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Published in:
Urban Climate

DOI:
[10.1016/j.uclim.2020.100642](https://doi.org/10.1016/j.uclim.2020.100642)

Publication date:
2020

Document Version
Author accepted manuscript

[Link to publication in ResearchOnline](#)

Citation for published version (Harvard):

Maharroof, N, Emmanuel, R & Thomson, C 2020, 'Compatibility of local climate zone parameters for climate sensitive street design: influence of openness and surface properties on local climate', *Urban Climate*, vol. 33, 100642. <https://doi.org/10.1016/j.uclim.2020.100642>

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Compatibility of Local Climate Zone Parameters for Climate Sensitive Street Design: Influence of openness and surface properties on local climate

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Abstract

Streets are the fundamental elements of urban form in terms of microclimate as well as place making in cities. Microclimate itself is influenced by climate critical parameters of the Local Climate Zone Classification (LCZ) system. Therefore, a key design question is the role, if any, of LCZ classification for climate guidelines at street scale. In this paper we explore the Intra LCZ zone temperature variation at three street typologies with North-South and East-West orientation within the city core of Glasgow as a case study. We then investigate the compatibility of LCZ parameters related to openness (determined by sky view factor and aspect ratio) and surface properties (determined by albedo) with Glasgow City Council's Development Plans Policies and Proposals for street design in order to identify the possibility of using these parameters for climate sensitive street design. The results suggest that a fixed design strategy would not be applicable across all street typologies and that the identified LCZ parameters combined with form-based parameters of orientation and façade geometry can play a vital role in climate-sensitive street design.

Keywords: Urban Microclimate, Street Design, Local Climate Zone, Compact Urban Form, Glasgow

Taxonomy: Urban Planning, Urban Climate, Urban Heat Island Effects

To be cited as:

Maharoo N, Emmanuel R, Thomson C. 2020. Compatibility of Local Climate Zone parameters for climate sensitive street design: influence of openness and surface properties on local climate, *Urban Climate*, DOI: 10.1016/j.uclim.2020.100642

1 Introduction and background

Today, more than half the world's population resides in urban areas and by 2050, 66% of the world's population is projected to be urban (United Nations, 2014). Even though cities occupy only 3% of the world's land, they consume 75% of all natural resources, produce 50% of all waste and are responsible for 60 to 80% of global greenhouse gas emissions. It is therefore largely in the urban environment where the pressure, and opportunity, for change lies (secretariat of UN Economic and Social Commission, 2017). The growing concerns of environmental degradation and energy consumption within the diverse urban forms resulting from the accumulation of human activity into one area are challenging planners to explore more sustainable urban development approaches. Compact Urban form is often touted as a solution to sustainable city development where density is the key 'tool' used by planners to assess compactness. However environmental quality is also an important aspect of a sustainable city and therefore it is important to understand the environmental behaviour of compact urban form and its impact towards inhabitants.

Even though the urban climate researchers have identified that the urban microclimate plays an important role in improving local quality of life of urban dwellers, urban planners struggle with the issue of how to promote area-specific urban environmental quality through municipal land use planning (Kyttä et al., 2013). One of the key impediments to implementing climate sensitive design is the lack of useful information that describes aspects of the form and function of cities at a detailed spatial resolution; that goes beyond an urban footprint analysis (Bechtel, Et al., 2015) in a consistent manner by which the climatic impact of urban form can be effectively assessed.

The Local Climate Zone (LCZ) classification system unveils new opportunities in bridging this gap as it standardizes urban form and function with regards to the local climate. (Stewart and Oke 2009). It enables a more detailed spatial understanding of the variability of intra-urban air temperature, rather than a simple description of urban-rural difference comprising climate critical parameters that can categorize zones at a local scale (10^2 to 10^4 m) (Stewart and Oke 2012). LCZ has been used in many different cities around the world for mapping urban areas (Bechtel, et al. 2015), run urban energy balance models (Alexander et al., 2015), assess the urban heat island phenomenon (Leconte et al., 2015), and explore planning possibilities (Perera and Emmanuel, 2018). Moreover, the global transferability of the LCZ approach has been demonstrated (Demuzere et al., 2019) based on the World Urban Database and Access Portal Tools (WUDAPT) protocols initiated in 2012 (Mills, et al., 2015). These developments in the LCZ classification system presents new opportunities for incorporating place-specific climate guidelines into urban planning.

At the same time, streets remain a dominant element in current place based or zone-based approaches to urban planning. The importance of street design in place making is highlighted by the fact that more than a quarter of the urban areas of historically planned cities (Manhattan, Barcelona, Paris, Hong Kong, Tokyo, Athens etc.) are covered by streets (Shishegar;2013, UN-Habitat; 2013). Furthermore, well-designed urban streets play an important role in creating convivial urban climate (Oke; 1988, Emmanuel and Johansson; 2006, Ali-Toudert; and Mayer; 2007, Yahia et al., 2017) and enhance thermal comfort (Johansson & Emmanuel; 2006, Johansson; 2006, Ali-Toudert & Mayer; 2007, Jamei & Rajagopalan; 2018). Oftentimes streets are the only open public space in compact urban areas (Csete & Buzasi, 2016).

Emmanuel (2016) noted that some of the commonly used methods in achieving climatically 'cool' urban spaces include;

- Partially shaded pathways;
- Strategically placed adequate vegetation cover;
- Water misting.

Similarly, Nouri (2015) found 4 principal categories of measures to address the threat of increased temperature and heatwaves upon Auckland's public realm; (1) Trees and vegetation; (2) shelter canopies; (3) materiality; and (4) water and vapour systems. At the local (neighbourhoods) and micro-scale (several buildings to entire streets) mitigation strategies have mainly focused on three aspects: albedo enhancement, increased vegetation cover and 'cool roof' strategies (Emmanuel, Rosenlund and Johansson, 2007). Lin, Matzarakis and Hwang (2010) agree that the outdoor thermal environment is impacted by several factors of the built environment such as anthropogenic heat, ground surface covering, evaporation and evapotranspiration of plants but also adds that shading by trees and man-made objects needs consideration.

