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RESEARCH ARTICLE

Urban microclimate and energy consumption: A multi-objective parametric urban design approach for dense subtropical cities

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Abstract Climate change within the urban contexts is a crisis that cities are confronting globally. This issue poses numerous negative consequences such as thermal discomfort and increased energy usage within the building sector. This is especially the case in Western Sydney, Australia, where the average maximum temperature has risen by 7–8 °C within the past 30 years. This increase in temperature is highly concerning, since this region is witnessing rapid urban and infrastructural development and is proposed as the third-largest economy of Australia. Temperature changes in this region will also result in considerably increasing the electricity used for cooling purposes. This paper presents a parametric approach driven multi-objective optimization methodology to discover optimum design solution based on the urban microclimate and cooling energy demand of multi-functional buildings within this urban context. Mitigation measures including a range of design factors at both building (typology and window to wall ratio) and urban scales (aspect ratio and urban grid rotation) are further suggested for developing context sensitive optimum urban layouts. The resultant solutions indicate an improvement in urban thermal comfort, cooling and heating energy use by up to 25.85%, 72.76%, and 93.67%, respectively.

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Abbreviations

UHI	Urban Heat Island
PET	Physiological Equivalent Temperature
CBD	Central Business District
CL	Cooling Load
Tmrt	Mean Radiant Temperature
HL	Heating Load
Ta	Air Temperature
EU	Energy Use
RH	Relative Humidity
DBB	Distance Between Buildings
V	Wind Velocity
SHG	Solar Heat Gain
H/W	The ratio of buildings height to street width
FA	Floor Area
AR	Aspect Ratio
VLT	Visual Light Transmittance
UGR	Urban Grid Rotation
BT	Building Typology
UTC	Urban Thermal Comfort
WWR	Window to Wall Ratio

1. Introduction

It is estimated that 66% of the world's population will live in cities by 2050 (UN, 2015). This rapid rate of urbanization has brought numerous changes to people's life. Critical amongst these are thermal conditions they experience in outdoor urban environments, and the energy sources used to provide an acceptable indoor condition. An increasing population rate is only one of the three main factors that make energy concerns more vital than ever before. Energy paradigm changes and the urban heat island (UHI) effect (Frayssinet et al., 2018), which are common phenomenon occurring in dense urban environments, are the two other factors that make governors, policymakers, and designers turn towards energy centric planning initiatives. Cities are responsible for 75% percentage of global energy use and 60% greenhouse gas emissions (Oliveira and Silva, 2013). This statistic occurs in a context where energy demand in the building sector, which is about 40% of the total energy use (EU, 2010), is directly affected by the context and microclimate in which buildings are located. Air temperature is usually higher within the urban context compared to rural areas (Piselli et al., 2018), mainly due to the higher thermal absorbance of urban surfaces (Frayssinet et al., 2018). The UHI effect further increases cooling needs (Allegrini et al., 2012) and imposes surplus pressure on the electricity grid during peak times. Numerous studies have shown that cooling energy use has increased by 23% between 1970 and 2010 due to the impact of global warming (Santamouris et al., 2015). Mitigating such concerning energy issues, from project planning to operation stages thus need to gain priority while creating urban development plans, especially during the early stages of design (Shi, 2020). Despite this urgency, only a few studies have been conducted exploring these critical issues simultaneously (Evola et al., 2020; Hwang et al., 2017). Focused research has either been conducted on exploring thermal conditions in various urban contexts to propose mitigation measures to provide a healthy, livable outdoor environment (Abdollahzadeh and Biloria, 2020; Ouali et al., 2020; Srivanit and Jareemit, 2020), or explored the impact of these influential design parameters on the energy demand of buildings as an independent structure (Garshasbi et al., 2020; Hwang et al., 2017), or as an element within an urban block (Evola et al., 2020; Frayssinet et al., 2018; Vartholomaios, 2017). Rather than researching on siloed indoor or outdoor attributes that impact energy consumption, this paper's objective is to present a holistic performance-driven multi-objective methodology for investigating the impact of design parameters on outdoor thermal comfort and energy consumption of buildings simultaneously.

1.1. Literature review

Energy-based urban designs aim to represent urban forms that minimize energy demand while providing a high level of comfort for users (Shi, 2020). A newly developed approach also explores energy systems efficiency and the potential use of renewable energies (Shi, 2020). All these studies have either evaluated existing urban blocks (Evola et al., 2020) or run a parametric approach to find the optimum layouts (Vartholomaios, 2017; Xu et al., 2019b). A vast range of design factors describes urban blocks, which can consequently alter their local climate and energy demand. However, street orientation, aspect ratio (the ratio of buildings' height to street width, H/W), urban surfaces coverage are the parameters that have been widely used in urban thermal condition and energy use of building units (Abdollahzadeh and Biloria, 2020; Deng and Wong, 2020; Vartholomaios, 2017; Xu et al., 2019a, 2020). Urban canyons with a higher aspect ratio provide more shading and decrease air temperature up to 6 °C (Kakon et al., 2009). However, street orientation of these canyons can also greatly influence the level of comfort they offer to outdoor users (Srivanit and Jareemit, 2020). North-South oriented streets have the highest level of thermal comfort due to the shorter time they are exposed to the solar radiation and the lower value of Tmrt (Deng and Wong, 2020). Nevertheless, they increase the energy demand of buildings for cooling purposes as they experience more heat loss through their envelope (Sudprasert, 2019). On the contrary, East-West oriented streets are regarded as the best option for energy-efficient urban schemes (Yahia et al., 2018). Accordingly, the use of shading on these streets is suggested to achieve both thermal comfort and energy-efficient design (Yahia et al., 2018). The physical properties of urban surfaces can also affect both thermal comfort and energy demand (Andreou, 2013). For instance, using high albedo materials on urban surfaces tends to reduce air temperature experienced by users of outdoor spaces (Piselli et al., 2018).

Numerous studies have also explored the relation between building typology and different environmental parameters, such as ventilation potential and cooling load (Javanroodi et al., 2018), outdoor thermal condition (Abdollahzadeh and Biloria, 2020), energy efficiency and solar potential (Zhang et al., 2019), energy demand and thermal comfort (Taleghani et al., 2013). A study by Xu et al. investigating urban microclimate in China with the use of genetic algorithms shows that an optimum urban layout constitutes of multistory blocks with high building enclosures, providing the highest level of outdoor thermal comfort for users (Xu et al., 2019a). Generally, high-rise building typology increases cooling energy demand due to its higher UHI intensity. Nevertheless, urban environments with higher densities and the associated self-shading also reduce cooling load (Natanian et al., 2019b). Different urban block typologies can alter the reduction of cooling load by up to twelve times. According to Zhang et al. courtyard and hybrid typologies outperform tower and slab urban blocks considering both energy use and solar PV development potential (Zhang et al., 2019). The courtyard form is also introduced to have higher energy and thermal performance by Taleghani et al., in 2013. In the same study, the design factor of surface-to-volume ratio describing a building's form is reported to have a high level of importance in achieving both energy efficiency and thermal comfort within an urban context (Taleghani et al., 2013). At a building scale, the physical properties of the facade, as a connecting element between buildings and their surrounding urban areas (Sanaieian et al., 2014), can change both energy use and thermal condition for both indoor and outdoor spaces. 60% of the buildings' heat loss occurs through their windows (Jelle et al., 2012). Material and window to wall ratio (WWR) parameters are among the most important design factors affecting these two objectives. Buildings with higher WWR and low-reflective glazing decrease energy savings. High-reflective materials have lower SHG values and thus improves indoor and outdoor thermal conditions (Abdulaziz, 2015).

