Double Skin Façade (DSF) Technologies for UK Office Refurbishments: A Systemic Matchmaking Practice

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1. Introduction

Buildings account for up to 50% of energy consumption and greenhouse gas (GHG) emissions in the UK (Steemers, 2003) and are at the forefront of action if the carbon reduction target set by the UK government (2008) is to be met. While improving build quality is certainly important, existing buildings still form the biggest portion of the UK stock. Estimates suggest that 87% of existing buildings will still be operational by 2050 (Kelly, 2008). Refurbishing existing buildings therefore plays a dominant role in reducing GHG emissions and energy consumptions (Thomas, 2010). Existing buildings also have advantages. Their load bearing structure is still sound and reliable, providing "an ideal basis for refurbishment and re-use" (Gorse and Highfield, 2009, p. 8). They are also "often central to the fabric of everyday lifestyles, communities, cultures and livelihoods" (Ravetz, 2008, p. 4463), thus preserving established communities with a clear social advantage (Gorse and Highfield, 2009) and diminishing the need to occupy unbuilt areas. Refurbishments can also be less expensive than new constructions (Ravetz, 2008; Gorse and Highfield, 2009) and improve the quality of indoor spaces without the ecological impacts of demolition and reconstruction (Itard and Klunder, 2007; Babangida et al., 2012; Gelfand and Duncan, 2012).

Refurbishments are different between domestic and non-domestic sectors, and it is in the latter where more consolidated actions can be expected. Within the non-domestic sector, office buildings are the most common type and account for around 40% of the total energy consumption (Pérez-Lombard et al., 2008). The improvement of buildings façades is arguably an effective strategy to reduce energy consumption which also enhances indoor environment quality (Shameri et al., 2011). Most refurbishments still involve the upgrade or replacement of the existing façade with high performance windows and walls but there is a growing tendency towards applying an additional glazed façade to the existing one, which is known as Double Skin Façade (DSF) (Brunoro, 2008).

The benefits of DSFs range from acting as a thermal buffer in winter to maximising the use of natural ventilation in summer. Existing studies suggest that DSFs are capable of offering significant reduction in operational energy of a building as well as improving its thermal comfort (Gratia and De Herde, 2004; Streicher et al., 2007; Kim et al., 2013). However, the use of DSFs in refurbishment projects is yet to be explored comprehensively, and there is not sufficient information to determine how existing UK offices and DSFs would best match because not all existing buildings are suitable for an additional second skin and, equally, not all DSF technologies may suit the application to existing buildings. The need for identifying appropriate buildings and the most suitable DSF technologies that can be used, therefore, arises. The present study aims at filling such a gap.

2. Research design

Robson (2002) defines research design as what is necessary to turn research questions into projects, and proposes a framework in which the theory and purpose of the study inform the research question(s), which in turn defines methods and strategies for data collection, analysis, and sampling. In the specific context of this article, the research question (i.e. how can DSFs and existing UK offices be combined in refurbishments?) generates two distinct objectives. Figure 1 shows the research framework designed for this work. Vertically, the two objectives are dealt with in parallel by adopting appropriate methods to achieve their specific deliverables. Horizontally, their interconnections are considered to ensure that individual findings will answer, eventually, the initial question. The need for such interrelation and balance of methods, strategies and techniques to achieve the purpose of a study is emphasised by Robson (2002).

Figure 1 around here

Case study research plays an important role in this study. It is intended as a strategy to conduct research given set procedures (Proverbs and Gameson, 2008), in order to investigate a specific topic within a rather not too broad context (Fellows and Liu, 2008) through the triangulation of different sources of evidence (Proverbs and Gameson, 2008; Yin, 2009). The first objective is achieved by means of a critical literature review and an in-depth review of field surveys, followed by data analysis and interpolation. This part can be seen as what Glass (1976) defines 'secondary analysis' and 'meta-analysis'. Secondary analysis involves "the re-analysis of data for the purpose of answering new [research] questions with old data" whereas meta-analysis is understood as "the analysis of results from individual studies for the purpose of integrating the findings" (Glass, 1976, p.3). The use of secondary data is not free from objections (Smith, 2008). In this research one issue lies in the impossibility to establish the share of the stock represented by each of the benchmarks developed because different sources were used. However, secondary data also offers methodological and theoretical advantages such as "limitless opportunities for the replication, re-analysis and re-interpretation of existing research" (Smith, 2008, p.333), providing that the limitations of using secondary data are understood and declared (Smith, 2008). The literature review on office benchmarks is used as an investigative tool to identify key parameters in categorical classifications of office buildings, which are then utilised as clustering criteria to develop 22 office benchmarks. A step-by-step procedure for the visual modelling of the benchmarks is formulated and practically applied to one of the models as an example to indicate how the proposed process works.

To address the second objective, methods include literature review on the use of DSF in refurbishments combined with primary data collection, and an in-depth review of what is likely to be the existing population[1] of DSF refurbishments from across Europe. 36 buildings refurbished using DSF technology were identified across European countries and used as case studies to draw conclusions on their common features and similarities. As suggested by Gay (1996) and Suskie (1996) for small populations (N < 100), there is little point in sampling and the study should include the entire population, hence the attempt to identify all European DSF refurbishments. Data are interpolated and meta-analysed to determine suitable DSF technologies for office refurbishments from a technical point of view. This is done to identify appropriate combinations of relevant DSF parameters to use DSFs successfully in refurbishment. The findings from the 36 case studies allowed to sensibly narrow down the number of UK office benchmarks which are most suitable for such a refurbishment strategy. Suitable DSF configurations have then been tested against a large sample of mainly new DSF buildings in the UK to establish whether European findings would fit within the UK current practice. The novelty of the approach proposed here lies with the combined use of the methods explained above, which have been selected and harmonised to enhance accuracy and reliability of this work.

3. Literature Review

3.1 Existing knowledge on non-domestic benchmarks in the UK

Benchmarks[2] provide representative samples of the existing stock. The main difficulty lies in identifying the common underlying characteristics that buildings have beyond their specific differences. Such benchmarks allow both for very specific analyses, such as the influence of energy measures at a building scale, and broader studies aimed at developing new standards or energy policies (Torcellini et al., 2008). Although building benchmarks

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[1] It is not possible to claim with complete certainty that all the office buildings refurbished with DSFs across Europe have been included. However, an extensive search through different sources has been carried out over the two years duration of this research project and therefore, at the time of writing, those 36 buildings represent all known publicised DSF refurbishments.

[2] Many of the literatures reviewed have used the term benchmark to refer to reference building models, or archetypes. It is therefore this meaning that is intended when the word benchmark is used in this study.

have been used internationally in the past 30 years, the breadth and the variety of the UK stock are poorly represented (Shahrestani et al., 2013). Not only have few attempts been made to realise benchmarks for the UK but also information that allows for their development is scarce.

Leighton and Pinney (1990) pioneered the use of standard offices to investigate the effect of shading devices on energy performance. They selected a set of six real offices and provided details about the building envelopes and other geometric characteristics. Nonetheless, these prototypes cannot be considered representative of the diverse building stock as stated by Leighton and Pinney (1990). Office building benchmarks in the UK resurfaced with the Energy Efficiency Best Practice Programme in 2000. In this document (EEBPP, 2000), UK offices are grouped into four types, namely: naturally ventilated cellular (1), naturally ventilated open-plan (2), air-conditioned standard (3), and air-conditioned prestige (4) (Figure 2a). All the four types can surely be found in the UK; however the basis for such classification is not clear, nor is the share of the stock which those four types represent.

Figure 2 around here

Analysing different scenarios for office retrofit, Dascalaki and Santamouris (2002) classified European office buildings into the following five types. However, no visual representation or significant details have been provided to be used in follow-up studies and there is too little information to consider them as benchmarks.

