of shading on the energy demand of buildings using parametric methods and energy simulations. Su et al., (2022) [10] evaluated urban forms and the outdoor environment in a cold northern city of China considering coupling relationships of thirty points between the urban morphology and outdoor environment performance at the pedestrian level for different scales. Cui et al., (2021) [11] investigated the impact of building layouts and envelope features such as balconies, overhangs, and wing walls on pollutant exposure to evaluate the health risks for pedestrians and near-road residents using CFD simulation. Guo et al., (2021) [12], in the humid subtropical city of Nanjing, China, explored the impact of greening strategies in reducing pollutant concentration at urban street intersections considering three-way, four-way, and roundabouts intersections and greening layouts. Yang et al., (2021) [13], in Guangzhou, considered the influence of natural solar heating to assess the efficacy of various urban street layouts for improved city breathability, ventilation and pollution removal. Li et al., (2022) [14] used wind tunnel tests to assess the impact of morphological variables (frontal area, planar area, shape and building layout) on the aerodynamic characters. However, these studies are only confined to a specific climatic region, and there is a lack in identifying the context for similar future research in tropical, humid and low-latitude high density cities.

In this regard, a thorough systematic assessment of how urban OTC is influenced by the building morphology would provide useful information for urban climate scholars, planners, and municipal policymakers in determining holistic climate adaptation and mitigation, especially with the twin drivers of urbanisation and climate change affecting future climate risk in settlements. Thus, in this paper, we examine the physical relationships between urban morphology, micro- and local-urban climate, and OTC for a large low-latitude city (Singapore). We first conduct a Systematic Literature Review (SLR), and subsequently propose a methodological framework accounting for climate modelling, observation of microclimatic variables, and the use of established thermal comfort indices.

2. Background and literature review

Based on other studies, especially within the cities in the tropical and sub-tropical climates, it is evident that urban morphology directly influences OTC [15–17]. However, there is a lack in formulating a comprehensive framework linking the impact on OTC by different built up and non-built-up variables associated with density. Identifying the knowledge gaps and associated uncertainties in observing and modelling OTC - through a thorough SLR - would enable planning that holistically reduces urban heat risk. For instance, the Singapore Green Plan 2030 (SGP30), has a focus on improving thermal comfort, reducing urban overheating, and increasing energy efficiency throughout the island state. Modifying urban morphology can be a viable science-based approach in contributing to the SGP30.

2.1. Methodology

We have adopted the SLR approach in this study (Fig. 1). We focus on 1) reviews and individual studies analysing the relationship between urban morphology, outdoor microclimate, and thermal comfort; 2) impact of various density-related morphological parameters on OTC; 3) their application on urban design proposals and guidelines, and 4) relevance of assessing OTC and urban morphology relation for tropical high-density contexts. In this manuscript, we have used the terms “morphological variables,” “density-related variables” and “density related morphological variables” interchangeably.

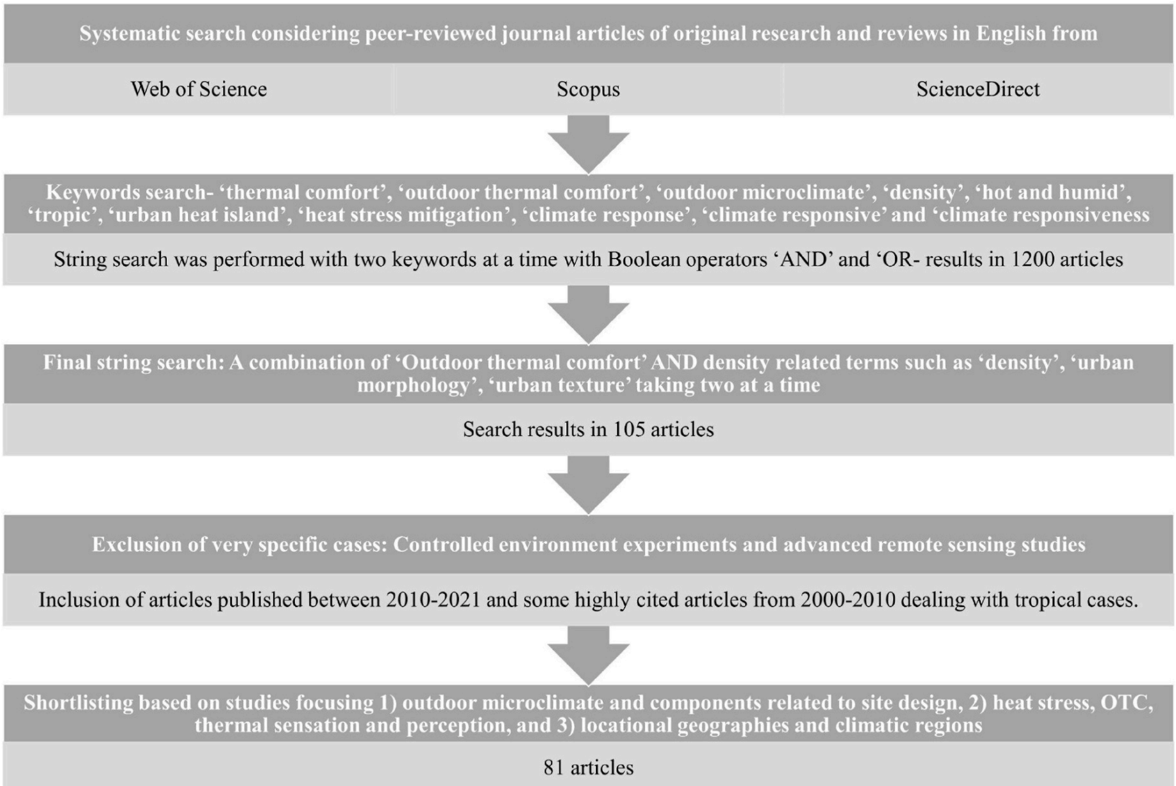

Fig. 1. Systematic Literature Review methodology, shortlisting and final selection.

The SLR used a systematic search considering peer-reviewed original research journal articles and reviews done in English from "Web of Science," "Scopus" and "ScienceDirect" databases. First, we searched keywords from several widely cited articles on OTC perception and microclimate research. These included 'thermal comfort,' 'outdoor thermal comfort,' 'outdoor microclimate,' 'density,' 'hot and humid,' 'tropic,' 'urban heat island,' 'heat stress mitigation,' 'climate response,' 'climate responsive' and 'climate responsiveness.' Then we conducted a string search with two keywords at a time using the Boolean operators 'AND' and 'OR.' This resulted in over 1200 articles with all combinations. We performed the final string search with a combination of 'Outdoor thermal comfort' AND density related terms such as 'density,' 'urban morphology.' Cumulative search results return 105 articles in Scopus. All the articles found in Science Direct and Web of Science overlaps with the mentioned two other databases. We excluded extremely specific cases, such as controlled environment experiments and advanced remote sensing studies, as the former uses experiments having controlled environmental responses (e.g., in laboratory chambers) while the latter analyses surface temperatures for SUHI while omitting UCL and UBL temperature data that are relevant for OTC.

We reviewed articles published between 2010 and 2021 and included several pioneering and influential research studies from tropical cities that were published before 2010 which were highly cited. Further, we performed a shortlisting based on 1) studies focusing on outdoor microclimate and its components associated with site design, 2) studies dealing with heat stress, OTC, thermal sensation, and perception, and 3) locational geographies and climatic regions. Hence, the final sorting culminates in eighty-one articles for this SLR. We grouped these studies into four categories: 1) neighbourhood morphology vs. OTC, 2) presence of vegetation vs. OTC, 3) wind corridor vs. OTC, 4) city breathability vs. OTC. The literature review helped in extracting variables related to urban morphology, density, and site planning (Table 1).

Further, we conducted a bibliometric analysis using VOSviewer, for keywords associated with extant literature. VOSviewer is a software which is used as a tool to create and visualize bibliometric networks. The analysis shows a shifting trend of the keywords over the last decade (Fig. 2), with the initial focus more on general keywords such as "urban heat island", "environmental planning", "climate change" and "cfd simulations"; however, towards the end of the decade (2010–2020), the focus was more on specific building-related keywords such as "building form", "cooling load", "discrete energy performance" and "airflow rate ventilation". This shows there is an increased trend of research considering Anthropogenic Heat (AH) and its influence on energy use on indoor cooling with building form. However, some generic keywords remained important such as "outdoor thermal comfort," "thermal comfort," "urban design," "microclimate," "computational fluid dynamics" (CFD) as well as "large eddy simulations" (LES). This association study also shows that during the past decade (2010–2020), 1) urban morphology and building form related studies dealt with cooling load and microclimate analysis, 2) thermal comfort related studies discussed urban design and street canyons, 3) airflow related studies adopted LES and CFD approach, 4) coastal cities focused on utilizing sea breeze for mitigating UHIs, whereas 5) cooling potential of vegetation was explored with respect to the leaf area.

