GIS Analysis for the Climatic Evaluation of 3D Urban Geometry
—The Development of GIS Analytical Tools for Sky View Factor

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Abstract

Climatic issues have been taken into considerations in urban design practices and theories for a few decades. However, the relations between the climatic factors and urban geometry are to be elaborated in a more quantitative way through visual representations, which will result in useful information for plan evaluations or design decision makings. In this paper, the emerging GIS technology is recognized as an operational solution for developing the analytical tools of climatic and urban form analysis. The sky view factor (SVF), one of the most important morphologic parameters in urban climatology, is utilized as an indicator of urban form performance for supporting climatic sound design decision making. Based on the spatial analysis functions in ArcGIS, the customisation of spatial analytical tools using ArcObjects and Visual Basic for Applications (VBA) has been developed for computing the SVF in any existed or delineated urban site.

A case study of the GIS-based SVF spatial analysis has been conducted using different geometric configurations for the same site, where various urban design proposals were compared using SVF as an essential parameter for climatic performance. The case study shows the advantages of precision and speed of SVF computation, which can be achieved through the development of GIS-based spatial analysis tools. The approach can be implemented in not only the existing urban sites, but urban design proposals for the evaluation of alternatives. It also reveals a feasible procedure for bringing climatic considerations into evaluation process and makes decision-making more scientific and effective.

Keywords: GIS, urban climate, sky view factor, urban geometry, urban design

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1 Introduction

1.1 Urban heat island and urban geometry

Urban heat island (UHI), refers to the higher temperature in urban area than in rural area, which leads to undesirable thermal condition and other related problems, e.g. energy usage, health and disease, etc. The phenomenon of UHI could be derived from climate, topography, physical layout and short-term weather conditions, etc. Since UHI is a dynamic result of combination of varies factors which influence the way heat is absorbed, stored, released and dispersed in the urban environment, the temperature difference caused by UHI is not constant due to the variation through time and space.

Compared with temporal variation, spatial variation of UHI is more related to physical layout. It was found that heat islands are not uniform across a city and their profile, in idealized form, has been described by Oke (1987). (See Illustration 1) Unequal development in urban area is one of the main factors contributing to the this “abnormal” phenomena of UHI. It has been found that vegetation, albedo, urban layout, and anthropogenic heat in urban area have great impact on the intensity and distribution of UHI. Among these factors, we will focus on urban layout, which has the most direct relation with urban design.

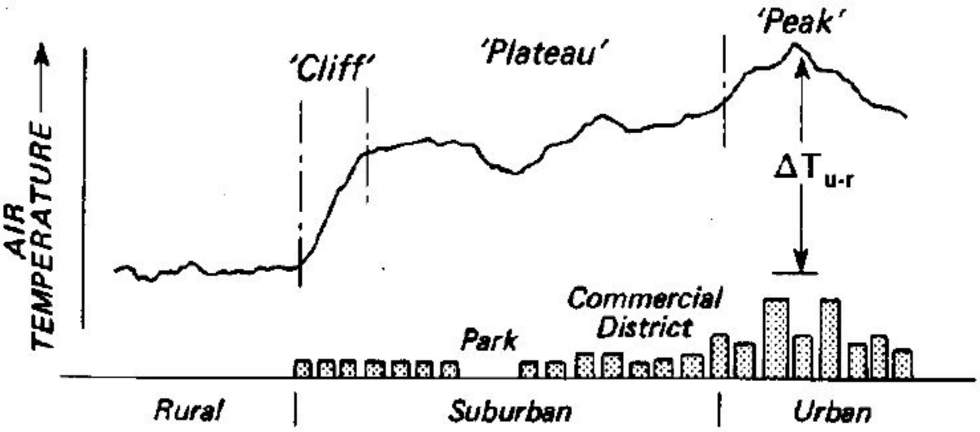


Illustration 1 Cross-section of a typical heat island (after Oke 1987)

Efforts have been made to evaluate the impact of urban layout to UHI phenomena from various aspects. In a city scale, it is commonly observed that the larger and denser a city, the greater the urban:rural temperature difference. (Givoni 1998) However, it is more complicated to examine the intensity distribution of UHI in a smaller scale. Although there is often a peak temperature effect at the centre of a city, this is to a large extent the result of numerous small pockets of temperature anomaly. The formation of these local temperature differences are more strongly influenced by the local surroundings of a particular site than by the city as a whole (Böhm 1998). Land use pattern and geometry has been found to have a certain relationship with UHI formation. (Steadman 1979; Stone et al. 2001; Stone 2002) However, in order to comprehensively understand the real interaction between urban setting and UHI phenomena and to carry on to an operational level, more local scale geometric characteristics have to be examined and analysed.

