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Technical Report: Reviewing the relationships between urban morphological variables and Outdoor Thermal Comfort (OTC) to assess comfort implication of densification for Singapore

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COOLING SINGAPORE

Reviewing the relationships between urban morphological variables and Outdoor Thermal Comfort (OTC) to assess comfort implication of densification for Singapore

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1 Abstract

Majority thermal comfort studies focus on exploring the relationships between subjective parameters such as personal, physiological, psychological, and behavioral attributes and how they shape Outdoor Thermal Comfort (OTC). Although some attempts have been made to analyze the impact of urban morphological variables, but few have explored the effect of urban densification on OTC. Assessing the impact of density attributes is especially important for highly dense cities such as Singapore. Keeping this in consideration, ths study aims to provide a review-based analysis connecting OTC and various density related morphological variables. Firstly, this report analyses existing literature to provide snapshots on various attributes of OTC such as definition, comfort ranges, tools, and indices as well as relevance of OTC research in tropics, next, it reviews existing research exploring impact of urban density and related morphological variables on outdoor microclimate for tropical and sub-tropical high-density cities. Further, it has explored existing building bye laws, urban planning guidelines and various Development Control Regulations (DCR) of Singapore to understand the climate responsiveness potential of the existing guidelines. Next, this report identifies and summarizes urban morphological variables related to site planning that can be considered for densification to positively impact OTC. Lastly, this study proposes a framework to connect density related attributes and OTC for a tropical city.

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2 Introduction

Until the beginning of the 21st century, negligible research was conducted on Outdoor Thermal Comfort (OTC) (Spagnolo & Dear, 2003), (Johansson et al., 2014), (Potchter et al., 2018). Previously, the majority of thermal comfort models were developed keeping in mind indoor steady-state conditions which were incapable of assessing OTC conditions for non-steady state or transient state cases (Potchter et al., 2018). However, in the next decade, the concept of human biometeorology has been employed mostly for assessing subjective perceptions of OTC. Most of these studies focused on exploring the relationships between subjective parameters such as personal, physiological, psychological, and behavioral attributes and how they shape OTC. Although some attempts have been made to analyze the impact of urban morphological variables, but few have explored the effect of urban densification on OTC.

Assessing the impact of density attributes is especially important for highly dense cities such as Singapore. Due to land scarcity and other physical constraints, it is essential to develop high density heterogeneous built environments. However, an increased density can lead to a decrease in open green spaces resulting in an uncomfortable outdoor space. Hence, densification should be planned strategically, without worsening current OTC levels while minimizing energy consumption (Shareef, 2021). Owing to the urban context of Singapore, it is necessary to densify various urban districts strategically for building types, such as residential, commercial, mixed use, schools, hospitals etc. for various contesting needs, keeping in consideration the physical and sociopolitical limitations of the country. Singapore also does not have any comprehensive framework evaluating urban density and its impact on OTC. Building design that considers effects of density (i.e., orientation and shading) on microclimate can improve thermal comfort of outdoor spaces by lowering ambient air temperature (T_a) and Mean Radiant Temperature (T_{mrt}) while ensuring shading. Various geometry attributes such as Site coverage, Floor Area Ratio (FAR), Green Plot Ratio (GnPR) and other urban morphological variables depend on socio-economic profile of any area and should be taken into account while designing in order to achieve optimum densification and maximize OTC (Nevat et al., 2020), (Santos et al., 2021).

Existing research in Singapore have so far discussed different ways to evaluate OTC performance of some heat mitigations strategies through Computational Fluid Dynamics (CFD) simulation (Adelia et al., 2020), validation and calibration of comfort requirements with respect to land uses by employing human biometeorological assessment of subjective perceptions (Kohler & Phillip, 2020), cognitive performance of older adults with respect to OTC as obtained from quasi-experimental data (Borzino et al., 2020) or impact of various design related mitigation impacts on outdoor microclimate (Ruefenacht et al., 2020). Keeping this in consideration, we attempt to provide a review-based analysis connecting OTC and various density related morphological variables (Banerjee et al., 2022). Our study:

1. Analyses existing literature to provide snapshots on various attributes of OTC such as definition, comfort ranges, tools, and indices as well as relevance of OTC research in tropics.
2. Reviews existing research exploring impact of urban density variables on outdoor microclimate for high density cities of tropical and sub-tropical climate.
3. Explores existing building bye laws, urban design guidelines and various Development Control Regulations (DCR) of Singapore to understand the climate responsiveness of the normative urban development guidelines.
4. Identifies and summarizes urban morphological variables related to site planning that can be considered for densification to positively impact OTC.
5. Proposes a framework to connect density related attributes and OTC for a tropical city.

3 Outdoor Thermal Comfort (OTC)

3.1 Definitions

As per the ANSI/ASHRAE Standard 55 (2010), thermal comfort denotes a condition of mind capable of expressing satisfaction with respect to surrounding thermal environment with respect to a subjective assessment (ASHRAE, 2010). OTC can significantly impact human health status, mortality and morbidity (Pantavou et al., 2011). People spend a significant amounts of time outdoors for various purposes, and OTC can be a key determinant of physical and mental wellbeing (Kuo & Sullivan, 2001), (McGregor & Vanos, 2018). A thermally comfortable environment can ensure increased usage of outdoor spaces, enhanced productivity of outdoor occupants (Shooshtarian et al., 2018) as well as overall quality of life (Chen & Ng, 2012).

