Utilizing simulation to predict natural ventilation and wind flow

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ABSTRACT

To predict ventilation and related air flow parameters, a lot of calculation techniques could be utilized; however the main difficulties concern ease of use and the providing of input data. Today, many advances are taking place, especially in the areas of user friendly access and embedded databases. To find reliable result in designing process and evaluate the performance of ventilation simulating methods are increasingly needed in every step of designing. They are especially important for making preliminary evaluations of complex ventilation and air flow strategies. (Liddament, 1996)
In both methods which have been reviewed in this paper, not only their needed data are easy to find and use, but also the results are applicable in a general and wide fields of design. The first one is a graphic base method which could be helpful in predicting wind speed and quality by using a minimum data required. The second one is based on raster image analyzing which will be more and more developed in future as remote sensing technology accelerates developments.
The outputs are useful in basic steps of design and in a scale between urban scale and a single building scale but not applicable in an especial building unless the utilized data and method become more accurate and developed. Therefore these approaches introduced as useful methods in very early stage of design.
Conference them: simulation of natural ventilation

1. INTRODUCTION

“Today Buildings should be designed to interact with the outdoor environment” and utilize it to create “an acceptable indoor environment whenever it is beneficial to do so.”(IEA-ECBCS,2002) Utilizing such passive systems depends on the outdoor climate, building use and location, and building design. As a case the primary purpose of ventilation is to provide acceptable air quality and thermal comfort.
In Natural Ventilation, the flow process is driven by wind and temperature while the main drawback is lack of control, in which unreliable driving forces can result in periods of inadequate or over ventilations both resulting excessive energy waste and lack of comfort. Thus it is a need to find that where and how it could be used as a beneficial system. There fore the short comings of natural ventilation, which in today buildings overcome by parallel mechanical ventilation (hybrid ventilation system), should be predictable. In addition the very important parameter in natural ventilation is the flow rate of outside which is critical to be known or predicted for designer. On the other words, It could not be forgotten that the better knowledge of natural ventilations (inside the buildings) and simultaneously wind flow (outside the building for both pedestrians and inside occupant as driving force) is still fundamental for obtaining optimal implementation of hybrid ventilation strategies.
Off course there is a lot of simulating programs and calculations methods which try to predict natural ventilation and solve the its problems, but these techniques tend to be too complex and they are not user friendly. This essay tries to explain the mentioned problems and introduce some simple approaches which are available to perform complex design tasks such as graphs and remote sensing methods. By using these methods, data could be converted to designer language to give him/her the ability of better designing and also better understanding of numerical techniques. This need has resulted in the development of improved algorithms and wider availability of design data.

2. SCALE AND VENTILATION

It is clear that in designing there are two major approaches defining comfort according to the wind flow for different users; described as a type of scale by authors:
• *Inside Building:* Natural/Hybrid Ventilation
• *Outside Environment:* Wind flow
Herewith we named the first scale the *Architectural Scale* and the second one the *Urban Scale*. Therefore architectural designing of a building should be coordinated with its urban scale surrounding as the first one is completely depends on the wind flow. Comprehending the importance of the mentioned relationship is necessary for architects who want to utilize natural ventilation strategies in their buildings (Gandemer, 1977).
On the other hand the coherence of the wind flow pattern and urban design is one of the most important approaches for the urban planning expertise; especially as the results of their designing is considerable in architectural scale.

3. DESIGN APPROACHES

As with all design processes, designing concept steps

for the natural ventilated buildings are part of an iterative process. In addition at each steps of designing the appropriate tools should be utilized to find the best approach, solution, and achievements. Therefore it is critical to separate the early stage of design from the final advanced steps of design developments and checking steps. In other words, the architects will not utilize the advanced criteria in their very first step of design unless they found it easy to use and applicable. On the other hand not only checking the efficiency of such fluid mechanical processes or such accurate and complicated methods in the first steps needs some experts, but also the creativity of the architect and the flow of his/her lines (means walls, ceilings, façade, etc. in designing procedure and conceptual designing) would be restricted if s/he wants to complicate her/his problems with the subject of natural ventilation by using such methods.
In addition, like all designing procedure in architecture, both the *comfort* as criteria and *environmental conditions* as potentials and restrictions are critical to be considered. It means that to achieve to the comfortable environment, even inside or outside in architectural scale, the design should change the condition to the desired condition according to the comfort criteria and simultaneously check the result in advanced later steps.
According to the noted design approaches, it is beneficial to divide the design into at least two major parts as below:

- A) Early stage of design

Architectural sketching, conceptual design, phase 0 and phase 1 of design

- B) Developed design

Phase 2, developed design, advanced design and checking the efficiency and applicability, measurements
For sure for the stage A, especially in the very early steps, using calculation methods is not that much appropriate in architectural designing. As a result the *simulation methods* are being used instead of them. But still those simulation methods which needs a lot of input data or accurate data are not applicable, even in phase one of the design. To solve such problems those methods are replaced with alternative methods which are more easy to use and user friendly.Calculations technique and simulation methods should be used to analyze the interaction of design options with fixed constraints. Such processes are necessary iterative, with adjustment made to parameters over which control is possible, until an optimum design solution is achieved.

4. NATURAL VENTILATION MECHANISM

The magnitude and pattern of natural air movement through a building depends on strength and direction of the natural driving forces and the resistance of the flow path. The driving forces for natural ventilation are wind and density difference which will be defined as follow.
For a given configuration and particular arrangement of openings, the rate of natural ventilation varies according to the prevailing driving forces of wind and indoor/outdoor temperature difference. Despite this variability, it is nevertheless possible for satisfactory design solutions to be developed, "provided that flexibility in indoor air temperature, air flow rate and instantaneous ventilation rate can be accommodated."(Liddament, 1996)
Natural ventilation is driven by wind and thermally (stack) generated pressures. (Liddament, 1996)

- *Wind pressure:* Wind striking a rectangular shaped building induces a positive pressure on the windward face and negative pressures on opposing faces and in the wake region of the side faces. This causes air to enter openings and pass through the building from the high pressure windward areas to the low pressure downwind areas (Givoni, B. 1998).
- *Stack pressure:* Stack effect is developed as a result of differences in air temperature, and hence air density, between the inside and outside of the building. This produces an imbalance in the pressure gradients of the internal and external air masses which results in a vertical pressure difference. Calculation of stack pressure is based on the temperature difference between the two air masses and the vertical spacing between openings.

The distribution of the pressure, according to the wind across the external surfaces, depends on (Gandemer, 1977):

- The type of terrain surrounding the building and presence of any local obstruction
- The wind speed and its direction
- The shape of the building

The wind pressure acting across a building is dependent upon the wind speed at the site. Not only the wind speed would be reduced, but also the pressure distribution on the buildings might be significantly influenced by local obstructions such as trees, other buildings, and etc. as an illustration a tall building just downwind a lower building can deflect the wind so that the down stream face of the small building is in a positive rather than a negative pressure region. Therefore the designer has to use the lay out of the site to maximize the robustness of the wind driven ventilation design; which may be done by careful orientation of the building according to the existing topography (Givoni, B. 1998).
It is visible that the careful orientation of a building in relation to the topography of the site and wind direction can maximize the potential for wind driven ventilation which can be enhanced by landscaping or decisions on the position of the building related to the building on the site. However high winds in winter, as well as low in summer wind speeds should be considered.

5. GENERIC CALCULATION METHODS

As the first step of wind flow and natural ventilation include both architectural and urban scale, the rate and pattern of air flow should be considered. This item throughout a building is uniquely defined by (Melaragno M. 1982) as a distribution and pressure of air flow. While (Liddament, 1996) the pattern of air movement within any individual space is influenced by some factors are: The temperature, velocity and turbulence of incoming air at each source, The location and flow rate of all sources of outgoing air, The distribution of flow obstructions (e.g. partitioning, furnishings and fittings) , The distribution and strength of all thermal sources and sinks, The thermal characteristics of all surfaces.