Furthermore, Emmanuel and Johansson (2006) found that horizontal shading is necessary to provide shade to people and urban surfaces around solar noon and suggest large tree canopies, covered walkways, pedestrian arcades, awnings or other types of shading to achieve it.

Therefore, it is evident that the street-based design guidelines although often introduced with attention towards improving the 'sense of place' is also crucial towards place making from an environmental quality perspective. The first step to achieving holistic neighbourhoods would be through the introduction a classification system that creates a common ground across both climatology and planning enabling compact cities to be collectively read and analysed. The ability to predict the impacts of urban built fabric on its microclimate with minimal data input is also a crucial in the development of such a system. The fact that The LCZ classification system has been adopted across different climate types and urban contexts for a variety of purposes and its ability to be translated into common density indicators due to the use of a wide variety of geometric and surface cover parameters such as Sky view factor (SVF); Aspect ratio; Building surface fraction (BSF); Impervious surface fraction (ISF); Pervious surface fraction (PSF); Height of roughness elements (HRE); Surface admittance; Surface albedo; and Anthropogenic heat output (Stewart & Oke 2012) as used by planners suggests that LCZ parameters could contribute towards a deeper understanding of the thermal climatic impacts of street design.

This research identified that it would be beneficial to explore the impact of these strategies within an identified compact urban area. Therefore, in this paper we explore how The LCZ based classification system could be adopted for climate sensitive urban planning in Glasgow Central Business District (CBD). The thermal comfort within the urban canyons of 3 street typologies in two different orientations- North South (N-S) and East West (E-W) found within a compact neighbourhood were studied for this purpose whilst keeping the building parameters a constant. The objectives of the study are:

1. Explore Intra LCZ zone temperature variations at street scale;
2. Investigate the possibility of using LCZ parameters for climate sensitive street design;
3. Investigate the compatibility of LCZ parameters with the Glasgow CBD development plan street design strategies and the possibility of using the parameters for climate sensitive street design.

2 Study area

Glasgow's city core area consists of a grid-iron street layout, mainly in N-S and E-W orientation, surrounded by a motorway to the North and west, green area to the south-east and River Clyde to the South (Fig 1). The area has been identified to fall under one local climate zone - 'compact midrise' by Emmanuel & Loconsole (2015) in a study conducted using LIDAR data available with local authorities.



Figure 1 nine identified districts of Glasgow City Development plan and plan of central business district

The City Development Plan of Glasgow (Glasgow City Development Plan, 2017) adopted on 29 March 2017 consists of two overarching policies: The Placemaking Principle and Sustainable Spatial Strategy which must be considered for all development proposals. The plan also consists of an action Programme which sets out how the planning Authority proposes to implement the Local Development Plan within the nine identified districts of Glasgow city (Fig 1). Street design is specifically addressed in several action programs of this plan including Enabling Infrastructure - Integrated Public Realm (EIIPR) programme more commonly known as Avenues program (Getting Ahead of Change - Glasgow City Centre Strategy and Action Plan 2014–19, 2013), the first Scottish policy statement for street design which emphasises place making (IPG1 Placemaking Part 1 - Interim Planning Guidance, 2017) and the City Centre Lane Strategy and activation fund. Furthermore (Designing Streets: A Policy Statement for Scotland, 2010) defines 4 main types of streets: boulevards, high streets, mews and residential streets. The key distinction between them is the degree of place and movement function:

- Mews – narrow streets formed by residences on either side (low movement function, high place function)
- Boulevards – high movement function, low place function.
- High streets – medium movement function, medium to high place function; and
- Residential streets – low to medium movement function, low to medium place function.

Figure 2 graphically shows the typical patterns of these streets.

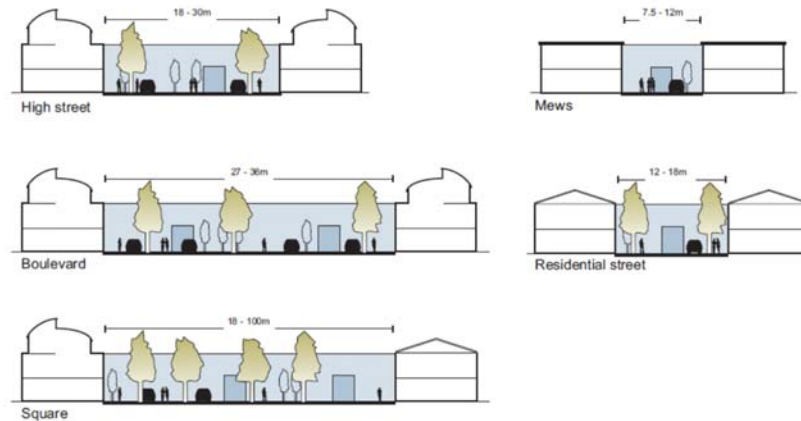


Figure 2 Street types and typical widths associated with Scottish definition of streets (Source: Designing Streets, 2010)

A study of the City Planning Guidelines enabled to identify several interventions that are proposed that could aid in a variation of the urban and street microclimate.

- Sun sails, Pop-Ups and Temporary Interventions (temporary shading)
- Avenue of trees (vegetation)
- Parklet Programme (propose to turn 1-2 parking spaces into little urban pocket parks)
- Surface finishes (cobble streets)
- Ground floor uses that contribute to activity and which animate lanes (Shopfronts with overhangs, Glass for ground floor)

However, none of the proposed action programs directly address the importance of environmental quality and pedestrian thermal comfort as key aspect of place making. Thus, the research design was developed to explore the thermal comfort aspect of the said street interventions.

3 Research Method

The first objective was achieved through a traverse study whilst the second and third were explored though a simulation-based study.

