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Urban Heat Island Minimisation, Local Climate Zones and Parametric Optimisation: A "Grasshopper" Based Model

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ABSTRACT

Many cities have undergone severe transformation, creating unliveable environments, polluted and stagnant air and effected by Urban Heat Island (UHI). With the prevailing rapid development in Sri Lanka in general, and Colombo in particular, the impact of the phenomena is evident. Thus, it needs to become a key consideration in the urban design process to optimise building morphology for minimum UHI impact, especially in the Tropics. The main objective of the study is to build a parametric model to analyse the behaviour of the Urban Heat Island (UHI) effect with the changing land cover and geometric properties, based on the Local Climatic Zone (LCZ) classification. A parametric model is developed using Grasshopper VPL to match the corresponding geometric and land cover properties and thereafter, used with a derivative free optimisation algorithm to find the respective forms that generate maximum and minimum UHI values. Findings show a direct association of the building height to the UHI intensity. Higher impervious land cover percentages contribute to the increase of the UHI value. As an outcome of the research, a protocol model process is presented, which allows the input of multiple variables and generates real-time adaptive results, dramatically reducing the time of the optimising process, for UHI minimisation. Thus, allowing planners and urban designers to explore different morphologies through real-time analysis.

Keywords: urban heat island, Local Climate Zone, Parametric Optimisation, Grasshopper, Urban Weather Generator

Introduction

As indoor overheating is directly associated with energy demand and thus has significant impact on the microclimatic context as waste heat, it has to become a key consideration in the urban design process to optimise building morphology for minimum UHI impact. However, the widely used orthodox method for reducing the UHI is to use heuristic data with trial and error methods based on the previous known experiences and protocols; this practice often uses a base case to compare between variations and their combinations, by selecting the best-generated options based on the stochastic data. However, this would be a very time consuming and inefficient method that may not provide a sufficiently good solution to an optimisation problem. Further, the practice does not generate sufficient data to analyse and it cannot predict or create a functional dependence for the behaviour of variables considered.

Alternatively, it is convenient to have a parametric platform that allows multiple variables and gives real-time adaptive results, as it would dramatically reduce the time and cost of the optimising process.

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The main objective of the study is to build a parametric model to analyse the behaviour of the Urban Heat Island (UHI) effect with the changing land cover and geometric properties of the Local Climatic Zone (LCZ) classification framework. In this particular research, only the LCZ1 (compact high-rise) is selected for modelling and analysis due to its high impact on UHI (Perera et al. 2012 and 2018; Perera, 2015) and as a limitation of research scope.

A research workflow using Grasshopper VPL as a parametric modelling platform is adopted, with Rhino 3D® platform to create a parametric model for LCZ1 in real-time. The Dragonfly plugin for Grasshopper, is utilised to set up the Urban Weather Generator (UWG) and calculate the average and maximum UHI. An evolutionary solver is applied to find optimum values and according to systematic inputs. The process is recorded, by setting up a recorder -Colibri plugin - to save the data. Next, the results are mapped to present the outdoor thermal comfort levels using the Ladybug tool.

The research outcome is focused on the behaviour of UHI against the defined parameters of LCZ1 of the LCZ classification system, to ascertain the maximum and minimum values possible in a given range. The analysed results seek to determine and communicate the best geometric and surface cover values for outdoor thermal comfort.

Background

As defined by (Rizwan, Dennis, & Liu, 2008), there are three major factors for urban warming; anthropogenic heat, land cover and ventilation. UHI manifestation and intensity is seen as the most representative form to communicate urban warming, especially in research. The simplest definition of the UHI is the atmospheric warmness of a city or an urban quarter compared to its countryside.

According to the description of (Stewart & Oke, 2012), This singularity occurs in cities despite its size, traditionally measured at 1-2 meters above ground level known as the urban canopy layer, just below the mean city roof height. When related with a rural area, the temperature in an urban setting at the same height is higher, in comparison to the rural areas and defined as the urban heat island effect.

