ENERGY AND BIOCLIMATIC EFFICIENCY OF URBAN MORPHOLOGIES:

A COMPARATIVE ANALYSIS OF ASIAN AND EUROPEAN CITIES

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Abstract

Cities and buildings are key energy users. The fundamental energy pattern of a city consists of various buildings and spaces. This urban morphology interacts with buildings, with people behaviour and local climate. The growth in energy consumption in cities simple laws derived from physics and thermodynamics. A sustainable building is an integrated entity: structurally, functionally and environmentally with the city through the city morphology. The proposed comprehensive analysis takes into account all the energy processes that happen in and around buildings in order to optimize bioclimatic design and new energies at building, neighbourhood and city scale.

By using the passive zone concept and a set of indicators, such as density, roughness, porosity, sinuosity, occlusivity, contiguity, solar admittance and mineralization, and by using an environmental oriented conceptual model of urban fabric, the analysis will connect architectonics, urban planning, energy flows, climate, and human patterns of behaviour. Comparing different urban morphologies, this cross-regional study will sample such six cities as Beijing, Shanghai, Paris, London, Toulouse and Berlin and make comparison and contrast of their development in bioclimatic and energy efficiency. What we will draw is an understanding of how the city morphology governs the patterns of energy flow in the urban texture, affects local climate and what the most suitable morphologies for renewable energies are at building and city scale.

Keywords: Energy, Urban morphology, Climate, Passive zone

1. Introduction

As noted by the Intergovernmental Panel on Climate Change [1] "the balance of evidence, from changes in global mean surface air temperature and from changes in geographical, seasonal and vertical patterns of atmospheric temperature, suggests a discernible human influence on global climate". Home of interaction between people and buildings, the city is where human civilization changes patterns of living and of energy consumption. Its development challenges the future of our human society. UK data show that the energy requirements for buildings in the domestic and non-domestic sector exceed those for transport and industrial processes [2,3]. In urbanized countries like UK buildings represent half of energy consumption; and with transportation, cities represent more than three quarters or energy consumption.

The carrying capacity of the Earth, that is to say the quantity of biosphere available to support human life is only an average of 1.7 ha per human being. The struggle against Global Warming and fair Earth share (an equitable share of the biosphere) implies a radical transformation of urbanism. Rural people in developing countries use less than 0.8 ha of biosphere per inhabitant. Urban dwellers use between 12 ha (USA) and 6 ha (Europe, Japan). The massive transition from rural to urban (which is a key feature of South east Asian societies) is the main reason of the ecological footprint overshoot, i.e. the fact that mankind uses 1.4 planets Earth now and will need at least 3 planets Earth by 2020. This urban transition is the most important driver of Climate Change.

A massive social, economic, cultural and political transformation takes place as Southern Asian countries develop vast mega-urban regions. The future of this populated region is an urban one, and the majority of its people will inhabit cities by 2020. Asia as a continent has overshoot its ecological carrying capacity as early as 1970, that is to say 15 years before mankind as a whole has overshoot the carrying capacity of planet Earth in 1985. The ecological footprint of Asia is already 1.75 times its carrying capacity. If the creation of mega urban regions in Manila, Jakarta, Bangkok, some of them 100 km radius, leads to a Los Angeles type urbanization of South east Asia, the subcontinent would need 10 to 12 times its carrying capacity. By following globally a Los Angeles urban pattern of development, Asia would need by itself the biosphere of several planets, with at least one planet for China alone with levels of efficiency similar to those of Canada and 3 planets with current Chinese levels of efficiency (see below the comparative analysis of Shanghai and Paris).

