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Room-scale profiles of space use and electricity consumption in non-domestic buildings

Rob Liddiard*

UCL Energy Institute, University College London, Central House, 14 Upper Woburn Place, London WC1H 0NN, UK
E-mail: r.liddiard@ucl.ac.uk

Understanding activities within premises can contribute to a fuller understanding of energy use within buildings and the building stock. Analysis of detailed surveys of over 300 non-domestic premises has produced empirical room-scale space-use profiles for 16 premises types. Electricity consumption and internal gains resulting from the operation of electrical appliances have been characterized for 295 combinations of internal space use and premises activity type. For each combination, the outputs include the energy-use intensity (kWh/m^2/year) profiles for: overall appliance consumption; 14 end uses of appliances (*e.g.* lighting, catering, computing); and 18 groups of appliance activity descriptions (*e.g.* sales, office work, process). These profiles of characteristics were created for application in an urban-scale energy-use model, based upon premises floor space recorded in property taxation data, without the need for detailed energy surveys of premises. Appliance electricity consumption and internal gains are revealed at a finer spatial resolution than previous methods, indicating the diversity of energy-use characteristics in greater detail than for entire homogenized premises or premises types. This method may be used for evaluating the current electricity consumption and consequent carbon emissions from the non-domestic building stock (or parts thereof) and for estimating the effects of potential interventions.

Keywords: building stock, commercial premises, electricity, energy modelling, energy use, non-domestic, space use

Introduction

The rate of new build in the non-domestic building stock of the UK is in the region of 1–2% per year (Ravetz, 2008). In 2008, the UK government committed to reducing total UK carbon emissions by 80%, from a 1990 baseline, by 2050 (HM Government, 2008). The operation of the non-domestic building stock accounts for approximately 20% of UK carbon emissions (UK Green Building Council (UK-GBC), 2011). In view of the slow rate of stock replacement, it becomes necessary to reduce the emissions resulting from the operation of the existing stock and not rely on new buildings to produce all the required emissions reductions. To enable effective interventions, a good understanding of the existing stock and its energy-use characteristics is required.

At the urban scale, some annual energy use data for the non-domestic sector are available from the Department of Energy and Climate Change (DECC) (2010a, 2010b), but these data are for overall use and at a granularity no finer than local government authority level, when all non-domestic use is included. In view of this, models can provide a means to estimate the energy use attributable to the operation of buildings and its end uses within those buildings. Previous non-domestic stock energy models such as the UK Non-Domestic Energy and Emissions Model (NDEEM) (Pout, 2000), the Energy and Environmental Prediction Model (EEP) (Jones, Williams, and Lannon, 2000), and the Carbon Reduction in Buildings (CaRB) Non-domestic Stock Model (Bruhns, Steadman, and Marjanovic, 2006) utilize energy data based on samples of whole premises, which are then applied at a local level (as in EEP) or nationally (as in CaRB and NDEEM). The EEP model, to some extent, also operates at a building level rather than premises, as it requires some surveying of the buildings in the area to be modelled. The other models rely on major data inputs – primarily areas and activity types – based on premises, not buildings. A more recent probabilistic model by Choudhary (2012) has been used to calculate the total energy use of the non-domestic buildings in each borough of London, UK. However, this model in part uses energy data that are not based upon actual use by buildings/premises. Its method also does not attempt to break down energy according to its end use.

Howard *et al.* (2012) describe a model of energy use at the property tax lot scale, for New York City in the United States. The model uses non-domestic energy use intensities (EUI) derived from the Commercial Building Energy Consumption Survey (CBECS). Four end uses are modelled – space heating, space cooling, water heating and base electric – with the modelled outputs validated against total annual energy use data provided by the New York City Mayor's Office of Long-Term Planning and Sustainability, at the ZIP code scale. The outputs are intended to inform decisions on local energy policy and design. However, as the base electricity end use category contains virtually all electricity consumption, the role of appliances and their spatial distribution is not addressed directly.

In terms of the level of understanding of equipment in non-domestic settings, Roberson *et al.* (2004) carried out detailed inventories of appliances in offices. Similar to the surveys used in this work, consumption was estimated in a bottom-up fashion, based on individual pieces of equipment. However, the breakdown of space use was not as detailed as that in the Sheffield Hallam University (SHU) data analysed for this current work. Also, Roberson *et al.*'s (2004, appendix A) work dealt with offices only, albeit a cross-section of office types, plus others such as 'University classroom building' and 'Outpatient clinic'.

Unlike the domestic sector, the non-domestic sector is extremely heterogeneous in its activities. Complexity increases when the diversity of built forms and fabrics is multiplied into the mixture. Furthermore, non-domestic activities within most building types evolve somewhat faster than the buildings that contain them (although some of the activity and associated energy use may take place outside of buildings). Examples of this may be seen in offices, where the population of computers has increased over the past 20 years, whilst the building containing the activity is far less likely to have undergone any significant change to its fundamental characteristics, such as shape, total floor area, fabric, glazing ratio and so forth. Service systems such as heating and cooling equipment may have been updated, but even here the rate of change may be over decades (Building Research Establishment (BRE) and The Royal Institution of Chartered Surveyors (RICS), 1992). In essence, activities and buildings evolve, but the rates of evolution may differ for both building characteristics (*e.g.* levels of thermal insulation) and activity characteristics (*e.g.* equipment types and hours of usage).

When a change of activity occurs, there is likely to be a noticeable change in the energy-using equipment in the space affected. For example, a change of use from retail to wine bar would likely result in the removal of strip lighting and the installation of more decorative or mood lighting, but the number of hours of operation might actually be the same. Such changes to/of activity-related appliances are likely to affect the operation of the heating and/or cooling equipment used to moderate the environment of the space (Chvatal & Corvacho, 2009; Jenkins, 2009). In some cases, the overall activity might not change, but the proportional use of space within the premises may alter, which in turn will have consequences for the spatial distribution of energy loads within the overall premises/building. Therefore, understanding activities and the possibilities for changes of activity– and hence, equipment – within premises can contribute to a fuller understanding of how energy is used in premises/buildings and thus the building stock.

Objective

The objective of this research is to facilitate improved estimation of electricity consumption in the non-domestic building stock using a method to infer the electricity consumption of appliances, and resultant incidental heat gains, for the internal space uses of premises, as identified in UK property taxation data. To enable this, it is necessary to establish reference values for consumption (kWh/m^2/year) that can be applied to the property taxation floor area data made available by the Valuation Office Agency (VOA). An urban-scale model, using such electricity consumption data and VOA data, is described by Taylor & Rylatt (2012).

The VOA collects information about domestic and non-domestic premises in England and Wales, which is used to place a taxable value upon the premises. In the case of the non-domestic sector, Business Rates property taxation is then levied on the value of the premises by the government. The VOA collects data solely for the purpose of taxation, so some information that would be useful for energy modelling is not collected. Even where such information may be recorded, it is not necessarily publicly available. However, the principal data available for energy modelling are still extremely valuable, covering approximately 1.8 million premises. The level of detail varies according to the major use classes, or Bulk Classes: Factories; Warehouses; Shops; and Offices. For each premises in these classes there are records for activities, at three levels: Special Category (SCAT) codes; Primary Description (PD); and Line Entry Description. Essentially, each is a subdivision of the previous, with the Line Entry Description being the use of space within premises. For example the hierarchy might be:

- SCAT: Factory/Warehouse/Workshop [whole premises]
- Primary Description: Factory [whole premises]
- Line Entry Description: Kitchen [subdivision of premises]

For the above, there would be records of floor area for the whole premises and for most of the Line Entry Descriptions. For activity types outside the Bulk Classes, such as hotels, schools, hospitals, public houses and petrol stations, there are few or no area records. Agricultural premises and places of worship and the Crown Estate are not taxed and do not appear in the VOA data.

The information currently available from the VOA does not include records of when premises were constructed, a factor that can affect the technologies used in their construction and, to some extent, in their operation. Figure 1 shows the spread of ages of the stock's floor space, in England and Wales, indicating that as a large proportion (64%) of the stock is more than 30 years old, the use of current design guidance values is likely to present an unrealistic view of the stock's characteristics. Also, in many cases it is not known whether premises constitute a single, whole building. Dimensional details and form are also unknown. These data-access limitations preclude the use of detailed energy simulation models that are commonly used for calculating the theoretical performance of new buildings. In view of the data access limitations indicated above, the use of data acceptable for detailed design analyses, or simulation, have been eschewed in favour of empirical data of the actual electricity consumption of sample non-domestic premises in use. These empirical data are of known provenance and collected using the same basic survey protocols and technique, across a number of premises and premises activity types. To update the profile of some appliances (principally lamp types and computers), some additional sources of information were used, together with limited assumptions, to determine likely populations, power ratings and usage.

Sheffield Hallam University (SHU) data

Between 1991 and 2000, the Resources Research Unit of SHU undertook detailed internal energy surveys of more than 700 non-domestic premises. Descriptions of the survey procedures, data processing and analysis techniques carried out for the original SHU research can be found in Mortimer, Ashley, Elsayed, Kelly, and Rix (1999), Mortimer, Ashley, and Rix (2000), Mortimer, Elsayed, and Grant (2000), Penman (2000), and Elsayed, Grant, and Mortimer (2002). Crucial to the method was the reconciliation of bottom-up calculations, based on equipment, with the metered energy use of each premises. The principal outputs of the original SHU research were profiles of energy use within a number of premises activity groups. The outputs included overall EUI (GJ/m^2/year) of both fossil fuels and electricity, for each premises type, together with the end uses of the energy. Analysis of room-scale energy use was not addressed.

Methods

This section describes how the SHU data have been re-analyzed to provide profiles of electricity consumption by appliances, in combinations of premises activity (Primary Description (PD)) and Room Use. These electrical appliances exclude equipment used for heating and cooling the room, so the profiles of use and consumption may also be seen as providing information on internal gains from electrical appliances. Within the data, some 'rooms' are not rooms in the strictest sense, *e.g.* petrol filling station canopies, but the term 'room use' is still used because activity types are addressed separately below.

The method used in this work is applied to the SHU raw datasets in several stages. At the end of the process there is information that can be used to infer electricity consumption in activity areas within non-domestic premises. The overall process is shown in Figure 2. Each procedure is explained in greater detail by Liddiard (2012). In Figure 2, the novel outputs gleaned from the data, for stock modelling, are shown in the shaded parallelograms.

