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An Integrated Spatial Analysis Computer Environment for Building Energy Efficiency at City Scale

Sun Yu[1], Leng Hong[*2] Wei Tian[3]

[1] Doctor, School of Architecture, Harbin Institute of Technology, China

[2] Professor, School of Architecture, Harbin Institute of Technology, China

[3] Professor,College of Mechanical Engineering, Tianjin University of Science and Technology, China

Abstract

In this paper we developed a new integrated analysis environment in order to thoroughly analyse urban-building energy patterns in cities. It is argued that cities and towns account for more than two thirds of world energy consumption. Thus, this paper explores techniques to integrate a spatial analysis environment in the field of urban building energy assessment in cites to make full use of current spatial data relevant to urban-building energy consumption and energy efficiency policies. By incorporating with parametric analysis of the impact of urban form on urban energy consumption for heating and cooling, the results model is able to describe the variation of energy consumption under different energy saving scenarios. This paper first describes the basic concept for this integrated spatial analysis environment IUBEA. Then paper discusses the main functions for this new environment in detail. The focus on the non-domestic sector enables a framework that accommodates diverse set of activities and uses of buildings within an urban region. The final part shows the results from a case study of building energy assessment in Greater London.

Keywords: Integrated spatial energy analysis,Building Energy Efficiency, Energy model, Scenario analysis.

1. Introduction

Cities and towns account for more than two thirds of world energy consumption (Bose, 2010), a significant proportion of which is spent on operating buildings. Ambitious national energy and emission reduction targets necessitate that energy demand due to buildings is considered as an important measure when any future evolution of a district or city is planned.Not only the accounting of present-day energy consumption of the built environment by regions and by sectors, but also the prediction of achievable reductions to meet relevant 2020-50% emissions targets. Indeed, in order to reduce energy consumption and associated carbon emissions globally, more attention should be focused on urban-scale energy analysis of the built environment. Urban planners typically use spatial analysis techniques to inform planning decisions. Despite the acknowledgement that energy is a relevant and necessary metric of interest, there is a lack of an integrated spatial analysis platform that can allow urban planners to run standard urban planning analysis, but also incorporate within it relevant information about energy consumption.However, there is still lack of an integrated spatial analysis environment for urban planners that can make full use of current spatial data relevant to energy consumed by the built environment.

Therefore, we develop this paper present the first version of a new integrated analysis platform that can be used to analyse energy consumption patterns due to buildings at the district and city scale. This new computational model can be used for spatial data visualization, data query, correlation analysis, regression analysis, scenario analysis, and optimization of districts. The model is named IUBEA from the initial letters of Integrated Urban Building Energy Analysis. The data used in the IUBEA includes physical features of buildings (eg. size, volume) per use type and per district, demographics, economics (eg. cost of land), and energy data at various spatial scales in cities. Another important feature of this computer model is that it is programmed within an open-source software (Netlogo), which allows other users to access it easily. In addition to being open-source, Netlogo (Tisue and Wilensky, 2004) is chosen in this project because it has many functions, such

as scenario-based analysis, GIS (geographic information system) environment, and agent-based modelling. Furthermore, it has several extensions to link with other programs, such as statistical program R, and numerical computing environment MATLAB.

This paper is structured as follows. Section 2 describes the basic concepts for this integrated spatial analysis environment IUBEA. Section 3 discusses the main functions for this new environment in detail. Section 4 shows some simple illustrative examples of urban scale data analysis of London.

2. Methods

spatial energy analysis

The data required includes spatial boundary GIS data, energy data, and attribute data. Geographically, boundary data of cities is used to display the data at different spatial scales. Energy data and corresponding attribute data are necessary for energy analysis; The energy and the corresponding attribute data (and both of them) can be either polygon type or point data, but with the same resolution as the GIS boundary data. Attribute data here denotes the factors influencing energy consumption of districts, such as floor area of buildings, building use, population, number of households and employment, household incomes, etc. The polygon data here means the regional data in a given spatial boundary, while the point data is usually for individual buildings.