These extra needs make the prediction of air flow patterns in enclosed spaces an extremely complex exercise. In reality, it would be a formidable task to identify the flow characteristics, driving forces, size and location of every opening. Instead it is necessary to introduce a number of simplifying assumptions which allow the main physical concepts of air flow to be represented without compromising results. It is the degree to which the flow mechanics is simplified that identifies the type of model, the detail of data needed and the range of applicability of results. Generic forms of calculation method used for the prediction of ventilation and air flow patterns in buildings include (Liddament, 1996):

- Estimation from building air-tightness data
- 'Simplified' theoretical methods,
- Network (zonal) models,
- Computational fluid dynamics.

In addition, energy, pollutant and heat loss models may be combined with air flow and ventilation models to simulate a wide range of building environmental conditions especially in the semi-advanced steps.

As had been shown , several approaches can be appropriate for advanced designing steps ,and also to use any common techniques , the designer will need to assemble a set of input data covering such as :building description, glazing ratios, orientation, schedules of internal heat gains, weather data, the timing of the ventilation flow, ventilation strategy ,etc. . But most out standing factors at early stage of design are ease, accuracy, scale and fluency of the use.

According to the applicability of outputs and inputs for early stage of design can be mentioned to two methods which are subsection of “simplified theoretical method “ at generic method : Numerical Method (Tahbaz 2005) , DEM (Digital Elevation Model). Which ones by utilizing graphical and computerize analysis provide the well worth outputs that can be applicable for meso-scale of design. Furthermore, this can make an appropriate answer for interaction of urban morphology and building design. However, some other approaches by utilizing complex analysis and formula create high accurate and detailed outputs, the authors believe these two methods because of their simplicity to set optimize outputs at minimize time for urban morphology and linkage of the building and city. And also we must mention which have some restrictions.

To declare the applicability of some other methods, and proving the importance of needed revision and reformation on common methods, some new approaches are explained as follow.

5.1 Numerical Method

Now in the first step the architect has to convert, transform and estimate the wind speed in the given urban terrain and in the study height - that is deferent from the height and terrain of the meteorology station - easily and rapidly, without being involved with different calculation procedures.

One of the climatic elements that can be controlled and modified by urban design is the urban wind. When wind flowing over an open area approaches the boundaries of the built-up area, it encounters a higher “roughness” of the surface, created by the buildings. The increased resistance resulting from the higher roughness reduces the wind flow at the level of the urban canopy. In this way a transitional zone is created between the ground and the undisturbed wind flow above the urban air dome, which is called “urban boundary layer”. The “undisturbed flow” is called the “gradient wind” and its velocity is called the “gradient velocity”.

The wind field is characterized by two parameters: the vertical profile of the mean wind speed and the turbulence spectrum. Both are affected and modified by the two profiles of the terrain and, in an urban setup, by the urban structure. The given method by Dr.Tahbaz is more concentrated on the first parameter: “the vertical profile of the mean wind speed” and it is supposed to achieve a graphic method to estimate the wind speed in a terrain. However the same structure might be applicable if the method would be developed.

The simulation process might be based on the calculation methods. In modeling the urban effect on the wind speed, the vertical profile of the wind, from the gradient wind level down to the ground is used. The simple formula – developed by Davenport (1960) - shows the profile of the wind speed in different height of an area. (Tahbaz, 2006) In figure1 the graph in the right upper side shows the relationship between height above the ground and the percentage of wind speed in different terrains (for heights less than 10 meters) and the exponent for different kinds of terrains. The graph in the right bottom side shows the relationship between wind speed at the height of 10 meters and the percentage of wind speed in the lower height. It shows the wind speed at the study height.

To estimate the wind speed in different urban areas with different density and terrain roughness the left bottom side of Fig1 is drawn, shows the relationship between observed mean wind speeds in the meteorology station at the standard height 10 meters and the mean wind speeds in four types of terrains at the same height.

On this graph it is enough to draw a vertical line from horizontal axis equal V m/s, the wind speed of meteorology station at 10 meters height. The horizontal line that crosses from the intersection of this line and the line of terrain category 1-4 shows the amount of wind speed in suburban area at 10 meters height. To estimate the wind speed at 2 meters height in suburban area, the graphs at the right side are used. On the graph at the upper part of the figure a horizontal line is drawn from 2 meters height of the vertical axis, to cross the curve line. The vertical line that is drawn from this intersection to cross continue of the horizontal line will cross the graph in the right bottom side. The intersection of this line with curved lines of the graph, show the amount of wind speed at the height of 2 meters in suburban areas. Wind quality is one of the most important result which can be extracted from this graph and utilizing at early stage of design.

