
Elif Esra Aydin¹, J. Alstan Jakubiec¹
¹Singapore University of Technology and Design, Singapore

Abstract

Urban settlements require design improvements towards increased comfort and reduced energy consumption through active and passive means to create liveable cities in the future. This study investigates the impact of 6 urban design criteria—building height, plot ratio, greenery, glazing ratio, shading, and materiality—on discrete environmental metrics for sustainability using Morris sensitivity analysis (SA) method. The authors calculate a series of critical and emerging environmental measures which indicate the suitability of an urban design: Urban Heat Island (UHI), Outdoor Thermal Comfort—using the Universal Thermal Climate Index (UTCI), Urban Energy Use Intensity (EUI), Urban Daylight Autonomy (UDA), and Annual Mean Ventilation. This study identifies essential parameters for comfortable and low-energy urban communities in early-phase urban design processes for tropical climates using Morris sensitivity analysis. The effort is focused on an increased modelling comprehensiveness—including more related and co-dependent sustainability measures compared to previous works—and understanding the impact of parameters investigated on a comprehensive set of environmental measures. The authors find that building height and site coverage ratio most significantly impact many of the studied environmental measures. However, all parameters are significant on at least one environmental measure; therefore, it is difficult to simplify the complex process of urban environmental and sustainable design.

Introduction

The global temperature has continuously risen during the last few decades. Urban settlements have a crucial impact on the rising air temperature as a reason for global warming. In the light of that, recently the phenomenon of urban developments is to focus on thermal comfort, energy efficiency, and daylighting issues for creating liveable, walkable, and comfortable cities. This study, therefore, predicts the urban heat island (UHI), urban thermal comfort (using UTCI), energy use intensity (EUI), Urban Daylight Autonomy (UDA), and urban ventilation metrics on the early-design of an urban cluster.

The prediction of air temperature is a challenge for urban planners throughout the design process (Jusuf and Wong 2009). Other contemporary studies of urban comfort modelling range from open source interfaces (e.g. Ladybug, Honeybee (Roudsari, Pak & Smith 2013) and closed sources (e.g. ENVI-met (Bruse and Fleer 1998), STEVE (Jusuf 2009), and Umi (Reinhart et al. 2013)). These tools are used by educational and professional fields to predict urban sustainable performance. Many studies predict thermal comfort of the urban context using these tools based on local urban air temperature. Besides thermal comfort, energy utilization has been an intense focus of urban analysis due to increased air temperature and diurnal UHI (Crawley 2008). Moreover, daylighting performance is another critical issue for urban scale studies to have healthy and comfortable living spaces both indoors and outdoors (Compagnon 2004).

Considering this emerging field, this paper investigates the importance of urban design parameters on a hypothetical model of an urban district, that is used to predict urban heat island effects, outdoor comfort levels, energy utilization, potential daylighting, and wind flows. Typical design parameters are varied to understand the design of more comfortable, liveable and healthy urban designs from the early design phase.

Several issues related to urban-scale prediction models are addressed in this paper. One of the most notable issues is computation time. Sensitivity analysis using the method of Morris is employed to identify relevant and less-relevant parameters in a time-efficient manner with fewer simulations. In summary, this study responds to the following significant questions:

- What are the main parameters for urban design modeling by estimating performance relevant to the comfort, energy use and daylighting?
- What are the dominant urban design parameters that influence varied environmental performance metrics?

Considering the objectives of the study, design parameters and metrics will be defined based on a review of urban performance analysis papers. Afterwards, a comprehensive simulation methodology will be described, and the parameterized model results will be assessed on the influence of the design parameters’ impact on urban sustainability metrics.

Sustainability urban performance metrics

This study calculated 5 annual performance metrics: UHI, Outdoor Thermal Comfort—using the Universal Thermal Climate Index (UTCI), Urban EUI, UDA, and Mean Annual Ventilation Potential (in m/s). UHI is the primary metric which has been used to describe more comfortable and liveable city design. In an example from Singapore,
Jusuf and Wong (2009) presented a UHI study discussing the development of a statistical regression model of air temperature prediction via means of Geographical Information Systems data and remote sensing.