3.2 Tools to assess OTC

OTC is generally evaluated through various thermal comfort indices. Physiological Equivalent Temperature (PET) has been used mostly so far as an OTC performance indicator in hot-humid climates (Binarti et al., 2020). PET output can be obtained from different models such as CFD models like ENVI-met (Huttner, 2012) and 3D radiation budget models such as RayMan (Matzarakis et al., 1999), (Matzarakis et al., 2007), (Matzarakis et al., 2010). PET calculation requires data on microclimatic variables which can be obtained from CFD simulations. These software frameworks should be capable of simulating various urban scenarios, such as urban geometries, solar radiation, Anthropogenic Heat (AH) emission as well as air-plant-soil interactions. These modelling tools predict scenarios based on existing physics and energy theories with respect to some appropriate fine tuning. To reduce the complexities, some assumptions and simplifications are made for certain approximations. Sometimes, this causes errors in outputs (Adelia et al., 2020).

3.3 Physiological Equivalent Temperature (PET)

For this review, we would mostly consider PET index for explaining comfort ranges pertaining to OTC. PET functions on thermo-physiological heat balance operating on a two node model after Munich Energy Model for Individuals (MEMI) (Höppe, 1999). PET is a preferable index as it combines climate conditions as well as personal and thermo-physiological factors. Calculation of PET requires various microclimatic, personal, and physiological information for the index calculation such T_a, T_{mrt}, Wind Speed (V_a) which can be derived from weather data records, field measurements or results obtained from CFD simulations. Further, to calculate the human thermoregulatory process, personal and physiological information is needed such as clothing insulation and metabolic rate. PET is measured in °C and is easy to interpret. PET is also not dependent on subjective measures and can be applied in both hot and cold climates (Deb & Ramachandraiah, 2011), (Borzino et al., 2020). In a humid tropical city like Singapore, high solar radiation coupled with humidity and low wind speed, as well as anthropogenic heat released from human activities, contributes to higher PET value. Hence, PET should be low for people in Singapore to feel comfortable (Adelia et al., 2020). However, this is to be noted that by default, PET takes into account the European clothing insulation and metabolic values performing light or sedentary activities (VDI, 1998).

3.4 Comfortable and neutral range

A comfortable range of OTC refers to the physical equilibrium condition of the human body when thermoregulation is possible to achieve with minimum metabolic rate in the absence of evaporative cooling (Paul H Perlstein, 1995). Neutral temperature is the range for which a person feels neither warm nor cold. Previously for decades, it was measured on a 7-point scale without considering geography or context (Potchter et al., 2018). Initially a thermally comfortable neutral range was proposed for mid latitude European cities between 18-23^{O}C with an overall range of 4-41^{O}C (A. Matzarakis & Mayer, 1996). The subjective assessment is perceived on a scale of -3 to 3 for reporting thermal sensation. Further, various other concepts have emerged such as thermal expectation (Nikolopoulou & Steemers, 2003) and thermal acceptability (ASHRAE, 2010). However, studies soon began reporting that OTC depends on subjective and similar non-climatic factors (Nikolopoulou et al., 2001), (Nikolopoulou & Steemers, 2003), (Kántor et al., 2018). Later, many other studies reported the necessity to evaluate various subjective parameters such as personal (Tung et al., 2014), (Cohen et al., 2019), physiological, psychological (Middel et al., 2016), (Krüger et al., 2017) and socio-cultural (Galindo & Hermida, 2018) attributes corresponding to objective microclimatic condition for evaluating neutral range. Studies conducted in tropics have concluded that neutral temperature is around 30^{O}C, however, the upper and lower acceptability range of OTC is variable (Binarti et al., 2020). Therefore, it is necessary to validate and calibrate studies in the tropics according to contexts and various land usages (Kohler & Phillip, 2020).

4 Relevance of understanding comfort requirements and implications in tropics

According to the Köppen-Geiger Climate classification, tropical (23°N to 23°S) region caters to Tropical Rainforest (*Af*), Tropical Monsoon *(Am)* and Tropical Wet and Dry or Savannah *(Aw)* zones impacted by the Inter-Tropical Convergence Zone (ITCZ), associated with sun angle and altitude as well as shifting of low-pressure zones contributing to rainfalls and monsoons (Giridharan & Emmanuel, 2018). However, almost similar climatic features can be observed in sub-tropical (30°N to 30°S) regions catering to Humid subtropical (*Cfa* and *Cwa*) climate classifications.

Current haphazard high-density urbanization increases the urban heating through heat accumulation, blockage and retardation of wind flow. Strategic densification plans to achieve a compact urban form can help increase OTC by forming spaces that are mutually shaded spaces and wind corridors for enhanced advection of warmer air away from urban areas (Johansson, 2006), (Chen et al., 2012), (Ren et al., 2018). Patterns of urban texture and site coverage proportion can also contribute to a modification in energy consumption scenario. High density developments leading to a high energy consumption can be detrimental towards OTC (Esfandiari et al., 2021).

One of the major concerns in tropical cities is to manage the high humidity for optimum comfort. The high moisture level of the air in these high-density cities can further exasperate the discomfort and heat stress among the population. Hence, it's of utmost importance to understand the humidity implications on the canopy layer microclimate which can potentially impact the thermoregulatory process and comfort of human body in outdoor spaces. However, the impact of humidity is one of the most contested questions in human biometeorology (Dzyuban, 2020). The most used term associated with humidity is Relative Humidity (RH), which has a strong correlation with T_a. In fact majority of the microclimatic simulation models also exhibit certain discrepancies owing to the correlation (Huttner, 2012).

However, ensuring an optimum comfort condition has many-fold benefits. Developing urban spaces convenient for regular outdoor physical activities such as exercises or sports can promote physical fitness, while acclimatizing a critical population of children and elderly population (Wakabayashi et al., 2011), (Maughan et al., 2012), (Notley et al., 2017), (Wright Beatty et al., 2015), athletes and spectators (Vanos et al., 2019). Comfortable outdoor conditions are required around playgrounds for children within residential and educational precincts (Somboonwong et al., 2012), (Vanos, 2015). Informal vendors, hawker center workers or outdoor construction workers also spend a lot of time outdoor, a comfortable outdoor climate can improve their productivity as well (Banerjee et al., 2020). Moreover, this can reduce chances of heat related health hazards such as morbidity and mortality in tropical cities (Goggins et al., 2012), (Green et al., 2019). Many tropical cities also have great tourism potential and a comfortable outdoor environment can ensure better tourist footfall (Ndetto & Matzarakis, 2017), potentially creating massive revenue generation.

