HIGH RESOLUTION ENERGY SIMULATIONS AT CITY SCALE

Wei Tian[1], Adam Rysanek[2], Ruchi Choudhary[3], Yeonsook Heo[4]
[1]College of Mechanical Engineering, Tianjin University of Science & Technology, Tianjin, China
[2]Institute of Technology in Architecture, ETH Zurich, Switzerland
[3]Department of Engineering, University of Cambridge, Cambridge, United Kingdom
[4]Department of Architecture, University of Cambridge, Cambridge, United Kingdom

ABSTRACT

The use of transient computer simulations (e.g. TRNSYS, EnergyPlus) for quantifying energy use of individual buildings is now standard in both research and industry. However, their use has been computationally prohibitive at larger scales, in the context of thousands or millions of buildings. Furthermore, physical and thermodynamic properties of buildings are often hard to translate into energy models at urban scale. As a result, city-scale analyses of the built environment, even when bottom-up, have to neglect or simplify dynamic and transient features of buildings. Yet, it is often that time-varying features (concurrence of peak energy demand) and dynamically interacting components (diurnal heat storage) yield the most economically achievable energy efficiencies. This paper describes an automated process of extracting information from high-resolution mapping databases to derive individual building gemeotries for energy modelling. Ongoing work constitutes refinement of model parameters and design of validation for such city-scale models.

INTRODUCTION

Urban/District scale energy modelling of buildings is a new and fast-growing area of research within the building science community (see Choudhary et al 2014 for review of literature, and for more recent work, Dogan et al 2014). Within the landscape of work on energy modelling at urban scale the following features hold: (a) a significantly larger proportion of studies focus on residential sector buildings, (b) in terms of purpose – they have been driven with the view of testing the influence of national/local government policies (ability to meet GHG emissions targets) rather than for short or medium-term urban retrofitting, (c) most studies follow the archetype approach – few representative buildings are analyzed and results are extrapolated across the stock.

Lack of reliable data for such models has been extensively brought forward in the literature. In 2010, the BR & I journal published a special issue “Research on Building Stock”, which brought to the forefront the challenges associated with lack of sufficient data upon which to base reliable models and the difficulty of translating GIS information for the purpose of energy analysis. Indeed, lack of reliable data is important in such models, but there have been very significant improvements very recently. The conflation of “data-deluge” and stricter building regulations has resulted in significantly better datasets at higher and higher resolutions (per billing meter and per half-hour in some cases). A very notable example is the outcome of the European Performance Buildings’ Directive (EPBD) adopted by member countries in 2003. As a result of the directive (2002/91/EC), most member states compile the information related to the creation of Energy Performance Certificates (EPC) in a central register since 2010. For all buildings, this set of information includes exact address, in addition to some key thermodynamic features of the building, primary fuel use, and inspection report of boilers/heaters, as well as a calculated benchmarked value of annual energy consumption. In many European countries, the public sector buildings are required to also report their metered annual energy consumption. Beyond EPBD, new policies such as the Carbon Reduction Commitment (CRC) scheme in the UK require large organizations to meter their electricity consumption at half-hourly resolution.

These are augmented by Geographic Information Services (GIS) that are now able to provide datasets of buildings and land use at very high spatial resolutions. What is still very much a challenge in the field though is the seamless translation of these datasets into energy simulation models and their parameterizations. In this sense, the work presented in this paper could not be better-timed: We see a landscape of new sets of high-resolution information emerging, albeit with still some spatiotemporal gaps. At the same time, there have been big advancements in inference techniques for overcoming information gaps, and ever increasing computational prowess. Indeed, it is timely to challenge the current state-of-the art. We present a dynamic energy simulation model of a district that is seamlessly extracted from high-resolution spatial maps (location, geometry, floor area, and building type) and by leveraging DEC/EPC Data Sets.

We use the City of Westminster, a borough within London, as a case study to illustrate how to convert GIS data into dynamic building energy models at urban scale. It presents the process underlying the seamless transition from GIS maps into input file templates for dynamic energy simulation. In addition to geometry, these include three types of input parameters for building energy models: building envelope, internal heat gains, and HVAC systems. Model parameterizations and validation are described in another forthcoming paper by the authors.