Luke Howard in 1833 described the UHI in London in his studies. The magnitude of the UHI was communicated as per the following equation;

UHI Magnitude = T_a in city centre – T_a in rural areas. (T_a - Ambient temperature)

Building Morphology and UHI

Various changes in the built form of the context modify the thermal environment around it, especially in relation to high-rise clusters - where the impacts are generally significant. Local climatic elements such as relative humidity, external air temperature and prevailing wind speed and directions also cause alteration of the microclimate around a particular urban plot. Solar access to urban canyons, incoming solar radiation effects in urban areas occur due to the qualities of the incident surfaces such as albedo effect, are also identified as causes for the variations of the climatic effects in urban areas. Due to these changes, classification of the urban zone is very important in understanding the climatic effects on urban spaces in particular.

Classification between urban and rural usually correspond with population magnitude and density of built structures. This can be interpreted as rural landscapes to be less populated than urban areas, with lesser-built structures and more natural space with vegetation, open soil, whereas urban landscapes have significantly more built structures with larger population. Stewart & Oke, 2012, states that the term urban evokes an eclectic mix of local settings from which its observations have originated, which means, the different characteristics of diverse urban scenarios.

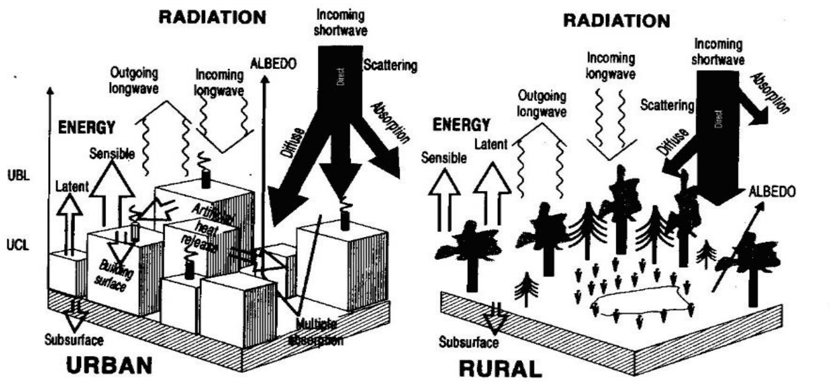

Figure 1: Difference between urban - rural energy exchanges. *Source*: http://urbanez.blogspot.com

Adopting the Local Climatic Zone (LCZ) classification for the study

The logical structure of the LCZ system is supported by observational and numerical modelling data (Stewart & Oke 2010; Stewart, 2011). There are seventeen standard types of LCZs, of which two are defined by construction materials and anthropogenic heat emissions. while the rest are defined by the surface cover and structure. Although there are seventeen different groups, it is still a generic system and thus, cannot capture all the various peculiarities of a city. Its view of the landscape universe is highly reductionist, and, like all classifications, its descriptive and explanatory powers are limited (Stewart & Oke, 2012). However, this classification can be easily applicable to most cities in the World.

The divided classes are "local in scale, climatic in nature, and zonal in representation". This allows to formally define local climate zones as regions of uniform value quantities. It also delivers a research framework for UHI studies with temperature observations in an urban level with a more standard format, which can correspond, with worldwide level. (Stewart & Oke, 2012). Defined, "local climate zones" as regions of uniform surface cover, structure, material, and human activity that span hundreds of meters (10^2) to several kilometres (10^4) in horizontal scale.

Approach to the study

With regard to calculating the optimum values of UHI effect in a selected area, a separate parametric model is created for optimisation in each design domain. This model is used to determine the optimum form of buildings within defined geometric properties limited to the LCZ1 parameter range. To measure these UHI values depending on different climates, certain data should be included into this aforementioned parametric model. Among the various input data needed in this calculating process, the anthropogenic heat value and the albedo effect values are considered as constant, thus a limitation in this process. Here, anthropogenic heat is a default value extracted from previous research.

Method

LCZ classification system is identified as standard protocol for urban temperature studies. The LCZ1 - compact high-rise of the LCZ classification signifies increased human activities and higher density. The scope of the study is limited to LCZ1.