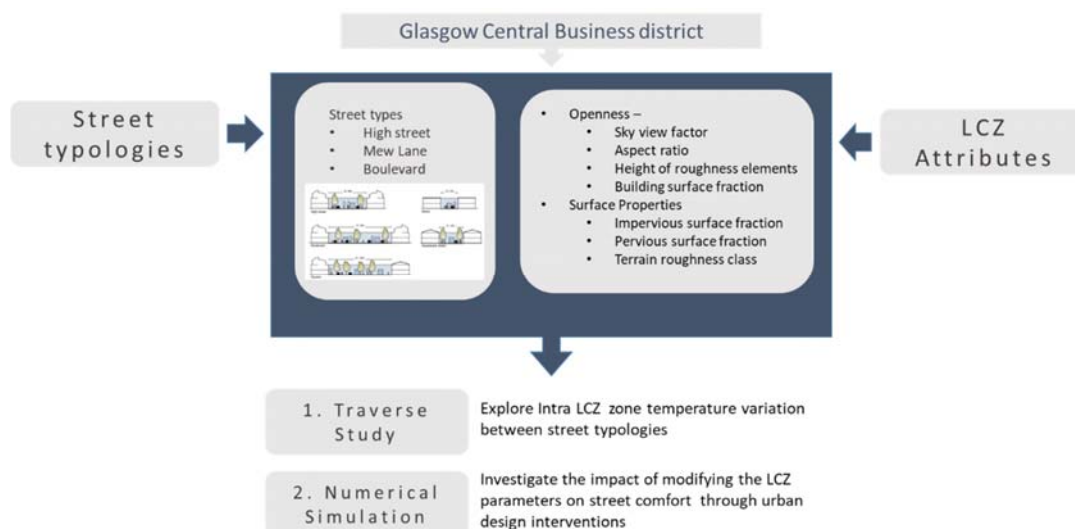


Figure 3 Research Method

Physical observations helped identify 3 main types of streets within the CBD of Glasgow in which the intra LCZ zone air temperature could be measured.

- High street – 18-30m (average of 20m was considered)
- Mew – 7.5-12m (average of 10m)
- Lane (not mentioned in street design of Scotland but is mentioned as a main feature of GCD plan –an average of 4m)

3.1 Traverse Study

Traverse air temperature data at 10 locations identified in avenues and lanes were collected for comparison. The data used were measured for a typical summer condition on 4th of July 2018 between 2pm -4pm when the air temperatures were most stable. The average air temperature was obtained from 5-min sampling resolutions worth of data in each location where temperatures were recorded at 2 second intervals. Measurements were taken using tiny tag air temperature data logger fixed to the backpack comprising of a naturally ventilated foil solar radiation shield. The loggers were located 1.5m above ground level. Fish-eye photographs were taken at each station for comparison of Sky View Factor (SVF).

The obtained temperatures were compared with regard to two key LCZ attributes identified – Openness which was measured with Sky view factor and Surface properties which was measured with surface albedo under the two main orientations of North South oriented streets and East West oriented streets.



Figure 4 Route and SVF at each location of Traverse Study.

3.2 Numerical Simulation Procedure

Observations from traverse study, urban climate literature and proposed Glasgow City Development plan initiatives were then used to narrow down design interventions that can assist in climate sensitive street design. Design interventions selected to be studied were limited to the approaches applicable to listed buildings of the CBD and focused on the proposed pedestrian streets/ avenues and lanes.



Figure 5 Selected Cases for Numerical Simulation

Given the focus on pedestrian quality of life in the outdoors, the comparisons are reported in air temperatures (T_a) and Predicted Mean Vote (PMV) values. Predicted mean vote (PMV) was developed by Fanger (1972) for assessing thermal comfort based on the heat balance of the human body. The PMV calculations consider four environmental parameters: air temperature, mean radiant temperature, wind speed and relative humidity; and two personal variables: clothing insulation and metabolic rate, as the inputs and predict thermal sensation on a thermal scale that runs from very cold (-4) to very Hot (+4). The PMV model was developed based on the indoor chamber experimental data. However, the Klima-Michel Model developed by Jendritzky and Nübler (1981) added complex outdoor radiation enabling the application of PMV to outdoor conditions. The basic PMV equation for all cases, indoor and outdoor, adopted in ENVI-met model for the purpose of the study is given by:

$$PMV = [0.028 + 0.303 \cdot \exp(-0.036 \cdot M/A_{Du})] \cdot (H/A_{Du} - E_a - E_{sw} - E_{re} - L - R - C)$$

Required input

Meteorological variables, all assumed to be defined at the biometeorological reference height of 1.6 m or the next closest level in case of model data:

- Air temperature T_a
- Mean radiant temperature T_{mrt}
- Vapour pressure e
- Local wind speed u

Personal settings human body

- Clothing insulation I_{clo}
- M : Mechanical energy production of the body
- η : Mechanical work factor (0 most of the time)

The PMV/PPD reference person is always 35 years old, male, with a height of 1.75 m and a weight of 75 kg. These assumptions cannot be modified in the PMV/PPD calculations. (ENVI-met, 2017)

3.3 Simulation Model

ENVI-met Version 4.3.1. was used for the numerical simulation part of the study. ENVI-met is a prognostic non-hydrostatic model for the simulation of surface-plant-air interactions composed by a 3D main model and in addition a one dimensional (1D) atmospheric boundary layer (ABL) model which extends from the ground surface up to 2500 m. ENVI-met has a typical horizontal resolution from 0.5 m to 5 m and a typical time frame of 24 h to 48 h with a time step of 1 s to 5 s, which meet the criteria for the accurate simulation of physical processes, suitable for microclimate studies at the neighbourhood scale. The atmospheric system solves Reynolds-averaged Navier–Stokes equations using a 1.5 order turbulence closure k-ε model. The software was selected as it is able to account for the three dimensional geometry of the street with the ability to conduct easy comparisons between urban configurations and their influence on urban climate. Many previous studies (Emmanuel, Rosenlund and Johansson, 2007; Emmanuel and Fernando, 2007; Roset and Vidmar, 2013; Taleghani et al, 2015; Jamei et al, 2017) have validated its performance as well as ability to conduct a fine analysis of the microclimate at street level due to high spatial resolution and the possibility of representing complex geometries including galleries and horizontal overhangs as well as various vegetation covers (Ali-Toudert; and Mayer, 2007).