5 Density and urban morphological variables

5.1 Density

Urban density does not have any standardized definition. Commonly it refers to a variety of concepts catering to density of dwelling units, population density, built up density etc. In this section, we investigate various existing theories of densities.

A particular report by the United Nations (UN) defines density as “population divided by the land area for that given population”. The UN generally refers “urban agglomeration population density” as urban density. “Urban agglomeration” denotes the population situated within a specific region without having any designated administrative boundaries. Urban agglomeration refers to the core city population as well as the suburban areas and the outskirts. However, in many cases, this data is not available, instead the data of the city proper or the core metropolitan area is used for the reference[i].

Another report analyses the urban density in terms of compactness and sprawl and explores the tradeoffs catering to energy and environment for high-density compact development and low-density sprawl development. Five different attributes for measuring sprawl were considered namely density, growth rates, accessibility, spatial geometry, and aesthetic measures. This study further reports that denser urban settlements are more efficient with respect to usage of land parcel and other resources. Ratio of the population of a metropolitan area with respect to administrative area is not a reliable statistic to measure density as the definition of urban boundaries and administrative areas vary between places and regions. Generally, urban models use a negative exponential density function within cities since population density decreases from the city core to the outskirts. The study also mentions that compact areas generate less AH due to the urban configuration, with a greater number hard- and built-up surfaces heat up the surrounding through radiative heating (Dodman, 2009).

A specific study considered the definition of urban density as “number of housing units per hectare and described residential development accordingly as an increase in the number of housing units per hectare. Within existing urban areas, they considered all (re)development of the built environment that results in higher densities per hectare as densification”. With respect to this definition, social development policy or gentrification or community development guidelines can become crucial in the definition of density (Claassens et al., 2020).

A study conducted by Organization for Economic Co-operation and Development (OECD) defines density as “the average population density of an urban area is the average number of inhabitants per km of populated urban space. This is the ratio of the urban area’s total population to the total inhabited surface within that urban area.”[ii] Royal Institute of British Architects (RIBA) defines “dwellings per hectare” as a measurement of housing density for

[i] (Source: Hannah Ritchie and Max Roser (2018) - "Urbanization". Published online at OurWorldInData.org. Retrieved from: 'https://our-worldindata.org/urbanization' [Online Resource]).

[ii] https://www.oecd-ilibrary.org/sites/9789264189881-5-en/index.html?itemId=/content/component/9789264189881-5-en

analyzing various cases of urban planning interventions. The definition assumes uniform density without considering socio-economic variation.[iii]

This is evident from various existing definitions that the concept of density varies across the cases and cities. In majority of the cases, population density is the proxy used to denote urban density rather than using the concept of built-up density. Hence, for a high-density city like Singapore, it is recommended to consider population density as the indicator of urban density. This also requires looking into the relationship of how much space is required by an individual for different purposes. This would enable us to analyze whether the existing building byelaws and urban planning guidelines are conforming with the spatial requirements with respect to human occupancy, subsequent microclimatic and comfort implications, and future densification cases. However, the existing literature also calls for the necessity to evaluate urban density considering various urban morphological variables correlated with population density while analyzing various use cases. Some examples of such variables would be Floor Area Ratio (FAR), Gross Plot Ratio (GPR), Setbacks or mandatory open spaces, floor to floor height, number of dwelling units, street width, building height, etc. and many more.

5.2 Existing building regulations and byelaws by different urban bodies

Strategic densification is capable of achieving a compact urban form resulting in cooler and comfortable outdoor due to mutual shading, building orientations and potentially more space for vegetation (Emmanuel et al., 2007), (Sharmin et al., 2015), (Morakinyo et al., 2017). A compact urban form exhibits better energy efficiency; however, high population concentration increases energy requirements and can generate more AH resulting in reduced level of OTC (Ignatius et al., 2015). Various future scenarios could be assessed in this regard, in accordance with the 2019 Master Plan, and aligned with the larger strategy of Singapore Green Plan 2030.

Currently, Singapore does not have any particular definition of urban density; various urban bodies have proposed their own urban design and planning guidelines as well as building byelaws.Urban Redevelopment Authority (URA) and Building Construction Authority (BCA) are two such major agencies in Singapore. Guidelines from this agencies mostly discuss built-up density correspond to household size. For example, HDB has proposed minimum area requirements for residential units and apartments (Table 1). For different types of residential and non residential developments, a wide range of building byelaws and site planning recommendations are made available by URA. (Appendix 1 and 2).

Table 1: Unit size proposals for residences by HDB

Unit size	1 & 2 BHK	3 BHK	4 BHK	5 BHK
Area requirements (sq.m/household) for HDB apartments	40	68	96	124
Area requirements for private houses (sq.m/households)	111			

[iii] Metricity: New measures of urban density, www.metricity.net, RIBA

5.3 Climate potential of normative guidelines

URA proposed residential development guideline allows adequate opportunity of including open spaces and greeneries within any site. Hence, this is important to explore the cooling impact of green infrastructure options while designing site plans. It also ensures usages of eaves, balconies, and various urban design elements. Combined effect of building blocks and urban design elements can ensure mutual shading on the site, with the help of an effective interplay of clustering patterns and orientations of building blocks. This also has the potential of strategically allowing wind flow within the site. The microclimatic factors have the capability of significantly impacting OTC. Width of street and height of surrounding buildings can significantly impact OTC by impacting the street canyon geometry. The open spaces, presence of hardscapes and exposed surface areas are also important as they can directly impact the radiative heat exchange owing to the surface material properties. Therefore, maximum climate potential can be achieved through efficient site planning.

