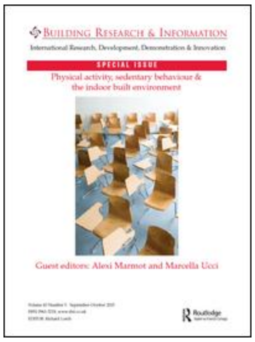

Building Research & Information

ISSN: 0961-3218 (Print) 1466-4321 (Online) Journal homepage: http://www.tandfonline.com/loi/rbri20

Modelling a whole building stock: domestic, non-domestic and mixed use

Stephen Evans, Rob Liddiard & Philip Steadman

BRI
BUILDING RESEARCH & INFORMATION
2017
https://doi.org/10.1080/09613218.2017.1410424

Routledge
Taylor & Francis Group

RESEARCH PAPER
OPEN ACCESS Check for updates

Modelling a whole building stock: domestic, non-domestic and mixed use

Stephen Evans, Rob Liddiard and Philip Steadman

UCL Energy Institute, University College London, London, UK

ABSTRACT

Work on energy use in buildings – in university research, professional practice and government – has tended to draw a broad distinction between 'the domestic stock' and 'the non-domestic stock'. A further tendency has been to focus attention on types of non-domestic buildings devoted to single uses (*e.g.* offices, shops or hospitals). This paper reports an empirical research programme in which the complete building stock in large areas of England and Wales is comprehensively represented in great detail, using a new method and model called 3DStock. The model breaks down activities by floor level and within each floor of every building. The results show that the extent of mixing of uses is much greater than has previously been acknowledged, especially towards the centres and in the older parts of towns and cities. These mixed-activity buildings are sometimes relatively simple combinations of domestic and non-domestic, *e.g.* urban retail with flats above, while others are complex mixtures of different non-domestic activities. The model can be used to investigate how these complex relationships influence energy use. It is argued that, at the larger scale, explicit account needs to be taken of the mixing of uses in future stock models for research and policy-making.

KEYWORDS

activity; building stock; buildings; energy model; mixed use; non-domestic buildings; residential; topology; urban analysis

Introduction

In mature industrial countries, the building stock changes slowly. Energy improvements to existing buildings assume particular importance if carbon-reduction commitments are to be met. Models of the stock for energy analysis have tended to focus on either the domestic or the non-domestic stock, and not their overlap. They have drawn data on activities from addressed footprints in digital maps, and in some cases have estimated floorspace by modelling buildings as simple prisms raised on those footprints. Examples of this approach are provided below in the review of previous work. Such an approach can work for houses; but greater difficulties are presented by blocks of flats, and even greater problems by many types of non-domestic building. Energy use has tended to be estimated using simulation.

The UK government's National Energy Efficiency Data-Framework (NEED) has no geographical or geometrical representation of buildings as such, but consists – in its non-domestic part – of a list of premises that are matched to energy meter data (BEIS, 2013). This is made possible by the way in which property taxes are levied on premises in Britain (not land), as explained below.

However, none of these approaches makes it possible to explore and represent the relationships of premises to buildings or groups of buildings, which can be complex. In particular, past work has tended to overlook the mixing of uses within buildings, or has underestimated the mixtures of both different non-domestic uses and non-domestic with domestic. The present paper uses a new and comprehensive method of stock modelling to investigate this issue of mixing. All activities are represented in detail within premises and buildings, broken down by floor levels. Non-prismatic forms of building are modelled.

With this new modelling method, actual electricity and gas meter data can be matched to premises, buildings or small groups of buildings by their addresses. The results for energy intensities are not given here. However, the model is designed for application within a philosophy of what has been termed 'energy epidemiology', in which actual consumption in very large populations of buildings is analysed statistically to give an accurate picture of current patterns of energy use (Hamilton et al., 2013). This can provide a platform from which simulation can then be used to explore

CONTACT Stephen Evans steve.evans@ucl.ac.uk
Supplemental data for this article can be accessed http://dx.doi.org/10.1080/09613218.2017.1410424.

future scenarios and evaluate measures and technologies for energy conservation or decarbonization.

The 3Dstock model

Computational advances in the past decade have meant that it has become possible to build detailed spatial models of national building stocks, where previously it was only possible to produce estimates of numbers and floor areas of premises devoted to different activities. Using these opportunities, we have developed a new type of iconic model called 3DStock, whose construction and data sources have been described previously (Evans, Liddiard, & Steadman, 2014, 2016). A summary is provided here.

3DStock brings together several public sources of data, of which the most important are three. Ordnance Survey (OS) digital maps provide footprint polygons for all buildings, linked to addresses of occupiers, both domestic and non-domestic. The Valuation Office Agency (VOA) of Her Majesty's Revenue and Customs (HMRC) provides data on the floor areas and activities of most non-domestic premises (VOA n.d.). These data are collected for the purposes of assessing commercial rates (property taxes) in England and Wales. Floor areas are given by floor level. The VOA's activity classification system is complex and comprehensive (VOA, 2014). It classifies the 'primary' activity of each premises (*e.g.* 'office', 'wine bar', 'hospital') and further classifies subactivities inside premises (*e.g.* 'sales area', 'storage' or 'office' within shops). More details are given below.

The VOA floor areas and OS footprints are linked together by matching addresses. Special attention is given in 3DStock to the potentially complex relationships between premises and buildings. These relationships may be many-to-one, as with an office building housing many separate office tenants; one-to-one, as typically with a church or small school; or one-to-many, as in a large school, factory or hospital that occupies several buildings on one site. The VOA surveys cover the majority of non-domestic premises, with some exclusions. Also floor areas are not measured for certain activity types subject to rates, including hotels and public houses.

The third important source is light detection and ranging (LiDAR) data from the UK Environment Agency: hundreds of thousands of laser measurements per second are made of the ground (and objects on the ground, such as buildings) from overflying aircraft, allowing highly detailed elevation models to be generated (Environment Agency, 2017). These are used for determining the volumes of buildings and estimating floor areas, where area data are not available from other sources. In this way, all buildings – domestic, non-domestic and mixed use – can be covered in the modelling. The forms of buildings are not represented as simple vertical extrusions of the map polygons: LiDAR data are used to model setbacks, courtyards and low-rise extensions to taller buildings.

Figure 1 shows a visualization of a 3DStock model of Camden High Street, London (which is best viewed in the supplemental data online for clarity). The colours code for the predominant activity in each case: many of these buildings contain mixtures of non-domestic activities. For example, the large office building coloured brown on the right (The Crowndale Centre) also contains a library and a public house. Grey indicates domestic premises, either houses or flats. The mixing of domestic with non-domestic is illustrated here by the many cases, along this commercial street in London, of flats (grey) above shops (yellow), restaurants (orange) and other non-domestic uses.

Note that in Figure 1 all buildings in the model are spatially located in relation to sites, roads and open spaces. This means the model can be used for geographical analyses, *e.g.* densities of development, densities of heat demand along streets or areas of land available for renewable energy installations. The boundaries of land parcels and sites are obtained from the OS 'Sites' product (OS, 2017b) and/or Her Majesty's Land Registry (HMLR) (2017). Further data, *e.g.* energy use measured by gas and electricity meters, building age, or material and structural characteristics, can be attached to premises and/or buildings by matching addresses. 3DStock models have been developed to date for 15 London boroughs and for the English towns and cities of Swindon, Leicester, Tamworth and Milton Keynes.

Issues in the classification of activities in buildings

Much depends in deciding whether or not buildings are mixed use, on how activities are classified and at what level of detail. Classifications of activities may be made at the level of premises as a whole, and at the level of sub-activities in zones or rooms within premises. The VOA system works at these two levels. Taking sub-activities first: any office building will typically contain areas devoted to office work, circulation, kitchens, storage, meeting rooms *etc.* These distinctions can be important for energy simulation, associated as they may be with different levels of demand for servicing and equipment. As mentioned, sub-activities are represented in 3DStock. However, they are ignored in this paper, where the focus is exclusively on the activity classification of premises as a whole.

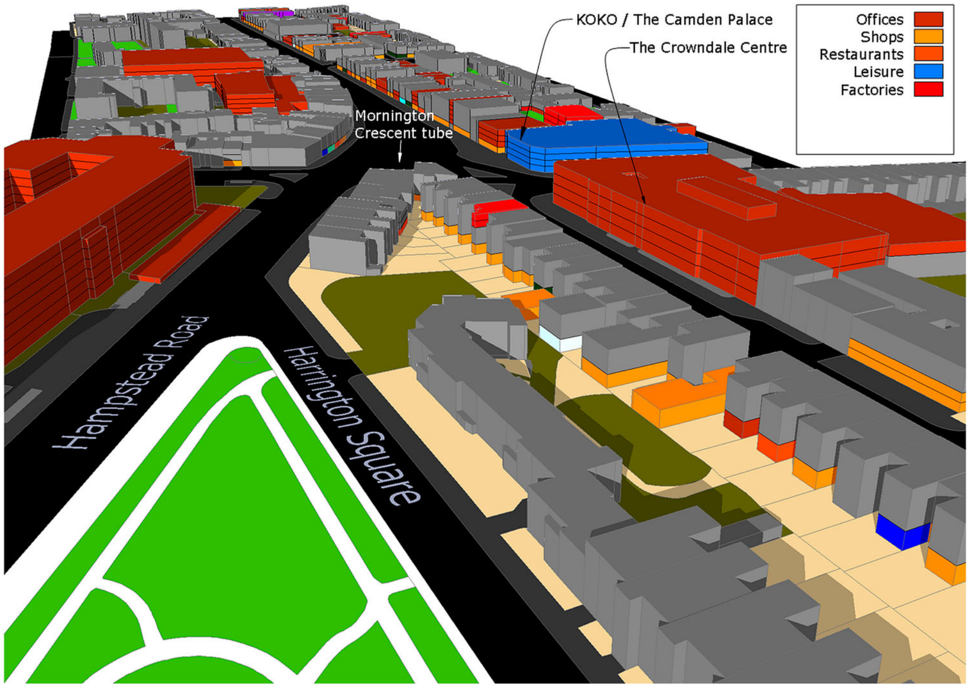

Figure 1. Three-dimensional representation of part of Camden High Street, London, showing the geo-location of self-contained units along with their principal activities.
Source: Map data © Crown Copyright and Database Right 2017. Ordnance Survey (Digimap Licence) supplied by the Ordnance Survey/EDINA service.