Data preparation

Cleaning and filtering of the SHU data were required to remove rooms, or in some cases entire premises, to produce data free of obvious errors but adequate to provide a usable sample. The original SHU research outputs were for entire premises, not for individual rooms within those premises (Mortimer, Elsayed *et al.* 2000). In this work, the need for adequate room-scale data forced a major reduction in the sample sizes of PD types. For example, the CS Shops sample reduced from 144 to 126; whilst the IF Factories sample reduced from seven to five. For letter codes, see Table 1. After all filtering, the smallest sample size per PD was three (for CG1, CS5 and CS7). The usable samples of premises types are, in

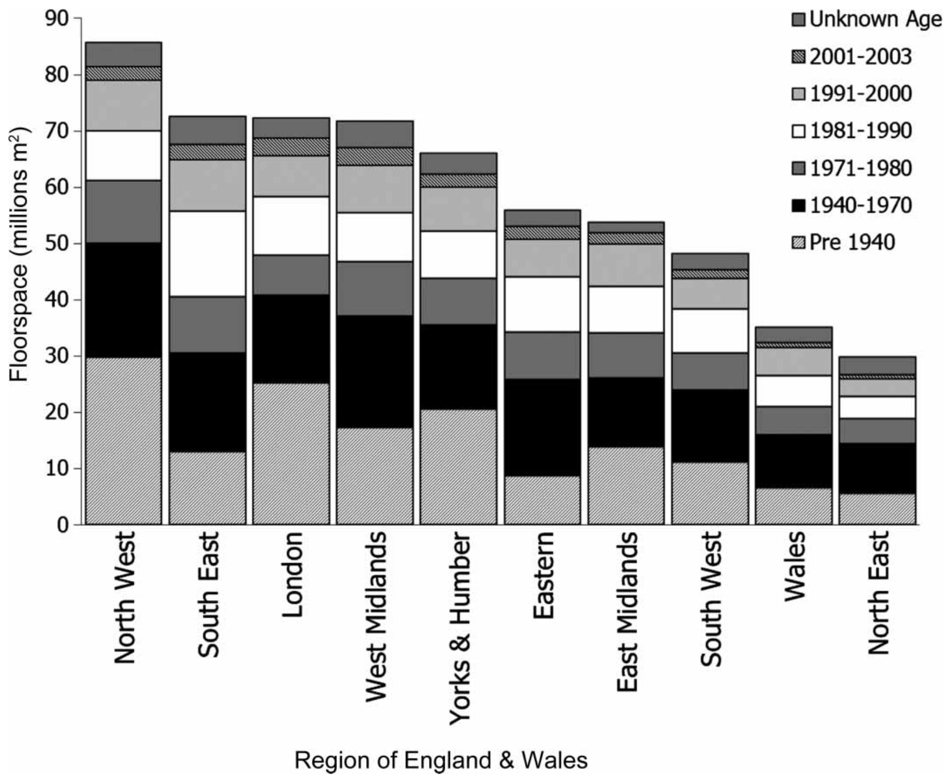

Figure 1 Date of construction of non-domestic premises floor space in England and Wales by region. Source: Department for Communities and Local Government (DCLG) (2005)

statistical terms, very small; however, as the analyses are carried out at the room scale, the sample sizes for combinations of Room Use and PD are less affected. Also, as the SHU data are the only known accessible dataset with the required breadth and level of detail, preservation of the samples, within reason, was paramount. After familiarization with the datasets, the cleaning and filtering processes included:

- minimal reclassification of Room Use and/or PD
- appraisal of the completeness of the recording of rooms within premises
- identification and removal of premises with unreasonable area use profiles
- identification and removal of rooms and/or whole premises with unreasonable EUI

The calculated electricity consumption of each piece, or group, of equipment was summed for each room and divided by the room's floor area to give a value of appliance EUI (kWh/m^2/year). For each PD and Room Use combination, the room record with the highest EUI was flagged and examined in detail. Where this room was found to contain a feasible inventory of appliances and patterns of use, that entire PD and Room Use combination was deemed to be reasonable. Also, a second flag was set at 5 SDs (standard deviations) above the mean, because early in the work it was realized that the more usual 3 SDs criterion excluded many records that were, upon detailed inspection, reasonable. Where flags occurred, the floor area of the room was examined as this was most frequently found to be too small for the recorded equipment. Sometimes, the floor area of a room might be accurate, but the equipment – usually the quantity of a specific item – was incorrect. As it was not generally possible to determine which of these two situations constituted the error, the room was excluded. In other cases, the room might be reallocated to another room use, reflecting the equipment it contained.

An example of an unreasonable inventory of equipment would be an office room of 12.7 m^2 (in Office premises), containing eighty 5-foot fluorescent tube lamps. Where an EUI value was in excess of the 5 SD threshold, but the appliance inventory was found to be reasonable, that record was retained. This process did not exclude many rooms. For example, in office rooms in Office premises, only the room described above was excluded, having an EUI of 1500 kWh/m^2/year. Other rooms of this type exceeding the 5 SD filter were found to be reasonable,

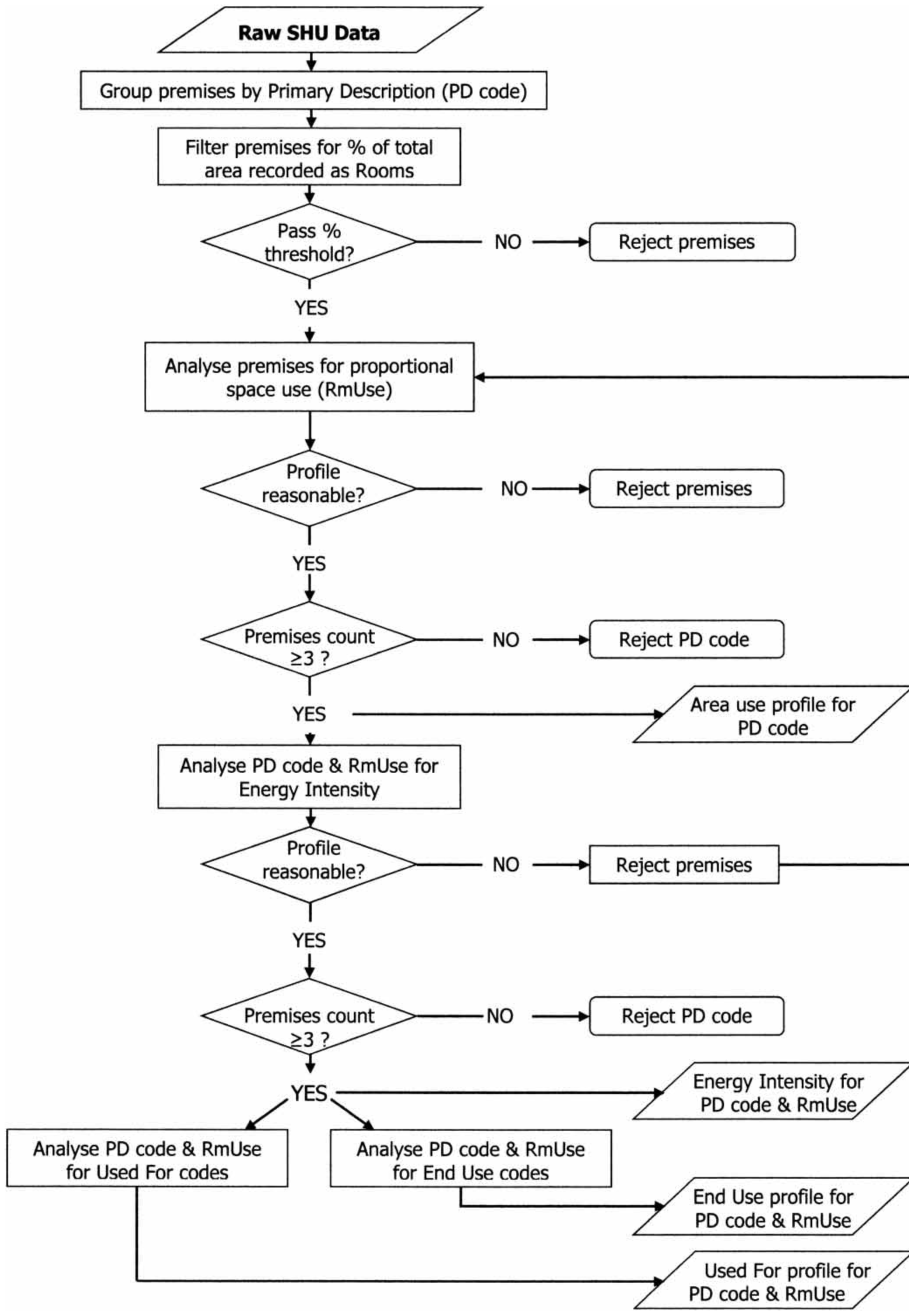

Figure 2 Flowchart of the overall method applied to the Sheffield Hallam University (SHU) dataset

with the highest EUI (930 kWh/m^2/year) being for a high density call centre operated 24 h 365 days per year.

In some cases either the room area, or records of equipment, were missing and these rooms were excluded from subsequent analyses. In total 295 combinations of PD and Room Use were analysed. Additionally, profiles for 57 generic Room Uses – from the whole sample of a Room Use, regardless of premises activity type – were also created. Table 1 shows the make-up of the samples after cleaning and filtering.

Despite the standardized technique adopted for the original surveys and the basic data cleaning methods applied for the work described here, with 28 171 records of appliances in 7278 rooms in the cleaned data, there are still likely to be errors. Chapman (1991) described errors pertaining to surveys as

Table 1 Composition of Sheffield Hallam University (SHU) Primary Description (PD) activity class samples at completion of the filtering/analysis processes

PD code	Primary description	Count of premises after filtering	Total area of the PD sample (m²)	Count of rooms
CG	Petrol filling station	9	4217	87
CG1	Vehicle repair workshop	3	2544	39
CH	Hotel	9	25 442	534
CL	Public house	4	1244	53
CO	Office	66	85 218	1954
CR	Restaurant	4	1094	51
CS	Shop	126	60 681	1264
CS1	Bank	16	7861	369
CS5	Launderette	3	381	26
CS6	Post office	7	4087	115
CS7	Showroom	3	2583	43
CW	Warehouse	10	14 198	127
EL	School	31	80 818	2165
IF	Factory	5	12 446	120
IF3	Workshop	6	1483	61
LC1	Clubhouse	6	7948	270
Total		308	312 245	7278

falling into five types: observational, conceptual/mapping, convention, measurement and keyboard. Without access to the physical reality, recorded in the surveys – *i.e.* the rooms and their contents, at the specific moment of the surveys – it is not possible to quantify such errors, or their effect, properly. Quantifying this type of uncertainty is not generally feasible or attempted for surveys of this nature, once the observations have been converted to data.

Table 2 Density of computers in office rooms (based on Sheffield Hallam University (SHU) data), before and after updating of computer population

	Area per computer before update			Area per computer after update
Premises type	Office premises	Non-office premises	All	All
Mean	13.49	12.92	13.25	11.13
Standard deviation	11.56	10.44	11.10	4.43
Minimum	1.21	1.53	1.21	1.21
Quartile 1	7.58	6.89	7.36	7.92
Median	11.00	10.33	10.85	11.18
Quartile 3	15.69	15.62	15.70	13.78
Maximum	136.5	100.24	136.5	24.17

Updating of appliances

Due to the age of the data, limited updating of appliance profiles was performed. This was restricted to the population of computers in office rooms, projectors and computers in classrooms, and the replacement of some lamp types with more up-to-date types in all premises. The objective was to attempt to reflect the current population and distribution of these appliances in the building stock.

For computers, the default SHU power rating of 130 W, for a computer and monitor combination, was updated to 105 W based on Department for Environment, Food and Rural Affairs (DEFRA) data (DEFRA, 2010a, 2010b), with the population assumed to be one per 13.25 m^2, with a minimum of one per room. This ratio of computers to office room area was derived from analysis of all office rooms containing computers in the SHU dataset, shown in Table 2.

Only default power ratings were altered and higher densities of computers were left unchanged. Use profiles were either from each room's data, or calculated from mean usage within the PD code and Room Use combination. Additionally, projector and computer populations and power ratings were updated in schools, using additional sources (Futuresource, 2010; Neufert, 1980; Prior & Hall, 2004).

Lighting updates were restricted to general illumination and the replacement of all T12 fluorescent tubes by T8 triphosphor (with appropriate adjustments for load factor). Also, based upon the rollout of legislation to remove these from the market, non-halogen 25–150 W incandescent lamps were replaced by approximately equivalent compact fluorescent lamps. Display lighting was not changed. Full details of all appliance updates can be found in Liddiard (2012).

Results

As the research outputs are for use in building stock energy modelling, not the benchmarking of individual premises, median values were deemed inappropriate for reflecting the probable spread of values within the diverse stock. All existing types of space use and electricity use characteristics should be expected in the stock; therefore, the use of medians would likely skew the results towards an underestimation of energy use, as for most room uses, the median of appliance EUI is lower than the mean. Also, as the sample premises did not all have the same combinations of room use, even within PDs it was deemed unsafe to use median values for either space use, or EUI. Further statistical outputs may be found in Liddiard (2012).

Space-use profiles

To generate the profile of space use in a given PD activity category, the areas of all rooms of each use type were summed and expressed as a percentage of the total floor area of all rooms in the PD category, thus generating an average percentage of total area used for a particular room activity, within the PD sample. Three categories of premises have been chosen to demonstrate space-use profiles in detail: Shops, Offices and Factories.

