287: Achieving Urban Sustainability through Urban Morphology Analyses and Optimum Ventilation

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Abstract

This is a work to establish a GIS-based methodology for climate maps making with neighbourhood scales. British city of Sheffield is chosen as the object for the study. In terms of extracting urban morphology parameters, available web-based urban morphology database will be used, and a self-defined GIS-programme which can generating those parameters by computing some of notable aerodynamic numerical models will be cooperated. Furthermore, local air pollution database and Ward's finding through flow regime studies will be employed to verify the outcomes. While the correlations between urban morphological parameter and wind-driven ventilation potentials have been validated, those illustrated guidelines can be established and be used to examine the appropriateness of urban planning.

Keywords: GIS, Urban morphology, Natural ventilation potentials, Environmental maps

1. Foreword

1.1 Introduction

The provision of fresh air in cities is one of the main drivers for sustainability. It is known that the composition of urban forms, known as urban morphology, can crucially influence the performance of the micro-climate at the urban canopy layers. It is how the case that as a result of serious urbanisation and inconsiderate planning, numerous urban areas suffered from inadequate ventilation with the resultant adverse impact on occupants' well-being and energy loads.

The majority of previous studies have mainly focused on isolated or relatively small clusters of buildings; it is advisable to look at the built environment as a whole, especially the intermediate scale corresponding to the neighbourhood or city block, in terms of efficient environmental management and assessment.

Numerous meso-scale projects such as FUMAPEX® in Europe and NBSD® in the USA have been conducted in recent years in order to establish a reliable code for the decision-making process when dealing with urban planning issues. In addition to research into predicting the complex urban wind field, issues such as thermal distribution, pollution dispersion, solar radiation and noise levels within urban spaces are routinely considered in order to give a general and quantitative understanding the correlation between built environments and urban climate. For purposes of understanding and visualisation, the figures yielded by these studies are usually defined as the urban canopy parameters and presented in the form of GIS-based urban climate maps.

The climate map of natural ventilation potentials in some major cities have been established as guideline for the purpose of developing assessment, but the time-consuming and labour-intensive nature of the mapping process has made it impractical to produce such maps for the majority of cities. Practitioners and authorities can only depend on their empirical estimation instead of evidence-based evaluations. Information about urban wind fields, which is normally unavailable, is vital for tackling the potential threat posed by increased urbanisation and climate of change.

1.2 Aims and Significances

This work not only explains the ideas and problems associated with such research and the strategies to be undertaken but also attempts to establish a simple, swift, feasible, affordable and effective methodology based on Geographical Information Systems using existing aerodynamics models and other subsidiary methods of parameterisation to produce a series of climate maps. It aims to adopt existing principles to formulate a quantitative correlation between urban canopy parameters and natural ventilation potentials using the self-defined GIS-based method, eventually presenting the outcomes in the form of maps.

Once the visualised climate guidelines have been established and classified, decision-makers can easily identify the problematic areas of NVP within cities and the corridors of fresh air as well. The guidelines will provide substantial improvement and manage any future development in such a way as to limit any potential negative impact. It is therefore essential to provide simple and clear guidelines to characterise wind fields within the urban context that correspond in terms of various indicators of urban morphology.

The guidelines will enable practitioners to bypass the rigorous scientific calculation required to establish NVP and to avoid both complex

Computer Fluid Dynamics simulation and testing scale models in a wind tunnel, which are time consuming, user- unfriendly and costly. The methodology adopted for this study can be applied generally to provide similar information in other locations in the future and may make a significant contribution with the ultimate aim of aiding evidence-based policy-making and management.

2. GIS and Urban Morphology

2.1 GIS and Built Environment Studies

GIS has typically been employed by geographers and planners for the specific purposes of land use management, transport and pollution prediction, housing stock and environment mapping. There has been an increasing tendency in many OECD countries to use GIS for predicting airborne pollutants' distribution and air quality, solar irradiation mapping, heat emissions mapping, thermal comfort performance, renewable energy evaluation, and post occupancy management etc. Those researches are all viable examples of GIS application in the study of built environment and have extended the uses of GIS in the drive to achieve evidence-based evaluation.

