Sustainable Cities and Society 114 (2024) 105779

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Climate-responsive urban planning through generative models: Sensitivity analysis of urban planning and design parameters for urban heat island in Singapore's residential settlements

Elif Esra Aydin[a,*], F. Peter Ortner[a], Song Peng[a], Anna Yenardi[b], Zebin Chen[a], Jing Zhi Tay[a]

[a] Singapore University of Technology and Design, Singapore
[b] Urban Redevelopment Authority (URA) Singapore, Singapore

ARTICLE INFO

Keywords:
Planning
Urban design
Performance simulation
Urban heat island
Sensitivity analysis
Correlation analysis

ABSTRACT

The Urban Heat Island (UHI) effect exacerbates the sustainability and well-being challenges of extreme heat events. While city planning and design measures have been shown to mitigate UHI severity, the complex interaction among these measures has limited the ability of previous research to assess their impact holistically and across urban scales. To investigate the cross-scalar effectiveness of multiple UHI mitigation measures, this study applies sensitivity analysis (SA) to nine parameters in an urban generative model. Previously unstudied planning parameters, land parcel area and road network density, are included in the analysis. From the SA of 21,000 model solutions for a 100 ha case study site in Singapore, building density, podium density, and land parcel area are found to have greatest impacts on UHI. This finding supports a hypothesis that urban planning parameters have a high potential for UHI mitigation. Key findings include that a high green plot ratio (>50 %) combined with a low site coverage ratio (<50 %) permits even high-density model solutions (gross plot ratio >4) to maintain annual UHI below 0.89 °C. The conclusion discusses the implications of the findings for heat-resilient city planning and demonstrates that performance-based evaluation of generative urban models can improve upon prescriptive planning approaches.

1. Introduction

Urban Heat Island effect (UHI) is a critical sustainability and public health challenge to cities throughout the world. It is associated with rapid urbanization and impacts a city's thermal and atmospheric characteristics (Oke, 1982; Stewart & Oke, 2012). UHI refers to the ambient air temperature increase observed in an urban settlement in comparison to its rural surroundings and is estimated to cause a 1.8 % increase in resident mortality for each 1°C increase above 28.2°C (Ho et al., 2023). UHI also intensifies urban sustainability challenges, inducing, for example, an increase in building cooling energy estimated at 19 % (Li et al., 2019). The IPCC emphasized in the 6th Assessment report that "current mitigation and adaptation actions and policies are not sufficient" to reduce the effect of UHI on cities (IPCC, 2023). Hence, sstudies of UHI mitigation strategies have been conducted addressing the numerous contributing factors and across a wide range of climates (Aflaki et al., 2017; Giridharan & Emmanuel, 2018; Qin et al., 2024; Rajagopal et al., 2023; Ramakreshnan et al., 2018; Zhang & Yuan, 2023). However, there is a need for research that can identify the most effective mitigation strategies across multiple, simultaneously interacting parameters in the planning and design of cities (You et al., 2023).

Key determinants of UHI, like urban mass, urban surface cover, and urban metabolism are emergent from the cross-scalar interaction of planning, urban design, and architectural design parameters (Soltani & Sharifi, 2017; Stewart & Oke, 2012). Studying these parameters in isolation (only in focus on architectural or urban design) is likely to lead to both incomplete results and partial understanding. Fig. 1, above, explicates the distinction between planning, urban design, and architectural design parameters as referenced in Table 2 and throughout this paper.

To investigate which planning and urban design measures most effectively mitigate UHI, this study applies sensitivity analysis (SA) to the key parameters of a large scale urban generative model. The term 'generative urban model' is used throughout this paper to refer to a computational urban model capable of iterating through many parameter combinations (see Section 2.2). This paper reviews existing

* Corresponding author at: Singapore University of Technology and Design, 8 Somapah Road, 487372, Singapore.
E-mail address: elif_aydin@sutd.edu.sg (E.E. Aydin).

https://doi.org/10.1016/j.scs.2024.105779
Received 8 April 2024; Received in revised form 22 July 2024; Accepted 26 August 2024
Available online 28 August 2024

regulations and implementations, related works, methods, and tools to identify a research gap in the cross-scalar analysis of planning, urban design and architectural parameter impacts on UHI mitigation.

1.1. Urban policy and research efforts for the mitigation of UHI

In response to the urgency of public health and sustainability challenges, government bodies in several global cities have sought to implement policies and planning guidelines to reduce the UHI effect and enhance climate resilience.

For instance, Singapore's the Ministry of Sustainability and the Environment (MSE) and the Urban Redevelopment Authority (URA) have collaborated on data-based, performance-driven policy recommendations since 2019 (Eveland [URA], 2023; MSE, 2021). Meanwhile, the New York City Planning Commission has approved zoning updates to support climate-change mitigation in 2023 (Carson, 2023; NYC zoning resolution, 2023). Furthermore, the European Commission and the European Environment Agency (EEA) have drafted the European Climate Adaptation Platform (Climate-ADAPT) targeting climate-informed policymaking and urban planning in European countries by 2050 (Climate-ADAPT, 2024a; 2024b). Stuttgart's climate-adaptive planning strategies exemplify preserving dense vegetation and wind corridors to reduce UHI and air pollution (EEA report, 2012).

Moreover, researchers have analyzed UHI mitigation strategies by using computational models to inform the development of policy. Regarding greenery-related regulations, Teo et al. (2022) analyzed Singapore's Green Mark certification for commercial buildings, skyrise greeneries, gardens, and national parks implemented in Singapore while Mehrotra et al., (2020) studied the correlation between urban built form parameters and land surface temperature in Mumbai. They suggest that multiple mitigation strategies reduced temperature increment percentage better than individual solutions (Teo et al., 2022) and policies controlling buildings and greenery can reduce thermal stress in local zones by reducing the land surface temperature (Mehrotra et al., 2020).

1.2. Overview of UHI prediction tools in research

Past research has used computational urban models to predict the contribution of key planning and urban design parameters to UHI. Current UHI prediction tools can be characterized as either stand-alone platforms or plugins for parametric design platforms.

Stand-alone UHI prediction tools (e.g., *Meteonorm tool, ENVI-met, STEVE tool*) are distinguished by their accuracy and comprehensive physics-based simulation capabilities (Bruse & Fleer, 1998; Jusuf & Hien, 2009; Meteonorm, 2024). They present limitations, however, in their ability to generate, test, and compare many different planning scenarios (e.g., Meteonorm) for annual simulations (e.g., ENVI-met) or hourly calculations in different climates (e.g., STEVE tools) (Aydin et al., 2019). In contrast, parametric design integrated UHI prediction tools like *UrbanMicroclimateFoam* tool (Kubilay et al., 2018) and *uhiSolver* (Urban Heat Island Solver) (Teichmann et al., 2021), enable designers to test many options in generative design workflows. However, they are computationally demanding due to their reliance on computational fluid dynamics (CFD) based UHI estimations.

Among contemporary plugins, Urban Weather Generator (UWG) was selected to use in this study due to its range of UHI metric estimation capabilities that use energy conservation principles (Bueno et al., 2013; Salvati et al., 2017), and for its relatively fast computation speed that permit the analysis of numerous large-scale urban design scenarios (Boccalatte et al., 2023; Chokhachian et al., 2020). Its user interface is applied within the Grasshopper parametric design platform (Roudsari-Pak et al., 2013), which makes it a highly compatible tool for generative modeling (Aydin & Jakubiec, 2018; Liu et al., 2024) as applied in this study.

1.3. Overview of sensitivity analysis methods in related work

Sensitivity analysis (SA) methods, in general, enable the systematic study of the relative impact of input parameters on a predicted outcome in a computational model (Gan et al., 2014). SA methods can provide parameter screening, effectiveness analysis, and uncertainty analysis (Saltelli & Sobol, 1995). The Sobol and Morris methods are the two global SA methods most frequently associated with environmental performance simulation in the computational urban models reviewed in Table 1, many of which, though not all, address UHI.