In Figures 3, 5 and 7 the total area of each Room Use is expressed as a percentage of the summed areas of the premises sample, showing average space use for each sample. Figures 4 and 6 expand the analyses, demonstrating that not all Room Uses appear in all premises of a given type. Each *y*-axis value is the percentage of floor area attributable to a Room Use within the premises in which it appears, which may be spread across one or more rooms, within given premises. The shaded boxes represent the middle two quartiles, whilst the lines above and below the shaded box represent the upper quartile and lower quartile, respectively. The solid dot is the median value and the small circle is the mean value for the sample of rooms. This mean is not the same as the percentages given in Figures 3, 5 and 7, as Figures 4 and 6 give the average percentage of floor area taken up by a Room Use in the premises where it appears only. Median values are included (and in subsequent similar charts) to demonstrate further the distribution of the data.

Within the cleaned SHU dataset, 126 shop premises are comprised of 27 Room Uses and 40% of Shop floor space is not used for purely sales activity, *e.g.* 17.2% of floor space is used for storage (Figure 3). The 'VARIOUS' category contains all remaining Room Uses that each represent less than 1% of the summed room areas of the sample. This applies throughout the paper. The difference in the means can be seen with rooms used for office work. The percentage of the total floor area of the Shops sample used for office work (Figure 3) is 3.4%. But for Shop premises where there are office work rooms, the mean is 10.3% of the area of those premises, as indicated in Figure 4. Where Room Uses appear in premises, their percentage of the premises' total area tends to be within a fairly restricted range and the number of different Room Uses is quite extensive. The space used for the core activity of sales has the greatest variability, presumably due to the existence/non-existence of other room uses in individual premises.

Figure 5 shows the total use of space within 65 Office premises.[1] As with the Shops sample, not all the Office premises are in fact used for the accepted core function of office work, with 38% of the total area used for non-office work. Figure 6 shows 31 Room Uses, but again the variability in the proportion of space used for a given Room Use is mostly quite small. In some room types, even those with large samples, the spread can be very limited, such as in meeting rooms and printing rooms. However, as with Shops, the greatest degree of variability is in the core activity space.

After filtering, the sample size of Factories is only five premises, but the variety of Room Uses is moderately

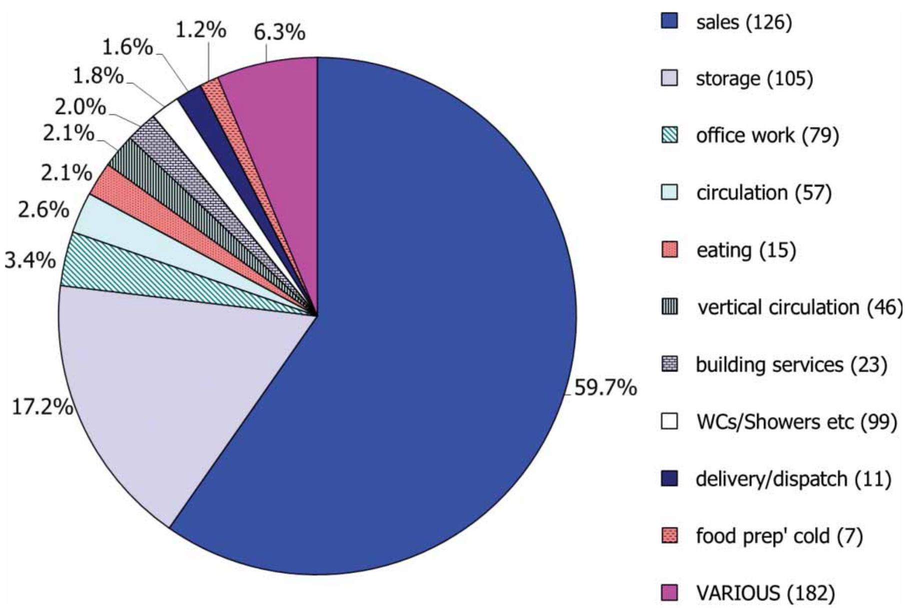

Figure 3 Total space use in shop premises, Primary Description code CS. Premises sample size is given in parentheses

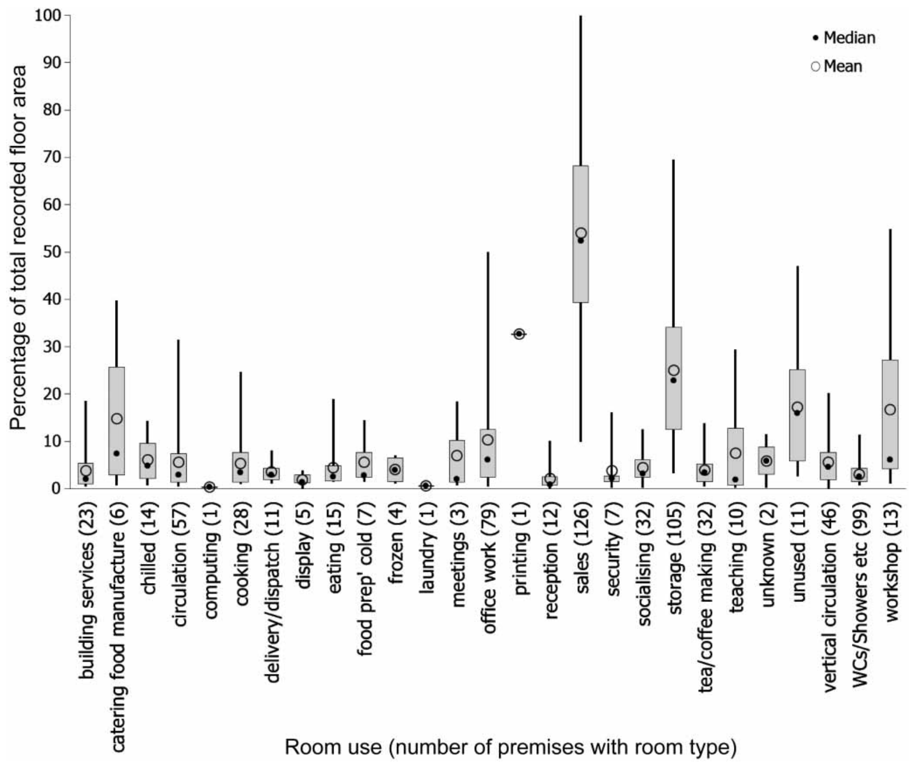

Figure 4 Distributions of space use in Shop premises. The *x*-axis includes count of premises containing the Room Use

large at 22 types, with the main uses shown in Figure 7. The spread of the proportion of each premises' area taken up by each Room Use is essentially small, most likely due to the limited number of data. The corresponding box chart gives little information and is omitted.

Energy use intensities (EUI) and end uses of electricity

Energy meters record when, and how much, energy is consumed by the equipment on the downstream side of the meter; but unless equipment is individually metered, it is difficult to know where energy is being used, or what is using it. As the SHU data

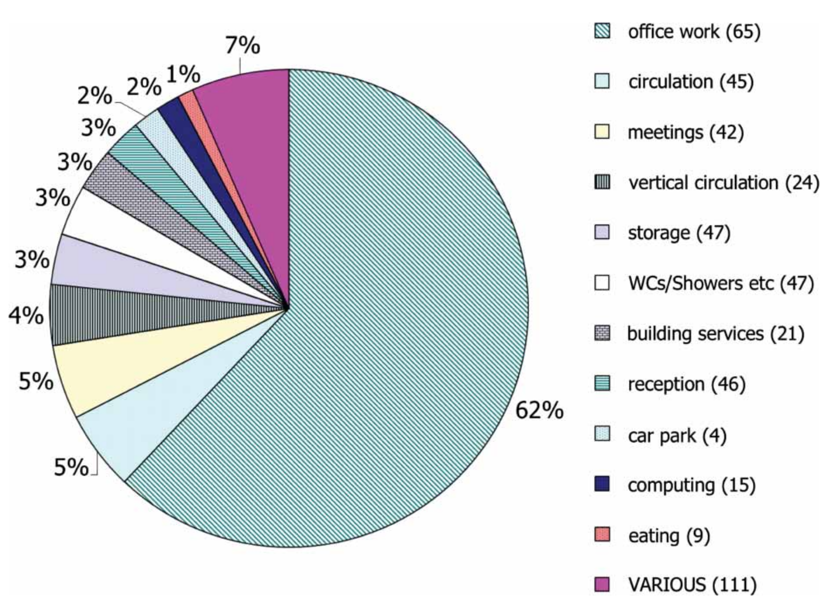

Figure 5 Total space use in Office premises. Premises sample size is given in parentheses

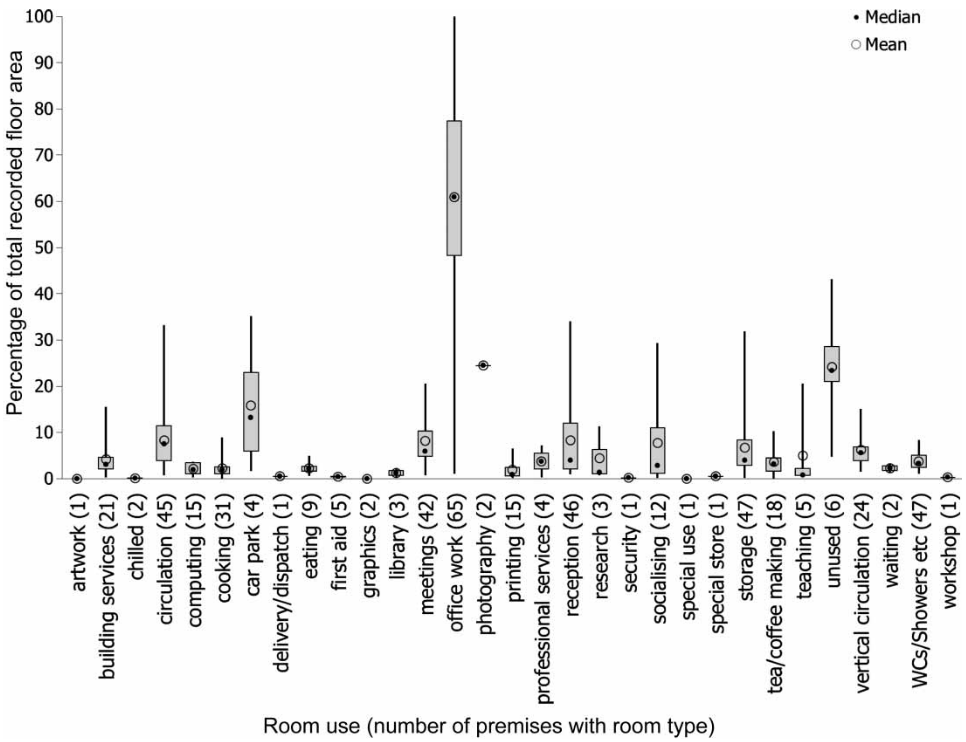

Figure 6 Distributions of space use in Office premises. The *x*-axis includes a count of premises containing the Room Use

include categories of end use for each appliance, disaggregation of electricity use by appliances in each room was performed for the following End Use categories: lighting; domestic hot water; process; heating, ventilation and air-conditioning (HVAC) controls; fans; telecommunications; small power; computers; computer accessories; catering; lifts (elevators); pumps; other; unknown.

