3DStock: A new kind of three-dimensional model of the building stock of England and Wales, for use in energy analysis

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Abstract
This article describes the development of a new three-dimensional model of the British building stock, called '3DStock'. The model differs from other 3D urban and stock models, in that it represents explicitly and in detail the spatial relationships between 'premises' and 'buildings'. It also represents the pattern of activities on different floors within buildings. The geometrical/ geographical structure of the model is assembled automatically from two existing national data sets. Additional data from other sources including figures for electricity and gas consumption are then attached. Some sample results are given for energy use intensities. The first purpose of the model is in the analysis of energy use in the building stock. With actual energy data for very large numbers of premises, it is possible to take a completely new type of statistical approach, in which consumption can be related to a range of characteristics including activity, built form, construction and materials. Models have been built to date of the London Borough of Camden and the cities of Leicester, Tamworth and Swindon. Work is in progress to extend the modelling to other parts of Britain. Because of the coverage of the data, this will be limited however to England and Wales.

Energy use in the non-domestic building stock

It is estimated that around 40% of primary energy use in Europe is in buildings (Joint Research Centre, 2015). In Britain, this figure divides into 28% in the domestic stock (houses and flats) and around 12% in non-domestic (all other building types)[1] (ECUK, 2014, table 1.05). Because of the slow rate of change in the stock, there is general agreement that the efficiency of energy use must be improved rapidly in existing buildings, and new supply technologies introduced, in order for countries to meet their carbon

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reduction targets. As a result, governments and others have been constructing databases and models of building stocks to understand their composition, and to test scenarios for energy interventions. More progress has been made on databases of the domestic stock than the non-domestic for two main reasons: greater availability of large-scale domestic data and the fact that non-domestic buildings are typically more complex and heterogeneous than houses. This article describes a new kind of model of the non-domestic stock of England and Wales, called 3DStock.

A wide range of factors can affect the use of energy in non-domestic buildings. Energy use is in general – although not always – broadly proportional to floor area (or building volume). The activities housed are important because they can determine the demands for heating and cooling, the use of electrical equipment and lighting, and the occupancy of the building (hours per day and days per week of operation). Fuels used, and types of servicing system (lighting, heating, air conditioning) can be significant. Rates of heat loss and heat gain will be affected by the materials of the envelope, in particular, the extent of glazing. They will also vary with the geometrical form of the building, in particular, the ratio of exposed surface to volume, and the building's depth in plan. The ages of buildings can have direct and indirect effects. This is not an exhaustive list. Ideally, therefore, a stock database or model should record and represent as many of these factors as possible at the level of individual properties.

'Premises' and 'buildings'

The relationship of premises to buildings assumes particular importance in representing the non-domestic stock. A 'premises' is an extent of floor space with a single owner or occupant. A 'building' is more difficult to define with precision – indeed in what follows we will use a somewhat different unit, as we will explain. In everyday language, of course a 'building' tends to mean a single structure, erected all at one time, in a homogeneous style and form of construction. In these terms, there can be different kinds of relationship of premises to buildings. Several premises can occupy a single building, as in the case of many tenants sharing one office building. One premises can coincide with one building, as is typically the case with churches. Or one premises can consist of many detached buildings on a shared site, as for example, a secondary school, a university campus or a large factory. It is possible for one premises to span across two or more buildings, as for example, when a shop or restaurant is extended into adjoining addresses in a terrace.

These facts create considerable complications for non-domestic stock modelling. Activities, occupancy and equipment are associated with premises; and the owners and occupiers of premises can make decisions about investing in energy improvements and making behavioural changes. Built form and materials, on the other hand, are obviously properties of buildings. Electricity and gas meters may be situated in individual premises. Alternatively where several premises occupy one building, the meters may be shared, as when a single central heating or air conditioning system serves the whole building. The 3DStock model has ways of coping with all these issues.

In the domestic stock, the situation is generally simpler. One 'premises' (the household) occupies one building (the house). By contrast, in a block of flats, many 'premises' (the flats) share a single building. There is a similarity with a multi-tenant office block. It is possible for buildings to be shared between domestic and non-domestic premises, as with flats over shops. Some domestic stock databases have been able to avoid these complications by excluding flats and using the building (the house) as the basic unit of analysis. Several non-domestic stock databases constructed to date have, on the other hand, used the premises as their accounting unit. This has meant that they have failed to represent buildings as such.

Previous databases and models of energy use in the building stock

Examples include the four detailed models/databases of the non-domestic stock of England and Wales constructed since the late 1990s. These were the National Non-Domestic Energy and Emissions Model (N-DEEM) of 1994 (Pout, 2000); two successive Carbon Reduction in Buildings (CaRB) models, the first in 2004 (Bruhns et al., 2006), updated as CaRB2 in 2011; and the Non-Domestic National Energy Efficiency Data-Framework (ND-NEED) of 2014 (Department of Energy and Climate Change (DECC), 2015a). All four models have had essentially the same structure. They have all consisted of comprehensive lists of premises or groups of premises, classified by activity, with data on total floor areas. In the N-DEEM and CaRB models, these floor areas were multiplied by typical energy intensities (kWh/m^2 of electricity and gas) obtained from sample surveys, in order to gross up to the national level. In ND-NEED, actual annualised electricity and weather-corrected gas consumption figures from meter readings are matched to individual premises by their addresses. Thus, none of the models have recorded characteristics of buildings. In many cases, a basic premises record relates to just part of a building, in other cases to groups of buildings collectively. This has made it difficult or impossible to relate energy consumption to such variables as materials and geometry.

The reason that the coverage of these models is limited to England and Wales is that the principal source of floor area and activity data in all cases is the British government's Valuation Office Agency (VOA, 2015). Commercial property taxes ('rates') in Britain are levied not on land as in most other countries but on premises, or what the VOA calls 'hereditaments'. For this reason, the Agency makes detailed surveys of the majority of non-domestic premises, as described in more detail below. One standardised system of data collection is used for England and Wales. Scotland and Northern Ireland are treated differently and hence are excluded from the stock models.

Two other countries/territories, New Zealand and Hong Kong, have building-based property taxation systems similar to Britain's. In New Zealand, valuation data were used as a sampling frame in the Building Energy End-Use Study (BEES), which surveyed a portion of the country's non-domestic building stock (Amitrano, 2014). Other countries have had to rely on government data collected for different purposes (censuses, employment data, building and planning permissions, insurance records, land registries, etc.) or on specially conducted surveys of the stock.

The United States government has carried out a Commercial Buildings Energy Consumption Survey (CBECS, 2015) at regular intervals since 1979. (The word 'commercial' is interpreted liberally in CBECS to refer to non-domestic buildings of most kinds including schools, hospitals, etc.) The Survey covers a random sample of the stock, based on a sampling framework. In 2012, some 6700 buildings were surveyed out of a national estimated total of 5.6 million. Activities, building data and energy consumption are recorded in tabular form. On the basis of the survey data, 3D models of theoretically representative 'archetypal buildings' are constructed, on which energy interventions are tested through simulation, and scenarios developed (see Coffey et al., 2009). Some other countries have similar survey programmes.

When energy use data for buildings or premises carry addresses or geo-references, they can be presented in the form of maps. Many such maps have been produced: the EC Joint Research Centre (2015) has made an international review. One example for Britain is the DECC's national Heat Map (DECC, 2015b). The non-domestic part of this map was created using VOA floor area data, typical benchmark values for gas use and other sources. A team at the School of Engineering and Applied Science at Columbia University have assembled a

map of energy use in New York City (Howard et al., 2012). Here statistical methods were used to estimate gas and electricity consumption at the level of blocks and lots (but not individual buildings).

Such maps can be informative and useful, but obviously they have no representation of 3D geometry. There have been very large numbers of 3D digital models of cities built around the world. Zlatanova and Prosperi (2005) and Van Oosterom et al. (2008) provide reviews. The great majority of such models represent buildings as empty polyhedra. Buildings are often modelled as simple vertical extrusions from their map footprints, with their heights derived from LiDAR measurements. The main applications are in visualisation. Sometimes, activities are attributed to building blocks (but not floors or premises) on the basis of classifications in the base maps (see Smith and Crooks, 2010).

To be useful in energy studies, however, much more detailed data needs to be attached to the 3D geometry, describing activities, construction and the other variables listed earlier. This has been done with some success for the domestic stock because of the one-to-one relationship of households to houses. House types can be recognised automatically from their map footprints and LiDAR measurements, and estimates made of their floor areas (see Orford, 2010). Mavrogianni et al. (2009) have built a 3D domestic stock model for London. Nouvel et al. (2015) have built two models of heating energy demand in domestic buildings in a district of Rotterdam, using 3D modelling and statistical estimation of gas use. In the non-domestic stock, what is needed by contrast is the simultaneous representation of premises and buildings and their spatial relationships. The 3DStock model offers a way of doing this. It is unique in Britain, and there is to our knowledge only one comparable model internationally.

The 3DStock model

The 3DStock model has the following characteristics:

1. The model represents (with some simplification) the 3D geometry of all buildings or small groups of adjacent buildings housing non-domestic activities. Relationships of buildings to sites, blocks and roads are also represented.
2. The model records floor areas by floor levels (including basements), with the distribution of premises on those floors, classified by their activities (including mixtures of non-domestic and domestic activities). Floor areas of premises are further broken down into sub-activities.
3. Data on materials, age and construction are attached to the buildings.
4. Actual energy consumption data, where available, are attached by matching meters automatically by their addresses, either to premises or groups of premises within buildings.
5. The geometrical model is built automatically from existing publicly available data sets. Models have been built so far of the London Borough of Camden and the towns of Leicester, Tamworth and Swindon. We will concentrate in this article on the model of Camden. Work is in progress to extend the coverage to large parts of England and Wales.

3DStock thus avoids the approximations made in other models and databases by using theoretical 'building archetypes', by estimating energy consumption statistically, or by using aggregated (actual) consumption data. The detailed representation of 3D geometry allows the automatic calculation of volumes, areas of exposed surface and plan depth.

These are particularly important because they affect heating and air conditioning demand (see Steadman et al., 2014), which are two of the largest end-uses of energy in many buildings. It is not always possible to link gas and electricity meters to individual premises for the reasons explained earlier. But in 3DStock, all meters are attached either to premises or to larger spatial units whose extents are known; thus all energy use is accounted for.

