A 3D GEOMETRICAL MODEL OF THE NON-DOMESTIC BUILDING STOCK OF ENGLAND AND WALES

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ABSTRACT

This paper describes the development of a 3D model of the non-domestic building stock of England and Wales. The model's purpose is to assess energy use in the stock, and study conservation options. Previous stock models have used data on floor area by activities, and have not represented building geometry. The present model by contrast combines digital maps and property taxation data to build a 3D representation in which separate premises are located within buildings, with floor areas on each level. Sub-activities per floor are also represented in 2D. A case study of the London Borough of Camden is presented.

INTRODUCTION

This paper reports work on the development of a comprehensive model of the non-domestic building stock of England and Wales. The purpose is to study energy use and the potential of a series of conservation measures and policies applied to fabric, systems, equipment, and occupant behaviour. The methods are being pioneered in a case study of the London Borough of Camden before being rolled out to the national scale.

There has been some international research on energy use in non-domestic building stocks, notably the model developed by Coffey et al (2009) using data from the Commercial Buildings Energy Consumption Survey (CBECS) conducted regularly in the USA. A recent issue of *Building Research and Information* (2009) reviewed European work in the field. To our knowledge however there has been no previous work other than that by Taylor et al (2014) for Leicester, on the kind of comprehensive 3D model described here. This is because the UK is one of only a very few countries to raise property taxes on buildings rather than just land. The resulting taxation data are the key to the present approach.

Three models have been built to date of the British stock. The first was the Building Research Establishment's National Non-Domestic Buildings Energy and Emissions Model (N-DEEM) (Pout, 2000). The second and third have been successive versions of the Carbon Reduction in Buildings (CaRB) model built at University College London (Bruhns et al., 2006). All three models have estimated the total amounts of floor area devoted to different activities, and multiplied those by typical energy intensity values to give total national consumption of electricity and gas. None of them however has represented buildings in the generally understood sense. Instead they have represented premises, which – speaking loosely – may correspond either to parts of buildings, to entire buildings or to collections of buildings. It has not been possible to attach geometrical attributes in any meaningful way to the individual premises data, other than floor areas, let alone any description of construction and services. The impacts of conservation measures have had to be assumed to be proportional to floor area.

The reason why these models have adopted the premises as their basic unit is that, although they draw on many sources of floor area data, the most important source has always been the Valuation Office Agency (VOA) of Her Majesty's Revenue and Customs. Property taxes ('rates') in Britain are levied primarily on buildings, based on the activity that takes place there and the market rents of similar premises in the locality. The VOA is responsible for making detailed surveys of buildings to support this process. The basic units by which the VOA's survey data are organised are not buildings, but premises – or what it terms 'hereditaments'.

A hereditament is a piece of floor space (or land) with a single occupant or landlord responsible for paying the rates. It may change ownership, or be rented individually. It can equate to a complete freestanding single building like a town hall. Or it can describe a group of separate buildings under common ownership on a shared site, like a secondary school, a hospital or a large factory. A hereditament can also be part of a floor, a whole floor or several floors, as for example a shop or office in a multi-tenanted building. The majority of hereditaments are listed in the VOA's Rating List. The VOA also makes available the Summary Valuations (SMV), which contain records of the total area (usually m^2 or ha) of a hereditament and the measurement convention used. Approximately 90% of hereditaments recorded in the Rating List are cross-referenced to records in the SMV.

The present model again uses hereditament data from the VOA; but now the hereditaments are aggregated or disaggregated into spatial units (to be defined precisely below) that are more like buildings. This is done by matching the hereditaments, by their addresses, to their corresponding building footprints in Ordnance Survey digital maps. The SMV usually disaggregates the hereditament's total area into 'Line Entries', which record sub-activities and the floor(s) on which these occur. This means in effect that hereditaments can be piled up on the map footprints to produce 'buildings'. The volumes and exposed wall and roof areas of the buildings can be measured, as can their depths in plan, for use in thermal modelling.