For each Room Use, the total consumption per End Use was divided into the total area for that Room Use to provide an average (across the whole sample) of

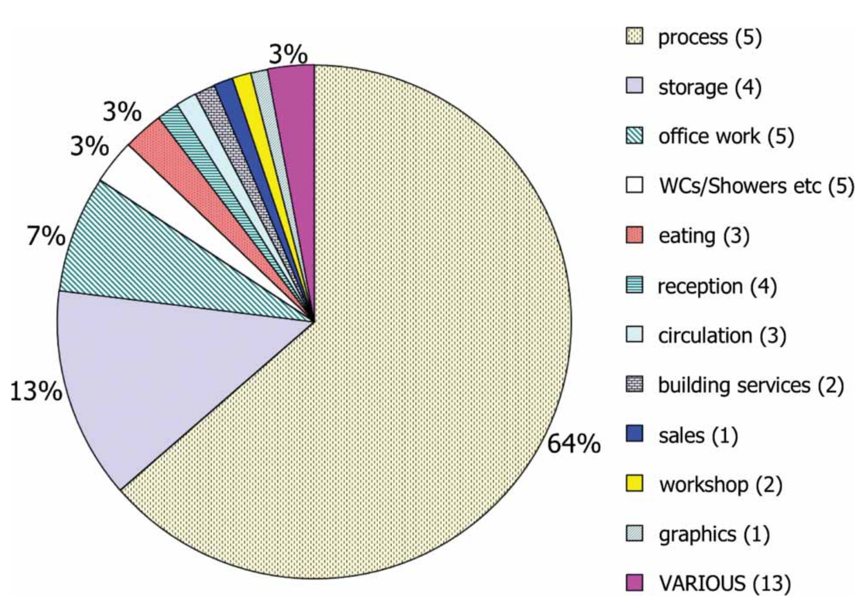

Figure 7 Total space use in Factory premises. Premises sample size is given in parentheses

energy use for each End Use. Figure 8 shows how the electricity consumption of appliances is divided between the End Uses in each PD sample. Lighting is the most noticeable consumer, with catering and process consumption being the other two large components.

Figures 9, 11 and 13 show how the electricity consumption of appliances, expressed as EUI (kWh/m^2/year), disaggregates across each of the Room Uses within the Shop, Office and Factory PD classes. These figures show the EUI within the whole PD sample, *i.e.* total electricity consumption per Room Use divided by total area of Room Use within the sample. Figures 10, 12 and 14 show the End Uses of electricity consumption.

In the Shops class (Figure 9), the highest EUI is for 'catering food manufacture' spaces, which in the sample are primarily bakery activities in retail premises. Of interest are the 'building services' rooms, where the End Use 'catering' accounts for a large proportion of consumption. This is due to the refrigeration equipment, linked to chilled/frozen storage equipment located in the 'sales' areas being located in plant rooms. This displaces the electricity consumption of this equipment, from the sales areas to the plant room where it belongs, and the heat gains might be vented using less energy. In terms of EUI, the Room Use 'sales' is ranked 13th, but due to its dominant area (Figure 3) it is the greatest consumer of appliance electricity.

Domestic hot water (DHW) appliances can have a significant effect on the electrical EUI of some rooms. If water heaters using fossil fuels had also been included in the analyses, these would have had additional effects on energy use and internal gains. In 'WCs/showers etc.' the hot water produced appears to be mostly for use in the same room. But there are instances where appliances are attributed to rooms (particularly 'storage') when the appliances and energy are likely to be used elsewhere (*e.g.* vacuum cleaners); so these high values should in reality be partially spread across other rooms. These effects have been ignored, as the overall floor areas of these room types are generally small in the property taxation data, to which the EUI are to be applied.

Figure 11 presents the EUI of Room Uses in the sample of Office premises. To improve clarity, Room Use 'chilled' is excluded as its EUI is extremely high (2125 kWh/m^2/year), but there are only two rooms in the 'chilled' category, both having small areas. One room is used for food storage, but the second is used 'for samples' storage, in the premises of a regulatory body and is thus not used for catering purposes; in essence this is a 'process' End Use. The 'chilled' Room Use is included in Figure 12.

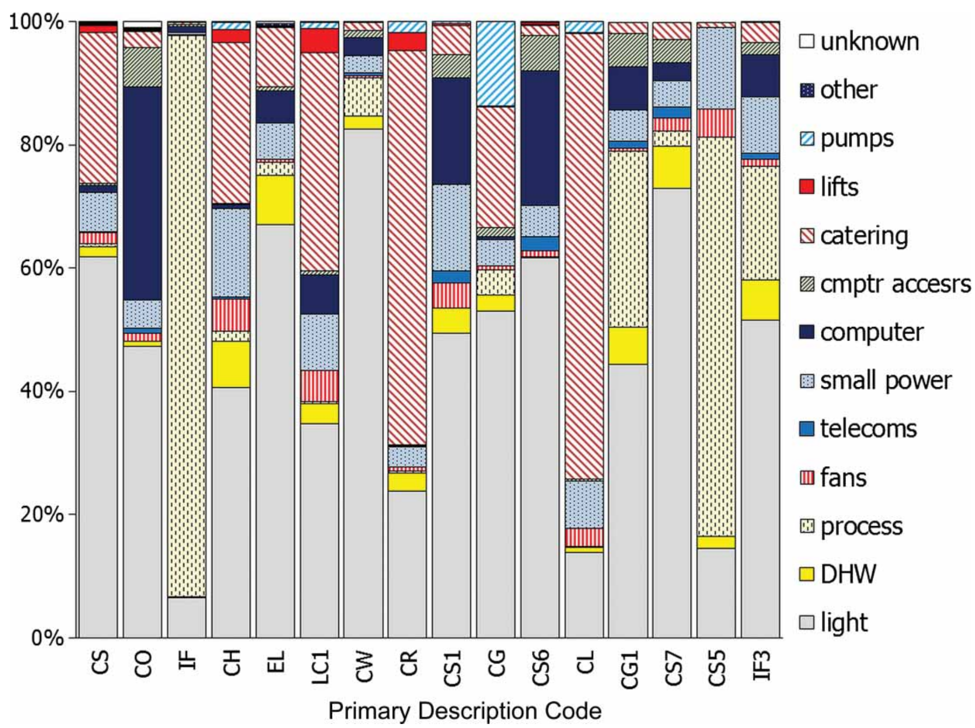

Figure 8 Percentages of total appliance electricity consumption per End Use, per Primary Description class.

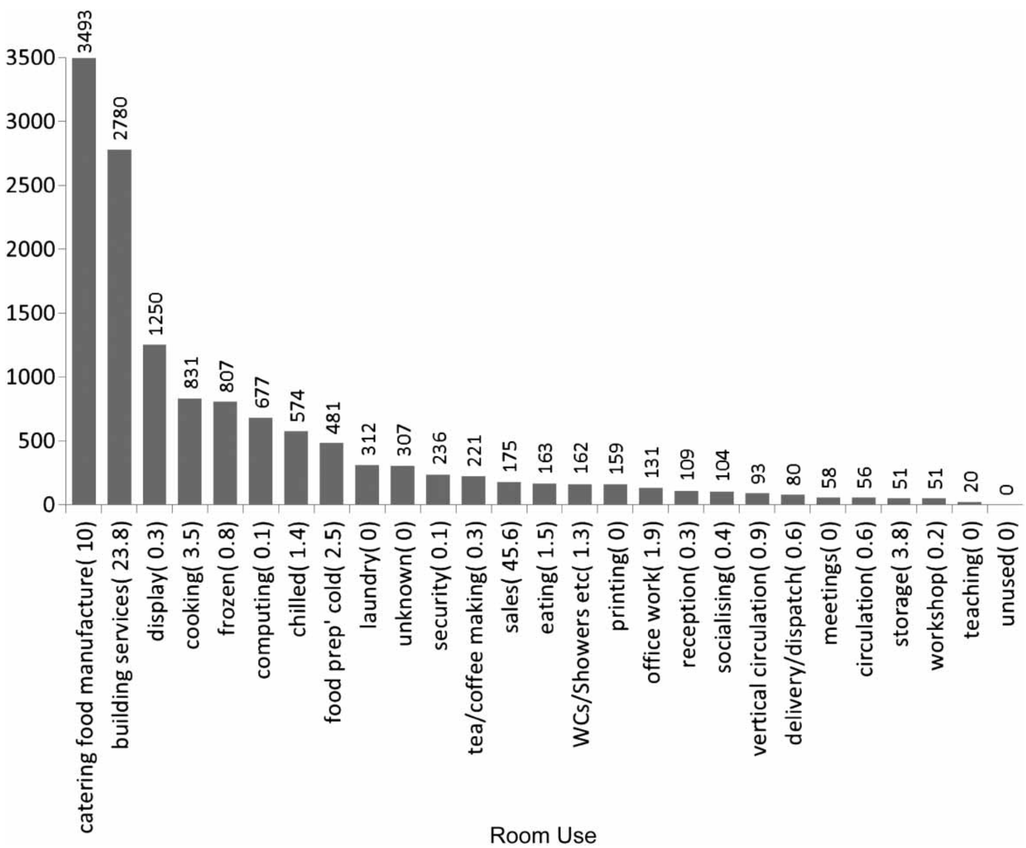

Figure 9 Appliance energy-use intensity (EUI) in Room Uses of Shops. *y*-axis units are kWh/m^2/year; the *x*-axis gives the percentage of a sample's total appliance electricity consumption occurring in the Room Use in parentheses

Electricity consumption in 'computer' rooms may not reflect current equipment and usage patterns, as servers were relatively scarce in the sample, only being found in 18 of 33 such rooms in Office premises. The sample ranges in size from 4 to 125 m^2, with a mean of 40 m^2 and in some cases rooms appear also to be used for office work activities. For the purposes of stock modelling, based upon VOA data, server rooms do not appear frequently, so any underestimation of electricity consumption is likely to have a relatively small effect at the city, or larger, scale.

The EUI of spaces in Factories is shown in Figure 13. Surprisingly, the process areas have only the third highest EUI. The 'printing' and 'research' rooms are higher, but constitute very minor portions of the premises in which they appear and the sample as a whole. In real terms, the process End Use in the process rooms dominates all other room uses, as shown in Figure 14, due to the predominance of process space.

What are appliances used for

In addition to the End Uses described above, the SHU datasets also include a 'Used For' code for each equipment record, describing the activity for which equipment is used. Due to the diversity of combinations of equipment and Used For codes, the codes have been aggregated into 17 'Used For' groups, to represent classes of activity: process; catering; sales; office work; learning; entertainment; specialist; illumination; refrigeration; telecoms; DHW; HVAC; transport; pumps; facilities; other; unknown.

The method of analysis follows that for disaggregation of consumption per End Use above. Figure 15 shows the profiles of consumption, per Used For group, for each PD sample. Here, as with the End Use profiles, the importance of consumption for illumination can be seen very easily, together with catering and, in some PD classes, process.