In designing the research protocol for this study, Sobol SA was selected over Morris SA due to three advantages. First, the Sobol SA quasi-random sampling method provides a more homogenous distribution and larger dataset to test for output performance metrics (Quaglietta & Punzo, 2013; Saltelli et al., 2019). Secondly, the Sobol SA method provides more in-depth analytic information on complex parameter/output interactions (Machard et al., 2023) through the independent effectiveness and uncertainty of each parameter (i.e., S_1 - first order effect) as well as the total order effects for each parameter which include interactions with the other inputs (i.e., S_T - total effect) (Kastner & Dogan, 2020; Saint-Geours et al., 2014;Şalap-Ayça et al., 2018). Finally, Sobol SA has been found to be "suitable for complex nonlinear and non-additive models" (Tian, 2013; Westermann & Evins, 2019).

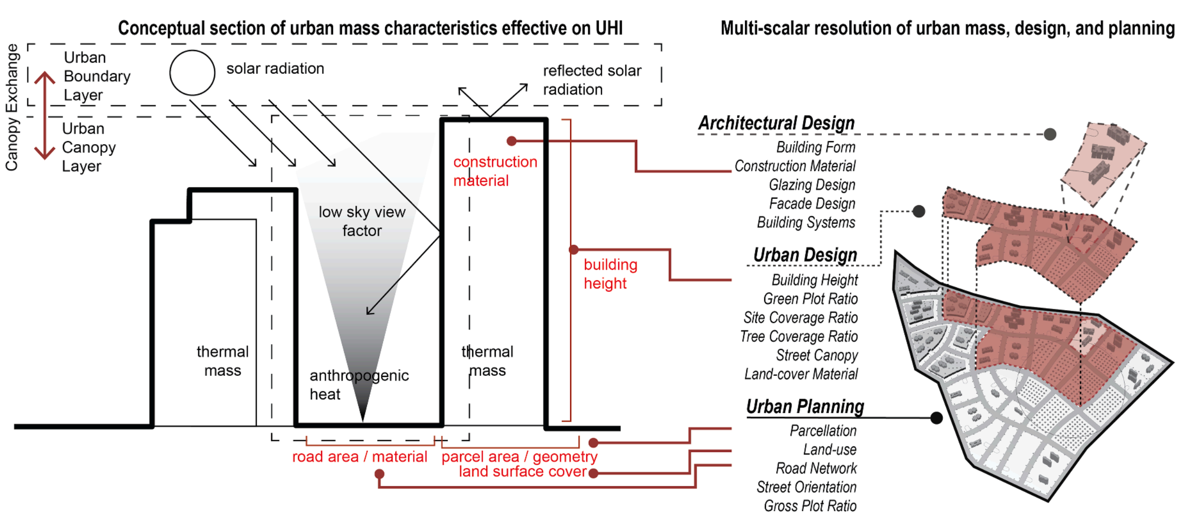

Fig. 1. Scales of design and planning parameters for UHI mitigation (section is adapted from Bueno et al., 2014; Soltani & Sharifi, 2017). Further details: Table 1 and Table 2.

Table 1
Summary of sensitivity analysis studies of environmental performance in computational urban models.

Reference	Scale	Climate	Performance Metric	Sampling Method	SA Method	Parameter Quantity	Total Sample
Machard et al., 2023	Building	Mediterranean and semi-oceanic	Building Thermal Behavior	Morris& Sobol	Morris and Sobol	19, 6, 6	650, 3000, 1600
Demir Dilsiz et al., 2023	Building	10 Climates**	Energy	Sobol sequence	Sobol	5	665,000
Yang et al., 2018	Building/ Micro	Tropical	UHI, Building Energy Balance (thermal)	Morris	Morris	6	NA
Vititneva et al., 2021	Precinct	Tropical	Solar Energy penetration	Quasi-Monte Carlo Saltelli	Sobol	3	280
Kastner and Dogan, 2020	Precinct	Warm summer	OTC	Sobol sequence	Sobol	4	100,000
Aydin and Jakubiec, 2018*	Urban	Tropical	UHI, OTC, UrbVen, EUI, UD	Morris	Morris	6	56
Maracchini et al., 2023*	Micro	Mediterranean	UHI	Sobol sequence, quasi-random	Sobol	25	26,624
Ren et al., 2023	Micro	Humid continental	UHI, CFD	On-site sampling	One-factor-at-a-time	3	38
Qi et al., 2021	Micro	Humid subtropical	UHI, UTCI, LST mortality, energy bills, economic productivity, cost.	Varying Parameters***	One-factor-at-a-time	4	10
Shi et al., 2020	Micro	Tropical	Energy (District Cooling)	Quasi-Monte Carlo Saltelli	Sobol	3	280
*Lemercier, 2019	Micro	Mediterranean	UHI and DI	Morris	Morris	10	161
Salvati et al., 2017*	Micro	Mediterranean	UHI	Varying Parameters***	One-factor-at-a-time	8	32
Mao et al., 2017*	Micro	Sub-tropical, Arid	UHI	Monte Carlo	Standardized regression coefficients	30	2000

* Studies using Urban Weather Generator (UWG) tool;.
** 10 ASHRAE Climate Zones: 1A, 2A, 3B, 3C, 4A, 4B, 4C, 5A, 5B, 6B
*** Manual variation of parameters to set the simulations. Scales: [*building*: 30 to 50 m, *precinct*: urban street canyon-50 m to 1 km; *micro-scale*: multiple building blocks including street canyon- 1 km to 100 km (Huang et al., and Spengler (2014); Mochida and Lun (2008); Murakami (2004), and Murakami et al., and Kim (1999))]; Performance Metrics: [*UHI*: Urban Heat Island, *OTC*: Outdoor Thermal Comfort, *UrbVen*: Urban Ventilation-CFD, *EUI*: Energy Use Intensity, *UD*: Urban Daylight, *DI*: Discomfort Index, *LST*: land surface temperature];

In the reviewed papers architectural and urban design parameters are more frequently studied than urban planning level parameters. A research gap for the analysis of the cross-scalar impact of urban versus architectural design parameters on environmental performance is identified based on the data presented in Table 2. Only two of the reviewed papers addressed the urban planning scale (Shi et al., 2020; Vititneva et al., 2021) and only a single paper studied environmental performance impact of design parameters across all three scales (Shi et al., 2020). Both studies at the urban planning scale used the Sobol SA method but did not apply this method to study the UHI effect. Model parameters selected from this review for further study in this paper are detailed in Section 2.3.

1.4. Research objectives

This study puts forward a methodology to investigate cross-scalar interactions between urban planning and architectural parameters on UHI in a large-scale generative model. Planning parameters, including parcel area and road network density studied poorly up till now, are hypothesized to provide UHI mitigation equivalent to or exceeding the impact of urban design parameters. This paper tests this hypothesis by determining the significance ranking of planning, urban design, and architectural parameters in a generative modeling case study and ascertaining the extent to which complex interactions between these parameters exert a significant impact on model outcomes. Consequently, this study intends to improve the understanding of how planning and urban design strategies can work synergistically to mitigate UHI, in particular for tropical rainforest climates represented by a case study in Singapore. Furthermore, the presented methodology aims to support the integration of generative urban design methods in evidence-based city planning and urban design processes.

2. Research methodology

The methodology employed in this study includes six steps required for modeling, UHI simulation, and result analysis (Fig. 2). After i) an initial site selection step, ii) the generative modeling phase provides land parcel, building, and greenery geometries. With the defined model parameters, iii) Sobol quasi-random sampling generates data variables and iv) UHI simulation is conducted for each sample. Subsequently, v) Sobol SA and Spearman correlation analyses (SCA) are applied to the results. Finally, vi) an evaluation step provides planning guidance for UHI mitigation based on these results.

2.1. Site selection and climate

The generative model has been applied to a site in Singapore, a city-state island located near the equator (1.35° N, 103.82° E), with a tropical rainforest (hot and humid) climate with two monsoon seasons annually (Meteorological Service Singapore, 2024; Peel et al., 2007). This climate is present in a broad region in Southeast Asia, as well as in Africa and the American continents. Singapore is classified as the third most densely populated country (Worlddata, 2024) with 8058 inhabitants per km^2 (DSS, 2023; NPTD, 2024). Most of the residents live in public housing, developed and managed by the Housing and Development Board (HDB) of Singapore. The HDB has committed to implement multiple new measures to mitigate UHI including increased integration of green open space for their high-rise, high-density new town models (BCA Green-Mark, 2021; HDB Green Towns Programme, 2023a; HDB Greenprint, 2023b). The selected site represents about 100-hectares residential district, 'Brick Land' (Fig. 3) of Tengah, the 24th new town in Singapore developed by HDB (HDB, 2016). It should be noted that the models and results presented in this paper do not constitute a planning study by HDB, URA, or any other Singapore government agency.

