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RESEARCH ARTICLE

Outdoor thermal comfort: Analyzing the impact of urban configurations on the thermal performance of street canyons in the humid subtropical climate of Sydney

Nastaran Abdollahzadeh [a], Nimish Biloria [b,*]

[a] *Shahid Beheshti University, Tehran, Iran*
[b] *Faculty of Design Architecture and Building, University of Technology Sydney, Sydney, NSW, Australia*

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Thermal sensation;
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Abstract The quality of outdoor space is becoming increasingly important with the growing rate of urbanization. Visual, acoustic, and thermal balance degradation are all negative impacts associated with outdoor comfort in dense urban fabrics. Urban morphology thus needs assessment and optimization to ensure favorable outdoor thermal comfort (OTC). This study aims to evaluate the thermal performance of streets in residential zones of Liverpool, NSW, Australia, and tries to improve their comfort index (Physiological Equivalent Temperature) to reveal optimum urban configurations. This evaluation is done by investigating the following urban design factors affecting OTC using computational simulation techniques: street orientation, aspect ratio, building typology, and surface coverage. Our findings reveal that street canyon orientation is the most influential factor (46.42%), followed by aspect ratio (30.59%). Among the influential meteorological parameters (air temperature, wind speed, humidity and solar radiation), wind velocity had the most significant impact on the thermal comfort of the outdoor spaces in this coastal region, which typically experiences intense airflow. The results of our analysis can be utilized by multiple stakeholders, allowing them to understand and extract the most vital design factors which contextually influence the thermal comfort of outdoor spaces. Outdoor thermal comfort has a direct effect on the health and wellbeing of occupants of outdoor spaces.

* Corresponding author.
E-mail addresses: Na.abdollahzadeh@mail.sbu.ac.ir (N. Abdollahzadeh), Nimish.Biloria@uts.edu.au (N. Biloria).
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1. Introduction

Urban heat Island (UHI) phenomenon, which refers to the higher temperature level in cities than in surrounding areas (Piselli et al., 2018), is a critical problem caused by urbanization and associated climate change (Akbari et al., 2016). The high temperature in urban areas can increase energy spending owing to a high rate of cooling demand, thus increasing the pressure on the electricity grid during heat waves (Pyrgou et al., 2017). An increase in ambient temperature can also negatively affect an individuals' health (Santamouris et al., 2017). Comfort, in conjunction with health, is being increasingly used to define wellbeing in the built environment (Bluyssen, 2010). There has thus been an increasing interest in studies concerning outdoor comfort (Srivanit and Jareemit, 2020). The value of well-designed open spaces in contributing towards a high quality of life is now acknowledged more than ever (Klemm et al., 2015). Outdoor thermal comfort (OTC) is one of the most influential factors which directly impacts the perceived quality of urban open spaces (Zhao et al., 2018) and thus the participation in outdoor activities (Lai et al., 2014). As a consequence, thermal comfort in outdoor space has recently attracted considerable attention for the sustainable design of cities (Emmanuel, 2016).

The effect of UHI can exacerbate in cities with a hot and humid climatic condition characterized by high air temperature, high humidity and low wind speed levels. Humid tropical climates tend to suffer the consequences of heat island effect twice as much as other regions. This also holds true for urban environments with humid subtropical climates (such as Sydney) during the summer. More than 33% of the world's population live in such cities, which cover one of the five climate classes of Koppen's (Cfa: humid subtropical climate, Cwa: dry-winter humid subtropical climate, Af: tropical rainforest climate, Am: tropical monsoon climate, Aw: tropical savanna climate with dry-winter characteristics). Such cities are exposed to hot and humid weather condition for a considerable period of time (Binarti et al., 2020). On the other hand, long periods of warm weather make outdoor and semi-outdoor spaces more favorable. People thus prefer to spend their time in open environments, in the absence of air-conditioning (Baruti et al., 2019).

The geometrical properties of urban blocks and construction materials are important factors affecting UHI (Falasca et al., 2019; Kantzioura et al., 2015). Well-designed outdoor spaces and thermally comfortable outdoor environments can enhance public health and well-being (Hendel et al., 2017; Jiang et al., 2019), tourism (Ge et al., 2017), the use of open spaces, and level of social interactions (Huang et al., 2019). Studies have found that people's activities in outdoor spaces decrease in summer with an increase in air temperature (Ta) (Lin et al., 2012). Urban outdoor areas lacking microclimatic considerations in their design thus tend to be avoided and remain unused (Lenzholzer, 2012), due to the lack of a practical and applicable design guideline for urban planning (Lenzholzer, 2010).

This study investigates the thermal environment of outdoor spaces in the humid subtropical climate of Sydney, NSW, Australia, and proposes an OTC-based urban planning guideline by deploying computational optimization processes. This process incorporates the use of parametric design and simulation techniques to optimize the thermal performance of street canyons. We evaluate the current thermal environment of selected case studies and subsequently optimize influential urban planning factors that embody the micro-climatic condition of the selected location.

1.1. Thermal perception in outdoor environments

Thermal perception in outdoor spaces is a complex issue that can be affected by climatic characteristics of regions (Indraganti, 2010). Based on a study conducted in highly-dense urban contexts, three elements: weather condition (solar radiation, humidity, and wind speed); personal health factors; and psychological parameters, affect an individuals' outdoor thermal sensation significantly (Sharmin and Steemers, 2020).

Among environmental factors, air Temperature is the most determining microclimatic factor affecting thermal sensation (Liu et al., 2016; Tan et al., 2019). Thermal comfort is also dependent on other climatic factors of radiant temperature and wind speed (Niu et al., 2015; Tan et al., 2019). Air movement with a velocity higher than 1.5 m/s has profound effects on the thermal sensation of users of outdoor spaces (Ali-Toudert and Mayer, 2006; Johansson and Emmanuel, 2006). Besides the pattern of solar radiation, various design factors can also lead to UHI phenomena (Ouali et al., 2018). Modifying a building's layouts can result in a significant difference in the level of thermal comfort of outdoor spaces, especially in moderate climate conditions (Ouali et al., 2020). Many studies have investigated different strategies focusing on OTC improvements, namely ventilation (Hong and Lin, 2015), materials (Taleghani, 2018), vegetation (Besir and Cuce, 2018; Zölch et al., 2016) and water bodies (Steeneveld et al., 2014). Besides this, various geometrical parameters of urban canyons, such as aspect ratio (H/W) and orientation affect environmental conditions such as solar access, wind status, air and surface temperature (Deng and Wong, 2020). Aspect ratio and Street Canyon Orientation are the most important factors in urban planning concerning outdoor thermal comfort (Bakarman and Chang, 2015; De and Mukherjee, 2018; Deng et al., 2016; Huang and Li, 2017; Taleghani et al., 2015). The following sub-section provides a brief overview of these two factors, and the urban surface condition factor, as influencers of OTC.

1.1.1. Aspect ratio

The ratio between a building's height and the width of the street, defined as aspect ratio, is one of the most critical design factors in thermal comfort-based urban planning (Srivanit and Jareemit, 2020). Deep street canyons with higher aspect ratio reduce solar access and air temperature (Deng and Wong, 2020), providing 3.5–6 °C cooler outdoor spaces (Kakon et al., 2009). Aspect ratios below 0.5 and equal to 2 connect to shallow and deep canyons, respectively. While an aspect ratio of 1 is considered adequate for uniform canyons (Ahmad et al., 2005).

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In a study conducted by Rodríguez-Algeciras et al., to achieve an acceptable OTC in summer and winter seasons, the value for this design factor (*H*/*W*) was suggested as 1 and 1.5 (Algeciras et al., 2016). In street canyons with an aspect ratio of 0.6, the center of streets provide a similar thermal condition, in all orientations except East-West, due to the low impact of shading (Andreou, 2013). The optimum value for a canyon's aspect ratio can vary with respect to the street orientation, and the preferred aspect ratio between 0.8 and 2, and >3 for North-South and East-West oriented streets, has been arrived at respectively (Ng and Cheng, 2012). The favorable quantity of this design factor can also be decreased in streets located on East-West axis by using street-level shading and tree coverage (Andreou, 2013). Since an East-West urban grid, orientation provides the most energy-efficient design for buildings blocks, several strategies such as using shades can be applied to achieve both goals of outdoor thermal comfort and energy saving (Yahia et al., 2018).