- A: free standing/heavy/core dependent/open plan
- B: enclosed/heavy/skin dependent/cellular
- C: free standing/heavy/skin dependent/cellular
- D: free standing/light/skin dependent/open plan
- E: enclosed/light/skin dependent/cellular

Hernandez et al. (2008) proposed a methodology to develop energy benchmarks through surveys. They eventually realised a prototype representative of Irish primary schools based on 108 responses to their questionnaire (Figure 2b). Their approach uses questionnaires to gather information in a context where data are unavailable. Hernandez et al. (2008) highlighted the questionable representativeness of their benchmark, yet their prototypical building is the only one available for primary schools in British Isles. Jenkins et al. (2008, 2009) developed one office benchmark (Figure 2c), which, they claimed, represents a significant proportion of the UK office building stock (20% in terms of floor area and 9% in terms of construction age). The building is four-storey high and fully defined with respect to geometrical parameters, glazing to wall ratio, U-values, occupancy profiles and internal heat gains. However, features like the layout of internal spaces are overlooked and these characteristics may influence the energy performance and consumption. It also seems unrealistic that just one building can represent one fifth of the extremely diverse UK office building stock.

Korolija et al. (2013) argued the impossibility to identify a small number of buildings representative of the majority of existing offices, and their alternative approach, is to develop parametric archetypal benchmarks. They based their work on the most recent broad study available for England and Wales[3] and developed four building types (Figure 2d), which are, respectively, open-plan side-lit (OD), cellular side-lit (CS), open-plan artificially-lit (OA), and open-plan artificially-lit combined with cellular side-lit (CDO). They included a historical review of building elements' U-values from 1965 to identify five possible building fabrics. Values for occupancy profiles, internal heat gains, and thermal conditions are derived from European standards, CIBSE Guide A, and ASHRAE Applications Handbook (Korolija et al., 2013). In total, they identified 14 parameters which led to 3840 models. However, out of those parameters only two refer to building characteristics, namely: the building types (as per Figure 2d) and the glazing ratio (25%, 50%, and 75%).

A similar approach can be found in Shahrestani et al. (2013) who also used the NDBS database to develop ten prototypical office buildings in two major built forms (deep plan and side-lit). Their benchmarks are characterised by only two glazing to floor ratios: 0.10 and 0.20 (respectively in side-lit and deep plan built forms) that seem to be oversimplified when compared to the surveys on which they are based (e.g., Gakovic, 2000). Additionally, the authors' claim that the ten benchmarks represent 95% of office buildings with a 95% probability seems too strong an assertion to hold up. It is worth noting that both Korolija et al. (2013) and Shahrestani et al. (2013) used the same NDBS database but the models from the two studies are substantially different. This reinforces the high level of complexity involved in assessing the variety of the UK non-domestic stock. It is likely that a higher number of prototypes can offer better representativeness at the cost of more complex and challenging analyses (Leighton and Pinney, 1990), and, as Shahrestani et al. (2013, p.46) pointed out, "the selection of a reasonable benchmark for a specific research aim involves a trade-off between the number of prototypical buildings and the extent to which the prototypical buildings should represent the building stock".

[3] It is the Non-Domestic Building Stock (NDBS); the most significant research project on energy use prior to CARB that was carried out more than a decade ago (1991–2000) for the Department of the Environment, Transport and the Regions. Being the most detailed and up-to-date information available, it is no surprise that the NDBS database forms a reliable basis for all succeeding studies on UK office building stock – including this research.

3.2 Double Skin Façades

Several definitions of DSFs exist (Compagno, 1999; Oesterle et al., 2001; Claessens and De Herde, 2006; Roth et al., 2007; Brunoro, 2008). In this study, a DSF is a hybrid system made of an external glazed skin added to the actual building façade, which constitutes the inner skin. The two layers are separated by an air cavity, which has fixed or controlled inlets and outlets and may or may not incorporate shading devices. The cavity may act either as a thermal buffer zone, as a ventilation channel or, more often, as a combination of the two. It may be naturally ventilated (NV) or mechanically ventilated (MV), and varies in width and height. All these parameters contribute to the defining dimensions of a DSF. The width, generally distinguished as narrow and wide cavity, influences the airflow and velocity, and the thermal buffer behaviour. Although some numerical figures to distinguish between the two exist (Poirazis, 2004), a general agreement still lacks. The Belgian Building Research Institute (BBRI, 2002) classifies narrow cavities as those with a width below 20 cm, whilst wide cavities are characterised by a width over 50 cm, thus leaving out all the widths in between. In this research, the possibility to access the cavity emerged as a key distinguishing element from consultations with European DSF practitioners and 40cm represents the minimum width required for maintenance purposes. Therefore, 40cm is assumed as the threshold between narrow and wide cavities.

The partitioning of the cavity is used to define the 'geometry' of DSF. The types pioneered by Oesterle et al. (2001), which have broadly been adopted since then, include:

- Box windows (BW)
- Corridor (C)
- Shaft box (SB), and
- Multi-storey (MS)

A further important parameter of the DSF involves the origin of the airflow (Saelens et al., 2003) and its destination (Loncour et al., 2004; Saelens et al., 2003). These elements define the airflow concepts as summarised by Haase et al. (2009), namely: supply air (SA), exhaust air (EA), air buffer (AB), external air curtain (EAC), and internal air curtain (IAC) (Haase et al., 2009). All these key defining elements are grouped into the classification of DSFs developed for this research (Figure 3).

Figure 3 around here

3.3 Double Skin Façades and Refurbishments

Haase and Wigenstad (2011) stated that the literature of DSFs for office refurbishments is still in its infancy and little has changed since then. Artmann et al. (2004) investigated summer overheating in the context of DSF refurbishments and concluded that venetian blinds are a suitable means to address overheating, identifying their optimal location further away from the inner skin. The authors also recommended operable cavity inlets and outlets to control airflow better. Blumenberg et al. (2006b) also studied the use of DSFs in refurbishments and concluded that the overall heat transfer coefficient of the building envelope could be improved by up to 50%. Their results also indicated that natural ventilation can be used up to 60% of the year – implying additional energy savings. Furthermore, the DSF doubles the noise reduction potential of single skin façades. Ebbert and Knaack (2007) developed an innovative type of DSF for refurbishments where building services are integrated. A case study based on a high-rise office building built in 1970 showed energy savings of up to 75% (Ebbert and Knaack, 2007). Cakmanus (2007) evaluated three different DSF technologies to refurbish a 14-storey office building in Turkey. The multi-storey DSF shows a 45% energy saving potential and the minimum payback period of less than 7 years. Positive results in Turkey have also been found by Yilmaz and Cetinta (2005) who reported a 40% higher energy consumption for a single skin façade compared to a DSF.

Brunoro (2007; 2008) and Brunoro and Rinaldi (2011) extensively explored sustainable technologies for the improvement of existing building envelopes in Italy. The DSF is the category mainly analysed in their works. They concluded that DSFs are suitable to be either added to the existing façade or to completely replace it along with a new inner skin. The sole addition of the second skin is more economically feasible and, in many cases, can be done while the building is still operational. Due to higher costs attributed to the DSF, its applicability is mostly encouraged for large office buildings (Brunoro, 2007; 2008). An interesting outcome lies in the comparison between applicability and economic viability of naturally against mechanically ventilated DSFs . The former score highly for applicability with low costs whereas the latter prove to be the opposite (Brunoro, 2008). Brunoro and Rinaldi (2011) analysed three buildings refurbished with DSFs in Northern Italy. Reductions in energy consumption, as a result of the second skin, are all consistent, with values in the 30% - 40% range and a payback period of 20-25 years (Brunoro and Rinaldi, 2011).