The VOA has several systems for classifying the activities that occupy hereditaments, two of which – the Primary Descriptions, and the Special Category (SCAT) codes – appear in the Rating List and describe the business or institution as a whole, as for example 'commercial office', 'hairdressing salon' or 'state school'. Within the Line Entries of the SMV are 'Line Descriptions'. These give a more detailed classification of the sub-activities that go on in hereditaments. Thus a shop might be made up of retail sales areas, storage, offices, and perhaps a kitchen. The same sub-activity descriptions can apply across Primary Descriptions and SCATs of many kinds: thus almost every institution or business will contain some 'office' area. The Line Descriptions can be associated with typical profiles of power-using equipment, making it possible to model electricity use by appliances.

The representation developed here thus preserves all the complex relationships found in the non-domestic stock between 'premises' and 'buildings'. It is important to maintain this complexity in the modelling, because for certain conservation measures especially those relating to activities, equipment and occupant behaviour, the premises is the relevant unit, while for other measures relating to fabric and geometry, the 'building' is the relevant unit. There is the further issue of the extents of floor space to which electricity and gas meters relate, which can sometimes be premises and at other times buildings or groups of buildings. In a multi-tenant building for example the tenants may all have separate electricity meters, while the meters for the central services and common areas will be the responsibility of the landlord. The present paper concentrates on the modelling of geometry and activities, and the relationships between these. The problems of introducing further data on building fabric and services, and detailed methods for modelling energy use, are left to future papers.

PREPARING THE DATA

The starting point for the model is the VOA Rating List. However, the Rating List dataset is not directly geo-referenced, that is to say the location of each hereditament in the List cannot be pinpointed on a map without first relating it to another dataset that is geo-referenced and which shares one or more common attributes.

The initial means for placing hereditaments into 'buildings' is to use the 'address' fields in the VOA Rating List, which can then be matched to a second dataset that contains geo-referenced addresses.

The Ordnance Survey produces several datasets that could be used, but the most appropriate is Ordnance Survey Address Base (OSAB), which holds all the addresses for the United Kingdom as well as details relating to each address such as spatial location, and whether it has multiple occupants. In many cases (but not all) it also holds a link to the VOA Rating List unique address reference number (UARN). Most importantly, OSAB also enforces compliance by local authorities with the national standard for the representation of address information using British Standard 7666 (BS7666), and coordinates and enforces the maintenance of Local Land and Property Gazetteers (LLPGs) by local authorities.

There are however cases where no match has been made between the Rating List and OSAB, so this research has developed an address matching module to clean addresses and match the maximum number of hereditaments to OSAB. For Camden, a 98% match rate was achieved for the 2010 Rating List, which was current at the end of May 2012.

Once a satisfactory level of matching is produced for a particular Billing (or local) Authority, the matched hereditaments can be given a precise location in a Geographic Information System. From here it is possible to investigate the relationship between hereditaments and buildings.

The next step in creating a geometrical model of the non-domestic building stock is to link a third dataset. This is the topographic map data that provide the outlines of buildings and other 'objects' viewable on a detailed map. The most consistent data set for the whole of England and Wales is the Ordnance Survey Mastermap Topography layer (OSTopo), which has the outlines and polygons of buildings, roads, rivers and railways. These data can be cross-referenced to the OSAB data. Once these three datasets are interlinked, the first steps have been made in placing hereditaments in 'buildings'. However, there are several more hurdles to overcome.

At this stage, for any given address there may be one or more hereditaments linked to that address. The address should also now be linked to a polygon. However, when there are multiple hereditaments at the address, the link takes no account of how these interact within the address. Are there several per floor or does one occupy more than one floor? By cross-referencing back to the Line Entries of the SMV it is possible to build a more detailed picture and 'stratify' the hereditaments onto the different floors of the address.

One flawed assumption up until this point is that a hereditament can occupy only one building polygon, since the OSAB address 'points' only relate to one polygon (the polygon that they fall within). This often leaves other 'un-addressed' building polygons which may or may not house non-domestic activity.