In 60% of the building optimization studies, a single-objective approach is usually applied (Evins, 2013), that is not able to provide a comprehensive sustainable master plan and guidelines for urban development. This issue can be highlighted for districts currently being developed such as Western Sydney. Therefore, the presented study employs a multi-objective approach to improve thermal conditions experienced in outdoor environments and reduce the energy used in a buildings' interiors. Accordingly, computational simulation is utilized to optimize design parameters at both urban and building facade scales. A similar approach to the proposed methodology is also used in previous urban studies (Evola et al., 2020; Xu et al., 2019b, 2020). According to Xu et al. (2019a, b), computer-aided optimization is an effective solution to improve the environmental condition of urban areas as can be seen in the thermal conditions investigated in their study (Xu et al., 2019b). This method allows for flexible design through parametric investigation of effective variables based on the set objectives (Evola et al., 2020).

2. Study context

Western Sydney, with a humid subtropical climate - based on Koppen-Geiger classification (Geiger, 1954), is now the target of urban development in order to address the predicted population growth of 3 million people by 2036 in Australia (Sokaris, 2018). The other reason that makes this region a unique spot for investigation is the climatic crisis it is experiencing. Temperature fluctuations are already being experienced in coastal cities, such as Sydney, for over four decades (Livada et al., 2019). Western Sydney region — which is typically farther from the sea, experiences twice the amount of days above 30 °C as compared to Sydney CBD with a maximum air temperature reaching 48.9 °C on January 2020 (Australian Government Bureau of Meteorology, 2021). Thirty-year weather data of this region shows that the average maximum temperature in Western Sydney is rapidly growing (about 7.5 °C) compared to Sydney's central district, with 4.2 °C temperature fluctuation during this period (Rachwani, 2021). Western Sydney experiences 6—10 °C hotter temperatures than the central business district of Sydney due to the scattered configuration of the city, lack of vegetation and being close to one of the most extensive deserts of the world (the Australian arid biome). Exposure to desert winds contributes heavily in differentiating Western Sydney's climatic conditions from that of inner Sydney (Byrne et al., 2008; Mirage News, 2020; Sydney Morning Herald, 2020). Western Sydney experiences both winds blowing from NE, SE (from Inner Sydney) and dry, warm desert wind from NW, SW directions. This causes ambient temperatures to increase and moisture depletion to occur in this region (Khan et al., 2020). A recent report further reinforces this climatic adversity and its societal implications by stating: "Western Sydney suburbs are slowly becoming heat sinks" and this has affected people's behavior in terms of outdoor and social activities, domestic violence, and children's ability to learn (Chang, 2021). Disconnection with the sea breeze not only results in mental and physical health issues but also affect thermal discomfort experienced in outdoor spaces as well as the energy consumed for cooling purposes. As has been observed by Santamouris, urban overheating causes an average increase of 4.6% in peak electricity use per degree Celsius rise in the ambient temperature (Santamouris, 2015). More importantly, it can cause adverse health impacts and put Western Sydney's occupants at high thermal risks. Therefore, mitigation measures such as creating urban corridors should be applied to allow more sea breeze from Inner Sydney to reach the Western parts. Climate conscious urban design and planning can result in mitigating heat stress and the reduction of associated health and energy issues simultaneously (Khan et al., 2020).

Despite the critical condition of Western Sydney, few studies have been conducted to explore urban planning addressing these issues simultaneously. Khan et al., in 2020 explored and confirmed a strong link between urban overheating and heatwaves in this region. In this study, three main zones of Eastern Sydney, Inner Sydney, and Western Sydney are explored with a special emphasis on the vulnerability of Western Sydney (Khan et al., 2020). A recent study conducted by the authors on the urban microclimate of this region suggested that using optimum urban layouts can provide an increase in comfort level by 47.26% - in streets with 45-degree rotation from the north-south axis embracing mid-rise linear buildings (Height/Width ratio: 1) (Abdollahzadeh and Biloria, 2020). Another study in the same region concluded that mitigation measures at a building scale including, adaptation measures (higher setpoint temperatures for cooling), increased ventilation and solar reflectance of the building envelope, window shading, and natural ventilation, can reduce energy demand for cooling in different functional types such as residential, schools and offices up to 70%, 59.4%, and 57.3%, respectively (Garshasbi et al., 2020). In contrast to these studies, this research paper presents a multi-objective optimization process to generate optimum design factors at both urban and building scales, thus reducing operational carbon production and the associated greenhouse gas emissions (Frayssinet et al., 2018).

3. Methodology

This study uses multi-optimization as a problem-solving strategy to find the optimum configuration for an energy-efficient and thermally comfortable urban environment. Therefore, different design factors, including urban grid rotation, aspect ratio, building use, typology, and window to wall ratio (Fig. 1) are optimized based on the two environmental parameters of urban microclimate and energy use of buildings located within an urban block. As explained more precisely in the previous section (Study context), the problem of the explored urban context is the microclimatic crisis it is experiencing, and thus the subsequent increase of energy usage in its building sector. Therefore, this study aims to optimize the aforementioned influential design factors based on the thermal condition experienced in outdoor spaces and the energy used for cooling and heating of indoor spaces.

In recent years, various computational tools are developed that empower architects to use design optimization processes. Accordingly, in this study, computational simulations are used and run through the application of multiple plugins in Rhinoceros V.6 (used for 3D modelling), Grasshopper3D (for developing algorithms and visualization), which provide the initial platform and required context for multi-objective optimization. Legacy plugins of Ladybug V.0.0.69 and Honeybee V.0.0.66 are employed to simulate the environmental parameter of urban microclimate and energy use of buildings in the Grasshopper environment. These tools use validated simulation engines such as EnergyPlus (EnergyPlus Team, 2017; Roudsari et al., 2013), and have been proven to present valid, reliable data (Evola et al., 2020; Natanian et al., 2019a).

The framework of this study is illustrated in Fig. 2, in which an integrated approach is suggested for urban thermal condition and the associated energy use analysis, either to remove heating load in hot seasons or to add it in cold times of the year to provide a comfortable environment in both indoor and outdoor spaces.