**Urban heat island (UHI):** Rising air temperature in urban developments, especially at night, has been demonstrated via UHI studies (Oke 1988). UHI results in this paper are illustrated by taking the difference between microclimate-morphed weather data and the original meteorological weather data (EPW file) obtained from the EnergyPlus weather data website (U.S. Department of Energy 2018). The results obtained from differences demonstrate annual mean UHI value in degrees Celsius, therefore, higher numbers indicate a greater UHI effect.

**Outdoor thermal comfort—universal thermal climate index (UTCI):** The analysis of thermal comfort is determined by the air temperature, radiant temperature, humidity, and air velocity within the urban context. The UTCI heat balance model is used to assess the thermal perception of people within a modeled urban context. This analysis requires the input of UHI-changed climate data, fluid dynamics to assess urban wind flows, solar modeling for shadow patterns, and thermal modeling to assess the heat storage and subsequent radiant temperature contribution of urban surfaces. The authors predict the percent outdoor comfortable area with the UTCI lower than 28°C more than 20% of hours in a year (UTCI≤28°C>20%). Higher percentages of the urban area meeting this criteria indicate better outdoor comfort conditions overall.

**Energy use intensity (EUI):** As shown by Crawley (2008) and Bueno et al. (2012), UHI has a significant impact on energy consumption of cities beyond other factors like the broader climatic context, building fabric, and urban & local shading. Considering previous research, energy utility is a crucial part of this study as reducing urban energy consumption is a strong societal goal. In this paper, EUI is represented simply by the site energy consumed by all buildings in an urban area in units of kWh/m² of floor area.

**Urban daylight autonomy (UDA):** Potential daylighting in the urban context is essentially influenced by the density and the urban fabric (WWR and visible light transmittance). In this study, UD potential is assessed by the percent of floor area daylight (achieving 300 lx more than 50% of hours in the year—DA≥300lx,50%).

**Wind potential:** Average annual wind speed in the urban context (spatial and temporal mean in m/s) is used in this paper to describe the wind potential of an urban site. Described in more detail in the simulation methods section, this is achieved by running 8 computational fluid dynamics simulations and interpolating the results annually using the meteorological weather data. This extrapolation is also used in the annual UTCI calculation. The metrics described above, when integrated, demonstrate comfort, energy and daylighting values for urban scale studies holistically. One novelty of this study is the integration of myriad performance models and sustainable performance metrics in one decision-making framework using SA whereas many previous studies focus on a single measure of environmental performance.

**Urban design parameters**

Design parameters of the urban context were selected based on early design studies in the literature. A review of relevant papers is summarized in Tables 1 and 2, which defines the design parameters utilized in this study for both the urban environment (Table 1) and building design (Table 2). The parameters defined in these tables illustrate either the parameters of design alternatives or inputs mentioned in the literature review. Overall, urban environment parameters are separated into 3 main categories: urban context (buildings), pavements (roads), greenery (green zones, parks, recreation areas). Building design parameters consist of detailed information about building geometry, orientation, construction, and façade properties. The authors’ approach the parameters from the broader perspective of urban design elements down to the specific details of buildings. In conclusion of the review summarized in Tables 1 and 2, the following 6 urban and building parameters are selected. The value ranges of these parameters are defined in Table 3.

**Investigated parameters**

1. Urban Environment Parameters:
   - Building Height (Height)
   - Site Coverage Ratio (SCR)
   - Total Green Plot Ratio (GnPR)

2. Building Design Parameters:
   - Window to Wall Ratio (WWR)
   - Exterior Sun Shading (Shade)
   - Material Choice (Materials)

<table>
<thead>
<tr>
<th>METRIC**</th>
<th>Publication Date</th>
<th>Urban Heat Island</th>
<th>Urban Environment</th>
<th>Daylight</th>
<th>Model Building</th>
<th>Thermal Comfort</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban Context</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Pavement</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Greenery</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Urban Canopy Layer</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Urban Boundary Layer</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Urban Surface</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Climatic Location</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

*Table 1 Reviewed literature of urban environment parameters*
Table 2. Reviewed literature of building design parameters