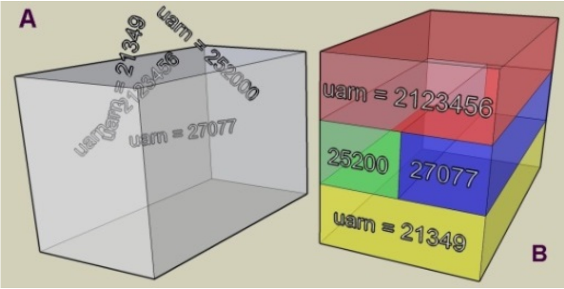

Figure 1: Example of how the hereditaments for one address (extruded building polygon) might be visualised before they have been layered (A) and after they have been layered (B).

In order to attempt to extend the model into these 'un-addressed' polygons (where relevant), bespoke software was developed, which uses a spatial topological model and combinatorial optimisation to resolve this issue. The software looks at the available neighbouring building polygons and attempts to find the best solution that creates a combined footprint to provide the closest match to the floor space recorded in the Line Entries of the SMV. This method we have called 'polygon capture'. In cases where two addresses are both competing for the same polygon, the solutions can be compared and the better result can prevail. In this way, the software can be run multiple times until the optimum solution is achieved.

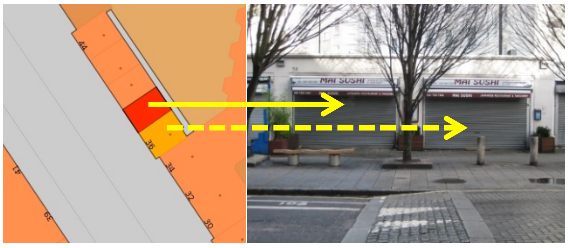

Figure 2: A capture example. The yellow polygon (with the yellow dotted line) is the 'addressable polygon' for this hereditament (a restaurant). The SMV shows that it requires $77m^2$ (GEA) but the yellow polygon only offers $41m^2$. The red polygon next door, which has no OSAB 'address' on the relevant floor, offers $37m^2$, which provides a combined floor area of $78m^2$. The software accepts this as an optimal match. (Data: © Crown Copyright/database right 2012. An Ordnance Survey / EDINA supplied service.)

This polygon capture process is spatially limited by the legal requirement that a hereditament should not normally be separated by roads or major routes. To enforce this rule urban blocks are created by removing the separators (roads, railway lines, rivers) and classifying the remaining regions (urban blocks) with unique identifiers, from which any capturing polygon must select other polygons for capture. At present, this method works well with the simpler cases where a hereditament occupies several adjoining polygons. More complex cases, such as hospitals, schools, factories and other 'campus' style sites require the development of a more complex method before they can be included in this capture method.

Figure 3: The creation of urban blocks (Data: © Crown Copyright/database right 2012. An Ordnance Survey / EDINA supplied service.)

A key problem area that is unresolved at present can be thought of as the opposite of the polygon capture problem: that is, when a hereditament occupies a polygon that is far too large for the recorded activity within that hereditament. This occurs in particular when small hereditaments occupy space under the 'umbrella' of a much larger structure such as a shopping centre with many small shops or a major transport hub (for example a mainline railway station) with small cafes and shops within the 'building'. Additional geometrical data (such as detailed plans of the inside of these buildings) would be required before the methodology could be applied to these types of structure.

WHAT IS ONE BUILDING?

Once the data have been cleaned and matched, the next logical step would appear to be the generation of the geometrical output. However, this in itself begs the question of what are we trying to represent with the geometry? The obvious answer is that it should be representing 'buildings'. But this in itself raises the question of what is ‘one building’? “It should be noted that no data source in the UK defines non-domestic *buildings* as such. Indeed there is no means by which the number of non-domestic buildings may even be counted…” (Neffendorf et al., 2009, page 27).

If we assume that the polygons within relevant digital map data are buildings we would be mistaken, since in many cases the 'building' can consist of several adjoining polygons. Each individual polygon might represent a change in the roofline or height of a wing of what on the ground would be considered to be one building. Likewise, the hereditament cannot be used to indicate what is one building, since a hereditament might occupy only part of one floor of a building, or at the other end of the scale it might consist of several detached buildings (for example, a large school, a hospital or a factory with offices, warehouses and packing sheds).

