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A review of existing building benchmarks and the development of a set of reference office buildings for England and Wales

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Abstract:

The modern built environment has become more complex in terms of building types, environmental systems and use profiles. This complexity causes difficulties in terms of optimising buildings energy design. In this circumstance, introducing a set of prototype reference buildings, or so called benchmark buildings, that are able to represent all or majority parts of the UK building stock may be useful for the examination of the impact of national energy policies on building energy consumption. This study proposes a set of reference office buildings for England and Wales based on the information collected from the Non-Domestic Building Stock (NDBS) project and an intensive review of the existing building benchmarks. The proposed building benchmark comprises 10 prototypical reference buildings, which in relation to built form and size, represent 95% of office buildings in England and Wales. This building benchmark provides a platform for those involved in building energy simulations to evaluate energy-efficiency measures and for policymakers to assess the influence of different building energy policies.

Keywords: reference office building, building benchmark, building energy simulation, building energy policy

Introduction

The UK has set a challenging target to reduce its greenhouse gas emissions by 80% below the 1990's baseline by 2050, following the implementation of the Climate Change Act in 2008. In the UK, buildings account for more than 38% and 45% of energy consumption and carbon emissions respectively (Lombard.L.P, Ortiz.J. and Pout.C 2008; CT 2009; HC 2009; DECC 2010) . Computer simulations for energy consumption analysis have been recognised as one of the most efficient ways to achieve optimal energy use in buildings. These simulations could be used to quantify the end-use energy consumption profiles of buildings, to modify various parameters involved in Heating, Ventilation, Air Conditioning and Refrigeration (HVAC&R) and lighting systems, and to assess the impact of the implementation of building energy policies on different types of buildings. Therefore, it is essential to understand the function of a building and its detailed characteristics, the end-users' requirements and energy systems characteristics in order to perform an accurate building energy simulation. However, building energy simulations based on a limited number of case studies face the attendant problems of being unrepresentative of the majority of real buildings in the existing building stock (Penman 2000). This highlights the need to establish a building benchmark including a set of prototypical reference buildings that are able to represent a reasonable percentage of buildings with detailed specifications in order to provide a robust platform for energy strategic studies especially in regard to building energy-efficiency measures and energy policymaking.

Building benchmarks are intended to be able to accommodate well-defined assumptions for building energy simulation analyses for the examination of the influence of different energy-efficiency measures and new standards and policies (Stocki, Curcija and Bhandari 2007; Torcellini et al. 2008). Although building benchmarks have been developed since the 1980's internationally (PNL 1983; Torcellini et al. 2008), the nature and extent of the UK building stock are not effectively addressed within the existing benchmarks. Therefore, this study aims to develop a set of prototypical reference buildings as a benchmark for office buildings in England and Wales.

Prior to developing a new building benchmark for England and Wales, it was important to review and critically appraise the existing building benchmarks. Despite the focus of this study on the UK building stock, review of existing building benchmarks is not restricted to the very limited benchmarking studies conducted for the UK (Leighton and Pinney 1990; Hernandez, Burke and Lewis 2008) and a range of building benchmarks developed in the US are also reviewed in this study.

Existing building benchmarks

Building benchmarks could be categorised based on different parameters including built form, building type, thermal property of the materials and the location of buildings that are aimed to be represented by the benchmark. These features, together with the data gathering approach used to develop the prototypical reference buildings, are the most influential parameters in the development of a building benchmark (Brigges, Crawley and Schliesing 1992).

In this study, the review of existing building benchmarks begins by taking into account the data gathering approach adopted to collect the specifications of buildings from the existing building stock. Then, other categorisation parameters will be clustered around this main approach. The existing building benchmarks are classified into three main groups. The first group includes the prototypical buildings that are developed to be identical to the specifications of some real buildings that exist in the building stock. The second group comprises the prototypical buildings, which are developed based on the information gathered from small-scale surveys of the existing building stock. Finally, the third group includes the reference buildings that have been developed based on the information gathered from large-scale national surveys of the existing building stock.

Benchmarks developed to be identical to the specification of some real buildings

In early 1980s, the Pacific National Laboratory (PNL) developed a set of actual prototype buildings as being representative of commercial building stock. The rationale behind the development of this benchmark was to provide recommendations on energy conservation and also to improve the existing energy standards for new commercial buildings in the U.S. The benchmark covers small, medium and large offices, small and large retail buildings, elementary and high schools, apartments, hotels, warehouses, churches, restaurants and hospital buildings (PNL 1983). This approach has been also adopted in the UK by developing a set of standard office buildings (Leighton and Pinney 1990). These standard office buildings were originally developed to provide data for a study of the effect of shading devices on the performance of office buildings. This set of office buildings includes six real office buildings and provides details of their fabric and other geometric information. However, these six standard office buildings were not representative of the existing office buildings stock (Leighton and Pinney 1990). Since then, the approach of developing reference buildings has been changed radically and newer reference buildings have been developed based on the information gathered from small and large-scale surveys of the existing building stock.

Benchmarks developed based on small-scale surveys

One of the early studies aimed at developing a set of reference buildings based on the information gathered from a small-scale survey of the existing building stock was performed by Synergic Resource Corp (SRC 1985). The study investigated the energy consumption of 10 prototypical office buildings grouped as small, medium and large size, which were divided into two sub-groups labelled as new and existing buildings. These reference buildings were developed based on the outcomes of on-site surveys of 61 office buildings in the northeast of the U.S. The Synergic Resource Corp carried out another study in the education and health sector, which had an identical approach (SRC 1986a). The investigation was conducted through an on-site survey of 62 buildings in the northeast of the U.S. The ten prototype buildings including primary and secondary schools, a hospital, a nursing home, physicians' offices and five college buildings were developed in order to study the end-use energy consumption of a range of buildings with different occupancies (SRC 1986a).

To enhance the applicability and accuracy of the proposed sets of prototype buildings in these two studies (SRC 1985; SRC 1986a), an extensive on-site survey of 1200 buildings was conducted in Florida (SRC 1986b). From this survey, a set of prototype buildings were developed for 11 building types including large and small offices, retail units, schools, higher education colleges, hospitals, hotels, restaurants, civic centres, theatres and churches (SRC, 1986b). These prototype buildings were used to simulate and analyse the end-use energy consumption of buildings in Florida.

The end-use energy conservation measures of a range of commercial buildings were studied by XEnergy Incorporated. The survey of 184 buildings in New York enabled XEnergy Incorporated to develop a set of six prototype buildings for offices, hotels, hospitals, retail units, supermarkets and schools (XEnergy 1987).

In order to investigate the end-use load profiles and energy use intensity of buildings, Lawrence Berkeley Laboratory (LBL) developed a range of prototype buildings from the on-site survey of 85 buildings in southern California. The developed benchmark comprises small and large offices, retail units, a supermarket, a restaurant, a fast-food shop and two refrigerated and non-refrigerated warehouses (Akbari et al. 1989).

Another study using the same approach was carried out by LBL. In that study, Akbari et al. (1994) developed a set of prototypes for buildings of two vintages (pre and post 1983) which was based on the on-site survey of 145 buildings in North California. The prototype reference buildings included small and large offices, a large retail unit, sit-down and fast-food restaurants, a food store, primary and secondary schools, hospital and a nursing home (Akbari et al. 1994).

To investigate energy conservation potentials in commercial building stock, the NEOS Corporation developed a building benchmark based on survey data from utility companies in California. The benchmark covered large and small offices and retail units, sit-down and fast-food restaurants, grocery stores, refrigerated and non-refrigerated warehouses, hospitals, nursing homes, primary and high schools, colleges, hotels and motels (NEOS 1994).

More recently, a building prototype for primary schools was developed during the investigation of an energy performance benchmark in Ireland (Hernandez, Burke and Lewis 2008). Energy consumption data together with building detail specifications were gathered through the survey of 108 schools. Unfortunately, the building construction details, type and efficiency of heating systems were often unknown by the questionnaire respondents. Therefore, this information was gathered from a number of on-site surveys from smaller sample of buildings together with Building Regulations in operation at the time of construction and personal experiences (Hernandez, Burke and Lewis 2008). Although, the ability of this prototype building to be fully representative of the entire school building stock is questionable, this is the only prototype building developed specially for primary schools in the British Isles.

To develop a building benchmark, using the data from any small scale survey creates difficulties when attempting to represent the entire building stock. In order to overcome this limitation, the outcomes of the large-scale national surveys are used in the following studies.