The model is being used primarily to study operational energy use. It might possibly have applications in studying the embodied energy associated with materials and the construction process. The 3D modelling, together with data on materials, would provide a means for making a very broad-brush quantification of the mass of the stock. Ongoing work on the relationship between footprint area and internal floor area measured according to different conventions could allow estimates to be made of wall thicknesses. These subjects are not, however, explored here.

The one other model known to us that has some similarities to 3DStock is the model of Basel, Switzerland, built by a team at the Swiss Federal Institute of Technology (ET Zurich) (Aksoezen et al., 2015). This covers both domestic and non-domestic buildings in a part of the city: these are represented in 3D in an ArcGIS database. Data relating to activities, numbers of occupants, construction year and type of heating system are attached. Actual gas consumption data are matched to the buildings, but not electricity. The modelling process is not automated.

Data from the Ordnance Survey and the VOA

Two national data sources are brought together to create the basic structure of the 3DStock model. The first source is the Ordnance Survey – the UK's national mapping agency – specifically the Ordnance Survey Address Base (OSAB) and Mastermap digital map products (Ordnance Survey, 2015a, 2015b). The second source is the VOA.

Property taxation or 'rating' data are available in the form of two VOA databases. The Rating List covers most premises – or what the VOA calls 'hereditaments' – with certain exceptions detailed below, giving addresses and the 'primary' activities of the occupants. The Summary Valuation (SMV) database gives more detail for approximately 90% of these same hereditaments, including their floor areas. Here, the primary activity (e.g. 'Commercial office') is broken down into sub-activities (e.g. office space, storage, kitchen, computer room, etc.). The database gives the floor areas devoted to these sub-activities on each floor level. The areas are measured according to different conventions, usually net internal area (NIA) or gross internal area (GIA). Analytical work carried out on VOA records and drawings in the 1990s showed that these measurements are very accurate, no doubt in part because they are open to challenge by ratepayers (Gakovic et al., 1993). Both Rating List and SMV are updated continuously, with revisions and new entries prompted by applications for planning permission and building regulations approval.

Some types including hotels, public houses, universities, schools and hospitals are covered in the Rating List but usually have no floor area data. Very large industrial hereditaments are valued separately, and are omitted from both Rating List and SMV. Three classes of activity are exempt from rates altogether: agricultural premises, places of worship and properties of Her Majesty the Queen. This last group – besides Royal palaces – includes the Ministry of Defence estate, which is extremely large. Floor area data in all these cases must be estimated or obtained from other non-VOA sources. Some area data are available from Display Energy Certificates (DECs) and Energy Performance Certificates (EPCs) (Department for Communities and Local Government, 2015).

Activity classifications in VOA data

The VOA has a complex system for recording activities in hereditaments, consisting of four layers of classification at successive levels of detail. At the top level are the 'bulk classes', which group very large numbers of quite diverse premises together under 'Office', 'Retail', 'Factory' and 'Warehouse' categories.

At the next level down are 'primary descriptions' (PDs), of which there are just over 100, each with a code. Examples include 'Petrol filling station', 'Wine bar' and 'Library'. Then, there are 'special category codes' (SCATs), of which there are some 360, which go into yet greater detail. For example, the 'Restaurant' primary description is associated with five SCATs: 'Restaurant', 'Drive-in restaurant', 'Drive-thru restaurant', 'Roadside restaurant' and 'Restaurant/café within/part of specialist property', this last being an independent restaurant within a larger premises such as an airport, station or hotel. In practice, the main activity in a hereditament is pinned down by a combination of primary description and SCAT.

Finally, at the lowest level are descriptions for the sub-activities found within hereditaments. These are given in 'Line Entries' in the SMV database. They are entered by surveyors as free text strings, which have had to be cleaned, classified and grouped into some 340 meaningful sub-activity descriptions. For example, an area originally described as 'Chill Out Seated Area' is re-classified as 'Lounge'. These cleaned descriptions account for around 99% of sub-activities, with only a few very specialised activities not coded. From this, it is possible to identify combinations of primary description and sub-activity. For example, within a 'Showroom' (primary description), there might be Line Entries for 'Showroom', 'Office', 'Servicing bays', 'Parts department' and 'Store'. The significance of the sub-activities is that they can be associated with typical schedules of power-using equipment, allowing estimates to be made of electricity use.

The use of Line Descriptions makes it possible to identify sub-areas that are internal and external, and that are (or are not) parts of buildings. Thus, a 'Balcony' could be internal or external, but in either case would be part of a building. On the other hand, a 'Yard' would, in general, be external and not part of a building, and would be excluded from the SCU floor area. This makes it possible to remove parts of hereditaments that consist of land not buildings, for example, parking space for cars on display outside showrooms. Together, such areas amount to about 10% of all 'floor area' in the SMV. (This is after hereditaments consisting wholly of land have been removed.)

For the 3DStock model, we have taken over the complete VOA system of activity classifications, leaving out certain 'non-building' categories and aggregating some PDs and SCATs that classify only small numbers of hereditaments. It has been necessary to add extra categories for non-rated activities such as 'Church/place of worship'. The VOA's classifications have many virtues and have been tested in rating practice over many years. In a few respects, however they are not ideal for energy analysis. Large numbers of 'Factories' are classified as such without further detail, where it would be desirable to know the nature of what is being manufactured, since this can determine the types of machinery used and the demands for cooling and ventilation. Similarly, there are many 'Small shops' in VOA records without further descriptions. We know that energy use can vary widely with the types of goods sold and services offered in shops, especially where equipment is involved such as bakery ovens, copying and photographic machines, or dry cleaning plant.

Distinctions between economic sectors at this level of detail are made in the Standard Industrial Classification (SIC), which is used widely in economic statistics across Europe

(Office for National Statistics, 2007). The SIC however classifies sectors of the economy, not building types, and for that reason is not ideally suited to building stock modelling. For example, the head office of a supermarket chain, the stores themselves and the company's warehouses would all be classified under the same 'Food (general) (retail)' SIC code. The SIC might be useful in principle for differentiating factories and shops by what they manufacture or sell; but making cross-links to the VOA's categories would not be straightforward.

Matching digital map footprints to VOA hereditaments

VOA hereditaments can be matched to map polygons representing building footprints, by their respective addresses. Ordnance Survey Address Base holds a link in many (although not all) cases to unique address reference numbers (UARNs) in the VOA Rating List. OSAB also enforces compliance by local authorities with the British Standard for the formatting of address information, BS7666 (British Standards Institution, 2006), and it coordinates and enforces the maintenance of Local Land and Property Gazetteers. For cases where this link does not exist, we have developed a special module to clean and match addresses. This module first cleans non-BS7666 addresses into something close to BS7666, and then uses a number of different methods to find the closest match within the OSAB database. For the Camden case study, a 98% match rate was achieved for the 2010 Rating List.

The OSAB data can then be cross-referenced to topographic map data providing building footprints and other map 'objects'. The Ordnance Survey Mastermap Topography layer (OSTopo) has polygons for buildings, roads, rivers and railways (Ordnance Survey, 2015c). For the buildings, the address data are attached to points within footprint polygons. In this way, Valuation Office UARNs can be matched to building footprints.

In practice, the picture is however more complex than this brief account would suggest. First, there can be more than one address point within one footprint polygon. Second, there can be several addresses attached to each point. Third, a single building may be represented by a group of adjoining polygons, only some of which are addressed in OSAB.

Taking these issues in order: Ordnance Survey addressing can sometimes have a hierarchical structure, where there is just one unique property reference number (UPRN) for an address that might contain several hereditaments, for example, an office building containing several office premises. In other cases, however, a single building might have a 'parent' UPRN, which in turn has related 'child' UPRNs that match to the individual hereditaments (UARNs). One building can thus have several UPRNs. These complexities are important when it comes to matching electricity and gas meter data, and for the units of construction defined for analysis in the modelling work, which do not equate simply to 'buildings'. These points are discussed further below.

'Polygon capture'

Then there is the problem that not all footprint polygons carry addresses. A typical case would be where a polygon on the street front corresponding to the major part of the building carries the address of a hereditament, but there are further unaddressed polygons corresponding to extensions at the back. Another frequent type of situation, mentioned earlier, is where a shop or restaurant in a row of terraced properties has expanded into a neighbouring building, and only one of the two footprint polygons in question carries the address.

To cope with this problem, we have developed special 'polygon capture' software using a spatial topological model and combinatorial optimisation. This compares the area of the

footprint polygon with the floor area on each level given by the VOA line entries for the hereditament in question (Figure 1). If these differ significantly – allowing for the respective conventions of area measurement – then the method seeks additional floor area in adjoining unaddressed polygons at the same level. The method finds the best solution that creates a combined footprint with the closest match to the figure given by the SMV Line Entries. In cases where two addresses are competing for the same polygon, the solutions can be compared and the better result retained. In this way, the software can be run many times until an optimum solution is achieved.

In general, the VOA does not allow one hereditament to cross a public road: thus every hereditament is contained within an urban block. This fact can be used to limit searches in the 'polygon capture' process. Urban blocks can be created in the maps by removing the separators (roads, railway lines, rivers) and classifying the remaining regions (the blocks) with unique identifiers. Any footprint polygon seeking to capture other polygons must select them from the same block.

This method works well for cases where a hereditament occupies several adjoining polygons. It is unable to cope with 'campus' hereditaments consisting of many separate buildings whose footprints are not adjacent. Here, a different approach is needed. We are relying in part on a new 'Sites' product launched recently by Ordnance Survey, which gives boundary polygons for campuses and similar multi-building sites (Ordnance Survey, 2015d). The coverage of Sites is not however complete, so we are also using land ownership boundaries from Her Majesty's Land Registry (HMLR, 2015). Figure 2 shows sample site boundaries in Camden from both sources.

One issue that is unresolved at present can be thought of as the opposite of the polygon capture problem. It occurs when a hereditament falls in a polygon that is far larger than the ground floor area recorded by the VOA. This situation occurs when small hereditaments occupy space under the umbrella of a much bigger structure, such as a shopping centre containing many small shops, or a major transport hub like a mainline railway station with

Figure 1. An example of 'polygon capture' where a restaurant has expanded into an adjoining building. The polygon at number 36 is the 'addressable' polygon for this hereditament. The SMV shows that it requires an area of 77 m^2 (GEA) but the polygon only offers 41 m^2. The unaddressed polygon at number 38 next door offers 37 m^2, which gives a combined floor area of 78 m^2. The software accepts this as an optimal match.

cafes and shops inside the 'building'. Additional geometrical data – specifically internal plans of these buildings – would be needed before the methodology could be applied in these circumstances.