2.2. *Urban morphology vs OTC*

Urban morphological variables such as street geometry, building height, and site coverage affect the microclimatic profile, hence significantly impacting the OTC (Table 2). Studies have discussed the influence of building porosity [29,51,52], mutual shading [24,20], orientation [26] and site design [28,19] implications on OTC for humid tropical and subtropical cities. In an editorial article, Emmanuel and Steemers, (2018) [53] discussed the context of urban density, form, and microclimate. They evaluated the consequences of compact urban form on energy, thermal comfort, ventilation, and air quality aspects while mentioning both positive and detrimental effects of shading on urban overheating. On the local- and district-scale energy implications of

Table 1
Density variables used for various studies (compiled by authors).

	Studies	Köppen Climate Classification	Density Parameters
Urban Morphology	[18]	Tropical rainforest (*Af*)	Floor Area Ratio (FAR), Gross Site Coverage (GSC), Open Space Ratio (OSR), Number of stories, Sky View Factor (SVF)
	[19]		Void-to-solid ratio, Building Height (BH), Height-to-depth ratio, Height from ground level, Green Plot Ratio (GnPR), Open Space Ratio
	[20]		Orientation, Aspect Ratio (H/W), Height profile, Block form
	[21,22]	Tropical monsoon (*Am*)	H/W, Presence of shade, FAR,
	[23]		SVF, H/W, BH, Amount of vegetation, FAR
	[24]	Tropical wet and dry climate (*Aw*)	Different street patterns, Built area coverage, BH, Amount of vegetation
	[25,26]	Humid subtropical (*Cfa*)	Street orientation, H/W, Building typology
	[27]	Bordering Humid subtropical (*Cfa*) & Mediterranean climate (*Csa*)	Floor to floor height, BH, FAR, Building length and depth, Building volume, Total façade, Constant air change, Occupant density, Materials for external wall, Tree type, Distance between trees
	[28]	Mediterranean climate (*Csa*)	SVF, Vegetation density, H/W, Surface density, Volume density
	[29]	Humid continental (*Dfa*)	BH
	[9]	Humid continental (*Dwa*)	BH, Building density (BD), FAR, Frontal Area Index (FAI), Roughness Length (RL), Vegetation coverage and impervious cover
Breathability	[30–32]	Humid subtropical (*Cfa*)	Availability of shade, Surface materials, Presence of vegetation, SVF
	[33]	Temperate oceanic (*Cfb*)	Homogeneity and heterogeneity of packing densities
	[34]	Monsoon-influenced humid subtropical (*Cwa*)	Canyon morphology
	[35]	Humid subtropical (*Cfa*) & Hot summer continental (*Dwa*)	Residential building arrangement, Building length, Lateral spacing and layouts on four typical space patterns under wind directions oblique or perpendicular to the main (long) building facade
Vegetation	[36]	Tropical monsoon (*Am*)	LAI (tree density and age), SVF, Shading distribution, Crown width, Crown height, Tree height (TH), Tree species, Tree grouping, Canopy density, Size and shape of a tree.
	[37]	Humid subtropical (*Cfa*)	SVF, Building footprints, BH, Street widths and orientation, TH, Tree crown radius, Length and diameter of tree trunk
	[38]	Monsoon-influenced humid subtropical (*Cwa*)	BH, Leaf Area Density (LAD), Presence of Roof greening, Tree coverage of the site area, Grass surface coverage, H/W
	[39]		SVF, BH, Street orientation, LAD, Crown Characteristics
	[40]		GnPR, Tree coverage and species, Type of canopy, FAI, Zero Displacement Height, RL, Friction velocity and drag force of trees, LAI
	[41]	Hot summer continental (*Dwa*)	Street canyon orientation, Presence of trees/shrubs/bushes/grass
Wind Corridor	[42]	Tropical monsoon (*Am*)	FAI
	[43,44]	Monsoon-influenced humid subtropical (*Cwa*)	FAI, Building density, BH
	[45]		Building separation, Building set back, and Green coverage.
	[46]		Ground coverage ratio, FnAR, plot ratio, varying building height
	[47]		Shape of the urban area (square or circular)
	[48]		FnAR, H/W, BH
	[49,50]	Monsoon-influenced humid subtropical (*Cwa*); Humid subtropical (*Cfa*)	Street width, BH

density, both shading and ventilation are individually important for mitigating heat, but the interaction between both is yet to be explored.

2.2.1. *Tropical climates*

Our search result shows studies in the low latitudes originate from the tropical rainforest *(Af)* [18–20], and monsoon *(Am)* [21–23] climatic regions per Köppen Classification, while relatively fewer studies take place in tropical wet and dry savannah *(Aw)* climates [24]. *Am* climate studies employed CFD simulation with ENVI-met to examine impacts of Aspect Ratio of Street Canyon (H/W) on outdoor microclimate and OTC. They concluded that compact and unplanned developed areas with narrow streets, flanked by tall buildings, provide better comfort and cooling conditions compared to the formally planned areas with wider streets [21,22,23]. Extant literature catering to *Af* climates discussed various site planning parameters in the context of Singapore such as Floor Area Ratio (FAR), site coverage, open spaces [20] as well as green coverage and impact of vegetation [18,19] to understand the impact of urban morphology on OTC. Ignatius et al., (2015) [18] reported compact urban forms reduce the external heat gain and sensible cooling load, while wider street canyons allow for better ventilation. Thus, urban geometry arrangement crucially influences wind profiles and energy consumption. Additionally, they mentioned the importance of ground level density (site coverage) to convert paved open spaces into greenery, which reduces outdoor temperatures and improves OTC. Gamero-Salinas et al., (2020) [19] reported that semi-open spaces (SOS) can function as thermal buffer spaces, and further stated that SOS microclimates are related to geometrical parameters such as void-to-solid ratio (VSR), height, height-to-depth ratio (HDR), height from ground level (HFG), green plot ratio (GnPR) and open space ratio (OSR). The study also concluded that including SOS in mid-rise and high-rise building forms ensures a comfortable microclimate for human activity, even for the hottest hours. A correlation analysis showed that geometrical parameters can explain variations in Air Temperature (T_a), Mean Radiant Temperature (T_{MRT}), Wind Speed (V_a) and Relative Humidity (RH) by 50.4%, 66.8%, 48.0% and 70.1%, respectively. T_a variations can be explained ($R^2 = 0.504$) by VSR, HFG and area-based open space ratio (OSRA). T_{MRT} variations can be explained ($R^2 = 0.668$) by VSR, HDR, GnPR, HFG and height. V_a variations can be explained ($R^2 = 0.480$) by HDR and perimeter-based open space ratio (OSRP). RH variations are explained ($R^2 = 0.701$) by VSR, HDR, HFG, GnPR and OSRA [19].

Acero et al., (2021) [20] discussed the impact of urban design scenarios on OTC using the concept of Outdoor Thermal Comfort Autonomy (OTCA), conceived as per the research conducted by Nazarian et al., (2019) [55]. They reported that in E-W canyons, elevated levels of cloudiness decrease direct solar radiation, whereas higher solar exposure under clear skies exhibited uncomfortable OTC levels. Similarly Yang et al., (2016) [56], commented that N–S oriented streets are most comfortable for Singapore. Rectangular blocks performed best with streets having H/W 2.5. Relevant improvements can also happen for wider streets (e.g., H/W 1.5), since higher solar radiation cannot be countered with higher wind speed [20]. For *Aw* climate in Dar es Salaam, Tanzania, Yahia et al., (2018) reported low-rise buildings were thermally uncomfortable for pedestrians. On the other hand, although street trees were effective in enhancing OTC, the decrease in wind speeds at pedestrian levels negated the cooling effect imparted by

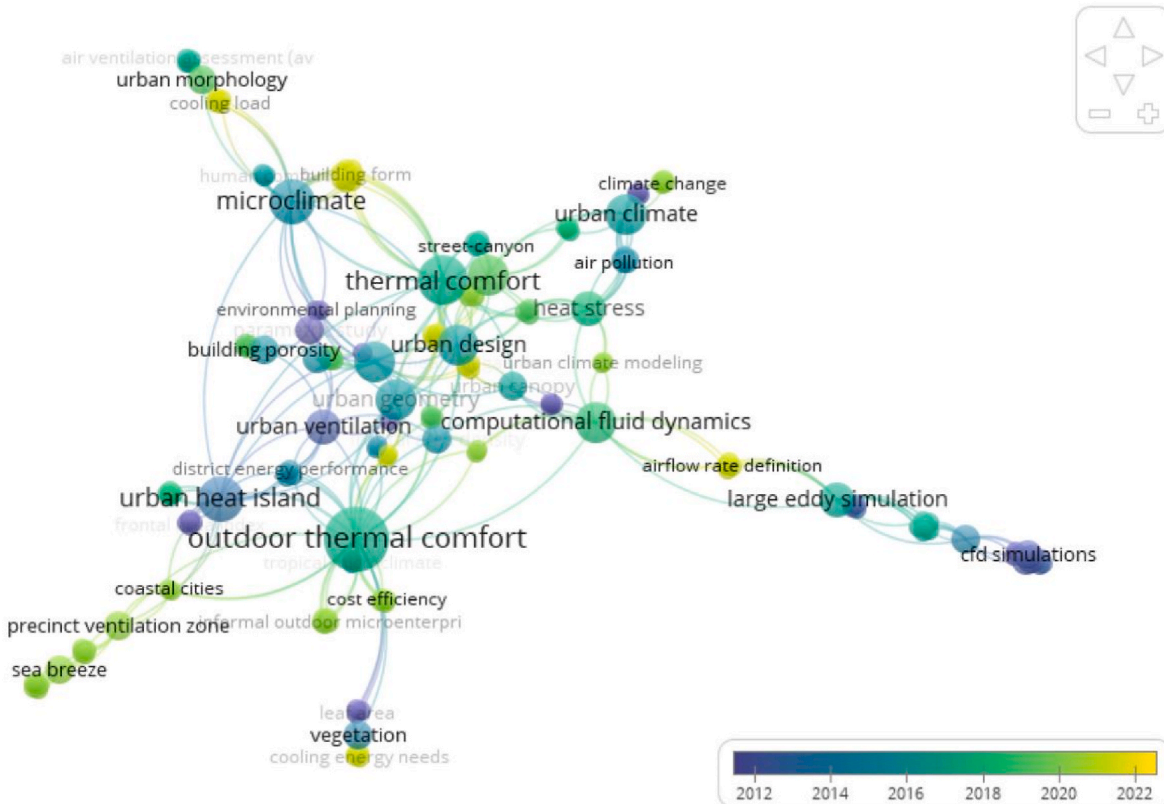

Fig. 2. Bibliometric analysis of the keywords in VOSviewer.