Benchmarks developed based on large-scale national surveys

A well-structured building benchmark based on the results of a national survey was developed in collaboration of Battelle Pacific Northwest Laboratory (BPNL) and the Gas Research Institute (GRI) in the U.S. (Brigges, Crawley and Schliesing 1992). The benchmark investigates how energy is used in office buildings and is based on the clustering analysis of the Non-residential Building Energy Consumption Survey (NBECS) (EIA 1989). The benchmark comprises 20 prototype reference buildings representing existing office building stock together with 10 prototype reference buildings representing new offices. In the NBECS (EIA 1989), Roof, wall, and window details were not clearly defined. Therefore, these attributes were introduced based on assumptions related to the age of the buildings, relevant standards at the time of construction and engineering judgments. Using a similar approach, internal loads and operation schedules were allocated to the prototypical buildings. In addition, the specification of the HVAC&R systems of the prototypical buildings were approximately defined using building size and vintage together with the judgment of construction professionals (Brigges, Crawley and Schliesing 1992). Although many assumptions were used in the development of the benchmark, employing clustering analysis to produce 30 prototypical buildings to represent office building stock in the entire U.S. is a significant strength of this benchmark.

In another study, broad ranges of prototypical reference buildings were developed in collaboration of LBL and GRI to perform a feasibility study on the application of cogeneration technology (Huang et al. 1991). This is a comprehensive benchmark including 481 prototypical buildings in the U.S. commercial sector. The benchmark was developed based on NBECS (EIA 1983) which later became the Commercial Buildings Energy Consumption Survey (CBECS) (Huang et al. 1991).

These prototype buildings were developed from the premise that the aggregate energy consumption of prototype buildings could be extrapolated to the national level, once it is scaled to the total floor area of the existing building stock. Among the 481 developed prototypes, there were 78 offices, which were divided into two vintages before and after 1980. These prototypical buildings were sited in 13 regions of the U.S. and are reasonably representative of all the office buildings in the U.S. (Huang et al. 1991).

Lawrence Berkeley Laboratory (LBL) has also developed a series of reference buildings for the commercial sector to quantify the contributions of different building elements and components such as the roof, walls, lighting and HVAC&R equipment on the aggregate heating and cooling loads (Huang and Franconi 1999). These reference buildings were based on the previous research, which developed 481 prototypical buildings in the commercial sector (Huang et al. 1991) together with a new survey, carried out by the CBECS (EIA 1992). The benchmark together with the location weight factors derived from CBECS (EIA 1992) are also claimed to be representative of the commercial building stock in the U.S.

In another study, a comprehensive set of standardised buildings has been developed by Stocki et al. (2007). This set of prototypical buildings together with a range of assumptions on internal energy loads, schedules and HVAC&R systems, introduce a baseline for studies on building energy-efficiency measures. This benchmark does not attempt to represent the entire commercial building stock; but provides a reasonable number of typical buildings to be used in building energy comparison studies. The benchmark comprises prototype buildings for offices, retail outlets, secondary schools, apartments, small hotels and hospitals. These prototype buildings include the required information for building energy modelling. The fabric of these buildings was assumed based on data published by ASHRAE (2004). In addition, the window to wall ratio of prototype buildings were defined according to the earlier study conducted by Huang and Franconi (1999). However, there was no clear statement to describe the rationale behind choosing different physical building shapes. It seems that a typical shape for different types of buildings was assumed. Finally, internal energy loads and operational schedules were chosen based on the recommendations of ASHRAE (2004) and the previous research conducted by Huang and Franconi (1999).

Stocki et al. (2007) have asserted that common HVAC&R systems are dedicated to prototypical buildings. However, there is no evidence why those HVAC&R systems are assumed as common. Stocki et al. (2007) have also noted that, rather than the dedicated HVAC&R systems, other HVAC&R systems could be assumed as common systems for the proposed prototype buildings (Stocki, Curcija and Bhandari 2007).

Aiming to develop the most energy efficient or even zero energy buildings, the U.S. Department of Energy (DOE) developed standardised building models through research collaboration with Lawrence Berkeley National Laboratory (LBNL), Pacific Northwest National Laboratory (PNNL) and National Renewable Energy Laboratory (NREL) (Torcellini et al. 2008). The benchmark was planned to cover up to 70% of commercial buildings in terms of building type, size and location by introducing 15 prototype reference buildings. The reference buildings comprise large, medium and small offices, warehouses, retail outlets, malls, primary schools, secondary schools, supermarkets, fast food outlets, restaurants, hospitals, health care buildings and large hotels. This building benchmark is developed based on the survey results provided by CBECS (EIA 1999; EIA 2003). Also, the benchmark covers three vintages, new, pre-1980 and post-1980 for 16 locations which represent all the U.S. climate zones (Torcellini et al. 2008).

These prototypical buildings were developed to be used in building energy simulations as a baseline for building energy related comparison studies by providing a set of reasonable and identical assumptions. Without such a baseline, the results of different researches are difficult to compare (Torcellini et al. 2008).

The DOE's benchmark (Torcellini et al. 2008) enhanced the previous benchmark (Deru, Griffith and Torcellini 2006) by modifying the range of building size, shape and incorporating the latest data from the CBECS (EIA 2003). This benchmark also provided prototypes that are more representative of real buildings.

The number of prototypical buildings in the DOE 2008 benchmark was kept small to help the process of building simulation by providing consistency without being overly complex. It is clear that the 15 prototypical buildings introduced in the DOE 2008 benchmark cannot truly represent the diversity of construction and design of commercial buildings in the U.S. They can only provide an approximate representation of the commercial building stock (Winiarski, Halverson and Jiang 2008).

In building simulation models, many details are needed which are unlikely to be found in data sources like surveys. Developing the link between building benchmarks and building energy simulations, Torcellini et al. (2008) used a range of assumptions including building aspect ratio, number of floors, window to wall ratios, HVAC&R systems, internal energy loads and occupancy schedules.

The assumed building shapes of the 15 prototypical buildings were based on the average aspect ratio reported in CBECS (EIA 2003), previous researches and typical building designs (Torcellini et al. 2008). The window area was estimated based on window to wall ratio (WWR) of CBECS (EIA 2003). For each WWR percentage interval (0-10, 11-25, 26-50, 51-75 and 76-100), the mid-point of the WWR data was assumed to be representative of the interval. The wall and roof fabric of the buildings were categorised into seven groups. Due to the lack of precision about the actual elements of each category, the DOE 2008 benchmark attempted to make a comparison between these 7 groups and the dominance groups introduced by ASHRAE (2004). This approach was not successful and resulted in the criteria for wall and roof fabric details being defined by the opinion of experts (Winiarski, Halverson and Jiang 2008).

The HVAC&R systems within the prototype buildings were initially defined based on CBECS (EIA 2003). One of the significant ambiguities of this approach was the extensive range of terminology used to define the different types of HVAC&R systems in the CBECS survey. It was reported that in the survey process, capturing the actual technical detail of a HVAC&R system was very difficult and in many cases did not culminate in an accurate description. For instance, in packaged units, for those who responded to the survey, it was not clear whether the heat source was a boiler or a water or air source heat pump. Therefore, the final HVAC&R systems of the prototype buildings were defined based on both survey data and through the approval of experts (Winiarski, Halverson and Jiang 2008). Internal heating loads and operation schedules have been assumed according to the existing standards and previous research (ASHRAE 2004; CEC 2004; Faramarzi and Walker 2004; SCE 2004). In the DOE 2008 benchmark, the size, number of floors, shape, internal heating loads and operation schedule of the buildings were assumed constant for all locations and vintages. This assumption made it easier to capture the influence of building vintage and location on energy-efficiency measures. Finally, it is worth mentioning that, the DOE 2008 benchmark has been introduced into ASHRAE Standard 90.1 as a baseline for building energy related comparison studies (ASHRAE 2010).

Summary of the existing building benchmarks

The review of the existing building benchmarks established since 1980s shows that early benchmarks (first generation) were developed based on typical actual buildings (PNL 1983; Leighton and Pinney 1990). Since then, this has been radically changed and newer building benchmarks, the so called the second generation, were developed based on on-site survey data from 61 to 1200 buildings (SRC 1985; SRC 1986a; SRC 1986b; XEnergy 1987; Akbari et al. 1989; Akbari et al. 1994; NEOS 1994; Hernandez, Burke and Lewis 2008).

The third generation of building benchmarks has been formed since the early 1990s. These benchmarks have been developed based on the information gathered from large scale national survey of the existing building stock (Huang et al. 1991; Brigges, Crawley and Schliesing 1992; Huang and Franconi 1999; Deru, Griffith and Torcellini 2006; Stocki, Curcija and Bhandari 2007; Torcellini et al. 2008). This provides the opportunity to capture the actual attributes of the existing building stock. Therefore, the reference buildings developed from large-scale national surveys could be representative of the existing building stock.

A summary of the existing benchmarks reviewed in this paper are shown in Table 1. This table demonstrates the number and type of prototypical reference buildings introduced in the existing building benchmarks.

(Place of Table 1)

In building benchmark development, the higher the number of prototypes for each building type, the more representative the results in relation to the building stock will be. However, a higher number of prototype buildings make further analysis more complex and challenging (Leighton and Pinney 1990). Therefore, the selection of a reasonable benchmark for a specific research aim involves a trade-off between the number of prototype buildings and extent to which the prototype buildings should represent the building stock. Therefore, a reasonable and useful selection can only be made following a detailed review of extensive information about each individual benchmark.