With the exceptions of these problematic cases, once these steps are complete, we end up with hereditaments that are 'stratified' and piled up on the relevant footprint or footprints to make three-dimensional 'pseudo-buildings' (Figure 3). The fact that the SMV database gives floor areas by floor levels means that hereditaments can be allocated to the correct level or levels (including basements). (Where two or more hereditaments share the same floor, it is not however possible to know exactly which parts of that floor each occupies.)

The Self Contained Unit (SCU)

It will be clear from what has been said so far that the 'building' is not a wholly satisfactory unit for modelling the non-domestic stock. Should buildings be taken as units, then premises could become split, and it would be difficult to relate meters and energy consumption to the different parts. For the present work, we have instead adopted the SCU introduced by Taylor et al. (2014).

Should one or more hereditaments occupy a building with a single detached footprint polygon, then building and SCU coincide. The SCU concept comes into its own with groups of adjoining footprints. Consider the two situations in Figure 4, showing three terraced properties, numbers 15, 16 and 17 High Street. In Figure 4(a), a single hereditament at ground level spans the two footprint polygons of numbers 15 and 16. The SCU (the black outline) is defined to contain the whole of both buildings. In Figure 4(b), there is in addition, a second hereditament spanning across numbers 16 and 17 at first floor level. Now the SCU (the black outline) must take in the whole of numbers 15, 16 and 17. The Taylor et al. definition of a SCU has been adapted for cases where premises are on a 'campus'. Here, the

Figure 2. The Ordnance Survey Sites product can be used to select all buildings in a campus as with this school (left). As the Sites product is not available in every instance, the land ownership boundaries from Her Majesty's Land Registry are used (right), where the thick black outline shows the land boundary being used to identify all four detached buildings that constitute the 'Corporation Yard and Engineering Depot'.
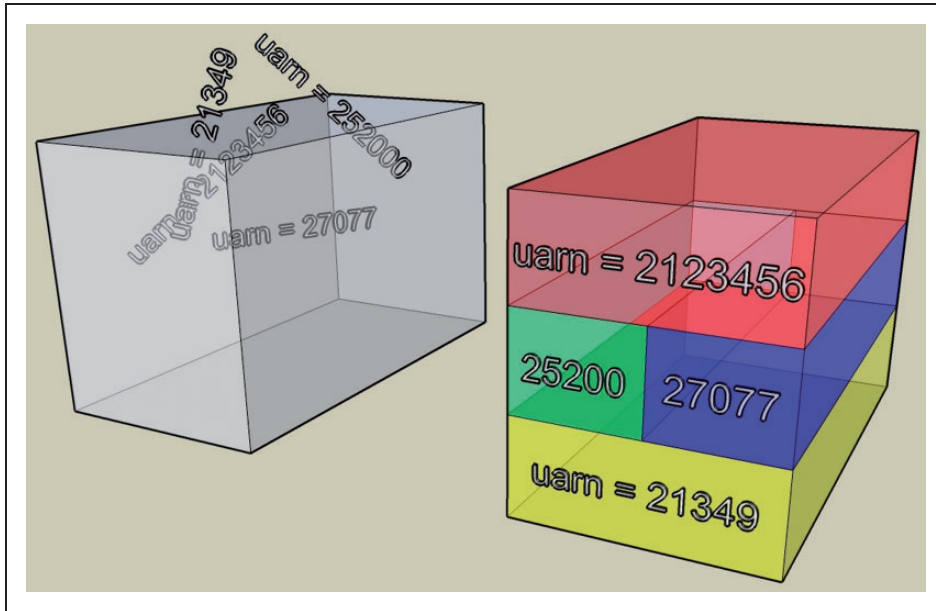
Figure 3. Hereditaments (UARNs) matched to a building footprint (left) and stratified by floor level (right).
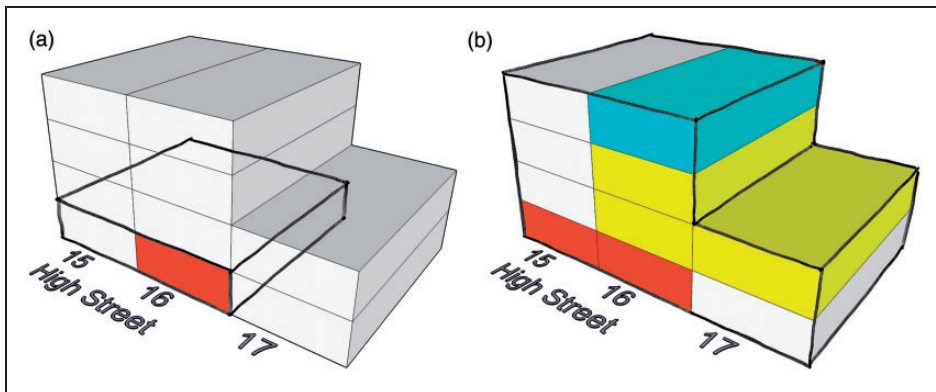

Figure 4. Self Contained Units (SCUs). Hereditaments are not broken between SCUs. (a) A hereditament extends across 15 and 16 High Street at ground floor level, so the SCU (heavy line) spans the two footprints. (b) Another hereditament at first floor level extends across 16 and 17 High Street. Now the SCU (heavy line) must span all three footprints.

building polygons within the site are classified as a 'poly-SCU' rather than a SCU. Poly-SCUs occur when two or more non-contiguous building polygons can be attributed to one or more hereditaments that occur within the campus (which itself is defined as a polygon boundary). Typical examples of poly-SCUs include large school and factory sites.

The basic criterion for defining the SCU is thus that it must not break hereditaments on any floor level. The SCU has two further properties that are of key relevance to energy analysis. First, it has a well-defined thermal envelope (roof and exposed external walls) through which heat is lost or gained. The second property is that it is generally possible

Figure 5. A Self Contained Unit in Camden containing two buildings with a ground floor shop extending across both addresses. In this case, the buildings are of similar age and construction. But in other comparable cases, they might not be.

to know the relationship between the totality of floor space within the SCU, and the total metered energy supplied to the SCU. It would often not be possible to determine this relationship of floor area to energy use at the hereditament or even the building level.

One drawback of the SCU, arising out of its very definition, has to do with the properties of the envelope. It is possible for different buildings making up one SCU to have different ages, different types of roof or different wall materials and patterns of glazing (Figure 5). These could all in turn affect rates of fabric heat loss and gain. However, this is an unavoidable dilemma, and there are only two choices: use the building as the unit and subdivide hereditaments, or use the SCU and accept the problem of mixtures of fabric properties. We have chosen the latter.

Table 1 gives statistics for the numbers of hereditaments, addresses, SCUs and floors in SCUs in the Camden, Tamworth and Leicester models. Table 1 also shows mean numbers of hereditaments/SCU and floors per SCU. The higher density of the building stock in Camden compared with Tamworth is reflected in the greater numbers of both hereditaments and storeys, on average, in the Camden SCUs.

Figure 6 gives total non-domestic floor area in the VOA SMV database for Camden by floor level. Note that basements rank third in total size after ground and first floors. The long

Table 1. Numbers of hereditaments, addresses, SCUs and floors in SCUs in the Camden and Tamworth models.

| | Billing authority | | |
	Camden	Tamworth	Leicester
Billing authority area (km^2)	22	32	75
Hereditaments (UARNs) matched	13,766	1803	10,679
Addresses (UPRNs)	13,360	1773	10,562
SCUs	6347	1364	7647
Polygons (in SCUs)	7184	1524	8865
SCUFs (floors of SCUs) which are 'whole' floors (excluding mezzanines, etc.)	15,144	1891	12,632
Average number of hereditaments per SCU	2.17	1.32	1.40
Average SCUFs per SCU	2.39	1.39	1.65
Average polygons per SCU	1.13	1.12	1.16

The mean numbers of hereditaments per SCU and floors per SCU are also shown. The figures illustrate the generally higher densities in Camden.
SCU: Self Contained Unit; UARNs; unique address reference numbers; UPRN: unique property reference number.
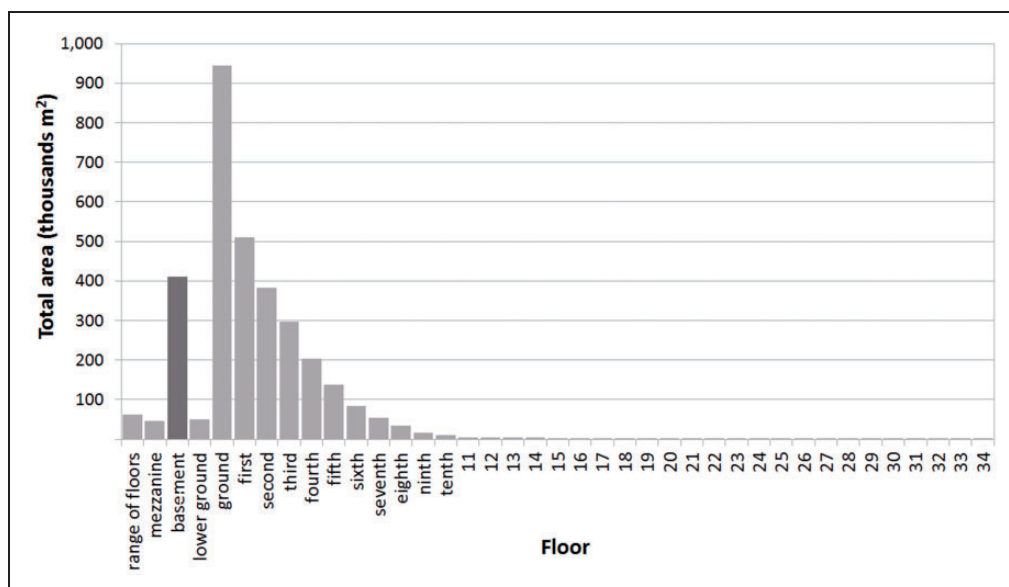

Figure 6. Distribution of floor area in Camden by floor level. (Only floor area in the SMV database is included.) Basements (−1) rank third in total area. The long tail is created by a few tall buildings.

tail in the distribution is produced by a few high-rise buildings. Figure 7 shows this same distribution by both activity and floor level, in the form of a Sankey diagram. Activities are distinguished at the left, in 14 groups aggregated from PD/SCAT classifications. Offices dominate, followed by shops. Floor levels are given at the right. Shops unsurprisingly are mostly at ground level while offices are found on all floors.