GIS is seen as one of the formalised and holistic computer-based information systems that capable of integrating data from various resources to provide the information for effective decision-making process. As concerns of urban sustainability become interdisciplinary, Geographic Information System （GIS）has became a significant tendency of sustainable development framework. It serves as a database and also a toolbox, facilitating practitioners efficient data retrieval, mapping and queries of the" what if" scenario. The visualisation merits of GIS essentially improve analysis quality, in turn leading to better communication between participants throughout the whole design process.

2.2 GIS and Urban Morphological Parameterisation

There are a number of researches associated with GIS and urban morphology, the majorities investigating the performance of the micro-climate and its impact on the built environments. Although the methodologies that adopted to determine the correlation between urban morphology and climate throughout the works varies, it is now the tendency for researchers to employ GIS either for computation or presentation purposes. Although moderate accuracy has been achieved in city scale evaluation, the labour-intensive and time consuming nature of on site surveys and computation that required are always cited as problematic by the researchers.

For instance, Katzschner [1] has created a synthetic climatical function map for the city of Kassel, Germany, based upon orthophotographic maps and infrared-thermography which provide a picture of the momentary temperature distribution on the earth's surface in high resolution images. These images act as strategic guidelines in terms of climatically preferential areas and local climate facts such as local air exchange processes, cold air blockage, and conflicts with existing uses. Further in-depth on site measurements have been carried out in problematic areas to draw up more detailed climate maps.

Burian et.al. [2] has utilised ArcGIS™ to compute urban canopy parameters for mesoscale meteorological models and air pollution dispersion modelling. A self-defined ArcGIS-based method namely the UMAP has been utilised to compute those 3D models and airborne LIDAR data to generate urban canopy parameters for major American cities. Those urban canopy parameters will then forming a series of strategic maps for the National Building Statistics Database (NBSD).

Ratti et.al. [3] employed a self-defined image analysis tool based on MATLAB™ to analyse DEM models and 3D urban databases to obtain the values of aerodynamic properties such as roughness length and displacement height by utilising existing aerodynamics models to establish refined dispersion models for some of the European and American cities.

Long et.al. [4] contributed to the FUMAPEX project used a purpose-defined DFMap® software to analyse the urban database BDTopo® of the French National Geographic Institute (IGN) to compute the statistical parameters describing the building morphology and ground covering models such as building height, perimeter, volume, compactness, plan area density, vegetation density, pavement surface density, and hydrographical surface network density over a grid for the city of Marseille, France.

Adolphe [5] has described urban forms by using nine urban morphology indicators computed by MapInfo®. Among those 9 indicators that were proposed were the indicators of rugosity, porosity and sinuosity, which are crucially correlated with NVP in different urban patterns. The indicator of rugosity treats the urban fabric as the composition of numerous prominent obstacles. The indicator of porosity treats the urban environment as a porous medium with a solid skeleton, where the speed of the air varies along the pores according to the local unevenness. The indicator of sinuosity which considered the street oriented with an angle θ of which against the pressure gradient flow.

3. The Morphometric Models

3.1 Methodology

This work is aiming to utilise a number of existing numerical models of aerodynamics and other quantitative methods that may describe the flux momentum of wind in urban canopy layers to compute the so called urban canopy parameters. The ArcGIS® is mainly utilised for computation and presentation purposes, along with data derived from several urban statistical databases. The outcomes achieved through computing various approaches will then be presented as GIS thematic layers together with their own attribute tables, and most of the themes will be in raster format. Further GIS-based spatial analysing approaches such as the Map Algebra process and the formal logic of raster will be carried out for deriving new information by transforming or making associations of information from existing raster layers.

It is important to bear in mind that constant and comprehensive principle or models for urban canopy layer parameterisations are not available yet. Every method has its own advantages and weaknesses, e.g. limitations on the arrangement and geometry of buildings, or density and scale of cities. Moreover, the calculation and modelling become even more complex when the parameters of terrain, topography and vegetation are also taking into account at the same time.

Given the complexities outlined above, it is advisable to make a careful review of the literatures before selecting the most appropriate approaches for the study, especially the researches relating to the parameterisation of aerodynamic properties. There are two conventional aerodynamics methods, which are the wind-based and land-use based methods respectively that recommended by Grimmond and Oke [6].