5.1.1 Wind Quality

Although the graph recommended by Dr.Tahbaz simplified the procedure of estimation the wind speed in the urban area, it is not clear for the designer how to use this information in architectural and urban design. The Beaufort scale can be used for this reason. This table shows the relation between the wind speed and the condition caused by it.

According to design needs, the multitude division of the Beaufort table (Penwarden and Wise, 1975) is simplified to 3 meaningful main groups and 8 subgroups. To distinguish these groups, 8 areas are shown on the right bottom graph of Fig 1 that helps to predict the quality of wind speed for urban design decisions.

As illustrated the mentioned method is a simplified graphical simulating tool which may be more developed. However there is no doubt that the more developments needs more considerations in composing and mixing graphs data and decision makings. On the other hand the mentioned approach was more according to the Architectural scale, in that the importance of the wind speeds and its role is to determine the inside conditions, however the method by itself is somehow applicable in the urban scale.

Now we must mention to some limitations of this method. The recommended graphic method has all the reliability limitations of the numerical method. In order to design for the effects of airflow around buildings, wind speed and direction frequency data should be obtained. Another limitation is that all the mathematical models of the vertical wind profile assume a smooth curve from the level of the gradient wind down to the ground or the roughness parameter height. This form represents the wind speed pattern to the top of the urban canopy (useful for the pollution and wind loading on high buildings). In a city near ground level, turbulent created by the buildings, causes a very complex wind field. So in urban canopy the wind field can not be defined by a simple smooth curve sloping down to the ground (Givoni, 1998, p. 265.)By Davenport's power laws relating wind speed near the surface to the geostrophic wind, taking in to account the effects of topography. But more recent work has shown that airspeed in the boundary layer is better described by a logarithmic relationship above the canopy layer(Macdonald2000).

5.2 DEM

Today these types of data are simply prepared and therefore they could be very helpful in all designing sections if appropriate methods or simulating programs get develop. There are a number of methods that are aimed at defining and deriving simplified morphological parameters which can be related to the urban winds. The below paragraph will show how these parameters can be calculated by analyzing urban DEMs with image processing techniques, thus informing the knowledge of urban winds. A number of image processing algorithms could be used to analyze every simple raster models of the urban geometry (the so-called Digital Elevation Model or DEM) and extract information relevant to flow and other transfer processes at the intermediate scale. The DEM is a compact way of storing urban 3D information using a 2D matrix of elevation values; each pixel represents building height and can be displayed in shades of grey as a digital image. It is becoming an increasingly available support to describe cities, due to recent advances in sensing technologies such as lidar. Its analysis with image processing techniques in the urban context has proven to be very conducive to the calculation of a number of urban parameters. Shadow casting (even sky view factor) scan be easily obtained (Ratti and Richens, 2004). On the other hand energy consumption in buildings can be simulated, based on the coupling of image processing techniques with the LT model (Ratti et al., 2000; Ratti, 2002). In addition space syntax measures of urban connectivity and various analyses of the city as a network of streets can be derived (Ratti, 2004).

In some instances, image processing techniques can suggest new types of analyses or interpretations that are currently not incorporated in urban climatology.

The primary reason for focusing on the urban intermediate scale was to inform design problems. So far the processing of DEM (Digital Elevation Model) seems a good way to analyze urban geometry at that scale.

Urban geometry or texture – in particular the width of Streets, their orientation, spacing, intersection and so on – is a major determinant of pollution dispersion, and urban ventilation which can be calculated by simplify formulae and algorithms .So just by a simple raster model of cities can achieve beneficial points for early stage of urban design and focusing on urban natural ventilation. A key parameter at the individual street scale is the height-to-width ratio of the street canyons (also called aspect or H=W).This is trivial when dealing with canyons of uniform height, such as those commonly found in the literature, but becomes trickier in real cities, which often present irregular building arrangements. Height-to-width statistics may be used to highlight urban areas with poor ventilation and pollution dispersal (large height-to-width) or little shelter (low height-to-width). Alternatively, the height-to-width ratio averaged over an area of the city could be used as a more concise measure. If plotted against orientation, it can give a polar graph or a polar histogram, showing the distribution of canyon height-to-width ratios.