It is possible to look at these patterns geographically by drawing maps showing the predominant activities in SCUs at different floor levels. Figure 8 shows predominant activities at ground level for an area close to Farringdon underground station in Camden. For the most part, this is a mixture of office and retail SCUs. Figure 9 shows the same location on the first floor level, where offices dominate. (It should be added in parenthesis that Camden contains only small numbers of industrial and warehouse premises. In England and Wales, these two activities account for more than half of all floor area in the SMV database. One reason for modelling Leicester, Tamworth and Swindon is that all these places have significant numbers of factory and warehouse hereditaments.)
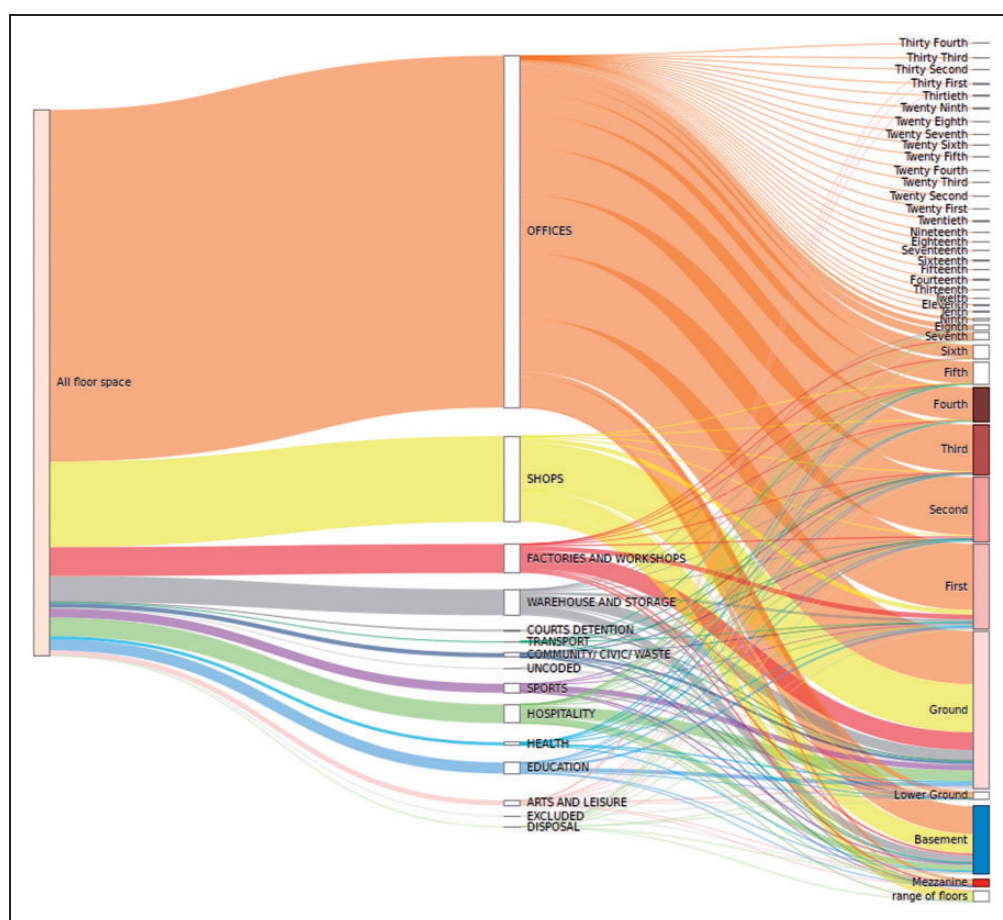

Figure 7. Sankey diagram to show the distribution of non-domestic activities in 14 groups (left) between floor levels (right) in Camden. (Only floor area in the SMV database is included.) Shops are predominantly on the ground floor while offices are found on all floor levels.
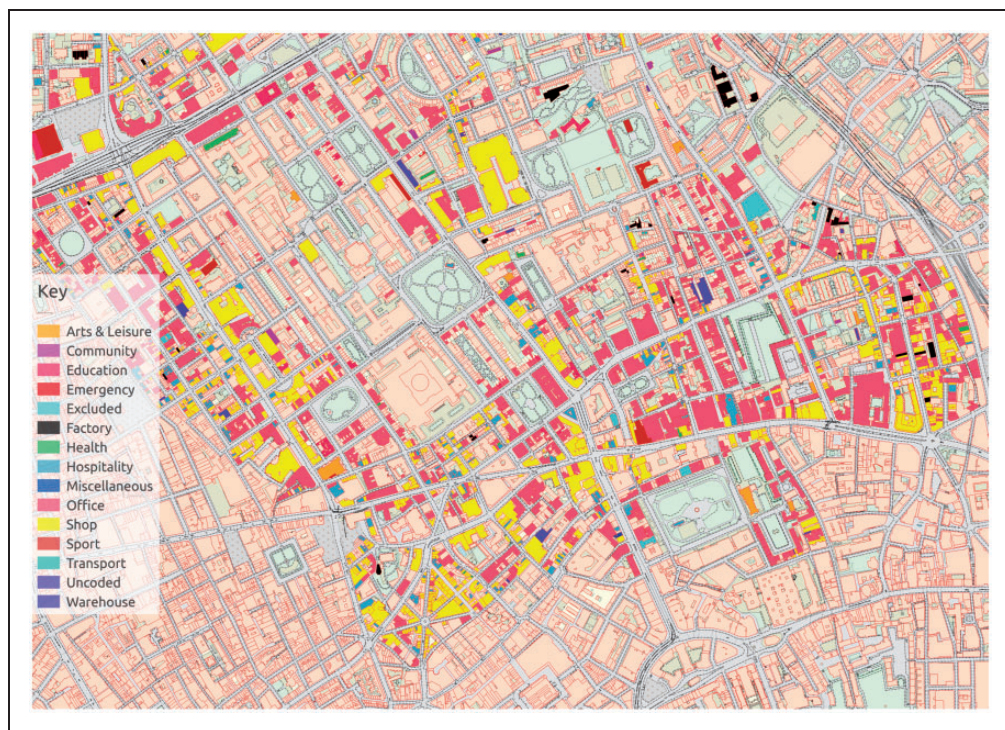
Figure 8. Map to show the predominant activity in SCUs at ground floor level in a part of Camden.
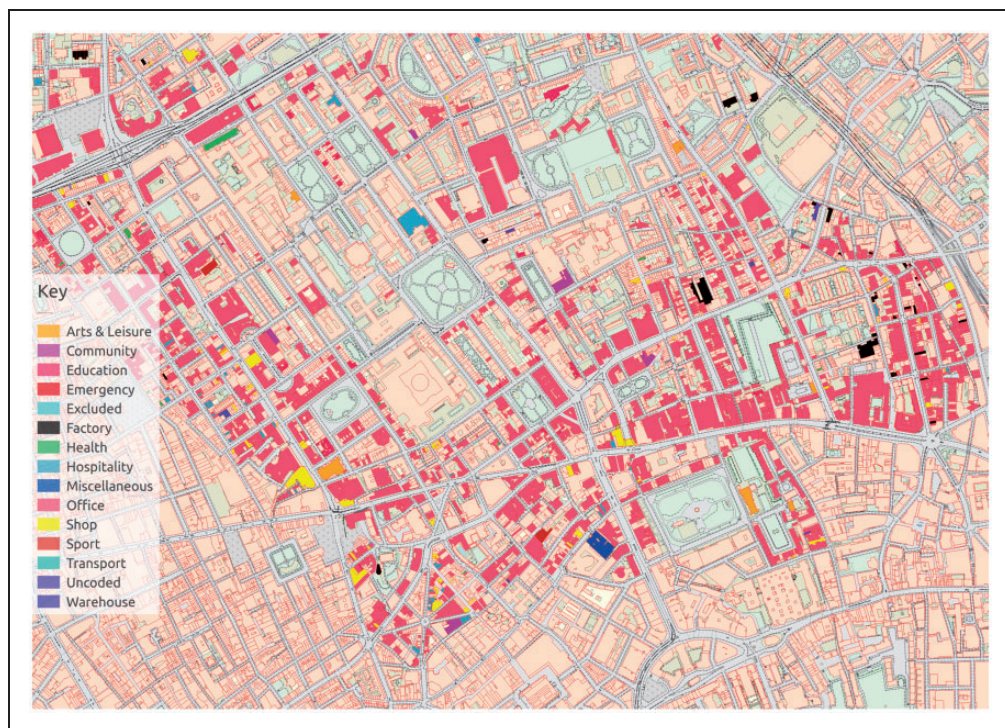

Figure 9. Map to show the predominant activity in SCUs at first floor level in the same part of Camden.

The geometry and material structure of SCUs

Once the VOA hereditaments within a SCU are stacked up on floor levels, the result is a three-dimensional model whose geometry can be measured. Total height is obtained from the Ordnance Survey Heights product, which relies on laser measurements (LiDAR) made from overflying aircraft (Ordnance Survey, 2015e). The result is a prismatic block with the same plan shape and area on each floor level. A 3D visualisation of part of the Camden model is presented in Figure 10, showing all SCUs in an area along Camden High Street. The colours code for predominant activities in floors within SCUs. Routines have been developed to take off measurements relevant to energy analysis including volumes, roof areas and exposed wall areas, including the areas of walls of courtyards (Figure 11). The ratio of volume to exposed wall area gives an approximate measure of the average depth of a plan: the ratio is roughly equal to half plan depth. Plan depth is likely to be significant in relation to the use of air conditioning. Where the depth of multi-storey buildings exceeds 14 or 15 m, air conditioning is generally essential. (Large and multi-storey warehouses and factories might provide exceptions.)