Any investigation into the potential of existing benchmarks to represent the national building stock requires an understanding of the rationale behind the development of each benchmark. Among the 16 reviewed benchmarks (Table 1), 6 of the benchmarks were developed based on national surveys. The original purpose of each of these 6 building benchmarks and their ability to be representative of the building stock are shown in Table 2.

(Place of Table 2)

Among the rationales involved in developing benchmarks are the characterisation of building energy consumption in the existing building stock, introducing baseline assumptions for building energy related strategic studies and developing a limited set of prototypical buildings to investigate the effectiveness of the standards for policymakers. Unfortunately, none of the benchmarks referred to in Table 1 has attempted to study the influence of building attributes on HVAC&R systems and selecting the most appropriate HVAC&R system for the prototype buildings. This issue has been addressed by Brigges et al. (1992) where the rationale behind selecting specific HVAC&R systems for each prototypical building was justified. Brigges et al. (1992) note that: “Non-residential Building Energy Consumption Survey provided very limited guidance to us in making HVAC system selection for the representative office buildings. As a consequence, our professional judgments and those of our consultants figured importantly in the selection of HVAC system".

This statement reinforces the notion that building benchmarks have significant potential to be used as a baseline to investigate the performance of a variety of HVAC&R systems and energy-efficiency measures as well as the more general reasons for developing building benchmarks.

In addition, review of the existing building benchmarks revealed that the survey results were not sufficiently detailed to include the wall, roof and window specification of reference buildings as well as the allocation of internal loads and operational schedules. Therefore, in the existing building benchmarks, these attributes are mainly defined based on the existing Building Regulations and Standards together with some professional judgments (Brigges, Crawley and Schliesing 1992; Stocki, Curcija and Bhandari 2007; Torcellini et al. 2008). However, this allocation process is associated with uncertainty, especially where the existing building stock includes a verity of buildings with different vintages and consequently the properties of the building fabric is different. To mitigate the level of uncertainty associated with the allocation of building fabrics to the reference buildings; this study provides a chronology of the detailed changes to wall, roof and windows thermal properties since 1965, in order to allow the reference buildings to be placed into different vintages.

Building benchmarks in the UK

Among the reviewed reference buildings developed in the previous studies, only two studies were conducted for the UK building stock. The standard office buildings developed by Leighton and Pinney (1990) did not attempt to represent the UK office building stock. Therefore, the reference building for primary schools developed by Hernandez, Burke and Lewis (2008) is the only reference building relating to the British

Isles building stock.

However, the building benchmarks have been indirectly addressed in several building energy benchmark studies (ECG-19 2000; CIBSE 2004; CIBSE-TM46 2008). Energy Consumption Guide-19 (ECG-19 2000) introduces an energy benchmark for office buildings. In this document, the office buildings are clustered into four general styles including; natural ventilated cellular, natural ventilated open plan, air-conditioned standard and air-conditioned prestigious (ECG-19 2000). In another study, the Chartered Institution of Building Services Engineers (CIBSE) extended the approach of ECG-19 to other non-domestic buildings in order to support the requirements of display energy certificates (CIBSE 2004). This was subsequently updated to the "energy benchmark technical memorandum 46" (TM46) to simplify the allocation of buildings into different categories (CIBSE-TM46 2008). The existing UK energy benchmark (TM46) has been reviewed based on the latest Display Energy Certificate (DEC) records (Bruhuns et al. 2011). Despite the valuable results drawn from real buildings within these three building energy benchmarks (ECG-19 2000; CIBSE 2004; CIBSE-TM46 2008) and also the latest UK building energy benchmark review based on the DEC results (Bruhuns et al. 2011), none of them provides a set of prototypical reference buildings as a representative of the entire or part of the building stock in the UK. Also, the broad categorisation of office buildings introduced in ECG-19 (ECG-19 2000) is inappropriate for building related studies especially for use in comparison and simulation studies on energy-efficiency measures.

The most recent study on Non-Domestic Buildings Stock (NDBS) for England and Wales was carried out for the Department of the Environment, Transport and the Regions (DETR). The aim of this research was to determine the pattern of energy used in NDBS and to estimate the resulting carbon dioxide emission (Penman 2000). The

NDBS study was able to access the building information part of the property taxation database from the Valuation Office of the Inland Revenue, which added considerable value to NDBS project. Due to the utilisation of this database, the results of the NDBS project are not solely reliant on random sampling of the building stock, which brings with it associated selection and representativeness issues (Steadman, Bruhnes and Rickaby 2000c).

In this study, the approach of utilising the outcomes of national surveys to develop building benchmarks is adopted from the described literature of building benchmarking studies. This approach together with the outcomes of the NDBS project (Pout, Steadman and Mortimert 1998; Brown, Rickaby and Bruhnes 2000; Gakovic 2000; Holtier, Steadman and Smith 2000; Penman 2000; Pout 2000; Rickaby and Gorgolewski 2000; Bruhns 2000a; Mortimer, Ashley and Rixt 2000a; Steadman, Bruhnes and Gakovic 2000a; Bruhns et al. 2000b; Mortimer, Elsayed and Grant 2000b; Steadman et al. 2000b; Steadman, Bruhnes and Rickaby 2000c) forms the basis of developing prototypical reference buildings as a benchmark for office buildings for England and Wales.

A prototypical office building benchmark for England and Wales

In general, to develop a set of prototypical reference buildings, the surveyed buildings are categorised based on their specifications including: building type (occupancy), location, built form, dimensional details, materials properties, windows area, type of HVAC&R systems, internal energy load and operating schedules. Among them, the built form is one of the most important attributes of buildings that should be considered to develop a set of reference buildings (Huang et al. 1991; Brigges, Crawley and Schliesing 1992; Huang and Franconi 1999). However, the diversity of building shapes makes the process of built form categorisation a challenging task. Categorisation of built forms in the NDBS study was established by a survey of 3350 addresses in four urban centres; Manchester, Swindon (Wiltshire), Tamworth (Staffordshire) and Bury St Edmunds. These urban centres were chosen to cover a wide range of population sizes, be spread geographically across the country and take into account a broad variety of building types (Steadman, Bruhnes and Rickaby 2000c). To make the categorisation of built form practical and accurate, three simplifying strategies were considered. First, all insignificant details such as surface articulation, attached features and balconies were ignored. Second, buildings with complicated forms were virtually disassembled into smaller parts of simple forms. Finally, forms were represented parametrically; for instance, a simple single storey building was described by the plan dimensions of width and length, height and slope of roof pitch (Steadman et al. 2000b). Daylit or artificially lit and room size were included in the built form categorisation criteria. The daylit rooms were assumed to use natural light. Therefore, using general results from empirical studies, the depth of rooms when measured from the windows should not be more that 6-7 metres (Steadman, Bruhnes and Gakovic 2000a; Steadman et al. 2000b). There is no such restriction on room depth for artificially lit spaces. In terms of space size, theoretically, rooms might take any plan size dimensions. However, in practice the surveys have shown that the rooms can be grouped into typical size bands. The NDBS project found three typical size bands, which were categorised as: 1-cellular, 2-hall including lecture theatres and court rooms, 3-chapels and open plans, where space is unobstructed by internal walls (Steadman et al. 2000b). Using simplifying strategies and the criteria for classification, 17 different built forms for non-domestic buildings were captured in the NDBS project. These forms are shown in Figure 1 and Table 3 (Steadman et al. 2000b).

(Place of Figure 1)

(Place of Table 3)

Using these built form categories, the total floor areas in different forms of office premises included in the NDBS project are shown in Table 4 (Steadman 1997).

(Place of Table 4)

In Table 4, the built form categories are related to the used floor area by organisations, which occupy premises, not to the physical structure in which they are housed. Using premises makes the distribution of built forms clearer by avoiding unnecessary definitions, for example, 'mixed-use' for the buildings having mix occupations (such as combination of shops in ground floor and offices in top floors).

According to Table 4, the total floor area of offices with “daylit (sidelit) cellular strip” (CS4 and CS5) and “daylit (sidelit) cellular strip around some or all edges of artificially lit or toplit” (CDO), are around 95% of the total floor area of the office buildings (Steadman 1997). To move beyond this 95% coverage, more built forms must be taken into account because they are spread across the other 14 built forms. This makes the associated building energy related studies significantly more difficult. Therefore, in this paper, the proposed building benchmark for office buildings has been developed from three built forms (CS4, CS5 and CDO). Steadman et al. (2000a) inferred the built form distribution of offices in different size bands for England and Wales and this is shown in Table 5.

(Place of Table 5)

In reality, each premise could be smaller or equal to the entire building in terms of size. Therefore, considering a prototypical building for each size band covers the possible buildings which are entirely designed as an office building for each size band category.

It should be noted that considering a variety of permutations of different premises in a prototype building would generate numerous prototypical buildings, which makes the building benchmark inapplicable for building energy related simulation studies. Therefore, in this benchmark it is assumed that the entire office building has been designed to accommodate a single occupancy. This is the assumption, which has been also adopted in all of the existing building benchmarks referred to in Table 1.