The simulation date and time is set to a typical summer day (15th January, from 0:00 to 24:00) for outdoor thermal comfort calculations, and the energy simulations are run on an annual basis. The analysis period of UTC is, however, for the daytime, from 6:00 to 18:00, based on what is suggested by similar studies (Fang et al., 2019; Natanian and Auer, 2020; Srivanit and Jareemit, 2020). The maximum urban thermal comfort (UTC) and minimum heating and cooling loads (CL and HL) are set as the objectives to provide the most optimal design solutions for an energy-efficient and climate-compatible urban scheme.

In this study, Physiological Equivalent Temperature (PET), which is the most commonly used index in hot-humid climatic conditions (Binarti et al., 2020), is employed to evaluate thermal comfort in urban space. This metric considers both environmental parameters (air temperature (Ta), wind velocity (V), radiant temperature (Tmrt) and humidity (RH)) defining urban microclimate and users' clothing and physical features that affect their thermal perception in outdoor spaces (Sharmin and Steemers, 2020). Accordingly, a 35-year-old male weighing 75 kg, with a height of 1.75 m, clothing insulation and metabolic rate of 0.9 and 86.21 W/m^2 is considered as the human model of the study. A PET range of 18–23 °C is also suggested as the comfort boundary in outdoor environments (Matzarakis and Mayer, 1996).

In this study, PET is calculated in the center of an analysis grid for a 20 m section of a street (Fig. 3, red colored). The proposed mesh is located 1.5 m above the

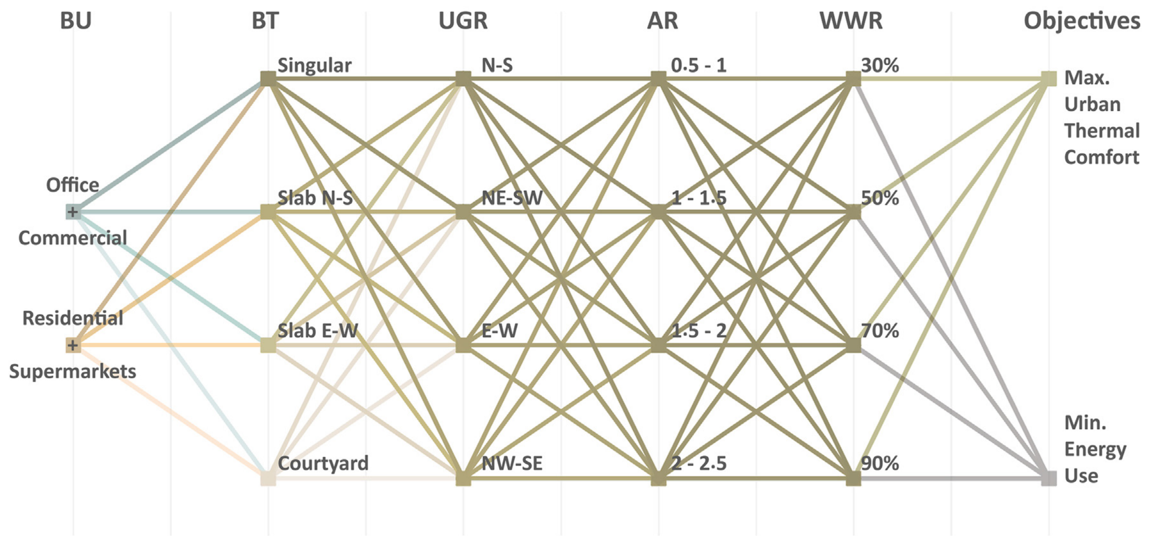


Fig. 1 Range of design parameters and selected objectives.

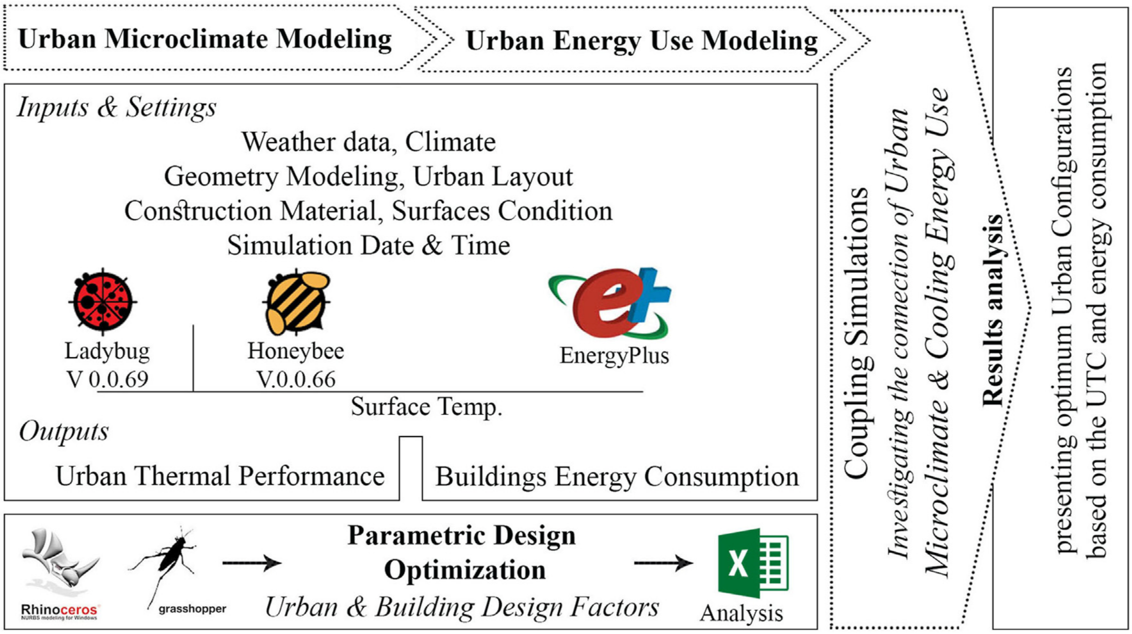
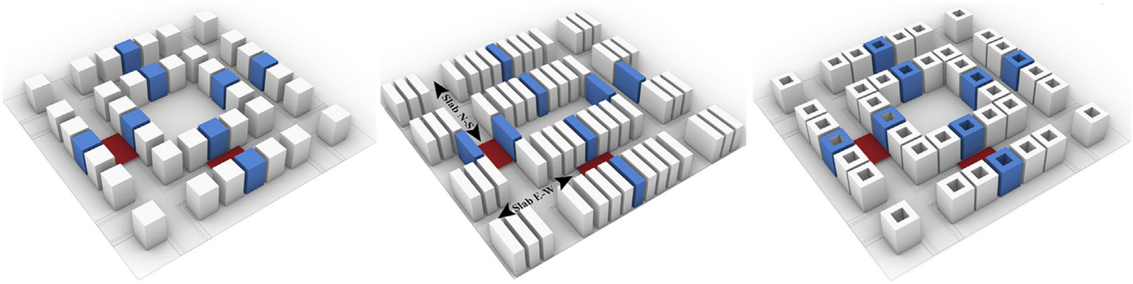


Fig. 2 Analytic framework of the study.