Table 2
Model parameters studied in three varying decision-making process and scale for sensitivity analysis evaluations of environmental performance in computational urban models.

		Architectural Design					Urban Design										Urban Planning				
Reference	Scale	Building Form	Construction Material	Glazing Design	Shading Design	Building Systems (HVAC)	Building Height [a]	Green Plot Ratio [a]	Site Coverage Ratio [a]	Footprint Ratio	Land-cover Material	Tree Coverage Ratio	Urban Morphology	Street Canopy	Traffic [b]	Climate [c]	Parcellation [d]	Land-use [d]	Road Network [d]	Street Orientation	Gross Plot Ratio [d]
Machard et al., 2023	Building		X	X	X	X															
Demir Dilsiz et al., 2023	Building	X														X					
Yang et al., 2018	Building/ Micro		X																		
Vititneva et al., 2021	Precinct	X																	X	X	
Kastner and Dogan, 2020	Precinct															X					
Aydin & Jakubiec, 2018	Urban		X	X	X		X	X	X												
Maracchini et al., 2023	Micro												X								
Ren et al., 2023	Micro										X					X					
Qi et al., 2021	Micro							X			X	X									
Shi et al., 2020	Micro	X							X	X				X			X	X			
Lemercier, 2019	Micro		X	X			X	X		X	X	X		X							
Salvati et al., 2017	Micro		X			X						X	X		X						
Mao et al., 2017	Micro			X		X	X	X		X	X	X	X	X	X	X					

[a] Defined upper or lower threshold boundary by regulations.
[b] Anthropogenic heat from vehicles.
[c] Climate, weather data variables (e.g., wind speed, solar radiation etc.), and atmosphere-urban context details.
[d] Defined by master planning codes and regulations.

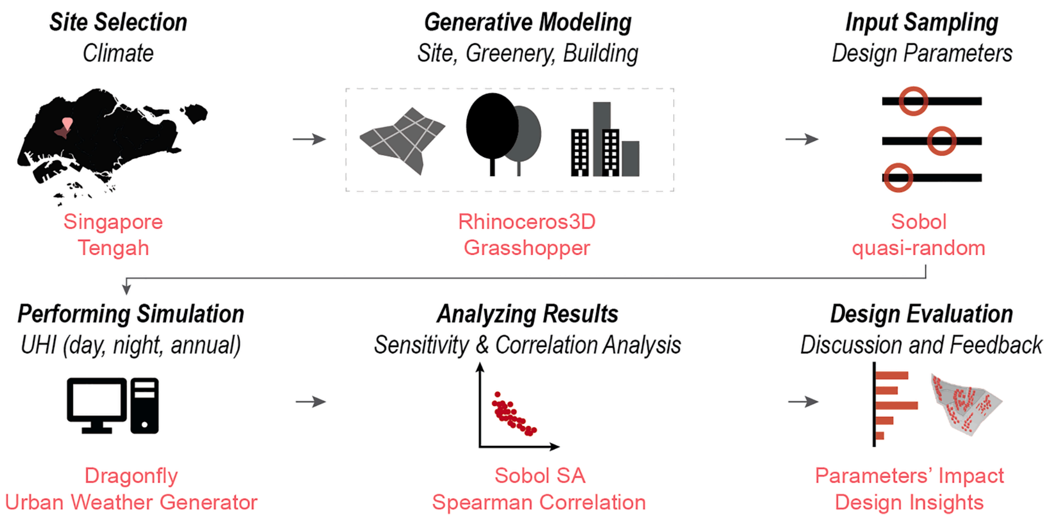

Fig. 2. Methodology flow.

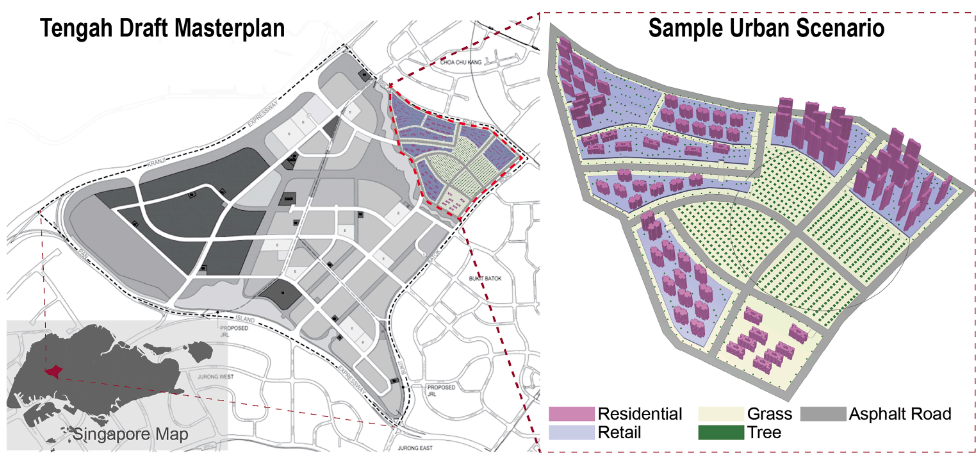

Fig. 3. Selected site and a sample model on draft masterplan (LTG, 2024; URA, 2024b).

2.2. Generative modeling

The generative model used for the study was created within the Grasshopper (GH) (Rutten, 2015) platform of Rhino3D (McNeel & Associates, 2024). Three linked computational modules generate the model geometries: i) parcel generation, ii) building generation, and iii) greenery generation (green park, green roof, tree allocation). The three generative modules have been developed by the research team for the

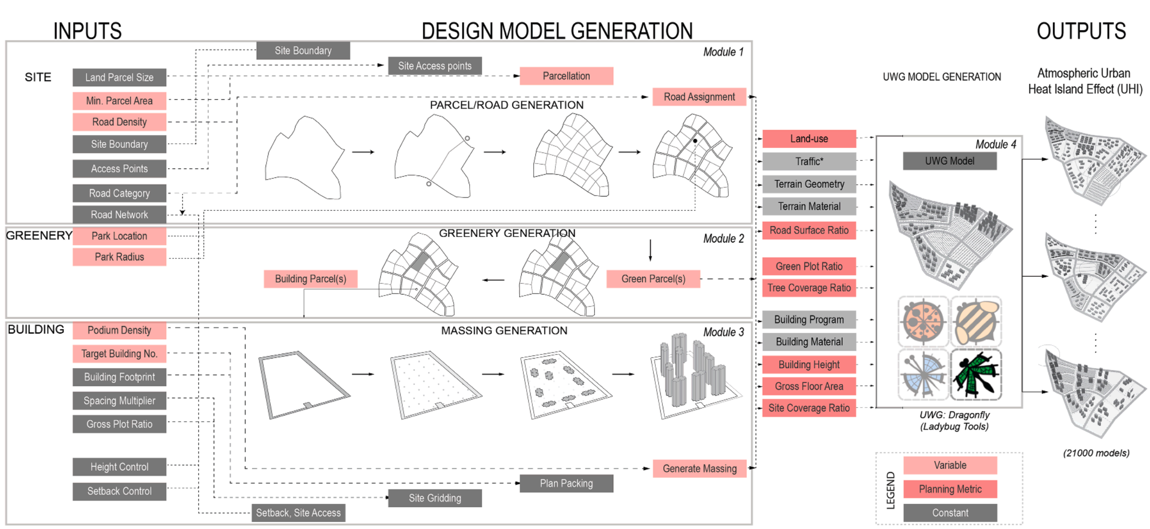

Fig. 4. Modeling steps (updated from Ortner et al., 2023a).

purpose of urban site simulation in Singapore and generate geometries constrained by the prevailing planning guidelines (Ortner, 2023a, Yenardi, & Zhi, 2023; Tay, Ortner, Song, Yenardi, & Chen, 2023). A fourth module integrates UWG and outputs the UHI simulation results. Fig. 4 illustrates these three generative model steps, as well as the UHI simulation step, with model parameters (variables). The set up and function of each module is described briefly below.

