Abstract

Urban heat island (UHI) effect is one of the most critical environmental issues for contemporary high-density cities. Previous studies show there is a strong co-relation between UHI and Sky View Factor (SVF), which constructs a potential linkage between UHI and urban forms. As cities grow denser and hotter, urban form manipulation strategies for mitigating heat island become an increasingly important challenge for urban planners and designers.

Taking high-density urban areas which have relatively high UHI intensity and low SVF value as the study subject, we develop an experiment to test the possibility of mitigating UHI through optimizing SVF of urban forms. The method adopted involves the use of digital techniques such as parametric modelling, programming and optimization algorithms. The experiment evaluates and optimizes a large number of urban form samples at both coarse and fine scales and searches out the optimum urban form for maximum or minimum SVF values under variable urban density constraints. The results of this study show that it is workable to mitigate UHI through manipulating urban form based on SVF, and indicate significant potential for urban form optimization modelling to enlighten urban planning and design decision making concerning on UHI whilst maintaining development yields.

Keywords: urban form; urban heat island; sky view factor; high density.

* Youpei Hu. Tel.: +86-25-8359-3020; fax: +86-25-8359-5673.
E-mail address: youpei.hu@nju.edu.cn
1. Introduction

Along with global climate warming and urban population rise, urban heat island (UHI) has become one of the most critical environmental problems for high density cities [1-7]. The term, UHI describes the phenomenon that urban temperature is commonly higher than that of surrounding suburbs, because that solar radiation is stored in urban canyon at daytime, and is released in the form of long-wave heat radiation at night time [8]. A considerable body of research has revealed that heat island is closely related to urban geometry and urban materials [9,10]. Built urban form has a permanency that is very difficult to change once established. Conversely, urban materials may be improved and enhanced by means of increasing green plant coverage, water bodies, and using lighter colored and low thermal-storage materials to reduce UHI impact [11-13]. Though changes ground surfaces are relatively easy to implement, urban form has a more fundamental function in the formation of UHI and is therefore the focus of this investigation.

The value or intensity of UHI can be obtained through actual meteorological measurements, while, it may also be inferred by calculating the urban canyon using an indicator called “sky view factor” (SVF). SVF is defined to be the ratio of the visible sky area and the total sky dome of an observation point on the ground; its numerical value is 0-1, and bigger value represents better sky visibility [14]. The numerical average of SVF from all the observation points in certain area is the average SVF (av.SVF) [15-17]. Studies conducted in a wide range of different cities all over the world show that in specific areas the av.SVF has relatively high negative correlation with UHI (general expression is $\Delta T_{u-r} = a - b \times SVF$; where $\Delta T_{u-r}$ is the UHI intensity; a is the linear coefficient; b is a constant; a, b of different cities differs) [15]. For urban development areas which have not yet constructed, the SVF calculation is valuable indicator that can be used by urban designers and planners to infer their design’s potential UHI impact.

For urban planning and urban design, mitigating or adjusting the heat island of certain urban areas through manipulating or optimizing urban form has a practical environmental significance [18,19]. However, before putting forward specific optimization schemes, we put forward the following important questions: to what degree will the heat island be mitigated through urban form optimization? What kind of urban forms are conducive to UHI mitigation?

Taking high-density urban area having relatively high heat island intensity as the study subject, this paper attempts to answer the above questions by developing an experiment on urban forms.

2. Methodology

The experiment is designed to be the following form: for a set urban area, there is a specified total building gross floor area to be modeled as physical urban geometry. The task of the experiment is to find the urban form with the optimum value (maximum or minimum) of av.SVF for the specified total building area constraint. The D-value of the maximum and minimum av.SVF outlines the dimension the optimizable space of heat island. Vary the amount of total building area, the experiment will produce a series of optimum forms. Through comparison of these optimum forms, some common points from therein might be observed, and thus the general features of the optimum form could be summarized.

One challenge for calculation in the experiment is that for a same total building area, there is an almost infinite quantity of possible urban forms, which compose the so-called “solution space”. It is not feasible to test all possible forms and so an effective search method is needed to find the optimum form (or the form close to optimum value) from the solution space. The experiment proposes a scheme of two stage optimization to address this calculation challenge (Fig. 1): Firstly, on a relatively coarse scale, urban forms are simplified as a group of boxes with different sizes on plots. We call this simplified form the “density distribution form”. Various iterations of density distribution form for the total building area onto plots were first generated randomly as the initial samples. Then, we refined these samples by applying an optimization algorithm finding the sample with the optimum UHI intensity.

Based on the optimum density distribution form found in the first stage, the experiment moved to the second stage on a fine scale. The simplified boxes at the last stage were re-modeled into diversified possible building volume forms according to the architectural rules and conventions for the layout of high-rise building complexes in the context of China. Optimization of these building volume forms was then performed, finding the building form sample for optimum UHI intensity value.