DATASETS

The datasets used for creating energy model inputs per building can be summarised within three categories: spatial geometry, building portfolio information, and spatially and temporally aggregated energy data.

The spatial geometry of a building is derived from digital boundary maps of buildings in a given area. The main source of this information is UKMap, a detailed topographic database that contains key geographic features in London (UKMap 2011). UKMap also provides orientation, height, and space use of polygons in Westminster (a polygon is the enclosed 2D region in GIS). In UKMap, a polygon representing a building can be a part of a larger building subdivided by ownership and/or height (UKMap 2011). Indeed, the definition of "a building" is very difficult in a formal way (Bruhns et al 2000), especially in urban settings because buildings are often connected to each other. The UKMap dataset also contains information of building use per polygon (including multiple uses per building). The total floor area of buildings in Westminster is around 28 million m^2 and the three main building types account for approximately 83% of the floor area. In addition, we merge the UK postcode dataset (Ordnance Survey 2013) to identify each building by its postal address.

Building portfolio information contains data per building or building type as the case may be. These are used to infer and assign some of the thermodynamic and operational properties per building that are not available per building (internal loads, schedules of use). For known features per building, two databases have been extensively used: information collected by auditors for EPC (energy performance certificate) and/or DEC (display energy certificate), and list of recommendations made by them for improving the DEC/EPC rating of a building. These are maintained by (UK DCLG 2013). EPCs provide energy rating for both domestic and non-domestic building, while DECs record actual annual electricity and thermal fuel usage by public buildings with a total useful floor area of more than $500m^2$. EPC databases for domestic buildings contain much more information than those for non-domestic buildings. Domestic EPC data include descriptions and energy efficiency for wall, window, roof, lighting, heating system, whereas non-domestic EPC have only basic information for buildings, such as floor area, heating fuel etc. In such cases, previous studies on UK building stock are used. For example, Smith (Smith 2009) details the development of thermal performance of building envelope for non-domestic buildings across different construction periods.

Finally, we also overlay the standard UK statistical boundaries on the spatial map: namely the MSOA (middle layer super output area) and LSOA (lower layer super output area) (ONS 2012), so that each building within UKMap can be associated with its corresponding MSOA and LSOA. UK Department of Energy and Climate Change (DECC) releases annual total electricity and gas data per MSOA and LSOA. Domestic energy data are available for both MSOA and LSOA areas, while only MSOA data for non-domestic sector due to disclosure issues. This dataset becomes useful for constraining and calibrating the model outputs per MSOA and LSOA.

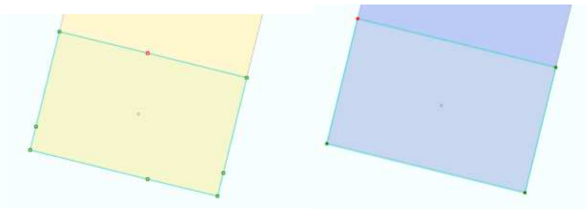
Table 1: Main Datasets Associated with the Modelling

Database	**Descriptions**	**Purpose in this study**	**Reference**
UK DCLG	EPC (energy performance certificate) for energy rating of both domestic and non-domestic buildings, DEC (display energy certificate) for metered energy data for public buildings	Input parameters for building energy models	(UK DCLG 2013)
UK DECC	Gas and electricity for domestic and non-domestic sectors in various spatial scales	Validation of building energy models	(DECC 2013b, DECC 2013a)
UK NCM	Typical internal heat gains for different building types	Peak gains and hourly schedules for lighting, equipment, and occupants	(BRE 2012)
UK ONS	MSOA (middle layer super output area) and LSOA (lower layer super output area) for census	Digital boundaries for various spatial scales	(ONS 2012)
UK Postcode	Code-point polygons to represent the spatial unit footprint within the same postcode	Assign input parameters for a groups of buildings in one postal area	(Ordnance Survey 2013)
UK VOA	Commercial and industrial floor space	Building age and floor area for commercial buildings	(VOA 2013)
UKMap	A detailed GIS database for London, including roads, buildings, rivers, etc.	Location of building, space use, floor height, polygon area etc.	(UKMap 2011)

These main databases described above are listed in Table 1, along with relevant references.