3. Problem formulation and methods

The analyses in IUEBA is implemented through four functions. The first displays the data spatially and can be used for data query at different spatial levels in cities. The second is to explore the relationship between various factors and energy consumption using correlation and regression analysis and also create statistical energy models. The third is to study the effects of different scenarios on building energy use, named "scenario analysis". The fourth is to investigate the optimization zones using mixed-use method based on energy use intensity of districts. This section will describe these four main functions in detail.
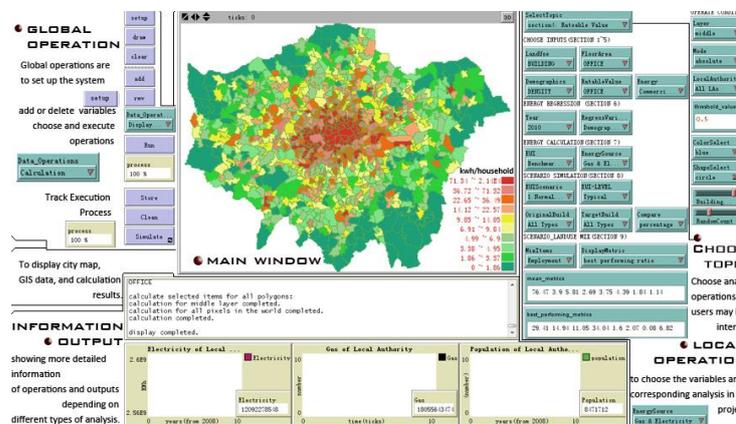
Figure 1: The interface of an integrated energy analysis environment IUBEA(interface shows distribution of commercial electricity per household in London at MSOA level)

Correlation and regression analysis of the randomlocal spatial effect

The analysis in this project has two main aims: interpretation and prediction. Both correlation and regression analysis can be used for interpretation, while only regression can be used for the purpose of prediction. Interpretation is to understand the relationship between energy and various independent variables. For instance, analysts may be interested in how the population number or floor area influences the energy consumption of districts and which of the two variables has more significant effects on energy consumption. Prediction is used to investigate how changes in independent variables will result in changing the energy consumption of a district. For example, it may be of interest to quantify the change in energy consumption due to future growth of household or population numbers. Note that whilst regression analysis can deal with one or multiple independent variables, the correlation analysis is used for only two variables.

The regression analysis currently implemented in IUBEA concerns the influence of land use in different districts of London on their energy consumption in Eq （1）. In this example, 9 categories of land uses and 10

categories buildings of non-domestic buildings in London are considered the percentage share.

$$\hat{E}_t = constant + \beta_{building} \times S_t^{building} + \beta_{road} \times S_t^{road} + \cdots + \varepsilon \quad \text{Eq. 1}$$

where:$\hat{E}_t$ is estimated energy consumption of a given area t,
$\beta_{building}, \beta_{road}, \ldots$, are the coefficient of building, road, etc,
$S_t^{building}, S_t^{road}, \ldots$, are the area of building, road, etc in a given area t,
ε is the random error term.
The equation above is only suitable for linear models. More complicated non-parametric regression methods will be added in a future version of IUBEA to analyse non-linear relationships.

Energy scenario analysis

Scenario analysis is used for what-if analysis.To implement the scenario analysis, analysts should have good knowledge on the effects of these independent variables on energy consumption. Furthermore, some form of validation of energy calculations is necessary to confirm that the prior assumptions in the model are appropriate. This paper discuss three different scenarios: electrification, change of building types, and improvement of energy efficiency.

1) Formulation & Methodology

The total energy consumption of buildings in a district can be expressed as the sum of energy consumption of its constituent buildings in the following form:

$$E_k = \sum_{i=1}^{N} \text{EUI}(i) \cdot \text{PA}(i, k) \qquad \text{Eq. 2}$$

where, E_k is the energy consumption of a district k in kWh/m2/ year, normalized by its total building floor area. $\text{EUI}(i)$ is the energy use intensity of a building type i in kWh/m2/year, $\text{PA}(i, k)$ is the percentage of built floor area of building type i in district k, and N is the total number of building types.