The abovementioned scheme is based on the hypothesis: Density distribution form reflects rough urban form contour and trend, and the optimum building form obtained from the optimum density distribution form is better than
the optimum building form obtained based on non-optimum density distribution form. For this hypothesis, the experiment may choose the optimum density distribution form to generate the building form directly, without embodying and optimizing all density distribution forms in the second stage, and this raises the searching efficiency.

The division of two stages on coarse scale and fine scale respectively in the experiment scheme not only raises the efficiency of calculation, but also has practical meaning. Namely, in urban planning and urban design, determining the layout of density distribution of an area has the same importance as, or in some cases even more fundamental than determining a specific building forms on plots. Therefore, finding the optimum density distribution form in the experience is not only a process result, but has been recorded and analyzed as a part of experiment result.

The experiment scheme is realized on the software platform of Rhino by using Rhino Script programming. The optimization algorithm adopts the standard Genetic Algorithm (GA). Initial urban form is generated at random, and on coarse scale, it meets the restriction on total building area; on fine scale, it meets the density restriction on each plot inherited from the optimum density distribution form. The technical details of the generation of urban forms is outside the scope of this paper and are detailed in related paper [20]. At both stages of coarse scale and fine scale, the av.SVF value, which is calculated adopting the shadow projection method put forward by Ratti [21,22], is the "fitness" parameter in the evolution procedure. Samples with relatively high SVF value were then inherited in the evolution process. The samples were evolved and screened generation by generation through Genetic Algorithm, so after a certain number of generations, the optimum solution emerged. Such method of generating and optimizing form automatically by relying on computer has an advantage that, it may test a large number of samples at one time. In one typical computation in the experiment, the computer tests 50 generations of individuals, with 50 form samples in every generation, namely total around 1275 (50+25×50) samples. A large number of experiment samples ensure high level of coverage of various possibilities, and the discovery of the optimum forms.

![Fig. 1. The experiment scheme of two stages](image1.png)

The experiment site (Fig. 2) was a simplified high-density urban area, which was divided into experiment area and surrounding area: The experiment area consisted of 25 square plots with side length of 100 m. The size of the plot is common for high-rise building complex, while the size of the experiment area approximates the scale of a typical Chinese big street block. The FAR (floor area ratio) of these plots was allowed to change within 2-25; the experiment area was required to have an un-built open space of no more than 10% of the plots. Building setback were uniformly set up to be 10 m along the edge, and a 20 m belt-shaped area not occupied by buildings was ensured between two neighboring plots, which was a simplification of the street grid in high-density area. The heat island generated by urban forms on experiment area was not only imposing effect on the experiment area itself, but also expands beyond the site outward and influence surrounding area. The effective scope of expansion of 200 m beyond the site was set based the recommended distance of attenuated influence [7]. In the 200 m wide influence area, distribute the square block of 41 m in side length and 24 m in height as per 100 m grid. The FAR of this block was determined to be 1, which was a simplified representation of normal-density urban areas. The calculation domain of av.SVF value was the sum of the experiment area and influence area, and it was a 900 m square area. The size of this domain was at the same order as the measurement units adopted for average heat island evaluation [15,23,24]. This correspondence guarantees that av.SVF value could effectively represent the overall influences of urban form in an area on UHI.
3. The Procedure of the Experiment

In the experiment, total building area was expressed with the average floor area ratio of plots (FAR). The average FAR 6 (total building area 1,500,000 m$^2$) was taken as an example to explain the experiment procedure.

Firstly, execute density distribution form optimization on coarse scale. Figure 3(a) records the optimization process. The small black dots therein represent the density distribution form samples generated in the process, and blue dots in each generation mark the mean SVF value of all individuals in this generation. Connect blue dots to form a line chart, and obtain the evolutionary curve of the optimization process. It may be discovered that, in early generations, sample dots are distributed in a relatively wide space, and the mean value curve is located in the middle of samples. At the late generations, the samples distributed are gradually converged to nearby the mean value curve. It means that, sample groups have collectively evolved into a relatively good (or bad) state, and the evolution process is a typical convergence process; the best (or the worst) sample with lowest (or highest) SVF value obtained from hereof is or approximate to the optimum sample in the whole solution space.

The best and worst density distribution form samples (with av.SVF value of 0.572 and 0.534 respectively) obtained from the above process were used as the scheme of density distribution layout to carry out experiment at the level of building form. Figure 3(b) and Figure 3(c) show the experiment optimization process based on the best and worst density distribution forms respectively. Fig. 4 records 3×11 samples (corresponding to the red dots in Figure 3) in the experiment process. Wherein, the first row is the samples selected randomly from the population in the initial generation, rows 2-4 are the samples selected at random in the process, and row 5 shows the best and worst samples obtained in the final generation. Two of the optimum samples in row 5 (the best building form of the best density form and the worst building form of the worst density form) are the extreme cases of all possible urban forms satisfied the total building area constraint, and mark the boundary of the solution space. The D-value of av.SVF of the best and the worst is 0.059, which means the optimizable space of UHI, in this case, is 5.9%.

