A GIS-based Method for Determining Natural Ventilation Potentials and Urban Morphology

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ABSTRACT: The provision of fresh air in cities is one of the main drivers for sustainability, helping to preserve occupants' health and comfort both indoors and outdoors. Moreover, it is well known that there is a crucial correlation between the natural ventilation potential (NVP) and the composition of urban morphology in built environments. However, only limited information on natural ventilation design within cities is available to local authorities and designers when considering urban planning strategies, and this is having a crucial influence on subsequent building design.

This paper explains the ideas and problems associated with such research and the strategies to be undertaken. Using up-to-date Geographical Information Systems (GIS) and Computational Fluid Dynamics (CFD) programmes, strategic guidelines and standards for urban morphology, microclimate and energy density can be identified and represented in a series of GIS-based climate maps. The methodology adopted for this study may be applied generally to provide data in other locations which will make a significant contribution to evidence-based policy-making and management.

Keywords: GIS, Urban Morphology, Microclimate, Decision-Making Process, CFD, Natural Ventilation Potentials, Sustainability, Energy Density.

1. INTRODUCTION

The motivation behind this work is the UK Government's emphasis on the significance of scientific knowledge in evidence-based policy-making in the field of sustainable development [1]. The work comes within the scope of the built environment and energy prediction [2] which is incorporated into Computational Fluid Dynamics (CFD) and embedded in the GIS, which is the principle interface for data input, storage, retrieval, and manipulation. With assistance from advanced IT capacity, further geo-process functions of queries, mapping, modelling, visualisation and spatial analysis can be carried out which is highly useful for the decision making process.

It is known that the provision of fresh air in cities is one of the main drivers for sustainability, which helps to preserve occupants' health and comfort both indoors and outdoors. Given the effects of urban form on Natural Ventilation Potential (NVP), it is highly advisable to look at the built environment as a whole. However, the majority of conventional studies are mainly focused on isolated buildings which not only limit the progress towards sustainability, but also have the opposite effect on the building itself and adjacent environments as well.

The significance of considering the urban wind field as a whole has been stated by Bottema in 1999 "*detail measures sometimes are far less effective than measures that effects the building as a whole or the distribution of building masses ….. even precise calculations are intervened in a stage of the design process where generally, only remedial action on details is possible*" [3].

This work can be used as a pilot study of the author's doctoral research topic and is aimed at formulating a correlation between urban form and microclimate, specifically the issues of natural ventilation potential to investigate their effects on health, comfort and energy density at an intermediate scale corresponding to the neighbourhood or city block with the ultimate aim of aiding policy-makers and practitioners.

1.1 The Changing Policy

The UK Building Regulations Part-F (which is the regulation for ventilation design) which requires a 25% improvement of energy efficiency of buildings. This requirement enhances the air tightness of designs while also encouraging natural ventilation for comfort and health on the other [4]. To conform to these even stricter regulations and promote energy efficiency with consideration to health and comfort, it is important to define the standards of NVP in the urban morphology at the initial stage of urban planning which could avoid possible problems in meeting natural ventilation potential.

The conflicts between energy efficiency and quality of life are believed to be deepened according to the monitoring report for the Home Energy Conservation Act 1995 in 2001 [5]. Local Energy

Conservation Authorities in England felt they were unlikely to achieve the 30% improvement in energy efficiency required under HECA, especially when attempting to achieve a balance of the above issues. Moreover, 85% of all ECAs identified the lack of a clear, simple and practical methodology and insufficient professional staff for modelling local environments, establishing baseline data, monitoring progress and the difficulty of directing limited funds as the key barriers for policy-making.

1.2 Wind Field Modelling and Prediction

The understanding of urban wind fields is crucial for achieving better sustainability through natural ventilation design. However, it is commonly felt that the wind profile above the urban canopy is complex and the information of wind field is hardly ever measured. Conventionally, the term of roughness length which comes from aerodynamic engineering is usually used to characterise the relationship between urban geometry and wind flow and other surface parameters.

Even though the provision of wind field information is essential for urban planning at the early planning stage when considering the benefits of natural ventilation design, practitioners and decision-makers can only rely on their empirical estimation when considering natural ventilation design currently due to the lack of urban wind field information such as simple, reliable data of pressure coefficient and airflow distributions.