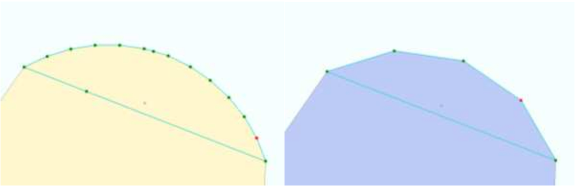
PREPROCESSING GIS DATA

In order to create building energy models, EnergyPlus Input Files (IDF) in this case, information from GIS maps need to be pre-processed in order to avoid unnecessary complex energy models.



Before simplification After simplification

(a) multiple-segments in one line



Before simplification After simplification

(b) small bends in one polygon

Figure 1: Two examples for simplifying polygons from GIS data

Geomtery corrections

There are two steps necessary in this case: simplify polygons; delete small polygons. The main purpose of the first step is to reduce the unnecessary complexity of energy models by removing extraneous bends while preserving essential shape. The second step is to delete stand-alone small and low-height polygons, which are likely to not be habited buildings. These are typically small sheds, bike-racks, or semi-open utility structures adjacent to buildings. There are at least two reasons why polygons from original GIS maps generally need to be simplified for energy models. One is that one line in polygons has several segments and the other is that some polygons have too many small bends. These can lead to a large number of vertices in ground or roof surface of a building energy model.

Figure 1 shows two examples for multiple-segments in one line and small bends in one polygon. Figure 1a illustrates an example for the first case, in which there are eight vertices in one four-sided polygon. In fact, there are only four vertices required for this tetragon. Figure 1b is an example of a polygon that has too many small bends. In this polygon, there are 18 vertices and after simplification this polygon only has 5 vertices.

Polygons with area less than 1 m^2 are deleted since they are generally not habited spaces within UKMap, and for these small geometries is hard to obtain correct coordinates from the corresponding GIS file. Independent polygons with height less than 1.5m are also deleted, as they are not conditioned spaces. After these two simplifications in our database of City of Westminster, there are 98,395 independent EnergyPlus models.

Floor area calculations

UKMap does not provide floor area of polygons, but only has land area, space use, and height. Based on these information, Choudhary (Choudhary 2012) has calculated the floor area for every polygon from London UKMap, which will be used in this study. The total floor area per polygon was calculated by dividing the height of the polygon by typical value of floor height, which varies depending on space use, total height, construction type, and footprint area. The results have been compared with the Valuation Office Agency in UK (VOA 2013). The calculation results are shown in Figure 2. More detailed descriptions on the method and the validation are available in (Choudhary 2012).

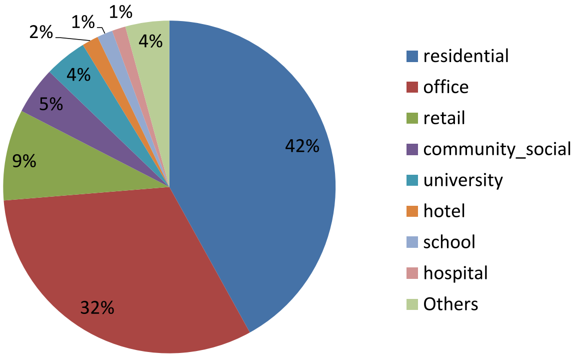


Figure 2: The percentage of floor area by building types in Westminster area

Coordinates of every point in all the polygons

Coordinates are both used in GIS data and EnergyPlus models. Therefore, the coordinates for all the polygons have been exported using WKT (well-known text) format in QGIS environment. The WKT is a text language used to represent vector geometry, such as point, line, and polygon. In this case, the coordinates for geometries are 2D for polygons from UKMap GIS data. In EnergyPlus models, surfaces are specified with geometric coordinates (DOE 2013). Thus, WKT data can be used to create interior or exterior surfaces in an EnergyPlus model. The heights and number of floors per polygon (building) are also extracted from UKMap. Note that the vertices in one surface in one building must be defined as the order required from EnergyPlus documents. As EnergyPlus models cannot deal with very large coordinate values, the actual coordinates used in EnergyPlus models have been reduced by a constant in both horizontal and vertical axes in order to show the building geometry properly in plugins such as the OpenStudio.