1.2 Sky view factor and local thermal performance

Sky view factor (SVF, or ψ) is an established parameter in urban climatology field. The definition of SVF is, a geometric ratio that expresses the fraction of the visible sky at the observer's location. It is a dimensionless number between zero and one (one represents unity)(Oke, 1987). SVF is picked in this study as a key geometry parameter with climatic significance because of its co-relation with local thermal performance and its potential significance in urban design process.

1.2.1 The strong co-relation between SVF and local thermal performance

SVF is deemed as one of the most important morphological factors that have essential impacts on urban climate.

The strong co-relation between SVF and surface temperature pattern in local scale has been recognized and analysed by Bärring et al. (1985), Eliasson (1990, 1996). While air temperature is the main indicator measuring UHI (urban heat island), surface temperature is also an important factor and also taken as an UHI indicator by some researchers (Johnson et al. 1991; Oke et al. 1991)

Not like surface temperature, air temperature in local scale does not have obvious correlation with SVF, because air temperature is dependent upon more complex and regional factors. However, in a larger scale, a strong co-relation between the maximum heat island intensity ($\Delta T_{u\text{-}r(max)}$, the difference between the peak urban air temperature and background rural air temperature) and SVF has been found (Oke 1987; Yamashita 1986). Oke concluded $\Delta T_{u\text{-}r(max)}$ is a function of the average of SVF over a large urban area ($\bar{\psi}$):

$$\Delta T_{u\text{-}r(max)} = 15.27 - 13.88\bar{\psi} \cdot \tag{1}$$

Based on above conclusions, we argue that SVF is not only an indicator of UHI phenomena, but an essential controlling factor of UHI effect, and that SVF can be used to adjust UHI effect (either to mitigate it or to enhance it according to local climate conditions).

SVF also has a significant influence on thermal comfort. Since surface temperature, which is co-related to SVF, is used to derive the Mean Radiant Temperature (MRT)[1], one of the key indices affecting thermal comfort, it is obvious that SVF plays an indispensable role for thermal comfort. Actually, SVF has been taken as a key determining factor in MRT predictive model (Matzarakis 1999). Since MRT is one of the main factors determining level of thermal comfort (other ambient factors are air temperature, wind speed and humidity), SVF is also related to local thermal comfort although it cannot totally control or determine thermal comfort.

1.2.2 Potential significance of SVF in urban design process

As a morphological parameter, SVF is directly defined by local scale urban geometry, which could be controlled by urban design practices. With significance for local thermal performance in both UHI and thermal comfort aspects, SVF has particular value for urban design.

However, although SVF is well recognized in urban climatology area and broadly employed in energy level analysis, it's still not commonly recognized and accepted as an urban geometry parameter which could be extensively utilized in urban planning or urban design area. There might be many reasons behind that:

- Lack of knowledge and awareness and lack of communication with climatologists.

[1] MRT is the average of the surface temperature of the surroundings with which the body can exchange heat by radiant transfer.

- Lack of sufficient evidence to show what does SVF mean to design objectives.
- Lack of sufficient and efficient tools to evaluate SVF quality or to support the interaction between SVF evaluation and design process.

Acknowledging that a supporting tool is essential for urban designers to utilize climatology knowledge and principles in their design practices, we are motivated to develop a new computer-aided SVF tool not only to evaluate SVF quality of urban environment (including both existing urban environment and proposals) but to interact with design processes.

1.3 Objective of study

The objectives of this study are to develop an efficient vehicle to measure SVF quality with certain urban geometry (either existing site or proposal) using GIS (Geographical Information System), and to examine the sensitivity of SVF in different urban geometry configurations of a same site, which is an important issue before SVF can be incorporated into urban design considerations. The result of this study will contribute to further researches in various aspects.

2 Methodology

This study includes basically two parts: vehicle development and empirical study.

2.1 Vehicle development

2.1.1 Mathematics of SVF computing tool

The mathematic mechanism of our SVF computing tool will be briefly introduced in this part.