At the level of complete buildings containing multiple premises, there can be two situations. The premises may all be classified as the same activity, as with a multi-tenant office building comprised exclusively of office suites; or the premises may be classified as housing different activities, as with a building containing some combination of offices, shops, restaurants, flats *etc.* In this paper we define the latter as mixed-use buildings.

Any quantification of the phenomenon of mixed uses will clearly be affected by the level of aggregation of the activity classification. If the classification 'retail', for example, covers both shops and hospitality (restaurants, cafés, wine bars), this category will not classify a single building combining those different activities as mixed use, whereas if 'shops' and 'hospitality' are distinct categories, the same building will be classified as mixed use. Further issues can arise where activity classifications of whole buildings are based – as in some stock models – on the activity that occupies the ground floor, as given by data attached to footprint polygons. Obviously, this can be quite misleading.

Previous work

Despite the fact that 'the domestic stock' and 'the non-domestic stock' are often treated separately, and mixed-use buildings have often been overlooked, the latter have not been totally ignored in previous research. Bruhns (2008) foresaw that this was an upcoming issue when he wrote that 'The complexity of the stock is further exacerbated by topology: the web of relationships between premises and buildings, and by mixed activities within buildings' (p. 390). Similarly, Gao, Malkawi, and Yi (2013) pointed out that 'the process of properly categorizing buildings has its own challenges since there are few cases in which only one activity takes place in a building' (p. 2349). However, there seems to be little consensus on how exactly the problem should be approached. The issue has been addressed in different practical contexts: the development of stock models and urban models, energy benchmarking, and tools for simulating the energy performance of individual buildings.

In the context of energy benchmarking, Kinney and Piette (2002), working in California, acknowledge the need to define 'principal building activity' as the function occupying the most floor area in a mixed-use building, but recognize that this is not a simple process. Reinhart and Cerezo Davila (2016), in a review of urban energy models, make it clear that such models require the representation of mixed-use buildings for more realistic thermal modelling.

The US Commercial Buildings Energy Consumption Survey (CBECS) (2007) appears to put forward the case for taking mixed-use buildings into account by requiring that an activity should occupy a significant part of a building (greater than 75% of floor area) before it can be designated as the 'primary activity'. The US Department of Energy (DoE) (2016) adopts a similar approach in ignoring activities that do not occupy significant parts of buildings, suggesting that a building with a minor secondary use should not be classified as mixed use if the smaller activity accounts for less than 5% of total area. In the UK, the Chartered Institution of Building Services Engineers (CIBSE) Energy Benchmarks document TM46 prefers to take account of all activity within a building, and recognizes that 'Mixed use buildings may be split into their component uses for separate assessment of each type of use … ' (Field, 2008, p. 10). A composite benchmark is then calculated, based on the percentages of area occupied by each activity.

Yamaguchi, Shimoda, and Mizuno (2007, p. 582) used a 'district clustering' approach in which 500 × 500 m areas of the city of Osaka, Japan, were categorized according to their overall activity. Only six district categories were identified, including 'mixed use commercial' (p. 583). The method developed by Jones, Lannon, and Williams (2001) for use in urban energy and environmental scenario modelling, takes desk research and surveys of a number of individual buildings to generate 100 archetypal domestic premises identified through cluster analysis. But there is no mention of blocks of flats or mixing with non-domestic premises, even though the latter also form part of the model. The more automated approach developed by Taylor, Fan, and Rylatt (2014) excludes domestic premises and thus does not address their mixing with the non-domestic stock, even though such premises may occur within the building(s) represented. Although these could contain multiple premises and therefore potentially multiple activities, the extent of mixing was not addressed explicitly, though non-domestic energy use was modelled for each building, but again excluding any domestic premises present.

The existence of mixed-use buildings is recognized by Nageler et al. (2017) in their dynamic heat demand model of a small town in Austria. The work derives the activities within buildings from data on land use, which may cover several land parcels, and the building's geometry, but mixed-use buildings are assumed only to be present in the town centre. Floor areas are derived from map polygons and LiDAR, with a single-height point for each building, so the buildings are effectively extruded map polygons. Each building may be divided into a maximum of three zones for energy modelling purposes. Assumptions are made about the position of each activity, such that where commercial, office and residential uses are thought to occur in the same building, the commercial is automatically made to fill the ground floor, with offices above and residential above that.

The European statistics agency EUROSTAT (2013) provides a clear methodology for use in statistics for the building stock. This states that a building should be classified by the activity that occupies at least half of overall useful floor area. For example, using this method, a mixed-use building with more than 50% of floorspace occupied by domestic activity would be classified as a residential building.

Kunze and Hecht (2015) showed that by accounting for mixed-use buildings, the disaggregation of population statistics (into buildings) is more accurate than if it is not recognized that there is non-domestic activity taking place inside the building. In doing so, they observed that mixed-activity buildings are an important category, particularly in or near to a town centre.

It is considerably more difficult to find examples in the literature of cases where people have attempted to quantify the amount of the building stock that can be considered 'mixed activity'. Theodoridou, Papadopoulos, and Hegger (2011, p. 2782) carried out a typological classification of the Greek residential building stock, concluding that approximately 10% of the count of the stock is in mixed-use buildings, and that this proportion rises to 13% in urban areas compared with around 8% in rural areas. Hecht, Meinel, and Buchroithner (2015) provided a detailed classification of the German building stock, but did not include any mixed-use category, although earlier work by other members of this research group using similar data sources (Meinel, Hecht, & Herold, 2009) did refer to mixed-use areas. The work of Hartmann, Meinel, Hecht, and Behnisch (2016), again using similar data sets, does include mixed-use buildings for the whole of Germany. The authors concluded that counts of mixed-use buildings make up 32.4% of all the building stock of Germany. However, they use land-use classifications to assign activity to buildings and their mixed-use classification occurs when no single land-use activity occupies more than 50% of the land area. According to the lead author, this is typical in rural areas with farms and in urban areas with three or more activities, none of which achieves more than 50% of the parcel (Hartmann, 2017). This explains these apparently large proportions of the total stock model that are classified as mixed-use buildings.

The nearest comparison with the work presented here is by Smith and Crooks (2010) who analysed Greater London at the building level using only digital maps. When mixed activity takes place in a building, they used the number of addresses as their means for estimating the most prominent function (a technique they recognized as inadequate). Using this method, they found that 2% of building polygons had multiple functions in Greater London, and that these were strongly clustered in Central London. However, when they checked the model by surveying two inner London locations, in detail, they found that:

> the vast majority of buildings from the surveyed streets are mixed-use buildings (around 90%), typically combining retail and office or retail and residential functions. This means essentially that geometrical measures are limited to assessing the footprint of buildings in this model. The vertical distribution of uses in multi-storey buildings is not known from the 2D [two-dimensional] topographic data, so measures such as floorspace and volume cannot easily be estimated. (p. 33)

Such a very large discrepancy illustrates the dangers of relying solely on addresses and activity classifications linked to map polygons.

From this review of previous work on mixed activity in the building stock, two things are clear. First, an agreed method of defining what constitutes mixed use is still unresolved. Second, past estimates of the percentages of building stocks represented by mixed-use buildings have varied wildly depending on the classifications and techniques of measurement used.

Classification of activities in 3DStock

3DStock uses a system for classifying premises by activities developed for a database of the non-domestic stock of England and Wales called Carbon Reduction in Buildings (CaRB) (Bruhns, Steadman, & Marjanovic, 2006), later updated as CaRB2. This builds on, extends and combines two systems of activity classification used by the VOA: the primary description (PD) and the special category code (SCAT). The latter is generally more detailed. These classifications use number and letter codes. Some of the PDs are simplified for CaRB2. Each SCAT/PD combination is given a meaningful activity description and a CaRB2 code.

There are 321 CaRB2 activities grouped into 18 classes: the latter are listed in Table 1. For a full listing of all the classifications, see Table S1 in the supplemental data online. Two of the 18 major classes are 'excluded', indicating premises that are not counted as buildings (*e.g.* telecommunications masts, surface car parks *etc.*), and 'uncoded', referring to premises for which the activity cannot reasonably be identified. The CaRB2 classification system has been adopted largely unchanged by the UK government in its NEED and Building Energy Efficiency Survey (BEES) programme (BEIS, 2013, 2016).

Table 1. Updated version of Carbon Reduction in Buildings (CaRB2) non-domestic activity classes.

Agriculture, countryside	Factory	Office
Arts and leisure	Health	Shop
Community	Hospitality	Sport
Education	Military	Transport
Emergency	Miscellaneous	Uncoded
Excluded	MoD	Warehouse

Note: MoD = Ministry of Defence.

How 3DStock works: the concept of the self-contained unit (SCU)

The 3DStock model was initially developed as a non-domestic model and as such was primarily driven by records relating to premises in the VOA Summary Valuations (SMV) data set, since this is where floor areas are defined. (The VOA refers to premises, as listed in this database, as 'hereditaments'.) The SMV describes both floor area and floor level for most records. By matching VOA addresses to OS AddressBase (OSAB) addresses, the VOA data can be georeferenced to give precise spatial locations, and to identify OS Mastermap Topographic layer (OSTopo) building polygons to which activities relate (OS, 2017a, 2017b). Using the floor area and floor level from the SMV makes it possible to 'stratify' non-domestic activities onto the correct floor levels, and to compare the available floor area for the OSTopo building polygon with the recorded floor area for each premises in the SMV (Evans, Liddiard, & Steadman, 2016). In some cases, adjoining OSTopo building polygons may need to be added if the SMV shows much more floor area than is available in the primary building polygon, and the conditions are suitable for these additional polygons to be captured (Evans et al., 2016).