Analysis according to the Used For groups gives an enhanced view of patterns of consumption. This can be seen in the percentages used for 'catering' and 'refrigeration' in Restaurants (PD code CR). The consumption Used For 'catering' far exceeds that for 'refrigeration', highlighting the effect of one of the sample Restaurant premises having no gas-fuelled catering equipment, resulting in all food being

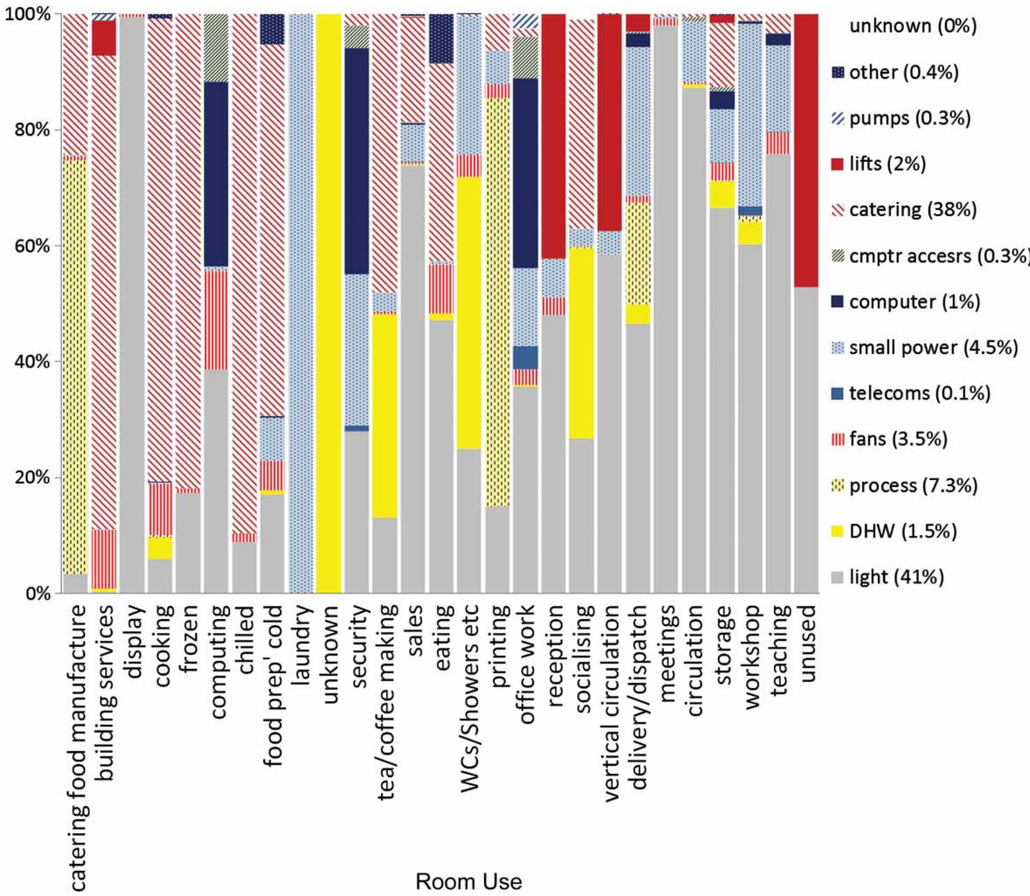

Figure 10 Percentage of electricity used per appliance End Use, per Room Use in Shops. Percentages of the whole sample's consumption, per End Use, are given in the key

cooked using electricity. In the Public House (CL) category, consumption by 'refrigeration' equipment (significant for the chilling of drinks) can be seen clearly in Figure 15, compared with Figure 8, showing End Uses. However, in Figure 15 the energy Used For 'refrigeration' seems slightly low in Public Houses, considering that chilled areas are commonplace.

The Shops profile of Used For groups is shown in Figure 16. In the building services Room Use most of the electricity consumption can be attributed to 'refrigeration', thus indicating that the End Use 'catering' (Figure 10) is mostly refrigeration and occurring in plant rooms. The high consumption levels for refrigeration, in building services rooms, is likely due to the influence of larger food stores, as smaller shops do not necessarily have plant rooms (Figure 4).

Figure 17 shows the profile for Used For groups in Office premises. In the End Uses Section 3.8, the chilled Room Use has the highest EUI, but the total consumption of the chilled Room Use is insignificant in terms of the whole sample's consumption and is contained within the Remainder category of the Various grouping of low consumption Room Uses. Similar to the sales areas in the Shops premises, the office work Room Use has a modest level of EUI, but still accounts for the bulk of total consumption, due to its total floor area: lighting and office work Used For groups dominate.

For Factory premises there are minimal differences between the analyses of End Uses (Figure 14) and Used For groups; consequently a chart for the latter is omitted. However, it should be noted that electricity consumed for industrial processes dominates overall electricity consumption and this ought to play an important role when evaluating the energy performance of premises, due to its effect on heat gains and thus the interaction between activity, building fabric and HVAC systems. For instance, where internal gains are high, it may be unwise to initiate a programme of fabric thermal insulation due to the consequent need to expel heat from the building. But it may also demonstrate how excessive heat from internal gains in process areas might be redirected to heat non-process areas. For reference, Figure 18 shows the Used For profile of consumption, per Room Use,

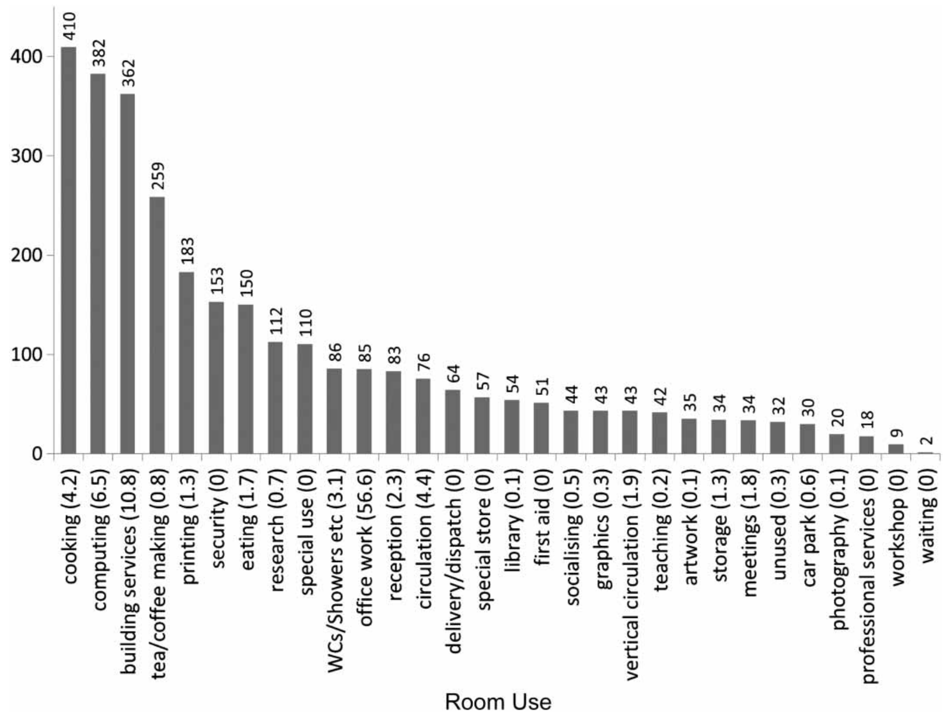

Figure 11 Appliance energy-use intensity (EUI) in Room Uses of Offices. *y*-axis units are kWh/m^2/year; the *x*-axis gives the percentage of a sample's total appliance electricity consumption occurring in the Room Use in parentheses. Room Use 'chilled' at 2125 kWh/m^2/year is excluded

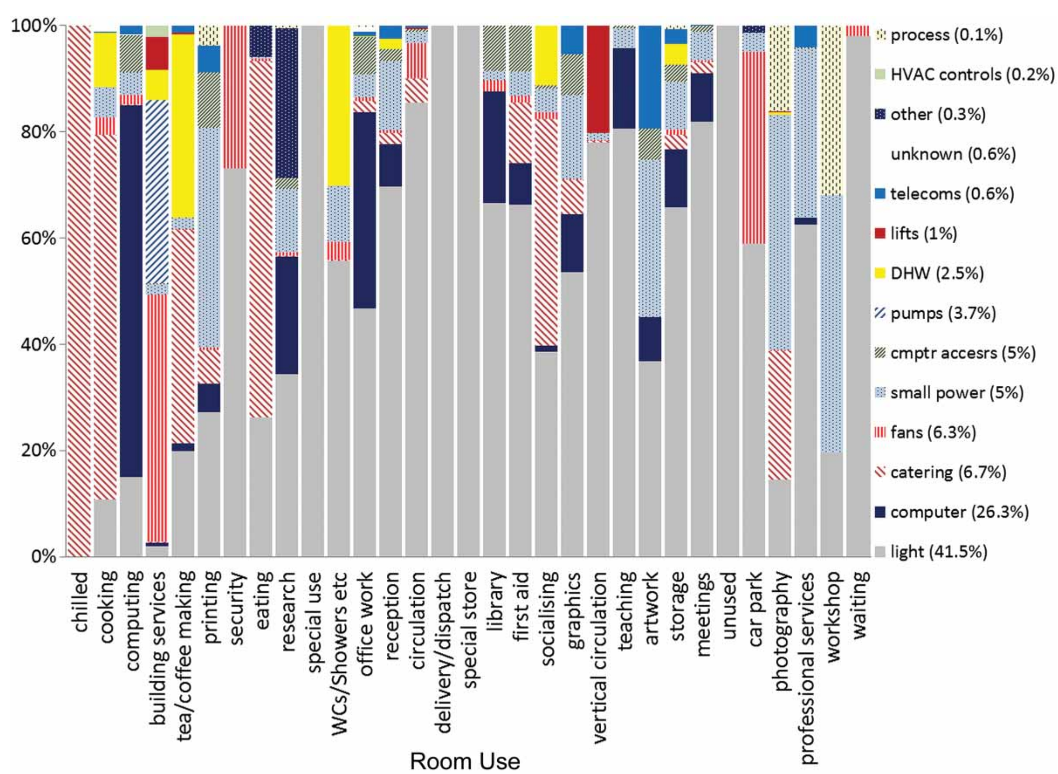

Figure 12 Percentage of electricity used per appliance End Use, per Room Use in Office premises. Percentages of the whole sample's consumption per End Use are given in the key

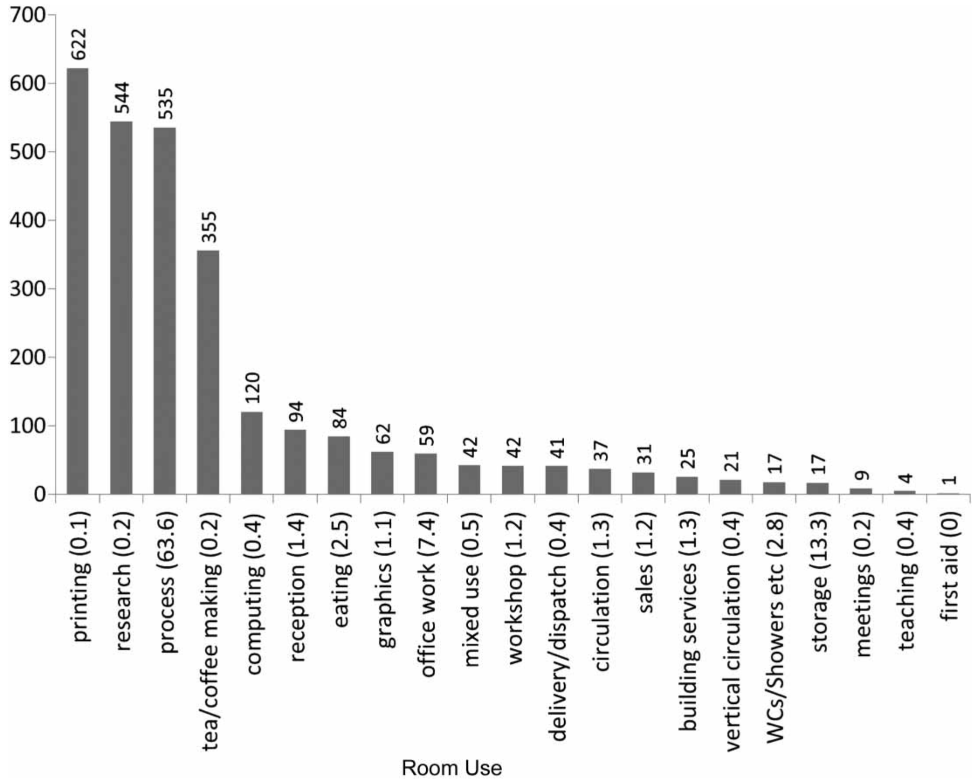

Figure 13 Appliance energy-use intensity (EUI) in Room Uses of Factories. *y*-axis units are kWh/m^2/year; the *x*-axis gives the percentage of a sample's total appliance electricity consumption occurring in the Room Use in parentheses