The literal definition of SVF (ψ) can be transformed to a more mathematical description: the ratio of the solid angle[2] (Ω) of the portion of sky visible from the observer point (origin or O) to the solid angle the hemisphere centred at the same observer point (Ω_0, equals to 2π), or

$$\psi = \frac{\Omega}{\Omega_0} = \frac{\Omega}{2\pi} \tag{2}$$

If we divide the hemisphere equally into n pieces inside the horizontal circle of 360° or 2π, each of which constitutes a horizontal angle of α and the solid angle of visible sky in i^{th} piece is ψ_i. In this case, ψ is equal to the accumulation of ψ_i.

$$\psi = \sum_{i=1}^{n} \psi_i \, . \tag{3}$$

In each slice of ψ_i, we assume the visible portion of sky is a continuous surface. we define β_i as the highest vertical visual angle from the observer point to the buildings.

2 Solid angle: The solid angle Ω subtended by a surface S is defined as the surface area of a unit sphere covered by the surface's projection onto the sphere. Solid angle is measured in steradians, and the solid angle corresponding to all of space being subtended is 4π steradians. (Eric W. Weisstein. "Solid Angle" From MathWorld--A Wolfram Web Resource. http://mathworld.wolfram.com/SolidAngle.html)

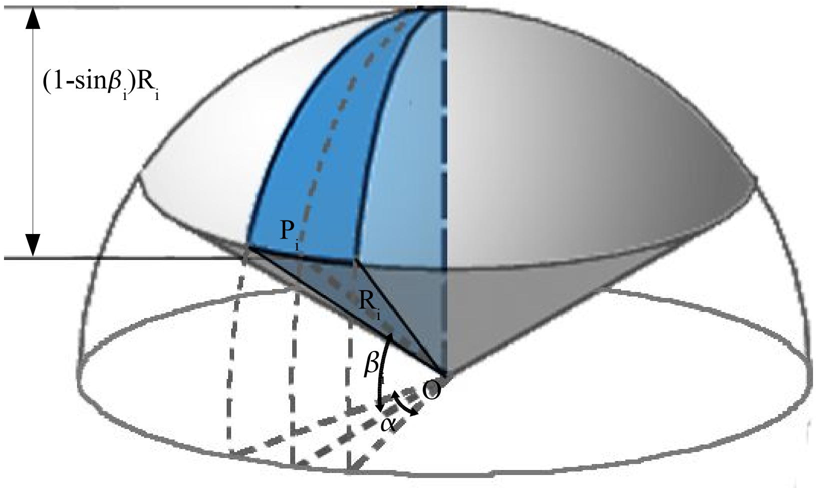


Illustration 2 Illustration for SVF computation

The obstruction point P_i which controls β_i has a distance of R_i from the origin O. Therefore,

$$\psi_i = \frac{\Omega_i}{(\Omega_0)_i} \approx \frac{2\pi R_i \cdot (1-\sin\beta_i)R_i \cdot \dfrac{\alpha}{2\pi}}{2\pi R_i^2 \cdot \dfrac{\alpha}{2\pi}} = 1 - \sin\beta_i \,, \tag{4}$$

where $\alpha = \dfrac{2\pi}{n}$, (5)

hence,

$$\psi = \sum_{i=1}^{n} (1 - \sin\beta_i) \,\cdot \tag{6}$$

2.1.2 Mechanism of SVF computing tool in ArcGIS

Using Visual Basic for Application (VBA) and ArcObjects, a development tool for ArcGIS[3] has been developed to perform the above computing procedures automatically (see Illustration 3). Two data files must be loaded in ArcMap or ArcScene[4] to run this tool: a three dimensional model in Triangulated Irregular Network (TIN) format, and a Point Shapefile which stores observer points. There is only one variable β_i in this calculation (see equation (6)), which can be easily detected using functions in ArcObjects. n is an constant, which can be customised in this tool. n is normally set as 360 although it might be increased or decreased to adjust the computing speed. After accumulative computation, the SVF (ψ) in any observer point in the open space (including streets) of the urban environment can be derived automatically. Batch computing can be easily achieved if multiple observer points have been stored in the Point Shapefile.

[3] A GIS software, produced by ESRI. The version we use in this study is 8.3.

[4] ArcMap and ArcScene are applications in ArcGIS. The two applications share some similar functions whereas ArcScene is capable in 3D modelling, visualisation and animation.