(a) (b & c) (d)

Fig. 3 Urban block Typologies; (a) Singular, (b) Slab N—S, (c) Slab E-W, (d) Courtyard.

ground level, resembling the height of a standing person, and contains 2×2 m^2 cells, which is claimed to provide accurate data with high resolution (Salata et al., 2016). For energy analysis, cooling load including the sum of sensible and latent heat that need to be removed from each zone, and heating load that should be added to interiors are calculated rather than the energy use parameter in order to avoid limiting the result to a specific HVAC system. The average data of the two middle buildings (Fig. 3, blue-colored) with two Mixed-use typologies: "Residential plus Supermarket" and "Office plus Commercial" are considered to generalize results (as the end buildings present far values from the middle ones) (see Fig. 4).

Study models use hypothetical forms with a similar approach employed in other urban studies (Abdollahzadeh and Biloria, 2020; Natanian et al., 2019a; Shi, 2020; Xu et al., 2020) to simplify complications and have a higher control on the analysis process (Oh and Kim, 2019). Urban layouts are simplified to 6 building blocks, each with a floor area (FA) of 200 m^2 and a distance of 4 m from each other (DBB), that is located across a 10-m-wide street with sidewalks (2 m width) and separating greenery (1 m) on each side (total width of 16 m). Model settings for energy and comfort simulations are summarized in Table 1. Simulation inputs are selected based on the commonly used materials in construction and the suggested default values to generalize results (see Table 2).

Variation in urban design factors, which alter the urban configuration, increases its potential for adaptation to climatic conditions (Navarro-Mateu et al., 2018). This objective can be achieved through parametric designs, which embrace a wide range of variables and provide the most advantageous design options according to the set objectives. In this study, the parametrically designed variables include:

- BT_Building Typologies of Singular, Slab N—S (type b), Slab E-W (type c), Courtyard (Fig. 3).
- UGR_Urban Grid Rotation; streets rotation from N—S axis: 0, 45, 90, 135 (degree).
- BU_ mixed Building Use of Office plus Commercial and Residential plus Supermarkets
- AR_Aspect Ratio; buildings height to streets width:
- WWR_Window to Wall Ratio: 0.3, 0.5, 0.7, 0.9.

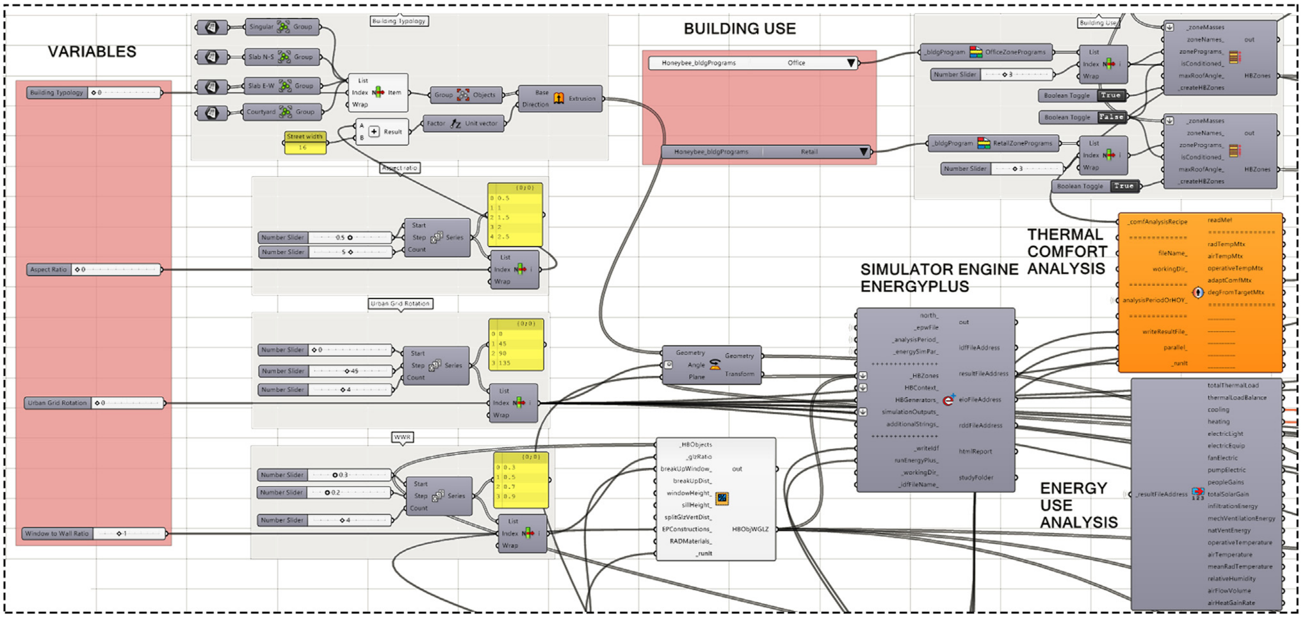


Fig. 4 Developed Grasshopper algorithm.

In the optimization process, each iteration is calculated varying the aforementioned parametrically designed inputs (using number sliders in the Grasshopper platform) to find the optimum option based on the set objectives. Maximum thermal comfort in outdoor urban environments (minimum PET) and minimum heating and cooling energy consumption of the buildings located within its context (annual use) are defined as the targets and calculated using the EnergyPlus simulator engine. Accordingly, a combination of 512 alternatives is generated and a total amount of 1024 simulations (for thermal comfort and energy use calculations) are run. Eventually, outputs are converted into the Microsoft Excell tool to compare and analyze designed urban scenarios based on the selected objectives. Like other multi-objective urban studies, this study offers diverse options rather than a singular average solution that provides designers and planners with the opportunity to select design measures based on their intended purpose. The presented study thus provides optimum design solutions at both urban and building facade scales to develop high-performance cities with humid-subtropical climates undergoing densification.

4. Results

This study shows that the employed approach allows subtropical cities to offer more thermally comfortable and energy-efficient urban environments up to 25.85% and 93.14%, respectively, after comparing the best and worst design scenarios. Among the selected design variables, building typology (BT) has the highest impact on the cooling and heating energy use within the buildings sector, followed by AR, WWR, and UGR. Although urban grid rotation is the least effective parameter impacting energy use of the building sector (compared to other evaluated scenarios), this design factor is found to have a considerable effect, after AR, on the thermal environment experienced by outdoor users. Fig. 5 illustrates the impact of each design factor on the set objectives of Urban Thermal Comfort (UTC), Cooling Load (CL), and Heating Load (HL) in mixed-use buildings.