By resetting the average FAR to be 3, 9, 12 and 15, and repeating the above experiment process, we may obtain the optimizable space and optimum form in condition of different total building areas. Fig. 5 shows the experiment result, and records the optimum samples and their corresponding av.SVF values.
4. Analysis of the Result

The analysis is conducted on two aspects: 1) the size of optimizable space of UHI; 2) the features of the optimum form.

4.1. Size of optimizable space

The av.SVF values of optimum samples in Fig. 5 are plotted in the chart of Fig. 6. The black vertical bar represents the optimizable space available at the level of density distribution form in condition of a certain total building area. The blue and yellow vertical bars represent the optimizable spaces available based on the best and worst density distribution forms at the building form level. The total length occupied by 3 vertical bars is the size of optimizable space in condition of a certain total building area.

Obviously, the size of the optimizable space is not big, and around 4-7%. The absolute numerical value is affected by the factors such as surrounding environment and size of plot, and will possibly fluctuate under different urban conditions. However, in terms of the order of magnitude, the size may be judged to be within around 10%. This result is consistent with the conclusion obtained from researches developed with different methods [6,24], so it further...
confirms the absolute size of optimizable space. It is mentioned previously that, the correlation coefficient of UHI and SVF in different cities is different. According to our experiment data and the coefficient of different cities, the UHI intensity which could be adjusted or mitigate, is up to around 1°C in the most distinctive city, and is around 0.4°C in the most indistinctive city.

As to the overall trend, the optimizable space increases along with the increase of total building area in experiment area. The optimizable space will reach the maximum value when the FAR reaches 12, and then, will decrease (under different field conditions, the numerical value of total building area corresponding to the peak value will possibly differ, but it must be a relatively big numerical value). The decrease after appearance of peak value shows that, over high total density induces the drop in the possibility of urban form, and further induces the reduction of optimizable space.

In the three-part-composed optimizable space, the optimizable space at density distribution form level (the black bars) contributes a relatively large part of it, and the former changes along with the fluctuation of the latter. This correspondence manifest that the layout of density distribution plays a main and fundamental role in the formation of heat island. The size of optimizable space at the level of building form (the blue and yellow bars) does not show the obvious trend of changing along with the change of total building area, but on the contrary, it is relatively smaller and fixed. This phenomenon implies that once the density layout is settled down, the optimizable space of UHI obtained through manipulating of building forms, is relatively small and fixed.

4.2. Features of the optimum Form

Let’s observe the density distribution form samples in optimization process in Fig. 4. It may be discovered that, when the optimization process proceeds towards maximum SVF value, the density distribution form will gradually converge and gather from random initial state, and the optimum form is the most compact form under the restriction
of the upper and lower FAR limits (2-25) on single plot; when the optimization process proceeds towards minimum
SVF value, an opposite process will be presented, the form will disperse gradually, and the worst form is the most
disperse form. This feature of optimum density distribution form may be re-verified in condition of different total
building areas (Fig. 5.). However, the observation result seems to conflict with our empirical judgment on SVF: The
visible sky area seems to be bigger when the separation of building volume is bigger?

Let’s observe the building form optimization process in Fig. 4. The abovementioned trend and feature are not so
distinctive on fine scale. As observed from 3D space, the 4 optimum forms are actually relatively close to each other
pairwise. Similarly, in condition of other total building areas, we may see similar situation (Fig. 5). This brings about
another question, namely how SVF is optimized at the level of building form?

By exporting the SVF data of 12 optimum forms in two groups with average FAR 6 and 12 to GIS platform, then
interpolating and coloring them, we may obtain corresponding SVF maps (Fig. 7). Firstly, observe the SVF map of
optimum density distribution form (first 2 columns). It may be discovered that, both on the maps of the best and the
worst, there are the dark grey areas of which the color is similar (actually, the color of the former is slightly darker
than the latter, but the difference is difficult to distinguish with naked eyes) at central area, and are the areas of light
color at the periphery; meanwhile, dark grey area of the best covers an obviously smaller area than the worst. This
means that, the best form is at the cost of forming a low-SVF area in the center through convergence, and induces the
increase of av.SVF value in the whole area; while the worst form is just the opposite, and it induces relatively high
av.SVF value by diffusing SVF to the whole area. This explains the mechanism of the influence of the optimum
density distribution form seen in the 3D form on average SVF; and also explains the first doubt mentioned above. In
the precondition of a fixed total building area, the form of convergence actually induces the decrease of visible sky
area within a small scope, but due to the calculation method of average SVF and the basic order of heat island scale,
convergence form will induce the increase of visible sky area in a broader scope, and thus might cause lower UHI
intensity.