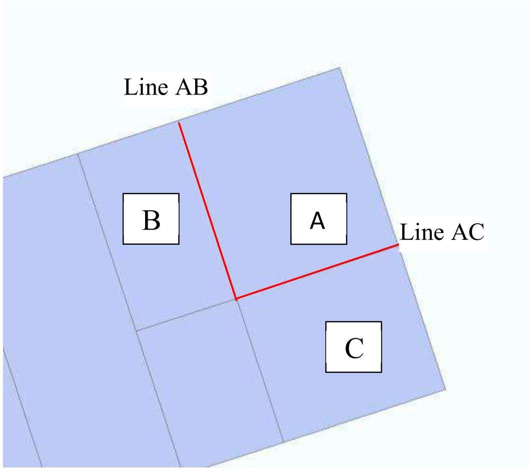


Figure 3: An example for determining internal walls in polygons from GIS data

Centroid coordinates for daylight analysis

For daylighting analysis, it is necessary to define the reference point to check if the electric lighting needs to be operating at full power. Since there are many irregular shapes from UKMap, it is hard to specify the desired location for this reference point. In this study, the centroid (geometric centre) of a polygon is regarded as this reference point. The calculation equation is based on Bourke (Bourke 2013). For a closed polygon, the coordinates for n vertices are assumed as (x_0,y_0), (x_1,y_1),…,(x_{n-1},y_{n-1}) and the coordinate for the centroid is taken as (C_x, C_y):

$$C_x = \frac{1}{6A}\sum_{i=0}^{n-1}(x_i + x_{i+1})(x_i y_{i+1} - x_{i+1} y_i)$$

$$C_y = \frac{1}{6A}\sum_{i=0}^{n-1}(y_i + y_{i+1})(x_i y_{i+1} - x_{i+1} y_i)$$

where A is the area of a polygon calculated as:

$$A = \frac{1}{2}\sum_{i=0}^{n-1}(x_i y_{i+1} - x_{i+1} y_i)$$

Internal or external walls

In urban settings, buildings are often attached together in one block as an example shown in Figure 3. It is therefore important to check whether the wall in one polygon is interior or exterior. The following procedure is used to determine internal or external walls in a polygon:

(1) Find which polygons are adjacent each other (function for calculating adjacency: vect2neigh from R spgrass6 package by Bivand 2013). Let us assume that a polygon *A* is connected with three polygons B, C, and D. (2) Calculate the intercept and slope for all the sides in polygons A, B, C, and D using the coordinates exported using QGIS program. (3) Compare the whether the intercept and slope are the same (or very close) in different polygons. (4) If both intercept and slope are the same for two sides in two polygons, then assume the data points for two lines: (x1,y1,x2,y2) in polygon A; (x3,y3,x4,y4). If (x2-x1) * (x4-x3) OR (y2-y1)*(y4-y3) is negative, then they are connected. (5) Continue the steps above for all the polygons. Then, choose lower height by comparing two heights in two adjacent sides. The lower height is divided by storey height to obtain floor levels, which are inside walls and no windows.

Figure 3 illustrates an example to show how to use the method described above to determine inside or external walls for polygons. In this figure, a polygon A is connected with polygon B and polygon C. The next step is to calculate the intercept and slope for all the sides in these three polygons. It is found that line AB has the same slope (-0.3046) and intercept (20413.77) from both polygons A and B. Polygons A and C also has one common line named Line AC with slope (0.3264) and intercept (1809.49). Then, follow the calculation method in the 4th step. This step is important because it has been found that some polygons with complex shapes may have two lines with the same slope and intercept. Finally, it can be concluded that Line AB and Line AC are internal walls, whereas the remaining two walls are external, exposed to outside environment. These need to be specified in building energy models.