All of this might seem pedantic, but it is fundamental if we are to use these data to aggregate energy use (or any other activity) into what we consider to be 'non-domestic buildings'. Taylor et al. (2014) explored this problem and argued that a well-defined building envelope was required, which should allow a reasonable degree of granularity but that can be generated automatically with no requirement for human judgement. Their solution was what they called the ‘self-contained unit’ or SCU. They argued that the SCU could be developed by analysing the relationship between the relevant building polygons and the hereditaments that occupy these polygons. In short they argue that a “SCU should be a set of contiguous bTOIDs [polygons] with a continuous boundary defined by (a) external walls and (b) party walls between bTOIDs [polygons] having no common premises.” (Taylor et al., 2014. page 8).

This means that a single hereditament inside a single polygon would constitute the simplest SCU. Likewise, several hereditaments, all inside a single polygon, would also be considered as one SCU. When a hereditament spans two or more adjoining polygons, the boundary around the exterior of the collection of polygons defines the SCU. However, if a SCU occupies non-adjoining polygons, these would be classified as separate SCUs (but recorded as what we have termed 'Poly-SCUs', as in the case of some large hereditaments spanning several non-adjoining buildings).

However, it is too simplistic to think of the SCU boundary in 2D, since hereditaments on different floors can occupy different polygons. With this in mind we have worked through the floors that make up the SCU and generated what we have called Self-contained Unit Floors or 'SCUFs'. This is essential in the process that generates the SCUs but it also allows us the ability to 'slice' through the SCUs floor-by-floor.

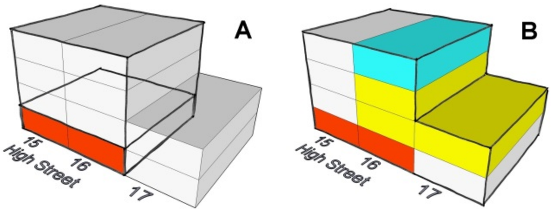

Figure 4: The creation of SCUs. A: The SCU is outlined in black in a case where the hereditament spans two building polygons on the ground floor. B: The hereditaments above the ground floor are introduced, resulting in a more complex SCU, with the different hereditaments spanning different polygons on different floor levels. The SCU floors that remain grey are assumed to be not non-domestic (and therefore probably domestic).

The result is that in cases such as those illustrated in Figure 4, a SCU could contain what in architectural and constructional terms we might want to call two or more buildings. These might be structures of a different age, or different materials. For this work however, it is essential that the starting data (from a single hereditament) are not cut into two or more pieces when the activity within the hereditament is taking place within a unified space. In many cases in the Camden data, it was found that the architecture and construction were actually very similar in these types of SCUs as illustrated in Figure 5 below.

Figure 5: Two separate polygons are illustrated (shaded) on this photo. The left and right polygons have been combined into one SCU, due to the ground floor of both polygons being occupied by a single hereditament (a small supermarket). Whilst the polygons indicate two separate buildings, which might otherwise be of different ages or materials, in this case the two buildings are almost identical.

SCU GEOMETRY

Once the SCUs have been generated, the final stage of the geometrical data processing is to calculate key geometrical values for each SCU. Before we can do this we need to assign a height to each of the building polygons in order to create a basic 2.5D model of extruded polygons. In this model, we have used LiDAR height data to extrude the polygons. Once the heights are in place, it is then reasonably straightforward to produce the geometry as follows:

- SCU footprint (m^2)
- SCU volume (m^3)
- Exposed wall area (m^2)
- Party wall area (m^2)

Care was taken not to double-count exposed wall areas, by using a topological spatial data model. When polygons of different heights adjoin one another, the exposed wall area was assigned to the 'taller' of the two polygons as per Figure 6.