2.2.1. Site and greenery generation modules

The site generation module co-generates a road network and land parcel polygons in an iterative process of polygon splitting and geometry optimization. The process is initiated with a vector-field derived from the site boundary. Then, a range of streamlines is generated to split the site and subsequently derive land parcels as closed polygons (Yang, Wang, Vouga, & Wonka, 2013, Ortner et al., 2023b; Chen, Song, & Ortner, 2024). The geometric criteria used in generating the land parcels are edge smoothness, number of edges, internal angle, edge length, parcel area, and orientation (anonymous citation, 2024). Of these criteria, *parcel area* is defined as a model parameter in this study. In co-generating roads with the land parcels, all land parcels are accessible by at least one road along an edge of adequate size to accept a vehicular access point. Thus, the module selectively assigns some parcel edges as roads based on an accessibility assessment. *Road density*, the percentage of all parcel edges containing a road, is defined as a model parameter for this study.

The greenery generation module generates an urban park based on *location* and *radius* parameters (Fig. 5). Tree coverage at park spaces, along roads and on podium roofs is controlled by a single *tree coverage density* parameter (Table 3). A UWG model parameter switches the roof type from conventional to green roof.

2.2.2. Building generation modules

The building generation module generates, for each designated land parcel, high-rise high-density housing according to rules derived from planning guidelines and the characteristics of contemporary housing stock in Singapore. The module initiates land boundary setbacks based on the adjoining road categories and uses, defines a primary access point, and lays out building geometries based on the *building density* variable (Fig. 4, Table 3). Site setbacks, maximum building height restrictions, minimum spacing between buildings and floor-to-floor heights are automatically defined as model constraints following Singapore's prevailing urban planning guidelines (BCA, 2014; URA, 2024a; Ortner et al., 2023a).

Table 3
Variable model parameters, units, and value ranges (*Roof construction details are given in Appendix Table 2).

Parameter name	Range	Unit Description
Parcel Area	2.0 – 10.0	*Hectare* per parcel
Road Density	0.0 – 1.0	*Fraction factor* per site
Park Location	0 – 100x & 0 – 100y	*Coordinate* in the site
Park Radius	100 – 350	Radius *meter*
Tree Coverage Density	0 (none) – 9 (all)	*Percentage factor* per site
Building Density	2 – 20	*Number* of buildings per parcel
Podium Density	0.2 – 1.0	*Fraction factor* per site
Podium Height	4 – 12	Floor to floor height *Meter*
Roof type (C or G)	0 (Conventional) – 1 (Green)	material characteristics*

The layout algorithm samples a range of possible building footprints to achieve the configuration closest to attaining the target *building density*. Mixed-use podiums are generated for a portion of the site, with the model parameter *podium density* determining the percentage of sites with podiums, and a second model parameter controlling *podium height* (Table 3). The podium's floor area is added to the site total gross floor area (GFA value) and its' height increases the average building height.

2.2.3. Urban weather generator model

The generated urban fabric (i.e., land parcels and roads), buildings, green spaces, and trees are input to the UWG module for UHI simulation. A baseline Singapore weather data file (EnergyPlus Weather, 2024) was morphed to create a synthetic weather data reflecting the urban mass impact. A constant floor-to-floor height of 2.8 m and a window-to-wall ratio (WWR) of 24 % for residential buildings (BCA, 2014) and 50 % WWR for podiums (Bueno et al., 2014) were specified in the UWG module. The building programs were defined as high-rise residential for towers and as commercial for the podiums. Default materials settings were applied to all building envelopes in the model (Appendix A - Table 1) except for roof surfaces which can toggle between a conventional roof assembly and a green roof (Appendix A - Table 2). All roads were assigned as asphalt surfaces, and the remaining terrain areas (excluding building areas) were assigned as grass land surface. The road and green surface definitions permit evaluation of albedo (Liu et al., 2024) and material permeability effects of asphalt versus greenery

Fig. 5. Illustration of the minimum, average, and maximum values for seven of the variable model parameters.

material (Liu et al., 2021) in the model. Sidewalk surfaces and other non-road hardscape areas were neglected in this study.

2.3. Model parameter selection and sampling

The parameters selected for study in this paper were guided by the literature review (Table 2) while emphasizing capabilities of the site and building generation algorithms that have not been available to previous researchers. The generative modules described above permit the creation of a wide variety of options for urban design scenarios with a minimum number of parameters. In total, nine variable model parameters were selected for analysis of their impact on UHI and defined for the generative models as described above. Table 3 lists these parameters with corresponding range and unit details as illustrated in Fig. 5: parcel area, road density, park location, park radius, tree coverage density, building density, podium density, podium height, roof type.

The nine selected parameters are balanced across the three generative modules, with 2 addressing site generation, four addressing greenery generation and three addressing building generation (Fig. 5). These groups of parameters support analysis respectively of i) land-use, ii) greenery, and iii) urban mass (buildings) for impact on UHI (Jusuf et al., 2007; Li & Norford, 2016; Matthews et al., 2015). From this limited set of parameters, we obtain results that demonstrate variation across 12 of the 20 model parameters derived from the review of related works (Table 2). Interpretation of the results in terms of the expanded list of urban metrics is shared in Section 3.2. The 8 omitted parameters from the review of related works were excluded for being either too narrowly relevant to architectural design (glazing, shading, building system design), or exceeding the scope of the study (climate, traffic, land cover material, street canopy, and orientation.)

To the best of the authors' knowledge, the Site Generation variables (parcel area and road density) studied here have not been previously assessed for UHI mitigation strategies in a generative model. Land-use strategies for UHI mitigation are tested in the model by, (i) designating land parcels as either built or open green space, (ii) allocating building typology (i.e., residential as high-rise and commercial as podiums), and (iii) varying road density in relation to land parcel area. This study inspects parcel area and road density explicitly (as model parameters), while land-use and gross plot ratio (GPR) are indirectly examined in the results. Urban mass strategies are tested for UHI impact by varying building density (quantity and height) and including different typologies (high-rise tower with/without podium).

Greenery is tested in our model with four variables: (i) open green-space size (designated green park area), (ii) the location of green park effective on open space allocation in the site, (iii) tree coverage density, and (iv) green roof (either applied on the rooftop of all buildings or not). From variation in these parameters can further extract measurements of green plot ratio, tree coverage ratio, and green roof impact from the model.

2.3.1. Model sampling and simulation

For each variable model parameter 1050 samples were generated. This sample size was selected, based on the findings of Gan et al. (2014), as the minimum necessary to obtain meaningful results. The SALib code library (Herman & Usher, 2017; Iwanaga et al., 2022) was used to generate the input sampling list with a uniform distribution for the ranges defined in Table 3. The parameter ranges were normalized during sampling. To assess the first and total order indices, the Sobol quasi-random sequence equation (Eq. (1)) was employed, resulting in obtaining 21,000 data inputs (a combination across all parameters). In Eq. (1), N is the total number of sampling (21,000), k refers to the trajectories (1050), and p refers to the number of parameters (9) (Sobol, 1976).

Sobol quasi-random sequence Eq.:

$$N = k * (2p + 2) \tag{1}$$

All samples were generated in the parametric model and simulated for UHI. Three outcomes were derived from the UWG simulation: annual, daytime, and nighttime Heat Island Intensity. The UHI temperature increment was obtained by taking the yearly average dry bulb temperature difference between the reference and the newly morphed data for annual UHI (UHI_yr). Daytime UHI (UHI_d) hours were assigned between 7am and 7pm to reflect Singapore's equatorial climate, with the remaining hours assigned to nighttime UHI (UHI_n).

The simulation of the 21,000 urban models plus debugging took approximately 288 h (12 days) using parallel computing with 16 processors on a high-performing workstation (12th Gen Intel(R) Core (TM) i9–12,900 K, 3.20 GHz, Windows 64-bit operating system). Approximately 100 of the 21,000 urban model samples required additional time for manual debugging. The output data was postprocessed and visualized with RStudio (RStudio Team, 2020).