The reference buildings proposed in this study are developed based on the survey results of the NDBS project (Steadman et al. 2000b). In NDBS project the built form of the buildings are captured after virtual decomposition of the compound buildings. In other words, the shared walls and parts between two adjacent buildings are not taken into account.

To describe the rationale behind this approach Steadman et al. (2000b) have stated that: " the present classification would categorise these various component forms separately and preserve little or nothing of the relationship in which they are assembled, again on the assumption that-to a first order of approximation-such relation are not significant for energy use." For instance, the complex built form of 19th century public bath in Swindon (Figure 2) is still in use as a health centre. In this compound building, different built forms are accounted separately without considering the adjacent walls and parts. In this case, the L-form part of this centre is accounted as a separate L-shape office building. Therefore, the reference buildings developed in this paper are aligned with this classification assumption embedded in the NDBS study where adjacent walls and parts are not considered.

(Place of Figure 2)

The total floor area of different built forms for office buildings shown in Table 4 confirms that, CS4 and CS5 are the dominant built forms in the sidelit group and together cover more than 95% of the offices in this group. Table 4 also shows that, the CDO built form is the dominant shape for offices with deep plans and covers up to 99% of offices with deep plan shapes. Therefore, in Table 5, with more than a 95% probability, the sidelit shape is represented by the CS4 and CS5 forms.

Based on the above analysis, it is possible to reconfigure the built form distribution of office buildings in different size bands for England and Wales with at least a 95% probability as this is the minimum of the 95% and 99% probabilities. This is shown in Table 6.

(Place of Table 6)

By recognising the most common built forms and related size bands, it is possible to develop prototypical reference buildings to represent these criteria in the office building stock. Therefore, based on the comprehensive review of the existing building benchmarks together with the aforementioned analysis, 10 prototypical buildings are proposed in this paper. A prototype reference building is assigned to each principal built form in each size band (Table 6). The size of the prototype buildings generally complies with the mid-size of each size band to allow a normal distribution of sizes within each size band. Figure 3 represents these 10 prototypical reference buildings in five size bands and two principal built forms (deep plan and sidelit).

(Place of Figure 3)

With the form and size of the prototypical buildings defined, it is now necessary to identify the detailed specification of the wall, roof and windows for each prototype building.

The amount of glazed area within each prototype building is defined based on the results of the NDBS project. In the NDBS project the glazing area is reported as the ratio of glazing area to floor area (G/F). This ratio is inferred from the survey of four urban centres and modified by the VSA report of the valuation office (Gakovic 2000). The typical ratio of glazed to floor area for buildings with different types of structure is shown in (Gakovic 2000).

(Place of Table 7)

Buildings with deep plans are considered as both "framed, deep plans" and "traditional" in terms of building structure as shown in Table 7 (Gakovic 2000). Therefore, the G/F ratio of each reference building with a deep plan (CDO) is assumed as the average G/F ratios of buildings within these two building structure categories, which is 0.10. Also, using the same approach, buildings with sidelit built forms (CS4,CS5) are considered as, "framed curtain wall", "traditional" or "framed, other" in terms of building structure as shown in Table 7 (Gakovic 2000). Therefore, The G/F ratio of each reference building with sidelit forms (CS4, CS5) is assumed as the average G/F ratios of buildings with these three building structure categories, which is 0.20.

The NDBS project did not define the wall and roof materials in detail. In one part of the NDBS project (Mortimer, Elsayed and Grant 2000b), to develop the national non-domestic building energy and emission model, the U-vale or thermal conductance of roof and wall were assumed based on the requirements of the Building Regulations

(DCLG 1995). This was justified by the assumption that all non-domestic buildings comply with this regulation (Pout 2000). Unfortunately, there is no evidence in the open literature to support this assumption. Therefore, this paper provides a chronology of the detailed changes to wall and roof U-values since 1965, in order to allow the reference buildings to be placed into different vintages. These changes to wall, roof and window maximum U-values are shown in Table 8.

(Place of Table 8)

In order to assess the occurrence distribution of different HVAC&R systems in the existing building stock, the NDBS project categorised the HVAC&R systems into four principal groups. Details of this categorisation are shown in Table 9 (Rickaby and Gorgolewski 2000)

(Place of Table 9)

Even though this categorisation attempted to cover the vast majority of HVAC&R systems, there is an emphasis on secondary HVAC&R systems and primary systems are less well represented. In addition, the NDBS project stated that it was not possible to distinguish subcategories of each principal type of HVAC&R systems during the survey (Rickaby and Gorgolewski 2000). Therefore, the NDBS project includes very limited information about HVAC&R systems used in the office building stock (Rickaby and Gorgolewski 2000). The occurrence of principal HVAC&R systems is one of the limited aspects of the NDBS project and this is shown in Table 10 (Rickaby and Gorgolewski 2000).

(Place of Table 10)

This information about HVAC&R systems provided in the NDBS project (Rickaby and Gorgolewski 2000) is not sufficiently robust to make any assumption about the type of HVAC&R systems for the reference office buildings in this study. Therefore, due to the lack of detailed information about the distribution of HVAC&R systems in the office building stock and also strong interrelationship between attributes of the buildings, the HVAC&R systems and building energy consumption (Korolija et al. 2011), this study does not attempt to allocate a typical HVAC&R system to each reference building. Instead, the common HVAC&R systems proposed by CIBSE (2005) are to be used for the comparison studies based on this benchmark (Table 11). By not allocating a specific HVAC&R system to the prototype reference buildings in this study, an opportunity is created to investigate the effect of different HVAC&R systems on the proposed building benchmark.

(Place of Table 11)

Internal energy load is one of the attributes which has to be defined for each prototype reference building. This energy load comprises the human body heat rejection, lighting and electrical equipment load (CIBSE 2006).

For the occupancy density, this benchmark adopts the CIBSE recommendation of a maximum occupancy density of 12 square metres per person (CIBSE 2006). Also, for typical office activities, human body sensible and latent heat rejection are respectively assumed to be 75 and 55 Watts per person. For lighting energy loads, based on the Code for Lighting provided by the Society of Light and Lighting (SLL 2009) to achieve an illuminance of between 300 Lux to 500 Lux, a power load of 15 Watts per square metre is assumed. Finally, for the electrical equipment load, in a typical modern office, 200 Watts of equipment load is assumed for each occupant. It should be noted that a variety of internal loads, schedules and lighting systems have been described in Simplified Building Energy Model (SBEM) which is a valuable source that could be considered for further studies on building energy-efficiency measures (DCLG 2012).

Figure 4 shows the structure of the proposed reference office buildings in two principal built forms of sidelit and deep plan and five size bands. The specified characteristics of glazing ratio, fabric types, HVAC&R systems and internal energy loads are also shown in this figure.

(Place of Figure 4)

Conclusion

First, this paper proposed a comprehensive review and a unique classification of the existing building benchmarks into three generations. In the first generation, the building benchmarks include the reference buildings that were developed to be identical to the specification of some real buildings. Therefore, these building benchmarks were not able to represent the existing building stock. Since then, to overcome this deficiency, the approach of developing building benchmarks has been changed radically and the newer building benchmarks (second and third generations) were developed based on the information gathered from surveys of the existing building stock. The second generation of building benchmarks were developed based on the information gathered from small-scale surveys. However, using small scale survey created difficulties when attempting to represent the entire building stock. In order to overcome this limitation, the third generation of the building benchmarks were developed based on the information gathered from large-scale national surveys.

These categorisations demonstrate the trend of evolution in the development of building benchmarks since 1980. The type and number of reference buildings proposed in the previous building benchmarks were provided in Table 1. In addition, the main purpose of development and the ability of office building benchmarks to represent the existing building stock are summarised in Table 2. These are the unique attributes of the building benchmarks that are classified for the first time in this paper.

Second, this paper proposed a comprehensive building benchmark for office buildings for England and Wales. The review of the existing building benchmarks together with the building stock information obtained from the NDBS project (Steadman, Bruhnes and Rickaby 2000c), provided a reliable basis for the development of the proposed building benchmark.

In this study, the developed building benchmark includes ten reference office buildings in two principal built forms (sidelit and deep plan) and five size bands (0-300, 300-1000, 1000-3000, 3000-10000 and over 10000 m^2). Fabric details of the reference buildings are introduced based on the requirements of the Building Regulations in the UK since 1965. This is one of the strengths of the proposed benchmark as it provides an opportunity to investigate energy-efficiency measures of buildings with different vintages. In addition, the internal energy loads of the reference buildings are introduced based on the requirements of the existing Building Regulations. In fact, other parameters that influence the building energy demands such as, occupants' activities, equipment control and management strategies vary in the existing building stock. The proposed reference office buildings form a robust basis to evaluate the influence of these parameters on buildings energy performance. This robustness is due to the ability of the proposed reference buildings to represent 95% of office buildings in terms of built form and size in England and Wales with a 95% probability. Therefore, a wide range of heating and cooling control strategies, a variety of HVAC&R systems and numerous lighting control strategies together with a broad range of building energy standards and policies could be virtually implemented in these reference buildings and their performance could be simulated and compared. The results of these simulations could be used to study the influence of the implementation of the aforementioned strategies, standards and policies in the existing building stock in England and Wales.