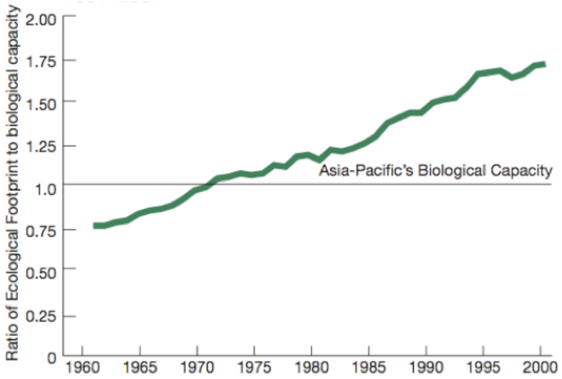

Fig. 1. Asia-pacific ecological footprint, 1961-2000

There is a specificity of the “Asian urban experience” [4]. Asian countries share a lot in common (high speed urbanization). Through comparative studies between Asian and European urban morphologies, in particular between Shanghai and Paris, we will better understand this specificity and contribute to develop a specific Asian way of sustainable development. Shanghai ecological footprint per inhabitant is already higher than Paris ecological footprint (6 ha per inhabitant in Shanghai against 5.58 in Paris) while energy consumption per inhabitant is almost double in Shanghai than in Paris (2.16 kilotons equivalent oil/year in Shanghai against 1.28 in Paris). This is partly due to the structure of economic activity (primary industry in Shanghai and services economy in Paris) but also to the huge differences in urban morphologies (urban sprawl in Shanghai compared to a density 6 times higher in the centre of Paris than in Shanghai). As the GDP per inhabitant is 8 times lower in Shanghai than in Paris, the result is an ecological efficiency 8 times lower in Shanghai than in Paris and energy efficiency 16 times lower in Shanghai than in Paris. In other terms, it requires 8 times more biological resources and 16 times more energy to produce a unit of GDP in Shanghai than in Paris. In this huge efficiency difference, urban morphology at various scales accounts for a big part. In 1980, the inhabitants of highly dense Hong Kong were consuming 50 times less energy than Australians for comparable standards of living.

The urban morphology interacts with buildings, with people behavior and with the local climate. An energy efficient urbanism associated with bioclimatic architecture, new systems and fundamental changes in people behavior and patterns of consumption can lead to a division of energy consumption and associated Greenhouse Gas Emissions by a factor 20. This is the goal to reach if we want to achieve a fair Earth share while using one planet only and limiting climate change. Sustainable construction movement concentrates mainly on the improvement of building systems (factor 2) and not enough on people behavior (factor2) and on urban and architectural bioclimatic and energy efficient forms (factor 5). Working on all the factors, and on urban design, and not only on systems, we can reach a factor 20. So, in a planet where 1 billion people are urbanized every 10 years, which represents a factor 100 in the intensity of urbanization, the urban planners and architects must take the leadership in the fight against Global Warming.

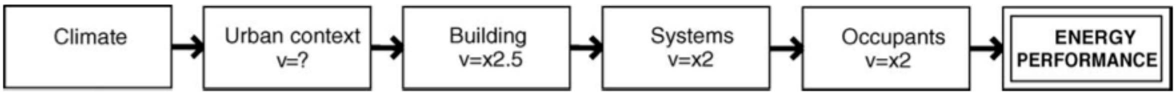

Fig. 2. Factors that affect the energy performance of cities according to Baker and Steemers

2. Morphology study

The growth in energy consumption in cities obeys simple laws derived from physics and thermodynamics. At present, cities are thermodynamics machines, which transform solar radiation into heat. They transform low entropy solar energy into high entropy heat. They must become positive energy cities and transform solar radiation into energy.

2.1 Problems considered

Cities are simultaneously human systems and complex porous physical surfaces that exist on several scales at the same time. They associate a high level of variability and a more or less organised subjacent structure.