Compact geometry for canyons, defined by lower aspect ratio, provides a higher level of outdoor comfort (De and Mukherjee, 2018; Deng and Wong, 2020; Yahia et al., 2018; Zhang et al., 2018). This higher level of comfort is mainly due to the shading effect of neighborhood buildings. People prefer doing their activities in shaded spaces in summer (Mi et al., 2020), but in winter, sunlit spaces are much more favorable (Mi et al., 2020). The higher ratio of Height/Width decreases wind velocity (Yahia et al., 2018), while wider streets result in higher wind speed (Johansson and Emmanuel, 2006). In deep street canyons, a variation in wind speed can change the temperature up to 5 °C (Mi et al., 2020). Outdoor spaces in highly-dense urban areas with high rise buildings also experience a higher level of mean radiant temperature (Tmrt) and wind speed. In contrast, with low rise buildings, the outdoor urban environment seems to be more uncomfortable.

1.1.2. Street canyon orientation

Along with aspect ratio, many studies found the street canyon orientation to be one of the most crucial design factors affecting outdoor thermal comfort (Srivanit and Jareemit, 2020). Several studies indicate that North-South oriented canyons provide the highest level of outdoor comfort for pedestrians, while East-West orientation has been regarded as the worst situation (Bakarman and Chang, 2015; Deng and Wong, 2020; Huang and Li, 2017; Srivanit and Jareemit, 2020). East-West streets experience extreme solar radiation and are dedicated to the highest value of mean radiant temperature (Tmrt) (Deng and Wong, 2020). Furthermore, in a few studies, North East-South West orientation for street canyons was found to be the optimum layout in urban planning (Chatzidimitriou and Axarli, 2017; De and Mukherjee, 2018). The North-South direction of street canyons provides the highest degree of thermal comfort for outdoor users, however, this urban layout causes extreme consumption of energy by buildings for cooling purposes (as building envelopes are more susceptible to heat loss) (Huang and Li, 2017; Sudprasert, 2019), and are less exposed to the sunlight (Srivanit and Jareemit, 2020). Street orientation also has a significant impact on the airflow factor at the pedestrian level (Chatzidimitriou and Axarli, 2017). Streets oriented in the same direction of the prevailing wind flow experience the highest wind velocity, and this value gets intensified by decreasing the aspect ratio of the street canyon (Deng and Wong, 2020; Emmanuel et al., 2007; Kakon et al., 2009). Variation in buildings height and asymmetrical aspect ratios can also create turbulence and impact the associated ventilation around high rise buildings (Emmanuel et al., 2007; Qaid and Ossen, 2015; Sharmin et al., 2015).

1.1.3. Urban surface conditions

In urban environments, due to the higher temperature of artificial materials, the direction of sensible heat flux is outward, resulting in increase in air temperature (Ta) (Erell et al., 2014). In an urban environment, surface temperature considerably affects both the thermal condition of outdoor spaces and the energy use of buildings. Therefore most urban configurations are in favor of E-W oriented streets, for maximizing solar exposure (Andreou, 2013). Strategies such as using high albedo surfaces can reduce the air temperature in urban open spaces (Piselli et al., 2018), (Santamouris et al., 2008; Synnefa et al., 2008). According to Zhang et al., increasing the albedo of urban roofs to 0.7 has similar effectiveness as covering half of them with green. Both result in near-surface air temperature reduction. Salata et al., in 2017, have also proven that a combination of cool roof and pavements and vegetation can improve comfort index to a great extent and reduce associated health risks up to 60% (Salata et al., 2017). The use of greenery is associated with alleviating the UHI effect (Gill et al., 2007) and alter the meteorological parameters of air temperature, wind velocity, and relative humidity (Byrne et al., 2008). A tree-planting pattern with 4 m distance can reduce the Mean Radiant Temperature by up to 23 °C compared to a treeless urban environment (Srivanit and Jareemit, 2020).

2. Methodology

This study aims to explore optimum urban layout for housing development in the city of Liverpool, NSW, Australia. Effective design factors of street canyon orientation, aspect ratio, building geometry, and tree-planting pattern in outdoor spaces are investigated in this research. Fig. 1 represents the methodological workflow in which the ENVI-met tool and PET index are used for evaluating both existing street configuration and designed scenarios.

2.1. Study area

Liverpool, as a part of the Western Sydney growth strategy, has been identified as a key district to host an increase in housing projects (Greater Sydney Commission, 2018). This increase in housing numbers can pose a significant change in the microclimatic conditions of the streets of Liverpool, resulting in an unfavorable outdoor thermal environment. Liverpool is primarily composed of three different street widths and two intersecting orientations. Liverpool's residential district have either two-lane width (7 m) or four-lane width (10 m) streets, and a limited number of 6-lane roads (more than 15 m) roads (Fig. 2, left). The evaluation in this research does not cover the 6-lane roads since

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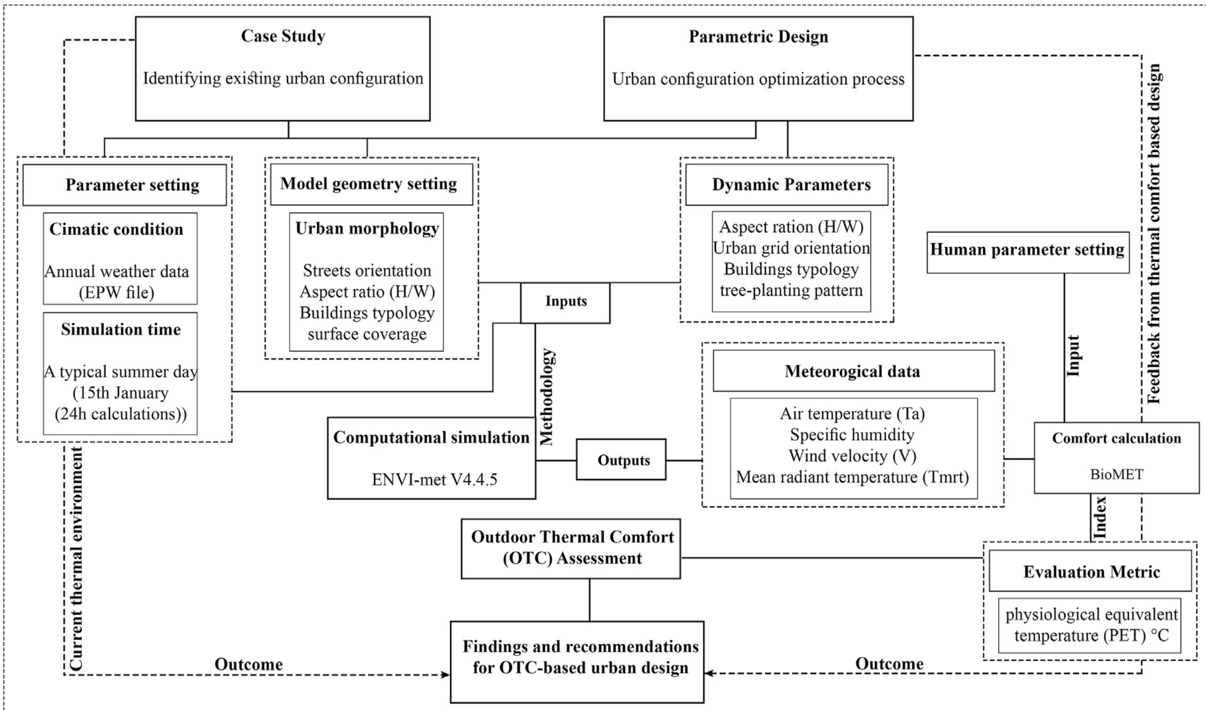

Fig. 1 Research process framework.