Aspect ratio and urban grid rotation are found to have the highest impact on the thermal condition of outdoor spaces, each dedicated an effective percentage of 12.47% and 8.95% on average. Nevertheless, they have the least impact (7.53% and 9.70%) on the average energy used in each floor of a building within urban blocks, compared to other evaluated design factors (BT and WWR). Building typology is reported as the most influential design factor representing an effective percentage of 51.09% on the total energy consumption of the building sector. This design factor can also differ thermal conditions experienced in urban environments by 6.65%.

Among the assessed BTs, Slab blocks extended in the North-South direction (type b) provide the highest level of comfort for outdoor users, while those extended in the East-West direction (type c) are the least thermally comfortable urban blocks. In other words, altering slab typologies from type b to type c (refer to Fig. 3) can increase PE temperature and thermal discomfort by up to 2 °C during the hottest time of the year. However, this typology (slab East-West) offers the most energy-efficient urban morphology, which can decrease total energy usage by around 60 kWh/m^2 in mixed use typologies (44.29%). On the contrary, the courtyard typology is responsible for the highest energy consumption in this study. This can be due to its higher surface to volume factor that allows more use of glass facades, resulting in an increase in the total energy use of commercial office buildings by 14.79% with 20% increase in WWR. This value is slightly lower in "Residential + Supermarket" building typologies (14.71%). The average energy use is also

Table 1 Inputs.

	Model Settings		
Urban Scale	Distance Between Buildings (DBB)		4 m
	Surface Coverage (SC)	Street	Asphalt, LRV: 0.1
		Sidewalks	Concrete, LRV: 0.4
		Vegetation	Grass, moist soil, LRV: 0.2
Building Scale	Floor Area (FA)		200 m^2
	Building programs		Mixed-use of Office plus Retail (2 floors on the ground level) Mixed-use of Residential plus Supermarket (ground floor)
	Construction Material	Wall surface	300 mm lightweight concrete with insulation and interior plaster finishing, U value: 0.96 W/m^2K, LRV: 0.4
		Window surface	Double glazing of 3 mm clear glass with air 13 mm gap, U value: 2.71 W/m^2K, Solar transmittance: 0.764, VLR: 0.81
	Shadings		No interior & exterior shadings
	Internal load	Equipment	Avg. 12.37 W/m^2
		Lighting	10.76 W/m^2
	Infiltration per area		0.0002 $m^3/s \cdot m^2$
	Occupancy		0.12 person/m^2

Table 2 AR variables.

		Office + commercial	Residential + supermarkets
Low-rise		1	0.5
Mid-rise	(a)	1.5	1
	(b)	2	1.5
High-rise		2.5	2

higher in "office + commercial" building type as compared to "Residential + supermarket" type due to intensive use of electrical appliances and equipment they incorporate. The average data of PE temperature, cooling and heating loads for each building typology is represented in Fig. 6. The legend on the right shows that UTC, CL and HL can be decreased by reducing AR and WWR design factors and rotating urban blocks to the east-west axis respectively.

Glass walls are more prone to heat loss and thus, increase the energy used for cooling and heating of the buildings up to 29.24% and 46.49%, respectively. A higher WWR also increases thermal comfort experienced by outdoor users due to the higher reflectivity they offer as urban surfaces. However, this design factor is the least effective parameter and has a trivial impact on urban thermal conditions (less than 1% and around 0.1 °C of PET). Each 20% increase in this design factor reduces PE temperature, cooling, and heating loads up to 0.32%, 10.63%, and 18.79%, respectively, which is equal to an average of 11.49 and 18.29 kWh/m^2 in the designed scenarios of this study. Therefore, a lower WWR is suggested for efficient planning.

Aspect ratio is the most influential design factor for UTC and the second important factor affecting cooling energy use of buildings. A higher aspect ratio improves outdoor thermal comfort while increasing both the energy use of the whole building and the average energy use per floor. The maximum aspect ratio in "Residential + supermarket" and "office + commercial" building typologies incorporating 8 and 10 floors, respectively, offer an average PE temperature of 25.56 °C and 26.01 °C. On the contrary, in urban contexts with lower aspect ratios of 0.5 and 1 represent the worst UTC conditions, with an average temperature increase of 3.73 °C. This can also affect the energy used for interior cooling - increased by 35.41 kWh/m^2. As a rule, an increase of 0.5 in AR can change PET, CL, and HL values up to 4.33%, 10.48%, 34.36%, respectively. Fig. 7 shows how varying UGR, BT, and WWR design factors can improve these variables. Variations in thermal condition, as well as energy consumption also increase in urban contexts with high-rise buildings.

North-south-oriented streets provide the highest level of comfort for outdoor users due to lesser exposure time to direct solar radiation they offer during the daytime (6:00 to 18:00). However, establishing building blocks on this orientation can increase the energy consumed for both cooling and heating purposes. Nevertheless, this design factor has the minimum impact on cooling and heating energy use (8.76 and 1.06 kWh/m^2) of buildings whilst being the second most influential parameter for UTC and can vary PE temperature up to 2–3 °C, which is considerable at a street scale. Fig. 8 (a) shows that by selecting the optimum urban morphology (BT, AR, and WWR) UTC can be improved. Moreover, northwest-southeast (135°) and northeast-southwest (45°) offer the minimum urban thermal discomfort (after N–S) and

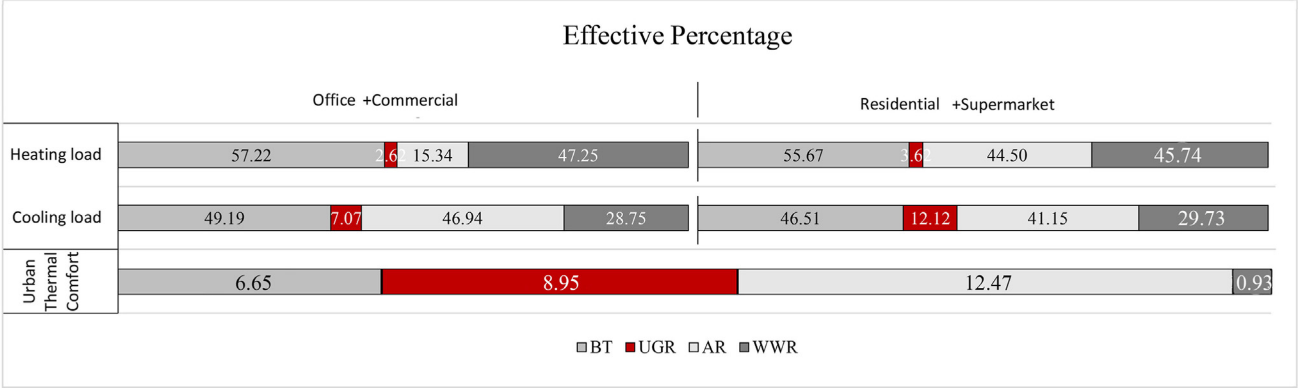


Fig. 5 [1]Effective percentage of design variables.