References:

Akbari, H., J. Eto, S. Konopacki, and A. Afzal. 1994. *Integrated estimation of commercial sector end-use load shapes and energy use intensities*. Berkeley, CA: Lawrence Berkeley Laboratory for Pacific Gas and Electricity Company.

Akbari, H., J. Eto, I. Turiel, and L. Rainer. 1989. *Integrated estimation of commercial sector end-use load shapes and energy use intensities*. Berkeley, CA: Lawrence Berkeley Laboratory for California Energy Commission.

ASHRAE. 2004. *Energy standard for buildings except low-rise residential buildings-Standard 90.1*. Atlanta: American society of heating refrigerating and air-conditioning engineers.

ASHRAE. 2010. *Energy standard for buildings except low-rise residential buildings-standard: 90.1*. Atlanta: American society of heating, refrigerating and air-conditioning engineers.

Brigges, R. S., D. B. Crawley, and J. S. Schliesing. 1992. *Energy requirements of office buildings (Vol. 1)*. Battelle: Pacific Northwest Laboratory for Gas Research Institute.

Brown, F. E., P. A. Rickaby, and H. R. Bruhnes. 2000. "Survey of nondomestic building in four English towns." *Environmental and planning B: Planning and design* 27: 11-24.

Bruhns, H. 2000a. "Property taxation data for nondomestic building in England and Wales." *Environmental and planning B: Planning and design* 27: 33-49.

Bruhns, H., J. P. Steadman, H. Herring, S. Moss, and P. A. Rickaby. 2000b. "Types, numbers and floor areas of nondomestic premises in England and Wales, classified by activity." *Environmental and planning B: Planning and design* 27: 641-665.

Bruhuns, H., P. Jones, R. Cohen, B. Bordass, and H. Davies. 2011. *Review of energy benchmarks for display energy certificates*. London: Chartered institution of building services engineers.

CEC. 2004. *Design guide 2: improving commercial kitchen ventilation system performances: optimisation makeup air*. California: California Energy Commission.

CEC. 2006. *California Commercial End-Use Survey (CEUS).* California: California Energy Commission and Itron Inc.

CIBSE-TM46. 2008. *Energy benchmark.* London: Chartered institution of building services engineers.

CIBSE. 2004. *Energy efficiency in buildings - Guide F.* London: Chartered institution of building services engineers.

CIBSE. 2005. *Heating, ventilating, air conditioning and refrigeration - Guide B.* London: Chartered institution of building services engineers.

CIBSE. 2006. *CIBSE guide A: environment design*. London: Chartered institution of building services engineers.

CT. 2009. *Building the future, today*. London: Carbon Trust.

DCLG. 1965. *Building regulations-statutory instruments No.1373*. London: Department for Communities and Local Government.

DCLG. 1972. *Building regulations-statutory instruments No.317*. London: Department for Communities and Local Government.

DCLG. 1976. *Building regulations-statutory instruments No.1676*. London: Department for Communities and Local Government.

DCLG. 1985. *Building regulations-conservation of fuel and power: Part L*. London: Department for Communities and Local Government.

DCLG. 1990. *Building regulations-conservation of fuel and power: Part L*. London: Department for Communities and Local Government.

DCLG. 1995. *Building regulations-conservation of fuel and power: Part L*. London: Department for Communities and Local Government.

DCLG. 2012. *A user guide to iSBEM*. London: Department for Communities and Local Government.

DECC. 2010. Digest of UK energy statistic 2010. London, Department of energy and climate change.

Deru, M., B. Griffith, and P. Torcellini. 2006. "Establishing benchmark for DOE commercial building R&D and program evaluation". In Proceedings of the *American Council for an Energy Efficient Economy (ACEEE)*, Pacific Grove, California.

DTLR. 2002. *Building regulations-conservation of fuel and power in buildings other than dwelling: Part L2*. London: Department for Transport, Local Government and the Regions.

ECG-19. 2000. *Energy use in offices*. The Government's Energy Efficiency Best Practice programme: Energy Consumption Guide.

EIA. 1983. *Non-residential buildings energy consumption survey-1983 (NBECS)*. U.S. department of energy, Washington: Energy Information Administration.

EIA. 1989. *Non-residential buildings energy consumption survey-1989 (NBECS)*. Washington: Energy information administration.

EIA. 1992. *Commercial Buildings Energy Consumption Survey (CBECS)*. Washington DC: Energy Information Administration.

EIA. 1999. *Commercial Buildings Consumption Survey* Washington DC: Energy Information Administration.

EIA. 2003. *Commercial Buildings Energy Consumption Survey*. Washington DC: Energy Information Administration.

Faramarzi, R. T., and D. H. Walker. 2004. *Investigation of secondary loop supermarket refrigeration systems*. California: California energy commission.

Gakovic, B. 2000. "Areas and types of glazing and other opening in the nondomestic building stock." *Environmental and planning B: Planning and design* 27: 667-694.

HC. 2009. *Programmes to reduce household energy consumption*. London: House of Commons.

Hernandez, P., K. Burke, and O. Lewis. 2008. "Development of energy performance benchmarks and building energy ratings for non-domestic buildings: An example for Irish primary schools." *Energy and Buildings* 40: 249-254.

HMGovernment. 2010. *Building regulations-conservation of fuel and power in new buildings other than dwelling: Part L2A*. London: Her Majesty's Stationery Office.

Holtier, S., P. Steadman, and M. G. Smith. 2000. "Three-dimensional representation of urban built form in GIS." *Environmental and planning B: Planning and design* 27: 51-72.

Huang, J., H. Akbari, L. Rainer, and R. Ritshard. 1991. *481 prototypical commercial buildings for 20 urban market areas*. Berkeley, California: Lawrence Berkeley national laboratory for Gas Research Institute

Huang, J., and F. Franconi. 1999. *Commercial heating and cooling loads component analysis*. Berkeley, California: Lawrence Berkeley national laboratory.

Korolija, I., L. Marjanovic-Halburd, Y. Zhang, and V. Hanby. 2011. "Influence of building parameters and HVAC systems coupling on building energy performance." *Energy and Buildings* 43(6): 1247-1253.

Leighton, D. J., and A. A. Pinney. 1990. *A set of standard office desciptions for use in modelling studies*. Watford: Building Research Stablishment by Building Environmental Performance Analysis Club.

Lombard.L.P, Ortiz.J., and Pout.C. 2008. "A review on building energy consumption information." *Energy and Buildings* 40: 394-398.

Mortimer, N. D., A. Ashley, and J. Rixt. 2000a. "Detailed energy surveys of nondomestic buildings." *Environmental and planning B: Planning and design* 27: 25-35.

Mortimer, N. D., M. A. Elsayed, and J. F. Grant. 2000b. "Patterns of energy use in nondemestic buildings." *Environmental and planning B: Planning and design* 27: 709-720.

NEOS. 1994. *Technology energy savings: Building Prototypes*. Sacramento, California: NEOS Corporation.

ODPM. 2006. *Building regulations-conservation of fuel and power in new buildings other than dwelling: Part L2A*. London: Office of the Deputy Prime Minister.

Penman, J. M. 2000. "A database and model of energy use in the nondomestic building stock of England and Wales." *Environmental and planning B: Planning and design* 27: 1-2.

PNL. 1983. *Recommendations for energy conservation standards and guidelines for new commercial buildings (for U.S. Department of Energy), Vol 3*. Berkeley, California: Pacific Northwest Laboratories.

Pout, C. 2000. "N-DEEM: the national nondomestic buildings energy and emissions model." *Environmental and planning B: Planning and design* 27: 721-732.

Pout, C., J. P. Steadman, and N. D. Mortimert. 1998. *None-domestic building energy fact file*. Watford: Building Research Establishment.

Rickaby, P. A., and M. Gorgolewski. 2000. "A classification system for services in nondomestic buildings." *Environmental and planning B: Planning and design* 27: 695-708.

SCE. 2004. *Design guide-1: improving commercial kitchen ventilation system performances - optimisation makeup air-selecting and sizing exhaust hoods*. Rancho Cucamonga, California: Southern California Edison.

SLL. 2009. *Code for lighting CD-ROM*. Chartered Institution of Building Services Engineers, London: Society of Light and Lighting,CIBSE.

SRC. 1985. *New office buildings end-use energy consumption survey - for Northeast Utilities Service Company*. Berlin, Connecticut: Synergic Resources Corp.

SRC. 1986a. *Education and health buildings end-use energy consumption survey- for Northeast Utilities Service Company*. Berlin, Connecticut: Synergic Resources Corp.

SRC. 1986b. *Cool storage market assessment - for Florida Power and Light Company*. Miami, Florida: Synergic Resources Corp.