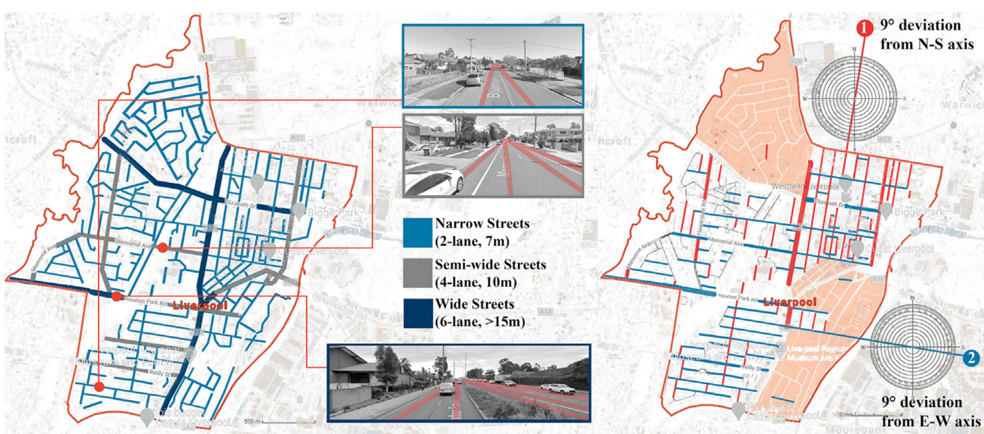

Fig. 2 Street morphology; Width (left) & Orientation (right).

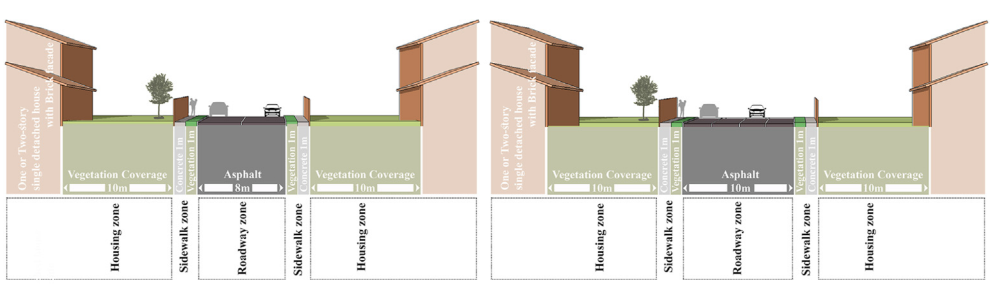

Fig. 3 Cross-section of narrow (left) and semi-width (right) streets in Liverpool.

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they are limited and away from the residential context. In this research, a street width of 8 m is considered for two-lane streets. Main streets constitute conventional black asphalt, and 1 m wide concrete pavements (Fig. 3).

Two orientations: North-South and East-West, both with 9° deviation, are dedicated to the majority of the urban blocks. Nonetheless, streets in the northwestern and southeastern urban blocks (Fig. 2 right) digress from the 9° deviation and are thus considered outside the scope of this study.

The housing typically comprises of one or two-story single-detached units with brick as a typical facade material. An average height of 4 m, considering the standard pitched roof in this region is decided upon. The housing typically are at 10 m distance from the main street canyon, which comprises of a yard covered with a high percentage of vegetation (low-density grass). This positioning has an impact on the adjacent street's microclimate due to an increase in greenery and the associated reduction of the urban heat island effect.

2.1.1. Weather data

Sydney's weather file (EPW) with the closest climatic data to Liverpool is considered for the simulation process (Fig. 4). The mean daily maximum temperature is recorded as 26–28 °C, and 17 °C in summer and winter seasons, respectively. The annual mean daily maximum is 22–23 °C in summer, and 5–8 °C to 17–18 °C in winter (Canberra: Australian Government Publishing Service, 1991). The average wind speeds at the pedestrian level (at the height of 1 m) are 1.8–2.2 m/s. Maximum daily summer solar radiation flux density peaks at around 1000 W/m^2, while in winter, the maximum peak is somewhat lower at around 650 W/m^2 (Spagnolo and de Dear, 2003).

The 15th of January, which represents one of the hottest days of summer, is selected to investigate the impact of different urban morphologies on the thermal perception of outdoor users. The simulation duration was set to 24 h to consider the diurnal temperature variation. Results are analyzed for a 12 h time frame, from 06:00 till 18:00 h, in line with similar scientific studies (Fang et al., 2019; Middel et al., 2016; Natanian and Auer, 2020; Srivanit and Jareemit, 2020).

2.1.2. Case studies

The research aims to provide an understanding of the current thermal environment of the streets in the residential district of Liverpool, NSW, Australia. Four typical case studies with narrow and semi-wide streets and two primary orientations were subjected to simulation for evaluating their comfort index. Fig. 5 shows the modeled urban streets. The models have been simplified, and an average of 25 cm dense grass has been considered as greenery to reduce the simulation time.

2.2. Design application

Several urban design scenarios with dynamic setting parameters of streets orientation (N–S, E-W, NE-SW, SE-NW), building typology (singular and linear), aspect ratio (0.5, 1, 1.5, 2), and tree-planting pattern (with a distance of 4 m and 8 m) are simulated to investigate the best layout for street canyons based on their thermal environment. To simulate actual conditions on ground, a 2-m wide low-density grass vegetation strip is assumed between the street and the sidewalks in each design scenario. The 2-m width represents a minimum possible value based on the modelling mesh dimensions. However, in order to evaluate the impact of greenery on outdoor thermal comfort, two tree-planting options (dense and sparse) with different distances (4 m and 8 m) have also been considered.

14 design alternatives are simulated and analyzed to provide guidelines for thermal comfort based urban planning. Each design factor is individually simulated, and the optimum option per design factor is carried forth to the next phase iteratively. The variables are finally evaluated cumulatively. However, it is only in the phase: Evaluation of the impact of tree planting on OTC, that the worst-performing option (aspect ratio of 0.5) is selected for input in the next phase. This is primarily due to the fact that streets with the optimum configuration (aspect ratio of 2) present an acceptable level of thermal comfort and do not require further improvements such as the inclusion of water or green bodies. Therefore, in the street configurations with an aspect ratio of 0.5, an attempt has been made to approach the optimal thermal condition by applying the aforementioned tree-planting patterns.

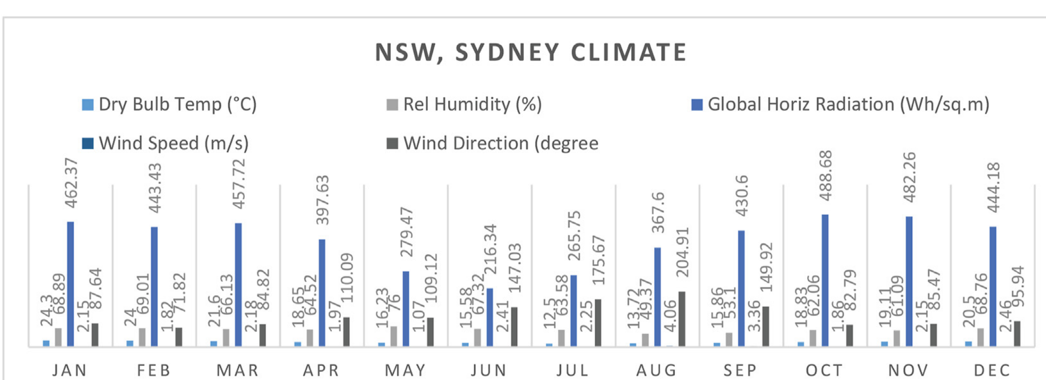


Fig. 4 Average monthly weather data.

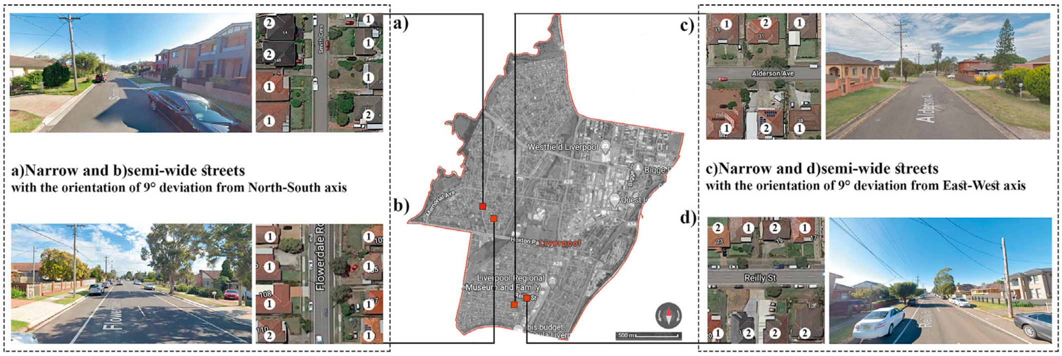


Fig. 5 Case studies (values on the buildings represents the number of floors).