ENERGYPLUS MODELS

To create EnergyPlus models from GIS data, the following data is needed: (1) Coordinate data for all the polygons; (2) Adjaceny information on all the polygons used to determine whether one side is inside or external walls in a given floor; (3) Base IDF file: those EnergyPlus model inputs that would not be changed in creating E+ models for different polygons (weather file, time-step, output values); (4) Main parametric input file for space use, building envelope, internal heat gains, and HVAC systems; (5) Hourly schedules for occupants, lighting, equipment, heating and cooling setpoint temperatures (8760 values) for the whole year.

In this preliminary version of city-scale modelling, we limit the analysis to one zone per floor, per polygon. As shown in Figure 4, the buildings in Westminster have been divided into different small polygons in terms of space use, ownership, and height. The floor area for most of polygons is small. Dividing these polygons into further zones without additional information is difficult – especially since individual floor area of most individual polygons is rather small. Another assumption is that inner rings in a polygon have been ignored. This is because EnergyPlus cannot create one-zone model with inner rings inside a large surface because there are at least two zones required to simulate these shapes (similar to courtyards or doughnut shaped buildings).

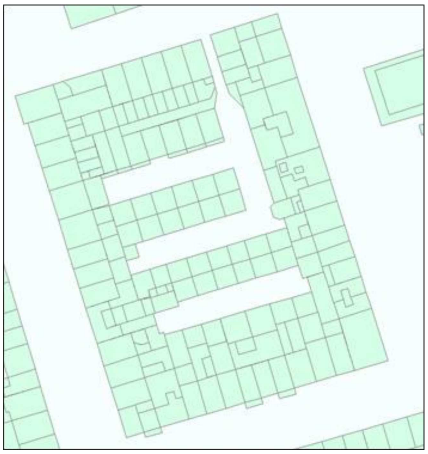


Figure 4: An example of GIS data from UKMap

The following procedure as shown in Figure 5 is used to create EnergyPlus models in R environment (R Development Core Team 2013).

1) Read all the five types of data (listed above) required for EnergyPlus models.

2) Start to create the geometries: For retail building, check whether this polygon is single-use or multiple-use polygon. This is because UKMap provides the information on the space usage above retail if the main floor is used for retail. For instance, for a three-storey building, the first floor is retail and the other two levels may be used for office or residential buildings. If this polygon is only for single usage, then create ground, top, and middle floors, depending on floor levels for a building. For a multiple-use polygon, then create the corresponding floor depending on whether it is located at ground, middle, or top floor. This is necessary so that energy models created here will consider the heat transfer among floors for the whole building. However, for the multiple-use polygon, floor or ceiling will be adiabatic in the corresponding zones. This is because there will be two separate energy models if one polygon has two different space uses in the corresponding floor levels.

3) Create surfaces (floor, roof, and walls) in one zone. The scripts check whether it is single-level or multiple-level building to assign boundary conditions in surfaces of a building and connect the inner floor with the inner ceiling in two adjacent zones. If the wall is exposed to external environment and the wall width is more than 0.8m, an external window will be created in this wall. If using daylighting, the centroid of one polygon will be calculated as a reference point to decide whether to use electric light in this zone. We then specify U-values for the entire external envelopes and also specify SHGC (solar heat gain coefficient) for windows. These are extracted either directly from the DEC and EPC database (if available), or inferred by building age and use type.

4) Add internal heat gains from occupants, lighting, and equipment. Also add hourly schedules (8760 values) for these components. The external files for these hourly schedules are used in this model, which means it provides, for future versions, more flexible solution to simulate stochastic occupant behaviour in actual buildings compared to typical weekday and weekend schedules usually used in building energy simulation. For instance, probabilistic occupant schedules can be implemented to investigate the influences of different schedules on energy consumption at urban scale. We also specify hourly schedules for heating/cooling set-point temperature.