2) Baseline scenario

This baseline scenario is to compare the calculated energy consumption with the actual energy consumption in cities. This step is very important. Therefore, analysts may use different assumptions based on their prior knowledge on energy use intensity in terms of building types. In this environment, may be based on three different sources of information: benchmark values, median values, and Monte Carlo method. The benchmark values are based on low, typical, and high values (EUI) provided in standards such as the CIBSE Guide F and CIBSE TM46. The median values are from actual observational energy data, but only use median values for different building types. Display Energy Certificate (DEC) and Energy Performance Certificate (EPC) data. Monte Carlo method is from actual energy data to directly sample the values from these actual data randomly in order to calculate the distributions of total energy use. Analysts may choose one or all these three methods based on data availability. As more building energy use data becomes available.

3) New scenarios
This section will describe three new scenarios to explore the possible change of energy consumption in cities.
(1) Electrification scenario: It seems there are more benefits for electrification in building sector if grid electricity can become gradually less carbon intensive. As an example, electricity emission factors in the UK have been reduced around 35% from 1990 to 2010 (UK Defra & DECC, 2012). This energy scenario is to explore how the total energy or carbon emissions would change if building sector would use electricity instead of gas for heating.
(2) Building type conversion scenario: In urban environment, it may have to change building types due to economic or social reasons. Then, it may be of interest to investigate the change of building types on the energy consumption in cities.
(3) Energy efficient Scenario: In order to reduce carbon emissions, it is important to understand how the improvement of energy use efficiency may influence the energy consumption in cities. Thus, this scenario allows analysts studying the influences of change of energy use intensities for different building types. the third method may be used to thoroughly explore building energy consumption patterns in cities.

3.4 Energy optimization based on compositional data

The purpose of energy optimization in this section is to find the best energy performance area in a city and calculate the overall difference of compositional data (independent variables) from this best area and other areas. The overall differences mean the extent of efforts that are needed for a specific area to get the best area ratios in best performance area in terms of energy consumption. The compositional data here means the elements are not-negative and sum to unity. For instance, the proportion of floor area for different building types in an area can be regarded as compositional data.

As an example, the following descriptions are based on the proportions of floor area in different building types in different city areas. It is assumed that a city has ten districts and the buildings can be divided into five types: residential, office, retail, education, and others. Both the energy consumption and the proportions of floor area in terms of five building types in these ten areas are available. The calculation for energy optimization is as follows:

(1) Obtain energy consumption intensity normalized by total floor area in all ten districts;

(2) Find the area with the minimum energy intensity from all the ten districts. This area (called BEST area) is regarded as the best energy performance area.

(3) Use the proportions of five building types in this BEST area as a base case to obtain the absolute differences of proportions for all the other 9 areas. Then average these differences to obtain the overall differences for all these 9 areas. Apparently, the overall difference for the BEST area is zero.

(4) Rank all the areas based on these overall differences in all the area.

4 . A case study of London building energy analysis

4.1 Description of the analysis cases

London has been used as a case study to explore its building energy patterns with this new integrated GIS environment. In this case-study, London has been divided into three spatial scales: LA (local authority, also called borough), MSOA (middle layer super output area), and LSOA (lower layer super output area). London has 33 LA areas and the city of London is also regarded as a special LA in this study..

The energy data includes regional data and point energy data in London. The regional energy data means the total energy in a specific area, while the point energy data is the energy data for individual buildings. Both electricity and gas data in domestic buildings in London has good quality from LA to MSOA levels although the energy data in a few number of MSOA areas is unavailable (DECC, 2013a, b, c). The third type of data is social economic data, including population, household, employment and rateable value in London (London datastore, 2013). The rateable values are the open market annual rental value of a non-domestic property from UK VOA (valuation office agency).

4.2 Results

1) energy use and spatial factors

The correlation analysis has also been implemented to calculate the correlation coefficients between gas/electricity energy intensity (kWh/m2) and total bulk rateable values (pounds/m2) for non-domestic properties at LA levels. As shown in Figure 2 MSOA level is not chosen in this analysis since the electricity data is unavailable at London MSOA level as explained in section 4.1. Total bulk rateable values here means the average rateable values for all the properties (including office, retail, warehouse, and industry properties) in a given area (VOA, 2013). The results indicate that there is a moderate correlation (0.59) between electricity use intensity and all bulk rateable values, while there is a weak correlation (0.11) between gas use intensity and all bulk rateable values.

As shown in figure 2, for the domestic sector in London, both the domestic floor area and population number have good linear relationships with electricity use in London. The coefficients of determination from two variables are very close, around 0.9, which means that either floor area or population number can explain approximate 90% of variations of total electricity use at London LA levels.