The mutual sheltering between buildings– which indicates how the perturbation due to each single obstacle adds up– can also be tackled from another perspective by focusing on the relation between the wind and the drag force on buildings. This connection can be characterized by the aerodynamic roughness length, z_o. z_o is a key parameter in studying the urban atmosphere, as it affects the wind over the city; large scale flow models utilize the roughness length (and its spatial variation) as a momentum-related boundary condition.

A number of methods have been suggested to determine the value of the roughness length. Historically, the classical way has been based on measuring wind profiles from tall masts (see Davenport et al., 2000 for instant). This type of measure, however, is difficult to obtain in urban areas as it requires observations from anemometers exposed at a level well above the average height of the buildings. A number of empirical formulas have therefore been suggested to calculate the roughness length directly, without wind measurements, when the geometry of the obstacles is known. These methods were limited to simple arrays of buildings till now, but the growing availability of large 3-D databases and computational capabilities is starting to allow unprecedented possibilities for roughness length determination (Ratti et al., 2002). These rely on algorithms based on the drag force on individual buildings and the interference between the flows around the buildings.

An extensive review of the technique is contained by Grimmond and Oke (1999), who use DEM analysis in urban areas to calculate the aerodynamic roughness in the framework of raster Geographical Information Systems (GIS). These parameters can be derived from the analysis of DEMs; Height of the buildings (weighted by frontal area) z_H, the plan area ratio λ_p and the frontal area ratio λ_f. By using these ratios in the formulas, a roughness rose can be calculated.The parameters z_H, λ_p and λ_f determined from DEMs or otherwise have been used recently for obtaining other wind-related variables such as the advective velocity within the urban canopy, the exchange velocity for transfer between the in and above-canopy flow and the characteristic turbulence levels within the urban canopy. Results for three case study sites in London, Toulouse and Berlin are given in Table 1and Fig. 3 . By noticing t o table 1, although the frontal area in London is large, the city has a comparatively small roughness. (Due to the tight spacing of buildings) has the maximum aerodynamic roughness, while having smaller frontal area. One approach would be to consider 'neighborhoods' each with a definable urban texture.

The surface roughness length is really a surrogate for the connection between the surface stress and the wind speed at some height above the urban canopy.

5.2.1 Urban texture directionality

At a basic level, the essential information about the urban wind is its direction. Therefore the first parameter to identify is the one that characterizes the directionality of the urban texture as this will strongly influence the winds near to and within the urban canopy.

In this way designers define rules of thumb for the layout and orientation of streets. The prime tool for studying directionality and periodicity in images is the 2-D Fourier transform. This is a standard function and can be applied to urban DEMs.

Despite their theoretical interest, the Fourier, Hough and Radon transforms of DEMs are not easy to interpret. An alternative approach to study the directionality of a given urban texture, taking inspiration from the flow in porous media, is based on a simplified estimate of the blocking effect of buildings at different angles 22 (This approach was first suggested by Dr. Nick Baker at the Martin Centre, University of Cambridge.). It leads to the construction of a polar graph, which we have named variance plot. Generally, on irregular urban DEMs, if the direction of scan is parallel to the street pattern, the profile will show strong troughs where the streets occur; while if the direction is oblique to the street pattern, a much smoother curve will appear. Hence the introduction of the variance (or square mean value: the sum of the squared differences between the profile and its mean value) as an estimate to quantify the smoothness or waviness of a profile (Melaragno M. 1982). This is plotted again the azimuth in the polar graphs of Fig. 4 for London, Toulouse and Berlin. The analysis of the variance plots presented in Fig. 4 underlines some features that can also be detected by sight, such as the prevailing North=South and East=West orientations in central London. A closer inspection, however, also shows details which are not immediately evident on the DEM and illuminates properties which are not otherwise apparent: for instance, the difference in magnitude between the North=South and East=West axes in London, which is due to the fact that most East=West streets are interrupted by Tottenham Court Road and do not line up across the site.