6 Summarizing urban density and site planning variables relevant to OTC

Extant literature reports various indices, variables, and matrices to analyze urban morphology in tropical high-density cities such as Singapore. Our analysis of the existing building bye laws and guidelines reveal a significant number of variables corresponding to urban morphology and density which can impact comfort and microclimatic implications directly or indirectly. In this section, we aim to provide a comprehensive list of variables that can be considered holistically, we further classify them in two categories, namely, 1) Building design related variables and 2) Site Planning and neighborhood variables (Table 2, definitions sourced from different urban local body guidelines). These variables can be useful to formulate policies as well as decision support framework to understand the impact of densification on OTC.

Table 2: Definitions and glossaries of density related urban morphological variables

	Variables	**Definition & Relevance**	**Type of data**
Building design related variables	Building Envelop	Building Envelope defines various components and elements of a building that can be enclosed by air-conditioned spaces through which thermal energy transfer from exterior spaces occur (Source: https://sso.agc.gov.sg/).	Descriptive information
	Building height	The overall building height for flats and condominiums is dependent on the number of storeys and the prescribed floor-to-floor height. This is also linked with Gross Plot Ratio (GPR). For residential developments, the number of storeys for flats and condominiums should conform to the GPR. (Source: https://www.ura.gov.sg/Corporate)	Continuous data, measured in meter (m)
	Front Area Index (wind flow and surface materials)	FAI indicates the surface or the building walls which face the wind flow from a particular direction (frontal area per unit horizontal area).	Continuous data, measured in square meter (sq.m) or unitless index

	Variables	Definition & Relevance	Type of data
	Area of dwelling units	This is the amount of area required for a residential unit for a specific household size.	Continuous data, measured in sq.m
	Gross Floor Area (GFA)	All covered floor areas of a building, except otherwise exempted, and uncovered areas for commercial uses are deemed the GFA of the building for purposes of plot ratio control and development charge. The gross floor area is the total area of the covered floor space measured between the centre line of party walls, including the thickness of external walls but excluding voids. Accessibility and usability are not criteria for exclusion from GFA (Source: https://www.ura.gov.sg/Corporate/Guidelines/Circulars/).	Continuous data, measured in sq.m
	Statistical Gross Floor Area (SGFA)	SGFA means in relation to one storey in a general building in a development, means the floor area of that storey; and in relation to 2 or more storeys in a general building in a development, means the aggregate of the floor areas of those storeys in that general building. Includes Balconies, Private Enclosed Spaces, Private Roof Terraces, & Indoor Recreation Spaces (Source: https://www.ura.gov.sg/Corporate/Guidelines/Development-Control/gross-floor-area/GFA/Introduction).	Continuous data, measured in sq.m
Site planning and neighborhood variables	Site Coverage	Site coverage ensures that there are adequate areas set aside for greenery and landscaping within the development (Source: https://www.ura.gov.sg/Corporate/Guidelines/Development-Control/Residential/Flats-Condominiums/Site-Coverage).	Continuous data, % share of different land usages
	Net Site Area	Computation of site coverage has been simplified to include all building structures that protrude more than 1m from the ground as seen from the top-down 'Site Plan' view and is expressed as a percentage of the net site area. The net site area refers to the area of the site excluding areas to be vested to the State for public roads, public road widening reserves, and drainage reserves. The minimum site area for a flats and condominium development is 1,000sqm and 4,000sqm respectively. Condominiums require larger site area to ensure that there is sufficient space for more communal and recreational facilities (Source: https://www.ura.gov.sg/Corporate/Guidelines/Development-Control/Residential/Flats-Condominiums/Site-Coverage).	Continuous data, measured in sq.m
	Setback	Flats and condominiums shall be sufficiently set back from the road and common boundary. The setback distance is measured from the road reserve line or boundary line to the external wall of the flats, excluding land to be vested to the State for road or drainage or public purpose. The setback for flats and condominiums from public roads are determined by the road buffer, which is dependent on the category of road that the site fronts and the height of development. This includes common boundary setback and planting strip (https://www.ura.gov.sg/Corporate/Guidelines/Development-Control/Non-Residential/Commercial/Building-Setback).	Continuous data, measured in meter
	Floor Area Ratio (FAR)	FAR is the ratio of a building's total floor area (gross floor area) to the size of the piece of land upon which it is built. It is often used as one of the regulations in city planning along with the building-to-land ratio.	Continuous data, unitless index
	Building orientation	Building orientation refers to the angle and orientation of building blocks with respect to the cardinal directions.	Continuous data, measured in angle
	Street Width	Street width refers to the width of the lane for various hierarchy of streets. Streets can be collector street within the site or local streets at neighborhood level.	Continuous data, measured in meter
	Clustering pattern	Clustering pattern refers to the layout of different building blocks and how they are placed together within the site.	Discrete or continuous data

	Variables	Definition & Relevance	Type of data
	Landscaping for Urban Spaces and High-Rises (LUSH)	LUSH is a comprehensive urban and skyrise greening programme comprising both Landscape Replacement Areas (LRA) requirements and incentives to provide greenery and communal spaces. The LRA requirements are calibrated by location, GPR and development type. A development may count Sky Terraces, Communal Planter Boxes and Covered Communal Ground Gardens (see Greenery sub-tabs) amongst other features, towards meeting the LRA requirement (Source: https://www.ura.gov.sg/Corporate/Guidelines/Development-Control/Non-Residential/SR/Greenery).	Set of information, mostly continuous data such as % of green space or Green Plot Ratio (GnPR)
	Public and Semi-public spaces	Public and semi-public spaces refer to civic spaces' surrounding a building, as well as the building facade, entrance, and ground floors. Club, community areas within a residential site is an example of this. This includes hardscaped and softscape open spaces as well.	Continuous data, expressed as %
	Gross Plot Ratio (GPR)	The development potential of a residential development is guided by the Gross Plot Ratio (GPR) specified in the Master Plan (MP). The MP plot ratio is the upper bound as it may not always be achievable because of site limitations like shape of the plot, site topography or ground conditions, building setbacks, building height or technical requirements of other authorities that may affect the site (Source: https://www.ura.gov.sg/Corporate/Guidelines/Development-Control/Residential/Flats-Condominiums/Gross-Plot-Ratio).	Continuous data, expressed as ratio