Steadman, P. 1997. "The non-domestic building stock of England and Wales: type, numbers, sizes and ages." In *Structure and style conserving 20th century buildings*, edited by Stratton, M., 49-72. York, E & FN Spon.

Steadman, P., H. R. Bruhnes, and B. Gakovic. 2000a. "Inferences about built form, construction and fabric in the nondomestic building stock of England and Wales." *Environmental and planning B: Planning and design* 27: 733-758.

Steadman, P., H. R. Bruhnes, S. Holtier, B. Gakovic, P. A. Rickaby, and F. E. Brown. 2000b. "A classification of built forms." *Environmental and planning B: Planning and design* 27: 73-91.

Steadman, P., H. R. Bruhnes, and P. A. Rickaby. 2000c. "An introduction to the national Non-Domestic Building Stock database." *Environmental and planning B: Planning and design* 27: 3-10.

Stocki, M., D. J. Curcija, and M. S. Bhandari. 2007. "The development of standardised whole-building assumptions for energy analysis for a set of cummercial buildings". In Proceedings of the *ASHARE Transactions*, 422-435. California.

Torcellini, P., M. Deru, B. Griffith, K. Benne, M. Halverson, D. Winiarski, and D. B. Crawley. 2008. *DOE Commercial building benchmark models*. California: National Renewable energy laboratory.

Winiarski, D., M. Halverson, and W. Jiang. 2008. "DOE's commercial building benchmarks: development of typical construction practices for building envelope and mechanical systems from the 2003 Commercial Building Energy Consumption Survey (CBECS)". In Proceedings of the *Summer study on energy efficiency buildings*, 354-369. California: American Council for an energy efficient economy (ACEEE).

XEnergy. 1987. *Study of energy end uses and conservation potential in selected segments of the commercial class - for Consolidated Edison Company*. New York: XEnergy Inc.

Table 1. Number of prototypical reference buildings developed for each building type in the existing building benchmarks.

Generation	Third						Second								First	
Building benchmark / Building type	(DOE)-Torcellini et al.(2008)	(DOE)-Deru et al.(2006)	Stocki et al (2007)	(LBL)-Huang et al.(1999)	(PNL-GRI)-Brigges et al. (1992)	(LBL-GRI)-Huang et al. (1991)	Hernandez et al.(2008)	NEOS (1994)	(LBN-PGE)-Akbari et al. (1994)	(LBN-CEC)-Akbari et al. (1989)	XEnergy (1987)	SRC (1986b)	SRC (1986a)	SRC (1985)	Leighton and Pinney (1990)	PNL (1983)
Office	3	3	2	8	30	78		2	2	2	1	2		10	6	3
Retail	1	3	1	8		39		2	1	2	1	1				2
Mall	1															
Warehouse	1	3		4				2*		2*						1
Assembly		2														
Service & safety		2														
Heath care centre	1	2														
Hospital	1		1	2		39		1	1		1	1	1			1
Nursing Home								1	1				1			
Doctor's office													1			
Large hotel	1	1		2		39		1			1	1				1
Small hotel	1	1	1	2		39		1								
Fast-food	1			2		26		1	1	1		1				
restaurant	1			2		26		1	1	1						1

Generation	Third						Second								First	
Building benchmark / Building type	(DOE)-Torcellini et al.(2008)	(DOE)-Deru et al.(2006)	Stocki et al (2007)	(LBL)-Huang et al.(1999)	(PNL-GRI)-Brigges et al. (1992)	(LBL-GRI)-Huang et al. (1991)	Hernandez et al.(2008)	NEOS (1994)	(LBN-PGE)-Akbari et al. (1994)	(LBN-CEC)-Akbari et al. (1989)	XEnergy (1987)	SRC (1986b)	SRC (1986a)	SRC (1985)	Leighton and Pinney (1990)	PNL (1983)
Supermarket	1			2		78				1	1					
Small food shop		1						1	1							
Food service		1														
General education		3		4							1	1				
College								1				1				
High school								1								1
Secondary school	1		1			39			1				1			
Primary school	1						1	1	1				1			1
College buildings													5			
Apartment			1			39										1
Prison						39										
Civic centre												1				
Theatre												1				
Church												1				1
Total	15	22	7	36	30	481	1	16	10	9	6	11	10	10	6	13
Notes				A		B										

Notes:

A. By using the location weighting factors these main 36 prototypes building are extended to 120 buildings for five cities: Minneapolis, Chicago, Washington, Los Angeles and Houston (Huang and Franconi, 1999).

B. For office and supermarket buildings, some 78 prototype buildings are formed by considering two operational schedules (12 hr and 24 hr for office buildings and 18-hr and 24-hr for

Generation	Third						Second								First	
Building benchmark / Building type	(DOE)-Torcellini et al.(2008)	(DOE)-Deru et al.(2006)	Stocki et al (2007)	(LBL)-Huang et al.(1999)	(PNL-GRI)-Brigges et al. (1992)	(LBL-GRI)-Huang et al. (1991)	Hernandez et al.(2008)	NEOS (1994)	(LBN-PGE)-Akbari et al. (1994)	(LBN-CEC)-Akbari et al. (1989)	XEnergy (1987)	SRC (1986b)	SRC (1986a)	SRC (1985)	Leighton and Pinney (1990)	PNL (1983)

supermarket buildings) for 39 prototype buildings.

*: Refrigerated and non-refrigerated warehouses are included.

Table 2. The purposes of each benchmark and its ability to be representative of the building stock.

Description / Benchmark	Purposes of development	Ability to represent national building stock
(PNL-GRI) Brigges et al. (1992)	To estimate the energy consumption used in office building stock.	Energy consumption and physical characteristics of the office building stock are represented by 30 prototype office buildings.
(LBL-GRI) Huang et al. (1991)	To estimate the energy consumption and feasibility study of the application of cogeneration technology for commercial buildings.	Energy consumption of prototype buildings is able to be extrapolated to a national energy consumption level for commercial buildings.

Benchmark \ Description	Purposes of development	Ability to represent national building stock
(LBL) Huang et al. (1999)	To quantify the contribution of building components such as the roof, wall, lighting and equipment to the heating and cooling loads in commercial buildings.	Weighting factors derived from CBECS (EIA, 1992) are used to represent the outcome of this study at the national building stock level.
Stocki et al. (2007)	To provide a reasonable range of standard buildings for comparison studies on building energy-efficiency measures for the commercial building stock.	The benchmark does not attempt to represent the existing commercial building stock.
(DOE) Deru et al. (2006)	To develop a set of benchmark buildings that meets the ASHRAE standard 90.1 (2004) to be used as a baseline for energy-efficiency measures studies in commercial buildings.	The proposed benchmark buildings represent approximately 70% of all commercial building stock.
(DOE) Torcellini et al. (2008)	To track the progress of new techniques for building energy-efficiency and providing the basis for proposing energy efficient strategies in new standards.	The proposed benchmark buildings represent approximately 70% of all commercial building stock.