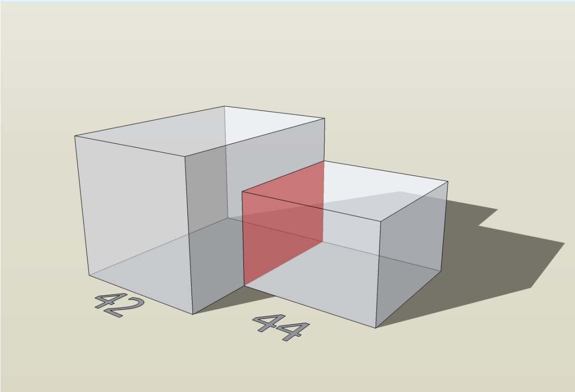

Figure 6: Two theoretical extruded polygons on a street (number 42 and number 44). Exposed wall area is the sum of all wall surfaces for each polygon that are 'exposed to the elements'. If a SCU is made up of more than one polygon, the exposed wall area for the SCU is the sum of the exposed wall area of its polygons. By contrast, 'party wall area' is the wall area that polygons share between them, such as the area shaded in red between these two polygons.

At present we have only processed the data for Camden and for Tamworth (Staffordshire). This allows us to compare some of the outputs from the two localities.

From the results shown in Table 1, it is clear that there are many more hereditaments and addresses than there are SCUs and polygons. This is as expected because:

- several hereditaments can occupy one address
- several addresses can occupy one polygon
- a SCU can be made up of several floors
(with several hereditaments on each floor)

Table 1: Counts of hereditaments, addresses, SCUs, polygons and SCUFs for Camden and Tamworth.

	Camden	**Tamworth**
Hereditaments (UARNs)	14,268	1,803
Addresses (UPRNs)	13,572	1,688
SCUs	6,229	1,024
Polygons (in SCUs)	6,725	1,208
SCUFs (including mezzanines etc.)	15,400	1,618
SCUFs which are 'whole' floors (excluding mezzanines etc.)	14,952	1,463
Average SCUFs per SCU	2.4	1.4

As a result there is an average of 2.3 hereditaments per SCU in Camden, and on average 2.4 SCUFs (non-domestic floors of a SCU) per SCU. By contrast, the Tamworth averages are 1.8 hereditaments per SCU and 1.4 SCUFs per SCU.

Whilst we currently have no way of verifying these numbers against any other dataset, the differences between the two local authorities are in line with what we might expect. Camden is an area where a large number of premises are packed tightly into buildings, and this competition for floor space results in the larger number of SCUFs per SCU, when compared to Tamworth. The data for Tamworth, by contrast, suggest an area where fewer premises occupy each SCU (on average), both in terms of how many there are in the SCU and in terms of how many floors of non-domestic activity there are within the SCU (on average).

The apparent demand to pack non-domestic activity into the SCUs in Camden can be seen in another statistic for the Borough. When all non-domestic floor area is summed per floor, the floor with the third largest area of occupied space is the basement (after the ground floor and the first floor).

If we look at a particular part of Camden in 3D then the results of the work can be visualised, as shown in Figure 7. At the hereditament level in Camden, the dominant use of non-domestic floor space is 'Offices' and the part of Camden shown in Figure 7, whilst having a large number of shops, restaurants and cafes on the ground floor, is no exception. 'Offices' make up over 70% of the floor space in these few built blocks (for the Camden SMV data the figure is 64%).