Once this process of geolocation, stratification and polygon capture is complete, a boundary can be set around the premises or collection of premises, which does not split either a premises or an OSTopo polygon. This is called a self-contained unit (SCU) (Evans et al., 2016; Taylor et al., 2014). In many cases, a SCU is just a representation of a single building, but in some cases to avoid splitting premises it can include two or more adjoining buildings; or in the case of some schools, large factories and other campus-based sites, it may include multiple non-adjacent buildings and is referred to as a 'poly-SCU' (Evans et al., 2016, p. 10).

Above we wrote loosely of 'buildings' as the basic units from which stock models are constructed. But for the reasons indicated, 'buildings' understood in the everyday architectural or constructional meaning are not ideal units for the purpose, since it is often the case that one premises extends across several buildings, hence the SCU. The SCU has another advantage for energy analysis. It is not always feasible to match electricity or gas meters to individual premises; indeed, in many cases, meters are shared between premises. However, it is possible in general to match meters either to premises or to complete SCUs. Thus, the totality of energy supplied to a SCU can be known, even if the precise division of this supply between premises cannot.

The VOA gives less information for rateable non-domestic premises that are not included in the SMV (which constitute approximately 10% of all premises), so these are dealt with slightly differently. A premises can still be geolocated to its addressed polygon and any other building polygons that fall within the OS Mastermap 'Sites' layer polygon if it exists, or to polygons within the HMLR boundary for the site. However, we do not know the floor level or the floor area of the premises in question. Thus, once located to a polygon or polygons, little else is known about its extent, except for whatever can be data-mined from the address field.

The introduction of LiDAR data into the SCU construction process allows the generation of a geometric three-dimensional (3D) SCU, which thus gives a volume above the map polygon, average heights for the SCU and other statistical data derived from the LiDAR. This method can be applied to single-polygon, multi-polygon and multiple non-contiguous SCUs (poly-SCUs). Using high-resolution LiDAR allows the model to produce good approximations of the 3D forms of SCUs.

The method used with the LiDAR data can be briefly summarized as follows. It involves taking a digital surface model (DSM) derived from LiDAR, which represents all terrain features, including buildings. Then for the same spatial extent a digital terrain model (DTM) is required, which is derived from the DSM, but with the buildings removed (sometimes known as a 'bare earth' model). All heights at this stage are relative to sea level. By subtracting the DTM from the DSM, the result is a digital height model (DHM), which ensures that all buildings have their base at or close to zero. This then makes the processing of the height statistics for each building polygon that make up each SCU less computationally intensive. The DHM is also a useful product in itself, since it can be used for rapid further analysis of each SCU (as outlined below). For the purposes of 3DStock, we used time-stamped tiles from the Environment Agency (2017), which were chosen to align as closely as possible to the year of the other model data (in this case, 2014). The data sets used were either the 50 or 100 cm spatial-resolution models. The 25 cm spatial-resolution data were available for some locations, but the increased processing time outweighed the observed benefits of using this very detailed data set. When time-stamped data were not available, then a composite LiDAR product was used (made up of data from a range of years). According to the Environment Agency, the LiDAR data had a vertical accuracy of ±15 cm root mean square error (RMSE). Further processing methods could be developed to determine roof shape and slope, but for the present model these calculations have not been made.

The process of generating volumes for each SCU, and stratifying premises onto particular floors, can be combined with assumptions about floor-to-floor heights, from which floor areas may be estimated for each SCU. Where there are SMV and non-SMV premises sharing a SCU – for instance, an office and a public house – this allows the SMV floor area (the office) to be deducted from the calculated total SCU floor area, to give a floor area figure for the non-SMV premises (the pub). Using this method makes it feasible to calculate volumes and floor areas of non-SMV premises, as a component of the entire SCU, where there are other SMV premises present.

Why domestic is included in the model

The OSAB data set provides non-domestic addresses for the construction of the non-domestic 3DStock model, but it also provides domestic addresses, which allows one to geo-reference domestic premises alongside non-domestic premises. Initially, these domestic addresses were not included in 3DStock, and the model simply classified such space as 'not non-domestic'. However, a project carried out for the UK Department of Energy and Climate Change (DECC) to match energy meters to addresses and SCUs made it apparent that within the sample data there were many non-domestic SCUs that also contained domestic addresses, in varying numbers. In some instances, the number of domestic addresses in a SCU far exceeded the number of non-domestic addresses, which then posed the question: how should these mixed SCUs be defined in terms of activity?

As cited above, the EUROSTAT recommendation is that buildings be designated as 'residential' if more than 50% of useful floor area is devoted to domestic uses (EUROSTAT, 2013). Hartmann et al. (2016) adopted this approach. Strictly speaking, this requires the measurement of floorspace throughout a building, although in theory the proportions could be estimated by counting the occupant addresses, or approximated by dividing the volume of the building between occupants. The problem with using floorspace for making this distinction in 3DStock was that at this stage the model only contained floorspace for non-domestic premises included in the SMV. There are no reliable sources of data on domestic floorspace covering all residential addresses in England and Wales. Domestic energy performance certificates (EPCs) have recently been made publicly available, which give floor areas, but these cover only a fraction of all domestic addresses.

How domestic is included in the model

One key reason for including domestic activity in 3DStock is to derive floorspace for all activities, both domestic and non-domestic. Since it is not known how much floorspace can be classified as domestic from other sources, this needs to be derived from the model itself. Below is a brief summary of the methods used to integrate domestic floorspace into the model.

The starting point is to calculate the probable number of floors in each SCU. This is achieved by taking each polygon, on each level, making up the SCU, looking at the average height of the floor to which the polygon relates, and then choosing the nearest integer number of floors that fit into the SCU with a floor-to-floor height of between 2.7 and 4.2 m, depending on the activities. These values are based on measurements made in the 1990s in the course of surveys of buildings at 3500 addresses in four English towns (Tamworth, Swindon, Manchester and Bury St Edmunds) (Brown, Rickaby, Bruhns, & Steadman, 2000). For cases where domestic activity occurs in the same SCU as non-domestic activity (which has already been assigned a floor level), then the domestic activity is assumed to occupy space above the non-domestic. The exceptions here are where it is possible to find words in the domestic address that refer to a floor level, as, for example, 'First floor flat'. These domestic addresses can be assigned to specific floor levels in the model. We refer to these cases as 'stratified'.

In cases where all premises in a SCU can be assigned to a specific floor, the count of floors is taken from this data table rather than from the average storey height method described above. Metadata on the methods applied are recorded in each case, making it possible to compare floor-to-floor heights from 'stratified' and 'unstratified' domestic SCUs. The histograms of floor heights for the two methods shown in Figures 2 and 3 give confidence that the more approximate method is reasonably reliable. Both methods produce a mean floor-to-floor height of around 3.2 m.

Once floor levels for domestic are assigned, the gross external area (GEA) of each floor level can be calculated. A relatively simple way to do this is to multiply the polygon footprint by the number of floors, but many buildings and in particular domestic buildings often have less floor area on their upper storeys. With this in mind, the present authors developed a method that takes the LiDAR data and slices it at the mid-storey point for every storey from the top downwards. If, for example, a building has three floors (including the ground floor) with an average floor-to-floor height of 3 m, then for the top storey, the DHM derived from LiDAR will be sliced at 7.5 m and the total square metres of DHM grid cells that fall within the SCU polygon are returned. The method is then repeated for the next floor down at 4.5 m and finally for the ground floor at 1.5 m.

For taller buildings, once the DHM area returned is equal to that derived for the ground floor, then all floors below this level are assumed to return the same value. The results for 19th-century housing in inner London clearly show the benefits of this method. Figure 4 gives one such example with the highlighted map polygon representing what is in reality a building with three floors, not all of which extend to the full polygon footprint. Using the LiDAR DHM slicing technique

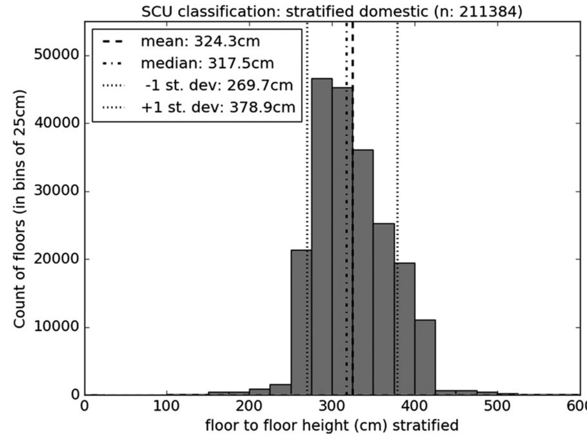

Figure 2. Histogram of floor-to-floor height showing the results for the stratified method.

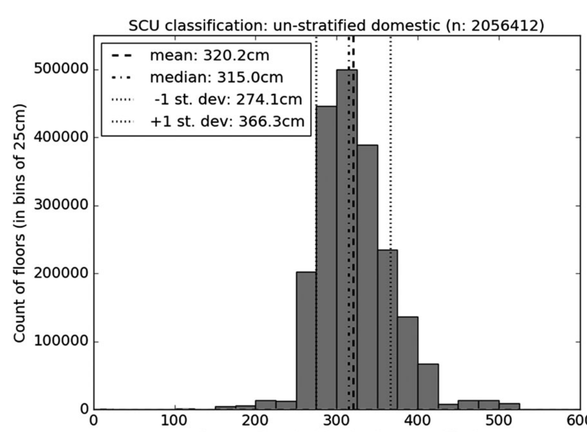

Figure 3. Histogram of floor-to-floor height showing the results for the unstratified method.