shading. Compared to built-area coverage and FAR, SVF was a better indicator of OTC demonstrating the cooling ability of compact building morphology and vegetation, as that can reduce the solar radiation causing thermal discomfort [24].

2.2.2. *Other humid climates*

Studies focused in Humid Subtropical (*Cfa*) climates discussed urban design options, building typology, occupant density, geometry, and H/W ratios [27,25,26], whilst studies situated in Mediterranean (*Csa*) climates showed the consideration of green coverage aspects [27,28] into the urban morphology for microclimate and OTC analysis. For *Cfa* climate, Ma et al., (2020) [25], reported that optimal urban design was dependent on H/W affecting wind flow and solar radiation within the canyon. They further concluded that tall buildings induced mutual shading can reduce Physiological Equivalent Temperature (PET) the most, followed by evapotranspiration and shading-driven cooling by larger trees.

Given that many tropical cities have complex urban morphology and dense buildings, several CFD studies found that a decrease in building lengths and increasing the low-level porosity are found to improve pedestrian-level comfort [51,52,57]. Highlighting urban design factors for optimum comfort, Abdollahzadeh and Biloria, (2020) [26] found street orientation (46.42%) and H/W (30.59%) to be the top significant variables for planning optimal urban configurations. The percentage here represents the ratio of the difference between the best and the worst option and the value of the best option. For the humid subtropical coastal region of Liverpool, NSW Australia, V_a and shading impacted OTC the most in outdoor areas. Additionally, N–S oriented streets offered more thermal comfort compared to E-W orientations. NE-SW axes with linear building typologies were most suitable to enhance shading and wind flow.

Mangan et al., (2020) [27] discussed trees to be more effective for open spaces in hot-humid climates bordering *Cfa* and *Csa*. The results showed that an increase in building height increases V_a, and decreases T_{MRT} and PET. Additionally, increased space between buildings with a decreasing H/W ratio can increase solar gain, resulting in decrease in total energy consumption in a context where heating energy is needed throughout the year. Some other studies considered building porosity and length while discussing pedestrian level microclimate and OTC. Ouali et al., (2020) [28] focused on the Open Urban Design (OUD) approach for *Csa* climate aimed to improve the ventilation and dissipation of heat accumulated on surfaces during daytime by designing building clusters in dispersed and porous forms around an open space. Results reported that ecological parameters can be introduced as an urban design decision criterion. The study reported T_{MRT} to be significantly impacted by latitude, cloudiness, vegetation, shading, and compactness, while also varying seasonally. They further commented that OUD might not be appropriate for climatic extremes, but this approach might be beneficial to improve OTC in moderate climates, based on morphological variables and vegetation density.

For a humid continental climate (*Dfa*), Berardi and Wang, (2016) [29] highlighted the capabilities of new high-rise constructions in increasing wind speeds around buildings by deepening urban canopies to enable airflow. Their ENVI-met simulations of the Church-Yonge corridor in Toronto, Canada, concluded that locations with increased wind speeds are consistent with lower T_a. Moreover, shadows cast by high-rise buildings not only reduced daytime T_a but lowered the average T_{MRT} too.

In total, most studies are situated in the tropical rainforest and monsoon climates, covering a combination of urban morphology characteristics such as aspect ratio, street orientation, building density and SVF alongside vegetation influence. Attributes related to building density that are less regarded are site coverage, FAR, GnPR that should be considered for optimal urban design and OTC.

Table 2
Changes in microclimatic and comfort variables with a change in urban morphology (compiled by authors).

Source	Changes in urban morphological parameters	Changes in Wind speed	Changes in MRT	Changes in PET	Changes in Air temperature	Conditions
[27]	H/W ratio of 1.00–2.00	Increase up to 0.27 m/s	Differences up to 27.9 °C, 27.4 °C, 26.4 °C, 24.8 °C respectively	11.8 °C, 12.1 °C, 14.3 °C, 14.8 °C respectively		For building heights of 3, 5, 10, & 15 storeys
	H/W ratios of 0.50–2.00		Differences up to 27.9 °C and 27.4 °C respectively	11.6 °C and 13 °C respectively		For 3 and 5 storeys respectively
	Presence of trees	Decrease by approx. 1 m/s	At night, with no direct solar radiation, MRT and PET values on streets with trees were higher than on the streets without trees		Decrease up to 1.6 °C	
[24]	33% plantation in a site	Decrease by more than 50%	Decrease by 7 °C	Decreased from 44 °C to 40 °C		
	Increase of SVF from 0.4 to 0.8			Increase of 3 °C		Compact urban forms reduce the time of solar exposure and amount of direct solar radiation on the ground surface.
[25]	10% increase in tree cover			Decrease by 1.3^{O}C		For a 3-storey building
	3% increase in tree cover			Decrease by 0.78^{O}C.		Hottest time during the extreme summer
	Canyon and open space			Difference of 0.8–12.6^{O}C		
	presence of Trees				Upto 0.3 to 9.2^{O}C decrease	
[28]	Difference between sunlit area and shaded area		MRT 50.9 °C in shade to above 79.6 °C in sunlit area			
	Presence of vegetation	77.2 °C				
[26]	Street width from 8 m to 10 m	Wind speed increases by 8.81%				Specific humidity increases when urban surfaces include greenery.
	NE-SW axis	59.09% higher than NW-SE axis		perform up to 24.95% better than the other three orientation alternatives		
	Increase of 0.5 in aspect ratio		Decrease MRT by 2.9 °C in early morning and 3.31 °C in an average			
	Increase from 0.5 to 1			Increases comfort hour by 30.59%.		
	Densely planted tree @spacing of 4 m		Decrease between 1.49 OC	Decrease PET values up to 12.07%.		
	sparse tree-planting pattern		Decrease 1.32 OC	Decrease to 7.83%		
[20]	High street aspect ratios (2.5–3) and on N–S oriented streets			Best OTC		Higher H/W in the N–S canyon causes wider canyons in the E-W direction resulting in higher exposure to the incoming radiation and worse mean OTC levels.
	NE-SW			Worst OTC		Worst OTC levels for Singapore is generally observed during 11.00AM–16.00PM
	H/W = 3.5 to 2.5, rectangular blocks	Wind flow reduces 0.2 m/s		Slightly worst OTC due to changes in mean wind flow inside the canyon		
	Square blocks			Performs even better than the rectangular blocks		
	Building configuration Low-High-Low to High-Low-High			Best to worst		
[54]	Every unit increase in FAR	Mean ratio reduces by 0.013				
	Mean increase of 20 m in building height	Mean ratio reduces by 0.012				
	10% increase in building density	Mean ratio reduces by 0.021				
	0.2 increase in degree of enclosure	Mean ratio reduces by 0.034				

(*continued on next page*)

Table 2 (*continued*)

Source	Changes in urban morphological parameters	Changes in Wind speed	Changes in MRT	Changes in PET	Changes in Air temperature	Conditions
	Every 20 increase in site spacing	Mean ratio increases by 0.0016				
	A 0.1 increase in SVF	Mean ratio increases by 0.056				

2.3. Presence of vegetation vs OTC

Extant literature reports the impact of vegetation on OTC, with majority of studies comparing the role of trees, shrubs, and grasses [36, 38–41]. For tropical cities, impact of vegetation is paramount as it directly affects ambient humidity. Studies have reported that impervious surfaces lead to more sensible heat vs. latent heat flux, due to reductions in evaporative cooling, low surface reflectivity and reabsorption of reflected radiation by vertical surfaces of buildings and canyons [2]. Greenery can increase the potential of using outdoor, semi-public, and semi-outdoor urban spaces. Trees can reduce radiant heat near the ground surface by reducing sensible heat flux from cooler surfaces and directly ensures evaporative cooling. Wong & Chen, (2008) [3] have promoted the concept of utilizing small green chunks strategically around buildings for their cooling potential.

