MODELLING THE LINK BETWEEN BUILT ENVIRONMENT AND URBAN CLIMATE : TOWARDS SIMPLIFIED INDICATORS OF THE CITY ENVIRONMENT.

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ABSTRACT

The important variation of the urban morphology has direct effects on the disparity of the outdoor climates, as well as indoor climates. In this context, this work aims at answering at the following question : how to simulate, in an operational way, the relation between urban form and climate, at an intermediate scale corresponding to the neighbourhood ?
Our approach tries to answer to this question,[1]by working at the neighbourhood scale, and by proposing a complete and operational system of morphological indicators of the built environment. These indicators are embedded in a GIS system, baptised "Morphologic".

In this paper, we will focus our attention on the tri-dimensional characteristics of the urban canopy, assimilated to a porous medium with rigid skeleton, and on the three relevant indicators, namely rugosity, porosity, and sinuosity. The possible applications of this system are challenging : analysis of outdoor microclimate, inter- district or inter- city comparisons , or modelling climatic effects of a future urban amenities. This GIS system has been used to evaluate the environmental performance of various European case studies.

INTRODUCTION

City configuration results from a complex game between miscellaneous parameters, either geographical, economical, geometrical, topological, astronomical, religious, or doctrinal. The rules of this game seem different for every new urban fabric. As a matter of fact, at the building or the block scale (scale that will be designated as « microscopic »), large differences exist between the apparent regularity of the laying out of foundation cities (such as for example « bastides » or colonial settlements), and the organicity of medieval cities plans.

This important variation of the microscopic morphology of cities has direct effects on the disparity of the outdoor climates, as well as indoor climates : wide range of dry air temperature, of wind speed (direction and velocity are different than in an undisturbed rural area), of the heat radiation exchanged with the sky volt, and of the available natural lighting…, with known microscopic (but also macroscopic) impacts such as the alteration of outdoor comfort conditions, modification of the thermal balance of buildings, systematic recourse to artificial lighting inside these same buildings, creation of a heat island effect, or confinement of atmospheric pollutants…

Nevertheless, if the observer's eye backs up to a district or city scale (the « macroscopic » scale), the nearly –randomness nature of the tri-dimensional microscopic shape is obliterated by mean characteristics of a medium that could almost look homogeneous.

So, as difficult as it is to describe and to simulate the interactions between urban morphology and climatic conditions, at the microscopic level, in particular because of the complexity of the frame geometry, it seems attractive to work at a macroscopic level, allowing to get away from local heterogeneity, and to consider large enough volumes and mean effects of the interaction between urban shape and microclimate.
In this context, it seems worthwhile to assimilate urban fabric to a porous medium with rigid solid skeleton, subject to various climatic solicitations and to study its macroscopic characteristics through a set of simplified parameters, in the same way as physical analysis performed on these porous media few decades ago **[1]** .
Our work is based on such an approach : a simplified spatial modelling of urban morphology complexity resulting in defining a set of indicators of the environmental performance of urban fabrics [2].
This model has been embedded in a Geocoded Information System (GIS), baptised «Morphologic » and applied to the analysis of existing urban fabrics.

HYPOTHESIS

The city is submitted to various interactive climatic solicitations : we will focus our approach around the four most significant : wind, temperature, solar radiation (heat and light), and humidity.

Looking at the first climatic solicitation, convection due to wind, our hypothesis will aim at the assimilation of the tri-dimensional medium, the urban canopy, into a porous medium with rigid solid skeleton, This hypothesis distinguishes climate conditions above the roofs and under the canopy [3], and considers that above the roof, the « background » conditions are solely functions of general (regional) climate conditions, and local conditions linked to topography (variation of the height of the mineral and vegetal canopy). This last effect slows down the quadratic speed of air compared to an undisturbed rural area, and can be evaluated using a first indicator baptised **rugosity** .

Finally, our fundamental hypothesis allows us to distinguish the open elements from the closed elements, in non built spaces. Urban fabric is in fact made up of open spaces such as streets and boulevards (equivalent to the medium pores), and of closed (or partially closed) spaces equivalent to cavities as in backyards or private gardens. The pressure gradient in open spaces can be easily evaluated by the useful front vertical area, and the orientation of the street direction against the direction of the air flow.
On the other hand, we will consider that the air in the closed spaces is acting as if it were heavier than the air in the stream lines. This inclination of the air to remain largely at rest is strong enough to consider that we can neglect the effect of closed spaces on the general pressure-gradient. These two complementary aspects are put in concrete form in this model, through two indicators baptized **porosity** and **sinuosity**. Compared to well established factors, like the height/width ratio of the urban canyons [4], they offer a semantic increase corresponding to volumetric instead of planar information.