Input details and the parameters used for the simulation procedure are demonstrated in figure 6. All parameters not mentioned were kept at the default values for ENVI-met.

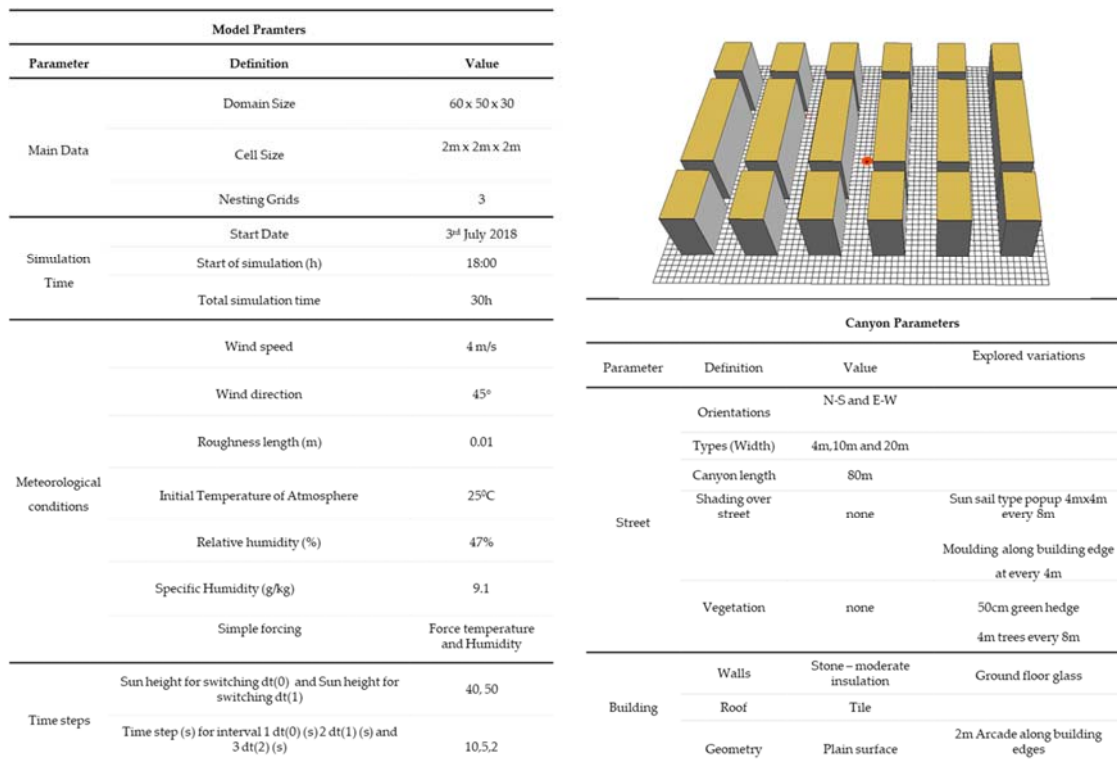


Figure 6 Input details for ENVI-met Simulations

4. Results and Analysis

In this section we first present the empirical findings from the traverse data to identify the correlations between the two key LCZ attributes studied (i.e. openness and surface properties). The left graph in Figure 7 shows the temperature variation at each location against the SVF. The results indicate that

only a weak co-relation exist between SVF and temperature within an LCZ zone. However the right graph reveals that the N-S Oriented streets have stronger correlation between temperature and SVF.

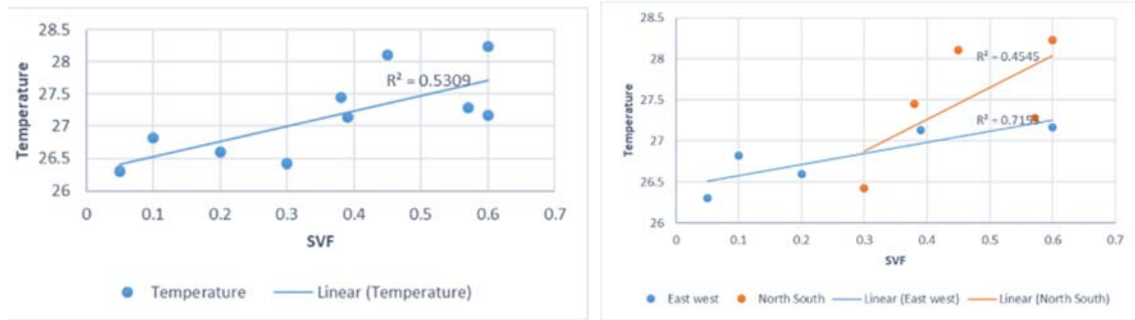


Figure 7 Temperature variation by SVF (Left) and Street Orientation (Right)