2.3.1. Tropical climates

Studies conducted in tropical areas considered vegetation as an integral part of the site planning process and analysed the combined impact of built density and vegetation on microclimate. A specific study conducted in tropical (*Af*) Singapore by Yuan et al., (2017) [40] reported the effect of trees on the wind flow depends on urban context density and typology of plant canopies. Tree species having dense and columnar canopy are acceptable, as average wind speed is not significantly impacted by these tree shapes at high-density urban areas. They also stated trees to be more effective than grass and shrubs. Hsieh et al., (2016) [36] explored the effect of plantings on pedestrian thermal comfort in a park for tropical Taiwan (*Am*) during summer. They reported that wind speed and shade influence OTC in terms of SET (Standard Effective Temperature). Higher-SVF areas having thin broad-leaf trees ventilated better, whereas field measurements exhibited areas with dense broad-leaf trees have lower SVF value. The study concluded that without proper planning, an overcrowding of trees can decrease OTC. For tropical and subtropical regions, wind corridors through the urban parks are suggested to promote ventilation and shade to improve OTC considering tree layout and proper trimming [36].

2.3.2. Other humid climates

Existing studies in subtropical and humid climates mostly explored the comparative effectiveness of vegetation options such as various trees, grass, shrubs, rooftop gardens on mitigating heat. Ng et al., (2012) [38] examined different combinations of vegetation scenarios to assess impact of different greening strategies on T_a at pedestrian level for a high-density residential neighbourhood in humid subtropical (*Cwa*) Hong Kong. The study reported the ineffectiveness of roof greening for human thermal comfort but showed the effectiveness of trees over grass surfaces to improve OTC, due to reductions in T_{MRT} from shading. Lowering of 1 °C of T_a required tree coverage of 33% of urban areas. Tan et al., (2016) [39] demonstrated an association between the cooling impact of urban trees and SVF. High SVF scenarios are found to be effective in T_a decrease (1.5 °C decrease). In the cases of vegetation arranged in wind corridors, reduction of T_a and sensible heat were twice higher than the leeward areas. They further reported that tree plantation coupled with proper planning can be effective in mitigating daytime UHI in Hong Kong.

Sabrin et al., (2021) [37] evaluated thermal benefits and cooling potential of street-trees in a humid subtropical (*Cfa*) area of Philadelphia by comparing with and without existing vegetation scenarios on OTC for pedestrians. In the residential and mixed-use sites with higher SVF, planting trees improved pedestrian comfort by decreasing radiative heat. Mixed-use sites provided improved thermal comfort, whereas commercial sites had the least cooling effect from street trees. The study further reported that the amount of radiation fluxes, evapotranspiration, and air circulation were impacted by urban fabric (vegetation and construction), urban morphology (building mass and spaces), and urban cover (types of surface materials).

Lin et al., (2008) [41] explored the effect of vegetation pattern on OTC for the comfort index SET through three numerical simulations, assuming a same total leaf area for the scenarios for trees, grass, and shrubs for the Monsoon-influenced hot-summer humid continental climate (Dwa) in Beijing, China. They reported that presence of trees did not always ensure better pedestrian comfort in summer compared to grass and shrubs, due to the capability of trees in decreasing wind velocity and changes in sun angle. However, the average SET of pedestrian spaces showed the effectiveness of trees over the other two options. They also report that the differential impact of three vegetation patterns on pedestrian comfort is impacted by orientations and arrangements of buildings.

Presence of vegetation is classified in the form of trees, shrubs and grasses with trees being the most beneficial. This is due to its provision of shading for improved OTC across climates. On the other hand, trees' cooling effects are counteracted by decreasing wind velocity that reduces pedestrian OTC. Thus, while trees have significant cooling potential, current urban morphology of the city must be considered prior to tree planting.

2.4. Wind corridors vs OTC

Urban morphology is capable of impacting wind corridors and urban ventilation [58] which can further impact OTC by increasing mean wind velocities, especially for cities in humid regions. Strategically designed buildings and urban design options enable urban spaces with ventilation paths and wind corridors with an efficient combination of built up and urban design elements, coupled with street width and presence of vegetation. For example, the Planning Department in Hong Kong proposed an air ventilation plan in 2003 to understand how to design city fabric for natural wind flow. Many studies subsequently researched the ventilation implications for the city (Fig. 3). As per the ventilation plan, urban design guidelines were proposed considering variables such as building separation, building setback and percentage share of greenery within the site [45]. Previous wind corridor and ventilation studies have covered tropical [59,60], subtropical empirical studies [61,62] and hypothetical studies analysing the impact of urban morphology on ventilation, wind corridor and thermal comfort [46,48,63,64].

Hypothetical cases mostly dealt with evaluating various simulation approaches for assessing wind speed and ventilation path. In one such study, Qu et al., (2012) [63] evaluated the ability of the 3D atmospheric radiation model in simulating thermal effects of buildings on the local scale atmospheric flow under low V_a condition. The study analysed near building cases where thermal stratification impacts the wind speed and

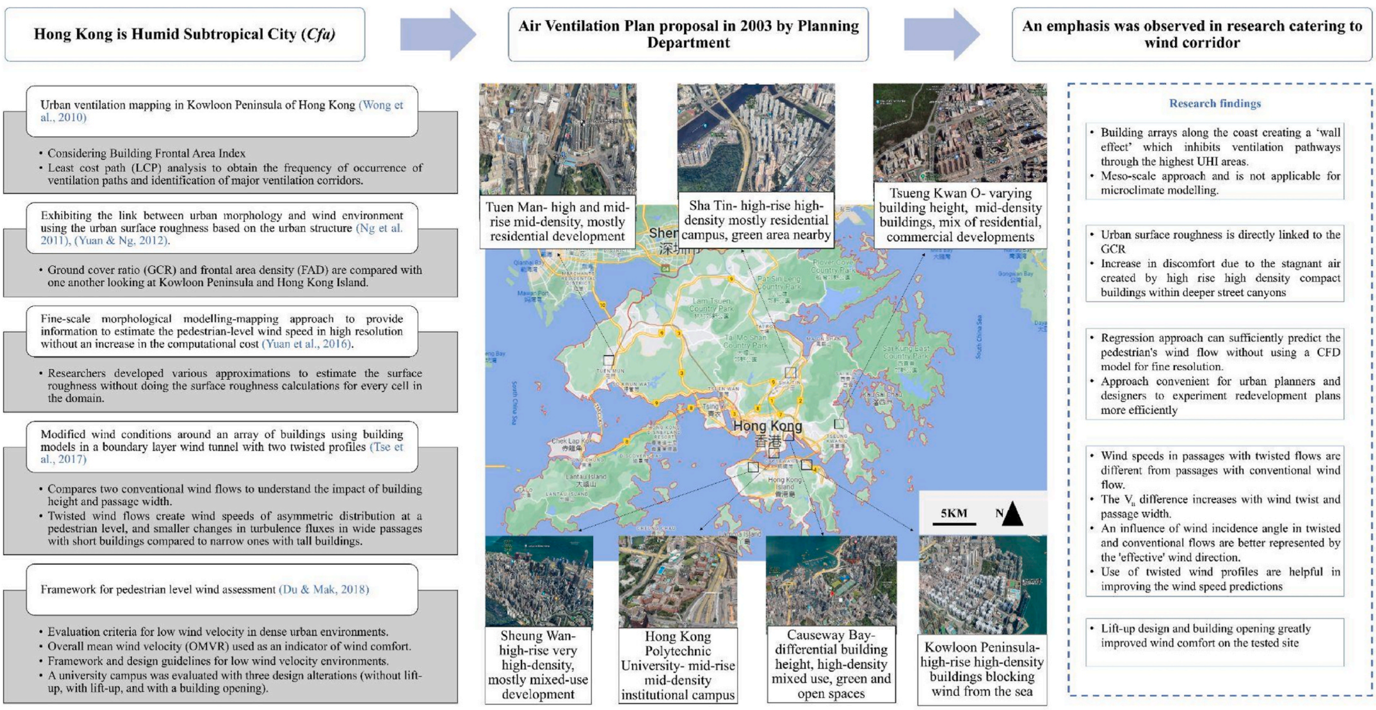

Fig. 3. Case study on wind corridor research in Hong Kong after the proposal of Air Ventilation Plan, 2003 (Figure source: Google Maps).

concluded that T_a and the vertical motion exhibits sensitivity of parameters such as surface albedo and other wall surface parameters. In a similar study, Lin et al., (2014) [64], used CFD simulations to investigate UCL ventilation for neutral atmospheric conditions with the same building area density (lp = 0.25) and frontal area density (lf = 0.25) while varying building height, urban geometry, and wind direction. As a result of building height variations, vertical air exchange occurs across street roofs, strengthening and weakening wind near tall and short buildings, respectively. The urban form having an overall square shape experienced better ventilation due to the parallel approaching wind compared to the oblique winds. The rectangular urban form witnessed the least UCL ventilation.