To discriminate between these many measures of urban directionality and choose the one that best represents the wind response to urban texture would require extensive experimental data arising possibly from field studies but more likely from physical modeling in a wind tunnel or from generic CFD studies (Melaragno M. 1982).

Finally, we must mention to the point that DEM is not the ideal and unique method but because of some appropriate property which can extract proper data about the urban geometry by using the space born remote sensing- it can have high resolution so could be benefit for achieving detailing information-.In addition it's precision would be outstanding item and provide the situation for accuracy assessment. According to these parameters Spatial Information System (SIS) and Geographic Information System (GIS) data could be based for obtaining information about morphology and geometry of urban and the influence of environment, terrain and urban morphology on climatology. By utilizing DEM other analysis have been done , measuring geometric parameters and predicting radiation exchange (Ratti.C. Richens.P,2004), flow and pollutant dispersion parameters to be calculated(Ratti et al., 2002).

For instance Tehran Urban Heat Islands have been simulated by the authors by using data from remote sensing images and analyzing by GIS and geographical software such as Idris and Arcview. Simulating urban heat island play key role for urban design and also beneficial maps are derived which can show the site position. In addition according on the given data architectural design policies could be formed to achieve optimum comfort level in that urban heat Island and environmental situation make limitations and potentials for architecture and urban design.

6. CONCLUSION

1. Simulation tools can make relation between two scales of design: urban design, architecture design, so the result of using simulation techniques is integrated design.
2. According to the factors which are the subject of the simulation, there are two different simulation methods:

• Approaches which focus on single item due to design details in architecture or urban design process such as wind, thermal, etc.

• Methods which cover all parameters involved with complex calculations or done computer software such as energy consumption.

At early stage of design, designer should consider the limitations and potentials in sketches, therefore approaches which could simplify the analysis by using graphs or raster images could be more suitable and for further development its progress can be simulated by complex equations. As a result the design process and chosen simulation method may be checked and changed iteratively.

3. This paper introduced two methods for early stage of design by attention on wind flow and natural ventilation. According to importance of climatic elements in urban design, this article introduced a new graph and graphic method which easily estimates the wind speed in urban areas. Although there are some computer soft-wares released for this regard, the graphs recommend another way to approach the result and are appropriate for those users that are not familiar with software or want to have a quick prediction of different conditions. The graphs are based on the power low formulas that predict wind speed in a desire height above the ground, according to the profile of the wind from the ground up to the gradient boundary layer for different terrain areas.

4. Another useful simulation tool was introduced in urban and even complex architectural scale; Urban DEMs prove very effective in the calculation of parameters that can be used to model winds within and near the urban canopy. For instance, they can be used to calculate the height-to-width distribution of canyons, or to estimate the aerodynamic roughness length which can be utilized in large scale flow models to provide a momentum boundary condition for determining the wind field. The compact representation of 3D urban geometry using the 2D support of a DEM is extremely versatile at the urban neighborhood scale and allows analyses that would be very difficult or impossible to carry out using traditional vectorial models.

5. Finally two methods which are mentioned have common properties that make them appropriate for designers. These approaches can predict different conditions quickly without being involved with complex calculation procedure and their input data are available for designer at early stage of design. Nevertheless CFD as a method for simulation of air movement is proper but its performance could be appropriate for an accurate engineering prediction purpose.