For the non-domestic sector in London, the non-domestic floor area can account for around 76% of the variations of total electricity use, while the employment number can increase this value to 82%. Therefore, compared to the floor area, the total employment can be more suitable to the electricity consumption at London LA levels.

As also can be seen from Figure2, the coefficients of determination for domestic sector are less than that from the non-domestic sector in London. This implies that the domestic electricity use is more related to the total floor area in comparison with the non-domestic electricity in London.
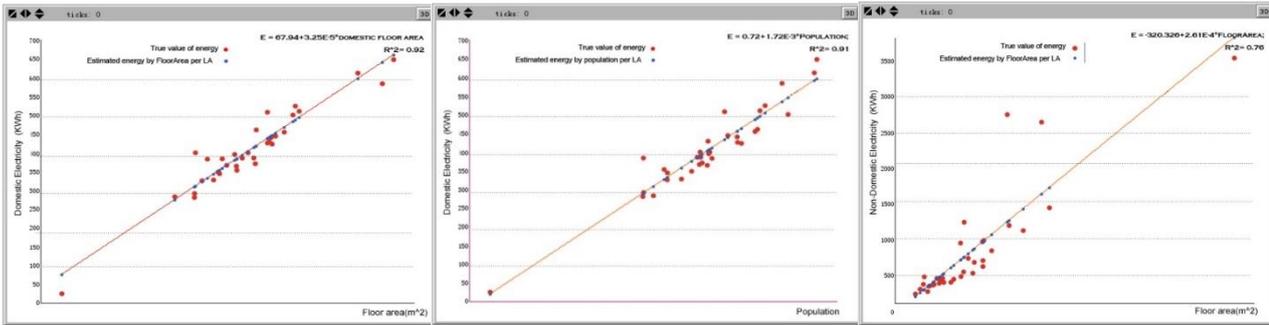
| (a) Domestic Electricity translated by | (b) Domestic Electricity translated | (c)Non-Domestic Electricity translated |

Figure 2: Analysis for electricity whit social and geo-factors in London LA (local authority) level

1) Energy scenarios of electrification in London non-domestic sector

This section is to study the effects of full electrification of non-domestic sector at LA level based on the Monte Carlo method as described in section 3. The distributions of energy use intensity in terms of building types are from UK DEC (display energy certificate) and EPC (energy performance certificate) data (UK DCLG, 2013). Note that the total energy use intensity used in this section is defined as the total energy use divided by the corresponding total floor area in a given LA area.
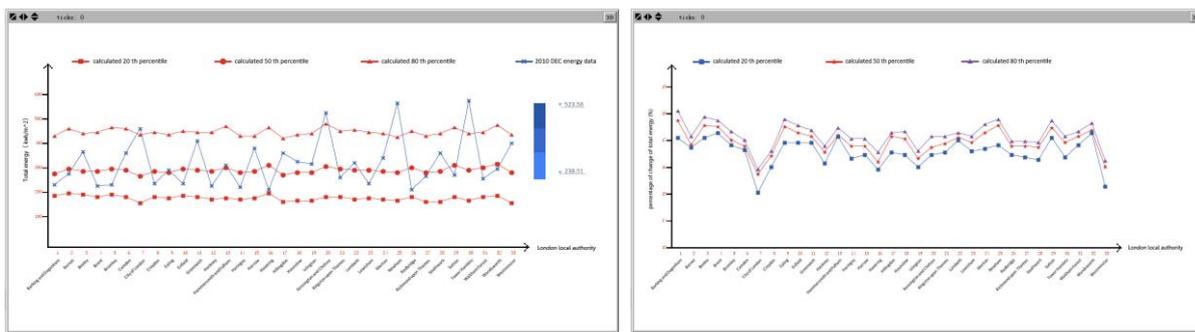
| （a）Comparison of calculated (10th, 50th, and 90th percentile) and actual 2010 total energy data | (b) Change (percentage) of total energy due to electrification |

Figure 3: Results for energy electrification analysis in London LA (local authority) level

Figure3a shows the comparison of calculated and actual 2010 total energy intensity in 33 LA areas. As can be seen from this figure, most of actual total energy values are within the 80 percent of confidence interval for total calculated energy use. The relative differences between the calculated median and actual 2010 data are below 20% in around 15 LA areas.