<table>
<thead>
<tr>
<th>METRIC</th>
<th>Publication Date</th>
<th>Model Building</th>
<th>Daylight</th>
<th>Heat Island</th>
<th>Thermal Comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>C. Kristl.</td>
<td>Cerezo</td>
<td>Compagnon</td>
<td>Rizwan</td>
<td>Bueno</td>
</tr>
<tr>
<td>Construction</td>
<td>Esch et al.</td>
<td>Reinhart</td>
<td>Dogan</td>
<td>Gago</td>
<td>Mackey</td>
</tr>
<tr>
<td>Façade / WWR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blinds &amp; Shading System</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 1. Flow-chart of a set of Simulation

Methodology
The methodology employed is a parametric simulation analysis of design strategies for urban forms in Singapore, a hot and humid tropical climate. The process and flows of data are illustrated in Figure 1. Urban design and building parameters were identified from the literature as described in the previous section. Based on these parameters, UHI was calculated first using the Urban Weather Generator to produce a morphed weather file accounting for the urban microclimate (Bueno et al. 2013). Subsequently, 8 CFD calculations from cardinal orientations were performed for each urban model and post-processed by interpolating between simulated and actual wind orientations and adjusted for wind velocity at each hour using the IWECL climate file for Singapore—this results in an annual wind velocity profile following Mackey et al.’s (2017) method. EUI—including the annual energy consumption of cooling, lighting and equipment electricity—is estimated by using the morphed weather file and floor-level thermal zones. Than annual wind data was used to assess the ventilation of the urban environment and forms as a critical component of outdoor thermal comfort (UTCI (28°C, 20%) calculations included thermal modeling. Lastly, UDA (30%, 59%) results were obtained independently from the other calculations using the Urban Daylight interface developed by Dogan, Reinhart, and Michalatos (2012). These simulation flows will be explained in the further ‘simulation steps’ section explicitly.

Hypothetical urban geometry modelling
The urban model is situated on a 300 m x 300 m square flat ground plane, and it includes 14 rectangular buildings which have planted borders in the range of 1.6 – 2.4 m offset. The terrain includes three different sized public greenery areas (parks). The rest of the ground has been defined as pavement and sidewalks as shown in Figure 2. Figure 2 also illustrates the building functions, which consist of commercial-office (8 – yellow), residential (4 – blue), school (1 – purple) and restaurant buildings (1 – orange). The floor-to-floor height is 3 m for all buildings. On the other hand, the total building height was defined with three variant ratios to form a more realistic city context. The trees were created for two sides of most buildings and in recreational zones to find out the impact of greenery in urban design (Figure 2). Shading estimation is one of the primary elements of building simulations for daylighting and energy studies. Because of this common parameter, this paper includes shading elements as a building design parameter via a horizontal overhang depth in the range of 0.1 m to 1.5 m.

Range of parameters
Three parameters have been chosen relevant to the urban context: buildings, pavement, and greenery. Three building parameters have also been selected: window-to-wall ratio, horizontal shading, and material selection. Cheng et al. (2006) state in “Urban form, Density and Solar Potential,” that randomness of the urban fabric on a vertical and horizontal plane is beneficial while designing the urban form to gain more potential daylighting. Responding to this point, the selected parameters were expressed as a range to obtain varying sizes of building heights and green areas, also adding to the realism of the hypothetical city by avoiding formally monotonous buildings.
Figure 3 illustrates an urban model of various parameters: height, SCR, and GnPR, while Table 3 defines the parameters, their ranges and their number of alternatives sampled by the SA.

- **Building height** separates the buildings in three different height definitions as low, medium and high that changes depending on the range. The boundary of building height is in the range of 12 m to 156 m.

- **Site coverage ratio** defines the total building footprint area ratio to the total area of the ground.

- **Total green plot ratio** is defined as the ratio of total grass and planted coverage area on site (grass recreational plots and planted gardens around each building) compared to areas of hard pavement.

- **Shading depth** is the overhang depth for each direction of each floor as defined in the range of 0.1 m to 1.5 m.

- **Window to wall ratio** refers to the percentage of the glazed area relative to the entire facade area.

- For **Material selection** 2 variant elements were selected: wall insulation thickness and the window type (U-Value, Solar Heat Gain Coefficient, and Visible Transmittance). Wall insulation thickness is in the range of 0.01 m to 0.07 m. The thickness of wall insulation changes U-value indirectly to alter wall construction by increasing the R-value as insulation increases. In the SA presented herein, wall insulation and window quality increase and decrease in tandem as a standing for the total envelope material quality of the building.