3. Results

This section presents and discusses the results of Sobol SA and SCA based on the 21,000 model samples tested for the UHI mitigation impact of the nine variable model parameters. These two complementary analyses support understanding of the importance of parameters in model outputs (Sobol) and interpretation of the correlation between model parameters and outputs (SCA). The Sobol SA provides an effectiveness ranking for each model parameter, with the first order index (S1) indicating the isolated parameter's impact on each UHI metric and the total order index (ST) indicating the interrelated parameters' impact on each UHI metric (Saltelli et al., 2010). Higher scores for both S1 and ST demonstrate greater impact. SCA results are presented alongside the Sobol SA results to aid in interpretation (Saltelli et al., 2019) by providing the effectiveness direction (positive or negative) and strength of correlations between model parameters and UHI metrics (see Figs. 7 and 9). Positive correlation refers to a parallel relationship, i.e., when a parameter value increases, UHI will tend to increase, or both will decrease. Negative correlation refers to an inverse relationship, i.e., when a parameter value increases, UHI will tend to decrease or vice versa. The observed correlations do not necessarily imply causation. Meanwhile, the strength of coefficients can be interpreted as the magnitude of the parameters' impact: +1.0 and -1.0 are the strongest, while 0 is the negligible impact (Schober et al., 2018). This result section highlights which parameters have the strongest impact on UHI metrics and which action with these parameters can most effectively mitigate UHI based on these correlations.

The Sobol SA results are summarized in Table 4. Fig. 6 further illustrates the Sobol SA results with color-coded bar charts representing S1 and ST for each performance metric. The podium height, roof type, and tree coverage density parameters were excluded from Fig. 6 as they produced no observable impact based on Table 4.

Table 4
Sobol first (S1) and total (ST) indices of each model parameter for each performance metric.

Performance	Annual UHI		Daytime UHI		Nighttime UHI	
Sobol Index	S1	ST	S1	ST	S1	ST
Building Density	0.224	0.424	0.212	0.370	0.232	0.517
Podium Density	0.290	0.382	0.357	0.468	0.182	0.245
Parcel Area	0.095	0.370	0.071	0.301	0.133	0.495
Park Radius	0.022	0.080	0.026	0.090	0.014	0.065
Park Location	-0.002	0.070	0.000	0.078	-0.004	0.059
Road Density	-0.002	0.047	-0.004	0.051	0.002	0.040
Tree Coverage Density	0.000	0.000	0.000	0.000	0.000	0.001
Roof type (C or G)	0.000	0.000	0.000	0.000	0.000	0.001
Podium Height	0.000	0.000	0.000	0.000	0.000	0.001

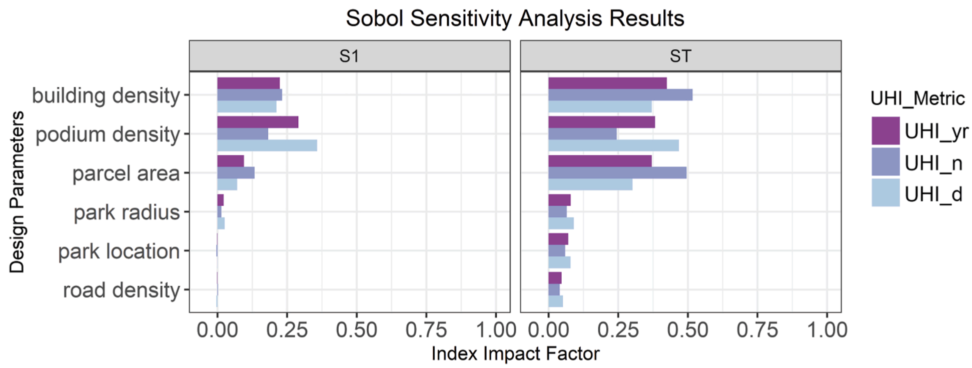

Fig. 6. Sobol Sensitivity Analysis Results. Left column: first order index (S1), and right column: total order index (ST).

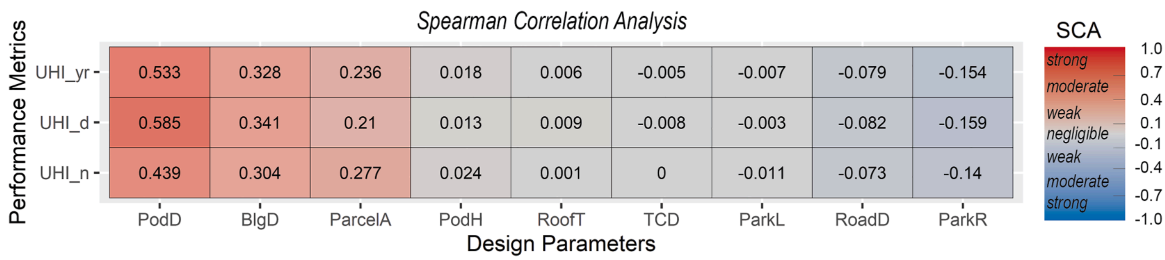

Fig. 7. Spearman correlation analysis (SCA) between all model parameters and UHI performance metrics (coefficient strength interpretation taken from Schober et al., 2018).

3.1. *Sensitivity and correlation analysis results*

The SA first order (S1) and total order (ST) indices demonstrate that three most effective parameters are building density, podium density, and parcel area across all UHI performance metrics (Fig. 6). For UHI_n (ST), which takes into account complex interactions with other model parameters, parcel area has a greater effect than podium density in comparison with UHI_n (S1) (Table 4). Parcel area is observed to have a stronger impact on UHI_n (S1&ST) than on daytime UHI (UHI_d); this is the reverse of podium density which is observed to impact UHI_d more than UHI_n (Fig. 6).

Park radius, park location, and road density are observed to be the weakly impactful parameters, particularly in their interaction with other parameters as evidenced by the ST results (Fig. 6). Park radius shows weak effectiveness in S1; however, park location and road density parameters are more effective in ST than S1.

The results from SCA align closely with the Sobol's first index (S1) SA results, with order of podium density (PodD), building density (BlgD), and parcel area (ParcelA) showing the stronger (mostly moderate positive) correlations with UHI_yr (Fig. 7) compared to other parameters. Increasing density and parcel area, therefore, tends to increase UHI metrics. Park radius and road density parameters follow them in the ranking with weak negative correlations. This negative correlation indicates that increasing green area and roads in a site may result in minor a reduction in UHI metrics. The other parameters (e.g., podium height, park location, roof type, and tree coverage density) indicate negligible correlations.

Fig. 8 illustrates the most five effective parameters and highlights some extreme and moderate scenarios. The scatterplots visualize the positive trends between podium density, parcel area, building density and UHI, while park radius and road density model parameters represent weak correlations with more even solution space distributions. In Fig. 8, 8681 models result (green) with larger green space areas (GnPR > 0.5) and lower building density (0.2 < SCR < 0.5) were observed to result in a UHI_yr between 0.57 and 1.03 °C. The range of GnPR and SCR values selected for highlighting in Fig. 8 is inspired by Singapore's building regulations which control both site coverage and green plot ratio (URA, 2024c).