The wind-based method, which is influenced by the wind direction and is totally empirical, was neglected in this work due to its restriction on assuming a horizontal homogeneity. Also a factor is the characteristic of over sensitivity to the form of the empirical function and values of coefficients which has led to a number of experimental failures when researchers have attempted to prove its reliability.

The land-use methods, which have proved more likely to provide reliable measurements of the substantial parameters of urban boundary layers in moderate-scale cities, are favoured for mapping purposes in this work. Basically, there are two land-use methods, the morphometric and the morphologic methods, which is necessarily to be distinguished initially.

The majority of researches favour the morphometric method which requires the advanced computation of geometric parameters through the analysis of urban statistical databases. Normally, databases containing information on shape, size, height, attribute, and arrangement of roughness elements such as buildings and vegetation are required for computation.

The second land-use method is the morphologic method which relies on the visual inspection of urban databases or aerial photography. The well known Davenport classification [7] of effective terrain roughness is an example of the morphologic method. It classifies the terrains into eight categories from Z_O=0.0002 (open sea or lake) to Z_O=2.0 （city centre） with text descriptions. Grimmond and Oke also classified roughness parameters into four categories following Ellefsen's [8] scheme listing seventeen types of urban terrains.

After reviewing a number of morphometric models, the simplified aerodynamics model of Grimmond and Oke together with Bottema's model [9] were recommended by Grimmond and Oke [6] and chosen as potential alternative methods for aerodynamic properties computation due to their complete range of frontal area density（λ_f）and plan area density（λ_p）,and the experimental validation of the models as well.

In addition to the main evaluation approaches mentioned above, a number of subsidiary methods and subsequent parameters that generated will be used for GIS computation, as stated in the following sections. This multi-criterion methodology will strengthen the reliability of the climate maps and compensate for any flaws in individual methods.

3.2 The Main Morphometric Models

3.2.1 Grimmond and Oke's Simplified Model

$$Z_o = \alpha_o \times h \qquad Z_d = \alpha_d \times h \qquad (1)$$

If only taking into account the mean height of buildings, the rule of thumb method proposed by Grimmond and Oke [6] is recommended. They proposed the coefficients of α_o and α_d are constant which is α_o =0.1 and α_d =0.5 respectively. The works by Hanna and Chang（1992）based on this equation also proposed the value of α_d=0.5, 0.6 and 0.7 for low, medium and high density urban sites respectively.

3.2.2 Bottema's Simplified Model

$$\frac{Z_o}{h} = \frac{h - Z_{d,pl}}{h}\exp\left(\frac{k}{\sqrt{\frac{C_{dh}\lambda_f}{2}}}\right) \qquad (2)$$

Where C_{dh} is unit building drag coefficient, k is the Von Kármán constant（0.41）, λ_f is the Frontal density ratio. The theoretical value of Z_d , which assumes buildings are of infinite length, is replaced by $Z_{d,pl}$, which is the displacement height in the building median plane. Assuming the validity of the equilibrium relationship at $Z = h$, the reference height that is conventionally used can be replaced by the mean building height h in this model.

3.3 The Subsidiary Morphometric Models

3.3.1 Mean Building Height

$$Hm = \frac{\sum_{built} Aihi}{\sum_{built} Ai + \sum_{nonbuilt} Aj} \qquad (3)$$

Where Ai is footprint area of building I, hi is height of building i , and Aj is area of non built elements.

3.3.2 Standard Deviation of Building Height

$$S_h = \sqrt{\frac{\sum_{i=1}^{n}(h_i - \bar{h})^2}{N-1}} \qquad (4)$$

where $\bar{h}$ is the mean building height, S_h is the standard deviation of building height, h_i is the height of building *i*, and *N* is the total number of buildings in the area.

3.3.3 Building Plan Area Density

The building plan area density *(λ_p)* can be defined as the ratio of the plan area of buildings to the total surface area of the investigate areas：

$$\lambda_P = \frac{A_P}{A_T} \qquad (5)$$

Where A_P is the plan area of buildings at ground level, i.e., the footprint area, and A_T is the total plan area of the area of interest, i.e., computational grid cell unit.