Wolf (2011) reported on three buildings refurbished with DSFs in Belgium. The use of DSFs has improved the energy performance of all three buildings but numerical figures are available only for one with results indicating a 50% operational energy reduction In the UK, ARUP adopted a DSF for the refurbishment of their headquarter, in London. The DSF has a multi-storey geometry with different airflow concepts (Gissen, 2005). One specific office in the building has been monitored and data on occupants' satisfaction were collected (Hernandez Tascon, 2008). The users showed satisfaction in terms of daylighting and air-tightness but glare has been reported as a problem. The reason could be found in the type of shading devices installed, since the louvers in the cavity are fixed and thus not very effective in preventing glare in mid-seasons. Baird and Dykes (2012) reported on case studies of façade refurbishments from the occupants' satisfaction point of view. One of the buildings they examined has a DSF and the overall performance after renovation was rated high for comfort and environmental factors, as well as design, productivity and health factors. Baird and Dykes (2012, p.1) concluded that "retrofits can achieve very high performance ratings, they can also surpass new design from the users' perspective". Haase and Wigenstad (2011) investigated the use of a multi-storey DSF for refurbishment of commercial buildings in Norway with two glazing options for the outer skin: a double-glazed unit and a single glass pane. Energy savings range between 49% and 59%, with the double-glazed unit performing better than the single glass pane. Kim et al. (2013) studied the use of DSFs in the renovation of a 5-storey building with a focus on different cavity widths and the use of shading devices. They showed that with a 90cm cavity, the annual heating and cooling energy compared to the base case can be reduced by up to 38%, which increases to 51% if the DSF is equipped with adequate shading devices. Further evidence of the benefits of DSFs for refurbishment of existing offices can be found in Rey (2004), who evaluated three refurbishment strategies (including DSFs) for three different buildings' ages – 1950s, 1960-1975, and 1973-1990. The study concludes that for buildings built in 1960-1990 period – which are also "those most commonly encountered in UK non-domestic refurbishments" (CIBSE, 2013 p.3) – DSFs score the highest performance in most of the analysed scenarios. The use of DSFs has also been investigated by Ballestini et al. (2005) and Asdrubali et al. (2013) in Italy promising interesting energy savings for the rehabilitation of old industrial buildings and multi-residential buildings, respectively.

4. Case studies of DSF refurbishments across Europe

A number of buildings across Europe have been refurbished with DSFs; yet, such body of evidence has not been systematically reviewed. A total number of 36 buildings refurbished with DSF technologies were found over the years of this research and are shown in Table 1. Cavity ventilation and the airflow concepts are indicated in the table using the same codes introduced in Figure 3. Furthermore, the effectiveness[4] of the refurbishment has also been

[4] The effectivness could refer to improvement of energy consumption of the building to which the DSF has been applied, its overall heat transfer coefficient, the indoor thermal comfort, improved natural ventilation, enhanced sound insulation, glare reduction, higher deployment of daylighting, increased users' comfort in terms of control over the openings, to name a few.

reported distinghuishing between 'perceived' effectiveness where qualitative assesment was used vs. 'assessed' effectiveness measured through quantitative assessment.

Table 1 around here

Information in Table 1 allows for useful analyses. In terms of geometry, the most common type is multi-storey probably due to its conceptual simplicity as well as its easier installation because of less partitioning within the cavity, which however requires careful design to avoid overheating the upper floors. Few corridor geometries were used in major refurbishments where the building was stripped down to its structural elements. Further, 78% of the buildings have naturally ventilated cavity, about 17% have mixed-mode ventilation, and only 5% show a mechanically ventilated cavity. When a naturally ventilated cavity is coupled with a 'supply-air' mode, the building can be considered naturally ventilated. This happens in over 60% of the buildings and confirms that satisfactory natural ventilation of an office building merely through proper DSF design is possible. This is a particularly positive outcome in this study because existing UK offices are mostly naturally ventilated (CIBSE, 2013) and also in light of the recommendations to maximise the use of natural ventilation over mechanical systems with the aim of reducing buildings' energy demands and CO_2 emissions (CIBSE, 2013). Indeed, when mechanical cooling is installed into UK existing offices it accounts for up to 30% of the total CO_2 emissions (Barlow and Fiala, 2007).

Data about the airflow concepts in Table 1 show the intrinsic flexibility of DSF. Over 90% of the buildings benefit from the combination of two or more airflow strategies, which helps understand how natural ventilation is likely to work throughout the year. For instance, 'air-buffer' and 'supply-air' behaviours can be used in winter to preheat air for the indoor spaces, whereas 'exhaust-air' and 'external-air-curtain' can be coupled in summer to cool the inner skin and extract excessive heat from the indoors. It is worth noting that an 'internal-air-curtain' mode is only observed in two cases, both related to major refurbishments, where the buildings were stripped back to their essential structure. This is because such mode needs to be planned from the beginning and incorporated within the Heating, Ventilation, and Air Conditioning (HVAC) system. Another interesting outcome is that 'air-buffer' and 'external-air-curtain' are often found combined. Such a peculiarity indicates that some forms of Building Management System (BMS) is in place because cavity inlets and outlets need to be closed for the 'air-buffer' mode but open for the 'external-air-curtain'. This conforms to recommendations found in the literature for a better control of the ventilation channel (e.g., Artmann et al., 2004).

Additional benefits of a DSF refurbishment emerging from the case studies are the possibility to retain the original façade and to often refurbish the building while it is still occupied. Finally, DSFs can be (and have been) applied to various inner skins, either light or heavy cladding, masonry walls, curtain walls, or façades with historical or heritage merit, worth preserving.

5. Findings

5.1 Benchmarks for the UK existing office stock

In this section, key elements of categorical classifications of office buildings in the UK are used as a basis to build upon the available body of knowledge to further develop the UK office benchmarks. As in two of the studies reviewed in Section 3.1, this research uses data from the NDBS project, which thoroughly addressed both the complexity and the variety of Britain's non-domestic stock (Steadman et al., 2000c). Brown et al. (2000) surveyed 3350 addresses in four representative towns totalling about 4 million m² to provide a classification of built forms that "contains reasonable numbers of all but the rarest and most unusual building types" (Steadman et al., 2000a, p.734). Figure 4 shows a synopsis of key parameters emerged from the literature reviewed and field surveys clustered as per their importance in this study. The hierarchical use of those parameters is shown in Figure 5.

Figure 4 around here

Figure 5 around here

The building parameters in Figure 4, through the process articulated in Figure 5, have been used to develop 22 benchmarks as indicated in Table 2. Interpolations and analyses done on the available field surveys are given in Appendix A. As a whole, the benchmarks aim to represent 75% of the UK existing office stock. Numerical values used for window-to-floor and wall-to-floor ratios are adopted from both Steadman et al. (2000a) and Gakovic (2000), which were used to calculate the third ratio. This has been done to check the consistency throughout the ratio values, and results comply with each other.

Table 2 around here

There are no two identical combinations and each office benchmark is a unique mix of the above parameters, which exclude the age of the building. Rather, each of the five age bands (and their respective sets of U-values) can be combined with each of the benchmarks leading to 110 configurations – although some combinations are more likely to occur than the others. To set appropriate U-values in a dynamic energy simulation, the envelope elements to be considered are: external walls, glazing, roof and ground floor. Sources of information in this respect are Approved Documents from 1965 onwards. This approach is not unprecedented (CIBSE, 2013; Korolija et al., 2013; Shahrestani et al., 2013). According to the Office of the Deputy Prime Minister (2005), around 90% of the total office floor spaces fall within the age bands considered in this research. Once the age of the building is known, corresponding U-values can be applied. Alternatively, having different age bands allows for broader analyses, e.g. to assess how a refurbishment strategy would work according to the age of the building it is applied to. Due to the age of the field surveys, it was deemed appropriate to consider building regulations available up to the date of surveys to increase consistency. In other words, the present work is limited to buildings up to the year 2000 as those are most likely to be refurbished in the near future.

The development of the benchmark No.1 has been used as an example to demonstrate the step-by-step procedure as articulated in Appendix B leading to the model in Figure 6.

Figure 6 around here

Few simplifications have been applied throughout the design process. Firstly, the layout of internal spaces is identical for all floors. This aspect is not always observed in reality but:

(1) No data are available for a more realistic approach or to suggest a significant enough alternative for internal layout;
(2) Small variations to internal spaces do not imply great variations to thermal performances of buildings.

Secondly, means of vertical access e.g. lifts and staircases and their corresponding areas have not been included in the model. The main reason lies in the variation that these may have from one case to the other, making it hard to extrapolate one identical occurrence with any reasonable frequency. Similar assumptions are intrinsic to the development of benchmarks and are also found in Steadman et al. (2000b) and Korolija et al. (2013).