Wang et al., (2017) [46] used LES to create urban air ventilation assessment scenarios using PALM. The study reported Ground Coverage Ratio (GCR) to be the most crucial factor impacting the ventilation performance. In high density urban scenarios, inhomogeneous buildings lead to higher winds and increased ventilation. This could be attributed to the inhomogeneous buildings generating higher vertical momentum flux inside the street canyons, which creates deficits in horizontal advection effects and further increases pedestrian level ventilation. The study further concluded that a single idealized parameter is incapable of capturing the effects of building geometries on air flow. Liu et al., (2016) [65] proposed an OTC prediction method employing field measurements and simulated wind velocities. They first compared the CFD simulation results of wind velocities around a single building with and without elevated design with those obtained from a wind tunnel experiment using Delayed Detached Eddy Simulation (DDES) and the RNG k-ε model considering two configurations, single building, and same building with three structure pillars at the prototype scale and total footprint being one-third of the building. The study concluded DDES well predicted the wind speed amplification area underneath the elevated building, whereas the RNG k-ε model over-predicted the area.

He et al., (2019) [66] analysed the impact of the road intersection angles for three types of angular road patterns for high-density urban setups. The study discussed the evenly distributed wind environment to improve the pedestrian-level OTC considering appropriate road segment orientations. A specific study compared PET and air quality differences for urban arrays with different frontal area densities (λF). Increase in λF leads to decrease in PET on the north, east, and west sidewalks, PET on the south sidewalk increases until λF = 0.25 and decreases after that [48]. Shirzadi et al., (2021) [49] examined the cross-ventilation in dense urban areas compared to isolated buildings in medium-dense urban areas employing wind tunnel tests and a high-resolution CFD model (ANSYS MESH) based on a validated LES model using the Standard Smagorinsky model to estimate the flow and dispersion around tall buildings. They adjusted the wind direction to evaluate varying orientations that might affect the wind flow pattern. The study further employed the concept that cross-ventilation flow can be broken down into mean flow parameters and turbulent statistics.

2.4.1. Tropical climates

Studies conducted in tropical climates explored various assessment methods to obtain impact of various site planning variables on wind profile of the streets or neighbourhoods. In a similar study in Singapore (*Af*), Wise et al., (2018) [59], examined how urban flow changes when the inlet wind direction is adjusted within a 20-degree range using OpenFOAM CFD to model an HDB district. The simulation data were compared to field measurements to conclude that the closer the building is to the inlet, the more the inlet direction influences where air stagnates. This can be helpful for urban planners to decide the location of inlets.

In another study conducted in Taipei City (*Am*), Abd et al., (2013) [67] investigated the impact of urban morphology, the plan area ratio, building aspect ratio, and variations of building heights, on the spatially averaged pedestrian wind flow as an index of urban ventilation using the Parallelized LES Model (PALM) code. The study used Frontal Area Ratio (FnAR) to estimate the wind environment. Another study conducted in Aracaju, north-eastern Brazil *(Am)* aimed to apply a sea breeze front (SBF) day classification employing an identification method of SBF, suggesting the weather conditions promoting the development of SBF. The study further assessed OTC under SBF days and Non-SBF days using T_a and comfort index information from an urban meteorological network and Local Climate Zone (LCZ) classification to conclude that SBF development had a detrimental effect on OTC whereas mean temperature and PET values on SBF days were higher than on the non-SBF days in all LCZ sites [60].

2.4.2. Other humid climates

Empirical studies conducted in other sub-tropical and humid climatic categories investigated the impact of various site planning and urban morphological variables in shaping the wind corridor and ventilation profile for the city. Yang, (2015) [61] assessed the impact of building form and density on wind environment considering wind and thermal comfort perception in the humid subtropical city of Shanghai (*Cfa*) considering three ventilation efficiency indices namely Net Escape Velocity[1] (NEV), Visitation Frequency[2] (VF), and spatial-mean Velocity Magnitude (VM).[3] The study reported from the field data that high-rise long-linear building layouts were the windiest building density design compared to an isolated apartment building and mid-rise linear building layouts [61]. Another study conducted in a similar climate of Nanjing, China (*Cfa*) aimed to visualize ventilation effectiveness in the urban microclimate and canyon in summer and winter. The study concluded that high-rise residential buildings appeared to function as windbreakers in the winter. They further suggested that depending on wind direction, the design of the city could improve or inhibit ventilation effectiveness. The research found that parallel wind flow in winter freshens the air better than the perpendicular wind flow in summer [62].

He et al., (2020a) [30] conducted several research in Sydney (*Cfa*), Australia to examine the precinct ventilation performance and its associated impact on precinct OTC to promote "wind sensitive design". The first study concluded that north-easterly wind brought more ventilation than other wind directions which produced lower RH and better OTC. The second study concluded that wind in more "open spaces" had a stronger influence on thermal comfort than in more closed spaces as decrease of solar radiation and increase in wind speed resulted in improved thermal comfort [31]. The third study concluded that morphological characteristics of the precinct strongly impacts the precinct ventilation as the increase in density results in the local urban morphological characteristics to become more dominant than the external meteorological conditions [32].

Bouketta & Bouchahm, (2020) [68] conducted a study in the Mediterranean, hot summer climate (*Csa*) of Jijel, Algeria to exhibit the impact of urban morphology to control the adverse impact of the wind in an urban space for a humid climate. The study concluded that outdoor space geometry, formed by the clustering pattern of the surrounding buildings, impacts the wind flow and at certain times, badly ventilated enclosed spaces are created with U and L geometric forms. The inferences can be important to plan amplification, canalization, or blockage of the wind flow. Roshan et al., (2020) [69] quantified the cooling potential of wind under different climate conditions in Iran catering to Mediterranean (*Csa* and *Csb*), and tropical savannah (*Aw/s*) climates. They found differing results for different climates; however, a meaningful relationship was observed between wind and thermal comfort with stronger winds contributing to lower PET.

Another study conducted in Xi'an, China (both a semi-arid climate (*BSk*) and humid subtropical climate (*Cwa*)), investigated the relationships between wind and building form (FAR, building height, building density, building enclosure, average maximum building height, height fall, SVF, aspect ratio) by employing ENVI-met and multiple regression analysis. The result reported the aspect ratio was negatively correlated with mean wind velocity ratio [54]. Another study in Bouzhou, China belonging to monsoon-influenced humid subtropical climate (*Cwa*) aimed to introduce a Ventilation Corridor Planning (VCP) model and to evaluate urban ventilation corridor using 3 steps: 1) determining wind direction and wind speed on the city level with the use of UBL model 2) identifying locations of ventilation corridors based on the ventilation potential defined by SVF and roughness length 3) analysing of thermal environment to optimize ventilation corridors and integration with surface urban heat island (SUHI). CFD simulation was also conducted to understand the impact of VCP criteria at the UCL. Study showed the usefulness of VCP model to identify wind corridors as different model parameters helped to define wind corridor properties, for instance, ventilation potential index influences the location of the wind corridor; and heat island intensity affects the volume of it [70].

A specific study conducted in the Humid continental climate of Toronto (*Dfa*) compared how changes in urban form affect wind development and its impact on pedestrian OTC through CFD simulation and wind tunnel experiments. The study showed that wind speed increased over 70 years of urbanisation reaching uncomfortable levels for pedestrians [71]. In a similar study, Zhang et al., (2019) [72] examined layouts of vegetation space and wind flow affecting T_a in an apartment housing complex in the monsoon influenced humid continental climate of Seoul (*Dwa*) using CFD. The study examined transpirational cooling and humidity produced by transpiration to calculate apparent temperature by comparing three scenarios. They aimed to check if increasing wind flow into the vegetated space would improve thermal comfort by reducing apparent temperature as more wind would remove the transpirational heat produced by the living beings in the space. They found that the elevated buildings increased wind flow, but it brought in hotter air from outside the domain and as such, reduced the air temperature decrease they expected. Elevated buildings to create more wind flow may not be helpful for thermal comfort as they found the increased wind flow advected warm air into the domain.

Overall, for hot and humid climate, it has been found that urban ventilation and wind flow are heavily reliant on urban morphologies and tree canopies. Harnessing wind corridors in the city by adapting building and tree layouts maximises wind velocity and in turn, enhances pedestrian OTC.

2.5. Breathability vs OTC

The term "city breathability" was first introduced by Neophytou and Britter, (2005), initially as a measure of urban air quality; considering pollutant concentration, heat, and moisture dispersion within the UCL as a measure of urban ventilation or breathability [33]. Existing research discussed city breathability and corresponding density variables to assess its impact on microclimate and OTC catering to humid subtropical climatic categories.

Hang et al., (2012) [34] discussed the impacts of mean flow and turbulence on city breathability in the UCL by simulating idealized deep canyons to investigate the level of wind flow parallel to street axes for humid subtropical climate (*Cfa*) of Hong Kong. Results showed that for densely populated cities, especially in residential tall buildings dominated areas, large open areas such as squares, gardens, grasslands, natural waterways etc. should be used to segregate a city-scale (~5 km–10 km) area into smaller chunks, less than 1 km, for an influx of more rural or sea breeze into urban areas, resulting in stronger wind along the streets. For the neighbourhood scale, the study suggests long streets with tall buildings have better breathability as it allows capturing more rural and marine air inside the street canyon, however, for city scale, long streets with tall buildings hindered the pathways to parallel approaching winds. They reported that if tall buildings are proposed as an option for re-densification, it would decrease wind-driven OTC.