3.3.4 Building Volume Ratio

the building volume ratio $a_p(z)$ can be defined as the average building plan area within a height increment divided by the volume of the height increment：

$$a_p(z) = \frac{\frac{1}{\Delta_z}\int_{z-\frac{1}{2}\Delta z}^{z+\frac{1}{2}\Delta z} A_P(z')\,dz'}{A_T\Delta_z} \qquad (6)$$

Where $A_P(z')$ is the plan area of buildings at height z', A_T is the plan area of the site, and Δz is the height increment for the calculation. Since A_T is not a function of height it can be brought into the integral in the numerator producing：

$$a_p(z) = \frac{\frac{1}{\Delta_z}\int_{z-\frac{1}{2}\Delta z}^{z+\frac{1}{2}\Delta z} \frac{A_P(z')}{A_T}\,dz'}{\Delta_z} \qquad (7)$$

Knowing $\lambda_P(z') = A_P(z')/A_T$ and assuming that the building plan area does not change noticeably within a small height increment Δz, equation (10) can be approximated by:

$$a_p(z) \cong \frac{\lambda_P(z)}{\Delta_z} \qquad (8)$$

3.3.5 Building Frontal Area Index (λ_f)

$$\lambda_f(\theta) = \frac{A_{proj}}{A_T} \qquad (9)$$

Where θ is the wind direction, e.g. θ=0 represent north wind direction and θ=180 represent south wind direction. According to the findings of Grimmond and Oke, the frontal area index **(λ_f)** can be obtained from the product of mean height, breadth, and density of roughness elements which presented as equation (10).

$$\lambda_f = L_y\overline{H}\rho_d \qquad (10)$$

where L_y is the mean breadth of the roughness elements perpendicular to the wind direction, $\overline{H}$ is the mean roughness element height, and ρ_d is the density of roughness elements per unit area ($\rho_d = n/A_T$). The λ_f value for the computational cell is determined for northerly, northeasterly, southerly, and southeasterly winds.

3.3.6 Complete Aspect Ratio

According to the definition by Voogt and Oke, the complete aspect ratio (λ_C) can be defined as the summed surface area of roughness elements and exposed ground divided by the total plan area. The equation (11) below is the presentation of complete aspect ratio.

$$\lambda_C = \frac{A_C}{A_T} = \frac{A_W + A_R + A_G}{A_T} \qquad (11)$$

Where A_C is the combined surface area of the buildings and exposed ground, A_W is the sum areas of wall surface, A_R is the sum area of roofs, A_G is the total area of exposed ground, and A_T is the plan area of the study site（the setting of grid unit）. A_C is calculated by summing the surface area of the buildings and the difference between the total plan area of the site and the plan area of buildings at ground level, i.e. the exposed ground surface. For dense urban areas with flat roofed buildings and without much vegetation, A_C can be approximated as the sum of the plan area of the site and the area of building walls which not including the area of rooftops.

3.3.7 Building Surface Area to Plan Area Ratio

The building surface area to plan area ratio（λ_B）is defined as the sum of building surface area divided by the total plan area, and as presented in equation (12).

$$\lambda_B = \frac{A_R + A_W}{A_T} \qquad (12)$$

Where A_R is the plan area of rooftops, A_W is the total area of non-horizontal roughness element surfaces, e.g. walls, and A_T is the total plan area of the specify grid cell, and the computation is based on a flat-roof assumption.

3.3.8 Height-to-Width Ratio

According to the equation (13), the height-to-width ratio (λ_S) is normally calculated for two buildings by dividing the average height by the distance between the two buildings:

$$\lambda_S = \frac{(H_1 + H_2)/2}{S_{12}} \qquad (13)$$

Where H_1 is the height of the upwind building, H_2 is the height of the downwind building, and S_{12} is the horizontal distance between the two buildings or commonly says the canyon width. For those idealised arrangements of buildings, the calculation of an average λ_S can be approximately achieved by taking the average building height divided by the average width between buildings according to the research of Grimmond and Oke [6] that represented in the equation (14).

$$\overline{\lambda_S} \cong \frac{\overline{Z_H}}{W} \qquad (14)$$

4. Preparation of Basic Maps

4.1 The Resources of Geo-Database

The British city of Sheffield where author located has been chosen as the site for this study. In terms of analysing the urban morphology, along with basic data relating to footprint areas and the perimeter length of the investigated buildings, digital elevation models and digital surface models containing information on height and surface conditions will be vital for urban-scale analysis.