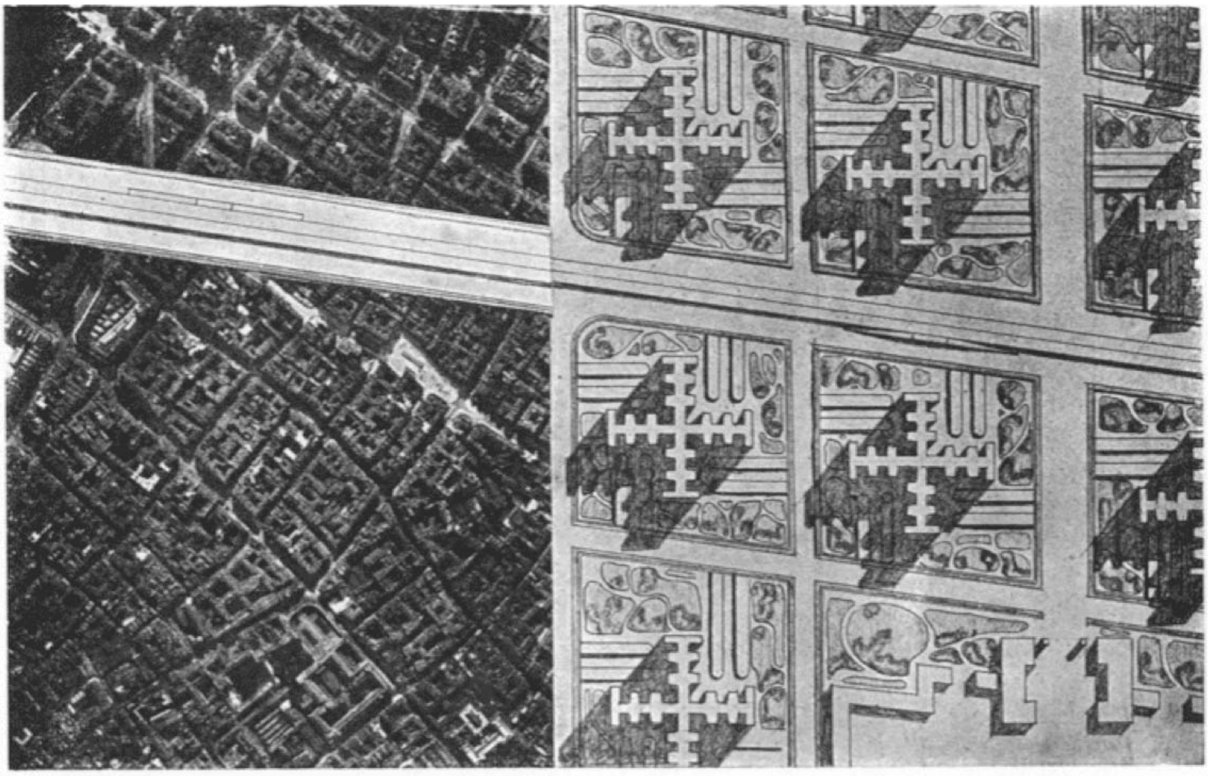

Fig. 3. The traditional urban texture of Paris versus the modern city,
as seen by Le Corbusier in his 1920 theory of modern urban planning.
One century later, all studies show that Le Corbusier theories lead to unsustainable cities

A survey carried out on 32 cities across the world by P. Newman and J. Ken worthy on the effects of density on energy consumption linked to transport, revealed a strong relationship between the transport of persons and population density. In 1980, around twice as much fuel was consumed for transport in American cities than in Australian cities, four times more than in European cities and six times more than in the considered Asian cities[1]. In 25 years, the situation has dramatically changed in South East Asia with the creation of mega-urban regions and an increased dependence on automobile in South East Asia. Newman & Kenworthy (1989) defined four criteria representing the automobile dependency of cities: the intensity of the use of space, the move towards non-automobile modes of transport, the constraint represented by traffic levels, and the centrality and performance of public transport systems. The relationship discovered by Newman & Kenworthy has remained steady and even increased over the last two decades. In Europe, according to Julien Allaire (Allaire 2006), there has been a tendency over time for energy consumption to increase in parallel with a reduction of density levels.