Figure 4. Storey area inference method applied to a fairly typical inner-London domestic building. Areas are calculated at the three levels marked by the yellow bands.

described above, this returns 92 m^2 for the ground floor, 84 m^2 for the first floor and 60 m^2 for the second floor (using the British convention for floor levels). With non-domestic and domestic floorspace included in 3DStock, it is now possible to calculate the share of floor area between activities, and the mixing of these activities within buildings and SCUs for large parts of England and Wales. This method of slicing the LiDAR data to give a calculated approximation of gross external floor area on each above-ground storey of each building could be replicated by other building stock models where such data sets are accessible, thus enabling energy-use intensities to be calculated per unit area, where energy data are also available. A caveat to the method is that it may not reliably infer the existence of atria, but these are generally rare in domestic buildings. The method of slicing LiDAR is, however, an improvement over simple extruded polygons, particularly for heating and cooling energy use, for which accurate volumes (not floor areas) are more relevant.

Measurements of the mixing of activities

The principal outcome of the research described so far is a move from the position of there being two building stocks – domestic and non-domestic – to the position of representing one unified building stock with a variety of activities occurring within it. In much past work, as mentioned, a fundamental separation of activity has been made into domestic and non-domestic, with some buildings that are wholly domestic and others that are wholly non-domestic: this has been the paradigm. However, in between these simple stereotypes, there is a whole spectrum of combinations that are neither wholly domestic nor wholly non-domestic. Furthermore, within buildings that contain just non-domestic activities, there can be mixes of these activities, with or without further mixing with domestic. These can now be measured.

In what follows we present a series of analyses to show the nature and extent of these combinations in the stocks of the 19 local authorities modelled in 3DStock to date. The unit of analysis is the SCU. Activities are categorized by the 18 CaRB2 classes listed above, plus domestic. The extent of each activity is measured by floor area (m^2 GEA). For convenience, in the charts and tables we distinguish eight situations as described in Table 2, with examples shown in Table S2 in the supplemental data online. Clearly, these groupings could be altered or further developed to show specific activity classes and different percentages.

The outputs are produced by taking each SCU and classifying it into the above categories according to the

Table 2. Classifications of mixtures of activities in self-contained units (SCUs).

Classification in figures	Description: a SCU comprised of …
Pure domestic: single household	Single domestic address
Pure domestic: > 1 and < 10 households	Two to nine domestic addresses. Likely to be large houses converted into flats
Pure domestic: ≥ 10 households	Ten or more domestic addresses. Likely to be purpose-built flats
Domestic and non-domestic: domestic dominant	Domestic and non-domestic premises, with the floor area of domestic exceeding 50% of the total floor area
Non-domestic and domestic: non-domestic dominant	Non-domestic and domestic premises, with the floor area of non-domestic exceeding 50% of the total floor area
Non-domestic: multiple activities	Multiple non-domestic premises with more than one CaRB2 activity class
Multi-non-domestic: same activity	Multiple non-domestic premises that share the same CaRB2 activity class
Pure non-domestic: single occupier	Single non-domestic premises

Note: CaRB2 = updated version of Carbon Reduction in Buildings.

number of activities and/or the amount of floorspace these activities occupy. For example, 'Non-domestic: multiple activities' are cases where there is no domestic, more than one VOA premises and the activity classifications are not all the same. 'Non-domestic and domestic: domestic dominant' is classified by selecting those SCUs where there is both non-domestic and domestic within the SCU, and then summing the floorspace for non-domestic and calculating it as a percentage of all floorspace in the SCU. If this is greater than 50% non-domestic, it is placed in this category. Once these classifications have been made, it is then possible to show the results as aggregate statistics for each SCU classification (in our case, counts and then volumes).

Figure 5 shows counts of SCUs, classified as in Table 2, for each of the 15 London boroughs and four cities. The horizontal axis is split in each case, with domestic SCUs to the left of zero, and non-domestic SCUs to the right. Both sides of the axis are positive, with the total for each bar equalling 100%. White shading indicates 'pure' domestic SCUs, while black shading indicates 'pure' non-domestic. The patterned sections indicate where there is mixing of domestic and non-domestic premises within SCUs, as indicated by the figure keys. This shading convention holds for further figures below.

The distance of the geographical centre of each borough was calculated, and the respective bars in Figure 5 are ordered top-to-bottom according to the distance of this point from the centre of the City of London. It is clear that in terms of the count of SCUs, the City of London – the financial and business centre of the capital – is dominated by non-domestic premises, whilst all other boroughs are dominated by domestic addresses. The four non-London local authorities (Milton Keynes, Swindon, Leicester and Tamworth) have predominantly single-address domestic SCUs, whilst London boroughs including Ealing have a more substantial proportion of multi-address domestic SCUs.

It is plausible to assume that SCUs containing 10 or more domestic addresses are purpose-built blocks of flats, and that SCUs with fewer than 10 domestic addresses are properties that have been converted into flats. If this assumption is valid, then London has a much higher proportion of these converted SCUs than the other cities.

Counting all SCUs modelled, 4.4% have a mixture of domestic and non-domestic premises. At 6.3% of all its SCUs, inner London is more mixed than the five non-inner London authorities (1.6%). Note that Ealing is an outer part of London, so not classified as inner London. Significantly, in some London authorities the number of SCUs, where domestic and non-domestic activities mix, exceeds 10% of all SCUs; namely in the City of London (19.7%), Westminster (19.4%), Camden (12.7%) and Tower Hamlets (11.5%). For inner London, 7.1% of SCUs contain multiple non-domestic activities or mixed domestic and non-domestic premises.

Figure 6, which uses the same labelling conventions as Figure 5, shows the actual counts of SCUs (not percentages). Most noticeable is the very small number of SCUs in the City of London compared with any other borough, whilst Leicester has a very large number of domestic single-address SCUs, followed by Milton Keynes and Swindon. Note also the large number of non-domestic SCUs in Leicester and Westminster, and how the non-London authorities have their non-domestic SCUs mostly in the 'pure non-domestic' category.

This picture is greatly changed when summed volumes of SCUs (m^3) are presented (Figure 7). Here, non-domestic volume exceeds the volume of the domestic stock in the City of London and Westminster (both major office centres). Beyond London, three of four local authorities have more than 40% of all their SCU volume within non-domestic. This is, of course, due to the generally larger sizes of non-domestic SCUs, especially industrial premises. Swindon, Leicester and Tamworth are all notable for large numbers of factory SCUs, while Milton Keynes is a major warehousing centre. For all the London boroughs and other boroughs added together, the volume of the non-domestic stock SCUs (including where it is dominant when mixed with domestic) is 36% of the total.

Figure 8 presents the same data on SCU volumes, but as percentages. It shows that in several London boroughs the bulk of non-domestic volume falls within SCUs that have a mixture of non-domestic activities, or SCUs that are mixed with domestic. Conversely, all the non-inner London boroughs have the bulk of their non-domestic volume in pure non-domestic SCUs. Note that in Swindon just one poly-SCU (a car factory) accounts for 10.4% of all the town's non-domestic volume, demonstrating that some SCUs can be very large indeed.

Figure 9 shows the distribution of floorspace for each SCU type in each local authority area modelled. Contrasting this with Figure 7 (volumes of SCUs) indicates how the volume of the non-domestic stock is a noticeably larger proportion of the stock than is indicated by just the floorspace. This is most probably the result of greater floor-to-floor heights, but will vary according to the activities occurring in SCUs. For example, it is likely that the large volume of the single-occupier pure non-domestic SCUs in Milton Keynes is due to its population of large warehouses, which will tend to have clear ceiling heights up to the underside of the roof, which gives higher ceiling heights than in, say, retail and offices. This contrast between floor areas and volumes may be

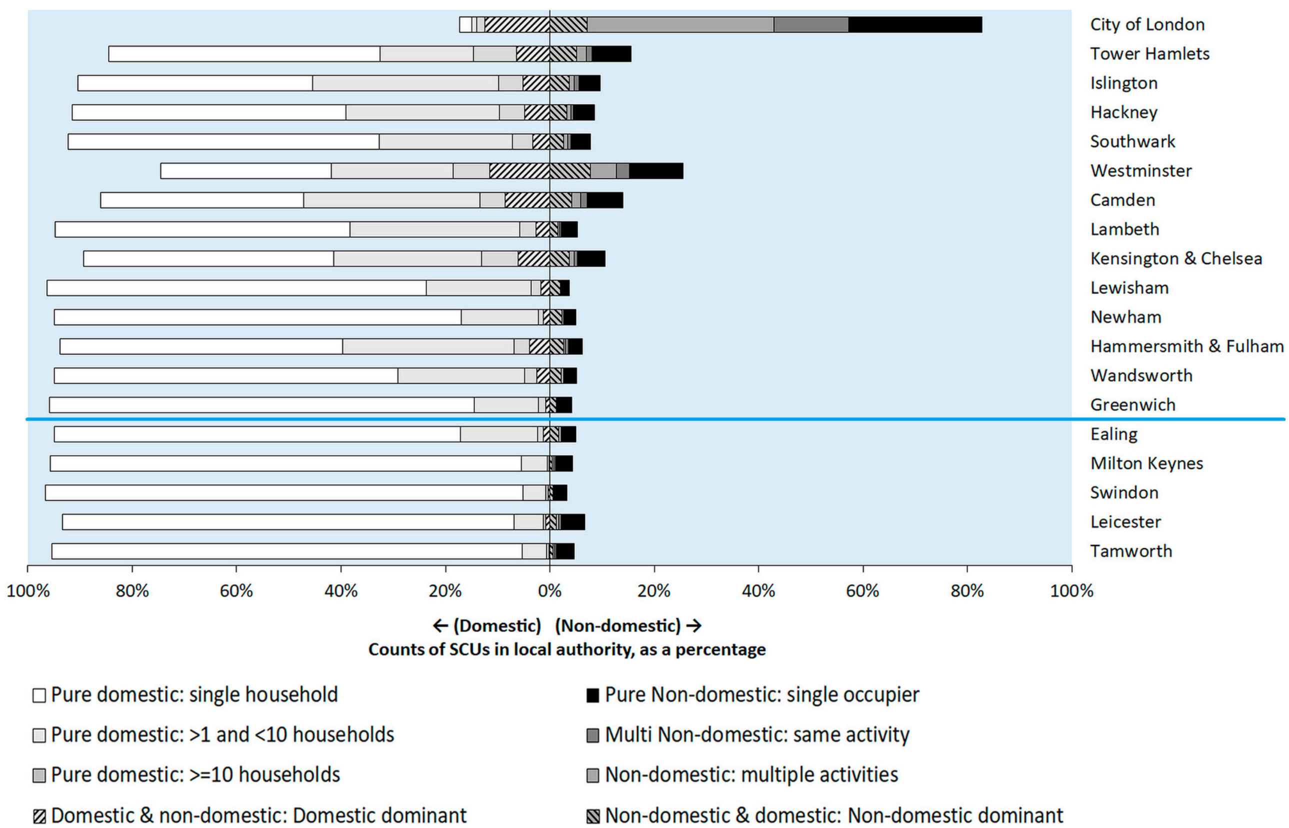

Figure 5. Classification of activities and mixing in 19 local authority areas, expressed as percentages of all self-contained units per authority. Authorities above the blue line are inner London. Ealing is a London suburb, but not inner London.