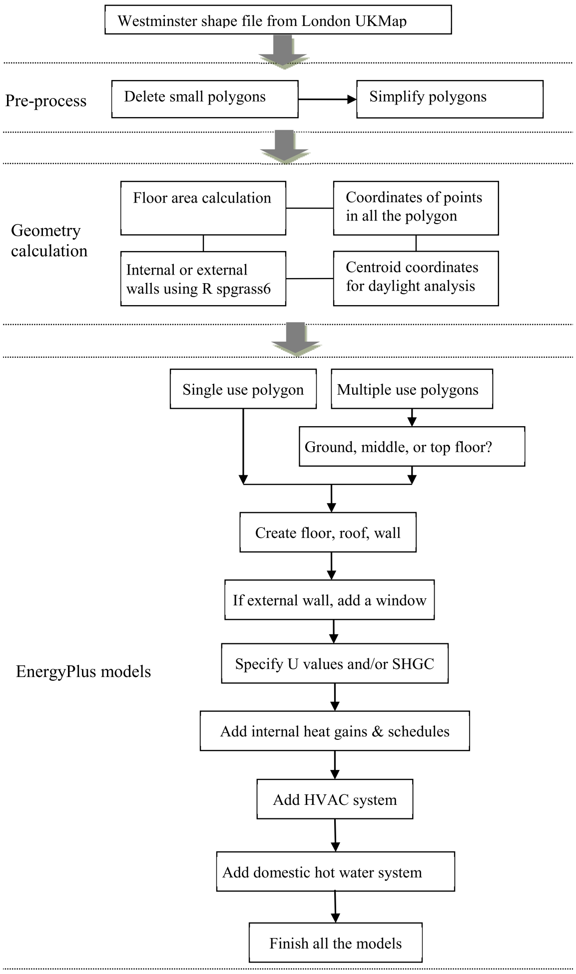


Figure 5: *Procedure for creating EnergyPlus models from GIS data*

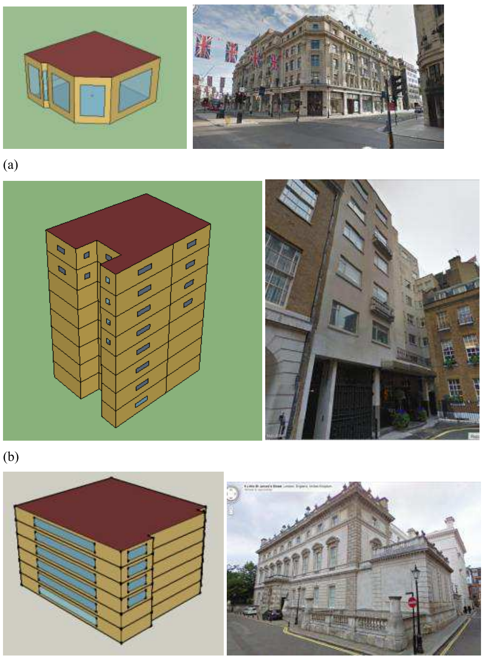
5) Define HVAC system whether it is natural ventilation or air condition system in one zone. For air conditioning zone, it is assumed that fan-coil system is installed. More different HVAC systems will be created based on the availability of systems installed in this area. Domestic hot water is added based on the method described in SBEM Technical Manual (BRE 2011).

6) Read a “Basic IDF” file to add all the information above to create an EnergyPlus model. Continue all the steps above to finish all the polygons in Westminster area. The final number of energy models created for both domestic and non-domestic

buildings in this project is 98,395 for Westminster area.

Spot Checks: Geometry

Three types of offices in terms of building geometry/shape shown in Figure 6 are chosen in this paper to check the geometric model against the actual building. Figure 6a shows an energy model for a top floor in a four-level building. This is an office situated above retail buildings. As can be seen from Figure 6a, this model represents the shape of building correctly. Figure 6b illustrates an energy model for a multi-storey office building. This is a complete building with partial exposure on side facades, and full exposure on front and rear facades. These details have been depicted correctly in this energy model. Note that there are two line segments for side façades since part of facades are connected with other buildings and windows only from the 5th to top level in around half of façade, whereas there a window in every level for the other half of façade. Figure 6c shows a three-storey office. In this model, the number of floor levels have been miscalculated because typical floor heights are assigned depending on space use. As can be seen from Figure 6c, the floor heights in different floors significantly vary for this building, which can likely be inferred by age of a building.