Podium density: As shown in Fig. 8.a1 the lowest range of the podium density parameter (20 to 40 %) results in UHI outcomes between 0.49°

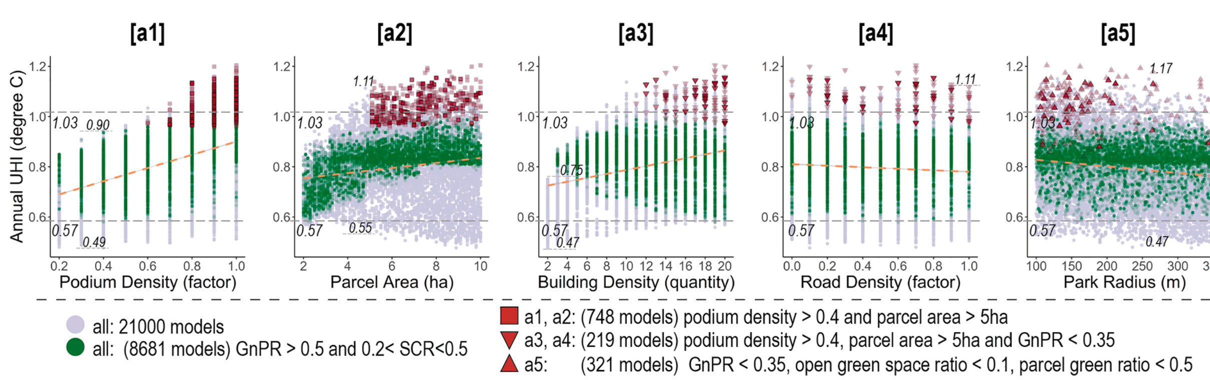

Fig. 8. Scatterplots of most impactful parameters with optimum and extreme case scenarios.

and 0.90 °C UHI. In the denser podium settlements with 50 % to 100 % podium density, the UHI outcomes are both higher and larger, ranging between 0.49° and 1.20 °C.

Parcel area: Smaller values for the parcel area (< 5 ha) parameter result in a narrower range of UHI impacts (0.55 to 1.11 °C). Larger parcel areas (>5 ha) were observed to result in a larger range of UHI outcomes (ranging 0.47 °C degree up to 1.20 °C degrees UHI) (Fig. 8.a2). While increasing the parcel area parameter on average resulted in an increase in UHI, well-performing model solutions with larger parcel areas were observed.

Building density: Higher building densities (10–20 buildings per parcel) are associated with a higher UHI value range (0.57 to 1.20 °C UHI_yr). Less dense settlements (2 to 8 buildings per parcel) resulted in a range of 0.47 to 1.03 °C UHI_yr (Fig. 8.a3). It should be noted that the lowest UHI value range (0.47 to 0.75 °C UHI_yr) was obtained with the '2 building per parcel models' (Fig. 8.a3) which due to their extremely low density do not represent common urban design solutions.

Park radius: Park radius was identified as the dominant green-space parameter by both the SA and the SCA, with larger park radius (> 250 m) contributing significantly to lower UHI outcomes (0.47 to 1.17 °C UHI_yr). Fig. 8.a5 expands upon this observation by demonstrating that even very low park radius values (>100 m) can still result in low UHI values if overall green space level remain high (measures as Green Plot Ratio, see Section 3.2).

Road density: The weak negative correlation between road density and UHI, as shown in Fig. 8.a4, is observed to be the result primarily of a narrowing of the range of UHI results. The upper limit of UHI results decreased from 1.20 °C to 1.11 °C as road density increases. Low UHI results can be found at all road density values, despite the observed negative SCA.

3.2. Results interpretation with common urban planning metrics

In this Section, the 21,000 model samples are further interpreted with six common urban planning metrics that are commonly associated with UHI: gross plot ratio (GPR), gross floor area (GFA), site coverage ratio (SCR), green plot ratio (GnPR), and average building height (BH). This analysis assists interpretation of the results by planning professionals and provides additional insights that support design and policy decisions. Four additional UHI-specific metrics are also studied: road surface ratio (RoadSR), tree coverage ratio (TCR), green roof ratio (GnRf), podium ratio (PodR). A detailed definition of each metric is provided in Appendix B.

The SCA results for all eight planning metrics versus all UHI performance metrics are presented in Fig. 9. The strong positive correlation between GFA and SCR is an expected result, confirming the link between development density and UHI. PodR and GPR also show strong positive correlation with all UHI metrics, in alignment with the Sobol SA results which evidenced a high impact of podium density and building density on increased UHI. In short, any increase in GFA, GPR, commercial type podium density, and site coverage ratio within a site has a high tendency to increase UHI. These findings reinforce the understanding that very dense settlements without mitigation strategies will experience more pronounced UHI.

The strongest negative correlation is shown for GnPR: strong correlations with UHI_d, UHI_yr metrics and a more moderate correlation with UHI_n metric. Accordingly, our results show that increasing the greenery in an urban settlement in tropical climate is among the most effective UHI mitigation strategies. RoadSR and TCR demonstrate weak negative correlations with all UHI metrics. Green roof ratio, though it shows a weak positive correlation with UHI, can be considered as having negligible impact on UHI given its low Sobol ST value. Building height indicates no/negligible correlation with UHI.

The six urban planning metrics most strongly correlated with UHI are further analysed in Fig. 10 (a1 to a6). The scatterplots indicate that none of the planning metrics have an entirely linear relationship with UHI. Interpreting linearity with regression lines for each parameter gives insights about the range of possible solutions and supports later discussion of potential mitigation strategies for UHI (Fig. 10.a1-a6). Fig. 10 also provides 15 sample results selected out of the 21,000 models, organized with respect to the parcel area and podium density model parameters. These 15 samples provide a visual aid to understanding the range of samples produced by the urban model (Fig. 10.b1-b15).

A non-linear relationship between a model parameter and output is observed as the modeled results get denser due to higher GPR, GFA, and SCR. This density change results in a non-linear UHI_yr increase, with samples falling increasingly above the linear regression line (Fig. 10.a1, a2, a3 & models b6, b12, b15).

GnPR also exhibits a non-linear relationship to UHI in our results. While GnPR overall exhibits a negative correlation with UHI (Fig. 8), in Fig. 10.a4 results with very high and low GnPR diverge from the regression line. Results with the lowest GnPR (>0.4) fall consistently above the linear regression line, and thus exhibit worsening UHI performance (Fig. 10.a4 & models b12, b15). This result is supportive of planning regulations that provide a lower threshold (around 0.4) for greenery ratios in an effort to limit the UHI increment.

Results plotted for BH versus UHI show an inverted U-shaped distribution, peaking at the center of the value range (Fig. 10.a5 & model b15), and falling to either side. This result distribution indicates a potential for tall developments to achieve relatively good UHI outcomes when combined with larger open green spaces (Fig. 10.a5 & models b4, b7, b13).

Lastly, the TCR scatterplot shows a clear decrease in the highest range of UHI outcomes as TCR increases (Fig..a6). Accordingly, although increasing tree canopy is a generally associated with UHI mitigation in our model, our results only support this up to a certain point (TCR < 0.6). Furthermore, as sensitivity analysis showed negligible impact of TCR on UHI outcomes (Table 4), further study is needed to clarify its impacts on UHI and benefits as a mitigation strategy.

The selected model solutions visualized in Fig. 10 provide further evidence of complex interactions between urban planning, urban design, and architectural factors in mitigating UHI. As both parcel area and podium density are positively correlated with UHI_yr, there is a tendency for the lowest parameter values (i.e., lowest density) to result in lower UHI_yr (Fig. 8). However, among the 15 results shown in Fig. 10, there is considerable variation from this trend. For instance, although models b3 and b11 have parcel area values of 2 ha and 8 ha respectively (as well different podium density and park radius values)

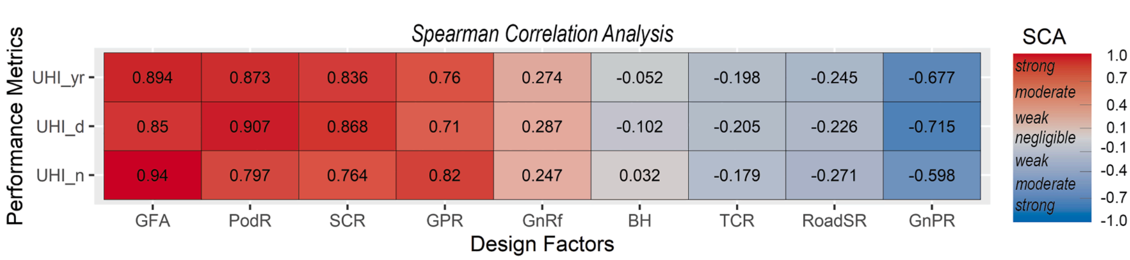

Fig. 9. Spearman correlation analysis (SCA) for planning metrics and UHI metrics (coefficient strength interpretation from Schober et al., 2018).