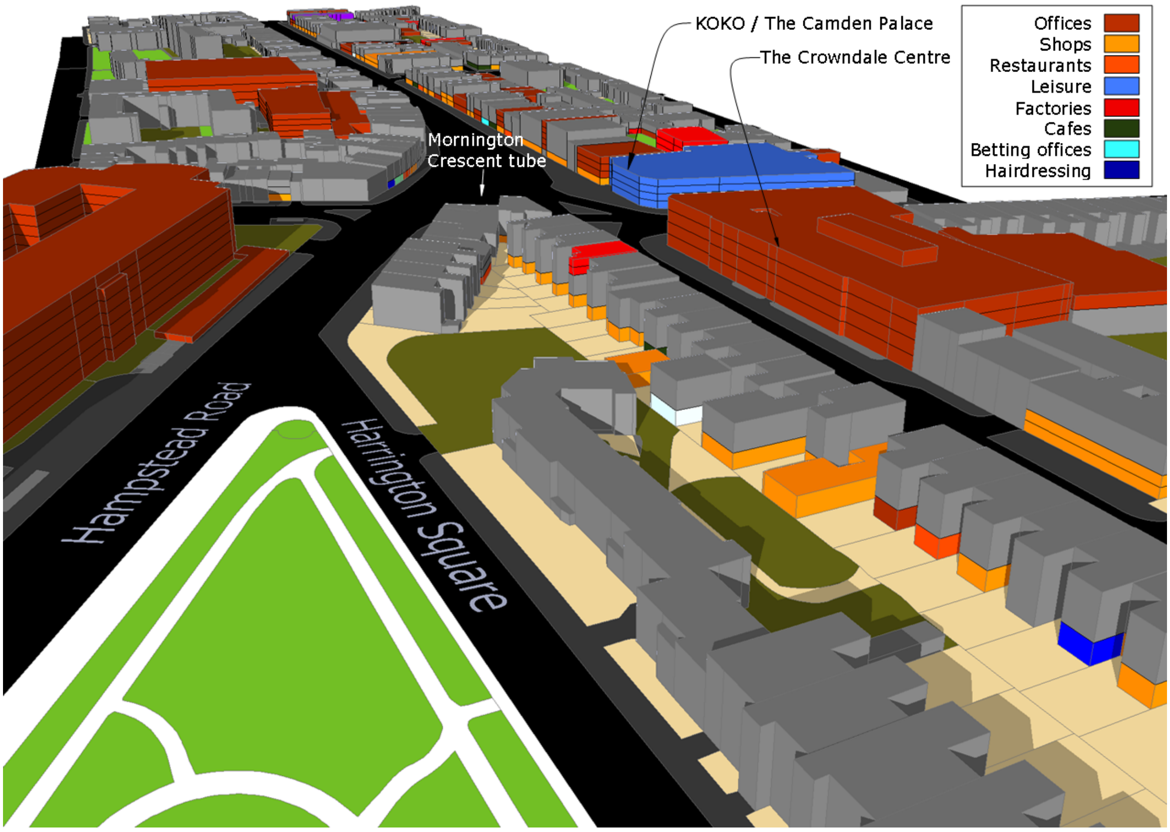

Figure 7: A 2.5D visualisation of part of Camden High Street (looking north). Hereditaments are grouped into SCUs, broken down into SCUFs. Each SCUF's dominant activity (by area) is colour-coded. Using our method, the grey floors and buildings are not non-domestic and are therefore probably domestic, but we cannot always be sure of this. Data: © Crown Copyright/database right 2012. An Ordnance Survey / EDINA supplied service.

SUB-ACTIVITIES

The 'granularity' of the geometric model is limited by the polygons that make up the SCU, but the new data model also allows us to explore activities within the SCUs themselves in even finer detail. In the SMV database, the Line Entries contain information about subdivisions of hereditaments including the nature of the activity in the subdivision, its area and the floor level on which it occurs. A Line Entry will describe an area of sub-activity, but this area may comprise several separate pieces of floor space that might not be contiguous. Also, a Line Entry may straddle more than one building, though this is rare. Some Line Entries describe multiple floors.

There are 162 'standard' Line Descriptions associated with Accommodation Use Codes (AUCs), with which the VOA categorises space use in Line Entries. However, there are 45,616 Line Entries and 2,964 different Line Descriptions (or distinct text strings) in the Camden SMV data. This diversity is the result of VOA surveyors overwriting standard AUC descriptions. Unfortunately, the AUCs themselves are not supplied by the VOA, only the Line Descriptions, so the database's text strings are searched for meaningful patterns to determine the sub-activity being described. For example, in Figure 8, the area shown as 'Lounge' was originally described as 'Chill Out Seated Area'.

For Camden, this process reduced the number of distinct Line Descriptions to 188 recognised sub-activities, with a further 339 Line Descriptions that are not captured. These 339 may not actually be important, as 99% of the summed areas and 99% of Line Entries have been assigned a sub-activity description. The use of Line Descriptions enables the identification of areas internal and external to buildings, whilst also making it possible to associate types of appliance with the sub-activities.