To reduce the calculation time, brick, which is the most commonly used facade material in Liverpool, is considered for buildings. Main streets and Sidewalk coverage materials retain the same properties as the existing condition. Table 1 illustrates different urban design scenarios for the proposed dynamic setting parameters.

2.3. Simulation process

Numerical simulation as a methodology is highly applicable in OTC investigation due to the complexities of urban climate (Arnfield, 2003) and the broad range of morphological variables, which makes field studies less preferable. Computational simulations have been used in numerous studies (De and Mukherjee, 2018; Salata et al., 2017; Yahia et al., 2018), with only a limited number of studies such as studies of Sharmin et al., Qaid et al., Lin et al., and Yang et al. (Lin et al., 2010; Qaid and Ossen, 2015; Sharmin et al., 2015; Yang and Lin, 2016), having conducted field measurement (Ali-Toudert and Mayer, 2006). This study utilizes the computational simulation of microclimatic conditions to analyze a total of 14 design scenarios using the 3D model ENVI-met. The ENVI-met is a microclimate-based tool (Deng and Wong, 2020), developed by Bruse (2004), which provides precise values for the parameters of air temperatures (°C), mean radiant temperature (°C), specific humidity (g/kg), wind velocity (m/s), and solar radiation, all of which serve as indicators of human comfort in outdoor spaces. EnviMET has proven to be a valid tool that provides accurate data close to real-time weather conditions (Salata et al., 2015; Yang et al., 2013), especially for the calculations during the summer (Bande et al., 2019). Further, the study uses the full forcing mode for all variables (temperature, wind, humidity and solar radiation), which further increases the model's accuracy (Koletsis et al., 2019). Hence, in this study, ENVI-met tool V 4.4.5 has been used to extract these effective meteorological factors. The study then utilizes BioMET (V2.0) for PET calculations.

An analysis mesh with 2×2 m^2 cell-size, which is approved to provide reliable data with a high degree of accuracy while decreasing computation time compared to higher resolutions with smaller-sized cells (Salata et al., 2016), is considered to examine the 3D models. The model domain covers a 56-m section of the street canyons (28 cells along the grid length). Results are extracted for a height of 1.4 m above the ground level, representative of a standing person to evaluate the comfort degree for outdoor spaces users.

2.4. Evaluation metric/comfort index

According to an OTC-based literature review in 2020, physiological equivalent temperature (PET) is the most commonly used index in hot-humid climates (Binarti et al., 2020). It is defined as "air temperature at which the heat balance of the human body is maintained with core and skin temperature equal to those under the conditions being assessed" (Höppe, 1999). This index is based on a simplified model of human energy balance using the "Munich Energy Balance Model for Individuals" (Thorsson et al., 2007) and was initially used for the VC13787 German guidelines (VDI, 1998).

"Physiological equivalent temperature" is suggested by numerous studies (De and Mukherjee, 2018; Du et al., 2020; Mi et al., 2020; Tan et al., 2017), and has proven to be a useful metric for outdoor comfort in almost all the climatic conditions. PET is based on the calculation of Tmrt with the combination of globe temperature, wind speed, and air temperature for outdoor comfort evaluation (Thorsson et al., 2007). Other than meteorological parameters, user's behavioral actions such as clothing and metabolic rate are included in PET calculations using BioMET. In this regard, the human parameter setting utilizes the model of a 35-year-old male weighing 75 kg, with a height of 1.75 m, and clothing insulation and metabolic rate of 0.9 and 86.21 W/m^2, respectively. The calculated PET is used to determine hours within the comfortable range, from 18:00–23:00 h, on a typical summer day. Table 2 illustrates the standard values for different thermal sensations and stress assigned to each PET range.

2.5. Model validation

Honeybee V.0.0.66, a Grasshopper tool is employed to evaluate the model's accuracy level represented by the root mean square error (RMSE). The Honeybee plugin is considered a valid tool and has been used in previous studies to estimate comfort condition in outdoor urban environments (Aghamolaei et al., 2020; Albdour and

Table 1 Designed scenarios for OTC calculations.

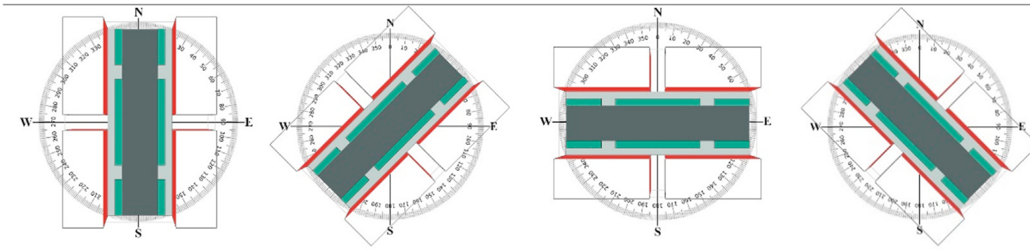
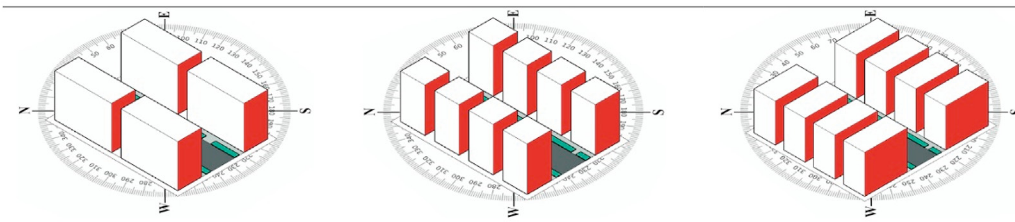
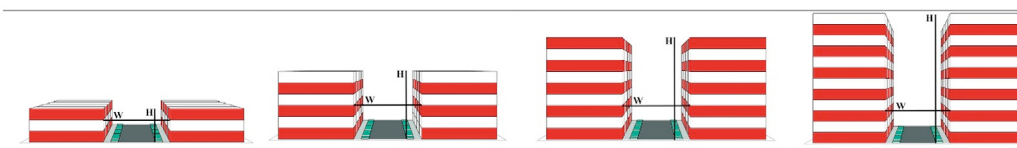
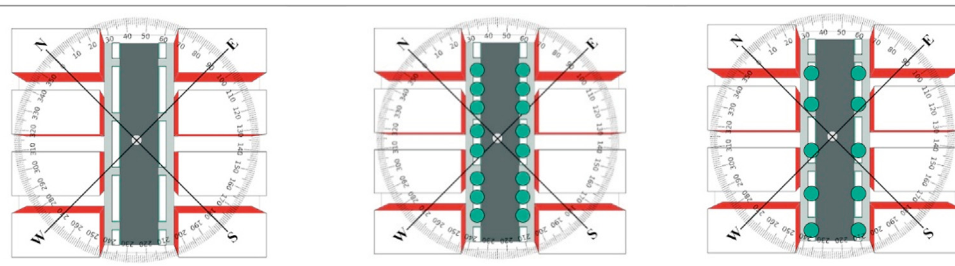
Dynamic parameters				
Street Orientation	N-S	NE-SW	E-W	NW-SE
				
Buildings typology	Linear.NE-SW	Singular	Linear.NW-SE	
				
Aspect ratio (H/W)	0.5	1	1.5	2
				
Tree-planting distance (m)	No tree	4 (dense)	8 (sparse)	
				

Table 2 Physiological Equivalent Temperature thermal sensation/thermal stress (Matzarakis and Mayer, 1996) *estimate of outdoor.*

Thermal sensation/stress	PET (°C)
Extreme cold stress	–
Very strong cold stress	–
strong cold stress	<4
Moderate cold stress	4–8
Slight cold stress	8–18
Comfortable	18 to 23
Moderate heat stress	23–35
Strong heat stress	35–41
Very strong heat stress	>41

Baranyai, 2019; Evola et al., 2020). Hourly Air Temperature data obtained from two different simulator engines: Energyplus and ENVI-met is compared for the same urban configuration to approve the models' accuracy. Results indicate that there is a strong correlation of 0.91 between Air Temperature parameter measured by Honeybee and ENVI-met tools. This very high value of R2 confirms the model's accuracy.