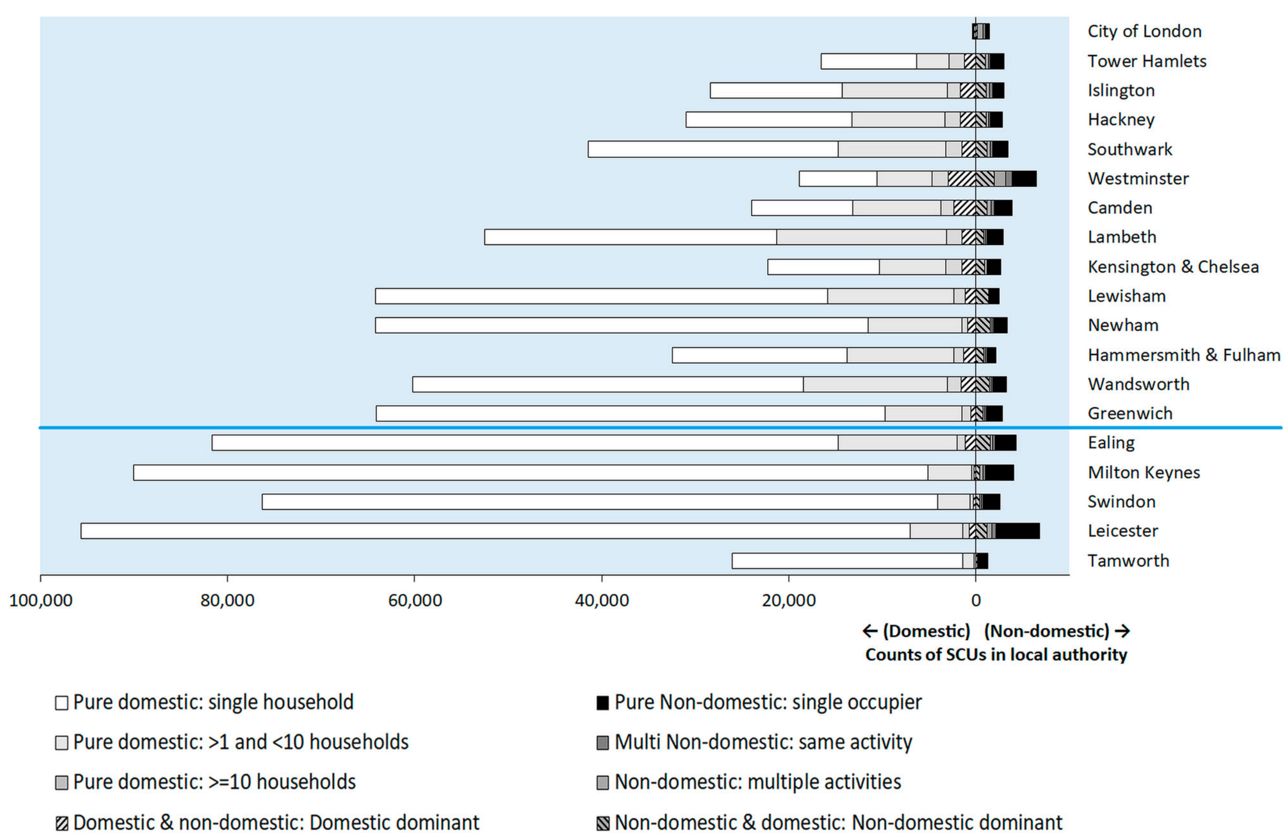

Figure 6. Counts of classifications of activities and mixing in 19 local authority areas, grouped per authority.

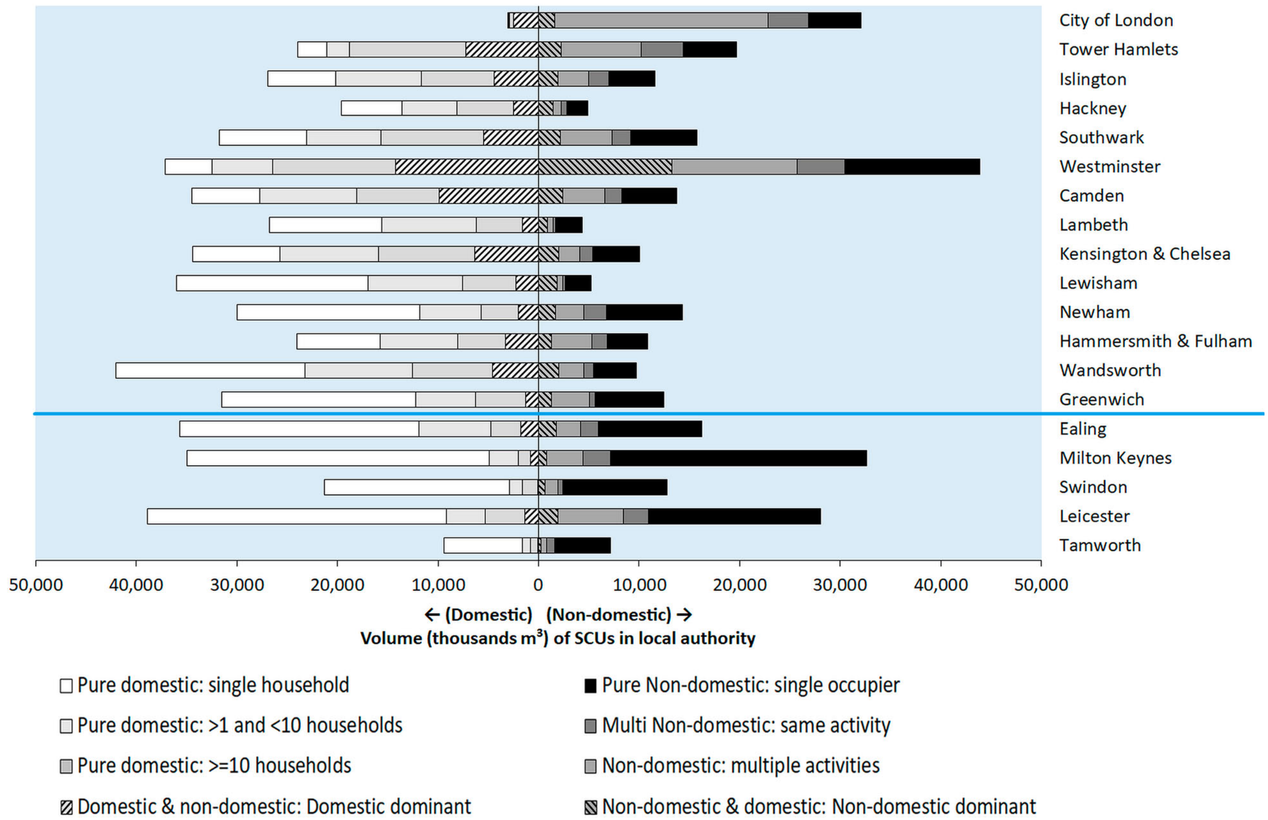

Figure 7. Total volume (thousands m^3) of self-contained units per mixing class, per local authority.