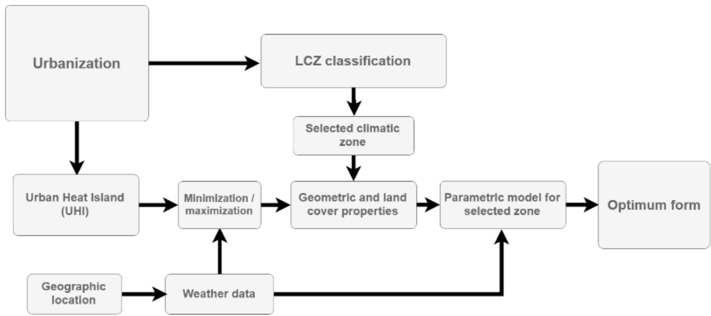

Figure 2: Research workflow. *Source*: Author.

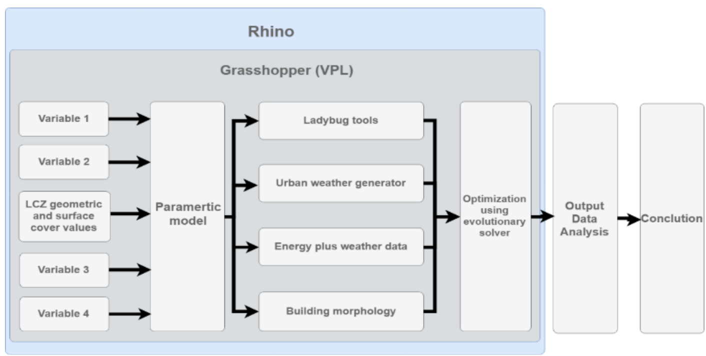

Figure 3: Methodology workflow. *Source*: Author.

Generating a block model for LCZ1

Rhino 3D was used as the primary modelling software with the Grasshopper VPL for the generation of the parametric model for LCZ1. As the first step, a square of 250m by 250m was created as the city block. The values of geometric land cover values for LCZ1 were used to subdivide the city blocks. Assumptions were made to have roads at the perimeter of the city block and 10m offset line was created so the 20m width of roads are created when the city blocks placed together in a grid. This surface area of the road falls under impervious land cover. Thereafter, another offset line was created, but the offset value is a variable defining the impervious land cover area, which is varied between 0-10% of the total area. Within the perimeter of a block, 49 dynamic points were generated in a 7x7m grid as the base points for the buildings (however this can be easily changed using a slider - mode of modification in VPL platform - and use any number of buildings for a particular study). Next, the area of the calculated building surface fraction (see Table1) is divided by the number of buildings, to correspond with the area from the last step. In height control, the slider will be connected to extrude the buildings surface squares according to the height range of the LCZ1. The value for height roughness elements (see Table1) for LCZ1 is >25, but a height limit maximum of 350m is adopted as a limitation for this study. The remaining infill areas between the buildings and road surface areas are considered as the impervious land cover.

Table 1. Values of geometric and surface cover properties of LCZ1 (Stewart & Oke, 2012)

Factor	Property	Value	Description
a)	Sky view factor	0.2-0.4	*Ratio of the amount of sky hemisphere visible from ground level to that of an unobstructed hemisphere*
b)	Aspect ratio	> 2	*Mean height-to-width ratio of street canyons (LCZs 1–7), building spacing (LCZs 8–10), and tree spacing (LCZs A–G)*
c)	Building surface fraction	40-60	*Ratio of building plan area to total plan area (%)*
d)	Impervious surface fraction	40-60	*Ratio of impervious plan area (paved, rock) to total plan area (%)*
e)	Pervious surface fraction	<10	*Ratio of pervious plan area (bare soil, vegetation, water) to total plan area (%)*
f)	Height of roughness elements	>25	*Geometric average of building heights (LCZs 1–10) and tree heights (LCZs A–F) (m)*
g)	Terrain roughness class	8	*Davenport et al.'s (2000) classification of effective terrain roughness (z0) for city and country landscapes.*