5.2 Benchmarks for DSF-related studies

Section 3.3 and Section 4 allowed the assessment of current practice and existing trends of DSF refurbishment in Europe. Such information allows to combine existing knowledge of DSF refurbishment with the benchmarks developed for UK offices. With respect to suitable benchmarks for a DSF refurbishment, the case studies show consistent trends in several aspects. All except two buildings have skeletal structure, which was expected considering all buildings are large, medium- to high-rise offices. Such information places buildings likely to be refurbished with a DSF within the last size band in Table 2 (10,000 m² - 30,000 m²), which seems to be skewed towards the lower bound of the floor area range.

In terms of number of storeys, apart from two exceptionally high buildings (22 and 34 storeys), all others belong to the medium- to high-rise band. This reinforces the choice of considering benchmarks from No.17 to No.22, which are the only ones with a compatible number of storeys. Regarding the external façade of the analysed case studies, it is also possible to identify two main groups. There are buildings characterised by heavy cladding and windows for ventilation, and others that, instead, have a curtain wall system. Such distinction is often linked to the internal layout of the building. Façades with heavy cladding and operable windows for natural ventilation are most likely to be found in cellular offices whereas curtain walling seems more common amongst open plan layouts. Such idiosyncrasy was also observed in the existing UK stock which showed that open-space offices have deeper plans characterised by a higher glazing-to-wall ratio to maximise daylight and solar gain. Open-plan curtain wall offices also present another distinctive trait. In most cases they are made of four principal areas built around a central core used as a circulation/access zone. Once again, this internal layout is to maximise daylighting. Therefore, by taking into account the conclusions drawn from the case studies analysed, it seems that benchmarks No.18 and No.22 are those most suitable to be refurbished with DSF in the UK. Table 3 and Table 4 present the main building characteristics, which allow the development of the 3D benchmarks following the step-by-step procedure developed in this study (Appendix B).

Table 3 around here

Table 4 around here

5.3 Double Skin Façades in the UK

The few UK-based publications contradict a fairly wide use of DSFs in Britain. In order to check the outcome from European case studies against the UK context and to understand the state-of-the-art and current practice of DSFs in the country, this research analysed a large sample of DSF buildings in the UK. In total 43 buildings (Appendix C) have been retrieved through different sources. The buildings assessed have been clustered according to the DSF geometry and further divided into four groups related to the number of storeys (Table 5).

Table 5 around here

It is worth noting that the totals sum up to more than 43 buildings. This is due both to the complexity and flexibility of the DSF. In some projects (e.g. Helicon Building, London – Appendix C) both multi-storey and corridor geometries are used within the same building. From Table 5, it can be seen that multi-storey DSFs represent the most common type across all storey-ranges, being used in nearly 60% of the UK buildings analysed. This confirms the suitability of multi-storey geometry to extremely diverse buildings in terms of height, built form, façade characteristics and materials, etc., as noted already from the analysis of the European case studies. Additionally, half of the buildings are between five- to ten-storey high as are the majority of European DSF-refurbished buildings. Corridor geometries are less used, and they seem to fit more medium- to high-rise office buildings. Very few examples of box windows and shaft-box façades exist. Eventually, five buildings (3- to 9-storey high) out of the forty-three buildings have been refurbished using a DSF, and four of them have a multi-storey geometry. This is coherent with the situation at European level, signalling that DSF technologies are gaining momentum in refurbishment, especially in medium- to high-rise offices and often coupled with multi-storey geometries.

6. Conclusions

This study contributes to deepening our understanding of the UK office building stock and constitutes a useful basis for research related to and assessment of the improvement of that stock, both at the single building level and at energy policy levels—with a specific focus on façade and building fabric refurbishments. 22 benchmarks, representing 75% of the UK existing office stock, have been developed based on review of the existing literature, available field surveys, and data analysis and interpolation. Each of the benchmarks is a unique combination of key classifying parameters for UK offices, i.e. structural systems, floor areas, external walls and glazing systems, number of storeys, roof type, and ratios between wall, floor, and glazed areas. Additionally, a review of the building regulations allows for combining each benchmark with a specific age band and its corresponding U-values for the building fabric in order to better define benchmarks within specific construction periods, for a total of 110 different combinations. The benchmarks have practical implications for all those involved in research related to the existing office stock of the UK and provide a reliable frame of reference to model different refurbishment scenarios for different age bands, to optimise a façade refurbishment for specific office types, or to study the environmental impacts of one or multiple renovation strategies – to name a few of practical applications of this study.

In exploring and assessing the suitability of the existing UK office stock for DSF refurbishment, this study has studied 36 cases of DSF refurbishments and has found that two out of the 22 benchmarks are more suitable for such a refurbishment approach due to their built form, façade characteristics, number of storeys, and layout. The two office models identified in Section 5.2 embed two important characteristics. Firstly, they are accurate representations of the actual office building stock in the UK and, specifically, can represent up to 40% of existing large UK offices in terms of façade characteristics (structure and materials). Secondly, they are also more likely to be considered for DSF refurbishment since they have been selected out of a comparative analysis with common features emerging from the analysis of the 36 European DSF refurbishments.

Guidelines on which DSF configurations appear to be best suited for an office refurbishment have also been formulated. Specifically, multi-storey DSFs with naturally ventilated cavities appear most suitable for UK office refurbishments and can fit a diversity of buildings. Not only does such a choice appear reasonable in terms of building physics and DSF working mechanisms, but it also seems to promise higher success of the refurbishment project. Findings also highlighted that, in cases in which the existing façade needs, or is intended, to be retained, the DSF can literally act as an added smart-clothing layer over the existing building façade. This represents the best possible outcome of a careful DSF design (Oesterle et al., 2001; Kaluarachchi et al., 2005). The 'smartness' of the DSF comes directly from its intrinsic flexibility, which allows for incorporation of multiple airflow concepts within a single DSF design as the cases studied clearly revealed. A further important finding that emerged from this research is the added value of BMSs in the design and operation of DSFs, even in the basic form of operable inlets and outlets of the cavity to adjust the DSF working mechanisms according to daily and seasonal climatic variations. In cases where major refurbishments were carried out, i.e. where the building is stripped off to its structural elements, corridor DSFs coupled with HVAC system and mixed ventilation of the cavity represent a further option to be considered and evaluated other than multi-storey geometry as this combination could offer higher performance of the DSF.

Outcomes from the case studies of European buildings refurbished with DSFs have been checked against the current practice of mainly new DSFs buildings in the UK. Results show common trends and similarities at EU and the UK levels, thus allowing the application of EU findings to the UK context. These findings do not replace however a careful evaluation of multiple DSF choices when approaching a refurbishment project, nor do they intend to be a blanket solution regardless of buildings' specific characteristics and constraints. Rather, they point out a more manageable and thoroughly defined set of options to evaluate when approaching this new, important field in both research and practice. Other than such applications, the reviews of the European DSF case studies and UK DSF buildings provide substantial information which was not previously available in the literature and can inform future DSF-related studies.

The available field surveys used in this study date back to the year 2000; in other words, buildings built in the last 15 years are excluded from the present work. Although this constitutes a limitation of this study, the scope of this research is to consider buildings in the need of refurbishment, which is hardly the case for newer buildings especially those under 15 years old. Additionally, the use and interpolation of secondary data from different sources do not allow the attribution of a share of the stock to each of the benchmarks. Moreover, few simplifications and assumptions had to be made in developing the benchmarks to favour applicability and coverage of a broader range of the stock. Finally, the benchmarks developed are not parametric models although variations can be obtained using different floor areas within each size band. Future research could foster the development of UK office benchmarks by removing some of the limitations/simplifications mentioned above, or by integrating newer field surveys when they will become available. Parametrisation of the models devised for this study also forms a basis for future research. With respect to DSF refurbishments, detailed in-depth case studies, monitoring of real buildings and environmental impact assessment are all interesting avenues for future work.