(a)

(b)

(c)

Figure 6: Comparison of three individual energy models and actual Google pictures

EXECUTION OF ENERGYPLUS MODELS

As described in the last section, around 100,000 EnergyPlus models need to be run for the Westminster area. This requires a lot of time if using one common PC. Cambridge HPC (high performance computing) Darwin computing cluster is used to expedite calculation for simulating around 100,000 EnergyPlus models. Ten nodes are allocated in this computation and every node is composed of two 2.6 GHZ eight core Intel Sandy Bridge E5-2670 processors. The total simulation time is around 4 hours. Note that simulation time for different models varies a lot in this study. Simulation time for models with a large number of sides and floor levels in one polygon may be significantly higher than the models with five-sided low-level buildings.

The size of simulation results from all EnergyPlus models is about 600-800 GB, mainly including hourly electricity/heating/cooling demand, error checking files, and other relevant files from EnergyPlus program. These original simulation results are firstly processed to the four types of results: annual load duration curves (heating, cooling, and electricity); hourly end-use energy demand, on average days (3) per month; monthly end-use energy demand; annual end-use energy demand. Finally, the energy consumption and associated carbon emissions are calculated by considering efficiencies of plant system and carbon emission factors. Compared to the simulation time (around 4 hours), much more time has been spend in post-processing simulation results.

Spot Checks: Energy Calculations

Two types of validation methods have been implemented for this preliminary version: spot checking and macro level comparison. The purpose of spot-checking is to compare building shape and thermal performance of individual polygons, whereas the macro-level comparison is to compare energy use in multiple spatial scales, depending on the availability of actual energy data. It should be noted though, that the modelling process needs further refinements in terms of model parameterizations, creation of multi-zone models per building, and designing a suitable methodology for validation and verification of model outputs. This is very much work in progress. Indeed, it is important to design the validation process carefully for such an exercise, as there is a risk that errors average out.

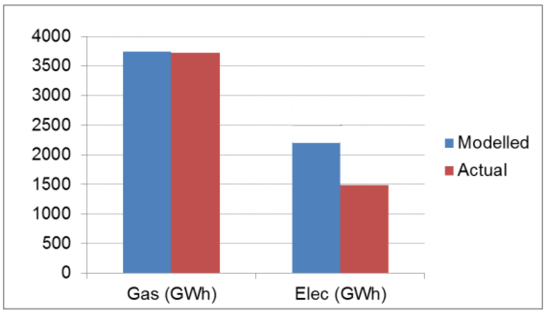


Figure 7: Comparison of gas and electricity from actual and simulation results

The gas and electricity results from these office buildings are within the range from previous studies

(CIBSE 2012, Choudhary 2012). Note that the results for individual buildings from this project cannot be directly comparable with actual monitored energy data for a specific building. This is because the input parameters obtained for energy models are not exactly the original buildings, but from the nearest building available from both EPC/DEC data. Therefore, for a given building, the input parameters used in energy models may not represent actual situations for this building. For a large number of buildings at urban scale, it is very unlikely that the analyst can obtain the accurate information for every building since at least hundreds of input parameters are required for dynamic hourly energy simulation. Figures 7-10 show the comparison of energy results in this Westminster area.

Validation With Aggregated Energy Data

This section validates the city-scale model with metered energy use data at two aggregated levels available in UK. DECC (2013a, 2013b) provides annual gas and electricity consumption at LSOA and MSOA levels for domestic buildings and at MSOA level for non-domestic buildings. In the dataset, a domestic gas user is defined as a building that consumes less than 73,200 kWh per year. Following this definition, we added gas predictions that are less than the cut-off point to a domestic gas estimate. In addition, non-domestic electricity data at MSOA level exclude half-hourly meters due to a potential risk of disclosure as buildings with half-hourly meters are typically very large energy consumers. Given the number of half-hourly meters per MSOA provided in the DECC dataset, we excluded the same number of the highest electricity predictions from a non-domestic electricity estimate.

We use a standard validation criterion, coefficient of variation of root mean square error (CVRMSE) to quantify differences between predicted and metered energy consumptions. Validation results are listed in Table 2. Overall, the city-scale model yielded electricity predictions in better alignment with measurements than gas predictions. Electricity consumption mainly comes from internal power loads that are modelled as a fixed schedule according to the building type. As occupant behavior in domestic buildings is notably known as diverse across the households, much larger discrepancy is observed in domestic electricity predictions than non-domestic ones. In addition to internal loads, many other factors, including building thermal properties, system efficiency, operation settings, determine gas consumption. Limited data available for estimating these parameter values resulted in larger CVRMSE values for gas predictions. Calibrating the city-scale model with existing energy data at different levels is a future study to improve the model reliability.