From the data above, only c), d), e), and f) were taken as the direct inputs for the parametric variables. a) sky view factor is a dependant of the above selected inputs and b) aspect ratio – is satisfied by the setting up of the road around the city block perimeter. g). Terrain roughness class – is a representation of the character of the category and not considered as an input (*All the above properties are unitless except height of roughness elements are in meters.)*

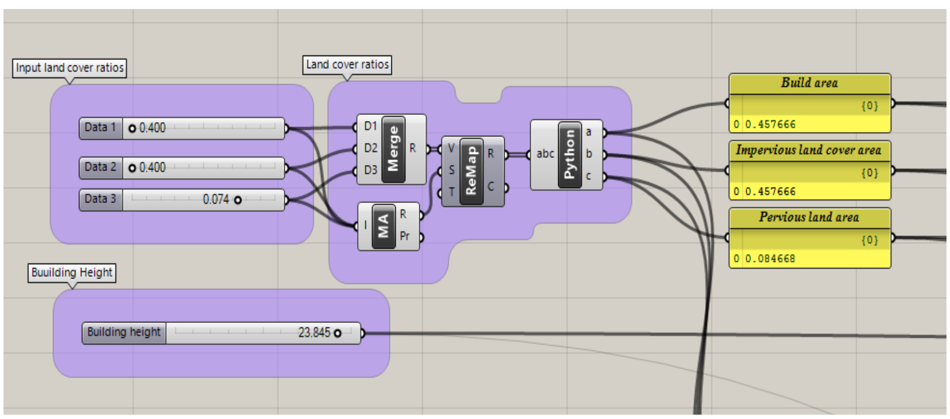

Figure 4: Input of geometric and surface cover properties for LCZ 1 as parameters. Source-Author

The Dragonfly tool (one of main components of Ladybug tools for Grasshopper) is utilised to run the Urban Weather Generator (UWG). UWG is a commonly used UHI modelling software.

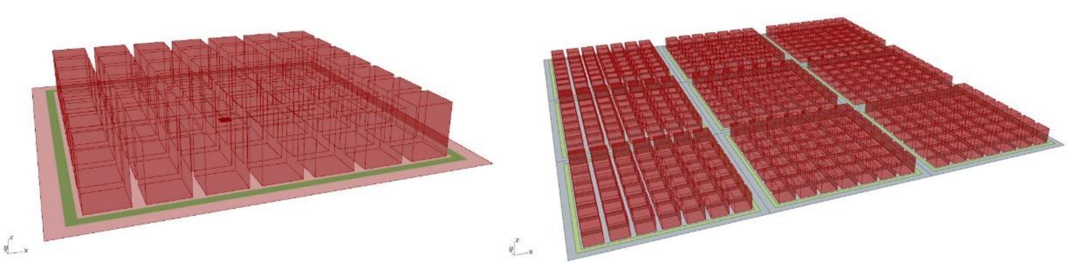

Figure 5: Left image -Completed block model for LCZ1 and Right image - Array of city blocks. Source-Author

The hourly values are calculated by UWG using the input weather data file and the created model. These output results can be easily transferred to other performance simulation processes as well.

UWG consists of four coupled modules,

1. The rural station model
2. The vertical diffusion model
3. The urban boundary layer model
4. The urban canopy + building energy model

After connecting the city geometries and other relevant parameters as inputs for Dragonfly workflow, the UWG is run to test the particular UHI values for that particular input values. Figure 6 shows the hourly data from the modified weather file and the original weather data file. Thereafter, a simple custom Grasshopper code filters out the maximum, minimum and average UHI values. The output data can be used for mapping outdoor comfort.

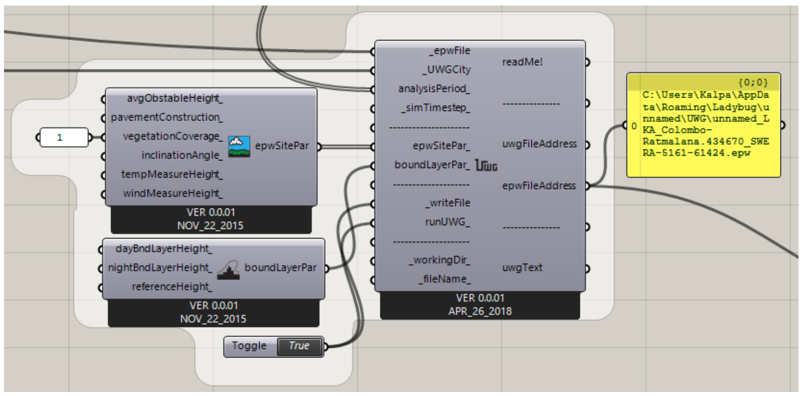

Figure 6: Urban Weather Generator component of Dragonfly. *Source*: Author.