It is therefore essential to provide a simple and clear guideline to characterise the wind fields within urban context that correspond to the various indicators of urban form. This “rules of thumb” can guide decision-makers trying to identify whether the overall planning is appropriate and the quantity of fresh air that is supplied is sufficient. Moreover, with less rigorous scientific calculation, practitioners are supposed to be more interested in natural ventilation design and will benefit by avoiding either complex Computer Fluid Dynamics simulation or testing scale models in a wind tunnel, which is time consuming, user unfriendly and costly.

It is undoubted that cities can also obtain maximum advantage when a series of fully illustrated climate maps become available for decision-making purposes, as baseline information can be identified, progress monitored, and the problematic areas within cities can be recognised.

2. NATURAL VENTILATION IN URBAN CONTEXT

2.1 Significance of Enhancing Natural Ventilation Potential in Built Environment

The knowledge of air movement patterns around buildings and within urban areas is important in relation to various aspects. Optimising natural ventilation can dilute indoor air pollution, moderate the Urban Heat Island Effect and enhance air quality and thermal comfort within cities especially during the hottest season of the year [6]. Nevertheless, a well-designed urban ventilation system is also necessary to provide appropriate wind shelter, which could enhance the thermal performance in the winter.

The built environment, health and comfort of the public, as well as compromising energy efficiency are all seriously threatened due to increased global warming and rapid sprawled urbanisation. The enhancement of NVP creates the possibility of ensuring an acceptable indoor air quality by natural ventilation only [7] and inhabitants’ quality of life can be assured due to provision of fresh air in cities. The significant energy demands of air conditioning can also be reduced by means of adequate and appropriately designed natural ventilation systems. Basically, it is important to keep in mind that the three objectives of natural ventilation design in buildings which are indoor air quality, thermal comfort and energy saving can possibly achieved when an adequate design of NVP did applied.

Actually, the conflict between energy performance and occupants’ quality of life, which is the key issue in sustainability, is always challenging practitioners. Approximately 30% of the energy delivered to buildings is dissipated in extract ventilation and exhilaration air streams. In the UK climate, significant energy savings can be achieved by enhancing the efficiency of space heating, which accounted for 40% of all non-transport energy consumption in the UK in 2000 [8].

It is evident that the UK government intends to reduce energy wastage by enhancing air-tightness and envelope insulation performance through stricter building regulation. However, it is well known that sealed buildings without appropriate ventilation can cause sick building syndrome and poor user satisfaction. The attempts of the UK government must also take into account the need for natural ventilation in order to maintain adequate indoor air quality and prevent discomfort due to overheating in the warmer season.

2.2 Factors that Influence NVP

The terms “roughness of terrain” and “roughness length” that are derived from aerodynamics are conventionally used to describe the wind field of open space. However, in even complex urban environments, more morphological parameters such as indicators of rugosity, porosity and sinuosity which relate to the urban wind field were proposed to quantify the forms of built environment and their correlation with microclimate.

It is known that the driving forces of natural ventilation are mainly caused by wind pressure difference (ΔP) and temperature difference (stack effect). In this work, the investigation is mainly focused on wind pressure difference forces, and the key factor that is required in this study is the pressure coefficients (C_p) and volume flow rate (Q_v). The pressure coefficients on the façades of buildings depend on the wind direction and surrounding buildings [9].

The value of the pressure coefficients can be determined either experimentally in wind tunnels or numerically using CFD and can have any value between -1 and +1 [9], depending on the shape, dimension and location of surrounding buildings. It is important to consider building clusters as a group of prominent objects which temporary ignoring the detailed opening of buildings. Because ΔP is the pressure difference due to airflow effects on a surface, not to the pressure drop through a hole impingement or the pressure coefficient no longer has a meaning.