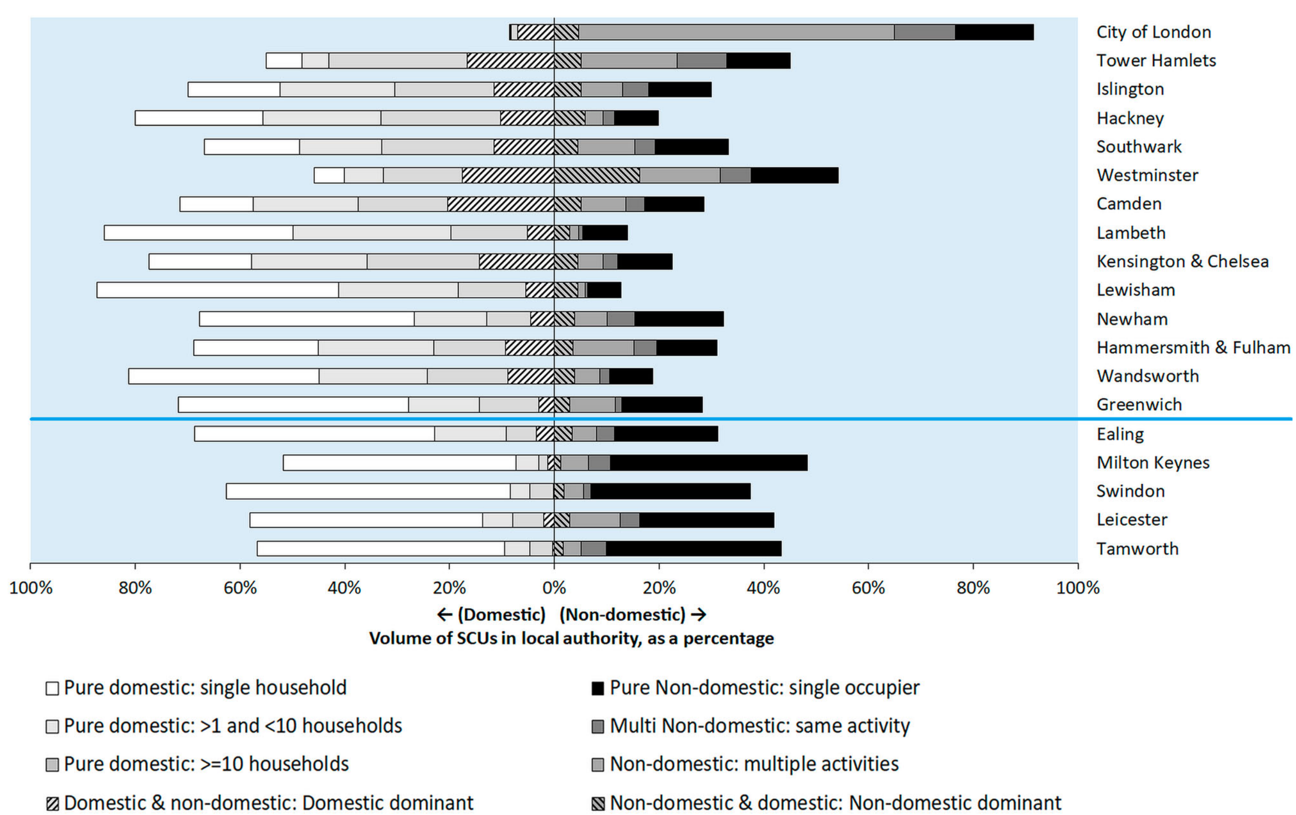

Figure 8. Total volume of self-contained units per mixing class, expressed as percentages, per local authority.

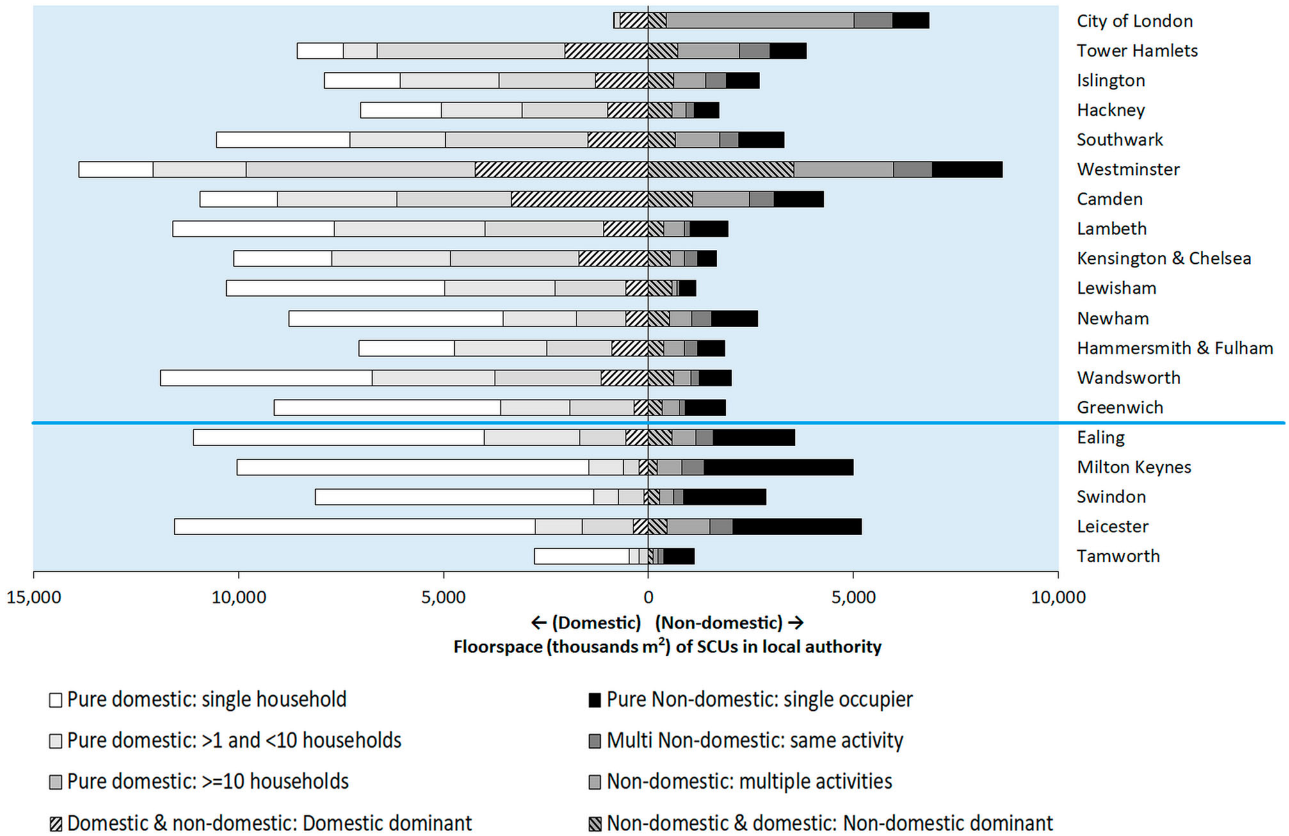

Figure 9. Total floorspace (thousands m^2) of self-contained units per mixing class, per local authority.

considered when developing policies aimed at reducing energy use in such buildings, with regard to space heating/cooling upgrades versus fabric upgrades.

A transect across London

Figures 5–8 have shown in broad terms how the extent of mixing of activities varies across the 15 London boroughs, ordered by their distances from a notional centre of the metropolis located in the City of London. Boroughs nearer this centre tend to have higher percentages of 'pure non-domestic' measured by the numbers and volume of SCUs, while those further out are dominated by 'pure domestic', and increasingly by single houses. This general pattern is very obvious and is only to be expected from urban location and land value theory.

The phenomenon can be illustrated differently by taking a transect across London, as shown in Figures 10 and 11. This has been done by defining a band 250 m wide across the metropolis from West to East, divided into 250 m squares, passing through St Paul's Cathedral in the City. SCUs cut by the edge of the strip are included if more than 50% of their footprints fall within the band. In Figures 10 and 11, the definition and shading of the bars follow the same conventions as previous charts, but are displayed vertically.

Figure 10 presents results by total volume with SCUs dominated by non-domestic above the zero axis and SCUs dominated by domestic below the axis. Figure 11 gives the same results as percentages. West is to the left; east to the right. The two very high peaks in non-domestic to the West occur because the transect has happened to catch some very large buildings at Hammersmith Hospital and Paddington. Transects in different orientations would likely be affected by other such local contingencies. But an overall pattern of non-domestic in the centre and domestic towards the edges is again evident, with some local sub-centres disturbing this simple picture. Two maps shown in Figures S1 and S2 in the supplemental data online illustrate spatial distributions of mixed-use SCUs at small and large scales. In the small-scale map, the clustering of mixed-use buildings is evident along older primary road routes and towards the urban centre. The large-scale map indicates how mixed small geographical areas can be.

Mixed uses and density

What also becomes clear from the transect and maps is the relation of density (SCU volume per 250 × 250 m unit of land area) to the phenomenon of mixing. The

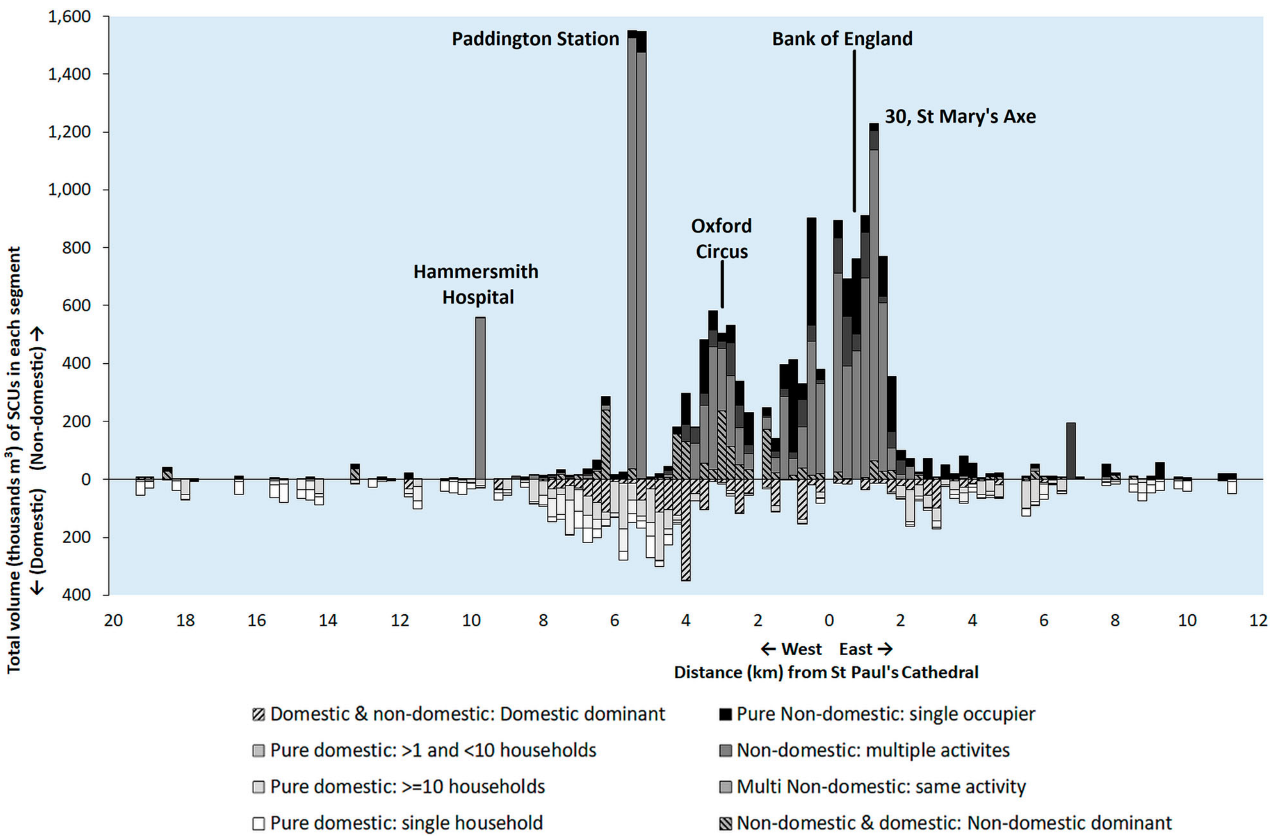

Figure 10. West–East transect of inner London showing the total volume (thousands m^3) of all self-contained units that fall within each 250 × 250 m segment, classified per mixing class.

greatest mixing appears to occur in localities just outside the principal office concentrations at the centre of London, where smaller offices, retail, entertainment, residential and perhaps some minor industrial uses are found together (as in Camden High Street in Figure 1). It is our intention to pursue this relationship of density to mixing in a future paper. The general phenomenon is not perhaps surprising, but 3DStock opens the prospect of making precise measurements.