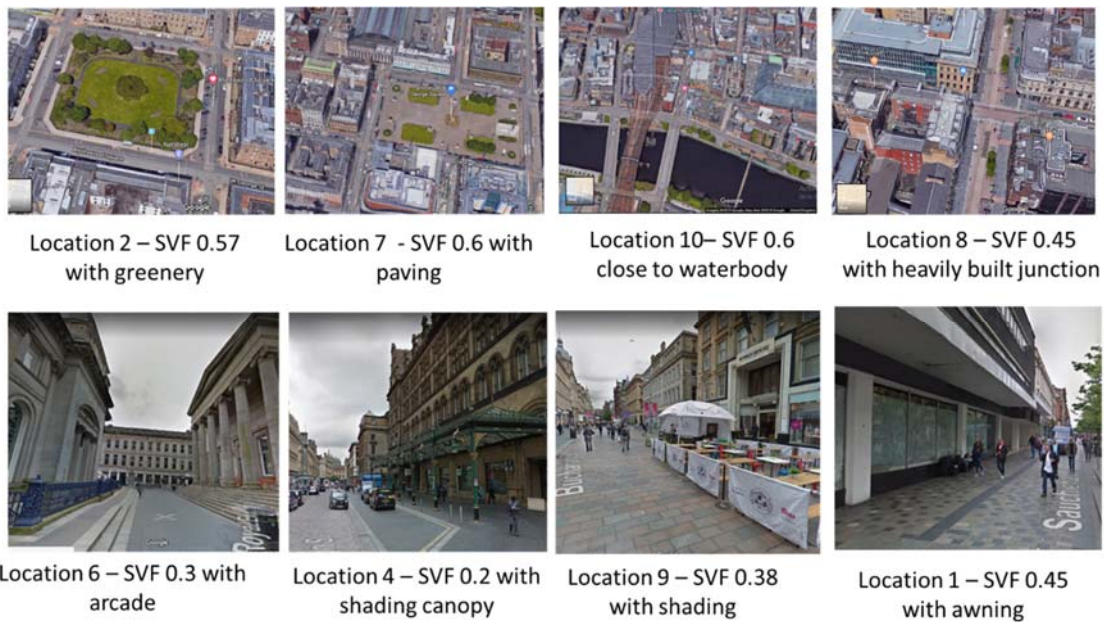


Figure 8 photographic comparison of selected traverse measurement locations against their street geometries

Fig 08 shows a photographic comparison of selected measurement locations against their street geometries, where the degree of ‘openness’ (as determined by SVF, street width and aspect ratio) are similar. It appears that surface properties such as proximity to a waterbody, greenery or the type of building materials could significantly contribute towards temperature variations within the zone. Furthermore it could also be observed that the influence of façade geometry (ranging from mouldings, overhangs and shading devices) is significant. Such aspects have not been accounted for during the LCZ classification process. Thus, a parametric analysis was undertaken to further explore their effects.

4.1 Simulation Cases

Each case was modelled within a domain size of 60 x 50 x 30 and a resolution of 2m x 2m x 2m, making a total model area of 120m x 100m x 60m. The Base case building and canyon attributes were selected to represent the ‘typical’ built fabric found in Glasgow Central Business District which generally has a homogeneous building height and construction material (mainly stone and slate tiled roof), asphalt paved streets and scarce greenery. A fixed height of 20m was selected for the buildings to comply with

CBD conservation guidelines. A Receptor was placed in the middle of each 80m canyon (most blocks range from about 70m – 90m in CBD) with 10m deep buildings on either side. (Figure 6). The façade geometry was reserved of details for the base case scenario.

Figure 5 depicts the seven variations to this base case which constitute of two cases that explore variation in surface properties – cobbled street, glass façade for ground floor; two cases that explore variation to sky view or openness – 4m high trees every 8m (50cm green hedge was used as tree case for the Lane as it would not be practical to have large trees in a 4m wide street), 4m x 4m Sun sail type shading every 8m and two cases that explore variation in façade geometry – moulding along building edge at every 4m; 2m Arcade along building edges. Each of these variations were explored individually whilst keeping all other features of base case constant. The canyon parameters table in Figure 6 summarises the base case attributes and variations explored.

4.2 Parametric analysis

This section discusses the variation in air temperatures and PMV across all the identified cases. Comparisons are first done between the cases with regards to street orientation and street aspect ratio which define the street typologies. The section then proceeds to discuss the impact of the proposed design interventions within the three identified LCZ parameters.

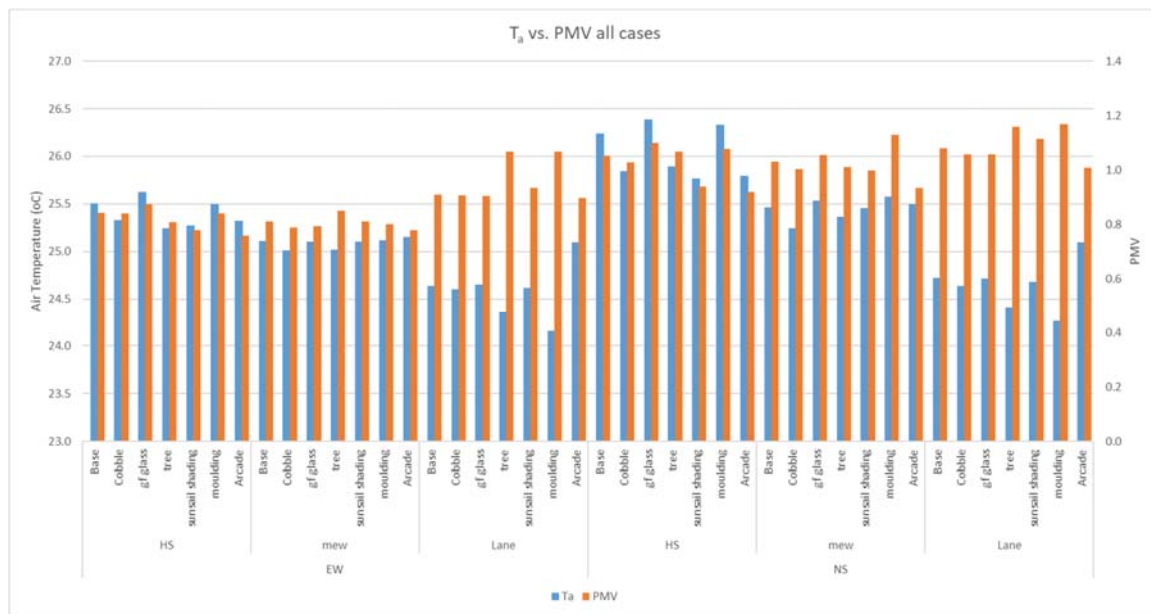


Figure 9 Air Temperature and PMV values recorded across all street typologies and design interventions

A comparison of all the identified cases in Fig 9 reveals that a 2.5°C variation exists between the total cases considered despite them all falling within the same LCZ area.