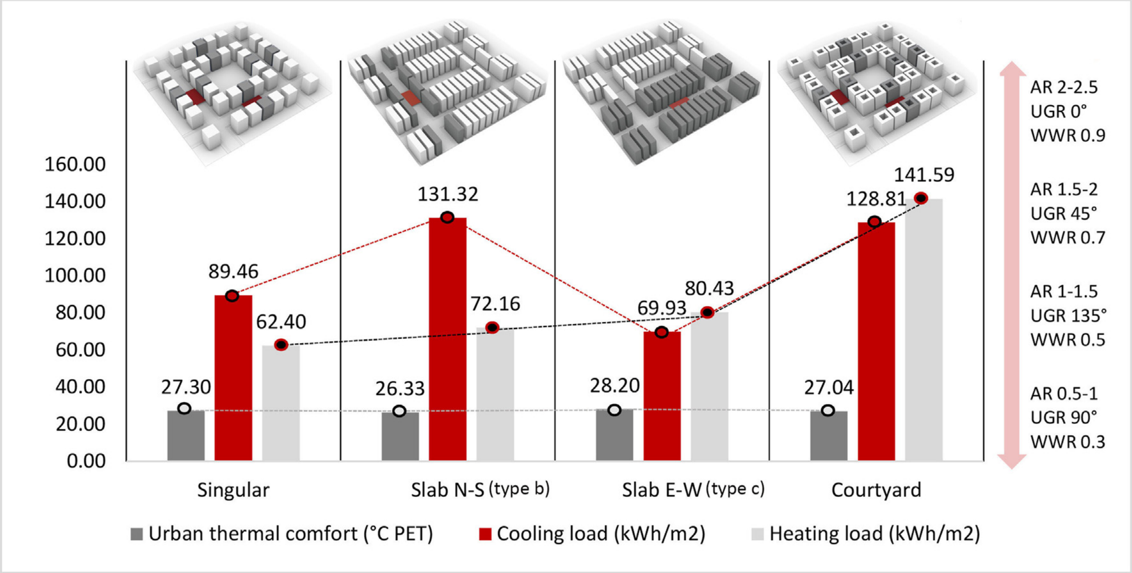
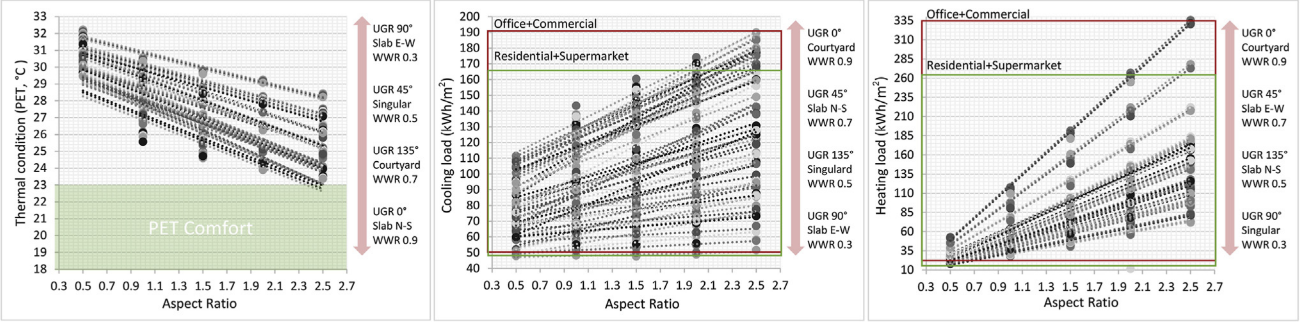


Fig. 6 Impact of building typology on the set objectives (UTC, CL, HL)[2].



(a) (b) (c)

Fig. 7 Impact of Aspect Ratio on the three objectives of the study (urban thermal comfort (a), cooling (b) and heating (c) loads per building block).

energy use (after E—W) (Fig. 8b and c), which can be applied in UTC-based and energy-efficient multi-objective urban schemes.

The diagrams in Fig. 8 contain all the simulation data categorized by the direction of the urban canyons. Therefore, the lowest values are achieved where the graph lines

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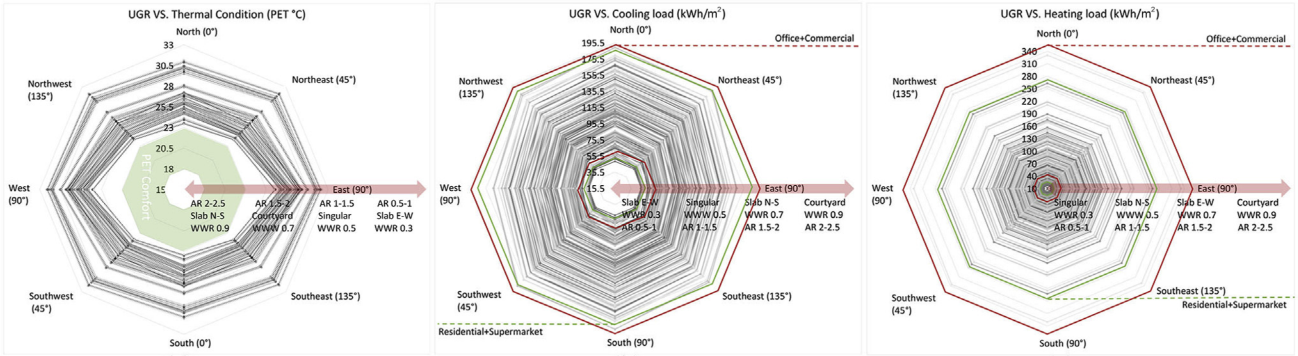
[1] The effective percentage of each design variable is calculated comparing the best and worst scenario.

[2] The legend on the right indicates that how varying other DFs can alter UTC (not PET), CL, and HL.



(a) (b) (c)

Fig. 8 Impact of urban grid rotation (street direction) on the three objectives of the study (urban thermal comfort (a), cooling (b) and heating (c) loads of building blocks).

are compacted into the center, and where the lines are expanded outwards it indicates to the highest values, both in terms of PE temperature and in terms of cooling and heating loads. For instance, in Fig. 8 (a), data are closer to the outer edge of the chart in East-West orientation (90° deviation from N–S axis) and thus indicate to a higher PE temperature and less thermal comfort in this direction. On the contrary, in Fig. 8 (b), East-west direction has the lowest cooling values and graph lines are compacted towards the center. Fig. 8 (c) also shows that heating load is less affected by UGR design factor, as confirmed in Fig. 5.