**Figure 2. Plan sample of hypothetical model**

**Table 3. Simulated parameter ranges**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Range</th>
<th>Unit</th>
<th>Altern.*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Height (Height)</td>
<td>12-156</td>
<td>meter</td>
<td>6</td>
</tr>
<tr>
<td>Site Coverage Ratio (SCR)</td>
<td>10-22</td>
<td>%</td>
<td>7</td>
</tr>
<tr>
<td>Green Plot Ratio (GnPR)</td>
<td>18-36</td>
<td>%</td>
<td>5</td>
</tr>
<tr>
<td>Window to Wall Ratio (WWR)</td>
<td>0.2-0.9</td>
<td>%</td>
<td>8</td>
</tr>
<tr>
<td>Shading Depth (Shade)</td>
<td>0.1-1.5</td>
<td>meter</td>
<td>8</td>
</tr>
<tr>
<td>Material Selection (Materials)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Wall Insulation Thickness</td>
<td>0.01-0.07</td>
<td>meter</td>
<td>8</td>
</tr>
<tr>
<td>b) Window Material</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b1. U-Value</td>
<td>3.35-1.98</td>
<td>W/m²K</td>
<td>8</td>
</tr>
<tr>
<td>b2. SHGC</td>
<td>0.65-0.25</td>
<td>%</td>
<td>8</td>
</tr>
<tr>
<td>b3. Tvis</td>
<td>0.75-0.4</td>
<td>%</td>
<td>8</td>
</tr>
</tbody>
</table>

*Altern.*. The number of alternatives organized to match the sampling methods.

**Figure 3. Parametric model alternatives**
Sensitivity analysis

Sensitivity Analysis (SA) is a well-known analysis method for assessing the influence of input parameters on output results. Because of the extreme time commitment of individual calculations in this study, the Morris SA method was adopted to minimize the number of simulations required in obtaining a conclusion, following others (Morris 1991; Campolongo, Cariboni, and Saltelli 2007; Brembilla, Mardaljevic and Hopfe 2015). Fifty-six holistic urban performance simulations were calculated, their need illustrated by Equation (1) below,

\[ n = k(D + 1) \tag{1} \]

where \( n \) is the total amount of samples, \( k \) is the number of incremental sampling trajectories, and \( D \) is the number of input parameters. Each parameter was organized to achieve between 5 and 8 variant alternatives to match the sampling methods used in this paper (Table 3). With 8 trajectories and 6 input parameters, 56 simulations were required. SALib, a Python library for SA, was used for the sample selection and results analysis components of this study (Herman and Usher 2016). 56 full sets of simulation results were used to assess the relative impacts of design decisions on the selected urban performance measures.

Detailed simulation steps

As mentioned in the ‘urban design parameters’ section, 6 parameters—building height, site coverage ratio, green plot ratio, WWR, shading depth, and materiality—were selected to organize regarding the defined ranges deterministically in GH model as first. This section describes further computational details in achieving the results predicted in this paper: mean hourly UHI value, \( UTCl_{28C, 20\%} \), EUI, \( UDA_{300lx, 50\%} \), and mean wind velocity metrics.

- **Computational fluid dynamics model**
  
  CFD analysis was repeated 336 times to have wind speed values for each simulation alternative—6 building heights and 7 site coverage ratios from 8 cardinal wind directions. Post-processing described by Mackey et al. (2017) results in 8760-hours of spatial wind velocity data. The CFD analysis was run using the Butterfly interface to OpenFOAM (Jasak, Jemcov, & Tukovic 2007). The validity of the results was determined using a series of velocity probes showing that results stabilized between solver iterations in combination with a minimum normalized residual number for velocity and pressure which needed to be met.

- **Urban weather generator model**
  
  The Urban Weather Generator (UWG) creates a new meteorological weather data as an epw file for air temperature and humidity using a given original weather file, site context information, building thermal information, and construction details (Bueno et al. 2013). To estimate mean UHI differences, all parameters of the models except for horizontal shading were included in the UHI calculations. The urban parameters of Height, SCR, and GnPR were needed to calculate building separation, density, and the extent of greenergy available in the urban context. Building thermal information and WWR defines the cooling set points, material construction details, and WWR information in the Urban Weather Generator’s resistance-capacitance model.