The formulae that are listed are cited from Section A4 of CIBSE Guide A which is the basis for air infiltration and natural ventilation design in the UK [10]. Equation (1) represents the volume airflow rate through opening and equation (2) represents the figure of pressure coefficient.

$$Q_v = AC_d \left(\frac{2\Delta p}{\rho} \right)^{0.5} \tag{1}$$

Q_v = volume flow rate (litre/s) C_d = discharge coefficient (0.61)

A = area of opening (m^2)

Δp = applied pressure difference (Pa) ρ = density of air (kg/ m^3)

$$C_p = \frac{(p - p_0)}{\frac{1}{2}\rho u_r^2} \tag{2}$$

C_p = pressure coefficient

p = mean pressure at any point on surface of building (Pa)

p_0 = static pressure in undisturbed wind (Pa)

u_r = mean wind speed at height equal to building height (m/s)

The key parameters that regarded in this work are mainly focused on wind pressure difference (ΔP), pressure coefficients (C_p) and volume flow rate (Q_v) in built up environments. It is known that the distribution of polluted air and the exposed level of noise in urban environments are one of the crucial factors that may affect NVP significantly, and it seems inevitable to take into account at the same time while considering the influences on NVP. However, due to timing and capability that available currently, further descriptions in this paper seem unable at the moment, and may leave the extension of this prospected research into author's future studies.

3. GIS and URBAN MORPHOLOGY

3.1 GIS on Built environment Studies

GIS has typically been applied in the profession of geography and planning for the specific purpose of land use management, transport and pollution prediction, housing stock and environments mapping. In the last decade [11], there has been an increasing tendency in many OECD countries to extend the use of GIS into different sorts of built environment in the drive to achieve evidence-based evaluation.

As urban sustainability becomes an interdisciplinary concern, GIS is one of the formalised computer-based information systems that is capable of integrating data from various sources to provide the information necessary for effective decision-making in urban planning. The prediction of air distribution and air quality [12], solar irradiation mapping [13], heat emissions mapping, thermal comfort performance [14], renewable energy evaluation [15], and post occupancy management [16] etc. are all viable examples of GIS application in the built environment studies.

Moreover, GIS also serves as a database and a toolbox for practitioners and authorities enabling efficient data retrieval, mapping and queries of the"what if" scenario [11]. Practically, the visualisation merits of GIS can improve analysis quality in turn leading to better communication between participants throughout the whole design process.

The composition of urban morphology has a crucial effect on microclimate performance and energy density. In order to provide reliable strategic guidelines and management methods for decision-makers, it is essential to extend the concepts of urban morphology for NVP into the built environment, especially when excessive urbanisation posing a global threat.

3.2 Urban Morphology on Built Environment Studies

Research into Urban Morphology has been going on since the end of the 19th century, and the majority of the work that has been carried out was generally in the fields of geography, history, archaeology, sociology and estate management [17]. In the last two decades, the so called Space Syntax theory developed by Prof. J. Hanson and B. Hillier [18] has been successfully applied to form the examples of quantitative spatial analysis such as pedestrian modelling, crime analysis, traffic pollution prediction, and way-finding processes. With improvements in IT capability, even more precise and efficient spatial analysis tools have become available, such as GIS along with various extended programmes, e.g. Axwoman of ArcGIS [19] and Morphologic of MapInfo [20].

3.3 Gap of Previous Works

The proceeding work was inspired by Prof. Luc Adolphe's theory of urban morphology indicators in 1999 which is embedded in GIS software of 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. Prof. Adolphe has used this self-developed GIS-based method so called the Morphologic to examine the forms of three different cities in various locations with its own climate and historical background. His research has made a significant contribution to an understanding of the correlation between urban morphology and microclimate.

The formulae that are listed are derived from Prof. Adolphe's work on urban morphology indicators [20]. Equation (3) and equation (4) represent the indicator of absolute rugosity and relative rugosity respectively in the designated areas. These indicators treat the urban fabric as the composition of numerous prominent obstacles, and the purpose of calculation is to obtain the mean height of the urban canopy. The higher the indicator the lower the NVP and vice versa.