East-West oriented urban blocks embracing low-rise slab (type c) buildings with less glass facade represent the optimum urban configuration for least energy consumption, while high-rise courtyard buildings in a North-South direction with a high percentage of WWR represent the worst planning scenario for attaining energy-efficient performance. On the contrary, the North-South orientation with taller buildings are favorable for achieving high UTC urban designs due to the shading effect they provide to outdoor environments. Additionally, an increase in material reflectivity of urban surface, which can be achieved by a higher WWR, reduces solar heat gain, and improves the thermal condition of these spaces. Therefore, North-South-oriented streets surrounded by high-rise slabs buildings can offer the maximum thermal comfort for urban environments in the selected region. Thermal condition and energy use of the optimum and the worst urban design scenarios with "office + commercial" buildings are represented in Fig. 9.

Nevertheless, if both maximum UTC and minimum CL and HL are desired, mid-rise slab (type c) buildings with a 135-degree rotation (NW-SE) and 0.5 WWR, are suggested for urban blocks with the under-study humid-subtropical climatic condition. As the impact of BT and WWR on energy use is higher than on urban thermal comfort, design scenarios that offer fewer values for this parameter are suggested (a lower WWR and slab (type c)). In multi-objective studies with contradictory objectives, the intermediate value is usually reported as the solution or the data might be weighed based on different values and approaches. In this study, a similar approach is applied, and the optimum urban design is introduced according to the effective percentage of design variables regarding each of the UTC and energy consumption goals.

5. Discussion

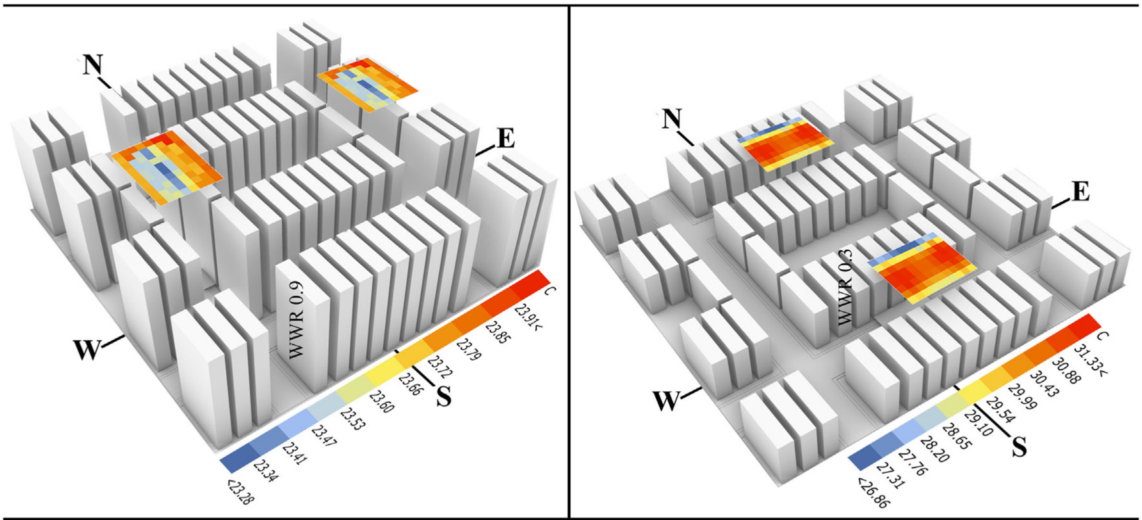
Findings indicate that PE temperature can diminish up to 8.33 °C in an optimum UTC-based design while the energy used in the building sector for cooling and heating purposes has the potential to decrease by 140.17 and 307.76 kWh/m^2, respectively. Therefore, the suggested guidelines should be prioritized based on the desired design objectives (UTC or Energy consumption).

- Low-rise (AR) slab buildings (BT) exposed to east-west streets (UGR) by their shorter edge with less glazing facade (WWR) offer the lowest energy use.
- High-rise (AR) slab buildings (BT) exposed to north-south streets (UGR) by their longer edge with high glazing facade (WWR) provide the highest level of thermal comfort in urban environments.

Nevertheless, for an integrated approach, the correlation of UTC and cooling and heating loads can provide helpful insights covering all design scenarios. Accordingly, higher cooling and heating loads are imposed on buildings in order to counter the impact of an urban microclimate to achieve an acceptable indoor thermal environment. However, a low correlation of determination ($R^2 \approx 0.4$) is found between these parameters (Fig. 10). It should be noted that the selected simulation time is limited to the hottest time of the year, and thus, it is suggested to run the comfort analysis on an annual basis simultaneously with energy calculations.

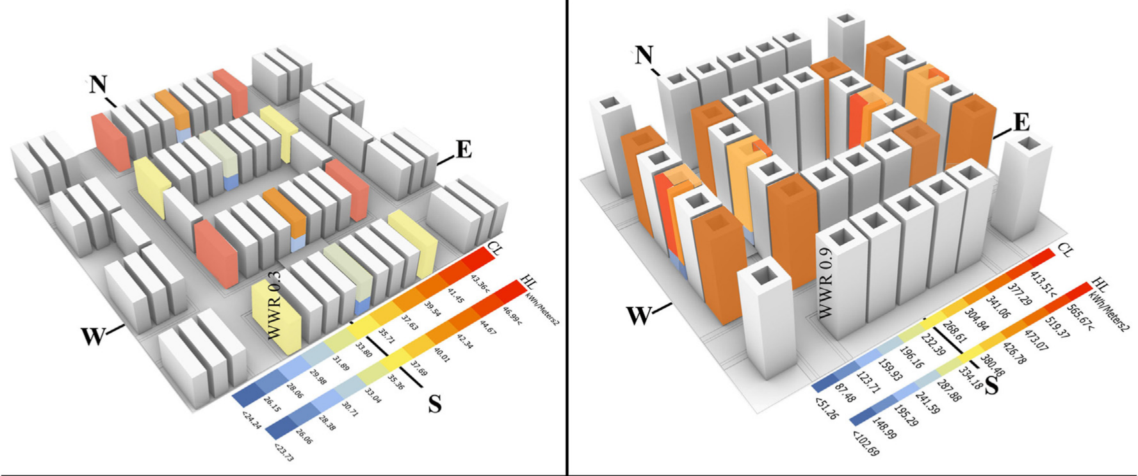
As reported, with each 1 °C increase in urban temperature (measured by PET) cooling and heating energy use within buildings increases by almost 10 and 15 kWh/m2, respectively. Furthermore, none of the design scenarios offer a thermally acceptable environment (PET 18–23) in this extreme time of the summer. This implies further improvements need to be deployed including the use of shading mechanisms, urban greening, and water bodies in urban blocks if UTC is the planning goal.