However, studies on the relations between density and energy remain too general to be able to define operational action criteria for existing cities. Global studies do not analyse the various morphological components of the cities, the impact of the grid, the fragmentation of the distribution of activities on the generation of mobility, or the impact of size, hierarchy, accessibility and connectivity of movement networks. The city is seen as a homogenous entity and the complex linking of factors resulting in the global relationship between energy and density is not analysed. Cities are both built volumes (solids) and empty spaces. The analysis of the discrete spaces forming the solids (being the buildings) has undergone considerable developments in terms of their bioclimatic and energetic aspects. However, far less work has been devoted to the overall texture of the city (grain size, porosity, grid density, connections between empty spaces, major and minor breaks). To attain operational results, it has become necessary to refine and quantify the morphological description of the various types of density in terms of their impact on mobility and the microclimate. The urban texture offers various degrees of insulation from the natural climate. While the urban microclimate affects external spaces it also needs to have an effect on the internal climate of buildings to create passive bioclimatic architectures able to reduce energy intensity and the carbon footprint. For example, the possibilities of using natural ventilation depend on the morphological properties of the buildings as well as the climatic conditions next to the buildings, such as air movement and atmospheric and noise pollution. These conditions depend on the urban morphology. It has now become necessary to study the link between modes of travel, urban density and energy consumption through the interaction between transport systems, activity morphologies and grids, and to specify the role of speed as a pivotal variable in urban organisation.

2.2 Cases analysed

The comparative analysis of Shanghai and Paris that we envisage carrying out and that we will further extend to mega urban regions of South east Asia will reveal how population and activity density gradients and profiles can be used as variables for urban interactions and the way that these now affect the possibilities of modal transfers towards other modes of transport with reduced energy intensity and a lower carbon footprint. In order to form a database that can help identify the underlying interaction mechanism between the urban morphology and the energy patterns, a number of cases were constructed by studying the GIS of different cities one square kilometre morphology.

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[1] This relationship between energy consumption and the population density of the city was confirmed by subsequent studies: P.Naess (1996) concerning Scandinavian cities, V. Fouchier (1997) for the Ile- de-France, ECOTEC (1993) for Great Britain, etc.

Fig. 4. Paris (lower left) and Shanghai morphologies at the same scale

2.3 Methodology

The analysis include the following stages:

(i). The construction of a typology of urban forms and the intensity of the connection of these urban forms on the global scale of Shanghai and the various density modes.

The construction of this typology will result in the calculation of quantitative parameters. The parameters will describe morphological types:

- On the one hand, through their physical characteristics: form of constituent units, grids, sizes, degree of regularity, modes of assembly, degrees of connectivity,
- On the other hand, their economic and social characteristics: levels of mixed uses, intensity of activities, density of occupation and uses, size of the use grid, distribution of activities, density (number of inhabitants per hectare).

This morphological and typological analysis will be carried out on several scales, from the agglomeration to the district and the plot, and concern the urban fabrics of Geneva and Paris.

(ii) Evaluation of energy consumption and greenhouse gas emissions of the various urban fabric typologies in Paris and Shanghai.

The 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, of the heat radiation exchanged with the sky voltage and of the natural lighting. Thus, as it is difficult to describe and simulate the interactions between urban morphology and climate conditions, this paper is proposing a simplified spatial modelling of urban morphology complexity resulting in defining a set of environmental indicators. The DEM (Digital Elevation Model) 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. The analysis of DEMs with image processing techniques has already proven to be an affective way of storing and handling urban 3D information, and being very conducive to a number of urban analyses [6,21–23].

Our ongoing project with Tongji University in Shanghai is structured into the following main tasks:

- The proposition of a set of innovative environmental indicators typical of microclimate conditions in urban spaces, through a large bibliographic survey, and experts' analysis,

- The validation of a set of indicators, such as density, roughness, porosity, sinuosity, exclusivity, compacity, contiguity, solar admittance and mineralization, through the environmental survey,

- An implementation of the final set of indicators in a comparative GIS analysis of Shanghai and Paris, using an environmental oriented conceptual model of urban fabric.