Equation (5) represents the indicator of porosity and treats urban environment as a porous medium with solid skeleton, the speed of the air varies along the pores in accordance of the local unevenness involved. The higher the indicator the higher the NVP and vice versa. Equation (6) represents the indicator of sinuosity which considered the street oriented with an angle θ of which against the pressure gradient flow. In the case of flow parallel to the street, the sinuosity is zero which means it has the highest potential for natural ventilation. As the included angle between wind direction and street direction enlarged, the resistance of wind pressure also increased at the same time, which has a negative effect on NVP.

$$Hm = \frac{\sum_{built} Aihi}{\sum_{built} Ai + \sum_{nonbuilt} Aj} \tag{3}$$

Ai = footprint area of building i hi =height of building i

Aj = area of non built element

$$R\alpha = \frac{\left[\sum_i (hi - h\alpha)^2 li^2\right]^{1/2}}{\sum_i li} \tag{4}$$

hi =height of the (built or non built) element I of the canopy.

$h\alpha$ = mean height of the urban canopy in the direction of α .

hi li = width of the element I of the canopy in the plane of direction α .

hi $\sum_i li$ =diameter of the urban canopy which is studied.

$$Po = \frac{\sum_{openspaces} \pi r_{hi}^2 Li}{\sum_{openspaces} Vi + \sum_{built} Vj} \qquad r_h = \frac{lh}{1+h} \qquad A_u = \pi r_h^2 \tag{5}$$

$A_u = \pi r_{hi}^2$ =useful area of the street Li =length of the open space

r_h = hydraulic equivalent radius Vi = mean volume of the built volume

Vj =mean canopy volume above open space

l =mean street width h =height of the canopy of the street

$$S_o = \frac{\sum_{StreetSegment} L_i \cos^2(\theta_i)}{\sum_{StreetSegment} L_i} \tag{6}$$

L_i =length of the linear segment

θ_i = angle between the given flow azimuth and linear azimuth

However, Prof. Adolphe's work merely compared factors in different locations in relative aspect, but set no "absolute factors" for any given region and its climate. This means that the standard of NVP in one specific city within one particular climate zone can hardly to be established. Moreover, his broad view of Urban Morphology implies that the investigation of NVP and its effects on urban morphology can be even more detailed. Further precise simulation and analysis of NVP needs to be carried out, and more indicators which correlate to NVP such as Terrain indicator and Vegetation Indicator need to be added to complete this multi-criteria theory.

4. METHODOLOGY AND PROCEDURE

4.1 Site Selection of Study

The British city of Sheffield which is the most accessible and feasible site for detailed site survey and measurement, and is one of the most rapidly growing cities in the UK was chosen as the focus for this research. Overall, Sheffield has seen a 16.8% increase in the number of planning applications since 1999, the housing and retail sector seeing a 30% and 3% rise respectively. The continued rise in planning applications is a reflection of the overall increased attractiveness of the city as a place to work and live [21].

Moreover, Sheffield is very likely to see another 4105 dwellings built in the city centre over the next 10 years in addition to the 2,000 residential units which already exist in the city centre. With a potential total of 6,152 dwelling units required and limited housing sites available, the city council has carried out assessments of a number of sites that are not appropriate for housing development but which are still likely to be used for this purpose. It is estimated that the population in the city centre will grow to 18,000 by 2010, a three fold increase on 2002's baseline figure of 6,500.

It is evident that the urban morphology will be dramatically changed, and that this will seriously impact upon the microclimate and energy performance. Evidently, unless careful consideration is given to urban design, the effect on the population's quality of life will be dramatic. It is important to make the right decisions at the initial stage of every planning application. This research is essential to enable Sheffield city authority and planners to assess changes in urban forms and their effects on sustainability.

4.2 Assumptions of Study

The detailed meteorological data of air temperature and wind-rose for the past ten years were derived from one of the Meteorological stations based in Weston Park, Sheffield. Selected climatic data during the hottest summer and coldest winter period which is the essential NVP related were specially taken into account in this research.

Regarding the setting of buildings and their adjacent environments, the influences over NVP due to air infiltration, size of opening and minor obstacles such as low-height vegetation, individual vegetation and fences were temporarily ignored due to the consideration of preciseness level and the purposes of this research. Only the composition of building clusters, volume of buildings and orientation of openings were concerned at the present time. In other words, this study treats the urban environment as a composition of numerous prominent objects.