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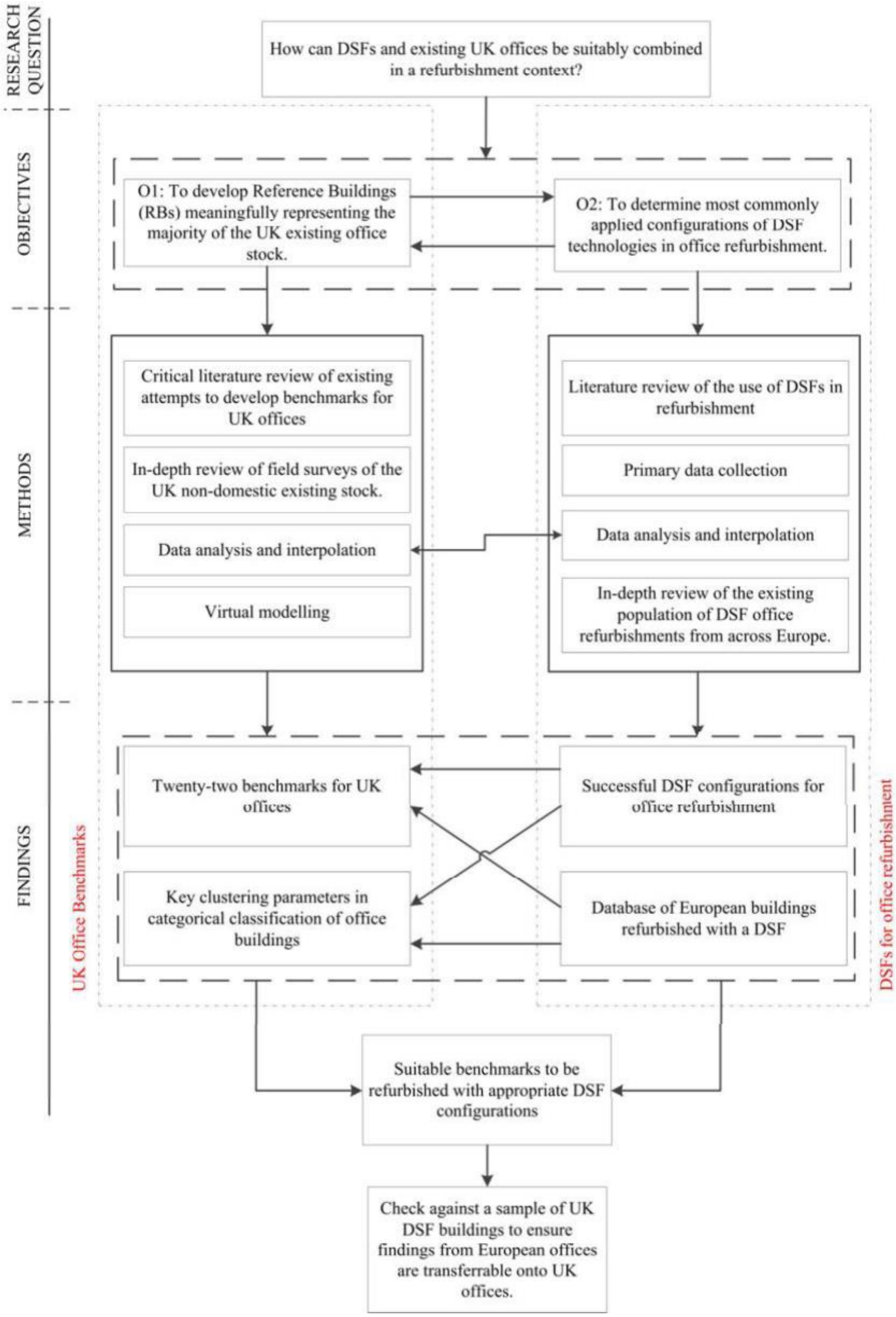


Figure 1 – Framework of the research design

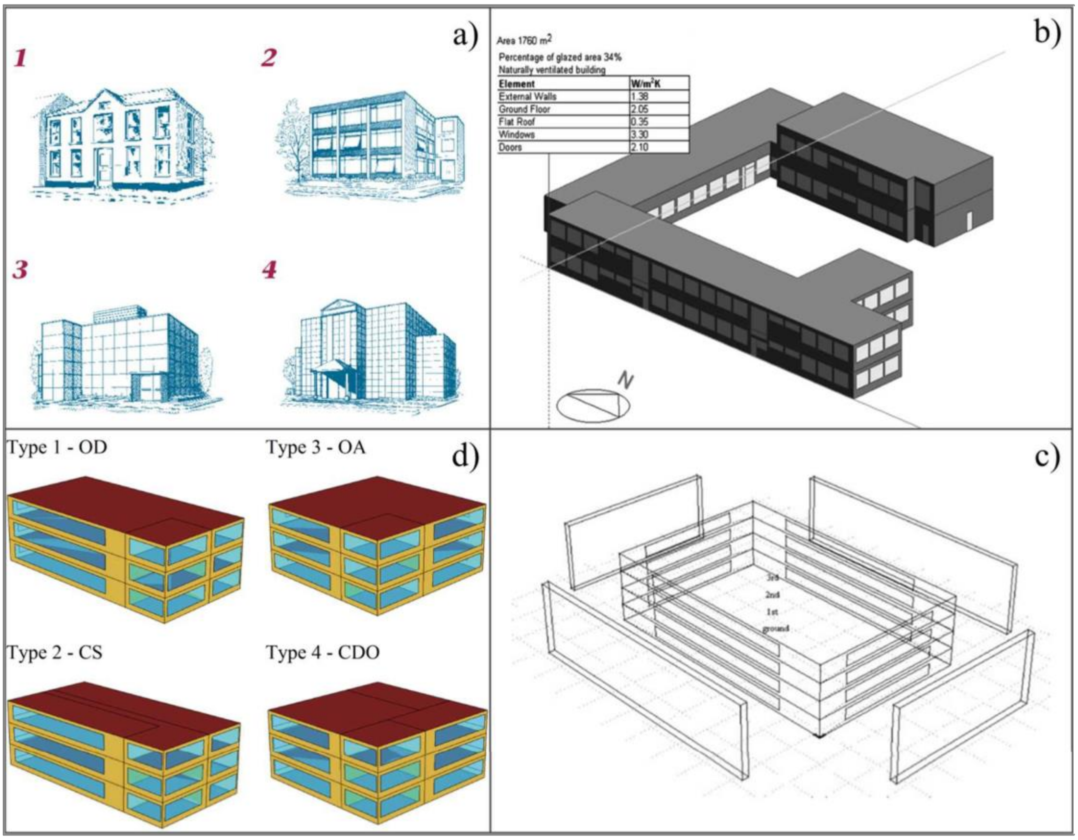


Figure 2 – a) generic office types (EEBPP, 2000); b) school sample model (Hernandez et al., 2008); c) four-storey office building (Jenkins et al., 2008); d) office building model archetypes (Korolija et al., 2013).