The entire workflow is attached to an Optimisation solver for Grasshopper called Opossum, to find the maximum and minimum of UHI from the model iterations and their respective geometric land cover and building input values relative to LCZ1. Opossum is suitable for time intensive multi objective performance simulations like building energy demand calculation with daylighting and solar radiation optimisations. (Wortmann, 2017)

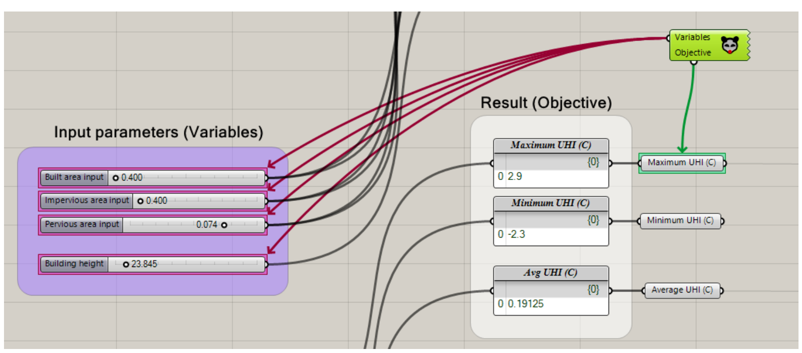

Figure 7: Opossum solver attached to input variables and one of the outputs. *Source*: Author.

Results and discussion

Results from the simulations compare the effect of UHI intensity with the varying LCZ1 parameters. The parametric models generated for LCZ1 is connected to the rest of the workflow to generate a series of iterative simulations to find the best form for each given optimisation, either minimum or maximum UHI value. Mean Radiant Temperature (MRT) is used as the means to communicate outdoor thermal comfort and comparative urban warming.

Recorded Minimum and Maximum Changes in the UHI Values

Case1 - Search for the maximum magnitude warmer UHI values recorded (in hourly data) and its corresponding geometric values

Build %	43.7729
Built area	27358.0625
Impervious %	54.9451
Impervious land cover area	34340.6875
Pervious %	1.2821
Pervious land area	801.3125
Building height	75
No. of Buildings	49
Block(Length)	250
Block (Width)	250
Total area	62500
% Sum	1
Area per building	558.327806
Max UHI (C)	2.5
Min UHI (C)	-3.1
Avg UHI (C)	-0.14375

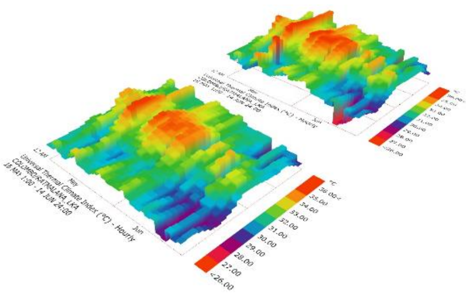

Figure 8: Input values and 3D chart for Case 1. The chart shows the changes of hourly MRT against rural temperature. *Source*: Author.

The hourly MRT values in the chart above (Figure 8.) show a significant increment in both lower and higher MRT values compared to the rural weather data chart. However, the magnitude of increments in the higher MRT values are consequently lower than the increment in lower temperature values. The maximum UHI possible (2.5^{o} C) for this particular zone is caused where, building height reaches its minimum, pervious land cover percentage reaches its minimum and built percentage reaches a below average value (43.7%). However, the average UHI recorded for this form is still a minus value, albeit with a small magnitude (-0.14375).