Several complications arise however in relation to SCU heights. The OS Heights product gives two figures, one for the notional height to the eaves, and the second for the maximum height. This latter figure can include structures situated on roofs. For flat roofs, the eaves measurement should give a reasonable approximation for the height of the roof surface.
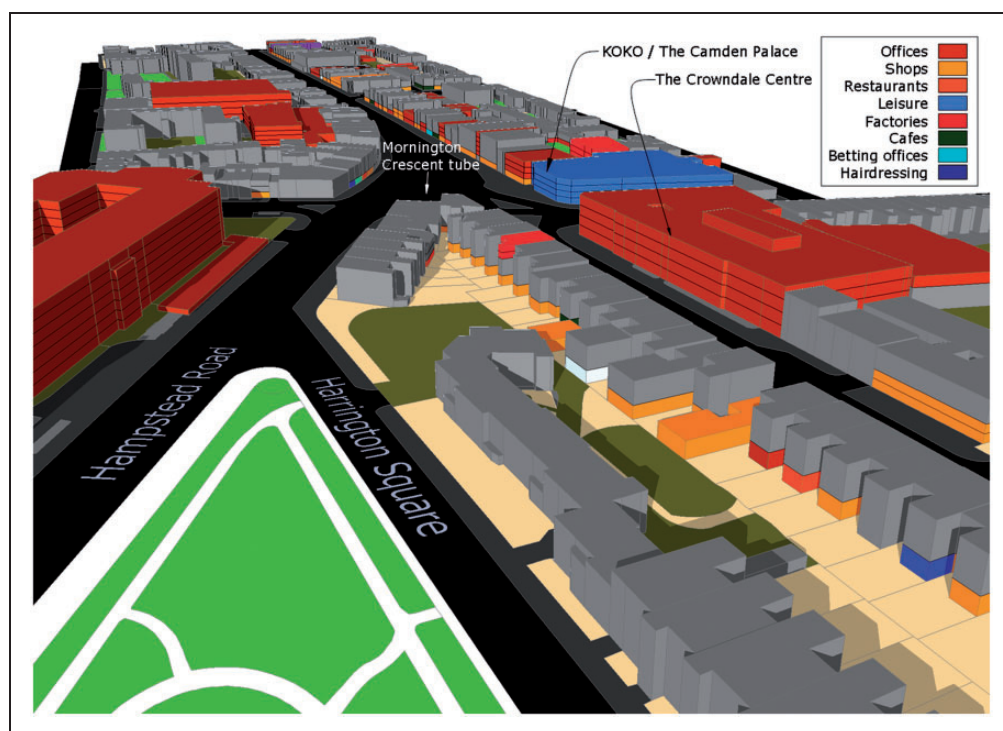

Figure 10. Three-dimensional visualisation of part of the Camden model for an area along Camden High Street. The dominant activity in each floor of each SCU is colour coded. Hereditaments that are not non-domestic (hence probably domestic) are shown in grey.
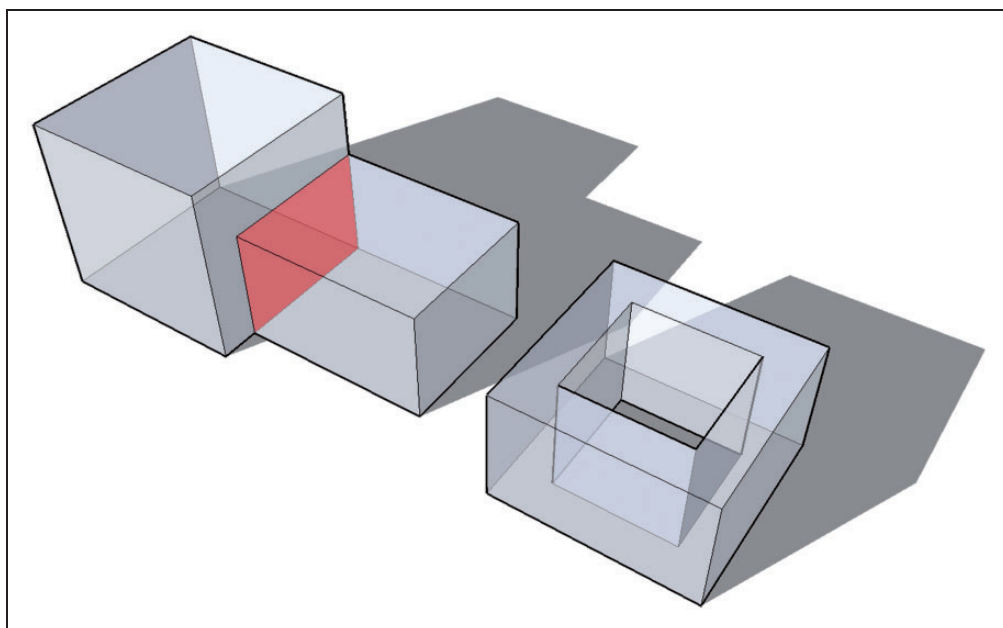
Figure 11. Geometrical measurements of Self Contained Units, including volume, flat roof area and exposed wall area. The wall area calculations allow for courtyards, and for cases where adjoining buildings are of different heights. An approximate figure for half plan depth is given by the ratio of volume to exposed wall area.

For pitched roofs, the measurement to the 'eaves' is actually an average between eaves height and ridge height, while using the maximum height may give too large a value if there is say a tall chimney or roof-top plant room. At present, pitched roofs are not represented as such in 3DStock, and the effective 'thermal roof' is taken in all cases to be flat – which would not be the case when a pitched roof is open to the interior as in a hall or in an attic conversion.

There are also many SCUs in which hereditaments with floor area from the VOA's SMV database are not the sole occupants, but are found together with non-domestic hereditaments or premises whose area is unknown, or with domestic hereditaments (i.e. flats) or both. Here, there will be some parts of the SCU that will remain empty in the process of model construction described so far, and need to be filled in. There will, for example, be many SCUs that contain flats above shops or offices. Non-domestic hereditaments without SMV floor area might be found on any floor level.

We have commissioned the GeoInformation Group to make a survey of all buildings containing non-domestic premises in Camden. They have collected data on materials of wall and roof, structural systems and number of storeys above ground; and they have estimated building age. We also have more detailed information on age from a second source (Hudson, 2015). These data have been collected for buildings not SCUs, so there are some problems of reconciling the two types of unit. The data have nevertheless been attached to SCUs to provide additional information for energy modelling, in particular, estimating the thermal transmission properties of envelopes.

Meanwhile, the data on total number of floors makes it possible in simple cases to estimate the 'empty' space occupied by non-domestic premises without floor area, so long as these are not on the top floor. There can also be shared circulation space that in some

circumstances is not included in VOA floor area figures. Total SCU height can be divided by number of storeys to obtain an estimate of total floor area. The resulting values for mean floor-to-floor heights can provide a check on this calculation. Known floor area can be subtracted from total floor area to give the area of 'empty' space. In this way, estimates can be made of floor areas for some of the activity types for which VOA has no information, as well as the areas of domestic premises such as flats above shops or pubs.

Difficulties arise however when the forms of the SCUs are not prisms. The different buildings within one SCU may have different heights. Also the Ordnance Survey in many instances gives single footprint polygons for structures that have parts with different heights, for example, where upper floors are set back, where there are single-storey extensions at front or back, or where what is a courtyard on the upper floors is filled in at ground level. We are presently working on some of these issues. Where SCUs are wholly made up of premises with floor areas in the SMV, then the differences in area on successive floor levels can give some indication of setbacks and mansards. In principle, the LiDAR data would be able to provide a more detailed picture of complex roof geometry, since these are collected at high spatial resolution (which in OS Heights are averaged across footprint polygons). But to do this would require both access to the original LiDAR data and considerable computation. Also the Heights product as yet only has partial coverage of the country.

Sub-activities

As already described, the VOA breaks each hereditament with floor area in the SMV into a series of Line Entries, which describe rooms or zones devoted to different sub-activities. On occasion, the area given by a Line Entry may comprise several pieces of non-contiguous floor space. Some Line Entries relate to multiple floors. In the majority of cases, however a Line Entry describes a discrete area of floor space on a specified floor.

Figure 12 shows a photo and 3D model rendering of a fairly typical mixed use SCU/ building on Theobalds Road, Camden, containing 10 hereditaments, all of which appear in the SMV. Figure 13 shows the use of space per floor, within the SCU, with the sub-activities aggregated per floor regardless of which hereditament they belong to. The largest single hereditament is a restaurant, at $88\,m^2$ total net internal area. In the SCU as a whole, the predominant hereditament activity is office, and the sub-activity occupying the greatest area is also 'office', i.e. the office rooms themselves. Note that the ground floor, which contains the restaurant hereditament, is classed by the VOA as a 'retail' sub-activity, whilst the office sub-activity is a separate hereditament. The basement houses a variety of sub-activities, including the remainder of the restaurant hereditament ('kitchen', 'restaurant' and 'internal storage') plus a separate workshop hereditament and sub-activity.