Density is likely to be important for energy use, especially for heating, since higher densities will in general lead to reductions in exposed wall area, with corresponding increases in party wall area; to a trend away from detached and semi-detached houses towards terraces and flats; to increased use of basements (as indicated by 3DStock models of some London boroughs); to greater use of space above shops for residential purposes; and to increases in building height (although higher densities do not always mean taller buildings).

Another general factor affecting mixing is likely to be the age of an urban locality, and the extent to which it is either the product of a slow process of 'evolutionary' change or a comprehensive planning process in which uses have been deliberately segregated by regulation. The 'new town' of Milton Keynes is an example of the latter; here, the percentage of mixed SCUs is small, as Figure 5 shows.

Implications of a unified stock model for energy analysis

All the above can be expected to have implications for the future study of what were previously accepted as 'the domestic building stock' and the 'non-domestic building stock'. For example, how much does domestic policy overlap or indeed conflict with non-domestic policy? Perhaps interventions such as the fitting of improved glazing, or external insulation to buildings of domestic flats will be complicated when these buildings also include shops and offices. Similarly, there may also be implications when modelling the possible effects of interventions aimed at, say, warehouses, when it is found that some warehouse premises share the same buildings/SCUs with offices and shops. These mixtures of activities within single envelopes also complicate energy analysis in terms of internal gains and heat flows.

The dominance of certain types of SCUs in different local authorities, such as the large number of single-address SCUs in Milton Keynes, or large numbers of smaller multi-address domestic SCUs in Lambeth,

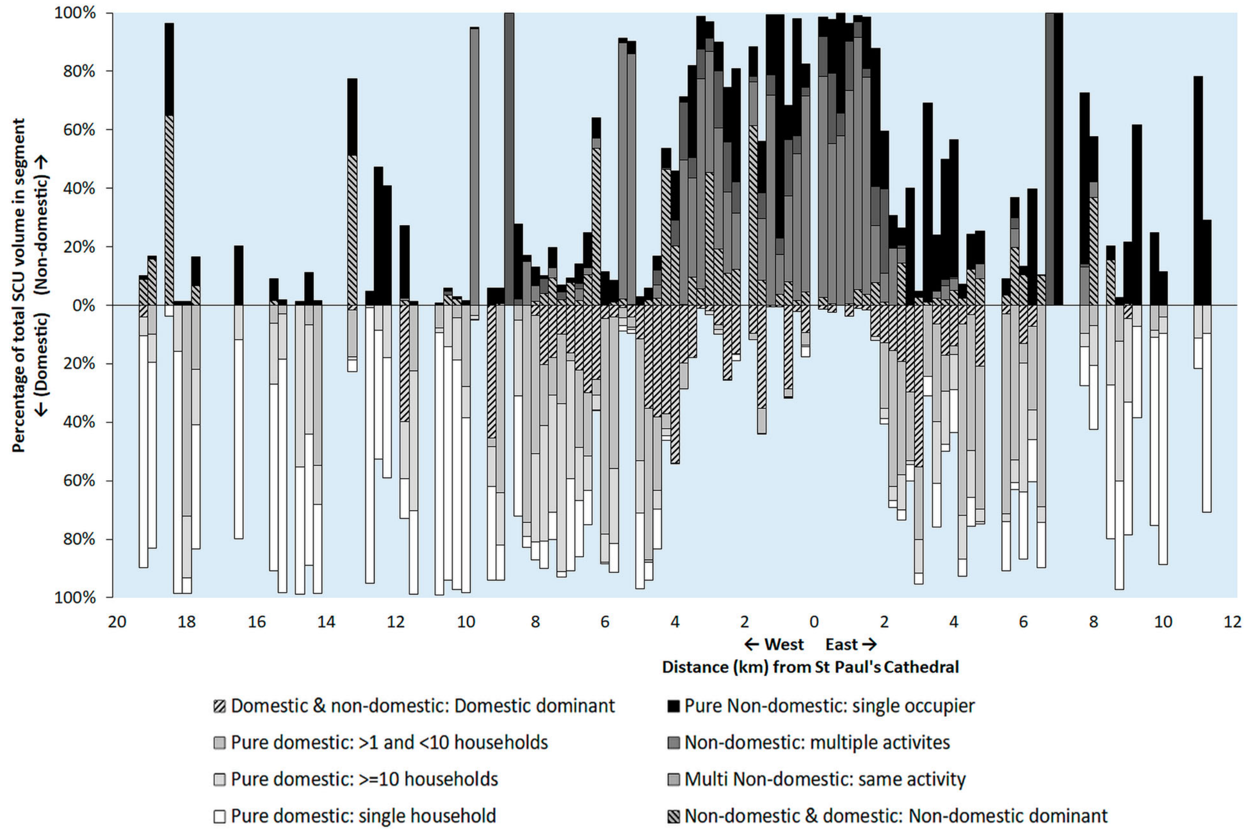

Figure 11. West–East transect of inner London showing the total volume of all self-contained units that fall within each 250 × 250 m segment, classified per mixing class, expressed as a percentage of all self-contained units in each segment.

suggest that intervention policies may be more effective in some areas than in others. For example, low-density areas such as Milton Keynes are less suitable for district heating networks than areas with multi-occupier domestic SCUs, such as Lambeth or Wandsworth. However, this is a simplification of density at the borough scale. Detailed analysis using 3DStock at the level of built blocks (*i.e.* areas delimited by the road network) seems likely to show useful geographical clustering of high-density SCUs. At the individual SCU scale, the model also allows the identification/modelling of potential small scale heat networks, such that all premises (domestic or non-domestic) could share a common heating/cooling system. Where electricity and gas meter data can be attributed to SCUs, these give further insights into the operation of buildings, especially in terms of the number of connections to the gas and electricity networks, and thus the number of bill-payers involved, which in turn may affect development and implementation of energy-efficiency policies.

The mixing of domestic and non-domestic activities seems likely to have an effect on patterns of hours of occupation for a building as a whole, which in turn could affect energy-use profiles, such that some parts of a building could be using energy at completely different times to other parts – despite the fact that they both operate within the one envelope, geographical location and position within an energy-supply network. Where there are concentrations of mixed-use buildings, the demand for energy seems likely to have a different temporal profile to an area where hours of occupancy are more homogeneous, *e.g.* the difference between a shopping centre complex, where hours of opening are all the same, and a high street with similar activities, but with more diverse operating hours. This could affect the design of local energy systems. Designers of district-scale energy systems should find the identification of mixed-use buildings and areas where these are clustered useful. A report compiled for the Mayor of London's Office indicates that areas of mixed activities are of particular relevance when considering district energy-sharing systems (DESS), in which heating and cooling loads are shared across and between buildings/premises, such that a DESS 'works particularly well in areas with a mix of heating and cooling loads such as residential and offices or retail' (Mayor of London, 2013, p. 25).

As mentioned previously, it was the matching of energy meters into SCUs in 3DStock that first highlighted the domestic/non-domestic fuzziness, requiring that the issue be recognized and addressed. In addition to the hours that premises are occupied (whether domestic or non-domestic), the supply of energy to each premises may be affected by how energy billing meters are arranged and located within each building. In terms of meters, the simplest arrangement is a one-to-one relationship between the premises (domestic or non-domestic) and the building/SCU, where the building is supplied by a single meter per energy vector. Anything beyond this becomes increasingly complex, with the potential for multiple domestic premises, multiple non-domestic premises, possibly with multiple activities and multiple energy meters. The mixing of uses in a building or SCU presents special issues for the benchmarking of energy performance. Should all the premises be benchmarked separately? But this ignores any interactions, *e.g.* heat transfer between premises. In any case, there are practical difficulties in estimating consumption for separate premises where these share meters. Or should single benchmarks be set for entire mixed SCUs? In its TM46, the CIBSE proposes a method for setting 'composite' benchmarks in such cases (Field, 2008, p. 2). But the idea is flawed, since the whole concept of benchmarking is predicated on making comparisons with other buildings of similar type, whereas the makeup of mixed-use buildings, in terms of activities and the proportions of floor area devoted to each, can vary widely. It may prove difficult to categorize mixed-activity buildings into a small number of 'comparable' types.

Non-domestic and domestic premises within mixed-use buildings may each be individual units in terms of organizational control. Simple SCUs can have one household in one building, with the household controlling all energy use. In non-domestic, one might have one office occupying all of one building and controlling all of the energy use. This has been what energy models have mostly assumed in the past. By contrast, 3DStock enables the study of how a range of organizations – be they multiple domestic, multiple non-domestic or a mixture – occupy the same building. Given the requisite energy data, the model can be used to investigate how these relationships influence energy use.