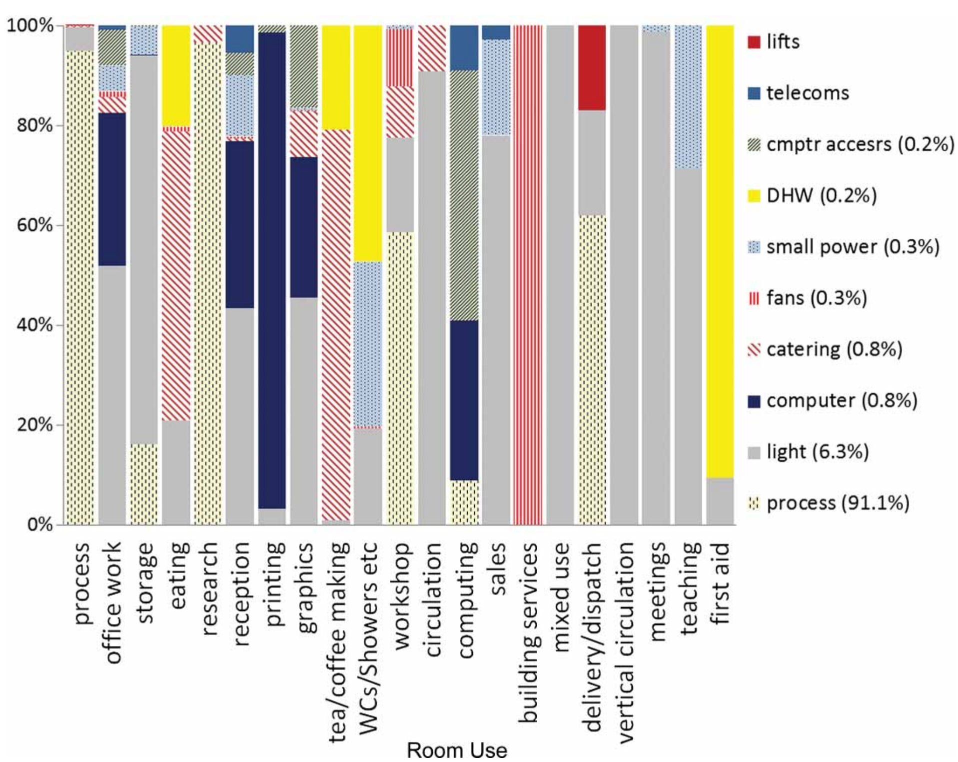

Figure 14 Percentage of electricity used per appliance End Use, per Room Use in Factories. Percentages of the whole sample's consumption per End Use are given in the key

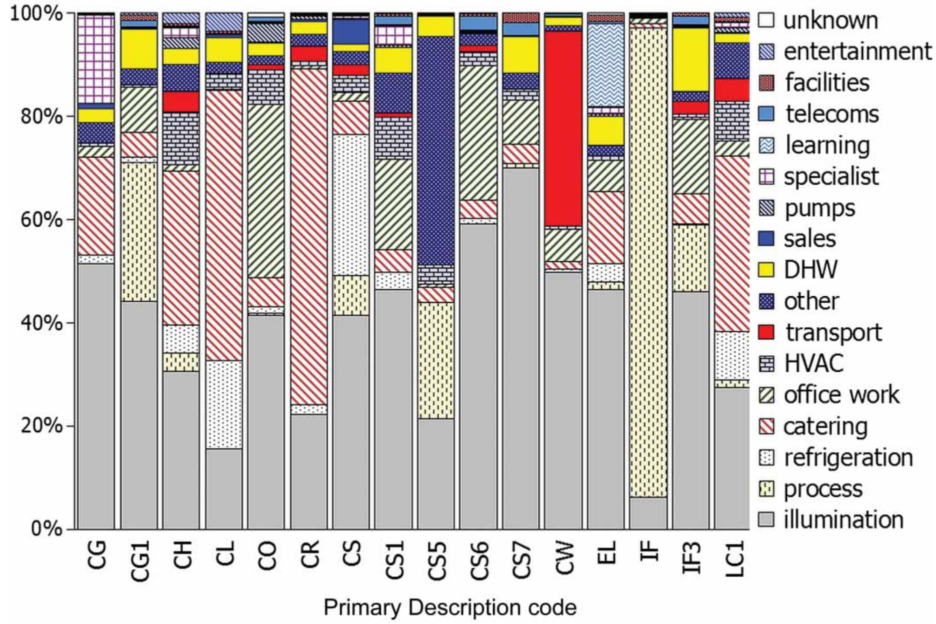

Figure 15 Breakdown of total appliance electricity consumption per Used For group, per Primary Description class

after process consumption has been removed. Here, illumination dominates due to the need to light large process areas.

Discussion

The sample sizes of premises types were, in most cases, reduced by the filtering processes applied to them. However, as this research was concerned with identifying patterns of electricity consumption for the activities performed in area and activity subdivisions (Rooms) of premises, the sample size of Rooms, per Room Use, is more important than the number of premises per activity type. In general, the number of Rooms per PD and Room Use combination was deemed usable for inferring appliance electricity consumption in stock modelling, in view of the restricted number of empirical data accessible to the research. More data, particularly for the poorly represented activity types, would be beneficial, but data collection should be targeted carefully, using a statistical analysis of the stock, to ensure a representative sample. The outputs are not intended for use in detailed simulations of individual buildings/premises; however, the spread of EUI for each Room Use in each premises activity type provides some indication of the probability of a given level of consumption (and consequential internal gains) resulting from activities in rooms.

As the data relate to non-heating and non-cooling appliances associated with the activities in rooms, it is possible that the analyses could be applied at a sub-yearly time scale, as weather adjustment is not required, though adjustments for hours of darkness would be required. However, no attempt has been made to obtain power densities (W/m^2) for the Rooms, as hours of occupation and equipment utilization were not considered, due to the outputs being intended for stock modelling, where occupation and utilization factors cannot be known reliably for the thousands of premises being modelled. Therefore, there is an intrinsic assumption that the samples of rooms and the appliances they contain are representative of the stock being modelled. This assumption is particularly relevant to the sample of Shop premises, due to the VOA not providing sufficient data to identify the detailed function of the CS Shop category, such that there is no distinction between a grocery store, a toy shop, or a clothes shop, for example. Therefore, there is an assumption that the composition of the SHU Shops sample is at least similar to the profile of shop types in the area to be modelled. However, there may be some minor strength added to the assumption, due to the identification of activity subspaces in the stock model and that each urban area is likely to have a similar profile of shop types.

The research shows that premises of the same overall activity do not all contain the same range of Room Uses. Some Room Uses, such as 'WCs', 'storage' and 'circulation', appear in almost all premises and may be seen as essential but non-core activity spaces. Core activities would be 'sales' in Shops, 'office work' in Office premises and so forth. The non-core activities have areas more limited in their percentage of the premises' total area, but the core activities are more varied in their proportion of the total space, as indicated in

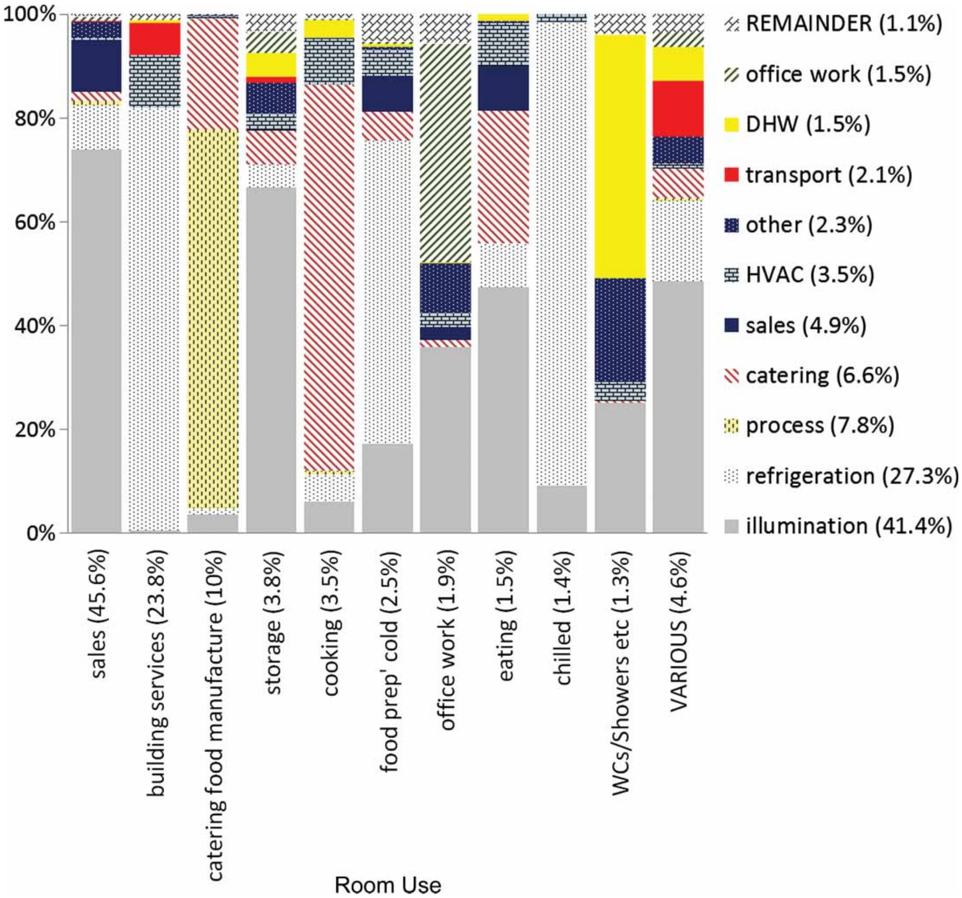

Figure 16 Percentage of electricity consumption per Used For group in major Room Uses in Shops. The percentage of a sample's consumption is shown on the *x*-axis. The key also gives the percentage of total Shop sample consumption, per Used For group

Figures 4 and 5. However, the average use of core and non-core space is similar across the three examples shown in Figures 3, 5 and 7, at approximately two-thirds core to one-third non-core. This may be coincidental, but might warrant further investigation for other premises types. The detailed pattern of space use (and non-use) can be coupled to the finding that the EUI of appliance electricity consumption is different across Room Uses, which may help explain the variation in consumption (after normalization for floor area) across premises within a given PD found in the real world. The modelling of building stock energy use usually ignores these variables and combinations of variables by homogenizing premises into overall activity types.

Figure 19 shows the spread of EUI values for all Room Uses, across all premises activity types. For clarity, the *y*-axis has been truncated at 3000 kWh/m^2/year. Figure 19 demonstrates the effect of outliers on mean values, but this is for all the premises in all the samples, so is not necessarily relevant when evaluating individual combinations of premises activity and Room Use. Of greater interest is the spread of intensity values for the different premises types, for each Room Use.

The EUI of 'office work' Rooms in each premises type is shown in Figure 20. This indicates that the spread is mostly quite limited even though activities may be assumed to occur in spaces with diverse physical characteristics, such as built form or fabric. This lends weight to the argument that activities drive the consumption of electricity, not a building's physical characteristics, though these may be having a mostly unseen influence on which activities take place in particular spaces of buildings. Removing the CG (Petrol Filling Stations), CL (Public Houses) and CR (Restaurants) samples would further restrict the range of values. As these three PD samples are small, further data collection might drag these apparently high EUI spaces more towards the range of values held in larger samples.