Floor areas on each floor level in Figure 13 are not equal, even though the building/SCU is prismatic, according to the polygon footprint and LiDAR data. In a building with multiple hereditaments such as this, the VOA does not usually levy rates on the areas in common use by occupiers such as circulation, foyers and toilets. In general, we would expect the proportion of all floor space accounted for by these common uses, especially circulation, to be greater at ground level and this probably explains the recorded ground floor area being slightly smaller than the first floor. The basement is larger than other floors most likely because it extends under the street's pedestrian path, which is common in this part of London. There are no records for toilets on any floor, even though there must be some in the building/SCU. We have been making some analyses to determine typical values for the proportion of unrated areas in different building forms.
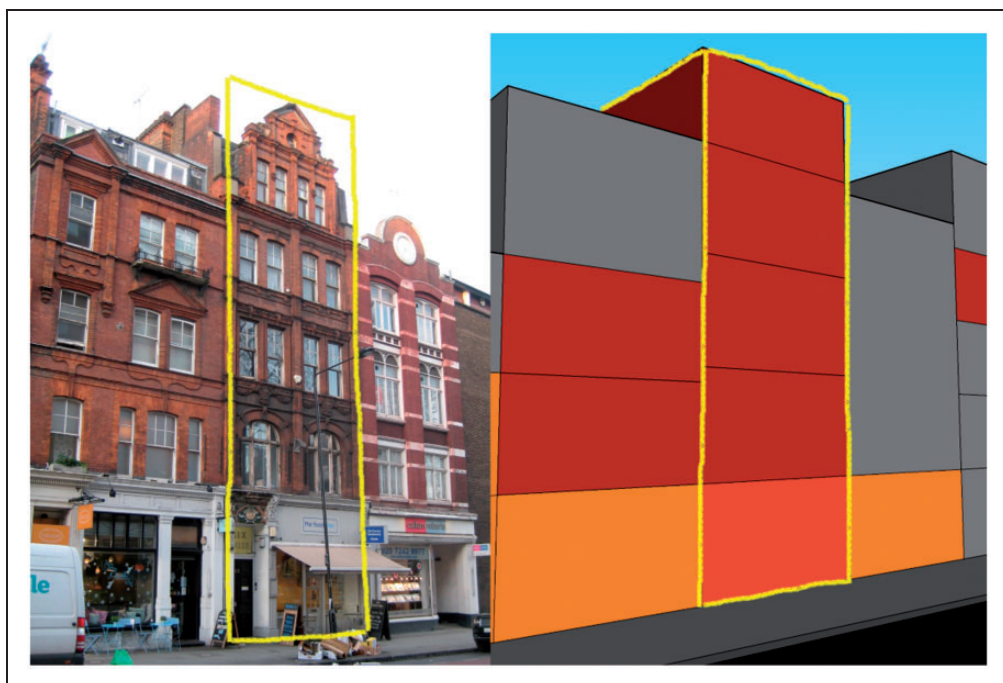
Figure 12. A mixed-use 'building', 42 Theobalds Road, Camden, with a restaurant on the ground floor and offices above; also shown as a 3D rendering of the SCU. Shops are in orange, restaurant in dark orange and offices in brown. Grey is either domestic or non-SMV.
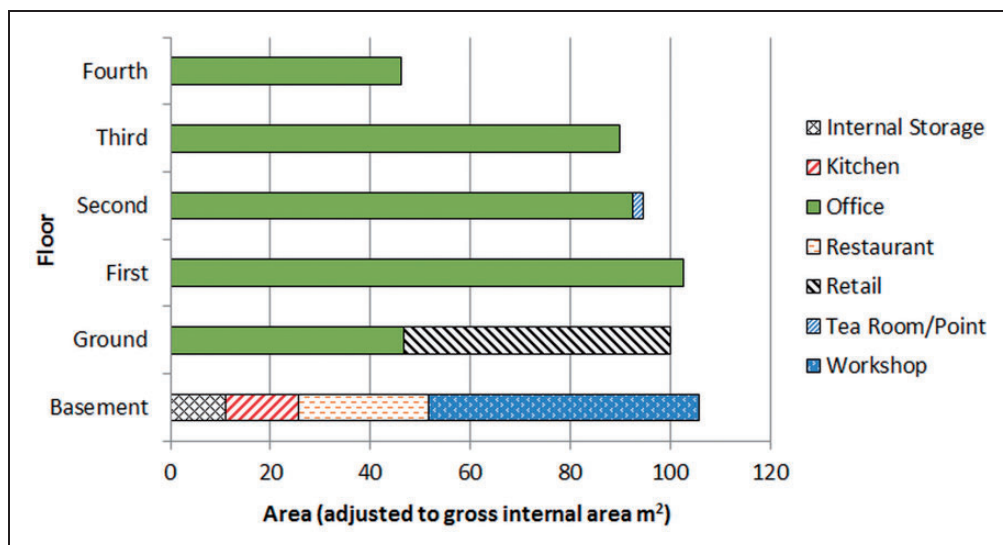

Figure 13. The Theobalds Road SCU, not only consisting mainly of office hereditaments but also containing a restaurant and workshop. The bar chart shows a breakdown of sub-activities by floor levels, as given by VOA Line Descriptions. The dominant sub-activity is 'office', but the ground floor and basement have a range of other sub-activities.

Matching electricity and gas meter data to SCUs

The DECC has made 2011 annualised gas and electricity meter data available to the project for almost all premises in Camden, both domestic and non-domestic. Use of these data is covered by strict confidentiality constraints. We will therefore discuss their processing and analysis in general terms, and present aggregated non-disclosive results.

Every electricity meter has a unique meter point administration number (mpan) with an address. The equivalent for gas meters is the meter point reference number (mprn). Both types of meter have been matched by their addresses to OSAB addresses (UPRNs). Through these, they can be matched to the addresses of VOA hereditaments (UARNs). The automated process of address matching was successful for 97% of gas meters and 99% of electricity meters in Camden.

Figure 14 gives a hypothetical illustration of the types of three-way relationship that can result. The meters here are all for electricity (mpans). The premises on the first floor at 42 High Street (A1 Hairdressing) is fairly straightforward. It is a child UPRN and has matched correctly to both a VOA hereditament and a meter, making it possible to assess electricity use in the hereditament as such. Downstairs, however, the VOA record for the Wine Bar and Premises has found the best match available, to the parent UPRN (42 High Street), despite the existence of a child UPRN for Bill's Bar – probably because of the difference between the two descriptions of the Bar. The electricity meter for this same hereditament has nevertheless matched correctly to the child UPRN for Bill's Bar. The result is a slightly less clear-cut
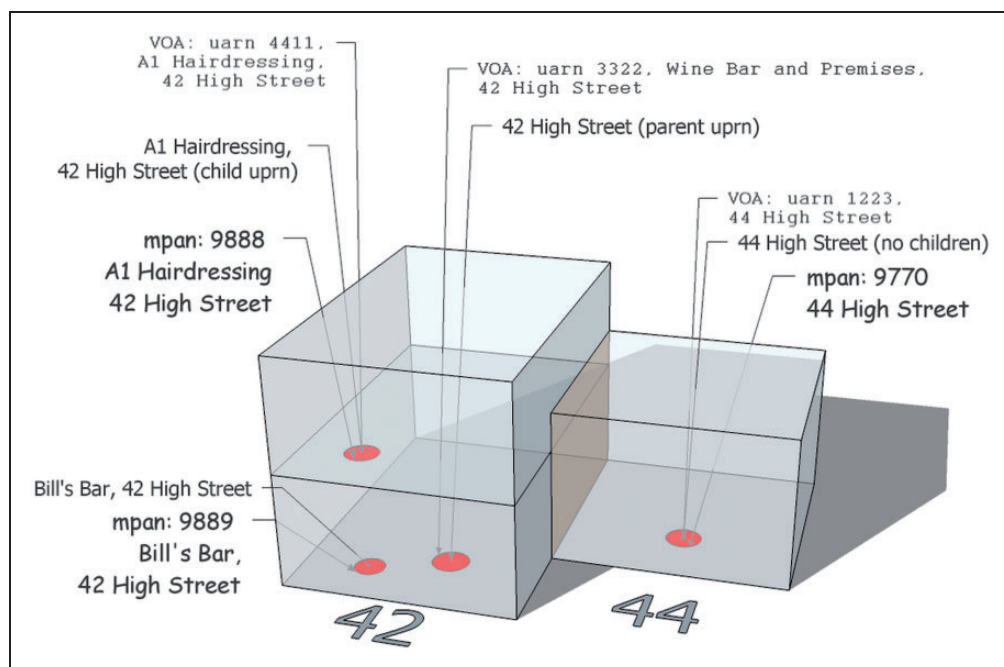

Figure 14. A hypothetical illustration of possible types of match within SCUs of electricity meters (mpans) and gas meters (mprns) with OSAB addresses (UPRNs) and VOA hereditaments (UARNs). (See text for detailed explanation.) Even where some matches are not made, the overall relationship between floor area, activities and energy use is known, showing the power of the Self Contained Unit.

relationship between hereditament and electricity use. On the other hand, when we look at total floor area and total electricity use for the whole SCU at number 42, then the overall relationship is correct. Here lies the power of the SCU.

In actual cases, such relationships can vary from the very simple to the highly complex, as emphasised by Neffendorf et al. (2009). We illustrate a series of real examples in Camden with all potentially identifying details removed. A SCU containing a single-storey shop (Figure 15) has one hereditament (UARN), one gas meter and one electricity meter, all matched to the single UPRN. This is as simple as the relationships get. A four-storey SCU (Figure 16) has one parent UPRN matched to a dry cleaner's on the ground floor, plus three domestic child UPRNs on the upper floors, one of which is a maisonette [duplex]. One gas meter is matched to the maisonette, and two electricity meters to the parent UPRN. These are presumably shared between the dry cleaner's and the flats.

A large office building SCU (Figure 17) has a parent UPRN with 14 child UPRNs, 13 of which are matched to different VOA UARNs. There are 12 electricity meters and 6 gas meters matched to the parent UPRN, and a further 2 electricity meters matched to the 14th child UPRN. Some large office building SCUs can nevertheless be simple in these terms. Figure 18 shows a multi-storey block under single ownership with one UPRN matched directly to one UARN, two electricity meters, and a gas meter.

The more complex cases here reinforce the case for the SCU as a basic unit in which the overall relationship between floor area and energy consumption can be determined, even if the proportions of gas and electricity use supplied to different parts of the SCU are unknown. This would, in many instances, be impossible for separate premises/ hereditaments, as the examples have shown. The combinations of uses that occur in
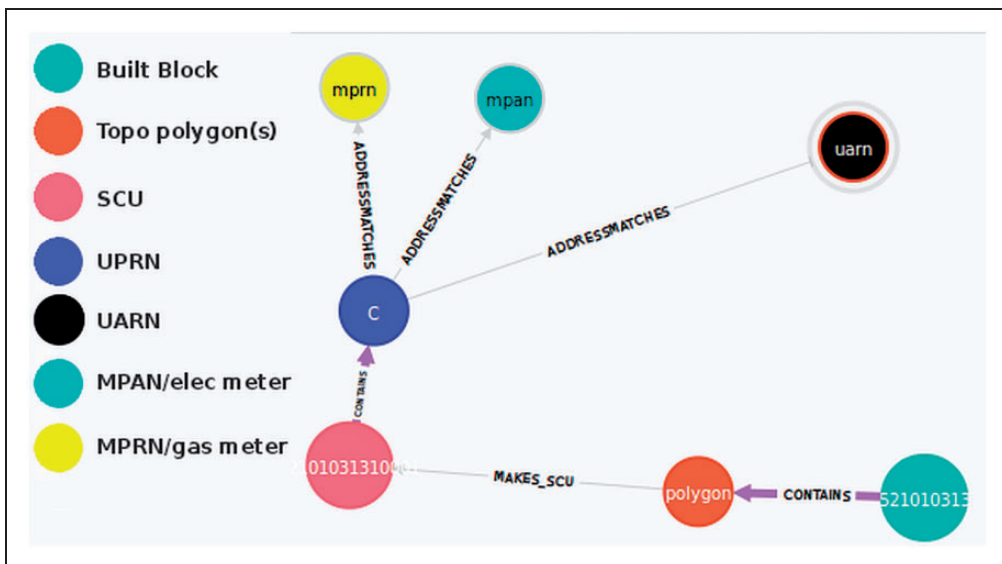