Case2 - Search for the minimum magnitude of warmer UHI values recorded (in hourly data) and its corresponding geometric values

The minimum magnitude of minimum UHI possible for this particular zone is caused where, the building height reaches its minimum, both building surface cover and impervious cover percentages are in similar value. The results show a similar scenario as the maximum magnitude discussed under Case1. In addition, the magnitude of decrements in the higher temperatures are consequently lower than the increment in lower temperature values.

Case3 - Search for the minimum magnitude of cooler UHI values recorded (in hourly data) and its corresponding geometric values

The hourly MRT values of the chart show a significant decrement in both lower and higher MRT values compared to the rural weather data chart. However, the magnitude of decrements in the lower MRT values are consequently lower than the decrements in higher temperature values. The minimum magnitude possible for maximum UHI is caused where building height reaches above average, both built and impervious land cover percentages are same and pervious land cover percentage reaches an upper limit value.

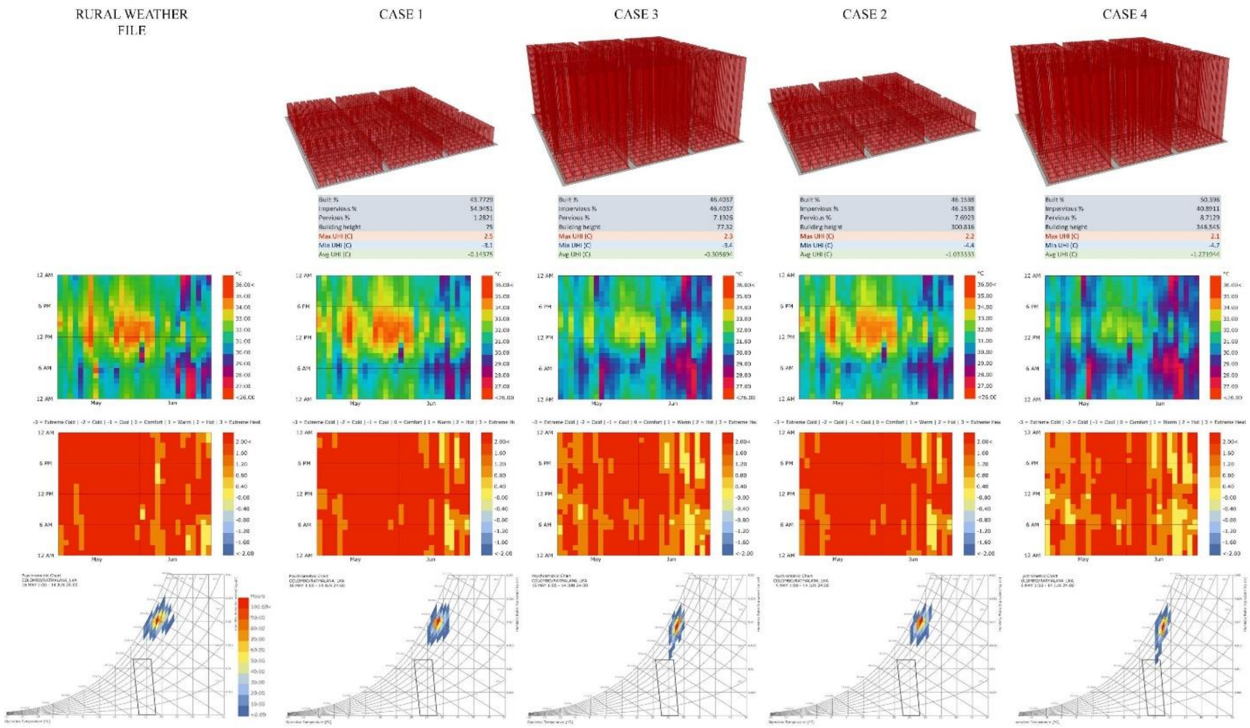

Figure 9: Comparison of results (case1 case2 case3 and case 4). *Source*: Author.

Case4 - Search for the maximum magnitude of cooler UHI values recorded (in hourly data) and its corresponding geometric values.