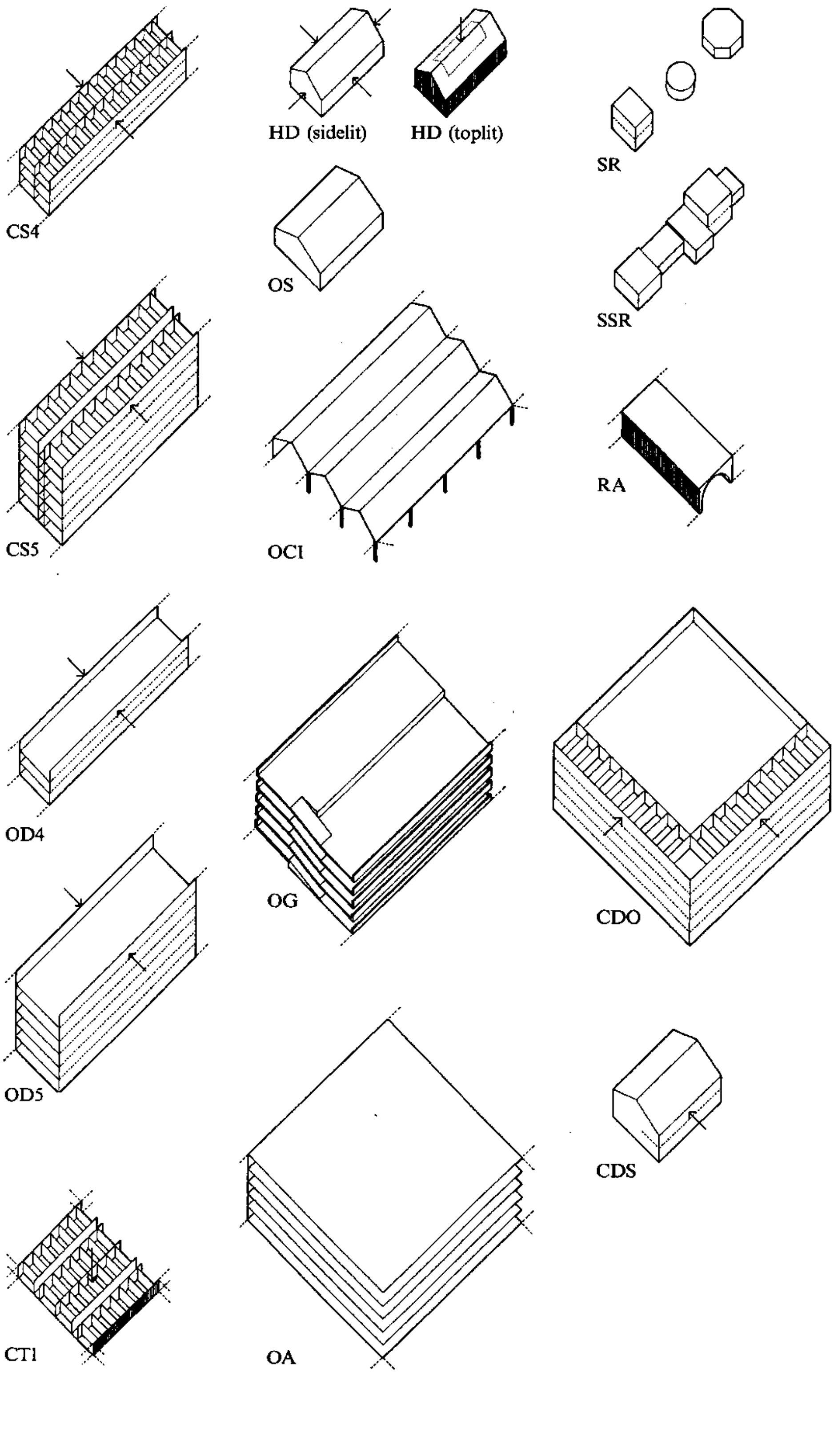

Figure 1. Built form categorisation. No diagram is shown for HA "artificially lit hall", which is equivalent to HD in form (Steadman et al. 2000b).

Table 3. Built form categorisation (Steadman et al. 2000b).

Principal form types		
Sidelit	CS4	Daylit (sidelit) cellular strip, 1 to 4 storeys
	CS5	Daylit (sidelit) cellular strip, 5 storeys or more
	OD4	Daylit (sidelit) open-plan strip, 1 to 4 storeys
	OD5	Daylit (sidelit) open-plan strip, 5 storeys or more
Deep plan	CDO	Daylit (sidelit) cellular strip around some or all edges of artificially lit or toplit
	CDH	Daylit (sidelit) cellular strip around some or all edges of artificially lit or toplit hall
	OA	Artificially lit open-plan multi-storey space
Others	CT1	Toplit cellular, single-storey
	HD	Daylit hall, either sidelit or toplit (or both)
	HA	Artificially lit hall
	OS	Open-plan space in a single shed
	OC1	Open-plan continuous single-storey space
	OG	Open-plan car parking or trucking deck
	RA	Railway arch
	SR	Single-room form
	SSR	String of single-room forms
	CDS	Open-plan shed with daylit cellular strip or strip inside, along one or more edge

Table 4. Total floor areas in different forms of offices in four cities of England (Steadman 1997).

Built form		Total floor area	
		Square Meter	Percentage
Sidelit	CS4	1643643	63.79%
	CS5	80028	3.11%
	OD4	6342	0.25%
	OD5	84373	3.27%
Deep plan	CDO	725304	28.15%
	CDH	-	-
	OA	9758	1%
Others	CT1	75	0.003%
	HD	233	0.01%
	HA	-	-
	OS	5734	0.22%
	OC1	2772	0.11%
	OG	6932	0.27%
	SR	1424	0.06%
	SSR	-	-
	RA	-	-
	CDS	9876	0.38%
Total		98762576494	100%

Table 5. Built form distribution of offices in different size bands for England and Wales. (Steadman, Bruhnes and Gakovic 2000a).

Size Band (m^2)	Built forms			
	Sidelit CS4,CS5,OD4,OD5	Deep plan CDO,CDH,OA	Other built forms	Total
0-300	70%	25%	5%	100%
300-1000	65%	33%	2%	100%
1000-3000	62%	33%	5%	100%
3000-10000	61%	33%	6%	100%
>10000	58%	30%	12%	100%

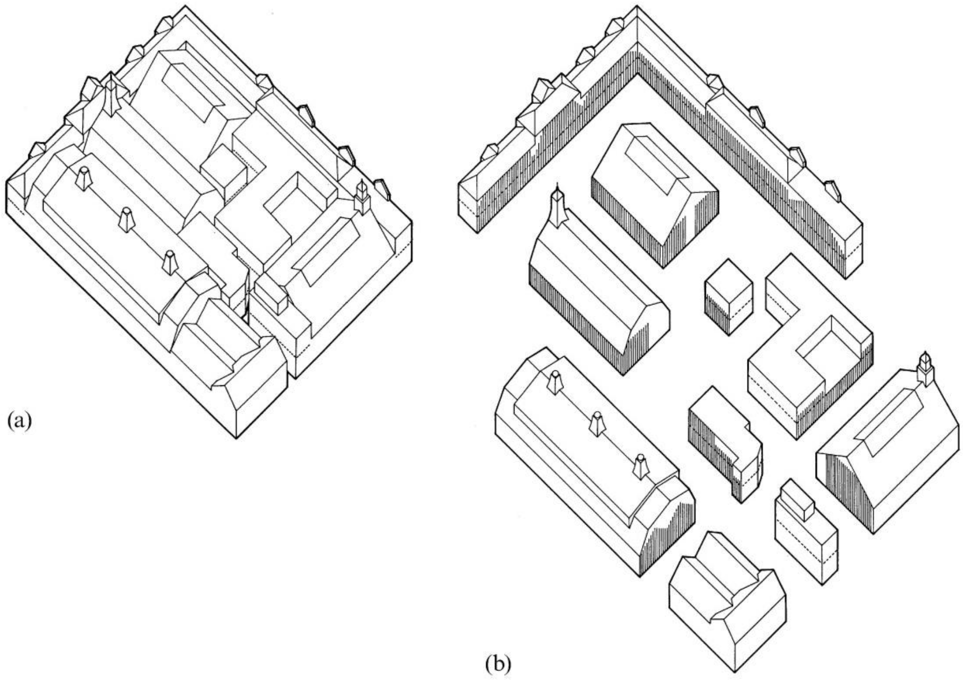

Figure 2. (a) The complex form of the 19th century public baths in Swindon, and (b) this form decomposed into simple built form elements (Steadman et al. 2000b).

Table 6. Built form distribution of offices in different size bands for England and Wales with a 95% probability.

Size Band (m^2)	Built forms			
	Sidelit	Deep plan	Other built forms	Total
	CS4,CS5	CDO		
0-300	70%	25%	5%	100%
300-1000	65%	33%	2%	100%
1000-3000	62%	33%	5%	100%
3000-10000	61%	33%	6%	100%
>10000	58%	30%	12%	100%