Figure 15. This and Figures 16 to 18 show real examples of different relationships between meters, premises and footprints in Self Contained Units. The key distinguishes urban blocks (BuiltBlocks), building footprints in the OS Topo layer (Topo polygons), SCUs, Unique Property Reference Numbers (UPRNs), VOA hereditaments (UARNs), electricity meters (MPANs) and gas meters (MPRNs). This figure relates to a single-storey shop.
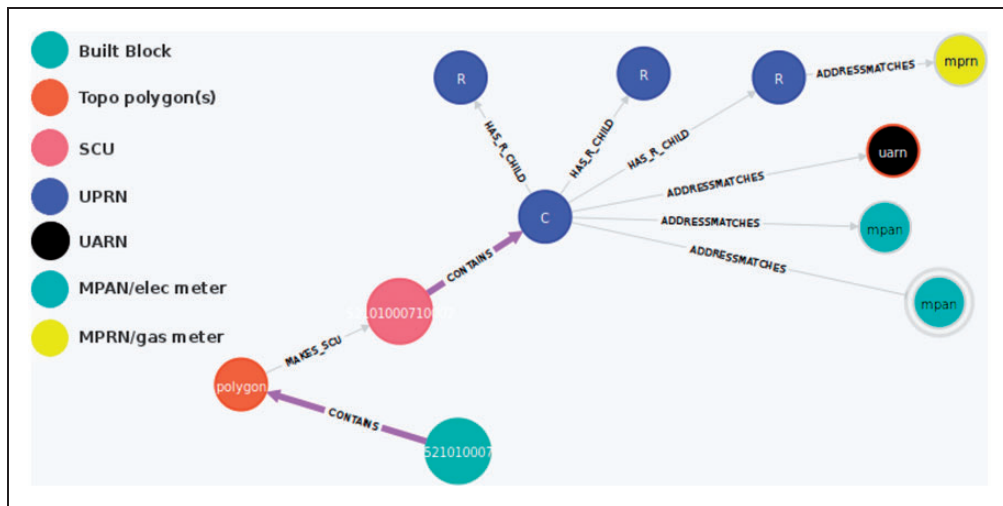
Figure 16. Relationships between meters, premises and footprint in a four-storey SCU with a dry cleaner's on the ground floor, and two flats and a maisonette above. (See caption to Figure 15 for key.)
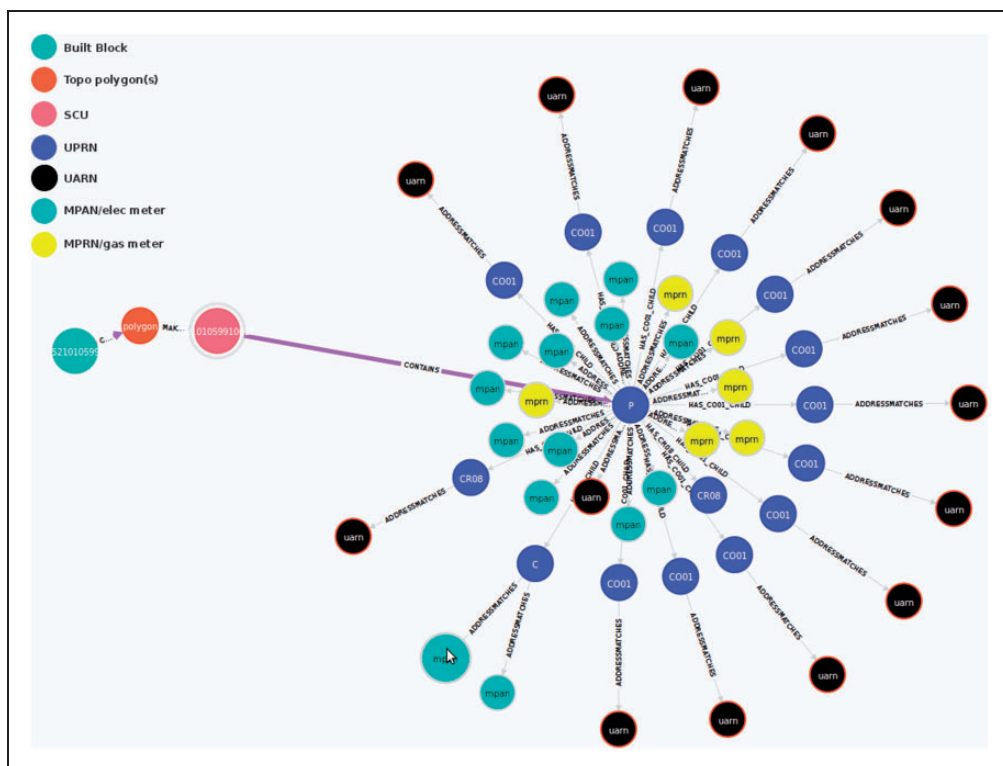

Figure 17. Relationships between meters, premises and footprint in a large multi-storey SCU containing 14 office hereditaments. (See caption to Figure 15 for key.)
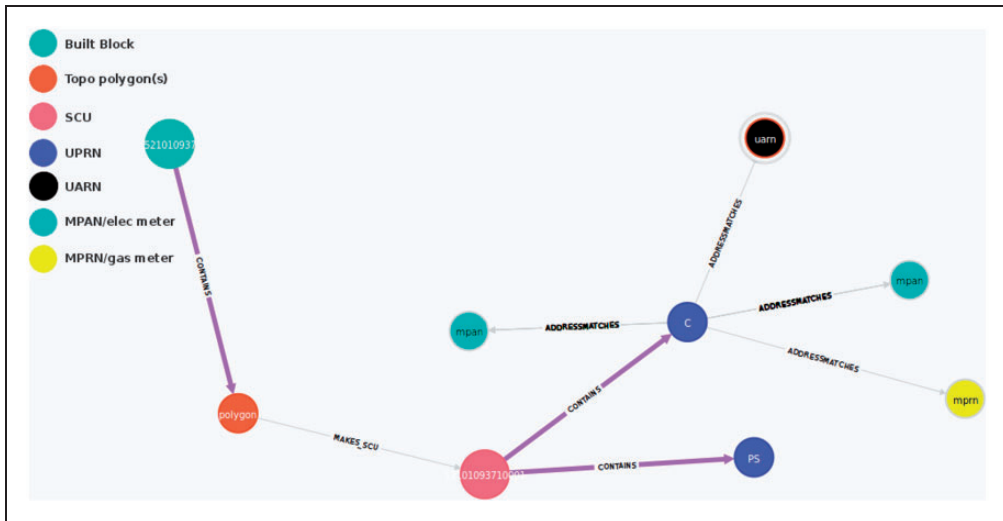
Figure 18. Relationships between meters, premises and footprint in a large multi-storey SCU with one office hereditament and two meters. (See caption to Figure 15 for key.)

buildings like the Theobalds Road example (Figures 12 and 13) nevertheless raise some problematic issues about what are actually meant by typical or benchmark values for energy intensity for specified activities. Should these be measured at the building/SCU level, in which case, they refer to mixtures of activities? Or should they be measured at the hereditament level? But those hereditaments may not be independent in energy supply terms, and may for example share a heating or air conditioning system. Also they will share an envelope with other hereditaments.

Non-domestic 'energy epidemiology'

Energy meter data (gas or electricity or both) have been successfully matched, as described, to 5329 SCUs in Camden. These data can be analysed in relation to activities and the results compared with energy benchmarks from other sources, for example, Display Energy Certificates (Department for Communities and Local Government, 2012). We are limited in publishing figures by confidentiality constraints. However, analyses of floor areas and the intensities of gas and electrical energy use are given below for a number of the more numerous activity types. Note that the analyses in Table 2 and Figures 19 and 20 refer only to SCUs that have been identified in each case as containing a single hereditament and no domestic (residential) addresses. This means there is a high probability that the SCU is a single building, containing a single non-domestic occupier. (Some anomalous consumption values have been excluded.)

Table 2 presents the profile of floor areas for a sample of significant SCU activity types in Camden, where meters have been matched. Floor areas have been standardised to VOA GIA. The samples clearly show the influence of outliers with large floor areas, especially in commercial offices, shops and workshops, less so in schools, restaurants and cafes. (For Figures 19 and 20, data have been purged of energy use intensity values (kWh/m^2/year) greater than three standard deviations above the mean within each activity class.)

Except for private schools, the spread of EUIs is extremely wide within each activity, considering these are cleaned data. Only restaurants and private schools have something

Table 2. Analysis of sample areas for selected types of activity in Camden.

| | Principal activity in single-hereditament SCU | | | | | |
| | Area of sample SCUs, standardised to gross internal area (m^2) | | | | | |
	Commercial office	Shop	Workshop	Restaurant	Private school	Cafe
Count	387	344	69	56	28	27
Minimum	9	11	37	39	134	23
First quartile	150	54	74	106	405	48
Median	278	94	158	164	563	72
Third quartile	574	150	390	215	801	104
Maximum	17145	1223	18164	383	2172	157
Mean	722	127	574	166	645	79
Standard deviation	1555	141	2217	78	404	37

These are for SCUs each of which contains just one hereditament with floor area and at least one electricity meter. SCUs: Self Contained Units.
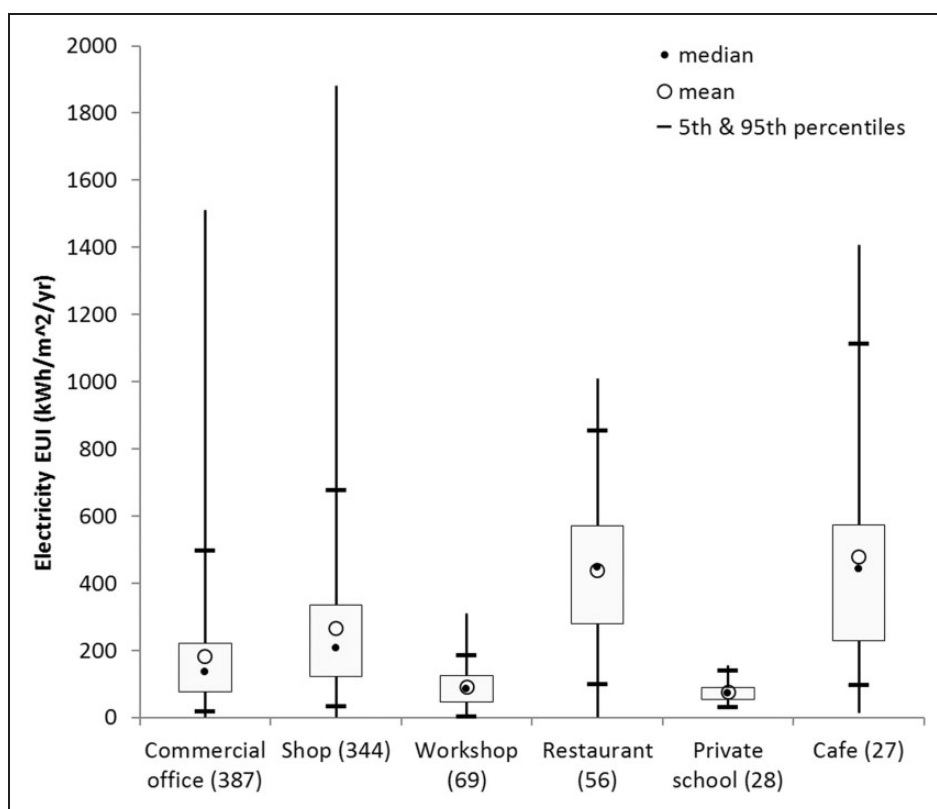