This study also explores aspect ratio (H/W) design parameters by increasing building heights rather than investigating different street widths. Therefore, a different result might be obtained in wider streets with lesser shading effect of urban obstructions. The impact of both



a: Slab (type b), UGR 0°, AR 2.5, WWR 0.9

b: Slab (type a), UGR 90°, AR 1, WWR 0.3



c: Slab (type a), UGR 90°, AR 1, WWR 0.3

d: Slab (type a), UGR 0°, AR 2.5, WWR 0.9

Fig. 9 The best (a &c) and worst (b & d) design scenarios regarding UTC and Energy Use.

building heights and street width variations thus needs to be evaluated in future studies with similar concerns. Also, a wider range of design variables with narrower alternatives can offer more accurate results.

To some extent, daylighting is now a requirement for new buildings in Australia. The Building Code of Australia (BCA) states that ‘habitable rooms’ require permanent access to fresh air and natural light, most commonly in the form of windows. This access must come through windows of a size not less that 10% of floor areas, or through rooflights (i.e. skylights) not less than 3% of the floor space of a given area. You can also use a proportional combination of windows and rooflights to satisfy the requirements.

The existing urban morphology of the selected case study; Western Sydney includes low-rise housings with one or two floors (such as those in the Black Town suburb), which can be referred to the selected design scenarios with AR 0.5. Taller buildings (such as those in the Parramatta suburb), which usually have a higher percentage of WWR, indicate a higher AR and increase thermal comfort in outdoor spaces while increasing the energy consumption of the building sector. However, these high-rise buildings are mostly placed with a sparse pattern, and thus, unable to improve urban temperature, a typical crisis these regions are confronting. These building typologies can be interpreted as singular or slab types, and courtyard blocks are less used in this area. Previously built housing units usually include a front yard with greenery, which were able to improve the thermal condition to a slight extent. However, as having a front yard implies a greater width of the urban canyon, this could increase solar radiation and associated air temperature. The orientation of most buildings depends on the urban block in which they are located. Most streets in Western Sydney are located on a north-south axis with 10–15-degree deviation and are intersected by perpendicular streets. As concluded in this study, urban grid rotation has the lowest impact on energy use and is one of the most important design factors affecting urban comfort. Accordingly, the existing northeast-southwest streets provide lower PE temperature compared to those in the

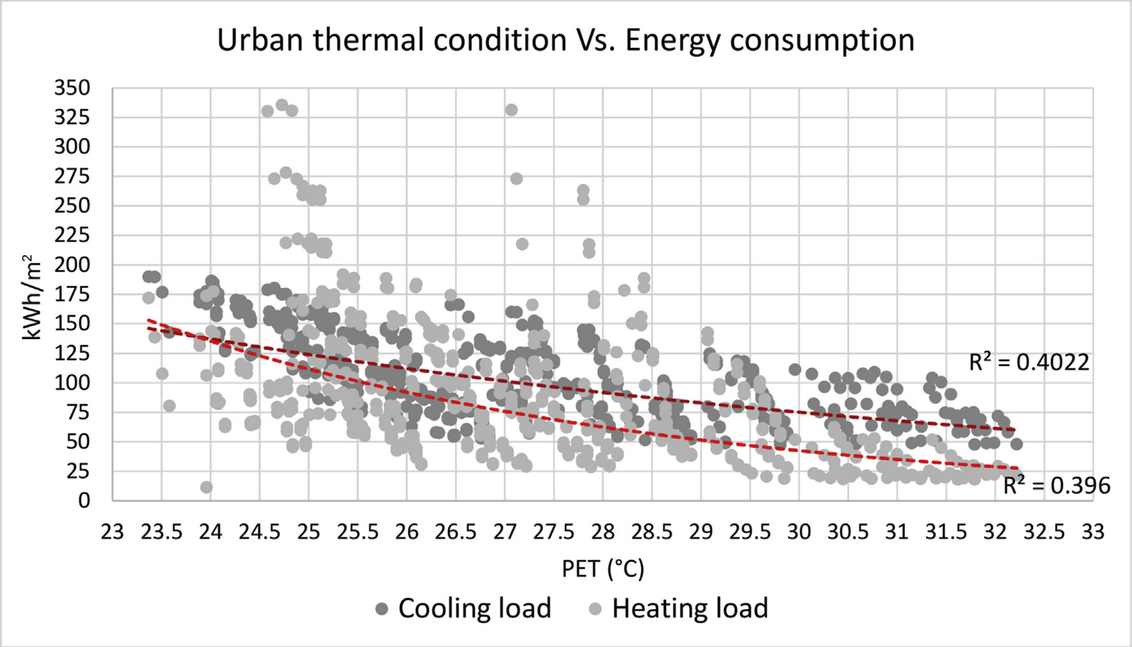


Fig. 10 The relationship of urban microclimate (UTC) and Energy use of buildings sector.

southeast-northwest direction. Although a desired range of design variables including an acceptable UGR and building typology is observed in these regions, especially in new developments in areas like Black Town, the perceived thermal condition is reported to be unpleasant. This is because in addition to its unfavorable geographical location and not having access to sea breeze, a low percentage of urban shading casted either by urban canopies or by obstructions and low-rise building blocks is a persistent condition in the Western Sydney region.

Existing urban studies are mostly single objective and thus unable to offer a comprehensive design scheme and planning scenario. In this study, however, a multi-objective investigation is conducted to find the correlation between the environmental performance of open spaces, namely thermal conditions, and the energy consumed in the building sector. Furthermore, existing literature indicates that most optimizations are either focused on the urban layout or building design. Nevertheless, this study considers both scales and attempts to conduct an integrated optimization process in the light of novel computer-aided design technologies. The outcome of the presented study has the potential to provide insightful guidelines for both architects and urban planners to improve the performance and environmental quality of their designs.

6. Conclusions

This study runs a multi-objective optimization process based on the two major crises the study context is witnessing: urban thermal conditions and the energy use especially for cooling purposes. A parametric approach is employed to explore optimized design scenarios at both urban and building scales to provide a comprehensive guideline for a thermally comfortable and energy-efficient design. A set of urban blocks embracing different building typologies, aspect ratios, street orientation, building use, and window to wall ratio are investigated using an integrated algorithm in Grasshopper, Rhino platform with a focus on urban thermal comfort and the energy use in the building sector. Furthermore, design factors are prioritized based on their effective percentage, and optimum and worst-case design scenarios are introduced considering the humid-subtropical climate of the Western Sydney region in Australia. Eventually, the correlation between these parameters is represented. The employed methodology offers a thermally comfortable urban environment and energy-efficient building design solutions and guidelines that can be used by designers in early planning stages and allied stakeholders to mitigate the climate and energy crisis such subtropical cities confront. Although most buyers and investors are looking for buildings equipped with renewable energy-based systems, such as PVs, an optimum design based on the guidelines, such as what is suggested in this study, can reduce the energy consumption of the building units considerably.

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.

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