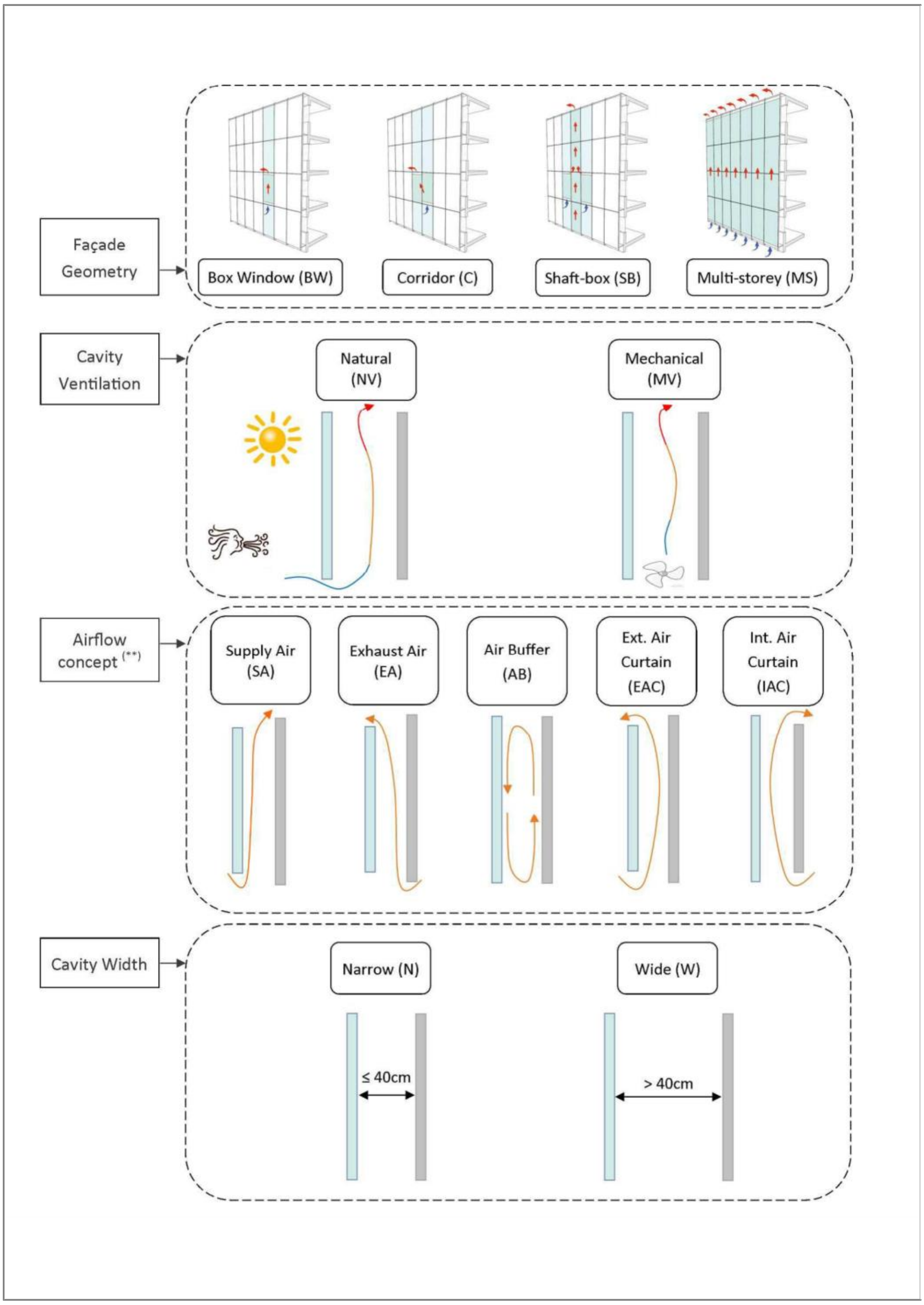


Figure 3 – Classification of DSFs – (**) airflow concepts after Haase et al. (2009)

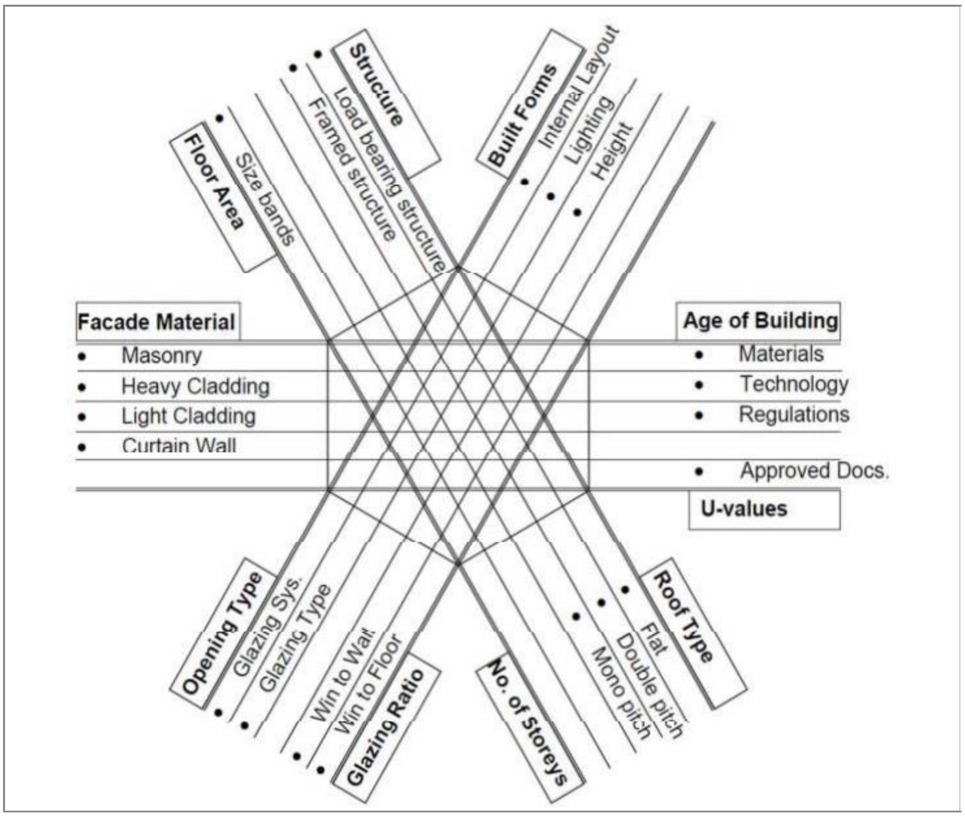


Figure 4 – Correlation between different parameters articulated in the existing literature with reference to office building typological studies

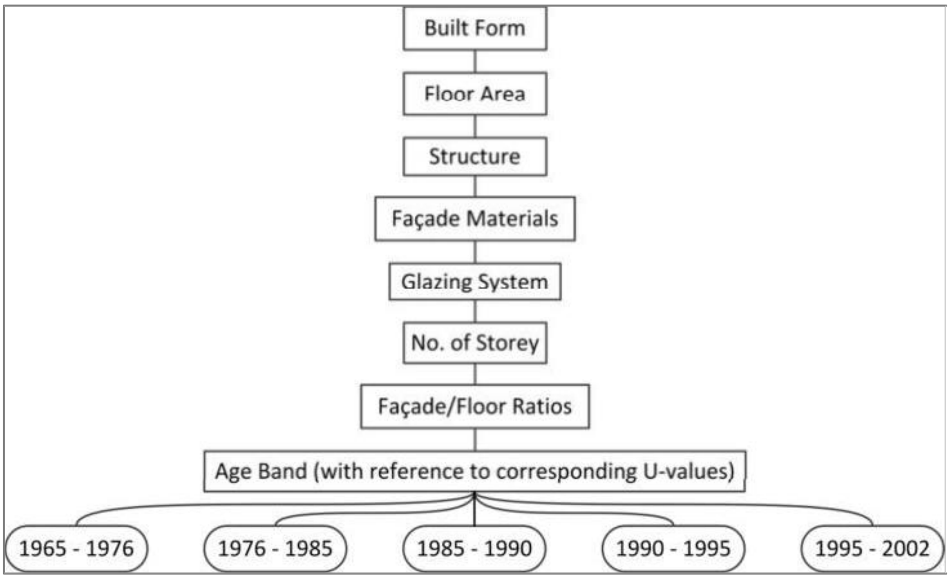


Figure 5 – Hierarchy of the parameters used to develop the benchmarks

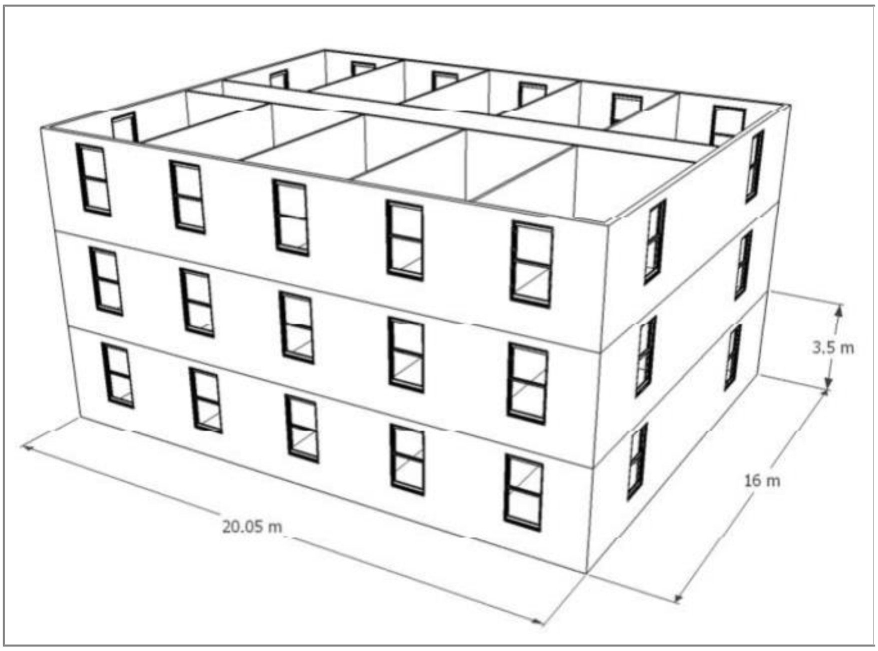


Figure 6 - Graphic visualisation of benchmark No. 1 (flat roof omitted to show the internal layout)