5. Impact of Street orientation

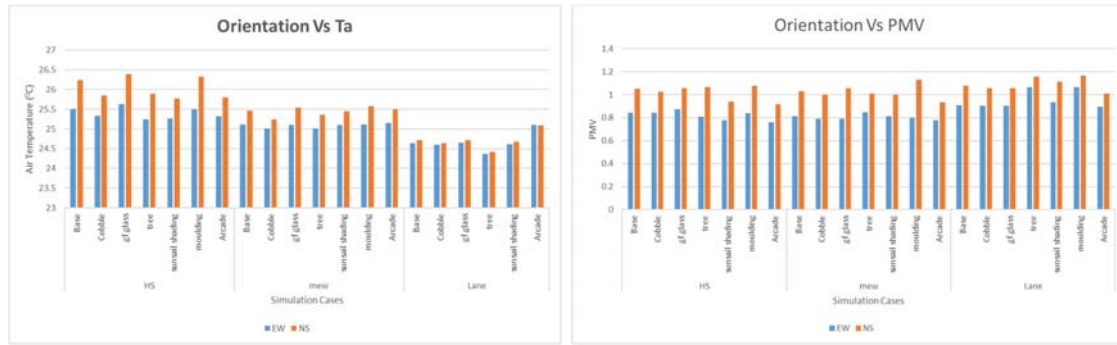


Figure 10 Impact of Street Orientation against air temperature and PMV

The results in Figure 10 indicate that the impact of LCZ Parameters on air temperature are heavily influenced by street orientation. N-S orientated streets always record ‘warmer’ air temperatures than E-W Street with the variation between the cases was 1.9°C whereas the variation between in E-W oriented cases was 1.3. However, PMV valued did not show significant variation to orientation. This implies that even though orientation plays an important role in street design its influence within an LCZ can be overwritten by other form parameters.

5.1 Impact of Street Aspect Ratio

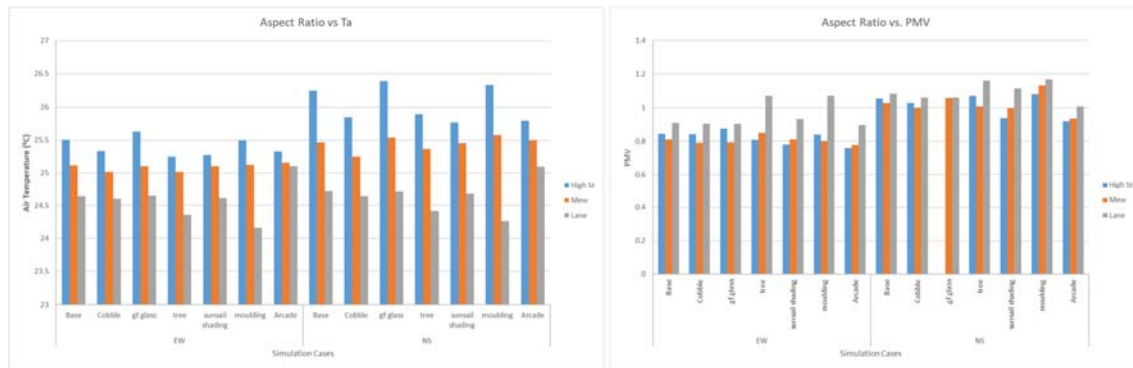


Figure 11 Impact of Street Aspect Ratio against air temperature and PMV

The LCZ parameter of aspect ratio in Figure 11 above show a significant correlation to both air temperature and PMV especially in the Mew case where the Height: Width ratio (H/W) was 2 and High street case with an H/W of 1. The Lane case with an H/W of 5 also showed a weak correlation suggesting that a fixed design strategy cannot be applied across all street typologies within one climatic zone.

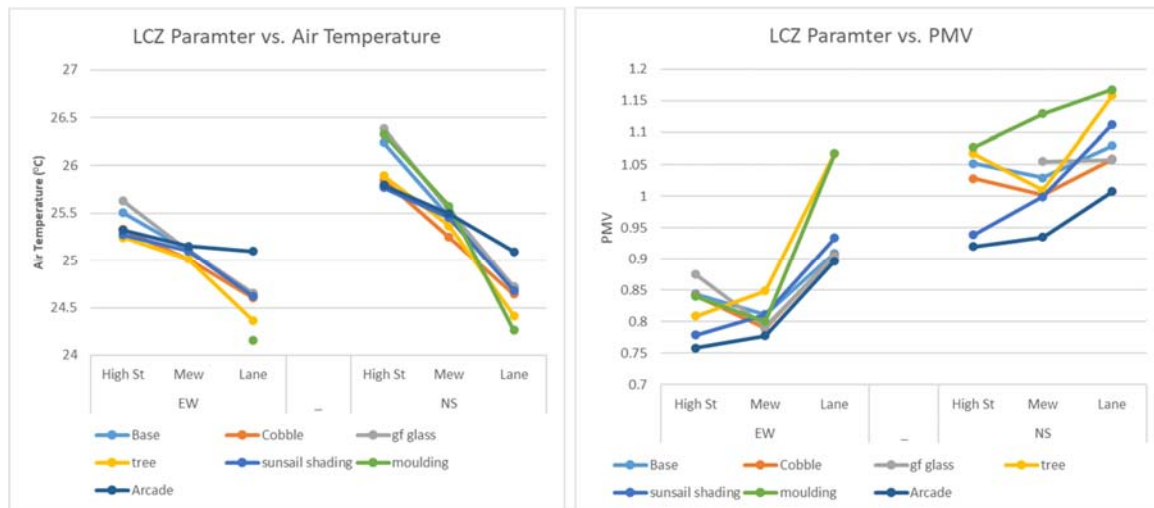


Figure 12 Impact of Design Interventions against air temperature and PMV

5.2 Impact of surface properties

Figure 12 reveals that the cobble paving resulted in a slight reduction in PMV and T_a whilst the glass resulted in a slight increase. However, their level of impact is modulated by the aspect ratio of street with significant impact only being present in the high street case (of aspect ratio less than 1).