Furthermore, the MSE mathematical method is employed to estimate the overall deviation between simulated values in the Honeybee plugin and the ENVI-met software. In this study, the small value of RMSE: equal to 1.48, highlights the reliability of the chosen framework and the precise simulation of microclimatic conditions for the case study.

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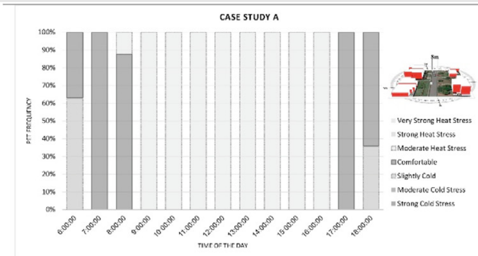
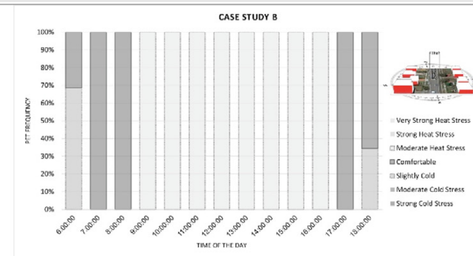
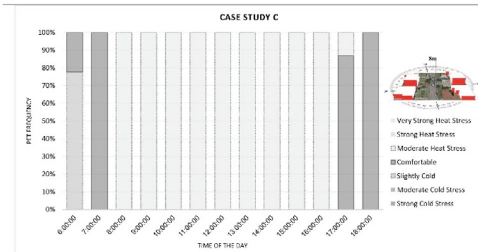
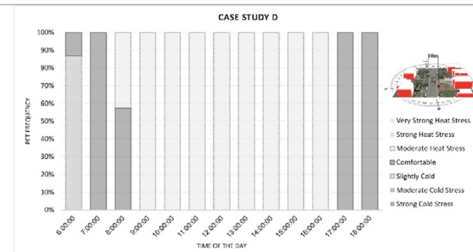
Table 3 PET frequency in case study streets of Liverpool[a].

	
a. Case study a (narrow street with 9° deviation from N-S axis)	b. Case study b (semi-wide street with 9° deviation from N-S axis)
	
c. Case study c (narrow street with 9° deviation from E-W axis)	d. Case study d (semi-wide street with 9° deviation from E-W axis)

[a] The charts present the percentage of the streets which embrace different ranges defined for thermal perceptions.

3. Results

The case study analysis results determine the thermal condition of Liverpool's streets located within residential districts. Streets situated on the north-south axis, offer a superior thermal comfort level than East-west oriented streets, and the PET values present the comfortable range for 12.33% for daytime (6:00 to 18:00). The design parameter of street width does not change thermal conditions dramatically. This is mainly due to the small difference in their values (2 m) and the low height of the surrounding buildings. Table 3 represents hourly PET frequency in different case studies.

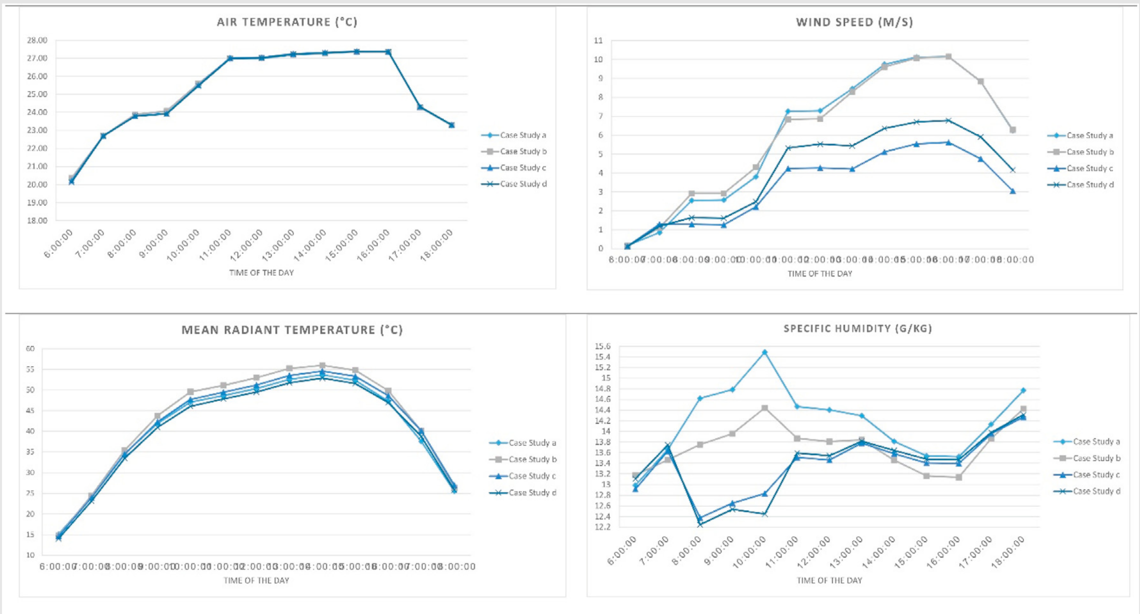
In the north-south oriented streets, the humidity and wind speed increase by an average of 4.02% and 34.02%, respectively (Table 4). There is a difference of 3.98 m/s in the airflow at its maximum (3 p.m.) in two street orientations of north-south and east-west directions with 9-degree deviation from the central axis. Semi-wide streets in Liverpool's residential regions experience higher wind velocity compared to narrow streets. Wind speeds on 10-m wide streets increase by an average of 8.81% during the day compared to the 8-m streets. There is no alteration in Air temperature values, and the variations in the mean radiant temperature parameter are less than 5 °C in the four selected case studies.

Table 5 presents variations in meteorological parameters affecting thermal comfort for designed scenarios, including air temperature (Ta), wind speed, mean radiant temperature (Tmrt), and specific humidity. Comparing the alternatives, we find that the air temperature parameter does not differ more than 1 °C. Despite this, the average mean radiant temperature and wind speed can vary significantly with respect to street orientation and aspect ratio design parameters. Specific humidity also increases dramatically only when urban surfaces include greenery (tree-planting scenarios are applied to simulate the same). Effective climatic parameters for each influential design factor are discussed in the following sections.

3.1. Street orientation

Street orientation is investigated as the first variable since this parameter presents as the most influential design factor in OTC-based urban planning. As shown in Table 6(b), results indicate that the streets on the NE-SW axis provide the highest level of thermal comfort, and on average, can perform up to 24.95% better than the other three orientation alternatives. This type of urban configuration offers outdoor users with thermally comfortable conditions (from 10 a.m. to 4 p.m.) in the hottest time of the year. In other times of the day, the thermal perception is included in the "slightly cold" range, which is still acceptable and desirable. This perception is mainly due to the effect of other meteorological factors of wind speed, which range between 0.09 and 9.77 m/s during the daytime (6–18), with air temperature (Ta) recorded as high (19–27 °C) during this typical summer day (15th January). Apart from shading, wind speed tends to be the most critical parameter affecting thermal comfort. It can thus be stated that the

Table 4 Meteorological parameters variation in Case studies.



urban design factor of street orientation, has a considerable influence on PET values in association with wind speed and wind direction (Andreou, 2013; Andreou and Axarli, 2012).

The N—S orientations for street canyons (Table 6(a)) is identified as the second priority in an OTC-based urban design and can result in outdoor spaces experiencing thermal comfort for 49.97% of the daytime. As regards outdoor thermal comfort in urban environments, the worst option for street directions was evaluated as the NW-SE orientation (Table 6(d)). As the solar exposure time and the average mean radiant temperature (Tmrt) increases, and the wind velocity decreases, the outdoor users face the lack of thermal satisfaction. These two parameters are proven to be the most influential climatic factors affecting outdoor thermal comfort. This type of street experiences "moderate heat stress" conditions for 33.14% of the daytime. The second worst orientation for street canyons was the E-W direction (Table 6(c)), which similarly increases heat stress at noon while improving thermal comfort in the early hours of the day. In these two street canyons, comfort level can be enhanced by increasing the shading effect and

Table 5 Meteorological parameters variation in designed scenarios*.