- **Thermal energy and outdoor comfort models**
  
  Each floor of each building is modeled as a single thermal zone. The schedules and loads are defined for each type of building separately using reference values from ASHRAE standards (ASHRAE 2013). The construction materials were typical types selected from the OpenStudio material library (NREL 2018) except for the parametrized wall insulation thickness and window glazing details. HVAC systems are modeled as ideal air loads systems with a COP applied. The results of the thermal simulation are processed for the EUI results, and the hourly surface temperatures are used to generate exterior radiant temperatures (which are solar-exposure adjusted) as an input to the UTCI outdoor thermal comfort calculation, which also uses the urban air temperature and humidity data, and the hourly wind speed in its calculation following Mackey et al. (2017). Thermal and outdoor comfort calculations were run using Ladybug and Honeybee (Roudsari et. al 2013).

- **Urban daylight model**
  
  Urban Daylight (UD) is run accounting for the local shading geometry, urban trees, the building massing with a 3 m floor-to-floor height, and the designed WWR. The authors of the paper directly modified the UD input xml files to enable the visible light transmittance of window glazing materials as input. The UD model output is the percentage area of Urban Daylight Autonomy at 300 lx achieved for at least 50% of the annual occupied hours (UDA\(_{300lx, 50\%}\)), following the Daylit Area study of Reinhart, Rakha, and Weismann (2014). Urban daylight was calculated using the tool of Dogan, Reinhart, and Michalatos (2012).

Results and discussion

The results, shown in Figure 4, express the sensitivity of sustainable urban metrics (discussed in the Metrics section) to the 6 studied design parameters: Height, SCR, GnPR, WWR, Shade, and Materials. \( \mu^* \), illustrated by bar charts, is the mean of the absolute values of the parameter effects on each specific urban environmental performance model. The error bars illustrate the estimated confidence interval of the SA.

Although urban design elements such as site coverage ratio, density, and landscaping have expected effects on urban performance metrics, WWR and material properties also express a significant impact, as building design elements, on UHI, and urban temperatures are influenced by changing the building WWR. Less heat is absorbed from radiation-reflecting glass—higher WWR’s positively affect mean UHI values. At the same time such WWR’s have a negative impact on EUI. Increasing SCR values provides a benefit on the one hand to decreasing UHI values by decreasing the amount of asphalt pavement, and the enlarged building footprint areas decrease normalized cooling energy consumption.
The EUI chart shows that most design parameters have a balanced impact on energy consumption with GnPR having a lesser effect and material choice having a larger impact. EUI is influenced primarily by building design parameters (material, shade, and WWR) before urban context parameters such as SCR and GnPR.

Design impacts on urban daylighting potential (DA300lx,50%) shows WWR is the most significant design element for daylighting, which seems obvious. GnPR shows the weakest impact, small enough to be negligible due to trees only shading the bottom level of tall urban designs. On the other hand, material selection, site density parameters (Height and SCR), and exterior shading have a substantial impact on daylighting potential.

Urban ventilation SA shows that the building height and SCR are sensitive parameters for urban velocity analysis (Figure 4). This is logical as they were the only two parameters used in varying the isothermal CFD wind simulations. GnPR and the presence of trees may have an impact on urban ventilation speeds at the ground level but were not included in this study.

While local building shading elements were not included in the outdoor comfort calculations for this study, building height was the most dominant parameter on its impact on UTCI. Building height’s impact on the sensitivity of UTCI and mean velocity shows a noticeable similarity. The UTCI results illustrate that building design parameters (WWR and Material) are similar in their impacts when compared to the urban contextual parameters except for height.