4.3 Procedures and Methodologies of Study

Phase-1: The latest GIS programme of ArcGIS 9.0 from ESRI [22] and the CFD simulation programme of IES [23] will mainly be employed throughout the research process. In this phase, the basic GIS maps the so called DigiMap in NTF format [24], are used to provide initial detailed understanding of the shapes, areas and layouts of the designated urban environments. Further site surveys will be carried out to obtain information of NVP such as opening, layout, orientation, height of buildings, adjacent obstacles and energy density for those sub-divided city blocks (Figure 2). The information and data that are collected will then plot onto GIS as the basic spatial and attribute data.

Phase-2: A self-developed urban analysis GIS-based method named UMIT by using exclusive ArcGIS language of VBA (Visual Basic for Applications) comes next in this phase for the purpose of obtaining urban morphology indicators that are specifically based on the climatic features of the UK and the urban fabric of Sheffield City. With this unique extended geo-process tool, it is possible to integrate, analyse and evaluate those interdisciplinary data which can affect NVP within urban areas into a simple urban morphology indicator and show various spatial and attribute data in a serial of GIS layers.

Through advanced geo-process by using exclusive spatial analysis tools that are embedded in ArcGIS, the layers will then be sub-divided into designated intervals and shown with varied gradation of colours for visual identification. For instance, the GIS-layer of porosity is divided into 5-grades with units of percentage (%) and intervals of 20%, and the colour shown for porosity layer is in a gradation from light blue to dark blue (Figure 3).

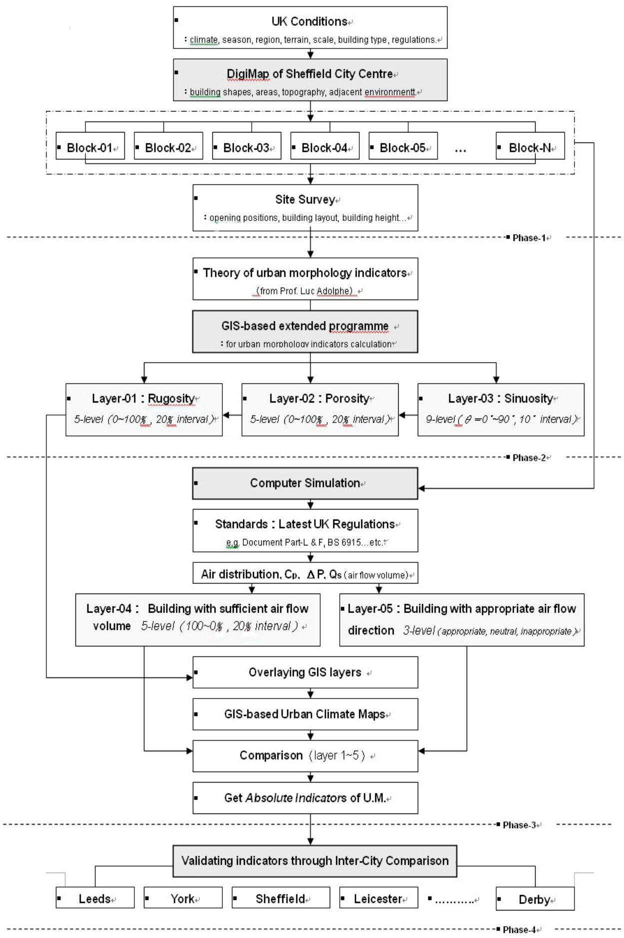

Figure 1: The Description of Experimental Procedure

Phase-3: Cooperating with ArcGIS is the up-to-date building Computational Fluid Dynamics (CFD) programme, Integrated Environmental Solutions (IES), to simulate the designated areas and obtain definite details of air distribution, volume airflow rate and pressure coefficients. The outcomes of the CFD simulations which against the latest building regulations such as Part-F and BS-6915, and current energy density of buildings will be plotted onto GIS as further layers of urban airflow performance for further geo-processing, in order to explore their correlation with the layers of urban morphology indicators. The scale of pressure coefficient will be divided into the interval of 0.2 and distinguished with 10 colours in a gradation of selected colour and similarly for the representation of external airflow quantity and appropriateness of opening orientation (Figure 4).