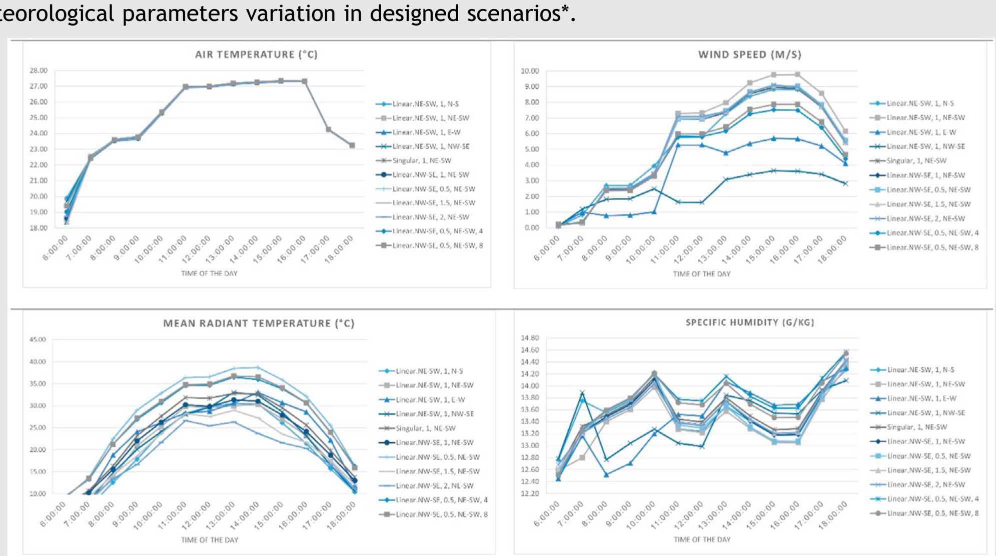
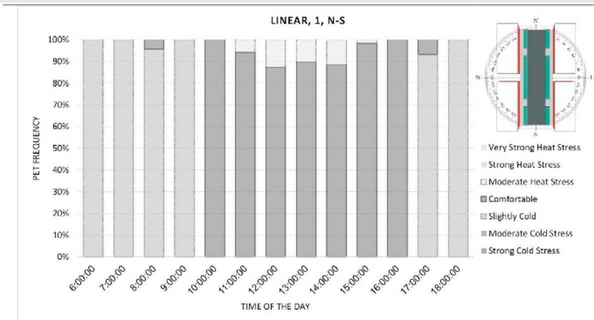
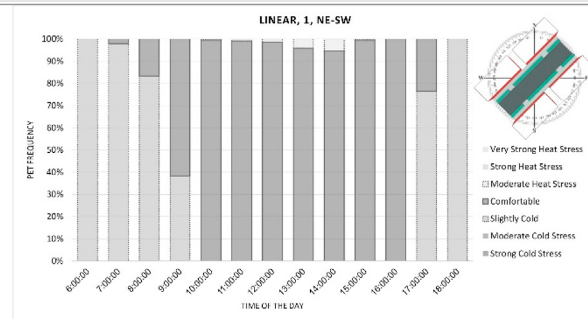


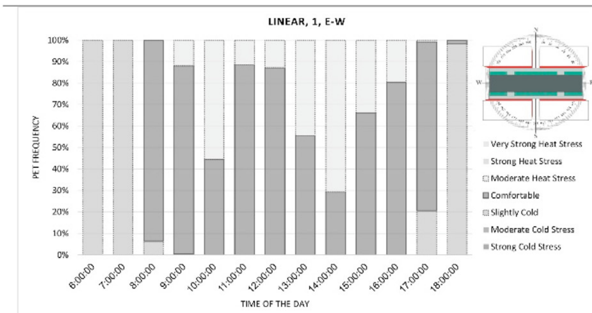
Table 6 The effect of Street Orientation parameter on PET frequency.



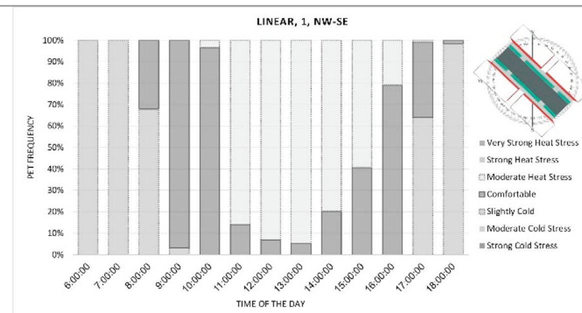
a. North-South oriented streets



b. North east-South west oriented streets



c. East-West oriented streets



d. North West-South east oriented streets

by using strategies such as designing high-rise buildings (for increasing aspect ratio) or planting trees.

All alternatives of street canyon orientation offer the thermal perception of being "slightly cold" in the early morning (before 8 a.m.) and late afternoon (after 5 p.m.).

Furthermore, as previously discussed, the climatic parameter of MRT can affect thermal perception significantly and is mainly associated with street canyon orientation. Hence, the average mean radiant temperature has the highest value of 33 °C in the E-W oriented streets, resulting in moderate heat stress for most of the daytime. The value of this parameter decreases to 8.24% in NE-SW oriented streets, thus presenting an optimum urban layout.

As shown in Table 7, in the best option (NE-SW oriented streets), the average wind speed is 59.09% higher than the streets located on the NW-SE axes. At the same time, the other meteorological parameters of humidity and air temperature do not change dramatically compared to other orientation alternatives. This highlights the significance of wind velocity for thermal comfort in this specific region with coastal climatic conditions. Accordingly, the highest wind velocity occurs in the most optimal street orientation.

3.2. Building typology

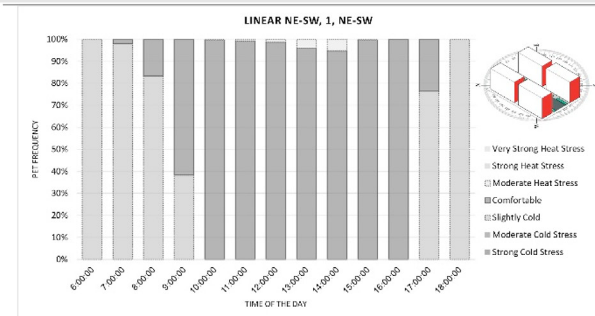
Buildings typology in this study resulted in showcasing the least impact on OTC among all variables constituting the urban morphology. Results indicate that the linear typology of buildings extended on the NW-SE axis (Table 7(c)) presents the highest level of comfort among the other two alternatives of singular and NE-SW extended linear typologies. Nevertheless, this design factor does not vary PET values dramatically and is of less importance for OTC-based urban planning. Generally, in the NE-SW oriented streets, the spacing between buildings does not improve thermal conditions. It is thus recommended to avoid using this arrangement of building blocks (Table 7(b)) in urban planning solutions. Although the linear typology extends perpendicular to the direction of the street, present preferable thermal performance results do not show significant variation in comfort condition, since the design factors of orientation and aspect ratio are constant in these three building typology options.

The wind speed experiences its highest value in linear buildings extended on the NE-SW direction. However, in the NW-SE direction, with extended linear and singular building typologies, wind speed decreases between 6.60% and 7.30%, respectively. There is also no notable change in the other climatic parameters concerning these three building typologies. The variations in the specific humidity and the mean radiant temperature are 1 g/kg, and 3 °C at their maximum, respectively.