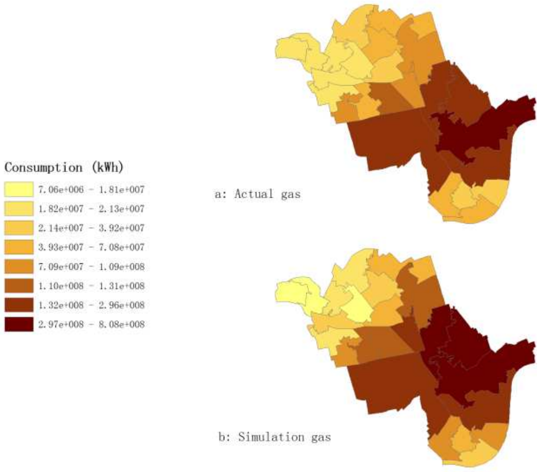


Figure 8: Comparison of gas from actual and simulation results for non-domestic buildings at MSOA (middle layer super output area) level

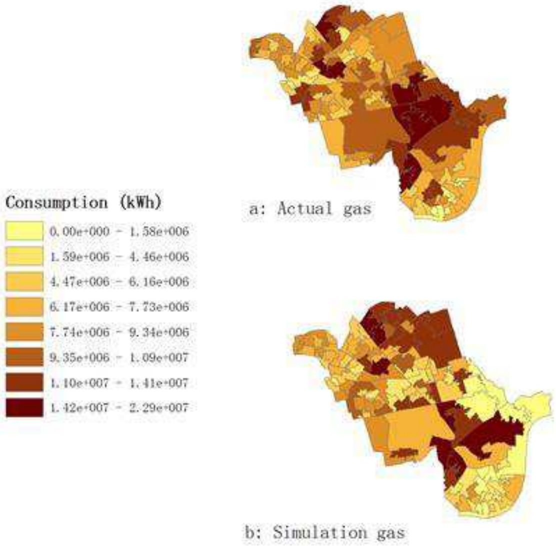


Figure 9: Comparison of gas from actual and simulation results for domestic buildings at LSOA (lower layer super output area) level

Table 2: CVRMSE Values of Model Predictions

	Gas	Electricity
Domestic Buildings		
MLSOA data	0.88	0.53
LLSOA data	0.99	0.63
Non-domestic Buildings		
MLSOA data	1.08	0.16

CONCLUSIONS

This paper has described how to create energy models based on GIS and other available information in urban environment -- automated the parsing of diverse and very recent databases to generate a baseline model of each building. The main feature of the method proposed in this paper is to directly use GIS data (shape file) to convert them to 3D building energy models. Since the shape file format is commonly used in urban studies, the method descripted in this paper can be easily adapted in other urban-scale building energy projects. However, there are still many issues that need to be addressed in converting GIS data to building energy models in urban settings. The following topics will be investigated in future research:

(1) It is arguable that multiple-zone energy models may be more appropriate for large buildings (Dogan 2014). It would be very interesting to compare the simulation results from one-zone energy models and multiple-zone models for this project. One must recognize that not all executions of the simulator will require all buildings to be modelled at a uniform time-step. Indeed, it may be the case that the time-varying behaviours of certain types of buildings are not relevant for the analysis, or certain areas of the city are less important than others, or certain buildings (being repetitive in most aspects) can be well-represented by a standardized set of parameters and executed as one model.

(2) The weather data used in this project is directly from EnergyPlus website and the data is from Gatewick airport. If the spatial variations of weather data can be obtained in Westminster area, it would be useful to analyse simulation results due to various weather files, such as the effect of urban heat island.

(3) The typical schedules for internal heat gains are used in this project. The stochastic occupant behaviours may be added in the future research to explore the effects of typical deterministic and stochastic occupant behaviours on energy results at urban scale.

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