2.4 Urban morphology parameters

Computer-based analysis techniques and methodologies will be applied to various datasets, including digitized buildings, land use/land cover, and other essential datasets for the Shanghai and Paris. This effort will use a database of urban morphology parameters:

- Mean and standard deviation of building height
- Mean and standard deviation of vegetation height
- Building height histograms
- Area-weighted mean building height
- Area-weighted mean vegetation height
- Surface area of walls
- Plan area fraction as a function of height above the ground surface
- Frontal area index as a function of height above the ground surface
- Height-to width ratio
- Sky view factor
- Roughness length
- Displacement height
- Surface fraction of vegetation, roads, and rooftops
- Mean orientation of streets

3. Energy study

3.1 Modelling the passive zone concept

According to C. Ratti et al. (2005[7]), the surface-to-volume ratio is an interesting descriptor of urban texture. It defines the amount of exposed building envelope per unit volume, and can be used in a number of different applications. Its relevance to the energy consumption of buildings, however, must be considered carefully. Minimizing heat losses during the winter requires minimization of the surface-to-volume ratio; but this implies a reduction of the building envelope exposed to the outside environment, thus reducing the availability of daylight and sunlight and increasing energy consumption for artificial lighting and natural ventilation.

In fact, the main energy distinction to be drawn within buildings is a function of the exposure to the outside environment. This concept is made explicit with the definition of passive and non-passive zones, which quantify the potential of each part of a building to use daylight, sunlight and natural ventilation. By a simple rule of thumb, based on empirical observations, all perimeter parts of buildings lying within 6 m of the facade, or twice the ceiling height, are classified passive, while all the other zones are considered non-passive.

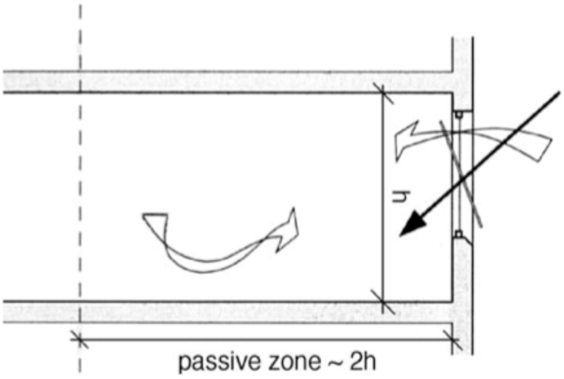

Fig. 5. Parts of a building, which can be naturally lit and ventilated, are called 'passive zones'. By a simple rule of thumb given by the LT method, they extend approximately for 6 m (or twice the ceiling height) from the facade. Image adapted from Baker and Steemers [2].

According to C. Ratti et al. (2005[7]), the surface-to-volume ratio, while being an interesting morphological parameter, does not describe the total energy consumption in urban areas. A better indicator seems to be the ratio of passive to non-passive zones, although accurate energy consumption values can only be derived from an integrated simulation such as LT (where LT stands for lighting and thermal). The proportion of passive to non-passive areas in buildings provides an estimate of the potential to implement passive and low energy techniques. It should be noted, however, that this is only a potential: the perimeter zones of buildings can still be wastefully air-conditioned or artificially lit. In some cases, passive zones can consume more energy than non-passive zones, especially when excessive glazing ratios and untreated facades make them particularly vulnerable to overheating during the summer and to heat losses during the winter.