Eventually, through analysis, of the above layers of urban morphology indicators and urban airflow performances, guidelines and standards for natural ventilation potential for city centre of Sheffield will be established. The results will be shown in a series of urban climate maps for the purpose of visualisation, communication and decision-making at the very beginning of planning process.

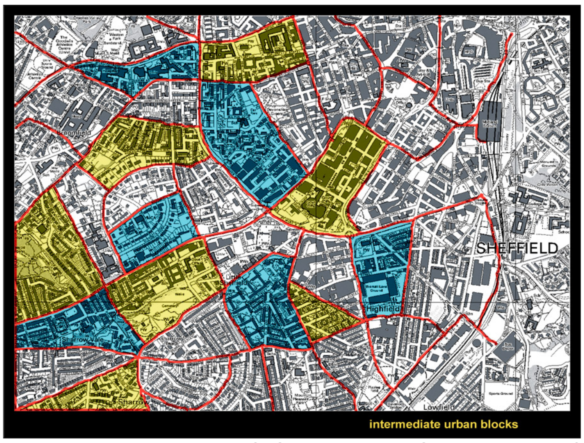

Figure 2: The Map of Sub-divided City Blocks of Sheffield City Centre.

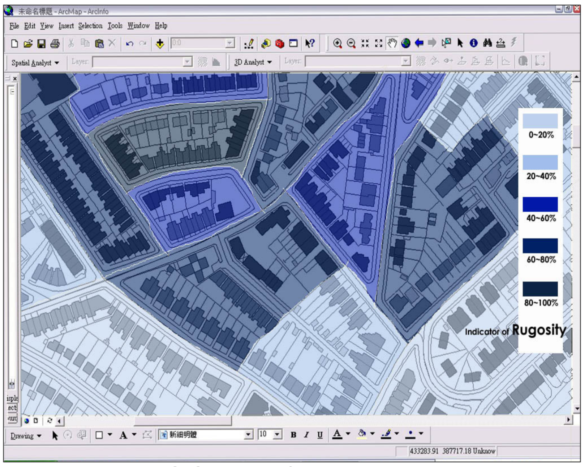

Figure 3: The GIS layer of Rugosity Indicator

5. CONCLUSION AND PROSPECT

According to the statements in above sections, the layers identified in the geo-processing will be shown in the form of a series of climate maps enabling decision-makers to understand, visualise and communicate throughout the design process. Using this method, urban areas with poor or excessive NVP can be identified. This will allow the authorities to invest more time and money in improving those problematic areas. Furthermore, when the baseline standards for urban form and NVP are established, this will enable authorities and practitioners to monitor the level of progress being made and facilitate the review of policy performance throughout the whole process.

This study of the correlations between urban morphology, microclimate and energy density will only be able to provide guidelines and standards for NVP design which suits the climatic feature of the City of Sheffield, or more specifically Sheffield City Centre. With capable timing and essential supports in the future, the methodology of this work can be extended into various locations of Sheffield City and other English cities as well. Moreover, the considerations of noise level and air pollution transference within urban areas and the producing of additional GIS layers which accumulated on current works are seriously anticipated and highly possible to be achieved in the near future.

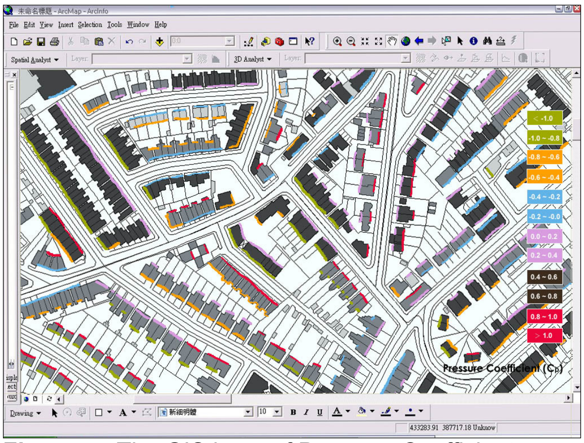

Figure 4: The GIS layer of Pressure Coefficient

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