Although there is clearly some variation between premises types, the overall pattern suggests that 'office work' is broadly similar in its EUI, across most premises types. The value of this comes in the stock

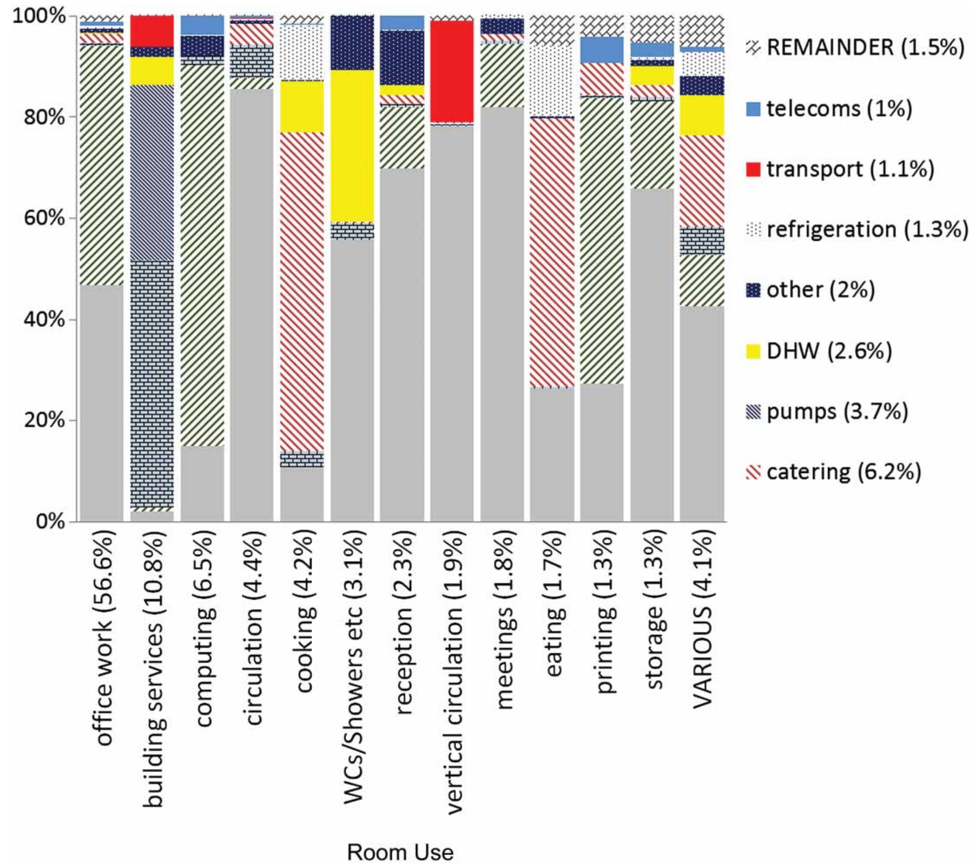

Figure 17 Percentage of appliance electricity consumption per Used For group in major Room Uses, in Office premises. The percentage of the sample's total appliance consumption is shown on the *x*-axis. The key also gives the percentage of total sample appliance consumption, per Used For group

modelling technique when seeking consumption profiles for space use and premises type combinations in VOA data (Line Entry Description and PD), for which there are no direct matches in the SHU data, when a profile may be substituted.

Figure 20 also shows the EUI for 1 SD below and above the mean. This hints at how much the electricity consumption by equipment in rooms in use may deviate quite markedly from the average consumption, even within each premises type, for a given room use. Although not fully quantified in this research, due to the intended use of the outputs in stock modelling, this phenomenon suggests that possible degrees of variance should be included when calculating the electricity consumption attributable to appliances in building simulations, using room or activity zone scale assumptions. The range of values included within 1 SD below the mean are effectively zero for Workshops (IF3) and Clubhouses (LC1).

Potential reasons for the 'office work' rooms in the CG (Petrol Stations) and CL (Public Houses) PD classes' different electricity consumption characteristics are investigated in Figure 21, showing that these rooms have much of their electricity being used for different purposes from most of the other premises types. In the CG class, 'other' and 'telecoms' together account for 36% of the consumption, with 'illumination' consumption being quite low at 16.5%. In the Public Houses, the bulk of consumption is accounted for by 'DHW', with 'illumination' somewhat less than 'HVAC' and the 'REMAINDER', which contains all consumption that constitutes less than 0.1% of the total consumption of all the 'office work' rooms. The other exception is class CS5 (Launderettes), which contains just two offices (both in the same premises) one of which contains a security camera and television, accounting for a quarter of consumption.

Figure 22 gives the profile of consumption, after the Petrol Filling Station, Public House and Launderette premises have been removed, showing patterns that are broadly similar. The updating of the population of computers may have had an homogenizing effect on the profiles, but if the assumption that all office

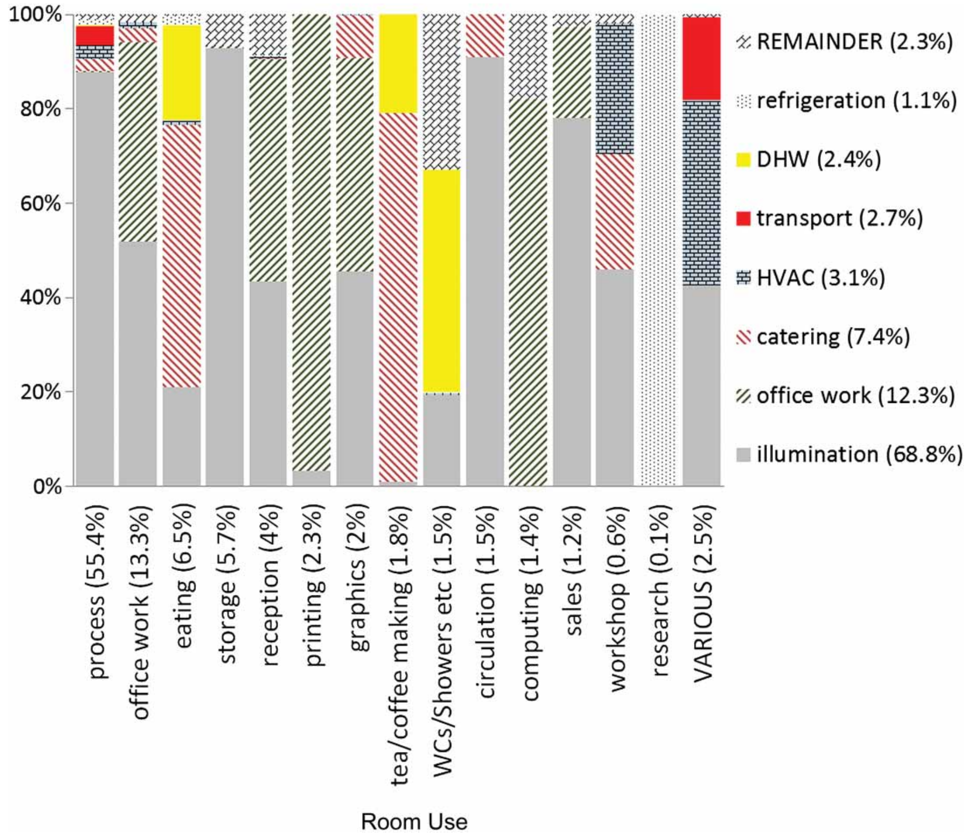

Figure 18 Percentage of appliance electricity consumption per Used For group in major Room Uses, in Factory premises. The percentage of the sample's total appliance consumption is shown on the *x*-axis. Percentages of total sample appliance consumption per Used For group are shown in the key. Excludes all 'process' energy use

rooms contain at least one computer is reasonable, the broad similarity is interesting and warrants further investigation.

These breakdowns of electricity use point toward the level of uncertainty surrounding the modelling of electricity consumption of activities in buildings/premises. What is partially obscured is that similar Room Uses, in similar premises activities, do not necessarily contain the same appliances with the same End Uses (or Used For group). For example, Table 3 shows the differences in EUI when only rooms where End Uses appear are compared with the sum of all such rooms, with the End Use consumption divided equally among them. The modelling of individual buildings might determine the appliance content of rooms, but stock modelling cannot do this due to insufficiently detailed data; therefore, the values averaged across all rooms are used. This averaging effect may, in fact, be a strength of stock models based on premises characteristics, where Room Uses are ignored and End Uses are aggregated, but this also assumes that all premises are average.

Potential effects of change in appliances and energy use

The subdivision of appliance electricity consumption, per Used For group and per Room Use, demonstrates how the use of equipment in those rooms can be extremely variable, perhaps with a diversity of patterns of operation that is not easily accounted for in energy modelling, even for individual premises/buildings. The effect of the distribution of appliances within rooms is further demonstrated in Table 4. For example, where an office work room in a Shop premises initially does not contain any catering appliances, a change to the average profile of catering appliances (for that premises and room use combination) would increase electricity consumption by 18%, in that room. This in turn would increase internal gains, which may have a knock-on effect on thermal comfort and heating and cooling energy use.

This variability in the use of space within premises and the use of equipment within those spaces highlights the importance of change in activities over time. In older buildings there are likely to have

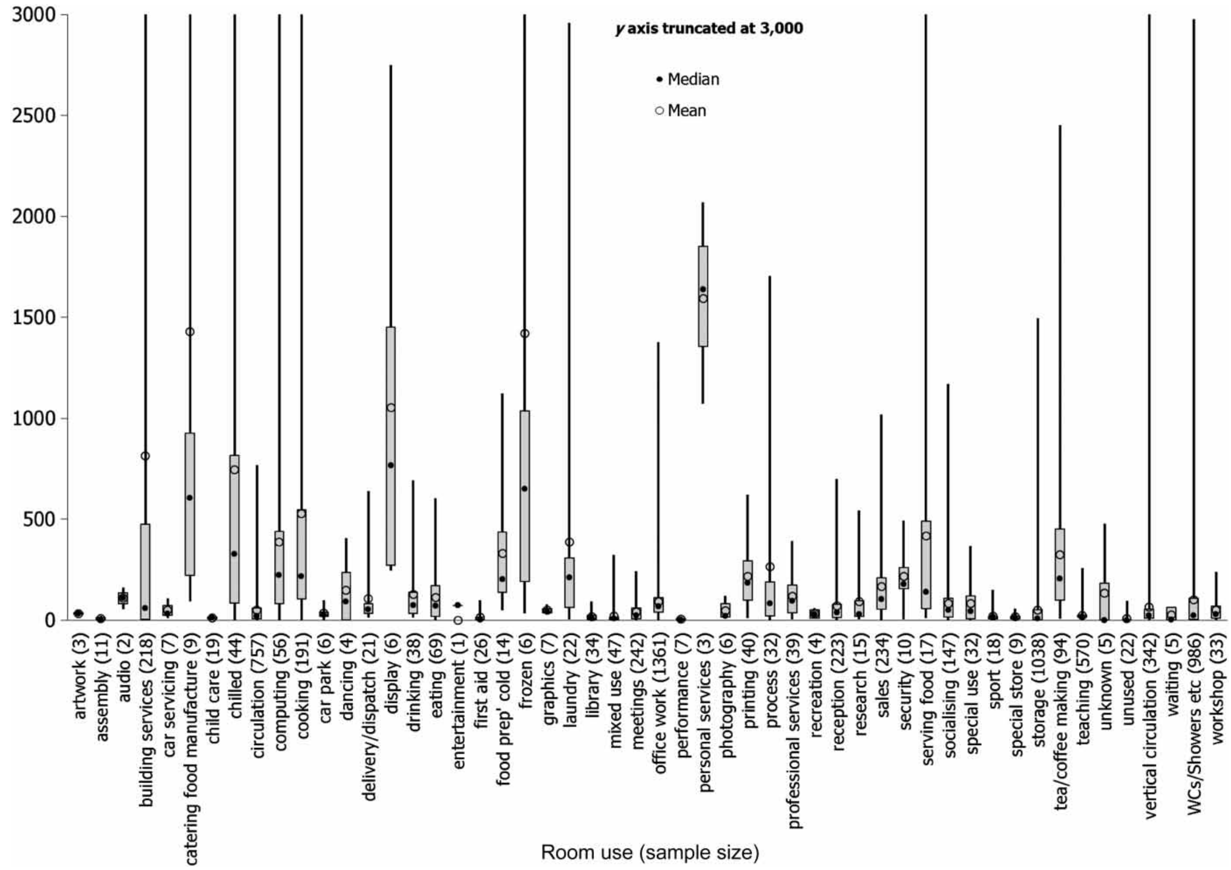

Figure 19 Distribution of energy use intensities (*y* axis EUI, kWh/m^2/year) per Room Use, all sample premises