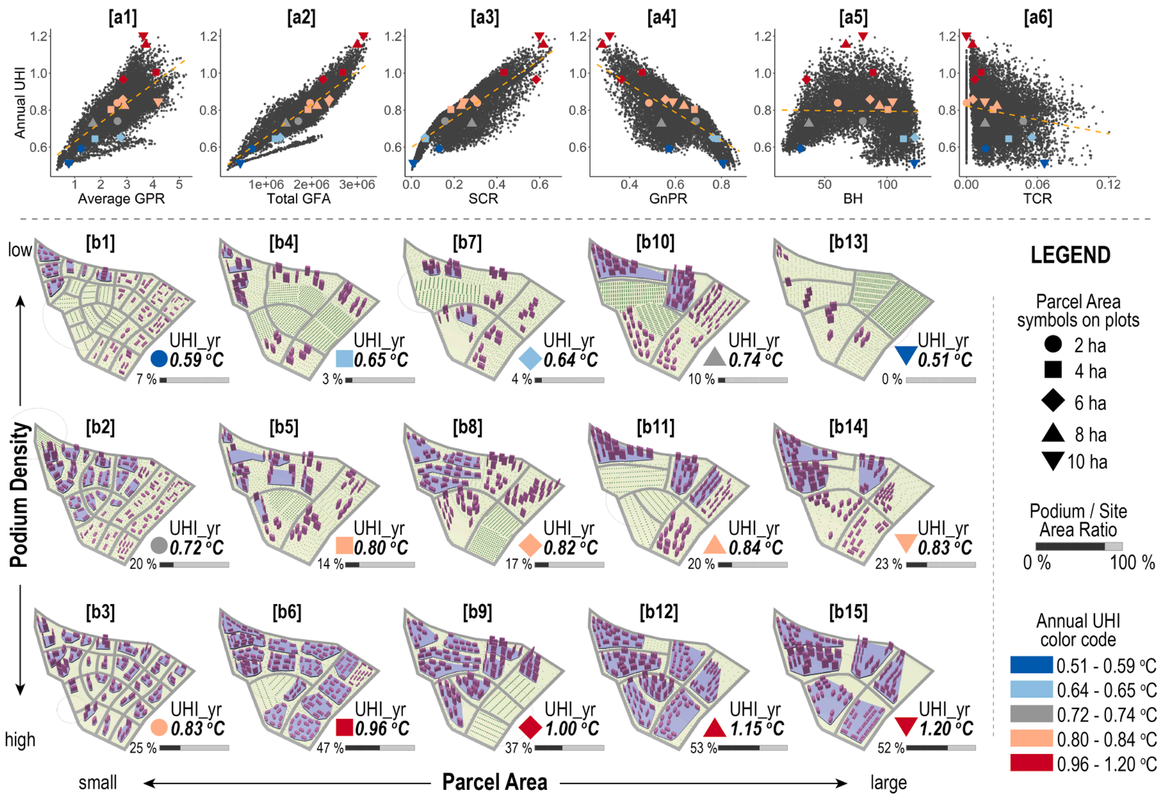

Fig. 10. Result visualization through urban planning metrics versus UHI_yr presented on scatterplots with their representative models.

they differ by only 0.01 °C UHI_yr. Larger parcel areas (8 ha: models b10 to b12; 10 ha: models b13 to b15) are observed to have a wide variety of UHI_yr results. This result may reflect that larger parcels have a wider range of building and greenery-related outcomes which can pre-determine their possible mitigation impact for UHI (Fig. 8).

3.3. Discussion

The results of the generative model sampling and analysis reveal strong trends between urban planning parameters and UHI mitigation (Section 3.2). Building density, podium density, and land parcel area were found to be the most impactful parameters on UHI levels respectively (Section 3.1). This finding, particularly the parcel area impact, supports the initial hypothesis driving this study: that urban planning parameters would present stronger UHI impacts than architectural or urban design parameters as studied within a generative urban model. The evidence of complex interaction between planning, urban design, and architectural parameters on UHI outcomes in this model, however, suggests that future research should define UHI as integrative multi-scalar planning and design approach.

The results further indicate a clear hierarchy of the most impactful urban planning metrics for UHI, with building mass factors (e.g., gross plot ratio, site coverage ratio, gross floor area) found to be more effective than terrain factors (e.g., green plot ratio, tree coverage ratio) in impacting UHI effect. This result aligns well with previously studied Morris SA for UHI in the Singapore context (Aydin & Jakubiec, 2018).

The primary aim of generating 21,000 scenarios is to produce a wide range of design solutions to support a comprehensive sensitivity analysis of the model parameters impact on UHI. As sensitivity analysis results, this set of scenarios necessarily includes extreme solutions which would present impractical urban design solutions. Although the extreme cases exemplified in Fig. 10.b1, b12, b13, b15 scenarios (with the lowest or highest UHI) should not be interpreted as suggested urban designs, to they do support improved understanding of model parameters' ranking and impact on UHI (Figs. 8 and 10). Furthermore, these extreme cases provide valuable tests of common planning metrics' association with UHI. While few cities will choose to put in place a GnPR above 0.8, our results do address this range and suggest that there are diminishing returns in UHI mitigation at these high levels. This result, as one example, can be helpful to planners and citizens to understand the limitations of UHI mitigation measures. A filtered range of more moderate and directly planning-relevant solutions are presented in Fig. 11 below for further discussion.

The wide range of results and the non-linear relationship between parameter values tested and UHI metrics suggest that the results of the study must be interpreted carefully with regard to any policy or design recommendation. Given the complexity observed in the model results, there are three urban metrics which may benefit from a performance-based planning approach to UHI mitigation instead of prescriptive planning controls.

1. Urban density, strongly correlated with UHI, presents an increasing range of UHI outcomes as density rises (Fig. 10.a1 to a3). This relation between density and UHI has been found in separate studies of the mediterranean climate when analyzed with urban morphology parameters (i.e., building height, site coverage ratio, façade-to-site ratio) (Salvati et al., 2017) and also of the oceanic climate analyzed with respect to development floor area ratio (FAR) (Chokhachian et al., 2020). Prescribing a maximum density would therefore likely exclude high density results with well-performing UHI. Instead, site specific density recommendations could be obtained by implementing generative urban models during planning phase.
2. The capacity of open green space to mitigate UHI was found to be the result of multiple model parameters (Fig.8.a3; Fig. 10. a4, a6). As suggested previously by Teo et al. (2022), performative planning could allow a range of green space mitigation strategies, balancing public green space with private green space and tree coverage, without requiring minimum levels for any single parameter or