THE MORPHOLOGICAL INDICATORS TYPICAL OF ATMOSPHERIC FLOWS IN AN URBAN FABRIC

From this fundamental hypothesis, we have derived four morphological indicators [1] that are presented as follows.

The **absolute rugosity** factor is the mean height of urban canopy , H_m,, given by the product of the height of buildings by their area, and divided by the total(built and non built) area [5]. Absolute rugosity specifies the global effect of a urban fabric on the slowing down of the mean wind speed. This indicator can be given as follows :

$$H_m = \frac{\sum_{built} A_i * h_i}{\sum_{built} A_i + \sum_{non\ built} A_j} \quad [m]$$

With A_i footprint area of building i,
h_i , height of building i,
A_j , Area of non built element j.

The **relative rugosity** factor , R_a, is the mean square deviation of canopy height (built and non built elements), for a given direction (and for a given fabric radius around a central point), weighted by the width of each element in the cross section plane. Relative rugosity specifies the alteration of the mean wind speed according to the variation of urban morphology. Its expression can been given as follows :

$$R_a = \frac{\sqrt{\sum_i (h_i - h_a)^2 * l_i^2}}{\sum_i * l_i} \quad [m]$$

With h_a mean height of the urban canopy in the direction ,
h_i , height of the (built or non built) element i of the canopy ,
l_i , width of the element i of the canopy in the plane of direction ,
$\sum l_i$ diameter of the studied urban canopy.

The **porosity** factor, the ratio of the useful open volume to the total volume of the urban fabric. Porosity , P_o, is given as follows :

$$P_o = \frac{\sum_{open\ spaces} \pi * r_{hi}^2 * L_i}{\sum_{open\ spaces} V_i + \sum_{built} V_j} \quad [/]$$

With L_i Length of the open space i.
r_{hi} Equivalent hydraulic radius of the open space i.
V_j Mean volume of the built volume j.
V_j Mean canopy volume above open space i.

The hydraulic equivalent radius, r_h [6], radius of a circular pore creating the same discharge for an identical speed, is given, for a rectangular section, by the following expression:

$$r_h = \frac{l * h}{l + h} \quad [m]$$

With h Height of the canopy for the street (mean height of the adjacent built and non built spaces).

l Mean street width.

The **sinuosity** factor, S_θ, in a given azimuth by weighting the elementary sinuosity factor of each street linear segment by its length. The relative sinuosity is then given by :

$$S_\theta = \frac{\sum_{segm.rues} L_i * \cos^2(\theta_i)}{\sum_{segm.rues} L_i} \quad [/]$$

With L_i Length of the street linear segment i,

θ_i , Angle between the given azimuth (of flow) and the azimuth of the street linear segment i.

Manner of rugosity, relative sinuosity factor may be plotted against azimuth on a polar diagram : a *sinuosity rose*. Long branches of this rose are corresponding to azimuth of high sinuosity (high resistance to wind speed), and the reverse. Superposition of this rose onto previous *rugosity rose* may point out the potential ventilation properties of an urban space : azimuth with high rugosity and sinuosity will correspond to azimuth where the wind speed is the slowest, and the reverse.

In that sense, superposition of these two roses onto local wind rose may be extremely useful for urban planners in terms of evaluation of the opportunities and risks of a given or future site for ventilation.

THE *MORPHOLOGIC* SOFTWARE PLATFORM : APPLICATION TO THE ANALYSIS OF URBAN FABRICS.