Table 1 - Case studies of DSF refurbishments across Europe

Item	Source	Building Location	Country	No. of Storey	Structure	Additional Information	DSF Geometry	Cavity(*)		Ventilation Regimes (*)				Effectiveness of the Refurbishment	
														Perceived	Assessed
1	(Blumenberg et al., 2006b)	IBM Office Building, Vienna	Austria	13	Framed	Original Façade: Curtain Wall	MS	NV		SA	EA			X	
2	(Wolf, 2011)	Berlayment Building, Brussels	Belgium	14	Framed	Original Façade: Heavy Cladding	MS	NV					EAC		X
3	(Wolf, 2011)	Charlemagne Building, Brussels	Belgium	15	Framed	Original Façade: Heavy Cladding	MS	NV					EAC		X
4	(Wolf, 2011)	Madou Plaza Tower, Brussels	Belgium	34	Framed	Original Façade: Heavy Cladding	MS	NV		SA	EA		EAC		X
5	(Artmann et al., 2004)	Munchner Ruckversicherung, Munich	Germany	5	Framed	Reduced to the ferro-concrete skeleton	C	NV				AB		X	
6	(Artmann et al., 2004)	Ministry for Regional Development & Environmental Affairs	Germany	7	Framed	Existing Façade: heavy cladding and windows	C	NV		SA	EA			X	
7	(Ebbert, 2010)	Stadtsparkasse, Dusseldorf	Germany	15	Framed	Reduced to the ferro-concrete skeleton	C	NV	MV	SA	EA		EAC		
8	(Hamza, 2004; Blumenberg et al., 2006b)	Deutsche Bank, Unter den Linden, Berlin	Germany	6	Load Bearing	Original Façade: bricks and windows	MS	NV				AB		X	X
9	(Blumenberg et al., 2006a)	Universität Mannheim	Germany	3	Framed	Original Façade: curtain walling	MS	NV		SA	EA	AB	EAC		
10	(Ebbert, 2010)	Dorma GmbH HQ, Ennepetal	Germany	9	Framed	Original Façade: heavy cladding (pre)/ curtain wall (post)	MS	NV		SA			EAC		X
11	(Artmann et al., 2004)	Kreishaus Bad Segeberg	Germany	10	Framed	Existing Façade: masonry and windows	MS	NV		SA	EA	AB		X	
12	(Pasquay, 2004)	Siemens Building, Dortmund	Germany	11	Framed	Original Façade: Curtain Wall	MS	NV		SA	EA		EAC		X
13	(Oesterle et al., 2001)	BML HQ Building, Bonn	Germany	13	Framed	///	BW	NV		SA	EA	AB		X	

Item	Source	Building Location	Country	No. of Storey	Structure	Additional Information	DSF Geometry	Cavity (*)		Ventilation Regimes (*)					Effectiveness of the Refurbishment	
															Perceived	Assessed
14	(Oesterle et al., 2001)	Gladbacher Bank, Mönchengladbach	Germany	5	Framed	Original Façade: Heavy Cladding and Window	SB	NV		SA	EA					X
15	(Eicker et al., 2008)	Zeppelin Carre', Stuttgart	Germany	14	Framed	Original Façade: Curtain Wall	C	NV		SA	EA		EAC		X	
16	(Clemmetsen et al., 2000)	GSW Headquarters, Berlin	Germany	22	Framed	Original Façade: Curtain Wall	MS	NV		SA	EA	AB	EAC			X
17	(Brunoro, 2007; Brunoro and Rinaldi, 2011)	Johnsons HQ, Milan	Italy	6	Framed	Original Façade: heavy cladding, windows and metal frame	MS	NV	MV	SA	EA	AB	EAC			X
18	(Brunoro, 2008)	Milan	Italy	7	Framed	Original Façade: Heavy Cladding and Window	MS	NV					EAC			X
19	(Brunoro and Rinaldi, 2011)	Torno Intnl HQ, Milan	Italy	8	Framed	Original Façade: Masonry and Window	MS	NV				AB	EAC			X
20	(Brunoro and Rinaldi, 2011)	Hines HQ, Milan	Italy	8	Framed	Original Façade: Cladding and Window	MS	NV					EAC			X
21	(Nastri, 2014)	RCS Mediagroup HQ, Milan	Italy	7	Framed	///	MS	NV					EAC		X	
22	(Marradi, 2013)	ICO Central Plant, Ivrea	Italy	7	Framed	Original Façade: concrete and windows	MS	NV		SA	EA	AB	EAC		X	
23	(Marradi, 2013)	Guna Building, Milan	Italy	5	Framed	Original Façade: masonry wall and windows	MS	NV					EAC			X
24	(Hamza, 2004)	AMOCO Building, University of Trondheim	Norway	5	Load Bearing	Original Façade: prefabricated concrete elements	MS	NV				AB	EAC			X
25	(Lee et al., 2002; Hamza, 2004)	Swiss Insurance Company SUVA HQ, Basel	Switzerland	6	Framed	Original Façade: walls and windows	C	NV			EA	AB	EAC			X
26	(Ebbert, 2010)	Mobimo Building, Zurich	Switzerland	12	Framed	Original Façade: steel columns, asbestos, glazing	MS	NV	MV			AB	EAC	IAC	X	
27	(Ebbert, 2010)	Ministry of Finance, The Hague	The Netherlands	5	Framed	Original Façade: concrete parapets and windows	C		MV	SA		AB			X	

Item	Source	Building Location	Country	No. of Storey	Structure	Additional Information	DSF Geometry	Cavity[*]		Ventilation Regimes [*]					Effectiveness of the Refurbishment	
															Perceived	Assessed
28	(Kurstjens et al., 2004)	Albatross Building	The Netherlands	8	Framed	Original Façade: Aluminium Frame, Single glazing	MS	NV		SA	EA		EAC			X
29	(Ebbert and Knaack, 2007)	Sparkasse Ludwigshafen, Delft	The Netherlands	10	Framed	Existing Façade not removed	MS	NV		SA	EA					X
30	(Ebbert, 2010)	Westraven Gebouw, Utrecht	The Netherlands	19	Framed	Original Façade: sealed windows and prefabricated parapets	MS	NV	MV	SA	EA				X	
31	(Cakmanus, 2007)	Ankara	Turkey	14	Framed	Original Façade: heavy cladding – Internal Layout: Cellular and Open Plan Spaces	MS	NV		SA	EA	AB	EAC			X
32	This Study (2013)	BBC Television Centre, Wood Lane, London	UK	3	Framed	Original Façade: Curtain Wall	MS	NV	MV	SA		AB	EAC			
33	(Hernandez Tascon, 2008)	University Library, Bath	UK	5	Framed	Original Façade: Curtain Wall	C	NV		SA	EA		EAC		X	
34	(Gissen, 2005)	ARUP HQ, Fitzroy Street, London	UK	7	Framed	Original Façade: Curtain Wall	MS	NV	MV	SA	EA		EAC	IAC	X	
35	(Chadwick, 2003)	338 Euston Road	UK	9	Framed	Original Façade: Curtain Wall	MS		MV			AB				
36	(AHMM, 2013)	New Burlington Mews, Regent Street Block - W4	UK	7		///	MS	NV					EAC		X	