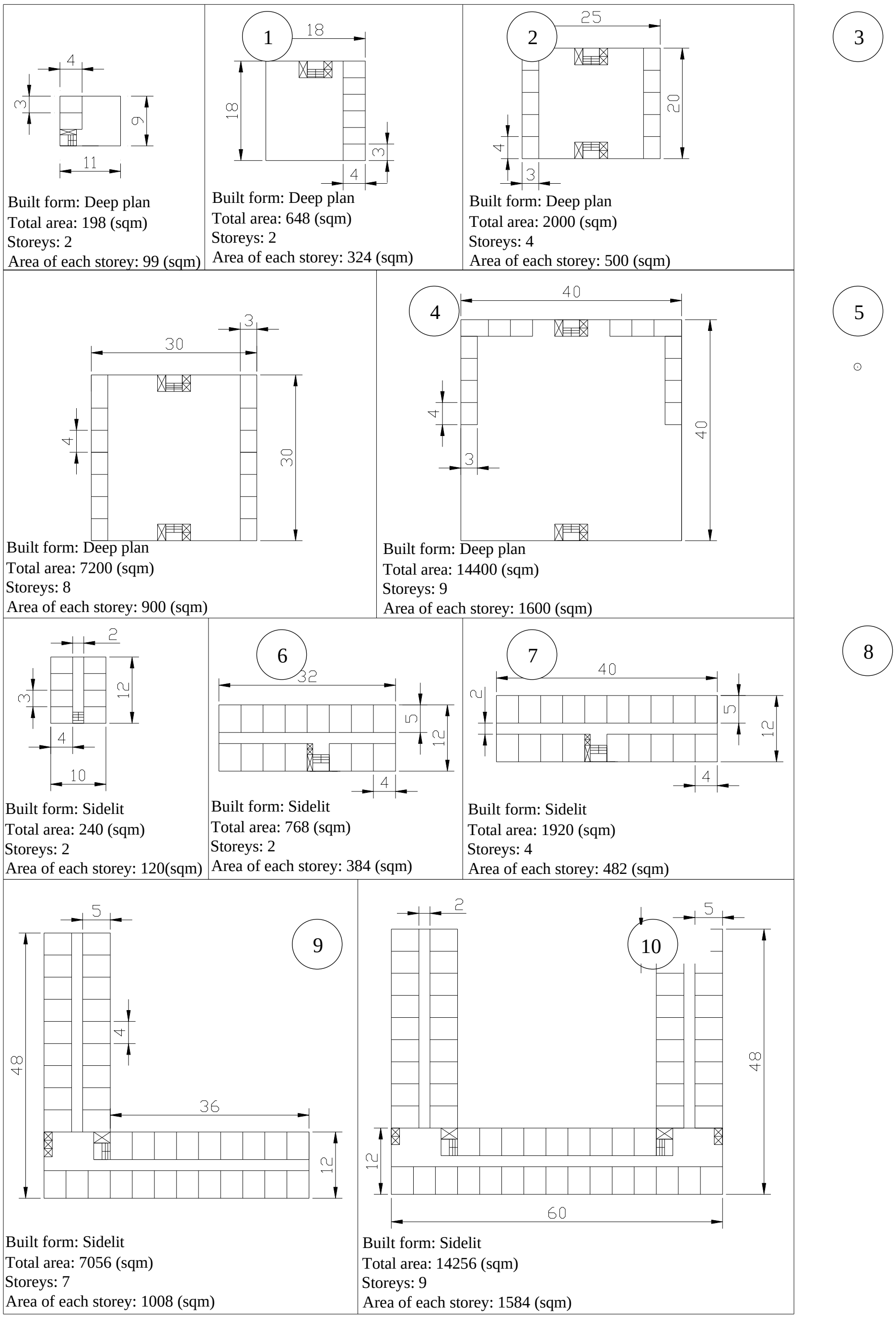

Figure 3. Ten prototypical office buildings in two principal built forms (deep plan and sidelit) and five size bands. (All dimensions in metre)

Table 7. Ratio of glazing to floor area for buildings with different types of structure (Gakovic 2000).

Categories of Building structure	Ratio of glazing per floor area
Traditional	0.13
Framed, curtain wall	0.29
Framed, deep plan	0.08
Framed, other	0.17
Sheds with rooflight	0.20
Sheds, other	0.12

Table 8. Wall, roof and windows, maximum U-values based on the historic development of the Building Regulations.

(Building regulation) take effect date-valid until	U-value (W/m^2.C			
	Wall	Roof type	Roof type	Windows
(DCLG 1965) 1965-1972	<=1.7	Pitched	<=1.42	<=4.8
		Flat	-	
(DCLG 1972) 1972-1976	<=1.7	Pitched	<=1.42	<=4.8
		Flat	-	
(DCLG 1976) 1976-1985	<=1.0	Pitched	<=0.6	<=4.8
		Flat	-	
(DCLG 1985) 1985-1990	<=0.7	Pitched	<=0.6	<=4.8
		Flat	-	
(DCLG 1990) 1990-1995	<=0.45	Pitched	<=0.45	<=3.3
		Flat	-	
(DCLG 1995) 1995-2002	<=0.35	Pitched	<=0.25	<=3.3
		Flat	<=0.45	
(DTLR 2002) 2002-2006	<=0.35	Pitched	<=0.16	<=2.2
		Flat	<=0.25	
(ODPM 2006) 2006-2010	<=035	Pitched	<=0.16	<=2.2
		Flat	<=0.25	
(HMGovernment 2010) 2010-present	<=0.28	Pitched	<=0.16	<=1.8
		Flat	<=0.18	

Table 9. Categorisation of HVAC&R systems in non-domestic building stock (Rickaby and Gorgolewski 2000).

Principal category	Sub categories	Details of sub category / energy sources
Small scale only heating	Boiler with radiator	Main gas
		Oil
		Solid fuel
		Other
	Warm air system	Main gas
		Oil
		Electricity
	Room heater	Main gas
		Solid fuel
		Bottled gas
		Paraffin
		Electricity
	Storage heater	Electricity – off pick
	Other systems	Main gas
		Electricity
Intermediate scale Central plant Only heating	Constant temperature	Main gas
		Oil
		Solid fuel
	Weather compensated by mixing valve	Main gas
		Oil
	Weather compensated by burner control	Main gas
		Oil
Packaged A/C providing mainly cooling	Store chiller	Electricity
	Mobile unit	self-contained
	Packaged unit	self-contained
	Packaged unit	single split

Principal category	Sub categories	Details of sub category / energy sources
Large scale HVAC mostly with air handling unit	Mechanical ventilation only	
	Central plant HVAC	Mechanical ventilation and heating
		Constant volume
		Variable air volume
		Dual duct
	Partially centralised	Multi-zone constant volume
		Multi-zone variable air volume
		Induction units
		Fan coil units
		Unitary heat pumps

Table 10. Occurrence of principal HVAC&R systems through the surveyed building in NDBS project (Rickaby and Gorgolewski 2000).

Principal HVAC&R system	Number of occurrence	Percent of occurrence
Small scale only heating	49	39%
Intermediate scale central plant only heating	40	31%
Packaged A/C providing mainly cooling	18	15%
Large scale HVAC&R mostly with air handling unit	19	15%
Total	126	100%

Table 11. Common HVAC&R systems (CIBSE 2005).

Principal Categories	HVAC&R systems
Local system (Unitary systems)	Through wall package
	Split unit package
	Reversible heat pump
	Variable refrigerant flow
	Night cooling
Centralised air systems (All-air systems)	Constant volume
	Variable volume
	Dual duct
	Ground air cooling
	Evaporative cooling
	Desiccant cooling
Partially centralised air/water systems (Air-water systems)	Centralised air with reheat
	Induction
	Fan coil
	Unitary heat pump
	Chilled ceiling
	Cooled floor
	Surface water
	Ground water
	Aquifer

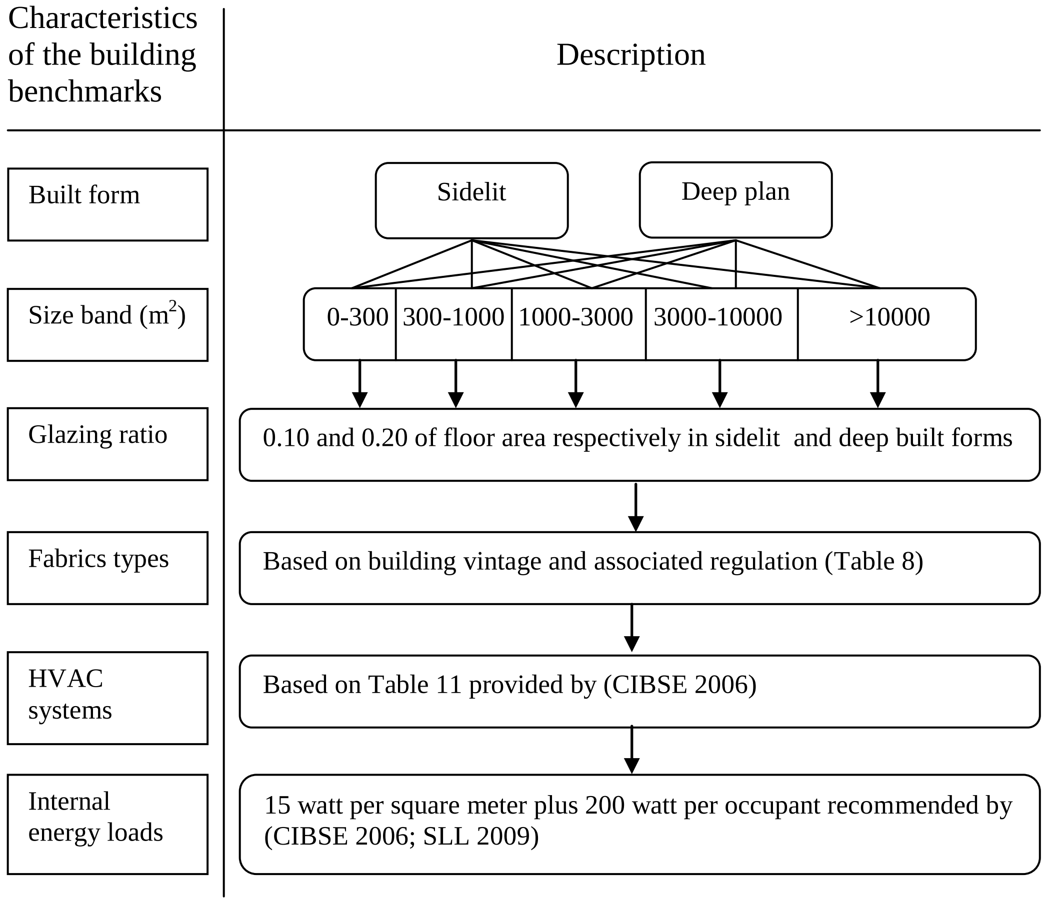

Figure 4. Structure of the proposed building benchmark.