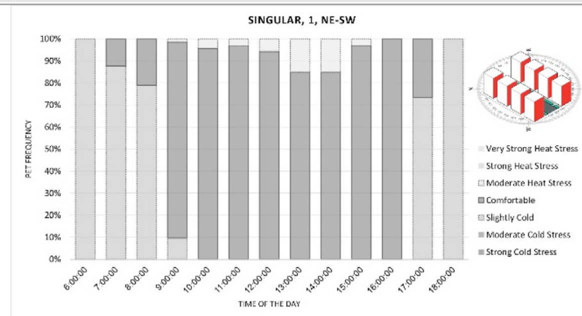
3.3. Aspect ratio

Aspect ratio, which is the second most important design factor in proving a thermally comfortable urban environment, is investigated in optimized street configuration

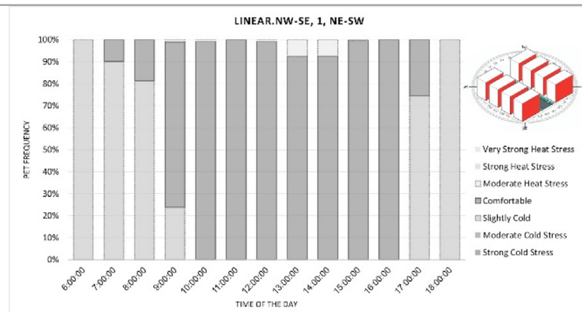
Table 7 The effect of Building Typology on PET frequency.



a. Linear, NE-SW extended buildings



b. Singular buildings



c. Linear, NW-SE extended buildings

with NE-SW orientation and NW-SE extended linear buildings. An increase of 0.5 in aspect ratio values can decrease the maximum mean radiant temperature by 2.90 °C on average in the early morning and late afternoon and consequently decreases PET values. The alternation of this design parameter from 0.5 to 1 increases comfort hours by 30.59%. Nevertheless, in this specific coastal region, which experiences excessive wind speed, increasing the *H*/*W* ratio to achieve aspect ratios of more than one is not recommended. This increase would move the "comfortable" range and cause the streets to experience a slightly cold condition for most of the day time (18–6 a.m.). A 0.5 increase in the value of aspect ratio will result in an average decrease in thermal comfort by 2.22%. Hence, the aspect ratio of 1 (Table 8(b)) is considered as the best option for buildings located in NE-SW oriented streets. On the contrary, an aspect ratio of 0.5 increases moderate heat stress between 10 a.m. and 3 p.m.

Generally, to achieve a satisfactory comfort level, there should be an increase in the aspect ratio value, which increases the shading percentage for horizontal surfaces. As aspect ratio increases, the mean radiant temperature decreases. Each 0.5 increase in aspect ratio values can reduce the MRT parameter by 3.31 °C (13.23%). There is also no significant variation in wind speed and humidity, which was recorded.

3.4. Tree-planting pattern

The use of vegetation and tree planting is also another effective parameter that can be considered as a solution to improve the thermal condition of the streets, especially in streets designed in non-optimal orientations with low-rise buildings. As the comfort level is already satisfactory in optimized urban configurations (containing the *H*/*W* ratio of 1), two tree-planting options are investigated in the optimized urban layouts with low-rise buildings (*H*/*W* ratio: 0.5).

The application of densely planted trees (at a spacing of 4 m) can reduce PET values up to 12.07%. However, this value can decrease to 7.83% for a sparse tree-planting pattern (Table 9(c)). These results can be used to reduce PET values in urban areas, which are unable to present a pleasant thermal environment.

Using greenery and planting of trees can increase specific humidity by 0.56 g/kg at its maximum and improve the associated thermal comfort on the streets. The average mean radiant temperature will also decrease between 1.49 °C and 1.32 °C by using dense and sparse tree-planting options.

4. Discussion

Existing streets in Liverpool's residential district have a deficiency in offering a thermally comfortable urban

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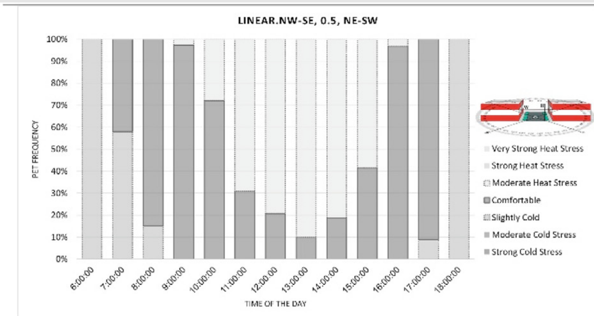
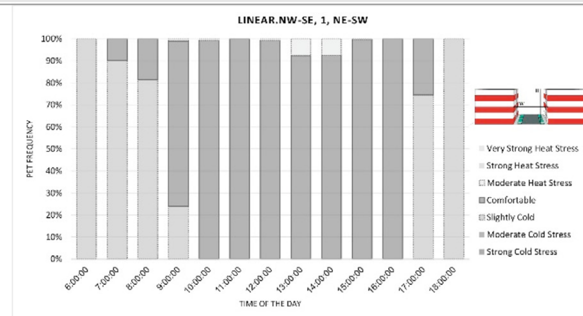
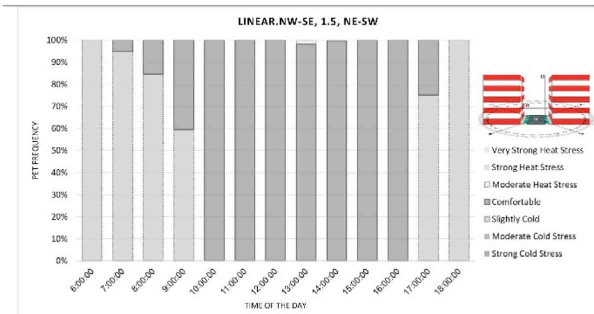
Table 8 The effect of Aspect ratio parameter on PET frequency.



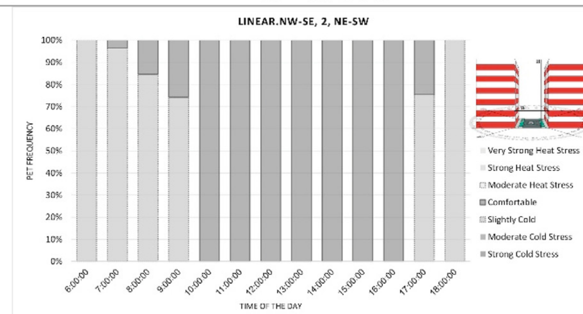
a. H/W: 0.5



b. H/W: 1

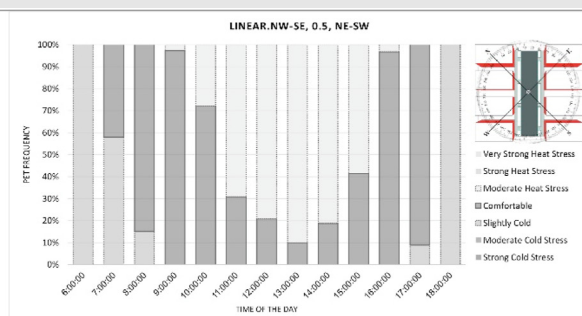


c. H/W: 1.5

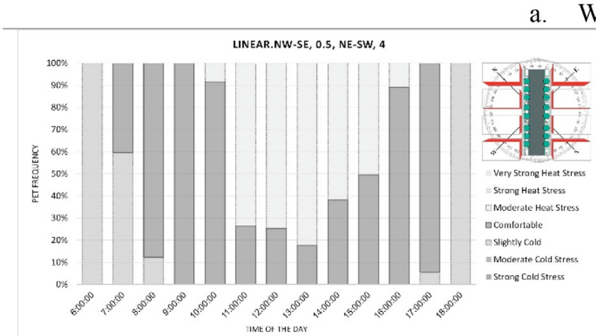


d. H/W: 2

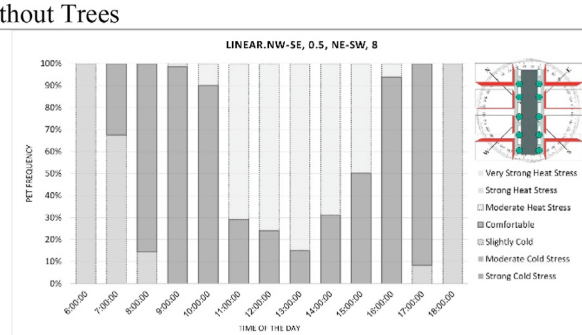
Table 9 The effect of Tree-planting distance parameter on PET frequency.



a. Without Trees



b. Tree distance of 4m (dense)



c. Tree distance of 8m (sparse)

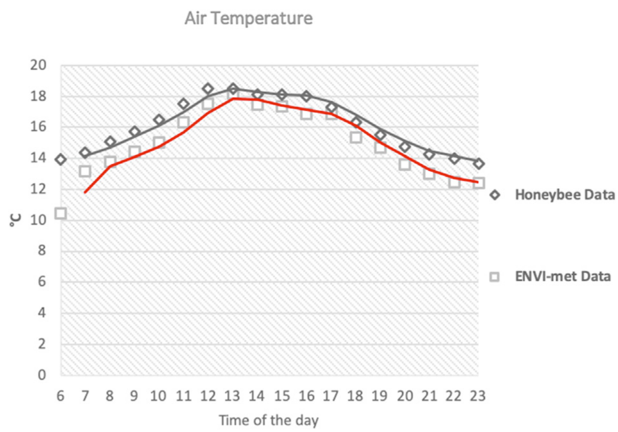


Fig. 6 Air Temperature (°C) data obtained from different tools of Honeybee and ENVI-met.