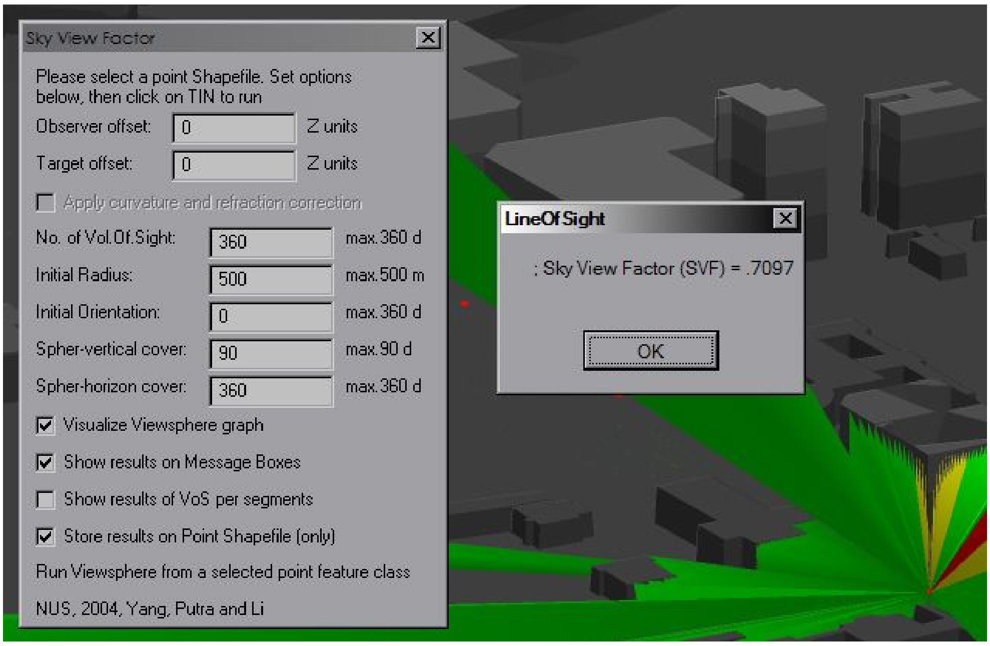
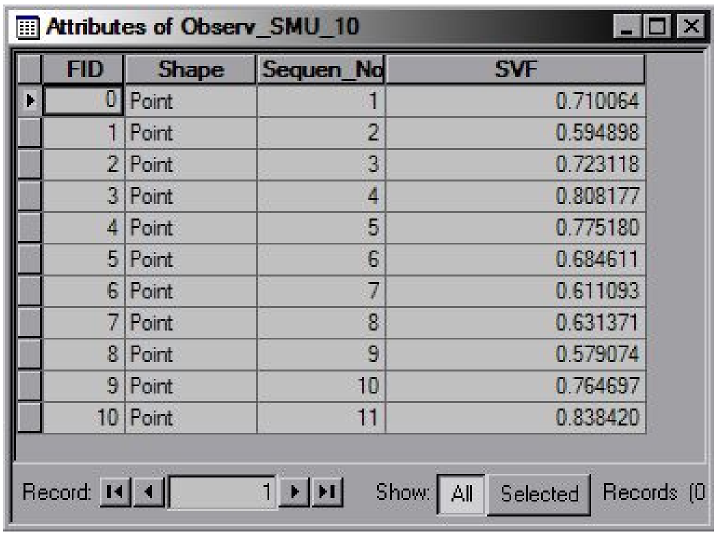


Illustration 3 A screenshot of Sky View Factor Plug-in for ArcGIS

There are two options for data output: pop-up Message Boxes (see Illustration 3) and/or output to the original Point Shapefile, in which a new data field "SVF" will be generated to its attributes table (see Illustration 4). The latter output method enables us to perform multiple points computing without being attended by users. Result Data stored in attributes table can be exported to external database or Geodatabase for further analysis.



Attributes of Observ_SMU_10

FID	Shape	Sequen_No	SVF
0	Point	1	0.710064
1	Point	2	0.594898
2	Point	3	0.723118
3	Point	4	0.808177
4	Point	5	0.775180
5	Point	6	0.684611
6	Point	7	0.611093
7	Point	8	0.631371
8	Point	9	0.579074
9	Point	10	0.764697
10	Point	11	0.838420

Record: 1 Show: All Selected Records (0

Illustration 4 A new "SVF" field generated in the attributes table of the observer Point Shapefile

2.1.3 Advantages and limitations

Compared to traditional fish-eye measurement approach (Chapman, 2001, 2002; Bradley, 2001), the above approach has following advantages:

- Rapid and costless if all required data are available and therefore easy to repeat if anything goes wrong.