Then, observe the building form (columns 3 to 6 in Fig. 7). The differences hidden in 3D space will be obviously
embodied. Similar to the feature discovered in density distribution form, the best optimum building form is more
compact on plane, while the worst is more dispersive. Such difference in plane is mainly originated from the
contributions of plinths under high-rise building volume, and there are generally more plinths in the best optimum
form compared with the worst one. The volume of plinth is relatively small and blocked by high-rise building volume,
so it is not easy to be observed in 3D space. Density distribution form is to realize the convergence and dispersion by
manipulating large volume in 3D space, while at the level of building form, convergence and dispersion are completed
on ground level by adding or deleting plinths. On high-rise building plots, FAR is mainly contributed by high-rise
building volume, while plinth volume possibly accounts for a relatively limited and fixed proportion, so the conversion
or dispersion degree of building form is relatively small and stable.

Let’s further observe the color change of SVF map of building form. The optimum forms present similar dark grey
color (actually, the color of the best form is slightly darker than that of the worst form) in central area. The difference
rests with that, the best optimum form is more compact on plane and its dark grey area converges to the centre, while
the worst form diffuses outward, and the dark grey area is smaller than that of the best form. Such difference is similar
to that of density distribution form. It shows that, building form is the same as density distribution form in terms of the mechanism of imposing influences on average SVF value. Both of them decrease or increase average SVF value by converging and diffusing dark SVF areas.

Therefore, the second doubt above may be explained: At the level of building form, SVF optimization is realized by changing the compaction and dispersion degree on the ground plane. The manipulating of building form is mainly based on plinth, while the adjustable scale is relatively small and fixed because the limited size of plinth. So in comparison with density distribution form, at the level building form, there is a relatively small and fixed optimizable space of UHI.

Through the abovementioned observation and analysis, we may preliminarily point out the general features of optimum forms: for heat island effect, the compactness of urban form is a key feature. On big block scale (around 500 m square block), compact form brings about poor sky visibility at the central area of a site, but has a bigger average SVF value for the whole area, and might be more beneficial for lowering UHI. Discrete form presents the very opposite situation, and might further increase UHI.

Parameters (such as surface ratio, average dispersion distance, average barycenter distance, etc.) could be used to measuring the compactness of urban forms, and the co-relation between av. SVF and compactness of forms could be established statistically, to further prove the general formal features of optimum forms brought forward herein. However, this verified work is not included in this paper.

5. Conclusion

In this paper, the urban form experiment on UHI effect in high density area is conducted on two scales of urban forms sequentially (the coarse scale of the density distribution form and the fine scale of building volume form). By adopting the techniques such as parametric modeling, numerical calculation, script programming and optimization algorithm, the av. SVF value (indicates the UHI intensity) of large number of samples has been evaluated, and the optimum urban form has been searched out. Based on the observation and analysis of the experiment result, we may draw the following preliminary conclusions:

1) The density (total building area) of an urban area is a decisive parameter affecting UHI intensity of that area. The higher of density is, the lower SVF value will be, which will causes the higher the UHI intensity. The size of heat island’s optimizable space, which is obtained by optimizing urban form, increases along with the increase of density. However, the absolute size is not large, and around 4-7%; corresponding adjustable UHI intensity is around 0.4-1°C. The density distribution layout and the building form play different roles in mitigating or adjusting heat island phenomenon. In condition of different density, the optimizable space available to obtain simply by adjusting building from is relatively small and fixed, and is around 3%. The adjustment of plot density distribution contributes the fundamental and changing part (1.6-4.9%, averagely 3.7%) of the optimizable space. This means that in the practice of urban planning and urban design, distributing density on the land in a proper layout has a fundamental significance for mitigating heat island.

2) On big block scale (around 500m square block), compact urban form induces a higher av. SVF value in overall area at the cost of a low SVF value at local place, might be more beneficial for lowering UHI intensity than discrete urban form. This conclusion seems to go against our daily experiences, and need to be tested in real urban condition. One point to be emphasized is that, it is not on any scale that compact form is preferable. The scale of compacting is definitely corresponding to the calculation scale of average UHI intensity, and it is around a big block scale.

The experiment developed in this paper is one part of our ongoing research project on urban heat island and urban forms. The conclusions obtained from the experiment are based on the simulation carried out on a simplified site condition, and is waiting to be verified in real urban environment in the future research.

Acknowledgements

This paper is supported by Chinese National Science Foundation (51108228, 51538005). Associate Prof. Tong Ziyu of Nanjing University provides the GIS technology support to this paper.
References


