Design Optimization of Dense Urban Neighbourhood with Computational Simulation and Genetic Algorithm for Improving Outdoor Thermal Environment

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Abstract
The outdoor thermal environment is of growing concern in the urban planning and design field, especially in tropical/subtropical regions. The layout and design of urban neighbourhood may have significant environmental impacts. Although computer simulation has been increasingly used to assess outdoor thermal conditions, it is yet to be fully adopted by practitioners in design thinking and processes. This paper proposes a design optimization method to reduce outdoor heat stress and increase the thermal comfortable area in urban spaces. The thermal comfort simulation software CityComfort+ is linked with genetic algorithms to optimize the thermal conditions of open space defined by a cluster of buildings. The method is tested with a hypothetical case in Hong Kong. The algorithm is able to identify high-performing design schemes within a reasonable period, given the site and project constraints. The method can be useful for practice and the further development of simulation-based optimization methods.

Key Innovations
- A simulation-based optimization method that integrates a thermal comfort simulation tool and genetic algorithms is proposed and tested to guide the design process of a hypothetical case of a subtropical high-density city.
- The proposed method can bring significant microclimate benefits in high-density cities at the early design stage.
- The proposed workflow can facilitate the application of computer simulation in urban design practice to reduce heat stress in open spaces.

Practical Implications
The method can be a useful tool to support early-stage design decisions. It can improve the ability of design participants to identify optimal design solutions to mitigate heat stress in high-density development modes. It also demonstrates the potential of smart design in achieving microclimate benefits.

Introduction
Hong Kong, a typical high-density city, accommodates over 7.5 million residents in an area of 1107 km² by the end of 2019 (Census and Statistics Department, 2019; Lands Department, 2020). The compact development brings about negative impacts on urban microclimate. The “wall effects” of high-rise buildings can block natural air ventilation (Wong et al., 2011) and lead to an increase in localized air temperature (Lau & Ng, 2013). The air temperature in the street canyons can be 4-6 °C higher than in rural areas (Nichol, 2005). Located in a subtropical climate zone, weak wind and stagnated air affect outdoor thermal comfort and air quality in the urban area of Hong Kong (T. Huang et al., 2017; Ng et al., 2011). Previous studies conclude that outdoor thermal comfort will be affected by building arrangement such as building height, building density, building orientation, etc. (Lan & Zhan, 2017; Li & Liu, 2020). Therefore, designers need to take the thermal environment into account when making design decisions. At the same time, optimizing the layout and design of buildings is conducive to reducing the negative impacts on the environment.

Many studies suggest appropriate urban design could improve urban microclimate (Du et al., 2018; Ng et al., 2011). Two main approaches to study urban microclimate are field measurements and computational simulations. The measurement method can provide accurate evaluation results, but only at limited sensor locations. The computational simulation is more popular because it can investigate the entire site, allowing comparative analyses of different design scenarios; and it is more flexible (Aflaki et al., 2017; Ng et al., 2011; Toplarlar et al., 2017). However, simulation tools are rarely applied to assist early-stage design, mainly due to computational complexity and high technical requirements (Cheshmehzangi, 2016; Natanian et al., 2019; Shi & Yang, 2013; Yuan & Lin, 2019). Moreover, a common practice is to evaluate the performances after major design decisions are made, then compare design options and choose the one with better performance. It often relies on the practitioners’ experiences and does not always result in the optimal solutions for the site. To address these problems, this study proposes a simulation-based optimization method that combines a thermal comfort simulation with the genetic algorithms (GAs) to achieve...
automatic optimization of design solutions for minimizing the percentage of thermal uncomfortable area onsite.

Simulation-Based Optimization Method

In this study, a simulation-based optimization method is proposed to link simulation engines with the Genetic Algorithms (GA) through Rhinoceros and Grasshopper platforms, allowing automatic optimization of design alternatives to maximize thermal comfortable area in urban spaces. The workflow is shown in Figure 1. The design variables combined as a design scenario will be passed into the 3D geometry generator to build the 3D model. The design scenario is linked with a simulation tool to calculate its thermal performance, which is taken as a fitness value that passes into the GA operator to guide the design development and optimization process. When the GA reaches the objective target or the fitness value yields no better performance than previous ones, the process would be stopped with the best solutions.