Figure 19. Analysis of electricity energy use intensity (EUI) for samples of Camden SCUs containing one hereditament. EUIs greater than three standard deviations above the mean have been removed prior to compilation. Floor areas are calculated to gross internal area. On the *x*-axis, the numbers in parentheses indicate the size of the sample.
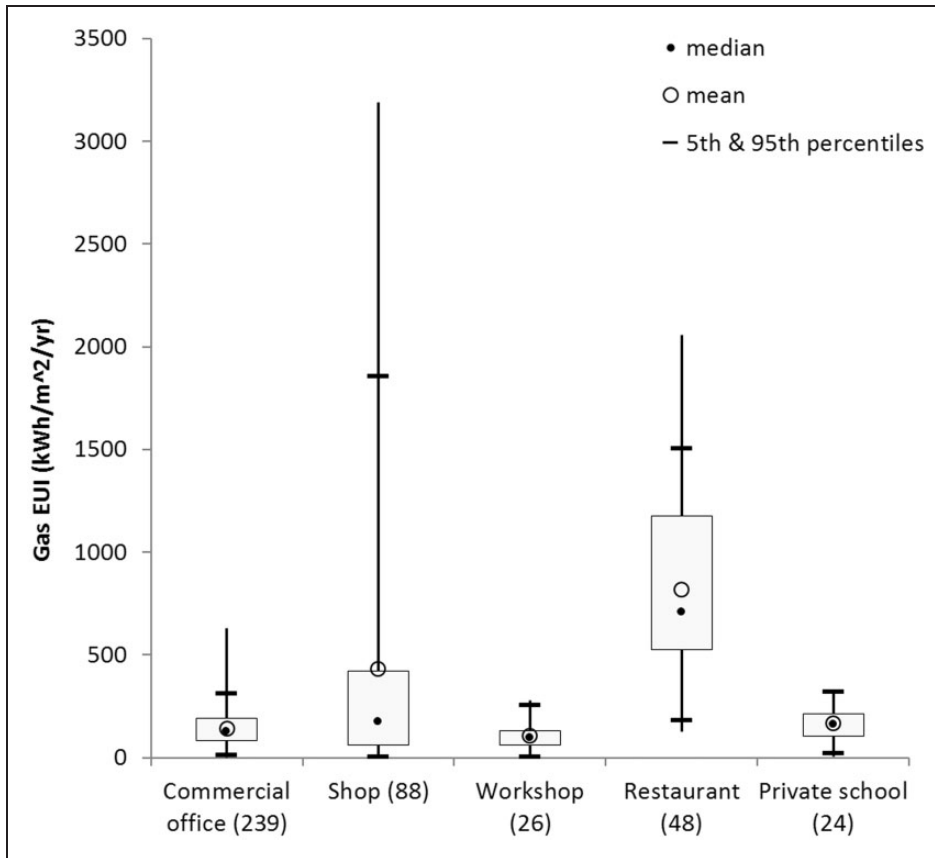
Figure 20. Analysis of gas energy use intensity (EUI) for samples of Camden SCUs containing one hereditament. EUIs greater than three standard deviations above the mean have been removed prior to compilation. Floor areas are calculated to gross internal area. On the x-axis, the numbers in parentheses indicate the size of the sample. Cafes omitted due to small sample size.

close to a normal distribution in both electricity and gas use, whilst electricity EUIs in workshops are slightly skewed. High outliers are tending to skew the results in other activity types, and the middle two quartiles (represented by the boxes in each figure) cover a broad range of values in most activities. This degree of variability in the annualised meter consumption data is testament to the difficulties of simulating energy use in the non-domestic sector, as opposed to studying actual consumption directly as here.

Beyond this, it is possible to study consumption in relation to characteristics of building geometry and construction, measured from or associated with SCUs. To do this for such a large sample of non-domestic premises/buildings has not previously been possible. For the domestic stock of Britain, DECC and the Energy Saving Trust have developed the Homes Energy Efficiency Database (HEED, now part of NEED), which has made it possible to study gas and electricity consumption in relation to a range of built form and household characteristics for millions of dwellings (Hamilton et al., 2011). This type of large-scale statistical approach has been called 'energy epidemiology' by analogy with epidemiology in medicine, where health outcomes in populations are studied in relation to lifestyle,

environmental and other variables (Hamilton et al., 2013). The 3DStock model opens the prospect of a non-domestic energy epidemiology.

This work is ongoing, and will be reported separately. Preliminary analyses for Camden however show some strong relationships of energy use to geometrical parameters. The intensities of both gas and electricity use are found to be correlated with exposed surface area (walls and roof) as would be expected. The volumes of basements are significant in Camden (where large amounts of accommodation are below ground, as shown in Figure 6), presumably because these are in effect highly insulated, they have permanent artificial lighting, and many are likely to be air-conditioned. Gas use is related to the ages of buildings in subtle ways. One of the main effects here seems to be change in the ratio of exposed surface area to volume, brought about by two trends over time. The first trend is variation in the average size of buildings/SCUs, larger buildings having lower ratios of surface to volume. The second trend is variation in the total area of party walls between buildings/SCUs, since more party wall area means less exposed wall area. The extent of party wall would be related in turn to the density of development.

One weakness of the Camden case study as noted is that the Borough has only small numbers of industrial buildings. It would be very desirable to have meter data for the other locations for which 3D models have been built, since these all contain numerous factories and warehouses.

Modelling energy use in SCUs

'Epidemiological' analyses can identify the drivers of energy use, and can rank them in order of importance. But these relate to current patterns of total use of electricity and gas, with no breakdown into separate end uses. For making projections of future consumption, or testing the impact of possible abatement measures and new technologies, it is necessary to resort to modelling, which can be informed by the epidemiological results. For these purposes, we have been developing two additional models.

The first model predicts annual electricity use in appliances and lighting, and has been tested for both Leicester and Camden (Liddiard, 2014). It makes use of data selected from detailed room-by-room surveys of 700 premises made in the 1990s by a team at Sheffield Hallam University, who collected information on all power-using equipment (Mortimer et al., 2000). These data have been used, with suitable updating for changes over the intervening 20 years, to associate typical schedules of equipment, together with power ratings and hours of use, with the sub-activities distinguished in the SMV Line Entries. These schedules can differ between activities categorised at the PD level. Thus, 'office' areas in 'Office' hereditaments would have different equipment from 'office' rooms in 'Shops'. This appliance and lighting model can be applied to premises on different floors of a SCU, allowing analysis of energy use by number of storeys.

The second model, developed with colleagues at UCL, is a dynamic simulation tool called SimStock (Coffey et al., 2015). This is a specially customised version of the EnergyPlus package (US Department for Energy, 2015). It takes geometrical and fabric data directly from the 3DStock SCUs, with predictions of electricity use from the appliance and lighting model, and applies a series of default assumptions about occupancy, HVAC configuration and efficiencies and other variables, to simulate total energy use including uses in heating, cooling and air conditioning. The results can be calibrated against actual consumption as given by the meter data. The tool then allows scenarios to be constructed, with changes to the values of variables to represent abatement measures, and makes further simulations for future years. Since the

modelling process and data entry are automated, it is feasible to make simulations for large numbers of SCUs within reasonable amounts of computing time.

SimStock and 3DStock are currently being used in a project for the UK DECC, in connection with the Department's programme of Building Energy Efficiency Surveys (BEES) (DECC, 2015c). Some 4000 premises across England and Wales have been surveyed for BEES by telephone, with a sub-set of 300 premises having site surveys. End uses of energy have been estimated in each case by DECC's consultants Verco using a spreadsheet-based model, which has difficulty however dealing with heating and cooling since building geometry is not represented. UCL has been commissioned to test Verco's predictions using SimStock. To do this, geometrical models of the relevant premises/SCUs are being produced with 3DStock. SimStock at present makes estimates of energy use by floor area. But the three-dimensional representation in 3DStock would make it possible to model energy use per unit volume within SCUs. This is arguably more appropriate for dynamic modelling of heat flows and their moderation.

3DStock has also been used in a second project for DECC in 2015. Self-contained units are located geographically on Ordnance Survey maps by their footprints, in relation to city blocks and the street network. The model can thus be used to assess the potential, in geometrical terms, for a range of renewable and low carbon technologies, including areas of roofs available for roof-mounted photovoltaics, adjoining site areas suitable for ground-source heat pumps, and linear densities of heat demand along streets, allowing the potential for heat networks to be assessed. Analyses of these options were made for all SCUs in Camden, Leicester and Tamworth.

Future work

It seems possible that certain missing properties of premises, buildings and SCUs – including floor areas – might be inferred statistically with reasonable levels of reliability. The fact that the 3D model of Camden comprises data on built form, materials and building age, as well as activities, opens the prospect of a programme of statistical work on correlations and the possible derivation of types, by which unknown properties might be inferred from known properties. These results could be used in developing models of other locations. Work on basements has already shown that their incidence and size is related to building age. Work in the 1990s using detailed measurements of glazing areas and glazing types in a sample of 100 non-domestic buildings showed strong relationships between glazed area and floor area in day lit built forms (Gakovic, 2000).

The information on building structure, materials and age collected by the GeoInformation Group is limited to Camden. National sources of such data are needed ideally to extend this aspect of 3DStock to other locations. In fact, the VOA does collect data of these kinds for England and Wales. At present, they do not make these available for research, but that situation might change.

Work is under way as mentioned to roll out 3DStock to large parts of England and Wales. Where meter data for individual addresses are not available, we plan to use spatially aggregated electricity and gas consumption data published by DECC, together with typical energy use intensities derived from the epidemiological work already discussed.

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Note

1. The latter figure is approximate, mainly because of uncertainty about the split between industrial process and other energy uses in factories and workshops. Process uses are not counted within the 12% figure.

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