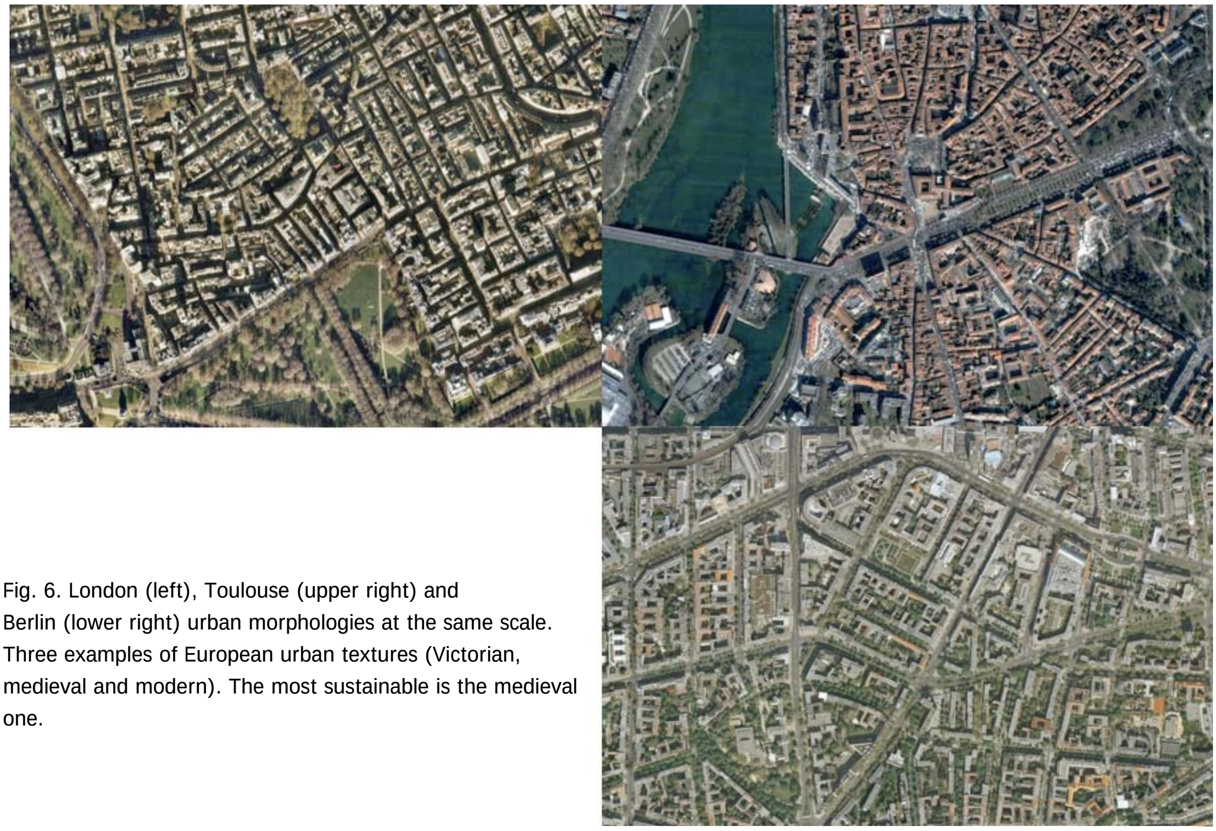

Fig. 6. London (left), Toulouse (upper right) and Berlin (lower right) urban morphologies at the same scale. Three examples of European urban textures (Victorian, medieval and modern). The most sustainable is the medieval one.

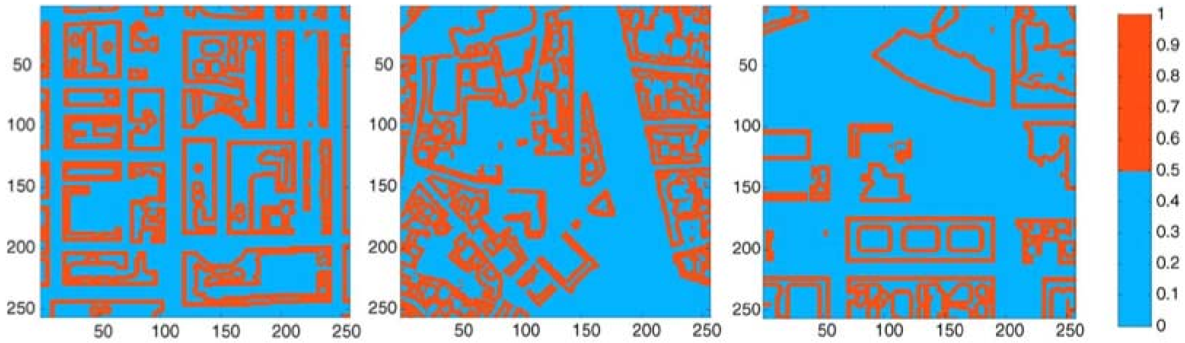

Fig. 7. Passive zones (within 6 m from the facade) in London, Toulouse and Berlin, second floor.
The image was obtained by thresholding the Euclidian distance transform (from C. Ratti et al. 2005[7]).