Thermal index

Some thermal indices were developed in the past considering the heat balance between environmental factors and the human body to assess the thermal comfort, such as Standard Effective Temperature (SET*) (Gagge et al., 1986), Physiological Subjective Temperature (PST) (K Blażejczyk, 1994), Out Standard Equivalent Temperature (PET) (Höppe, 1999), Predicted Mean Vote (PMV) (Ole Fanger & Toftum, 2002) and University Thermal Climate Index (UTCI) (Jendritzky et al., 2002), etc. PMV and SET* are designed for indoor use while PST, OUT_SET*, and UTCI are mainly developed for outdoor use. As UTCI has been widely adopted in microclimate researches and can represent various climate conditions (Krzysztof Blażejczyk et al., 2012; Bröde et al., 2012), it is adopted as the thermal index to measure pedestrian heat stress in this study. A temporal averaged UTCI from 10:00 to 17:00 is calculated to represent the daytime thermal condition. The calculation method is as Equation (1), in which \( UTCI_{i,j} \) refers to the heat stress of \( i^{th} \) sensor point in \( j^{th} \) hour. \( P \) is the total number of sensor points within the site and \( H \) is the total number of calculated hours.

\[
\overline{UTCI}_{site} = \frac{1}{P} \sum_{i=1}^{P} \left( \frac{1}{H} \sum_{j=1}^{H} UTCI_{i,j} \right)
\]

The acceptable range for thermal conditions depends on local climate, population, society, etc. According to the research of Huang et al. (J. Huang et al., 2016), the acceptable thermal zone is adjusted as 15.2–28.8 °C in UTCI based on a field experiment conducted in Wuhan, a humid sub-tropical city in China. Considering the climatic similarity between Wuhan and Hong Kong, this study defines the local community’s acceptable thermal conditions to be within 15.2 ~ 28.8°C.

Geometry generator

The 3D geometry generator is developed to build the 3D model by controlling variations of building location and height under design constraints. Each combination of different design variables represents a design option. The algorithm of the generator is written via Grasshopper, a graphical algorithm editor of Rhinoceros (Anton & Tǎnase, 2016). To simplify, the building outline is fixed as a standard unit. The modeling will be performed by following steps, 1) to move the building outline by defined horizontal and vertical offset from the base point, the left corner of each parcel; 2) to extrude the closed curve along a perpendicular vector with the length of the building height. The output 3D model will be applied as the input physical model to the simulation tool.

Simulation tool

After 3D geometry is built for a specific design option, it will be passed into a simulation software to conduct performance assessment. CityComfort+ (J. Huang et al., 2014) is used to simulate pedestrian heat stress. The tool runs on Rhinoceros as a plugin. It uses inputs of 3D geometries with surface properties and weather data to model environmental variables including air temperature, wind speed, mean radiant temperature and calculates the thermal index in the urban area. This simulation tool has been validated by field measurement and applied on some industry projects (J. Huang et al., 2014) successfully.

Optimization tool

The design optimization process is driven by the Genetic Algorithm (GA). It applies natural evolution theory that the species evolve with crossover, mutation and selection process over generations so that organisms adapt themselves to the changing natural environment (Carr, 1997; David E. Goldberg, 1989; Kramer, 2017). To implement GA in the pre-defined urban design problem, the design parameter becomes the gene, the design scenario becomes the individual, and the design objective determines the fitness value.

Evolutionary solver in Galapagos (Rutten, 2013), a GH plug-in developed by David Rutten is selected as an optimal operator in a hypothetical case below. The operator contains two inputs. The Gene side allows one or more parameters to be set as variables and the Fitness side could receive one value calculated from the simulation tool for a given maximum or minimum problem. The outputs are a series of solutions to a defined problem.