7 Proposing a framework to connect density related attributes and OTC for a tropical city

Negligible comprehensive framework exists on linking climatic and spatial dimensions for neighborhood urban spaces despite the existence of sufficient literature showing a strong correlation between urban morphological and density related variables and OTC, . Uncertainties exist for micro-climate models to predict air temperature, wind speed, relative humidity, and mean radiant temperature for outdoor spaces for different density options. Extant literature also reports that there can be discrepancies in thermal comfort indices to predict perception, acceptable range, and preference related to OTC for cases that are non steady state, such as outdoor and transition spaces. Taller buildings and denser neighborhoods can reject more anthropogenic heat into the street canyons due to increased usage of air conditioners (Roberts, 2012). Increased daytime shading also can dynamically affect microscale radiant conditions at pedestrian levels. This shows that considering anthropogenic heat emissions are important for assessing the effect of densification in the microclimate modelling framework.

Keeping these factors into consideration, we propose a methodological framework (Figure 1) for predicting OTC based on various input variables and uncertainties at various stages. A weather model for predicting microclimatic variables as output, requires certain input variables such as neighborhood urban geometry, vegetation profile, surface materials profile, some input climatic variables for initiating the simulation, as well as some fixed parameters for the simulation (indoor air temperature etc). For example, some of the morphometric and geometric variables such as site coverage and frontal area ratio are important for a wind corridor analysis. However, several uncertainties are associated for such types of analyses. Majority of the times, the ezisting three dimensional built up profile needs a simplification to impart more numerical stability to microclimate simulation models (Huttner, 2012), (Crank et al., 2018). Two such simplified metrics used for wind corridor analysis could be roughness length and zero displacement height. However, uncertainties exist in the input data as often times, discrepancies happen while carrying out the field measurements (Huttner, 2012). These two sets of approximations can already cause a significant deviation of the input conditions as compared to actual site conditions.

At the simulation and output level, further discrepancies can happen due to the inability of the weather model in predicting precision perfect microclimatic data as output and further the output in terms of the OTC index such as PET. Existing microclimate simulation models majorly does not take care of socio-economic attributes of any neighborhood, such as anthropogenic heat generation, discomfort induced mortality and morbidity, ethno-cultural attributes as well as affordability related attributes, such as willingness to pay towards attainment of thermally comfortable neighborhoods. OTC output coupled with socio-economic attributes can ensure better policy decisions.

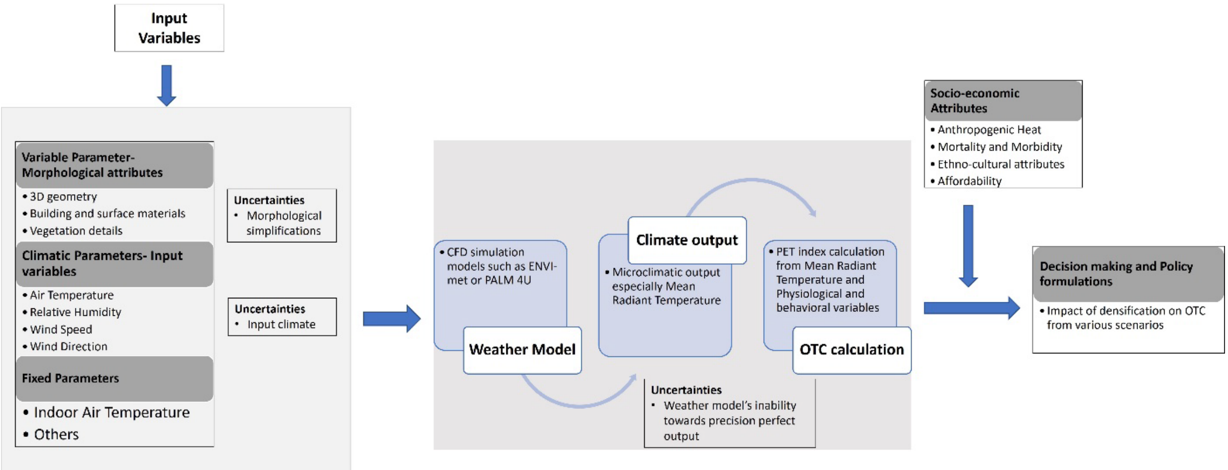

Figure 1: Methodological Framework

(Source: Banerjee et al., 2022)

More investigation is required to understand the effect of urban geometry and how it is related to urban density variables. The conventional simulation approach is mostly employed to evaluate such relationships as obtained from the extant literature, however, there lies apportunity of considering an alternate statistical approach for better predictive ability such as surrogate models. An urban density matrix can be proposed which would consider majority of the morphological variables (Table 4). Another decision matrix could be proposed with related policy options. Such comparisons are capable of comparing grid wise differences between multiple densification scenarios in the spatial-temporal scales. The output metric should be capable of providing information about the magnitude of increased or decreased thermal comfort due to a change in densification caused by urbanization.