5.3 Impact of Openness

Both trees and sun sail shading as indicated in Figure 12 result in a reduction of air temperature which is more significant in the high street and mew cases. The sun sails case results in a significant reduction in PMV in the high street whilst the impact is more diluted in the mew and lane case. However, the tree case results in a higher PMV in the lane case which can be due to the blocking of free airflow along the street.

5.4 Impact of Façade Geometry

The impacts of arcade and moulding in fig 12 show the most complex correlations to PMV and T_a . The moulding case resulted in a higher PMV and T_a in the high street and Mew cases whereas T_a was reduced and PMV increased in the lane case. This once again implies that the PMV was influenced by the blocking of wind movement by the mouldings. On the other hand, the overhang/ arcade case resulted in a significantly lower PMV across all cases whereas its impact on air temperature in the mew case is not significant and increased in the lane case.

6. Implications of Using LCZ Parameters for Street Design

The above simulations indicate that the air temperature behaviour is not always synonymous with PMV. This variation can be interpreted for street design purpose in several ways.

Firstly, orientation has more impact on air temperature than thermal comfort (PMV). On the other hand, both temperature and thermal comfort are influenced more by the street aspect ratio. Thus openness (as controlled by the aspect ratio) might be the controlling factor in determining street level thermal comfort, offering greater flexibility in the positioning of pedestrianized streets irrespective of their orientation. Furthermore, street design would need to adopt more customized strategies such as the types of shading and ventilation in conjunction with street openness.

Secondly, the impact of surface properties and openness had no strong correlation to temperature. However, both show significant correlation to PMV implying that they are indeed of importance for the place making process in terms of pedestrian thermal comfort during the street design process. Most importantly it suggests that one fixed design strategy would not be applicable for all street cases within a zone and would need to be modified according to the aspect ratio of the street.

Lastly, the newly introduced parameter of façade geometry was found to play a key role in the temperature variations as well as thermal comfort of compact streets. However, a reduction or increase in temperature did not necessarily indicate that the PMV would behave in the same manner. This suggests that LCZ classification would need to further classify the façade properties in order to be integrated as a tool for climate sensitive street design.

7. Conclusion and Recommendations for Future work

This study was conducted with the main aim of exploring how The LCZ based classification system could be adopted for climate sensitive urban planning in a compact urban area. Summary of key findings include,

- The Temperature variations between all considered cases within the same LCZ zone was 2.5°C.
- Street Orientation has a greater influence on air temperature rather than PMV with the N-S oriented streets being always 'warmer' than E/W oriented streets.
- The Street aspect ratio (H/W) has a strong correlation to both air temperature and PMV highlighting its need to be considered during the urban design process.
- LCZ classification would need to include façade properties in order to be integrated as a tool for climate sensitive street design.
- Improvements in street level comfort mainly comes from the shading effect; however, wind speed and humidity cannot be ignored when studying the impact of LCZ parameters on street design.

The study concluded that that one fixed design strategy would not be applicable across all street typologies and that several from based parameters including orientation, street aspect ratio and surface and façade properties can play a vital role in climate sensitive street design. The findings can be further refined by conducting studies;

- Across different LCZ classes to further refine the research findings
- On the impact of seasonal variations and the impact of the findings in a heterogeneous urban environment such as in Asian / Developing city (built fabric is quite homogeneous in European cities such as Glasgow, given its largely 19th century urban plan)
- Across latitude variations to identify the impacts of solar angles and shading.

Design interventions selected to be studied were limited to the approaches applicable to listed buildings of the CBD. The study was also limited to only the pedestrian streets/ avenues and lanes. The wind speed and humidity can both have an effect on PMV and MRT which was not considered during the study. However, the results indicate that it is a comfort parameter that cannot be ignored when studying the impact of LCZ parameters on street design.

Author statement

Nusrath Maharroof: Conceptualization, Methodology, Data curation, formal analysis, Visualisation, Writing- Original draft preparation

Rohinton Emmanuel: Conceptualisation, Methodology, Funding acquisition, Software, Visualization, Supervision, Writing- Reviewing and Editing