The most up-to-date 2D and 3D models were extracted from airborne LIDAR data which provided by the UK's Environmental Agency. The original images then converted into raster format data by using ESRI ArcGIS® software to present and process the images properly.

The latest OS MasterMap® from the UK-based Ordnance Survey® were obtained and then processed as the basis for mapping. GIS layers such as buildings, roads, water and lands were pre-classified according to the data contained within the attribute table relating to building properties such as areas and length of perimeter, and the width and length of roads.

The geographic data required by GIS such as information on terrain, boundaries, land use, levels of air pollution, occupancy rates, and other substantial neighbourhood data were derived from the UK-based EDiNA UKBORDERS® databases and National Statistics® databases respectively. Those statistical data which have significant influences on urban morphology and climate performance can be converted and totally integrated with existing OS MasterMap® attribute tables for the subsequent computing process.

4.2 The Integration of Basic Maps

The rasterised LIDAR data then merged with the OS MasterMap® in order to integrate the height information into the attribute tables of the OS MasterMap® through a specified geo-process. This semi-automatic process will avoid conventional labour-intensive as well as time-consuming site surveys which providing an effective approach of presenting information on elevation of buildings and terrains at city scale.

Due to differences between data deriving time and ongoing urban developments, it is inevitable that the initial mapping results may not be matched completely with the actual worlds. The refinement in terms of accuracy is made possible through 3-D aerial view with reference to web-based MS Virtual Earth® and Google Earth® to examine the accuracy of maps.

5. Outcomes of GIS Computation and Validation of Climate Maps

5.1 Assumptions and Limitations

The extent of Sheffield city centre within ring road with broadly similar terrain has been chosen for the investigations. Prevailing wind of north-east and south-west directions are set for the studies. Detailed meteorological data were derived from the nearest meteo-station. In terms of simplicity, a number of physical properties of buildings and their adjacent environments, e.g. the effects on NVP due to air infiltration, openings, roof types, materials and minor obstacles such as vegetations and fences were temporarily neglected at this stage due to reducing the complexity level of this work.

Only the composition of building clusters and the physical properties of buildings, e.g. average height, footprint area and length of perimeter will be taken into account at this stage. The buildings under investigated are mainly rectangular shape treated as clusters of prominent objects over the ground surface. In terms of presentation, the final mapping results will be shown in the raster format embedded in GIS with a grid cell resolution of 100m×100m. Further works for investigating buildings and their influences of noise level, air pollutants dispersion capacity, terrain effects and vegetations roughness etc. are recommended in the future.

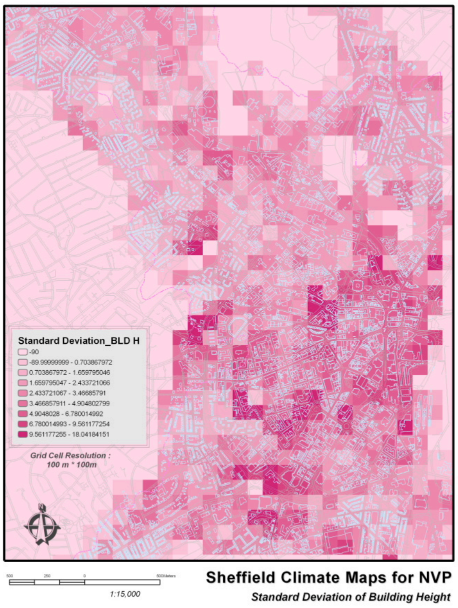

Figure 1: Map of standard deviation of building height, Sheffield, UK.

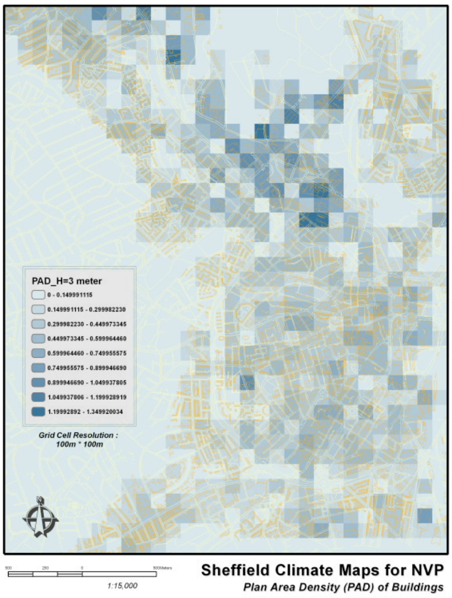

Figure 2: Map of plan area density, Sheffield, UK.