The context of computer aided urban design

The urban design process is a complex act relying on the transformation of constraints linked to heterogeneous knowledge and skills into shapes, spaces and flows. The early stages of design have a hegemony weight over the basic decisions. Paradoxically, it is during these stages that the available information on the project is the weakest, because it is impossible to directly apply all the constraints to satisfy, or to decide on eligible procedures to reach a goal ; the problem does not have a definitive expression.
The potential consequences of decision support tools are maximal during these stages. The traditional engineering tools requiring a practically total information on the urban objects are only applicable at the end of the design process, when the design freedom is the weakest : engineering is very often more curative than preventive .
The urban design can be characterised by numerous actors: urban planners, architects, engineers, users, owners… related to each other through complex relationships of delegation, subcontracting... The urban design process passes through a compromise search among prescriptive, functional and financial constraints that are extremely interactive. The environmental issues are very often seen more as constraints than opportunities.
Urban Sustainability cannot be reduced to a monocriteria approach, for example the optimisation of energy efficiency of buildings. Urban Sustainability must then proceed through a multicriteria approach involving various domain-related analysis like climate, building, milieu, services, emissions, energy, transport, or urban form. Urban decision makers must then try to find a good **compromise** between these various dimensions. A decision support tool for urban planning and monitoring should then take into account as most extensively as possible all these dimensions (while staying operational) and their integration into a multicriteria decision framework.

Methodology

In this context, the *Morphologic* information system for sustainable urban development is characterised by two aspects as follows:
- integration into urban design through bridging urban planning and environmental engineering, with bottom-up approaches using evaluation tools compatible with the highly conceptual early stages of design ,
- co-operation, through the use of different state-of-the-art advanced computer technologies necessary to match the complex problem solving context of urban design: GIS in MapInfo, analytical and heuristic algorithms developed in C++ and MapBasic, Graphical User Interface developed in MapBasic.

A typical work session starts with the geometrical and topological design of urban objects in the GIS (MapInfo) through the use various pre defined classes (Building, Streets, open spaces…) embedded into GIS “ tables ”.

From the relevant alphanumerical information given on these objects, appraisal modules provide estimates of the environmental indicators (for example, a urban pattern indicator like occlusivity; or the emission rate of a street network due to traffic). The outputs of the environmental analysis are displayed both in a numerical way, and in the traditional graphical ways used in GIS (like thematic maps, buffers…).

Development of the GIS environmental analysis system, Morphologic.

We realised that one family of computer tools was especially suitable to this context, namely Geographical Information Systems (GIS) mainly for their semantic increase in comparison to other data models, for instance the raster models used in various tools, analysing the urban fabric pixel by pixel [7], for the ability to nest various geographical scales , for their inclination for spatial analysis, and graphical outputs like thematic maps. Geographical Information Systems are indeed very appropriate to the embedding of environmental indicators.
To embed this system of morphological indexes, we have developed a software environment, baptised *Morphologic* : its main characteristics are described below. The chosen software architecture is based on a shell of development of Geocoded Information Systems (GIS), namely MapInfo [8].

The outputs of the evaluation procedures take advantage of the graphical outputs offered by the GIS shell : automatic display of roses, bar graphs and thematic maps (see figure 1).

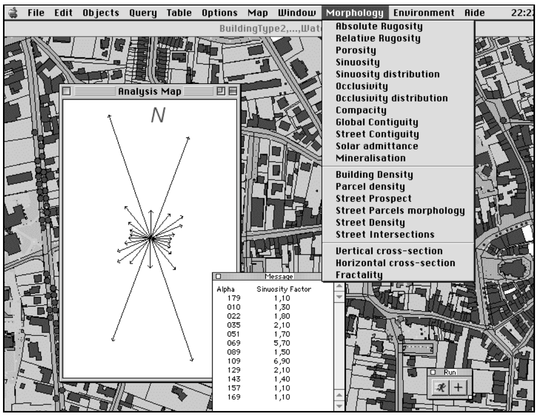


Figure 1 Screenshot displaying special menus and sub menus calling the indicators defined previously, and a sinuosity rose of a neighbourhood in Blagnac (France).

APPLICATION OF *MORPHOLOGIC* : EFFECT OF A MODIFICATION OF AN EXISTING URBAN FABRIC.

Let's suppose that we want to study the impact of an unlikely "haussmannian" cut in a dense medieval district of Toulouse (see Figure 2- next page). What will be the modifications of the various indicators of our model ?