8 Conclusions

8.1 Summary of findings

In this review, we investigate the existing research exploring relation of urban morphological variables and Outdoor Thermal Comfort (OTC) to understand comfort implication of densification in Singapore. We have first analyzed existing literature to provide snapshots on various attributes of OTC such as definition, comfort ranges, tools, and indices as well as relevance of OTC research in tropics. Followed by that, we review existing research exploring impact of urban geometry on OTC and outdoormicroclimate for tropical and sub-tropical high-density cities. Further, we explore existing building bye laws, and urban planning guidelines and various Development Control Regulations (DCR) of Singapore to explore effectiveness of normative guidelines with respect to the climate responsiveness. Moreover, we identify and summarize urban morphological variables related to site planning that can be considered for densification to positively impact OTC for high density cases such as Singapore. Finally, we propose a framework to connect density related attributes and OTC for a tropical city.

8.2 Future Scope

Furthur research is possible to understand the impact of microscale urban geometry and density on canopy layer microclimate and OTC by parameterization of density parameters for specific neighborhoods. This can be beneficial to understand, for a predefined level of OTC, what is the maximum level of density that can be obtained. Moreover, inferences can be drawn to understand what the preferable and acceptable range of OTC for a specific density level for a surveyed population is. Based on this, urban planning recommendations can be made on maximum height and building density for optimum OTC. Such guidelines would be useful to plan a zoning based on a set of site planning criteria such as built-up and open area ratio, morphological parameters and building information which would eventually help in preparing heat mitigation strategies for locations of high heat stress.

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10 Appendices

10.1 Appendix 1

(Sourced from URA documents)

Type of Building	Setback from Common Boundary	Plot size, width, and depth	Building Setback	Building Appendages	Site Coverage/ Gross Plot Ratio	Floor to Floor Height	Envelope control Guidelines	Building height	Unit Size
Detached	Main building, car porch column, patio/terrace: 3m, Roof eaves, car porch eaves: 1.6m	Within GCBA: Size-1400sq.m, Width: 18.5m, Depth-30m	**Main Building:** Cat 1 Road-24m (5m green buffer), Cat 2 Road - 12m (5m green buffer), Cat 3 & 4 - 7.5m (3m green buffer), Cat 5 - 7.5m (no green buffer), **Patio/Terrace:** Cat 1-2 Road: Maximum depth of patio/terrace protrusion into the road buffer not to exceed 5m, Cat -5 road: 5.1m, **Car Porch roof eaves:** Cat 1-2 road: car Porch protrusion into road buffer not to exceed 5m depth, Cat 3-5 road: 2.4m	**Main Roof Eaves**: into road buffer:2m, into common boundary setback:1.4m, **Cantilevered Edges**: into road buffer 1.4m, into common boundary setback:1.4m, **Horizontal sun-shading devices or vertical fins (without supports), planter boxes:** into road buffer 0.5m, into common boundary setback: 0.5m	40% max	NA	The permissible building envelops for a 2 storied or a 3 storied landed house is controlled by the envelop control guidelines. The guidelines define the allowable building envelope based on the setbacks, storey height, and external platform level, 2 storey height-8m, attic 3.5m, 3 storey height-12m, attic 3.5m	NA	NA
	Main building, car porch column, patio/terrace: 2m, Roof eaves, car porch eaves: 1m	Outside GCBA: Size-400sq.m, Width: 10m, Depth-no minimum	**Main Building:** Cat 1 Road-24m (5m green buffer), Cat 2 Road - 12m (5m green buffer), Cat 3 & 4 - 7.5m (3m green buffer), Cat 5 - 7.5m (no green buffer), **Patio/Terrace/ Car Porch roof eaves:** Cat 1-2 road: car Porch protrusion into road buffer not to exceed 5m depth, Cat 3-5 road: 2.4m	**Main Roof Eaves**: into road buffer:1m, into common boundary setback:1m, **Cantilevered Edges**: into road buffer 0.5m, into common boundary setback: not allowed, **Horizontal sun-shading devices or vertical fins (without supports), planter boxes:** into road buffer- not allowed, into common boundary setback: not allowed	50% max				
Flats and Condominiums	Varies from 3.0 m to 15.0 m depending in proposed storied height	NA	NA	NA	Varies from 1.4,1.6,2.1,2.8 or more than 2.8 as stipulated in the prevailing master plan, Bonus GFA can be obtained for balcony incentive scheme, conserved bungalows scheme, indoor recreation spaces, Site Area for Flats: min 1000sqm, Condominiums: min 4000sqm, maximum 50% site coverage is allowed, it has been simplified to include all building structures that protrude more than 1m from the ground as seen from the top down "Site Plan" view	Type/GPR 1.4/More than GPR 1.6: 1st Storied/5.0m/5.0m, Top Storied/3.6/5.0, Other Storied/3.6/3.6, PSTS/5.0/5.0, Predominant Sky Terrace Storied are floors where the sky terrace occupies equal to or more than 60% of the floor plate. Floors with less than 40% of sky terrace are considered “other storied"	Attic: max height:5m, maximum pitch:45 degrees from the springing line, attic and the unit below cannot be strata subdivided	GPR/Max no of Stories: 1.4/5, 1.6/12, 2.1/24, 2.8/36, >2.8/>36, Except the following: have street block plans, have technical height control, have conservation or urban design requirements, have security considerations, do not conform to the GPRs shown on the left, GPR 2.9, GPR 1.7	For flats outside the central area, maximum no. of DUs=MP allowable GPR*Site Area/85 sqm, for flats within the estates in Map2.10: maximum no of DUs=MP allowable GPR*Site Area/100sqm, as a guide, all self-contained dwelling units island wide shall be more than 35sqm nett in the internal area