The findings presented in Table 4 are the range of resulting metric values, which give the reader an idea of the variability within the parametric urban model employed in this study.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Range</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean UHI</td>
<td>0.435 - 0.6891</td>
<td>°C</td>
</tr>
<tr>
<td>UTCI30C,50%</td>
<td>0.0554 - 0.5019</td>
<td>% area</td>
</tr>
<tr>
<td>EUI</td>
<td>374.22 - 406.67</td>
<td>kWh/m²</td>
</tr>
<tr>
<td>UDA300lx,50%</td>
<td>0.0042 - 0.6685</td>
<td>% area</td>
</tr>
<tr>
<td>Mean Velocity</td>
<td>0.9397 - 1.322</td>
<td>m/s</td>
</tr>
</tbody>
</table>

**Figure 4. Sensitivity analysis of UHI, UTCI, EUI, UDA and Mean Velocity**

**Note:** For sensitivity analysis where the $\mu^*$ impact of a parameter is 0, that parameter was not included in the calculation models for the specific urban performance measure, usually due to a lack of feasibility in existing calculation tools.

**Figure 5. Normalized sensitivity ranking for metrics**

(* Only Height and SCR are investigated for Mean Velocity)
Figure 5 expresses the ranking of parameter sensitivities normalized in the range of 0-1. As seen in Figure 5, the model simulated demonstrates the building height is the most crucial design element to assess the sustainability performance of urban context. Globally, building height seems to have the strongest impact on the greatest number of outputs (mean velocity, UTCI, mean UHI, and urban daylighting potential). The Site Coverage Ratio (SCR) follows behind with large impacts on mean UHI and mean wind velocity. The other model parameters, in terms of their overall impact on the output measures, could be sorted as follows: WWR, material selection (MS), green plot ratio (GnPR) and shading depth (SD).

**Limitations and future works**

This simulated model has been run only for the tropical climate of Singapore due to the lengthy simulation time involved and space limitations in the paper. Other climates such as dry-cold and mild-marine types are intended for future analysis.

This study applied SA using 56 simulation models sampled across 6 design parameters; however, to conclude with more certainty (smaller confidence intervals), the amount of simulation runs should be increased. This brings attention to a natural limitation in the urban analysis—simulation effort and time. This study used approximately 32,000 GHz-hours of computation time to complete—the CFD and urban microclimate models took the lion’s share of simulation time. In addition, over 500 GB of output and temporary files were generated in the process. Checking this output for error and sanitizing it takes a significant amount of user effort.

It seems clear that urban performance analysis has real computational limitations that would benefit from improved computational strategies. To be applied during a design process, the current state of climate-based urban performance calculations are far too slow to be effective.

**Conclusion**

This study defines an approach to urban design parametrization and predicting several environmental performance outputs at the urban scale via a hypothetical model. The parametric modelling setup and analysis of outputs gives guidance about urban design for designers who may be seeking for areas to focus on. UHI, UTCI, EUI, UD, and CFD were estimated using a model parameterized broadly by 6 parameters gathered from an extensive literature review.

The Morris SA Method was used to evaluate the sensitivity ranking of parameters per each defined metric. Sensitivity analysis at the urban scale and across such a diverse range of performance metrics has not been undertaken before. Therefore, this study provides a more holistic assessment of urban environmental performance than is typically found in contemporary research, and it should provide new guidance to urban designers and building scientists alike.

Considering the ranking of sensitivities in Figure 5, this study infers that the dominant design parameter for the defined metrics is the building height. Regarding to wind potential, height overall has a positive impact on thermal comfort via speeding up wind flow. In addition, the shades created by increasing height demonstrates its importance for daylighting studies. EUl and UHI are influenced because larger building surfaces have sensitive interaction with air temperature and can store more heat.

Beyond these findings, the results shown in Figures 4 and 5 also suggest that many parameters are important. For example, to design for a reduced UHI, 5 of 6 parameters studied are balanced in their impact. Likewise, the impacts of most parameters on most models are at least somewhat significant. To enable better designs and retrofits of future urban spaces, it is critical that tools can efficiently utilize a complex set of performance factors, and it seems that reducing the parameters used in calculating sustainable urban measures is not warranted at this time, though the investigation can be guided by the results presented herein for tropical climates.

The authors wish to position this paper as a step forward in investigating environmental impacts of urban design considering many urban and building factors and the ways in which they contribute to several diverse measures of urban environmental performance—UHI, ventilation, energy consumption, comfort, and daylighting. Height and site coverage are illustrated as being of primary importance for many of the metrics tested; however, a variety of urban design parameters are still critical to consider when designing sustainable urban centres. In the future, faster computational tools are needed to enable designers to improve our cities without using incredible computers or spending long time periods waiting for results.

**References**