- Only software operation is required; specialized knowledge in climatology, geometry or statistics is not necessary.
- Applicable for both built and proposed environments whereas fish-eye approach is not suitable for measuring non-existed environment. (except that physical models have been built)

However, some limitations are inevitable at present:

- Preparation of 3D digital model is necessary
- Accuracy depends of the quality of the 3D model, which is restricted by the 3D GIS data structure Triangulated Irregular Network (TIN) in ArcGIS 8.3. For the same existing built environment, the traditional fish-eye approach may have more accurate results than our approach.
- Urban vegetation is not included in the model because of its complicated characteristics, whereas it can be easily incorporated in fish-eye method.

2.2 Empirical study

Using above approach, theoretically we can evaluate SVF quality in any urban environment, no matter existing sites or proposals. The wide compatibility of this approach is valuable for urban design practices. The objective of this empirical study is to test the capacity of this approach in supporting climatic sound urban design. It is constituted of two parts: evaluation of SVF quality in urban space, and interaction with urban design process. The following are some preliminary results of our ongoing study.

2.2.1 Sequential evaluation of SVF quality in urban space

The campus of Singapore Management University (SMU) was selected as our case site, for which four proposals was compared along with the existing site environment. For each one of the totally five spatial configurations (see Illustration 5), SVF quality was computed, based on which a comparative analysis was conducted.

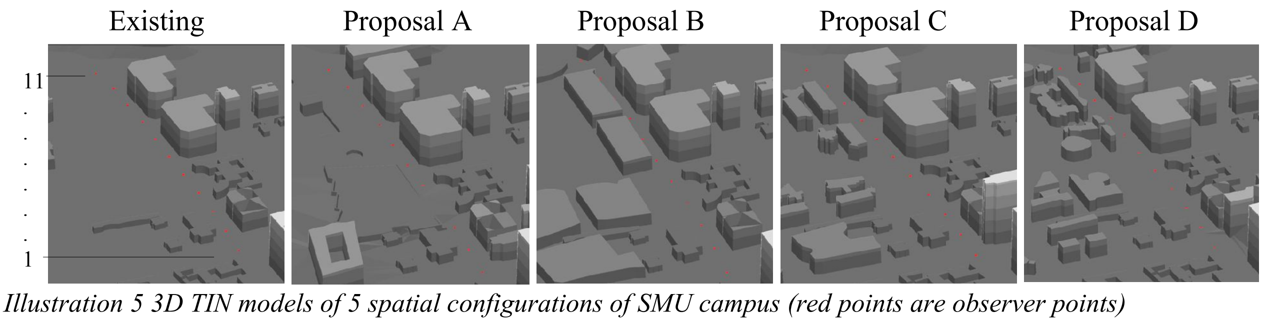


Illustration 5 3D TIN models of 5 spatial configurations of SMU campus (red points are observer points)

Since our basic approach to get SVF value is point based, we set a route in the main street which existed in all the five spatial configurations, and plotted 11 points along this route equally with a spacing of 50 metres. The SVF values on all these 11 points were processed as a batch in every setting and the results were stored into the attributes table of the Point Shapefile, and subsequently plotted into the following profile:

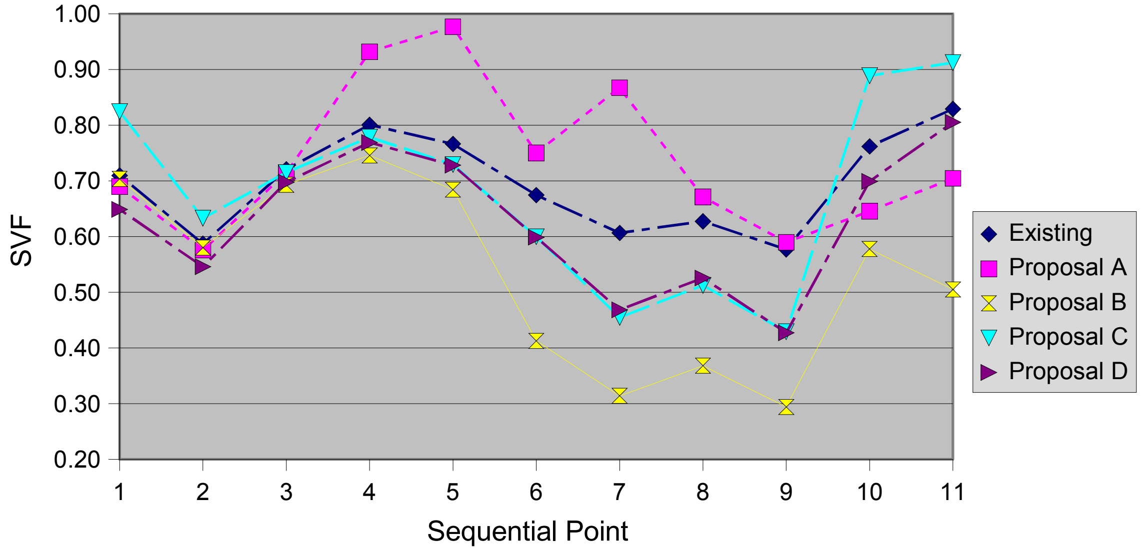


Illustration 6 Sequential SVF quality comparison among 5 different spatial configurations

From this profile, we can see the apparent differences of SVF quality not only among different locations in the same urban setting, but among the five cases according to the different urban geometry configurations, which shows the high sensitivity of SVF to urban geometry. We can also get the average SVF value for each configuration, which shows the overall SVF quality. Statistically, more indicators can be derived, such as standard deviation, although their meanings for climatology and urban design have not been identified at present. (see Illustration 7)

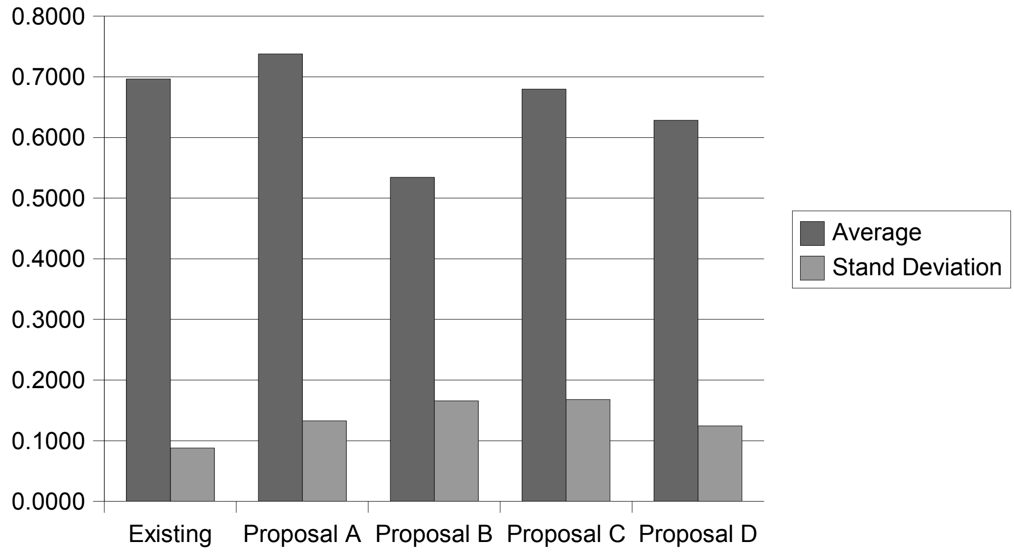


Illustration 7 Comparison of average and standard deviation of sequential SVF data

2.2.2 Future directions

a) Zonal evaluation of SVF quality in urban space

Using the similar approach with sequential evaluation, zonal evaluation of SVF quality is proposed. Array of points can be plotted in designated zones and be processed as a batch and results can be stored into the Point Shapefile. Thereafter, the SVF data of each point can be mapped into raster data so that both visualisation and further raster-based analysis could be realised. Empowered by raster analysis functionalities in ArcGIS, more indices can be derived. More efforts are to be made in this part of study in the near future.

b) Interaction with urban design process

During the SVF computation, more SVF related information is found possible to be derived. For instance, we can have all the obstruction point (P_i) location and all the vertical visual angles (β_i) stored for further analysis. These data will enable us to design a more comprehensive tool in order to interactively evaluate SVF quality in design process.

3 Conclusion

Although this study is only partially done, from the results we have achieved we can conclude that:

1. SVF can be computed in ArcGIS effectively and efficiently for urban environment (including existing built area and proposals), although technical limitations exist.
2. SVF has high sensitivity in different urban geometry configurations of a same site, which means SVF is suitable to be incorporated into urban design evaluation and decision making.
3. SVF has potential to be a key geometry parameter of urban design evaluation for climatic performance.

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