Figure 8 shows the use of space, per floor, in the SCU for the Crowndale Centre in Camden (see Figure 7.) containing seven hereditaments, five of which appear in the SMV. It is not possible, from the existing data, to determine where exactly each sub-activity occurs on its respective floor and so, for Figure 8, sub-activities are aggregated per floor, regardless of which hereditament they belong to. In an energy model the combination of overall hereditament activity and sub-activity would be used, as for example a kitchen in an office hereditament.

On first assessment, it appears anomalous that the ground floor is significantly smaller than the floors above, but this is most likely due to the manner in which the VOA surveys hereditaments. The VOA uses the convention that areas of no commercial value, or areas in common use by occupiers, are generally not valued; thus ground floors frequently appear smaller due to the increased proportion of circulation and support spaces (such as toilets) on this level. It is also interesting that although the total area of the ground floor is the smallest of all floors, it has the greatest diversity of activities. This is partly a result of there being six SMV hereditaments on the ground floor, one of which also includes areas on all other floors (there is one hereditament with area only in the basement). This highlights the heterogeneity of sub-activities within a single SCU, or indeed building, which is likely to affect energy use.

Figure 8 provides no evidence of the other two hereditaments in the SCU, because they are not included in the SMV and thus have no records of area. The hereditaments – a library and a nightclub – are presumably on the ground floor (reducing the proportion of floor area taken up by common areas etc.) but may also occupy some of the floor(s) above or below. In this particular SCU the aggregated mezzanine areas lie between more than two floors, which may be ascertained from a description in the architectural press (Greenberg, 1990). However this could not normally be known from the VOA data alone.

The sub-activities within a second SCU, containing a single hereditament (the Koko nightclub, in Figure 7), are shown in Figure 9. Again this SCU has a ground floor that is apparently smaller than the first floor, which may be expected, and the existence of staff toilets in the basement is recorded but without a floor area given. For the third floor to be larger than the second is puzzling and for the basement to be significantly larger than the ground floor demonstrates the complexity of the construction and use of the building, which was originally a theatre. Intriguingly, the ground level polygon area of the SCU is 1,201m^2 making it larger than any of the other floors. If the floor of this 'basement' includes the floor of the auditorium, summing the areas of the ground and basement floors gives 1,079m^2, which is a reasonable match to the area of the polygon, considering that the VOA measurements are to NIA and the polygon is GEA. A large proportion of the building's volume will be accounted for by the auditorium's high ceiling. The cases shown in Figures 8 and 9 are particularly complex, chosen for the purposes of illustration. Many SCUs will be much simpler.

Integration of the sub-activities into the 2.5D visualisation requires further work, but the disaggregation of hereditament activities may allow greater precision in targeting energy interventions, as appliance types may be assumed to occur in particular areas of sub-activity.

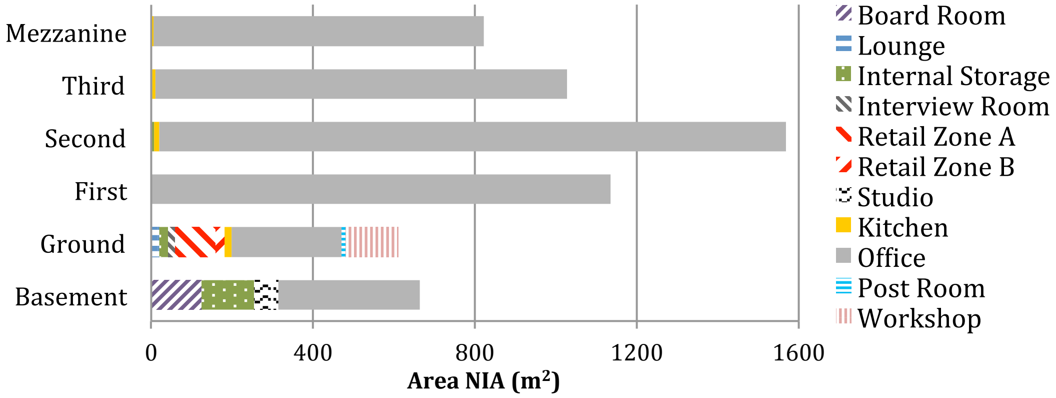

Figure 8: Sub-activities, per floor, in a multi-hereditament SCU that might be classed as an 'office building'.