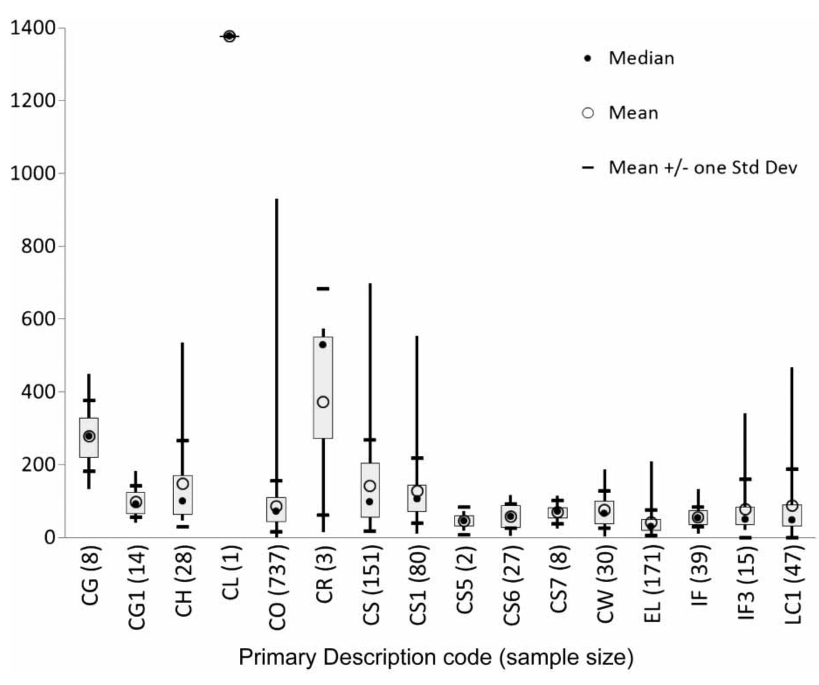

Figure 20 Energy use intensities (*y* axis EUI, kWh/m^2/year) of 'office work' rooms in each Primary Description sample

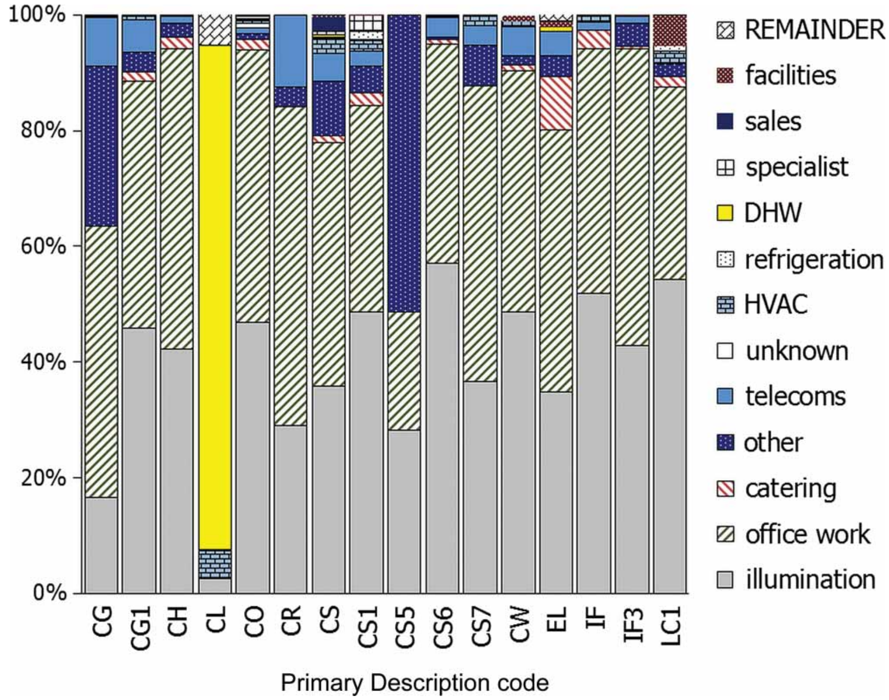

Figure 21 Breakdown of total consumption of all 'office work' rooms in SHU samples, per Used For group and Primary Description class

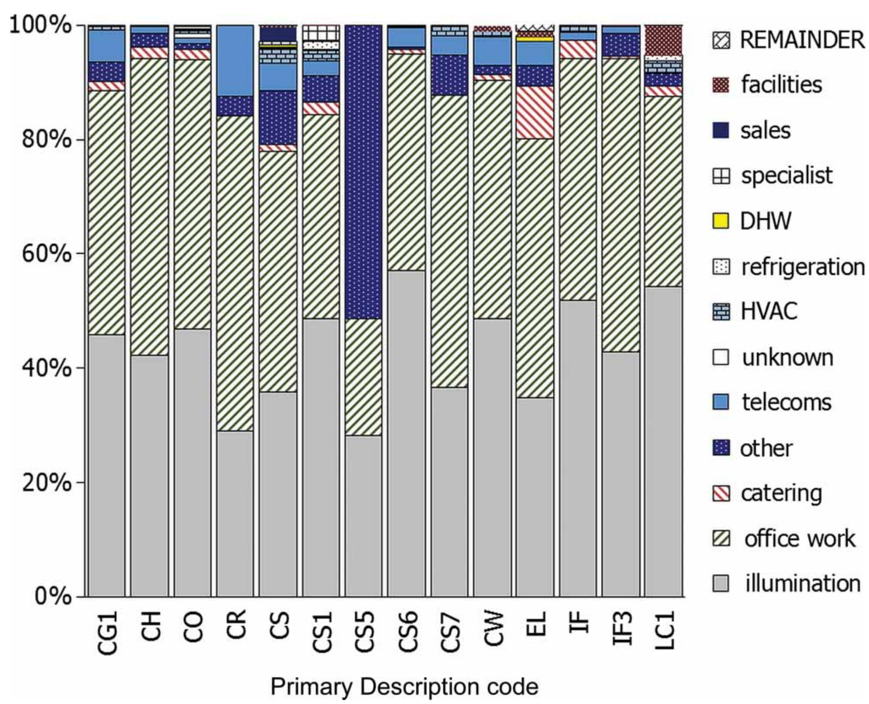

Figure 22 Breakdown of total consumption of all 'office work' rooms in SHU samples, per Used For group and Primary Description class, excluding CG, CL and CS5

Table 3 Breakdown of appliance electricity consumption in 'sales' areas of Shop premises

End use	kWh/year	Total area of rooms containing end use (m^2)	Total area of all rooms (m^2)	Mean kWh/m^2/year where an end use appears	Mean kWh/m^2/year for all rooms
Catering	1 147 215	21 298	36 288	53.9	31.6
Computer accessories	7460	9961	36 288	0.7	0.2
Computer	18 370	11 466	36 288	1.6	0.5
Domestic hot water (DHW)	12 076	3627	36 288	3.3	0.3
Fans	26 320	12 492	36 288	2.1	0.7
Lifts	14 669	321	36 288	45.7	0.4
Lighting	4 709 119	36 288	36 288	129.4	129.8
Other	19 918	7837	36 288	2.5	0.5
Process	2626	4170	36 288	0.6	0.1
Pumps	3186	2637	36 288	1.2	0.1
Small power	403 026	32 943	36 288	12.2	11.1
Telecoms	2816	5559	36 288	0.5	0.1
Unknown	793	18	36 288	43.2	0.0
Sum	6 367 594	–	–	297.1	175.5

been more changes of activity and changes of activity subspaces than in newer buildings and changes in appliances and service systems are consequently also more likely, making the operation of the space increasingly distant from the original design. In view of this, the understanding of activities and how they change in non-domestic premises/buildings may be seen as requiring a fuller appreciation of the appliances that perform those activities and how they are used.

Conclusions

The non-domestic building stock is recognized to be heterogeneous in its built form and its activities and the combination of these compounds the diversity of the characteristics affecting energy use. By disaggregating samples of premises into activity spaces (Room Uses), it has been possible to gain detailed profiles of how activity spaces are used within overall premises activity types, with breakdowns of non-heating and non-cooling electrical appliance consumption in each Room Use. The EUIs (kWh/m^2/year) for each End Use in 295 combinations of premises type and Room Use (plus 57 generic Room Uses) have been derived for use in urban scale non-domestic stock energy modelling. To enable this modelling method, it will be necessary to align the SHU Room Use profiles with the subdivisions contained in VOA property taxation records. This is the subject of further research.

As the identified electricity consumption characteristics are based on empirical data, not design guidance, their applicability to the actual building stock should be an improvement over stock modelling methods using design-based assumptions. The adoption of mean values for stock modelling, as opposed to values based around the median, is likely to represent the full spectrum of activity EUI, rather than what is believed to be 'normal' as used in energy benchmarking, but moderated by the distribution of space use types within premises. Although there is some broad similarity in the EUI of similar Room Uses, considerable variation has been found, even within the same overall premises activity type. The inclusion of high value outliers presents problems that may be better understood and overcome through the collection and inclusion of more data; so the collection of and access to similarly detailed samples is recommended. Due to the costs involved in detailed data collection surveys, sample premises should be selected not randomly, but according to a statistical analysis of the make-up of the stock, with particular attention paid to activities under-represented in the SHU samples.

This research has been built upon extremely detailed data, being mostly at the level of individual appliances, providing the ability to modify their populations, their power ratings and their usage to discover how potential future changes in appliances might affect the electricity consumption of the non-domestic building stock. Also, as the use of many of the appliances is

Table 4 Breakdown of appliance electricity consumption in 'office work' rooms of Shop, Office and Factory premises.

Premises type	End use	kWh/year	Total area of rooms containing end use (m^2)	Total area of all rooms (m^2)	Mean kWh/m^2/year where an end use appears	Mean kWh/m^2/year for all rooms
Shops	Catering	3721	145	2066	25.6	1.8
	Computer accessories	19 161	958	2066	20.0	9.3
	Computer	88 609	2066	2066	42.9	42.9
	DHW	909	87	2066	10.4	0.4
	Fans	7161	856	2066	8.4	3.5
	Lighting	96 677	2014	2066	48.0	46.8
	Pumps	6744	85	2066	79.6	3.3
	Small power	36 353	1456	2066	25.0	17.6
	Telecoms	10 885	488	2066	22.3	5.3
Offices	Catering	99 860	16 998	52 990	5.9	1.9
	Computer accessories	311 860	44 810	52 990	7.0	5.9
	Computer	1 668 127	52 990	52 990	31.5	31.5
	DHW	8474	1588	52 990	5.3	0.2
	Fans	25 879	23 101	52 990	1.1	0.5
	Lighting	2 114 342	52 922	52 990	40.0	39.9
	Other	65	181	52 990	0.4	0.0
	Process	4791	58	52 990	82.7	0.1
	Pumps	54	17	52 990	3.2	0.0
	Small power	201 950	39 628	52 990	5.1	3.8
	Telecoms	35 962	26 855	52 990	1.3	0.7
	Unknown	47 376	3082	52 990	15.4	0.9
Factories	Catering	1664	43	917	39.1	1.8
	Computer accessories	3782	546	917	6.9	4.1
	Computer	16 544	917	917	18.0	18.0
	Fans	638	430	917	1.5	0.7
	Lighting	27 881	917	917	30.4	30.4
	Process	31	17	917	1.9	0.0
	Small power	2819	408	917	6.9	3.1
	Telecoms	498	212	917	2.4	0.5

Notes: There are minor discrepancies in areas (*e.g.* lighting, in Office premises, where it appears that not all of the area is lit). These anomalies have been ignored due to their minor overall effect.
DHW = domestic hot water.

not weather dependent, changes in characteristics may inform calculation of the secondary effect of appliance electricity consumption (internal gains) on the need for heating and cooling in individual room types. When these room types are mapped onto property taxation data, the overall effect on the building stock's energy use may be estimated in greater detail than with previous methods.

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Endnote

[1]The colour scheme does not match Figure 3, as Room Uses differ. This also applies to Figure 7.