For a similar climatic condition in Sydney, He et al., (2020b) [31] explored the cooling potential of sea breeze on OTC for a public square on a sunny day. This study found that daily average V_a was proportional to SVF, while presence of wind could be increased by channel effect and building disturbance. Highest daily average T_a were reported at the most

[1] NEV reflects the effective and net contaminant transport and dilution velocity, which relate not only to the wind speed but also to the flow reversal [35].

[2] VF refers to the number of times a pollutant enters the domain and passes through it [35].

[3] The instantaneous speed of the object (wind), averaged over a given space [35].

"open" point with high SVF. Presence of trees was more effective in minimizing T_a due to shade, which was not possible for grasslands. Results showed that solar radiation and wind speed impacted T_a significantly. The wind from more "open" areas had better cooling potentials, but wind belonging to the shading or wind amplification zone had less significant cooling potential. Wind had better cooling potential in warmer environments. In a similar wind environment, building shading is more effective than tree shading.

For the subtropical temperate oceanic climate (*Cfb*) of central London, Panagiotou et al., (2013) [33] discussed the breathability in heterogeneous urban areas using CFD simulations and investigated the implications arising for urban designers and planners towards planning wind sensitive urban spaces. Two average velocities at two different characteristic heights were considered for this analysis, one at canopy level (slower) and the other above the average building height (faster). The height difference functioned as a force ensuring the exchange flow between and above canopy flow, resulting in breathability. Results reported that the exchange velocity in heterogeneous areas was higher than idealized geometries of equivalent packing density in homogenous areas. This could be attributed to the enhanced flow mixing associated with urban inhomogeneity. Skimming flow in high density areas prevented the air from penetrating inside the canyon, hence, decreasing breathability. These results can provide insights for urban planners and designers to show how much deviation happens between idealized homogenous packing density and real-life heterogenous packing density.

You et al., (2017) [35] explored the process of evaluating performance of regional spatial ventilation for designing residential building arrangements on areas of humid subtropical (*Cfa*) and hot summer continental (*Dfa*) climate categories. They adopted three indices related to ventilation efficiency (VE), such as NEV, VF and spatial-mean VM to assess the impact of variation of designs on VE. Results demonstrated NEV, VF and VM to be significant VE indices, capable of reflecting distinctive features of flow pattern in the regional domains. They concluded that wind direction is the most significant factor for improving spatial ventilation. Therefore, design operations should consider local prevailing wind direction, especially for building orientation; considering wind direction is significant for residential building arrangements. The study reported that in the prevailing up-wind direction, surrounding building arrangements should be considered for cases of lateral spacing and staggered design, to organize air flow paths, to improve ventilation performance.

Lastly, for urban breathability that refers to UCL ventilation, it is similarly determined by how meteorological conditions such as wind direction and speed interact with high density, heterogenous configuration of buildings. There may also be opposing effects of building density in terms of breathability and wind flow across neighbourhood and city scales. Therefore, diversity and dispersal of building heights and open canyons throughout the city should be carefully considered.

2.6. Understanding gaps and uncertainties

The reviewed literature shows the mutual linkages between various urban morphological, site variables, and OTC. However, several gaps and uncertainties are identified in terms of urban elements, morphologies, vegetation, simulation process, practical problems, implementation, and strategy related uncertainties (Table 3). Morphological densities can be attributed to the simplifications of geometries in majority of the cases, whereas, vegetation related uncertainties can be related to approximations of tree species, shapes and sizes, evapotranspiration, locations and spacing of the trees, as well as soil-plant interactions. Even if these uncertainties and gaps attribute to negligible differences in the comfort evaluation process, approximations and generalization of various microclimatic models can attribute to significant deviation in the comfort prediction. We provide a comprehensive list of various gaps and uncertainties associated with comfort implications of site planning and density variables.

Table 3
Urban morphological and density related gaps as identified from the studies (compiled by authors).

Element and morphology related	● Studies did not consider roughness in the form of a vegetation [33,34], ● Studies did not consider material aspects [33]. ● This study only considers through primary streets with no puncture or any secondary perpendicular street, [34]. ● Non-homogenous building profile consideration could possibly generate inhomogeneity of flows around each building, this is different from studies assuming regular cube-arrays where flow profile develops over several building rows and reaches consistency [33] ● Buildings are considered as cube or cuboid box, how to model uncertainties associated with notches? [35]
Vegetation related	● How to measure the joint effect of both tree and building on OTC/wind flow in a single framework with minimum error? [36,38,39,41,37] ● How to optimize the tree planting pattern or distance or canopy characteristics to obtain maximum OTC for a given urban built configuration? [36,38,39,41,37] ● How to find an optimum landscape scheme with an effective vegetation- configuration pattern to maximize wind flow and OTC? Here vegetation refers to trees, shrubs, bushes, grasslands etc with respect to gap between vegetations, LAI, LAD, Crown density and shape, species, age of trees [36–41]. ● How to minimize the uncertainty in climate modelling when thermodynamic and aerodynamic properties of a tree will be calculated? [36–41] ● How to include hourly changes of sun angle and shading pattern? [36,38,39,41,37] ● How to model efficiently the evapotranspiration driven comfort? [36,38,39,41,37] ● How to minimize the uncertainty in modelling different indigenous tree species, soil conditions and their individual interaction with OTC? [38, 36] ● How to accurately model the impact of tree imparted shade and building shading? [36] ● As for the planting parameter settings, the tree crowns were simplified and assumed to be a cube-shaped grid composed of leaves through which air flows, (choosing character- such as spherical or conical) where how the air flows within the grid depends on the leaf density. How to take care of this generalization? [36,40]
Simulation and climate model related	● RANS model's inability to predict accurate turbulence in urban areas [34] ● Presence of notches create discrepancy in turbulence output [33] ● Simulation models are known mostly inefficient in predicting cloud cover and overcast and resultant change in radiation [33]. ● How to minimize uncertainty in coupling various patterns of air circulations such as synoptic wind and sea breeze to mimic the actual atmospheric boundary [30–32] ● How to take care of averaging and binning related uncertainties? [30–32] ● What are the effects of simplifying real conditions and generic forms for simulations and errors happening due to this? [38] ● How to obtain a general optimization model instead of working out various scenarios? [38] ● How to minimize the risk in formulating an interaction model considering urban design parameters and urban climate for better planning and decision-making? [38]
Real Problems	● Studies does not consider practical climatic on ground uncertainties of local climatic variation [34]

(*continued on next page*)

Table 3 (*continued*)

	● How to take care of the uncertainty in measuring the changing wind direction temporally? [30–32] ● Wind speed and directions are measured at a temporal interval, how to take care of the uncertainty associated with the change in microclimate due to the change of wind pattern in between two measurements? [39,30–32] ● A specific study assumes that the study happened during summer holiday, anthropogenic interventions were minimal, so no such factors are associated. How to take care of this uncertainty? [30–32] ● Studies indicate that air temperature was the combining result of the wind and solar radiation in association with locally morphological characteristics. This is like a scenario-based sensitivity analysis problem, how to convert this into an optimization problem taking care of an objective function and some constraints? [30–32] ● Studies mostly consider limited quantity and typology of spatial patterns and calculated data, which indicates a preliminary trend of variation in the influence of spatial patterns, however, how to construct a comprehensive optimization model taking care of all aspects? [35]
Implementation and Strategies	● It is not considered whether a mitigation strategy at neighbourhoods level is not counterbalanced by the strategies at city scale [34].

3. Future research direction for tropical cities: Proposing a methodological framework for a Singapore case study

The SLR conducted in this study affirms the fact that urban morphological parameters can significantly impact outdoor microclimate and OTC for tropical, subtropical, and humid regions. Extant literature also reports that current unplanned high-density growth exacerbates urban heating through heat storage and blockage of wind flow.

Planned densification efforts leading to a compact urban form can improve OTC by ensuring mutually shaded spaces and ventilation in urban areas [15–17]. Urban geometry and ratio of site coverage can also impact energy consumption scenarios. Studies report that high density and high energy consumption have a negative impact on OTC levels [73]. Managing the heavy humidity level is a complex issue in tropical cities complying with comfort requirements. The high moisture content in the air in the high-density cities make the comfort situation worse. There lies the necessity to understand the implications of humidity at pedestrian level capable of impacting the thermoregulatory process of the human body and eventually OTC, although the humidity implication is a contested topic in human biometeorology [74].

Holistically, an optimum comfort condition outdoors can be beneficial in many ways. A thermally comfortable outdoor space is convenient for physical exercises, sports etc. capable of promoting physical fitness, as well as acclimatization to a vulnerable population such as children and elderly population [75–78], audience, spectators, and athletes [79]. Comfortable outdoor playgrounds for children can contribute positively to various wellbeing aspects [80,81]. Such places can also help in improving productivity of informal vendors, hawker centre owners or outdoor construction workers who spend a considerable time outdoors [82]. Eventually, heat related mortality and morbidity in tropical cities can be reduced by designing thermally comfortable outdoor spaces [83,84]. Further, many tropical cities attract significant tourist footfall throughout the year, a comfortable outdoor environment can affirm an increase in the number of tourists and increase local tourism revenue [85].