	London	**Toulouse**	**Berlin**
Total passive volume [%]	*77*	*84*	*61*

Fig. 8. Data for London, Toulouse and Berlin(from C. Ratti et al. 2005[7]).

According to C. Ratti et al. (2005[7]) two conflicting exigencies for energy conservation appear: reducing the building envelope, which is beneficial to heat losses, and increasing it, which is favourable to the availability of daylight and natural ventilation. Which of the two phenomena prevails in the global budget of buildings? The above question is not likely to have an absolute answer. At very high latitudes, where solar gains are scarce and temperatures harsh all year long, heat conservation strategies might well be prevalent over the collection of daylight and natural ventilation. In these cases energy efficient buildings should probably minimize the external envelope, while at low latitudes they might try to maximize them. More generally, the relative importance of the two phenomena (losing heat and receiving beneficial gains through the facades) will be climate-dependent and differ between, say, Beijing and Shanghai. For a given climate, it can only be assessed by a comprehensive analysis, which takes into account all the energy processes that happen in buildings.

3.2 Coupling of the Digital elevation model analysis with the light and thermal simulation tools

The analysis of DEMs (Digital Elevation models) will be used to explore the effects of urban texture on building energy consumption in various areas of Shanghai. DEM is an effective support to derive morphological urban parameters quickly. Some of these will then be passed to a simulation tool (LT), in order to get energy consumption figures. CSTB's LT (where LT stands for lighting and thermal) models are well suited to simulate energy consumption at the urban scale, as they capture the principal energy flows of buildings with reasonable accuracy without necessitating the computational demands of full dynamic simulation. Nevertheless, the LT models requires numerous inputs to perform energy consumption calculations, including building U-values, interior and exterior reflectances, illuminance data, heating efficiency and setpoint, etc.

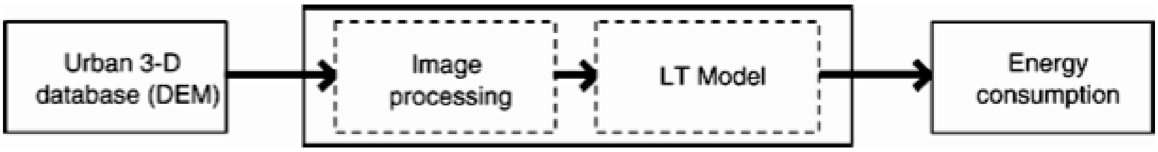

Fig. 8. The image processing/LT interface and data exchange (from C. Ratti et al. 2005[7]).

4. Conclusions

Studying multiple cities at different periods of time, we will make a comprehensive comparison and contrast of city morphology efficiency between regional cultures in the west (Paris, Berlin, London, Toulouse) and in the east (Shanghai, Beijing, Guangzhou, Shenzhen , Hong Kong), between periods of time of the rapid growth (Shanghai and Beijing) and the steady growth (Paris, Berlin, London and Toulouse). A number of results will emerge on the relationship between Shanghai city texture and energy consumption. The morphology of Shanghai will be characterized and quantified in considerable detail primarily for simulation, and analyses, but this can also be used for improved urban planning, and other urban related activities. A new integrated computational analysis for the prediction, evaluation and optimization of Shanghai morphologies will be developed. This will be applied to several case study sites to develop new knowledge regarding optimal means for urban growth and change, based on a scientifically rigorous interpretation of sustainability. The proposed approach allows a simplified diagnosis of urban sustainability, useful for comparing the bioclimatic and energy efficiency of different urban morphologies, useful for design and planning, but also monitoring of the long term urban planning. This cross-regional study therefore, is an attempt to explore the general laws that govern energy flows and climate in cities in many distinct ways. It is also an attempt to maintain in this global world the cultural distinctiveness in city evolution and architectural design. In a second step, we plan to extend it to Vietnam and to the mega urban regions of South East Asia.

Acknowledgements

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