A slight modification of the building density (built /total area ratio) will be induced (10% less), due to the lower footprint area of the buildings in the neighbourhood.
Variations of the absolute rugosity (the mean height of the urban canopy) will be slight (minus 0.6 meter from an initial value of 7.1 meter), but six times more important than the mean building height because the area of non built outdoor areas created.
The comparison between the two relative rugosity roses (see Figure 3) shows a less regular polar distribution of buildings with the new boulevard, with slight variations of the rugosity in the direction parallel to the boulevard (up to 10%).
The comparison between the two relative sinuosity roses (see Figure 2) shows a more regular corridor effect due to the initial high sinuosity in the direction of the new boulevard, but higher relative variations of the sinuosity than the rugosity in the direction parallel to the boulevard (up to 2,5 times) : the distribution of open pores of this urban fabric is more disturbed than the distribution of buildings, by this new project.
The amount of open "pores" in the urban canopy, characterised by the porosity factor is also largely disturbed by this "haussmannian" cut with the porosity varying from 8.5% to 10.2% : a relative increase of 15%.
The distribution of the occlusivity in a medieval fabric despite few stories high buildings generating a narrow sky view angle varies slightly towards a wider sky-openness between the two projects.
The low initial value of the compacity is increased by about 10%, while the contiguity is dropping about 15%, a slight variation compared to the possible variation of this parameter according to the urban fabric.
The important shading effect of buildings upon their neighbours in an medieval district (typified by a high height of buildings when compared to the width of the streets) will be very reactive to the opening of a boulevard, inducing a wide variation of the solar admittance, On this example, the solar admittance factor will be increased by about 20% . Obviously, the mineralisation will not vary between the two situations.

CONCLUSIONS.

This work aims at answering to the two concomitant following questions :

- how to analyze urban morphology using simple geometrical and topological indicators ?
- how to simulate, in an operational way, the relationship between urban form and climate at an intermediate scale corresponding to the neighbourhood ?

To do so, we have developed a simplified spatial model relying on a set of original morphological indexes typical of the environmental performance of urban fabrics. This simplified approach at an intermediate scale (neighbourhood or community) differs from traditional centripetal approaches based on elaborate simulations of the effects of the outdoor environment on the building indoor climate. Our approach tries to combine this approach with a centrifugal approach which appraises the feed-back influence of buildings on their environment.

Our concern here is also to develop a complete, non redundant and operational system of indicators compliant with tools used daily by urban planners on real projects. Therefore, a prototype of software, Morphologic (readily available for educational purpose from the School of Architecture of Toulouse), has been developed on a standard GIS shell, and input data can be provided by typical urban databases (with few minor improvements).

The applications of this approach may be numerous and challenging : simplified analysis of outdoor urban climates (after establishing statistical relations between these indicators and various climatic parameters), energy balance of urban fabrics (morphological characteristics of an urban fabric will have a large impact on its potentialities for natural ventilation, passive and active - photovoltaïc panels- solar designs, and so forth on the use of renewable energy into cities.), inter-neighbourhood or intercity comparisons, simulation of climatic effects of a future urban amenity (for example, the impact of a new boulevard, on porosity and sinuosity).

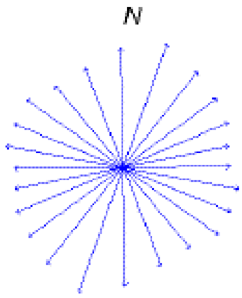
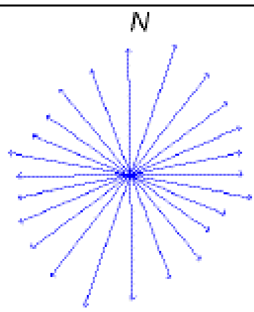
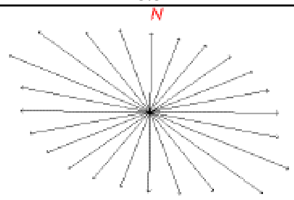
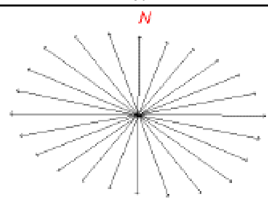
	Unit	Existing fabric	After "Hausmannian" cut
Density	**[/]**	**0.444**	**0.407**
Absolute rugosity	**[m]**	**7.1**	**6.5**
Relative Rugosity	**[/]**		
Porosity	**[%]**	**8.5**	**10.2**
Sinuosity	**[/]**		

Figure2 Effect of an "haussmannian" cut into a medieval urban fabric (Toulouse).

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