Integration of Computer Simulation and Genetic Algorithm

The workflow is controlled by GA Operator in finding optimal solutions based on the rule that survival of the fitness. A thermal comfortable area ratio refers to the percentage of site area that falls into the aforementioned acceptable thermal is used as the fitness value for GA. The higher the value represents the better performance in fitness. This study combines CityComfort+ with the GA by scripts written in Python language through GhPython, an open-source Python interpreter for Grasshopper.
(Davidson, 2019). The scripts connect the three operators including Geometry Generator, Simulation engine, and GA Operator that can facilitate the iteration process by extracting output from the previous step and transforming it into an input for the next step. This process is repeated until a pre-defined fitness value is reached.

3D geometry generator is developed to generate design solutions for assessment which arranges 12 buildings onsite automatically based on the design requirements. For each building, the variables describe building location includes offset from the basepoint named \( V_1 \) and \( V_2 \); the variable describes building height is the number of the storey named \( V_3 \) multiply by 3 m. To simplify, we assumed that building height alters symmetrically in the same type of parcel denoted by P1, P2, and P3 respectively (Figure 2). Table 1 and Figure 3 show the definition of variables for each building.

### Table 1: Selected variables and their range for each building

<table>
<thead>
<tr>
<th>Category</th>
<th>Variable</th>
<th>Unit</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building location</td>
<td>( V_1 ) : horizontal offset distance from the base point</td>
<td>m</td>
<td>Discrete value, 0, 5</td>
</tr>
<tr>
<td></td>
<td>( V_2 ) : vertical offset distance from the base point</td>
<td>m</td>
<td>Discrete value, 0, 5, 10, 15</td>
</tr>
<tr>
<td>Building height</td>
<td>( V_3 ) : number of the storey of each building</td>
<td>Storey</td>
<td>Continuous value, 20–30</td>
</tr>
</tbody>
</table>

The design target is set to maximize the comfortable area ratio, defined as the percentage of site area that falls into the acceptable thermal zone, UTCI 15.2–28.8°C (J. Huang et al., 2016). The higher the ratio means the higher fitness of a design solution. The optimization objective function is shown as Equation (2), in which \( x_k \) denotes the \( k^{th} \) design variable, \( a_k \) and \( b_k \) are the lower and upper bound respectively. Each combination of 26 variables represents a design solution.

\[
\text{Maximize } \{ f(x_1, x_2, x_3, ..., x_k) \text{ }, k = 26 \}, \quad a_k \leq x_k \leq b_k
\]

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**Case study**

(1) Study area

To evaluate the performance of the proposed method, a hypothetical case in an empty site located in Hong Kong is introduced. The total area of the site is 40,000 m\(^2\) (200 × 200 m) with 4 types of the parcel of a fixed boundary, 39 × 39 m (denoted by P1), 37 × 39 m (denoted by P2), and 39 × 37 m (denoted by P3). The street width between parcels is 16 m. The design requires the overall Floor Area Ratio (FAR = total building floor areas / the site area) to be at 3.2. One parcel includes only one building with a fixed outline of 30 m in length and 20 m in width. All buildings adopt a ceiling-to-ceiling height of 3.0 m. The design optimization focuses on the arrangement of the building location and height which varies among pre-defined ranges and form a specific building layout. Figure 2 shows the site information.

![Study area and fixed parcel boundary. There are 3 types of parcel sizes with 4 parcels in each type. Pn-i denotes to parcel n in parcel type i.](image)

(2) Design variables and optimization objective

![Design variables that define one building.](image)
The simulations for calculating the UTCI equivalent temperature were run by CityComfort+ software in the daytime hours between 10:00 and 17:00. The sensor points were set in a 10 m interval at 1.5 m above the ground within the site boundary (Figure 4). The input wind speed file is extracted from the typical year file of Hong Kong weather data downloaded from the U.S. Department of Energy (USDOE, 2020). Wind speed variation results from different design solutions are not taken into consideration when simulating the thermal condition in this study. March 26th is selected as a typical day that represents Hong Kong’s overall climate conditions with an average daily air temperature at 23.0 °C, close to Hong Kong’s annual mean temperature of 23.0 °C (Hong Kong Observatory, 2020) and the daily air temperature ranges from 21.4 to 25.3 °C. The daytime period from 10:00 to 17:00 is selected to calculate the hourly thermal conditions. Surface materials for building and ground were set to the same properties for all solutions.