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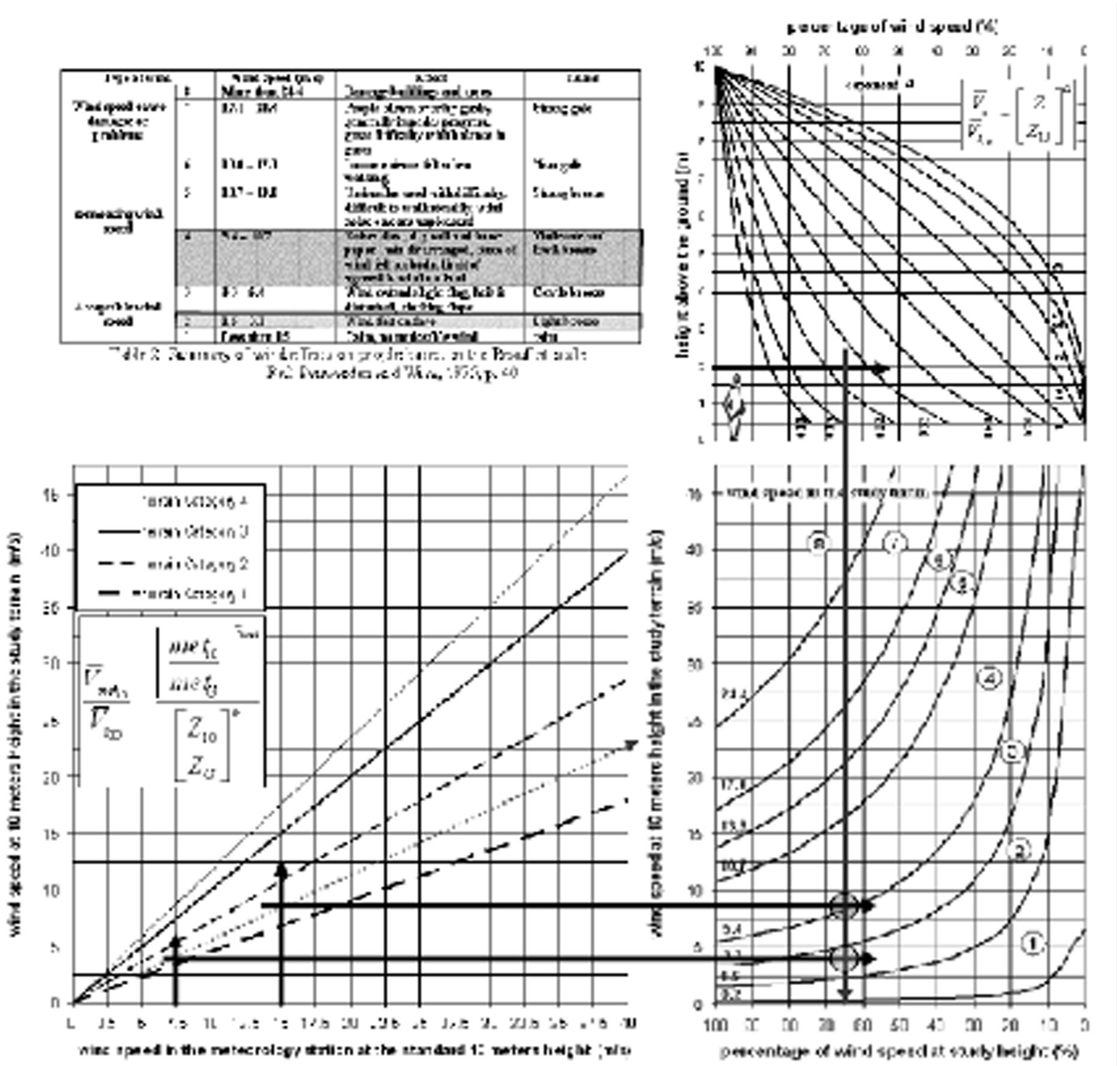


Fig. 1: Acceptable wind speed suburban and cities (Tahbaz,2006)

Table 1: values of geometrical parameters in London, Toulouse and Berlin

	London	Toulouse	Berlin
$\lambda_{p,}$Built to total area ratio[ ]	0.55	0.40	0.35
z_H Average of the heights weighted with frontal area (also averaged all azimuth)[ ]	14.8	16.1	19.9
λ_fFrontal area density ()average all azimuth) [ ]	0.32	0.32	0.23
z_oRoughness length (average all azimuth) [m]	0.30	0.92	1.18