5.2 Results of Computation and Validation on Climate Maps

Once sufficient information has been obtained from urban databases and basic maps have been prepared, the computing process will be utilised to generate urban canopy parameters either in form of attribute tables or raster/vector format maps. Some examples of climate maps that produced through computation process are shown in figures 1 and 2 to represent standard deviation of building height and plan area density of Sheffield city centre. The GIS-based analysis approach namely the Cost Surface method will be employed in analysing the individual thematic raster maps to generate a series of NVP maps, with main aim of assisting decision-makers in the urban planning process.

There are two validation methods been set for this work. The first validation process of those climate maps was carried out by using rasterised maps of NO_x concentration levels which derived from local air quality monitoring station that provided by Sheffield City Council. The coldest and hottest days in 2007 were selected as the examples for analysis. Those rasterised maps of NO_x concentration levels were computed by a web-based environmental GIS tool so called the Airviro®. Moreover, the Gauss Model within Airviro® system is used to simulate the distribution of ground concentrations of pollutants over various urban areas with a typical scale of one or a few tenths of kilometres. One hour mean values are simulated as it is known that the wind may be more or less constant during a period, and the resolution was set to 100m×100m grid cell.

The second validation process was done by using Ward's studies [10] on three types of flow regime and their correlations with urban densities, average building height. Ward's work is an advanced finding which adapted the studies of Lee & Hussain. The GIS themes of NO_x concentration levels and Ward's studies were superimposed and analysed through geo-process, and one of the examples is shown in figure 3. Eventually, a relatively accurate standard is achieved while comparing NO_x concentration maps and Ward's findings, and the computed outcomes of climate maps have shown that the results matched with initial assumptions.

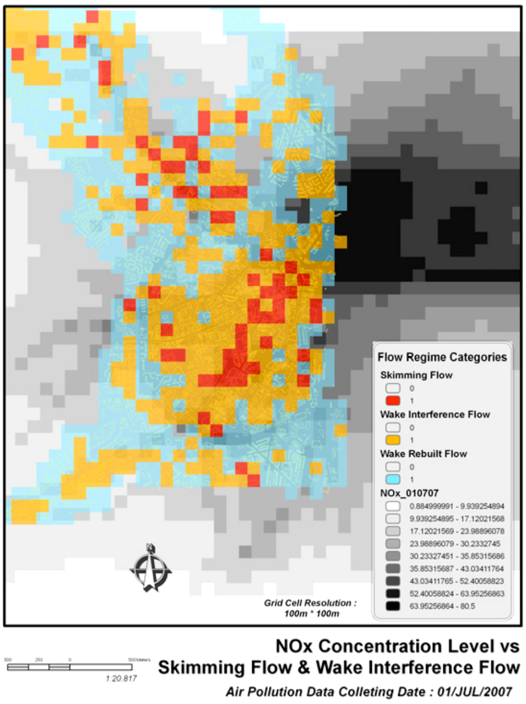

Figure 3: The superimposed map of combined flow regime types and NO_x concentration levels.

5. Conclusion and Suggestions

A city can be benefited significantly when a series of full-illustrated climate maps becomes available for assisting decision-making process. The ventilation route can be identified and those problematic areas of ventilation can be recognised as well. With the climate maps provided by this study, a general understanding of wind-driven ventilation potentials and their correlation with urban morphology through geographical aspects can be achieved by GIS mapping approaches. However, more works need to be done in order to broaden the computation capability and accuracy of this method in terms of applying to larger scale sites, and sites with complex varieties over urban morphology parameters.

Even though the absolute standards to suit one particular city and its climate are unavailable at the moment, it is likely to be achieved through further aerodynamic models studies such CFD and more information on urban morphological parameters become available. Further studies are essential in order to improve precision and completeness in the future will be carried out when time and funding are made available.

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