Type of Building	Setback from Common Boundary	Plot size, width, and depth	Building Setback	Building Appendages	Site Coverage/ Gross Plot Ratio	Floor to Floor Height	Envelope control Guidelines	Building height	Unit Size
Semi-Detached	Main building, car porch column, patio/terrace: 2m, Roof eaves, car porch eaves: 1m	Side to Side: Size-200sq.m, Width: 8m	**Main Building:** Cat 1 Road- 24m (5m green buffer), Cat 2 Road - 12m (5m green buffer), Cat 3 & 4 - 7.5m (3m green buffer), Cat 5 - 7.5m (no green buffer), **Patio/Terrace/Car Porch roof eaves:** Cat 1-2 Road: Maximum depth of patio/terrace protrusion into the road buffer not to exceed 5m, Cat 3-5 road: 2.4m	**Main Roof Eaves**: into road buffer:2m, into common boundary setback:1m, **Cantilevered Edges:** into road buffer 2m, into common boundary setback: 1m, **Horizontal sun-shading devices or vertical fins (without supports), planter boxes**: into road buffer- 0.5m, into common boundary setback: not allowed	NA	NA	The permissible building envelops for a 2 storied or a 3 storied landed house is controlled by the envelop control guidelines. The guidelines define the allowable building envelope based on the setbacks, storied height, and external platform level, 2 storied height-8m, attic 3.5m, 3 storied height-12m, attic 3.5m	NA	NA
Strata Landed Housing	**Setback from Common Boundaries with GCBA**- 1-2 storied: 3m (including 2m planting strip), 3 storied: 25m (including 2m planting strip) **Setback from Common Boundaries with all other developments**- 1-2 storied: 3m (including 2m planting strip), 3 storied: 3m (including 2m planting strip)	NA	Main Building: Cat 1 Road- 24m (5m green buffer), Cat 2 Road - 12m (5m green buffer), Cat 3-5 - 7.5m (3m green buffer)	**Within GCBA:** Main Roof Eaves: into road buffer:2m, into common boundary setback:1.4m, **Cantilevered Edges:** into road buffer 1.4m, into common boundary setback:1.4m, **Horizontal sun-shading devices or vertical fins (without supports)**, planter boxes: into road buffer 0.5m, into common boundary setback: 0.5m, **Outside GCBA: Main Roof Eaves**: into road buffer:2m, into common boundary setback:1m, **Cantilevered Edges**: into road buffer 1m, into common boundary setback: 1m, **Horizontal sun-shading devices or vertical fins (without supports)**, planter boxes: into road buffer- 0.5, into common boundary setback: not allowed	Site Coverage= outside GCBA- 50%, Within GCBA- 40%, GFA = for individuals units, the GFA for each of the individual strata landed housing unit is resultant of the building form and envelop, for overall development for developments comprising strata landed housing only, the overall gross floor area is resultant of the number of strata landed units allowed, for residential developments with a mix of strata landed housing and flat units, the overall GFA is controlled by the Master Plan GPR for the site	NA	The building footprint of each strata landed unit shall have a minimum ground contact of 50sqm. Strata landed housing is controlled by the envelope control guidelines.	NA	Max.no of strata landed units (within GCBA): no of units= 35% of site area/500sqm, Max. no of strata landed units (Outside GCBA): single housing form: No of bungalow units= 40% of the site area/200sqm, No. of terrace or No. of semidetached housing units= 40% site area/100sqm, no of terrace or no of semi-detached housing units=40% of site area/100sqm, Max. no of strata landed housing units (outside GCBA)- mix of terrace, semi-detached and detached housing forms- (No. of Bungalow units*200sqm) + (No. of Semi-detached units*100sqm) + (No of terrace units*100sqm) less than or equal to 40% of site area, Minimum Building Footprint per unit- 50sqm
Terrace Housing	Main building, car porch column, patio/terrace: 2m, Roof eaves, car porch eaves: 1m	**Terrace Type 1**: Intermediate-Size-150sq.m, Width: 6m, Corner- 200sqm, width: 8m	**Main Building:** Cat 1 Road- 24m (5m green buffer), Cat 2 Road - 12m (5m green buffer), Cat 3 & 4 - 7.5m (3m green buffer), Cat 5 - 7.5m (no green buffer), **Patio/Terrace/Car Porch roof eaves:** Cat 1-2 Road: Maximum depth of patio/terrace protrusion into the road buffer not to exceed 5m, Cat 3-5 road: 2.4m	**Main Roof Eaves**: into road buffer:2m, into common boundary setback:1m, **Cantilevered Edges:** into road buffer 1m, into common boundary setback: 1m, **Horizontal sun-shading devices or vertical fins (without supports), planter boxes**: into road buffer- 0.5m, into common boundary setback: not allowed	NA	NA	The permissible building envelops for a 2 storied or a 3 storied landed house is controlled by the envelop control guidelines. The guidelines define the allowable building envelope based on the setbacks, storied height, and external platform level, 2 storied height-8m, attic 3.5m, 3 storied height-12m, attic 3.5m	NA	NA

10.2 Appendix 2

(Sourced from URA documents)