Conclusions

Work on stock models and models of archetypal buildings, for the purpose of quantifying energy use, have until now tended to deal with either 'the domestic stock' or 'the non-domestic stock'. In reality, large parts of the stock are made up of buildings that contain a mixture of activities. The initial findings from 3DStock suggest that these are more prevalent in denser inner-urban areas and along major urban roads. This seems to be confirmed by previous work in the literature, although there are many methods for defining mixed-use buildings. This may be one explanation why those who have then gone on to attempt to quantify the proportion of the building stock that is mixed use can arrive at a wide range of results. By using the 3DStock model, it is now possible to make estimates of the proportion of the stock that is mixed, because the model breaks down activities by floor level for each building and includes both domestic and non-domestic activity. For an area such as inner London, our estimates suggest that around 7% of the stock of buildings (SCUs) has either multiple non-domestic activities and/or a mixture of domestic and non-domestic premises. A further 27% of SCUs contain multiple premises of the same activity class. 3DStock now allows researchers to go beyond this and identify a spectrum of different types of mixing within these mixed-activity categories.

The research has touched upon the relationship of building volume to floor area. The results suggest that volume may now be taken into account when modelling energy use within building stocks, which could then feed into the development of energy conservation policies. Further research will investigate the relationships of non-domestic activities and building volumes, for both single-activity and mixed-use buildings. Also, given the requisite data, how energy meters and energy use relate to such mixtures could be examined.

The results presented here may provide insights for other models, which do not have access to such detailed non-domestic activity data, on how the stock may be mixed in those areas being modelled. However, the age and history of each area's stock seems likely to have a bearing on the degrees and types of mixtures, which would bear further investigation. That said, the method could be replicated with any suitable data set (s) that can be address matched to map polygons and/or land parcels, with the LiDAR data appended to these.

When one considers energy use in these mixed-use buildings, then the energy-use profiles and the possibility of premises sharing energy supplies will likely differ from single-occupant buildings. Attempting to apply energy benchmarks to the former may be misleading. Likewise, any attempt to apply energy-saving policies to such buildings may be more complex to achieve compared with single-occupant buildings. Stock models that do not include both the domestic and the non-domestic buildings, or that do not recognize that a significant percentage of the model may actually be mixed-use buildings, could be overlooking a complex and important part of the building stock.

Acknowledgments

Data provided by the Valuation Office Agency (VOA) contain public-sector information licensed under the Open Government Licence v1.0. Map data © Crown Copyright and Database Right 2017. Ordnance Survey (Digimap Licence) supplied by the Ordnance Survey/EDINA service.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Engineering and Physical Sciences Research Council (EPSRC) funded 'Research Councils UK (RCUK) Centre for Energy Epidemiology' under EP/K011839/1.

ORCID

Stephen Evans http://orcid.org/0000-0002-6692-907X
Rob Liddiard http://orcid.org/0000-0002-8149-9573

References

BEIS. (2013, July 27). National energy efficiency data-framework. Retrieved from https://www.gov.uk/government/collections/national-energy-efficiency-data-need-framework

BEIS. (2016). Building energy efficiency survey (BEES). Retrieved from https://www.gov.uk/government/publications/building-energy-efficiency-survey-bees

Brown, F. E., Rickaby, P. A., Bruhns, H. R., & Steadman, P. (2000). Surveys of nondomestic buildings in four English towns. *Environment and Planning B: Planning and Design*, *27*(1), 11–24.

Bruhns, H. (2008, April 10–11). *Identifying determinants of energy use in the UK nondomestic stock*. Paper presented at the improving energy efficiency in commercial building conference (IEECB'08), Frankfurt, Germany.

Bruhns, H., Steadman, P., & Marjanovic, L. (2006). *A preliminary model of non-domestic energy use for England and Wales*. Paper presented at the COBRA 2006: The construction and building research conference of the Royal Institution of Chartered Surveyors, University College London. http://www.ucl.ac.uk/carb/pubdocs/CP-UCL-05-COBRA06-NonDom-Model-vf-07sep06-HRB-etal.pdf

Commercial Buildings Energy Consumption Survey (CBECS). (2007). Commercial buildings energy consumption survey (CBECS): Buildings questionnaire. Section B. Retrieved from https://www.eia.gov/survey/form/eia_871/2007/2007 20CBECS20EIA-871A20Buildings20Questionnaire.pdf

Department of Energy (DoE). (2016). Assigning use types for mixed-use buildings. Retrieved from https://help.building energyscore.com/support/solutions/articles/8000026035-assigning-use-types-for-mixed-use-buildings

Environment Agency. (2017). LIDAR DSM data sources (time stamp tiles and data selection tool). Retrieved from https://data.gov.uk/dataset/lidar-dsm-time-stamped-tiles http://environment.data.gov.uk/ds/survey/#/survey

EUROSTAT. (2013, October 18). EUROSTAT statistics explained glossary: Building. Retrieved from http://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Building

Evans, S., Liddiard, R., & Steadman, P. (2014). *A 3D geometrical model of the non-domestic building stock of England and Wales*. Paper presented at the BSO 2014 building simulation and optimisation, London, UK.

Evans, S., Liddiard, R., & Steadman, P. (2016). 3DStock: a new kind of three-dimensional model of the building stock of England and Wales, for use in energy analysis. *Environment and Planning B: Planning and Design*. doi:10.1177/0265813516652898

Field, J. (2008). *Energy benchmarks TM46*. London: Chartered Institution of Building Services Engineers.

Gao, X., Malkawi, A. M., & Yi, Y. K. (2013). *A new method for predicting mixed-use building energy: The use of simulation to develop statistical models*. Paper presented at the 13th conference of international building performance simulation association, Chambéry, France.

Hamilton, I. G., Summerfield, A. J., Lowe, R., Ruyssevelt, P., Elwell, C. A., & Oreszczyn, T. (2013). Energy epidemiology: A new approach to end-use energy demand research. *Building Research & Information*, *41*(4), 482–497. doi:10.1080/09613218.2013.798142

Hartmann, A. (2017, September 20). [Personal communication regarding activity classifications].

Hartmann, A., Meinel, G., Hecht, R., & Behnisch, M. (2016). A workflow for automatic quantification of structure and dynamic of the German building stock using official spatial data. *ISPRS International Journal of Geo-Information*, *5*(8), 142. doi:10.3390/ijgi5080142

Hecht, R., Meinel, G., & Buchroithner, M. (2015). Automatic identification of building types based on topographic databases – a comparison of different data sources. *International Journal of Cartography*, *1*(1), 18–31. doi:10.1080/23729333.2015.1055644

Her Majesty's Land Registry (HMLR). (2017). Land registry INSPIRE download service metadata. Retrieved from https://data.gov.uk/dataset/land-registry-inspire-download-service-metadata

Jones, P. J., Lannon, S., & Williams, J. (2001). *Modelling building energy use at urban scale*. Paper presented at the seventh international IBPSA conference, Rio de Janeiro, Brazil. Retrieved from http://www.ibpsa.org/\proceedings\BS2001\BS01_0175_180.pdf

Kinney, S., & Piette, M. A. (2002, May). *Development of a California commercial building benchmarking database*. Paper presented at the summer study in energy efficiency in buildings.

Kunze, C., & Hecht, R. (2015). Semantic enrichment of building data with volunteered geographic information to improve mappings of dwelling units and population. *Computers, Environment and Urban Systems*, *53*, 4–18. doi:10.1016/j.compenvurbsys.2015.04.002

Mayor of London. (2013). *London's zero carbon energy resource: Secondary heat. Summary report*. Retrieved from https://www.london.gov.uk/WHAT-WE-DO/environment/environment-publications/secondary-heat-study-londons-zero-carbon-energy

Meinel, G., Hecht, R., & Herold, H. (2009). Analyzing building stock using topographic maps and GIS. *Building Research &*

Information, *37*(5–6), 468–482. doi:10.1080/09613210903159833

Nageler, P., Zahrer, G., Heimrath, R., Mach, T., Mauthner, F., Leusbrock, I., … Hochenauer, C. (2017). Novel validated method for GIS based automated dynamic urban building energy simulations. *Energy*, *139*, 142–154. doi:10.1016/j.energy.2017.07.151

Ordnance Survey (OS). (2017a). Ordnance Survey AddressBase Premium. Retrieved from https://www.ordnancesurvey.co.uk/business-and-government/products/addressbase-premium.html

Ordnance Survey (OS). (2017b). Ordnance Survey Mastermap Products. Retrieved from https://www.ordnancesurvey.co.uk/business-and-government/products/mastermap-products.html

Reinhart, C. F., & Cerezo Davila, C. (2016). Urban building energy modeling – a review of a nascent field. *Building and Environment*, *97*, 196–202. doi:10.1016/j.buildenv.2015.12.001

Smith, D. A., & Crooks, A. T. (2010). *From buildings to cities: Techniques for the multi-scale analysis of urban form and function*. London: Centre for Advanced Spatial Analysis, University College London.

Taylor, S., Fan, D., & Rylatt, M. (2014). Enabling urban-scale energy modelling: A new spatial approach. *Building Research & Information*, *42*(1), 4–16.

Theodoridou, I., Papadopoulos, A. M., & Hegger, M. (2011). A typological classification of the Greek residential building stock. *Energy and Buildings*, *43*(10), 2779–2787. doi:10.1016/j.enbuild.2011.06.036

Valuation Office Agency (VOA). (2014). Property type classification lookup table. Retrieved from https://www.gov.uk/government/statistics/central-local-rating-lists-non-domestic-rating-in-england-wales

Valuation Office Agency (VOA). (n.d.) Business rates. Retrieved from https://www.gov.uk/topic/local-government/business-rates

Yamaguchi, Y., Shimoda, Y., & Mizuno, M. (2007). Proposal of a modeling approach considering urban form for evaluation of city level energy management. *Energy and Buildings*, *39*(5), 580–592.