3.1. Why is it important to discuss density implications of OTC in Singapore?

The Singapore government implemented SGP 2030 to advance the nation-wide efforts of sustainable climate resilient development [86]. This plan focuses on cross-agency, ambitious targets for the next decade to achieve long term domestic net-zero emissions. The plan has five major aims related to sustainable climate development; to allocate larger green areas and dedicated nature parks ("A City in Nature"); to increase usage of renewable energy ("Energy Reset"); to apply circular economy principles ("Sustainable Living"); to implement a higher carbon tax and an economic transition ("Green Economy"), and to reduce climate risks such as the UHI ("Resilient Future"). A major outcome of this plan is to allocate larger green space areas, and plant one million more trees across Singapore by 2030. This target further aims to ensure that every household should be within 10 minutes walking distance to a park. This requires efficient spatial planning and density allocation across different land use types.

Hence, analysing the density implications are significant for highly dense cities like Singapore due to their limited land area for development. A common characteristic in Singapore's landscape is both single-use and mixed-use parcels having high-density development due to land scarcity. Interestingly, Singapore at this stage, lacks a framework capable of evaluating urban density implications for OTC. Urban density depends on several site and geometry related attributes such as site coverage, FAR, GnPR etc. (Fig. 4). These parameters are dependent on, for instance, publicly funded vs. privately-owned residential land-use types, and ideally should be part of the design process for achieving optimum densification while ensuring OTC [87,88].

So far, existing studies in Singapore have discussed several ways to assess OTC performance of heat mitigations strategies [89], calibration and validation of comfort requirements through human biometeorological assessment [90], cognitive performance of older adults depending on OTC [91] or impact analysis of various heat mitigation strategies [92]. However, studies are yet to focus on analysing the implication on OTC of density and related site planning variables.

3.2. What are the comfort implications of existing building bylaws and site planning schemes in Singapore?

Carefully planned densification can help in achieving a compact urban form with cooler spaces and improved OTC, which can be attributed to mutual shading and building orientations [21,23,93]. Compact urban forms can be energy efficient; although high population densities can increase the demand for energy, eventually generating more AH and discomfort [18]. Strategic design of urban density is also aligned with the Green Mark Certification scheme of Building Construction Authority (BCA)[4] which aims to create climatic responsive designs for buildings to reduce the usage of energy, water, material resources and potential environmental impact. Currently, Singapore lacks any fixed definition of density. However, local bodies and government agencies have proposed several site planning and urban design guidelines and building bylaws. Two such operating bodies are Urban Redevelopment Authority (URA)[5] and BCA. Most of these guidelines discuss built-up density with respect to household size. URA has provided extensive building bylaws and site planning recommendations for various residential and non-residential developments.

The existing development guidelines allow sufficient provisions of open spaces within the site which includes the provision of green spaces as part of the site planning. The relative impact of various vegetation options can be explored to evaluate the impact on OTC as part of the site planning process for residential and non-residential developments. The

[4] https://www1.bca.gov.sg/.
[5] https://www.ura.gov.sg/Corporate/Guidelines.

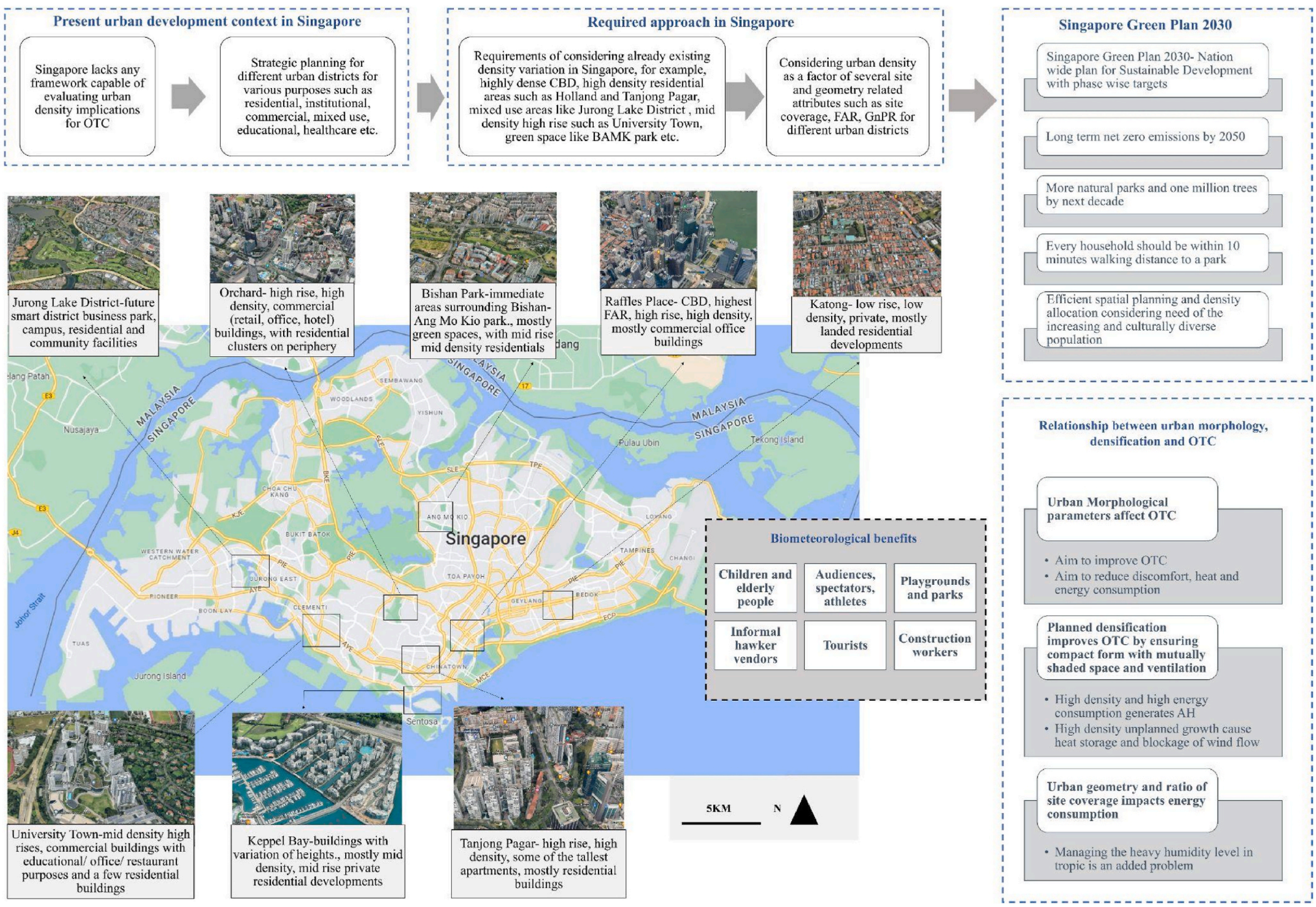

Fig. 4. Relevance of urban density in the present urban development context for Singapore considering SGP 2030 (Figure Source: Google Maps).

building bylaws and guidelines permits usages of balconies, eaves, and other urban design elements. Mutual on-site shading can be ensured by efficient usage of urban design elements, coupled with building blocks, which is possible due to different orientations and clustering patterns of building blocks, further ensuring a potential to strategically allow ventilation within the site. Hence, these microclimatic factors can

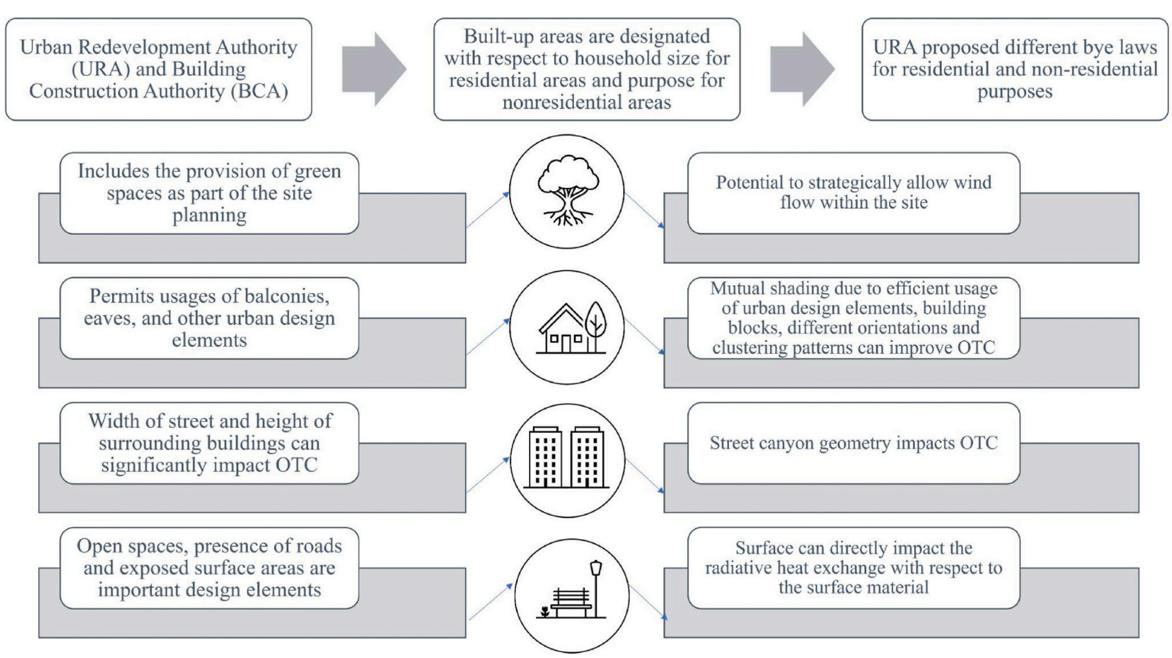

Fig. 5. Climate potential of existing building by-laws and site planning schemes.

significantly impact OTC (Fig. 5).