Table 10 Effective percentage of urban design factors on climatic parameters.

Design factor	Effective percentage				
	Ta	Wind speed	Tmrt	Specific humidity	PET
Street canyon orientation	0.39	59.07	14.69	1.24	46.42
Buildings typology	0.16	7.29	10.62	1.36	3.57
Aspect ratio	0.65	0.83	35.16	0.19	30.59
Tree-planting pattern	0.24	12.09	5.25	1.92	12.07

environment. Although North-South streets with a 9-degree deviation from the main axis struggle with heat stress issues for fewer hours of the daytime, they still can cause unsatisfactory thermal perception. This perception is mainly due to the low proportion of the Aspect Ratio parameter, which decreases the shading effect and increases the average mean radiant temperature within the street canyons. Fig. 6 represents the daily time percentage, in which different case study streets experience thermally comfortable conditions.

This study aims to improve the thermal condition of these outdoor spaces providing potential future use in the urban development and urban planning processes. Among the investigated urban design factors, street orientation is revealed as having the highest effectiveness (46.42%), followed by the factors of aspect ratio (30.59%), surface coverage (greenery), and building typology. As shown in Fig. 7, the percentage of time, in which thermally comfortable condition is experienced, increases by using the optimum urban layouts proposed in this research. Accordingly, the comparison of all alternatives shows that the best thermal conditions occur in streets located on the NE-SW axis, and surrounded by mid-rise buildings (*H*/*W* ratio of 1) expanded in the NW-SE direction (Fig. 8).

Results indicate that wind speed is the most influential parameter affecting outdoor thermal comfort in this specific coastal region with humid subtropical climatic conditions. Mean Radiant temperature i.e., the exposure to solar radiation, is of second degree of priority. Hence, street orientation and aspect ratio variables can undoubtedly change the PET values to a great extent.

Table 10 shows the correlation between urban design factors and the four effective meteorological parameters using effective percentage. This value represents the difference between the best and the worst option (divided by the value of the best option) regarding each design factors of streets orientation, buildings typology, aspect ratio and tree-planting pattern. Air temperature and specific humidity emerge as the least effective, suggesting that urban configurations can alter their value only to a limited extent.

The proposed growth of Western Sydney shall thus certainly benefit by considering the output of this research and aid in the development of livable urban environments, thus enhancing the overall wellbeing of citizens. The proposed guidelines can be useful as a part of the development

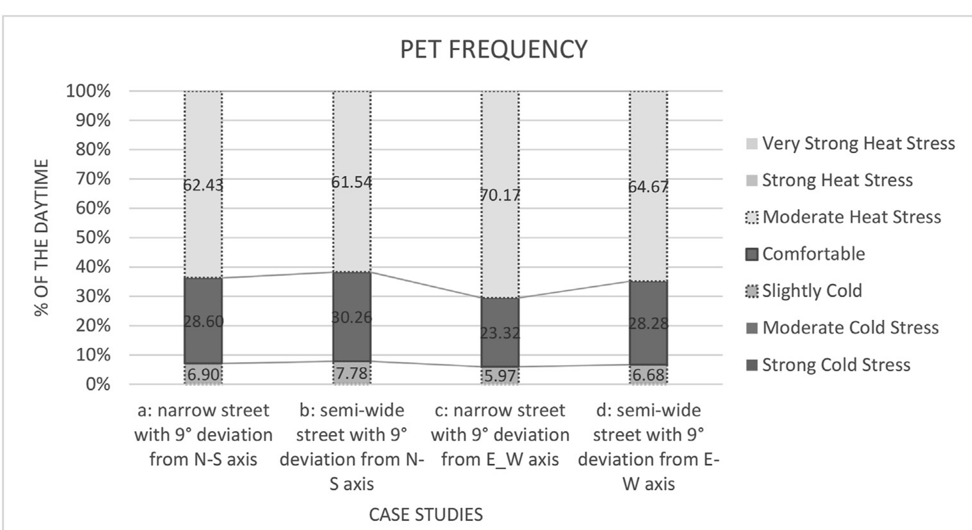


Fig. 7 PET frequency in four selected case studies.

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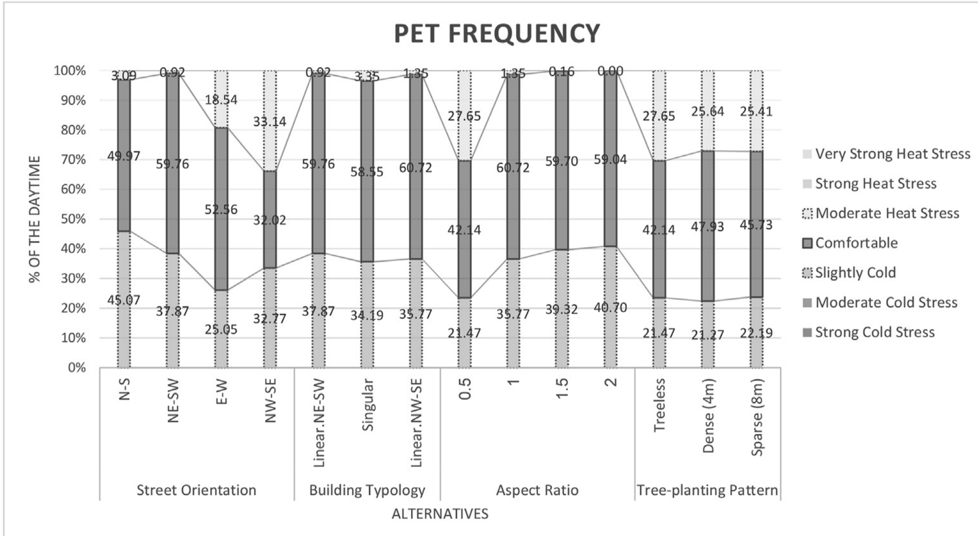

Fig. 8 The effect of street design variables on outdoor thermal comfort.

plan for urban blocks located in regions with humid subtropical climatic conditions similar to Sydney.

5. Conclusion

This paper investigates the thermal performance of the streets located in Liverpool, NSW considering the most common urban configuration in Liverpool's residential districts. A set of thermal comfort analysis was conducted to examine the impact of design parameters affecting outdoor thermal conditions using a parametric approach. The results are discussed in terms of meteorological parameters of air temperature (Ta), wind velocity (V), mean radiant temperature (Tmrt), and specific humidity, which define the comfort index of physiological equivalent temperature (PET) to describe the comfort level of street canyons in Liverpool. The presented study contributes to providing an OTC-based guideline for urban development by analyzing microclimatic conditions of street canyons and by investigating the degree of influence of the involved design parameters. The results demonstrate that a higher level of thermal comfort can be achieved using optimum design parameters and provide a pleasant outdoor living environment. The results of our analysis can be utilized by multiple stakeholders, allowing them to extract the most vital design factors which will contextually influence the thermal comfort of outdoor spaces.

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.

Acknowledgement

Each of the authors has substantially contributed to conducting the underlying research. Nastaran Abdollahzadeh conceived the study and was responsible for writing-original draft, software, methodology, data collection and analysis. Dr. Nimish Biloria was responsible for supervision, methodology, data curation and interpretation, review and editing.

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