Type of Building	Minimum Building Setback from Common Boundary	Minimum Road Buffer	Gross Plot Ratio	Floor to Floor Height	Building height	Permissible Uses	Non-Permissible Uses	Unit Size	Use Quantum
Agricultural Development	Min 4.5m including 2m planting strip for non-agricultural development, min 2m with no planting strip required for agricultural developments	Expressway- 15m (5m green buffer), Major Arterial A - 7.5m (3m green buffer), Major Arterial B - 5m (3m green buffer), Another major road, minor road, slip road - 5m (3m green buffer)	NA	NA	Only urban design height controls	Agricultural and ancillary uses as supported by Singapore Food Agency, National Parks Board or Singapore Land Authority, restaurant, showroom, shop of (200sq.m), visitor centre of (200 sq.m)	Residential use	NA	NA
Business 1 (Industrial)	Min 4.5m including 2m planting strip along common boundaries with non-industrial development, no setback along common boundaries with industrial development		Varies from 1.4 to 3.5 as stipulated in the master plan	Min 4.0m, 6.0m in Sindo Industrial Estate	No height control except, technical height control, conservation or urban design requirements, security considerations			Min 150sq.m per unit	Min 60% of overall GFA for predominant uses, Max 40% of overall GFA for ancillary uses
Business 2 (Industrial)			Varies from 0.6 to 4.0 as stipulated in the master plan	Min 4.0 m					
Business Park	Min 4.5m including 2m planting strip along common boundaries with non-industrial development		Varies from 1.2 to 10.0 as stipulated in the master plan	NA		White Component and Business Park Component are allowable uses		NA	White Component: Max 15% of the overall proposed GFA for land zoned "BP" maximum allowable is stipulated in the master plan for land zoned "BP", Business Park Component: Min 60% of overall GFA for predominant uses, Max 40% of overall GFA for ancillary uses
Civic and Community Institutions	Min 4.5m including 2m planting strip along common boundaries with other development		Within landed and low-density housing areas, at the fringe of landed and low-density areas- up to 1.0, within HBD estates- up to 1.4, within or at the fringe of industrial estate - up to 1.4, within central area- subject to evaluation and local urban design	Max 5.0m	Within landed and low-density housing areas- 2 to 3 story, at the fringe of landed and low-density areas- up to 3, within HBD estates- up to 4 story, within or at the fringe of industrial estate - up to 4 story, within central area- subject to evaluation and local urban design	NA	NA	NA	Ancillary uses may be considered subject to evaluation
Commercial	Min 3m including 2m planting strip along common boundaries with other development		As stipulated in the prevailing master plan, Gross Floor Area bonus schemes: CBD incentive scheme, strategic development incentive scheme, community, and sports facilities scheme etc.	Commercial Use: max 5.0m, Residential Use: 5.0m for 1st storey, 3.6 m for subsequent storied	No height control except, technical height control, conservation or urban design requirements, security considerations	NA	NA	Min 50sq.m	Commercial Uses shall be located on lower floors, below the residential uses, Commercial only zone: Min 60% of overall GFA for commercial uses, use of remaining GFA to be evaluated, Commercial+ Residential mixed use: Max 40% of overall GFA for commercial uses, 60% for residential uses
Educational Institute	Min 4.5m including 2m planting strip along common boundaries with other development		Within landed and low-density housing areas, at the fringe of landed and low-density areas- up to 1.0, within HBD estates- up to 1.4, within or at the fringe of industrial estate - up to 1.4, within central area- subject to evaluation and local urban design	Max 5.0m	Within landed and low-density housing areas- 2 to 3 story, at the fringe of landed and low-density areas- up to 3, within HBD estates- up to 4 story, within or at the fringe of industrial estate - up to 4 story, within central area- subject to evaluation and local urban design	For institutions of higher learning, the maximum allowable commercia; use if 5% of the total proposed GFA or 30000 sq.m whichever is less	NA	NA	NA

Type of Building	Minimum Building Setback from Common Boundary	Minimum Road Buffer	Gross Plot Ratio	Floor to Floor Height	Building height	Permissible Uses	Non-Permissible Uses	Unit Size	Use Quantum
Health and Medical Centre	Min 4.5m including 2m planting strip along common boundaries with other development		As stipulated in the prevailing master plan	Max 5.0m	No height control except, technical height control, conservation or urban design requirements, security considerations	Supporting commercial uses such as retail pharmacies, shops, F&B outlets, food court, banks etc. shall not exceed 5% of the total proposed GFA, private medical clinics may be allowed in commercial buildings of non HMC developments subject to: the total GFA for medical clinics in capped at 3000 sqm or 20% of the total floor area approved for commercial use, whichever is lower			At least 60% of the total proposed GFA shall be used for HMC purposes only, maximum 40% of the total proposed GFA are for supporting ancillary uses, ancillary visitors hostel shall not exceed 10% of the total proposed GFA or 1500 sqm whichever is lower
Hotel	Min 3m including 2m planting strip along common boundaries with other development		As stipulated in the previous master plan, balcony incentive scheme, landscaped roofs as bonus GFA up to a cumulative maximum of 10%	Max 5.0m	No height control except, technical height control, conservation or urban design requirements, security considerations	Hotel room and hotel related issues, Shopping		Retail size min 50sq.m	Min 60% of overall GFA for predominant uses, Max 40% of overall GFA for ancillary uses
Places of Worship	Min 4.5m including 2m planting strip along common boundaries with other development		Within landed and low-density housing areas, at the fringe of landed and low-density areas- up to 1.0, within HBD estates- up to 1.4, within or at the fringe of industrial estate - up to 1.4, within central area- subject to evaluation and local urban design	Max 5.0m	No height control except, technical height control, conservation or urban design requirements, security considerations, Within landed and low-density housing areas- 2 to 3 story, at the fringe of landed and low-density areas- up to 3, within HBD estates- up to 4 story, within or at the fringe of industrial estate - up to 4 story, within central area- subject to evaluation and local urban design			NA	Based on overall proposed GFA, minimum 50% praying area, max 50% ancillary uses (max 10% ancillary non-religious uses and max 20% columbarium use)
Sports and Recreation	Min 4.5m including 2m planting strip along common boundaries with other development		As stipulated in the previous master plan	NA	No height control except, technical height control, conservation or urban design requirements, security considerations	Accommodation facilities may be allowed but shall not exceed 30% of the total proposed GFA or 10000 sq.m, whichever is lower, commercial uses such as restaurants, bars and lounges, outdoor refreshment areas may be allowed but shall not exceed 30% of the total proposed GFA or 4000 sq.m whichever is lower			
Transport	Min 4.5m including 2m planting strip along common boundaries with other development		As stipulated in the previous master plan	NA	No height control except, technical height control, conservation or urban design requirements, security considerations				