Craig Thomson: Supervision, Writing- Reviewing and Editing

References

- Ng, Edward and Ren, Chao. (2015). *The Urban Climatic Map: A Methodology for Sustainable Urban Planning*. Routledge; 1 edition .
- secretariat of UN Economic and Social Commission . (2017). *Urbanization and sustainable development in Asia and the Pacific: linkages and policy implications*. Bangkok: United Nations Economic and Social Council - Seventy-third session.
- Alexander, P., Mills , G., & Fealy, R. (2015). Using LCZ data to run an urban energy balance model. *Urban Climate, 13*, 14-37.
- Ali-Toudert, F., & Mayer, H. (2007). Effects of asymmetry, galleries, overhanging façades and vegetation on thermal comfort in urban street canyons. *Solar Energy 81(6)*, 742-754.
- Ali-Toudert; F. and Mayer; H. (2007). Thermal comfort in an east–west oriented street canyon in Freiburg (Germany) under hot summer conditions. *Theoretical and Applied Climatology Volume 87, Issue 1–4*, 223–237.
- Bechtel, B., Alexander , P., Böhner, J., Ching, J., Conrad, O., Feddema, J., . . . Stewart,, I. (2015). Mapping Local Climate Zones for a Worldwide Database of the Form and Function of Cities. *ISPRS International Journal of Geo-Information, 4(1)*, 199-219.
- Csete, M., & Buzasi, A. (2016). Climate-oriented assessment of main street design and development in Budapest. *Journal of Environmental Engineering and Landscape Management 24(4)*, 258-268, DOI: 10.3846/16486897.2016.1185431.
- Demuzere, M., Bechtel, B., & Mills, G. (2019). Global transferability of local climate zone models. *Urban Climate, 27*, 46-63.
- Emmanuel R, Johansson E. (2006). Influence of urban morphology and sea breeze on hot humid microclimate: the case of Colombo, Sri Lanka. . *Climate Research 30*, 189–200.
- Emmanuel, R. (2016). Achieving Thermal Pleasure in Tropical Urban Outdoors. In R. Emmanuel, *Urban Climate Challenges in the Tropics: Rethinking Planning and Design Opportunities* (pp. 31-47). London: Imperial College Press.
- Emmanuel, R., & Fernando, H. (2007). *Urban heat islands in humid and arid climates: Role of urban form and thermal properties in Colombo, Sri Lanka and Phoenix, USA*. 241-251: *Climate Research 34(3)*.
- Emmanuel, R., & Loconsole, A. (2015). Green infrastructure as an adaptation approach to tackle urban overheating in the Glasgow Clyde Valley Region. *Landscape and Urban Planning, 138*, 71-86 10.1016/j.landurbplan.2015.02.012.
- Emmanuel, R., Rosenlund, H. and Johansson, E. (2007). Urban shading—a design option for the tropics? A study in Colombo . *Sri Lanka. Int. J. Climatol., 27*, 1995–2004. doi:10.1002/joc.1609.
- ENVI-met. (2017). *PMV/PPD - A holistic microclimate model*. Retrieved from apps/biomet_pmv: http://www.envi-met.info/doku.php?id=apps:biomet_pmv#pmv_ppd
- Getting Ahead of Change - Glasgow City Centre Strategy and Action Plan 2014–19*. (2013). Retrieved from Glasgow City Council: <https://www.glasgowcitycentrestrategy.com/project/city-centre-avenues>

- Glasgow City Development Plan, 2017*. Glasgow: Glasgow City Council.
- IPG1 Placemaking Part 1 - INTERIM PLANNING GUIDANCE, 2017*. Glasgow City Council.
- Jamei, E., Rajagopalan, P. (2018). Effect of street design on pedestrian thermal comfort. *Architectural Science Review*, DOI: 10.1080/00038628.2018.1537236.
- Jamei; Elmira, Ossen; Dilshan Remaz and Rajagopalan; Priyadarsini. (2017). Investigating the effect of urban configurations on the variation of air temperature. *International Journal of Sustainable Built Environment, Volume 6, Issue 2*, 389-399.
- Johansson, E. (2006). Influence of urban geometry on outdoor thermal comfort in a hot dry climate: A study in Fez, Morocco. *Building and Environment, Volume 41, Issue 10*, 1326-1338.
- Johansson, E., Emmanuel, R. (2006). The influence of urban design on outdoor thermal comfort in the hot, humid city of Colombo, Sri Lanka. *International Journal of Biometeorology 51(2)*, 119-33.
- Kytta, M. et al. (2013). Towards contextually sensitive urban densification: Location-based softGIS knowledge revealing perceived residential environmental quality. *Landscape and Urban Planning*, 113, 30-46.
- Leconte, F., Bouyer, J., Claverie, R., & Pétrissans, M. (2015). Using Local Climate Zone scheme for UHI assessment: Evaluation of the method using mobile measurements. *Building and Environment*, 83, 39-49.
- Lin, Tzu-Ping, Matzarakis, Andreas and Hwang, Ruey-Lung. (2010). Shading effect on long-term outdoor thermal comfort. *Building and Environment*, 45(1), 213-221.
- Taleghani M et al. (2015). Outdoor thermal comfort within five different urban forms in the Netherlands. *Building and Environment*, 83, 65-78.
- Mills, G., Bechtel, B., Ching, J., See, L., Feddema, J., Foley, M., . . . O'Connor, M. (2015). An Introduction to the WUDAPT project. *ICUC9 - 9th International Conference on Urban Climates*. Toulouse.
- Nouri, A. (2015). A Framework of Thermal Sensitive Urban Design Benchmarks: Potentiating the Longevity of Auckland's Public Realm. *Buildings*, 5, 252-281.
- Oke, T. R. (1988). Street Design and Urban Canopy Layer Climate. *Energy and Buildings*, 11, 103 - 113.
- Perera, N., & Emmanuel, R. (2018). A "Local Climate Zone" based approach to urban planning in Colombo, Sri Lanka,. *Urban Climate*, 23, 188-203.
- Roset, J.; Vidmar, J. (2013). *Evaluation of simulation tools for assessment of urban form based on physical performance*. UPCommons.
- Scottish Govt. (2010). *Designing Streets: A Policy Statement for Scotland*, ISBN: ISBN: 978 0 755 98 264, available at: <https://www.gov.scot/publications/designing-streets-policy-statement-scotland/>
- Shishegar, N. (2013). Street Design and Urban Microclimate: Analyzing the Effects of Street Geometry and Orientation on Airflow and Solar Access in Urban Canyons. *Journal of Clean Energy Technologies*, 1(1), 52-56.
- Stewart, I., & Oke, T. (2009). Classifying urban climate field sites by local climate zone: The case of Nagano, Japan. *Seventh International Conference on Urban Climate, June 29–July 3*,. Yokohama.
- Stewart, I.D., Oke, T.R. (2012). Local climate zones for urban temperature studies. *Bull. Am. Meteorol. Soc.*, 93, 1879–1900.
- UN-Habitat. (2013). *The relevance of street patterns and public spaces in urban areas UN-Habitat working paper*. United Nations Human Settlements Programme.

United Nations, D. o. (2014). *World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352)*. United Nations.

Yahia, M.W., Johansson, E., Thorsson, S. et al. (2018). Effect of urban design on microclimate and thermal comfort outdoors in warm-humid Dar es Salaam, Tanzania. *Int J Biometeorol.* 62, 373–385. <https://doi.org/10.1007/s00484-017-1380-7>