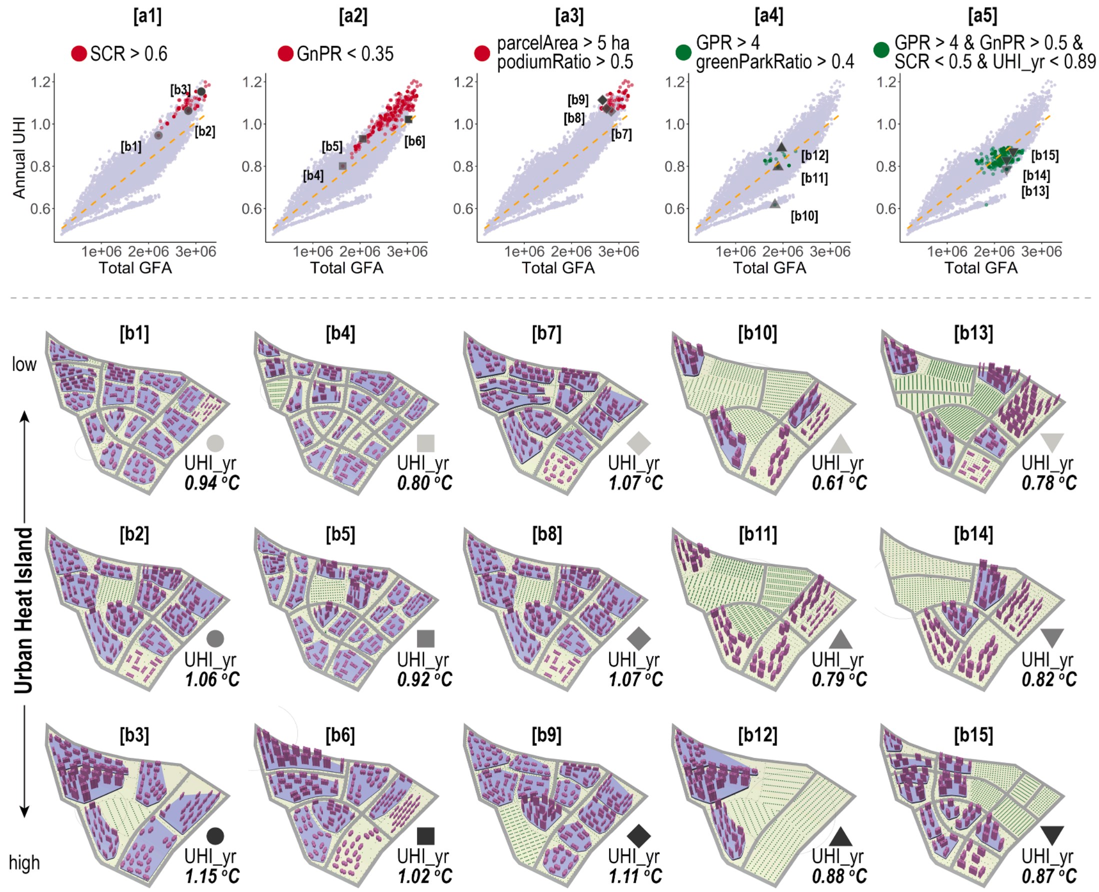

Fig. 11. Filtered design solutions for detailed discussion.

metric. Although our findings show a negligible relationship between the green space location with UHI metrics (Fig. 7.ParkL parameter), we note that the potential cooling effect of greenery location was emphasized when assessed in combination with wind speed and direction by Ren et al. (2023) and would thus require further attention both in future research and planning. The green roof parameter's weak correlation and negligible effectiveness for annual UHI observed in our study is supported by the findings of Yang et al. (2018) and may thus merit less emphasis in planning efforts to mitigate UHI.

3. Building height was found to interact complexly with UHI in association with other planning metrics and produced well-performing results even in its very highest ranges (Fig. 10.a5, b4, b7, b13). This result is meaningful for planning and urban design in spite of the weak correlation observed in this study and also supported by Aydin and Jakubiec (2018). Prescriptive limitations on building height would prevent identification of low UHI but very tall (and moderately dense) development scenarios.

Three parameter ranges or parameter combinations produced especially high UHI outcomes and can be highlighted as requiring careful scrutiny in UHI sensitive city planning. Fig. 11 visualizes filtered parameter combinations (a1-a5) and their representative urban design scenarios (b1-b15) for the following four points.

1. High site coverage ratios (SCR > 0.6) result in UHI outcomes that fall far above the trend-line as shown in Fig. 10.a3 & b12, b15. A total of 102 scenarios fell in this range and resulted in a UHI_yr range between 0.94 and 1.19 °C (Fig. 11.a1, b1-b3). In UHI sensitive planning this SCR range could be subject to special scrutiny or controls.
2. Low green plot ratios (GnPR < 0.35) obtained in 328 scenarios resulted in UHI outcomes with a range of 0.80 – 1.20 °C, which is above the trend line as shown in Fig. 11.a2, b4-b6. This finding is related to point 1 above, and similarly could be used to identify urban developments that would require special scrutiny or control to avoid poor UHI performance.
3. The combination of large parcel area (>5 ha) with large podium area (> 0.5) (111 scenarios) resulted in UHI values from 1.05 up to 1.20 °C (Fig. 11.a3, b7-b9). Planning controls and design strategies should seek to avoid these results.
4. While GPR shows a high positive correlation with UHI, we found that high density settlements (GPR > 4) can still result in UHI of below 0.89 °C. These dense results with moderate UHI were associated with large open green spaces (park space >40 % of site area), as observed in 35 scenarios in this study (Fig. 11.a4, b10-b12). Additionally, dense (GPR>4) and moderate UHI (<0.89 °C) results were observed in 343 out of 21,000 results when high green plot ratio (>50 %) was combined with low site coverage ratios (<50 %) (Fig. 11.a5, b13-b15).

3.4. Limitations and future work

This study is relevant for tropical rainforest climates, as typified by the case study site of Tengah, Singapore. The tropical rainforest climate spreads around the equator from Southeast Asia towards Africa to South America (Kottek et al., 2006). As Singapore is one of the representative locations for this climate, this study can be an applicable particularly to similar built environment contexts in Southeast Asia, and the suggested method can be replicated for other climates. Additionally, this study focused exclusively on atmospheric urban heat island to the exclusion of the nonetheless significant topic of surface urban heat island (Amorim et al., 2021).

To improve the accuracy of the UHI results and to obtain real-world planning and design scenarios, two strategies were applied: (i) using a generative model developed with Singapore specific regulations for site and building generations and (ii) applying the UWG prediction models' validated setups. Therefore, for other climates, urban models and architectural design regulations should be associated with the local governmental policies to provide site-specific sustainable solutions for cities. The developers of the UWG prediction model have a previously demonstrated accuracy of maximum RMSE 1.6°K and MBE 1.0°K for the Singapore neighborhood scale (Bueno et al., 2014). The detailed settings implemented in this study replicate the Bueno et al. (2014) set up, with full information provided in the appendices.

Considering the social and planning practices implications of the use of generative urban models represents one area of future work that may extend from the current study. The models presented in this paper have been developed specifically to assist urban planners in scenario creation and in understanding complex interactions between desired UHI outcomes and planning and urban design parameters. However, a number of challenges to the successful integration of generative modeling in the process of city design have been addressed in other publications (Baker et al., 2006; Oxman, 2008; Shi, 2010; Shi, 2024). These have investigated the extensive work needed to support trans-disciplinary collaboration between scholars, governmental agencies, and other stakeholders. Challenges to future work in this area include assisting urban planners to generate and assess very large datasets from urban models and including assessments of the social impacts of model recommendations including large-scale changes to the types of urban parameters explored in this study.

Additionally, future work should explore the UHI impact of planning and urban design parameters in other climates with the objective of attaining 'zero UHI impact' designs including assessments of energy efficiency, carbon emission reduction and indoor environmental quality improvement (He, 2019). Similarly, the building generation module was limited to Singapore's building height and site offset planning regulations. Including other environmental performance metrics in the analysis of the generative model may permit a more holistic understanding of sustainable planning and urban design.

Finally, the finding of a small but negative correlation between road density/ RoadSR and UHI should be reanalyzed. As other studies have found a significant effect of anthropogenic heat flux from buildings and traffic on UHI (Karimimoshaver et al., 2021; Quah & Roth, 2012), further study of the anthropogenic heat flux resultant from the expanded road and traffic network as well as its land cover material impact on UHI is needed.

4. Conclusion

This study investigates the impact of planning and urban design parameters on UHI for Singapore's tropical climate using a cross-scalar generative urban model. Nine model parameters were analyzed with Sobol SA and SCA to define the most and least effective parameters, and their corresponding impact on UHI.

Sobol SA demonstrated that planning parameters (e.g., parcel area, open green space size, and road density) are as effective in mitigating UHI as urban design parameters (e.g., podium density, building density). As UHI outcomes are the result of complex interactions between planning scale and urban design scale parameters, it is recommended that future research on UHI mitigation seek to span this divide. Furthermore, the results demonstrate a wide range of UHI outcomes even at extreme parameter values, suggesting that prescriptive planning that sets maximum density or building height controls may prevent discovery of well-performing scenarios. Performative planning, using extensive design space exploration and simulation, can be inferred to better support the achievement of dense and relatively low UHI urban scenarios.

CRediT authorship contribution statement

Elif Esra Aydin: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **F. Peter Ortner:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Song Peng:** Methodology, Software. **Anna Yenardi:** Writing – review & editing, Software, Methodology. **Zebin Chen:** Writing – review & editing, Software, Methodology. **Jing Zhi Tay:** Writing – review & editing, Software, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

This work was funded by the Urban Redevelopment Authority, Singapore, as part of the project *Computational Modelling for Optimisation of Planning and Urban Design Parameters* [grant number: RGURA2101].

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2024.105779.

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