The hourly temperature values show a significant decrement in both lower and higher MRT values compared to the rural hourly MRT chart. However, the magnitude of the decrement in the higher MRT values are significantly higher than the decrement in lower MRT values. The minimum UHI compared to the original weather file is caused where, building Height reaches its maximum, impervious land cover reaches its minimum and pervious land cover gets an above average value. Average UHI shows a minus value and it shows the highest magnitude among all the LCZ1 optimisation results (-1.271944).

Conclusion

The study is aimed at exploring the relationship between Urban Heat Island effect and the city form, using the existing Local Climatic Zone classifications as a base protocol. The initial inception turned toward the parametric modelling considering its potential of finding an optimal solution for the problem using the derivative free optimisation techniques.

Out of the 17 LCZ categories in the existing framework, LCZ1 was selected to analyse the UHI effect due to the density and high-energy consumption associated with it. Four optimisation runs were tested, focusing on the maximum and minimum boundaries of the warmer UHI values, maximum and minimum boundaries of the cooler UHI values of calculated hourly data of each optimisation.

- Findings clearly show the direct association of the building morphology to UHI as results depict particular parts of an urban block can create areas of reduced UHI intensity.

- The morphology optimisation for a LCZ1 block fails to create thermally comfortable areas within the zones (see Figure 9). Although, morphology changes drive comparably cooler areas. Thus, compact high-rise areas of a city are not conducive for UHI mitigation, primarily due to factors that research show are the main causes for UHI are heightened in this particular form.
- Building surface cover for the optimised forms showed lower percentages. Therefore, it is evident that a block form that is classified as LCZ1 needs a lower threshold of built space for UHI minimisation. The implication of which is that compact high-rise areas of a city should be avoided. If high-rise developments are needed the LCZ classification should be more towards LCZ4 or open-set high-rise, where the building surface fraction upper limit is 40%.
- It was found that higher impervious land cover percentages contribute to the increase of the UHI value.
- Optimised forms from LCZ1 suggest forms of higher UHI values consists of minimum pervious land cover percentages and forms of lower UHI values consists of higher percentages of pervious land cover values.

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According to the above observations, it is possible to generally suggest the possibility to minimise the UHI by raising the building heights, reducing the impervious land cover and maximising the pervious land cover in zoning stages. However, the input percentage variables are interdependent of each other and this rule of thumb could possibly be valid only inside the parameter value range of LCZ1 and cannot suggest a globally valid answer for different forms outside the parameter value range. Further, the minimisation occurs at specific parts of an urban block, not as an overall phenomenon. As the study explores, building a custom parametric model to correspond with the context and then running the optimisation is recommended to gain more accurate and finite results.

The search for optimum block form for UHI minimisation is crucial in today's warming city contexts in particular and the world in general. Evaluation protocols that can be developed from this platform signifies the way forward, where overall planning and building regulation thresholds are insufficient to deal with specific parts of the city, with differing orientations and exposures to natural boundaries. The ultimate step could be an approval system that evaluates UHI impacts, albeit over-the-counter, encouraging climate sensitive intervention into everyday urban design.

Limitations of Methodology and Study

- The parametric model is developed only as a block model and does not explore the possible forms of complex building shapes.
- Anthropogenic heat input value added during the calculation is a default value based on the city characteristics and does not use a proper calculated method for the selected city.
- City block is considered to have no vegetation; which research shows as a significant means for UHI mitigation.

Future Research

This initial research limits its scope to a context to consider the parametric model-based analysis to cater to a design process of built morphology in urban planning viewpoint. This could be further developed by increasing the scope of the study where much specific details and characteristics can be included to increase the precision of the results. In addition, this parametric model only explores the behaviour of UHI with a block model of a cuboid shaped buildings and further developed for testing of different types of cities with different building languages.

Additional parameters also could be considered in calculations as anthropogenic heat, albedo and vegetation. In addition, it is possible to integrate the advanced material properties into the workflow as well, where the inclusion of these properties will also improve the precision of the results. These implementations can be done in future researches as to improve the realistic nature of the calculations and simulations to gain much more precise results to work on productive building technologies and architecture to cater for the sustainability of urban contexts.

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