Street canyon geometry is capable of also impacting OTC. The open spaces, presence of roads and exposed surface areas are significant owing to their capability of radiative heat exchange with respect to the surface material. Similar observations are applicable for other types of land usages and built-up typologies. Hence, efficient site planning can ensure maximum climatic benefits.

3.3. What can be an ideal approach to evaluate density implications on OTC accounting all the uncertainties?

In this section, we introduce a novel framework that links the impact of density on OTC considering socioeconomic attributes and system uncertainties. Although existing literature shows a direct link between urban morphology, density and site planning variables with OTC, a negligible comprehensive framework exists. Micro-climate models include some level of uncertainties while predicting T_a, V_a, RH, and radiative heat exchange at outdoor spaces of different built-up densities. Extant literature reports discrepancies in thermal comfort indices as sometimes they exhibit errors in predicting acceptable range, perception, and preference of comfort for non-steady state conditions, such as outdoor and transition spaces.

Increased population density is further capable of impacting the OTC. Taller buildings and denser neighbourhoods are known to reject more AH in the street canyons attributed to air conditioning [94]. Microscale radiant conditions are deeply impacted at pedestrian levels by increased daytime shading. Hence, there is an increased need of considering AH emissions while evaluating the impact of densification within any microclimate modelling tool.

Keeping the above-mentioned factors into consideration, we propose an approach (Fig. 6) to predict OTC based on input variables and uncertainties. Certain input variables are required at each stage within a weather model capable of predicting microclimatic conditions. Some commonly required input variables are urban geometry of the neighbourhood, vegetation details, surface materials details. To initiate the simulation, some climatic variables, and some fixed parameters such as indoor air temperature etc are required. For example, a wind corridor analysis requires inputting morphometric and geometric variables such as site coverage and FnAR. However, all these processes include several uncertainties. For example, to impart more numerical stability to turbulent flux calculations, most of the weather model input requires simplification. The existing three-dimensional geometry of the neighbourhood is simplified to provide more regular forms [95,96]. Two such simplified metrics used for wind corridor analysis are zero displacement height and roughness length. Certain discrepancies also happen within a system due to incorrect or approximated field measurements [95]. A significant deviation is caused by these two sets of approximations compared to the existing site conditions.

Further discrepancies can occur at simulation and output level owing to the weather model's inability to predict accurate output of micro-climatic data precisely if input meteorological data are, for example, taken from weather stations not sited within the study area [97,98]. Another set of discrepancies occur when the climate model predicts OTC indexes such as PET without accounting for adaptive calibration of human responses e.g., with two-node models [99]. Existing microclimate models do not consider socio-economic aspects, such as AH generation, discomfort induced health hazards, ethno-cultural and affordability factors e.g., willingness to pay for thermally comfortable neighbourhoods. Better policy decisions can be obtained by coupling socio-economic attributes with OTC output.

The methodological framework can be divided into four segments. Urban morphology, climatic variables, and input fixed parameters such as indoor air temperature and system uncertainties are the inputs. Second stage consists of an integrated weather model, such as CFD models of ENVI-met, Ansys or Palm 4U. This stage should further address uncertainties not accounted for in the CFD model. Probable sets of uncertainties are already listed in Table 3. Once the simulation results provide outputs, socio-economic attributes are factored in to obtain policy decisions.

The discourse catering to the impact of urban morphology and geometry and its relationship with density related variables require more investigation. The existing simulation approaches are used to predict such relationships; however, an alternate statistical approach can also be useful in predicting the relationships more accurately. An urban density matrix considering most of the morphological variables can be an interesting input in this regard. Any physical space. For example, it

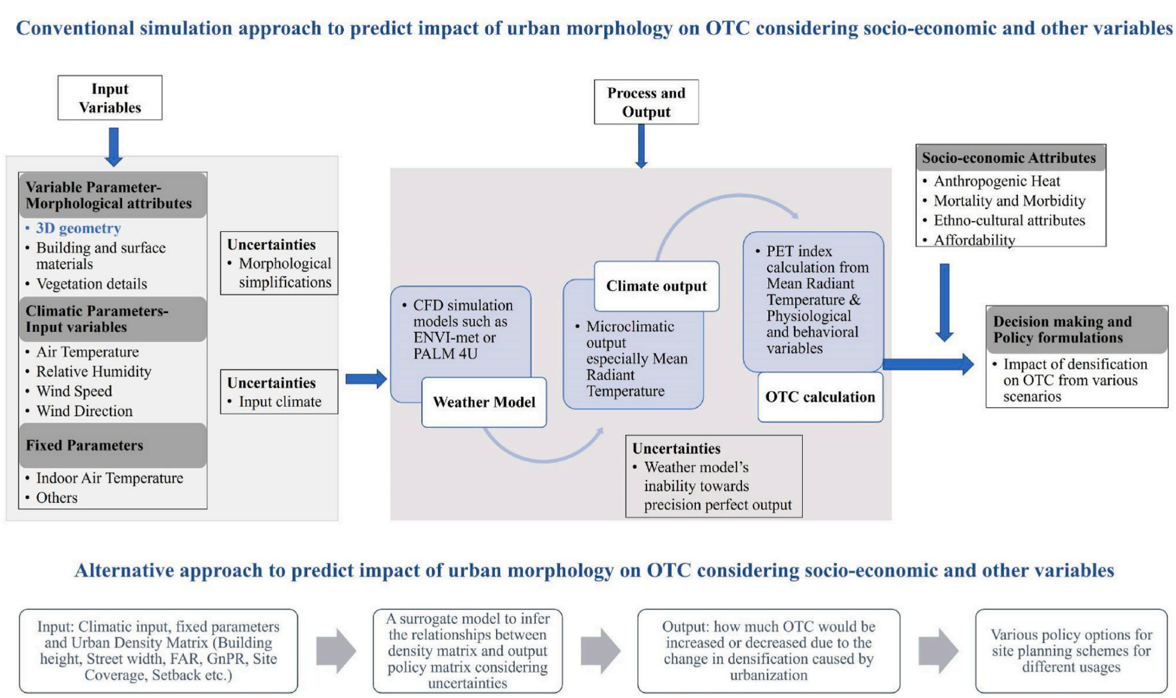

Fig. 6. An approach to evaluate density implications on OTC accounting all the uncertainties.

could be a set having variables like building height, width of street, floor area ratio, green plot ratio, distance between two buildings etc. Further, a decision matrix can be proposed for choosing various policy options. A surrogate model would be useful to infer the relationships between the density matrix and the output policy matrix. A Surrogate model is an instrument that is used to replicate scenarios of higher order models. In other words, surrogate models require fewer parameters but produce equivalent results for complicated multi-tier processes. Comparative scenarios can address point wise differences between various densification options in a same spatial-temporal scale. The output metric ideally should provide the inferences in terms of how much OTC would be increased or decreased with respect to a change in densification caused by urbanization.

4. Conclusion

In this research, we reviewed the existing literature investigating the relationships between urban morphological variables and OTC to assess the comfort implications of density for tropical cases with respect to site planning, vegetation, breathability, and wind corridor. Next, we identify the existing research gaps and uncertainties pertaining to the tropical and subtropical cases. Further, we explore the future research directions for tropical cities by analysing a case of Singapore by discussing why it is important to consider densification for Singapore. Moreover, we explored existing building bylaws, urban design, and urban planning guidelines of Singapore to understand the climate potential of normative guidelines. Our research shows the existing state of the art lacks a proper definition of urban morphology or density as well as a lack in considering socio-economic factors and uncertainties. Finally, we attempt to propose an approach to evaluate density implications on OTC accounting socio-economic factors and the uncertainties.

Future research can be conducted to evaluate the impact of densification on canopy layer microclimatic variables as well as on OTC by parametric studies of density attributes for specific neighbourhoods, which would be useful to assess the maximum achievable density for a predefined level of OTC, as well as the acceptable and preferable ranges of OTC for a specific community. Based on this, climate responsive policies can be proposed considering urban design and planning attributes. Further recommendations can be made on heat mitigation strategies for critical areas of acute thermal discomfort by modifying building morphology.

CRediT authorship contribution statement

Shreya Banerjee: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Graces Ching N. Y:** Writing – review & editing, Writing – original draft, Validation, Investigation, Data curation. **Sin Kang Yik:** Writing – review & editing, Writing – original draft, Validation, Investigation, Data curation. **Yuliya Dzyuban:** Writing – review & editing, Writing – original draft, Validation. **Peter J. Crank:** Writing – review & editing, Writing – original draft, Validation. **Rachel Pek Xin Yi:** Validation. **Winston T.L. Chow:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization.

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.

Data availability

No data was used for the research described in the article.

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