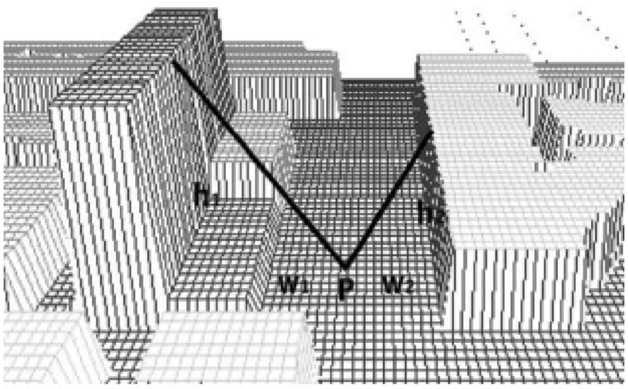
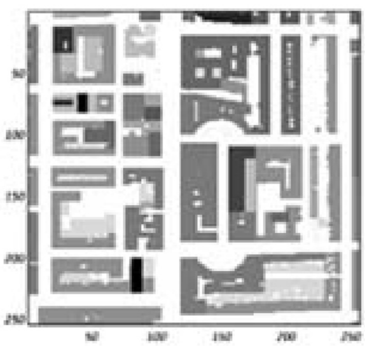
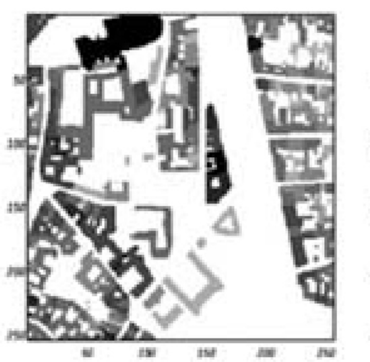


Fig 2: while the definition of the height –to –width or aspect ratio is trivial in canyons of uniform height, it becomes more complicated in real cities with irregular building patterns. The figure above shows a possible way to calculate it based on the obstruction angles in opposite directions: (Ratti C. 2002)

$$(H/W)_{Pi} = \frac{h\,1 + h\,2}{2(w\,1 + w\,2)}$$





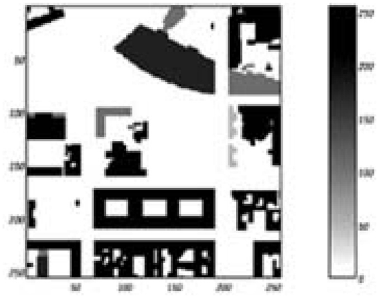


Fig 3:case study sites in central London, Toulouse and berlin (from left to right):they all measures 400*400 m in plan(Ratti C. 2002)

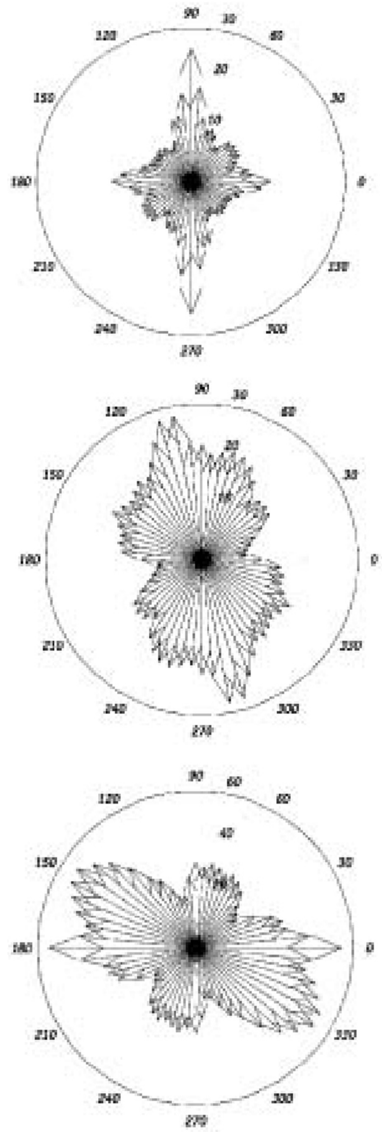


Fig 4: Polar diagram showing the variance of the average urban profile in different directions; The case study sites in London, Toulouse and Berlin are shown from left to right (values in m) (Ratti C. 2002)