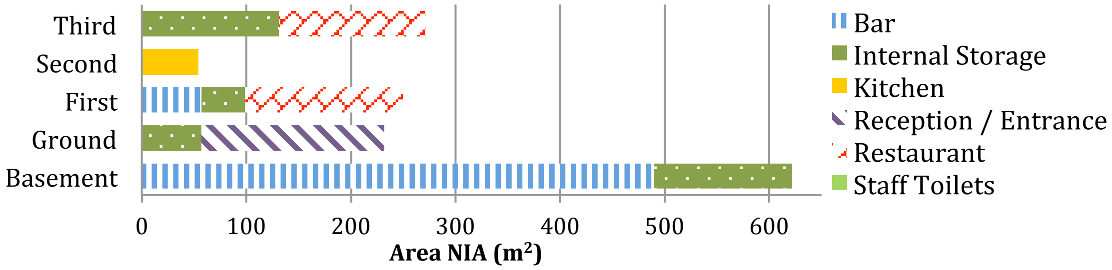

Figure 9: Sub-activities, per floor, in a single-hereditament SCU, containing a nightclub.

FURTHER WORK

The Camden model is well advanced but further developments are needed before it provides comprehensive coverage and can be used in energy analysis. Although the SMV database contains information on the majority of non-domestic hereditaments, there are several types of building that it does not cover. These include churches, central government offices, law courts and prisons. Some other types are included in the Rating List, for example hotels and pubs, but have no Line Entries or area data in the SMV. Information on floor areas for these types will have to come from other public and commercial databases.

Some SCUs contain both domestic and non-domestic properties, for example flats over shops, as can be seen in Figure 7. The domestic component needs to be allowed for. In other cases, as mentioned, a single hereditament will comprise many separate SCUs on a common site (a 'polySCU'). A new Ordnance Survey 'Sites' product may prove useful here, since this will provide site boundaries for premises of this type.

We plan to attach data to SCUs on materials, construction type and building age. The GeoInformation Group is supplying data for Camden, collected in connection with their UKMap product. We will investigate the possibility of inferring glazing ratios and fabric U-values from these data.

The combined geometrical and fabric data will be used for thermal modelling. The breakdown of hereditaments and floors into sub-activities as specified in the SMV Line Entries makes it possible to associate these with typical schedules of appliances and equipment, together with estimates of typical hours of use. A modelling method along these lines has already been developed (Liddiard, 2012), using data from a programme of detailed surveys carried out in the 1990s by a team from Sheffield Hallam University (Mortimer et al., 2000). The model has been tested on both the City of Leicester and the Borough of Camden. The predictions of both heating and equipment models can be calibrated against figures for total gas and electricity consumption published by the Department of Energy and Climate Change.

Many difficulties and gaps in the data remain. In principle however, once the methods described here have been further refined, because they are automated they can be extended directly to the remainder of England and Wales.

NOMENCLATURE

AUCs: Accommodation Use Codes used by VOA
GEA: Gross External Area
GIA: Gross Internal Area
LLPG: Local Land and Property Gazetteer
NIA: Net Internal Area
OSTopo: Ordnance Survey Mastermap Topography layer
SCATs: Special Category Codes used by VOA
SCU: Self-Contained Unit (Taylor et al 2014)
SCUF: Self-Contained Floor Unit
SMV: Summary Valuations database of VOA
UARN: Unique Address Reference Number
UPRN: Unique Property Reference Number
VOA: Valuation Office Agency

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DATA SOURCES

Data provided by the Valuation Office Agency contains public sector information licensed under the Open Government Licence v1.0.

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LiDAR height data made available by Centre for Advanced Spatial Analysis, UCL.

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