The parameters used for optimization in Galapogas are summarised in Table 2.

<table>
<thead>
<tr>
<th>Item</th>
<th>Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>20</td>
<td>Total number of genes combination for each iteration</td>
</tr>
<tr>
<td>Max stagnant population</td>
<td>50</td>
<td>Total number of populations that has the same fitness value as the one in the previous iteration</td>
</tr>
<tr>
<td>Maintain rate</td>
<td>10%</td>
<td>The percentage of the population that will survive into the next iteration</td>
</tr>
<tr>
<td>Inbreeding rate</td>
<td>60%</td>
<td>The percentage of genes been selected in the gene pool as parents to generate child population</td>
</tr>
</tbody>
</table>

Results & Discussion

The study proposes a design optimization method to reduce outdoor heat stress in urban areas. The optimization process in the hypothetic case focused on optimizing the height of building blocks and the distance between adjacent blocks within a site for a fixed floor area ratio. The outdoor thermal conditions were calculated by a Rhino plug-in named CityComfort+, while the design generation and optimization process were operated by Galapagos based on Genetic Algorithms. For simplicity, only one typical day is considered in this study.

A total of 2091 valid design solutions were generated in 168 hours, using a standard desktop computer equipped with i7-7700 CPU, 3.60 GHz, and 32 GB RAM. The performance of each design solution, the percentage of the site area that falls into the acceptable thermal range is shown in Figure 5, which is fluctuant between 71% and 79% and an overall increasing trend. A decreasing trend of site average UTCI at pedestrian height along with the optimization process driven by GA is also observed, showing a significant improvement of site thermal comfort with the design development process. The site average UTCI of optimal design solutions is observed at 27.32 °C, achieving a 0.34 °C reduction compared with the worst option.

Two of the best and two of the worst design options are illustrated in Figure 6 and Figure 7, respectively, indicating that an appropriate arrangement of building height can improve the thermal comfort of the site. Due to the settings of the design parameter, building heights in the same type of parcel are the same, and the variations of the 12 buildings are symmetrical. Some common characteristics are observed: 1) In the best solutions, buildings near the squares of parcels P2 and P3 are taller than the ones further away, which is inverse in the worst design solutions. Taller buildings could provide more shaded areas that reduce heat from direct solar radiation. 79% of the site area falls into the acceptable thermal zone in the best solutions, the arrangement of buildings observes less the exposure area to the sun during the daytime compared with the worst ones. 2) The 12 buildings in the best solutions have a greater variation in height than the worst solutions. This may be due to the shadow effect from differential height buildings. Results show that the proposed method which integrating a simulation engine with a genetic algorithm into design thinking can assist designers to identify optimal design features in a large design space efficiently. It can support smart design decisions in the early design stage of urban neighbourhood development.
This study proposed a simulation-based optimization method that combines computational simulation and genetic algorithms within design development. This method is tested in a hypothetical case of Hong Kong and the results show a significant improvement in the outdoor thermal environment on a typical day. The method facilitates the application of simulation tools for performance evaluation at an early stage of the design process, which could be a useful method to support smart design decisions in urban neighbourhood development.

**Conclusion**

This study proposed a simulation-based optimization method that combines computational simulation and genetic algorithms within design development. This method is tested in a hypothetical case of Hong Kong and the results show a significant improvement in the outdoor thermal environment on a typical day. The method facilitates the application of simulation tools for performance evaluation at an early stage of the design process, which could be a useful method to support smart design decisions in urban neighbourhood development.

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