Figure3b illustrates the relative change of total energy use intensity due to electrification. The conversion efficiency from gas to electricity is taken as 0.7 from (Carbon Trust, 2012). The total energy use intensity would be reduced in most of London area. The city of London and Westminster have low percentage change in comparison with other LA areas. This is because the gas use accounts for small percentage of total energy use in these two areas.

1) Energy optimization based on building types at MSOA level in London

This section is to analysis the energy efficiency secnario based on urban space form in London.Table 1 lists the descriptive statistics of the data used in this analysis, including floor area for eight building types and gas use intensity (kWh/m2). Figure4 shows the results for spatial distributions of overall difference of floor area. The black area is the best performance area in terms of gas use intensity.

Table 1 Descriptive statistics for the data used in energy optimization analysis

Statistics	Floor area percentage (%)								GasEUI
	Domestic	Office	Retail	Industry	Culture	Education	Hospital	Others	(kWh/m2)

Mean	76.47	3.90	5.81	2.69	3.75	4.39	1.84	1.14	130.70
Median	81.69	0.90	4.34	0.48	2.61	3.51	0.61	0.44	130.91
SD	16.33	8.46	5.26	6.00	4.65	3.65	4.28	2.07	23.28
Kurtosis	2.63	23.92	10.54	25.44	37.98	8.38	24.93	18.20	9.15
Skewness	-1.56	4.37	2.45	4.38	5.12	2.18	4.72	3.79	1.45
Range	94.34	76.90	47.50	57.66	53.49	31.60	37.43	19.23	248.31
Minimum	3.54	0.00	0.04	0.00	0.04	0.00	0.00	0.00	54.28
Maximum	97.88	76.90	47.53	57.66	53.53	31.60	37.43	19.23	302.59
Count	951	951	951	951	951	951	951	951	951
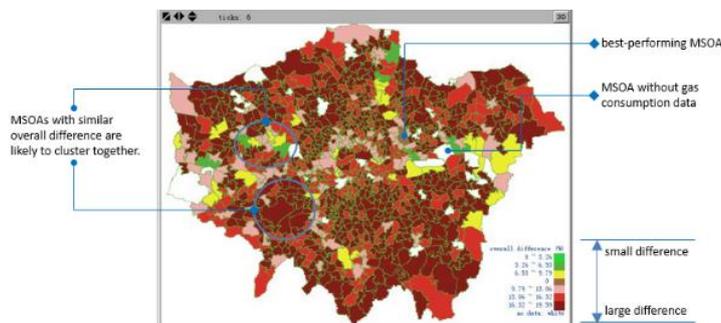
Figure 4: Simulation result of energy efficiency secnario based on urban space form in London MSOA (middle layer super output area) level (black colour, the best performance area)

As can be seen from Table 1, the residential building is the dominant type in terms of floor area in London and the variation for the percentage of residential building is also the largest one. Both the kurtosis and skewness values shown in Table 1 can measure the shape of a distribution. The kurtosis is to measure the peak or flat of a distribution and the zero kurtosis means a distribution is close to a normal distribution. In contrast, the skewness is to show the symmetry of a distribution and the zero skewness means a distribution is symmetric. As can be seen from Figure5, the overall differences of floor area percentage based on gas use intensity are not clustered as large area, but more spread around the London. However, it still presents the characteristics of spatial distribution to some extent. Polygons with less overall difference are apt to cluster together. The overall difference can reveal the distribution of gas energy consumption. So Figure5 is also a demonstration of spatial features in cities, which means that energy consumptions in an area are to some extent influenced by where the area is located in a city.

5 Conclusions

This paper has described a new integrated spatial analysis environment IUBEA to perform a thorough analysis of energy performance in city buildings. This energy analysis environment can be used for multiple functions, including spatial data visualization, data query, regression analysis, scenario analysis, and energy optimization in urban settings. London has been used as a case study to illustrate its main functions. Moreover, this environment can be used for different locations and analysts can add their own functions for their purposes since this environment is based on public-domain software Netlogo. As more spatial data related to energy performance in cities is becoming increasingly available, this environment would become more useful for both urban planning and building energy analysis in cities.

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