[*] <u>VisualRepresentations</u> available in Figure 3 - <u>Abbreviations</u>: NV = Naturally Ventilated; MV = Mechanically Ventilated; SA = Supply Air; EA = Exhaust Air; AB = Air Buffer; EAC = External Air Curtain; IAC = Internal Air Curtain

Table 2 - Details of the developed benchmarks

	Building Parameters							Building Properties		
Model No.	Floor Area [m²]	Structure	Built Form	External Wall Material	Glazing System	Storeys	Roof Type	window to floor ratio	window to wall ratio	wall to floor ratio
1	< 1000	Load Bearing	Cellular Side-lit	Masonry	Ventilation Window	3	Flat	0.13	0.19	0.7
2			Deep open-plan	Masonry	Ventilation Window			0.13	0.26	0.5
3		Framed	Deep open-plan	Masonry	Ventilation Window			0.17	0.34	0.5
4				Heavy Cladding	Ventilation Window			0.17	0.34	0.5
5	1000 - 3000	Framed	Cellular Side-lit	Masonry	Ventilation Window	4	Flat	0.14	0.23	0.6
6				Heavy Cladding	Ventilation Window			0.14	0.23	0.6
7				Glazed Curtain Wall	Curtain Wall			0.29	0.48	0.6
8			Deep open-plan	Masonry	Ventilation Window			0.13	0.33	0.4
9				Heavy Cladding	Ventilation Window			0.13	0.33	0.4
10				Glazed Curtain Wall	Curtain Wall			0.29	0.73	0.4
11	3000 - 10000	Framed	Cellular Side-lit	Masonry	Ventilation Window	5	Flat	0.10	0.20	0.5
12				Heavy Cladding	Ventilation Window			0.10	0.20	0.5
13				Glazed Curtain Wall	Curtain Wall			0.29	0.73	0.4
14			Deep open-plan	Masonry	Ventilation Window			0.08	0.20	0.4
15				Heavy Cladding	Ventilation Window			0.08	0.20	0.4
16				Glazed Curtain Wall	Curtain Wall			0.29	0.73	0.4
17	10000 - 30000	Framed	Cellular Side-lit	Masonry	Ventilation Window	9	Flat	0.10	0.25	0.4
18				Heavy Cladding	Ventilation Window			0.10	0.25	0.4
19				Glazed Curtain Wall	Curtain Wall			0.29	0.58	0.5
20			Deep open-plan	Masonry	Ventilation Window	8	Flat	0.08	0.27	0.3
21				Heavy Cladding	Ventilation Window			0.08	0.27	0.3
22				Glazed Curtain Wall	Curtain Wall			0.29	0.73	0.4

Table 3 - Features of benchmark No.18

Building Model No. 18 – Type: Cellular – Wall Material: Heavy Cladding	
Predicted Area [m²]	10,000
No. of Storeys	9
Predicted Area per storey [m²]	1,111
Floor to ceiling height [m]	3.5
Room depth [m]	7
Room area [m²] – 2 people occupancy	26
Corridor width [m]	2
Depth of the building [m]	16
Width of the building [m]	66.6
Effective Area per storey [m²]	1,065.60
Glazing to Wall Ratio (design parameter)	0.25
Glazing to Floor Ratio (predicted)	0.10
Glazing to Floor Ratio (effective)	0.12
Wall to Floor Ratio (predicted)	0.40
Wall to Floor Ratio (effective)	0.37

Table 4 - Features of benchmark No. 22

Building Model No. 22 – Type: Open Plan – Wall Material: Curtain Walling	
Predicted Area [m²]	12,000
No. of Storeys	8
Predicted Area per storey [m²]	1,500
Floor to ceiling height [m]	3.5
Open-Plan Spaces [m] (Korolija et al., 2013)	15 x 23
Predicted Open Plan area [m²]	345
Effective Open Plan area [m²]	337.5
Corridor width [m]	3
Circulation Area [m²]	156
Effective Area per storey [m²]	1,596
Glazing to Wall Ratio (design parameter)	0.73
Glazing to Floor Ratio (predicted)	0.29
Glazing to Floor Ratio (effective)	0.33
Wall to Floor Ratio (predicted)	0.40
Wall to Floor Ratio (effective)	0.45

Table 5 - UK buildings divided by storey-range and DSF type

No. of Storeys	MS	C	BW	SB	Totals	%
< 5	5	2	1	0	8	17.39%
5-10	13	5	2	3	23	50.00%
11-20	4	4	1	0	9	19.57%
> 20	4	0	1	1	6	13.04%
Totals	26	11	5	4	46	100.00%

Appendices

Appendix A – Data analysis and interpolation used for the development of UK office benchmarks

Table A1- Major form types (after Steadman et al., 2000a; 2000b)

Type	Floor area [m²]	Percentage of the stock	Notes
CS4	1343247	38.09%	daylit cellular strip, up to 4 storey
CDO	771402	21.87%	daylit cellular strip around artificially lit open plan
OC1	245359	6.96%	single storey
OS	224676	6.37%	open plan shed
OA	216322	6.13%	artificially lit open plan multi-storey space
CS5	207516	5.88%	daylit cellular strip, 5 storeys or more
OG	173558	4.92%	garages and parking spaces
CDS	106454	3.02%	cellular shed
OD5	79632	2.26%	daylit open plan strip, 5 storeys or more
OD4	36615	1.04%	daylit open plan strip, up to 4 storey
HD	33967	0.96%	daylit hall
HA	26555	0.75%	artificially lit hall
SR	23456	0.67%	single room
RA	20378	0.58%	railway arch
CDH	9114	0.26%	daylit cellular strip around an artificially lit/toplit hall
CT1	4204	0.12%	single storey
SSR	4087	0.12%	string of single rooms
Total	3526542	100.00%	

Halls, sheds, garages, parking spaces, railway arches are unrelated to the office concept (Steadman et al., 2000b) and are not included in this work.

Table A2 - Cellular and Open Plan Construction in the UK non-domestic building stock (interpolation from Steadman et al., 2000a)

Main layout of internal spaces	Percentage of the stock
Cellular	43.97%
Deep Open Plan	31.31%
Total	75.28%

Table A3 - Size bands and structural systems for offices (interpolation from Steadman et al., 2000a)

Size band [m²]	Cellular Side-lit Forms	Deep Open-plan Forms
0-100	LBS (87%)	LBS (70%)
100-300	LBS (84%)	LBS (70%)
300-1000	LBS (71%)	LBS (50%), FS (50%)
1000-3000	FS (58%)	FS (58%)
3000-10000	FS (76%)	FS (70%)
10000-30000	FS (75%)	FS (75%)

LBS = Load Bearing Structure; FS = Framed Structure

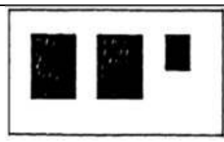
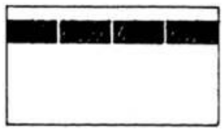
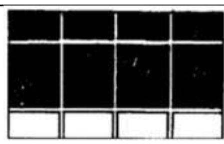
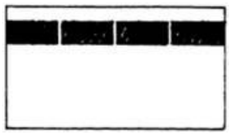
A percentage in Table A3 indicates the probability of having one structural system within a specific size band. This information helped to identify which categories are worth investigating more than the others.

Table A4 – Façade materials, structural systems and built forms (interpolation from Steadman et al., 2000a)

	Framed Structures		Load Bearing Structures	
Material	Cellular Side-lit Forms	Deep Open-plan Forms	Cellular Side-lit Forms	Deep Open-plan Forms
Masonry	66%	76%	94%	93%
Heavy Cladding	14%	10%	6%	7%
Light Cladding	12%	7%	0%	0%
Glazed Curtain wall	8%	7%	0%	0%
Total	100%	100%	100%	100%

Additional information with respect to buildings' façades is provided by Gakovic (2000) and Ebbert (2010). Gakovic (2000) surveyed 101 locations in the UK, focussing on glazing and openings. Ebbert's survey (2010) includes 265 buildings across the UK totalling a façade area of 1.3 million m^2. Gakovic (2000) identifies the glazed curtain wall as a category that accounts for around 80% of the surveyed stock with a framed structure. Although he clarifies that such a high percentage is due to a big number of large multi-storey office buildings that he surveyed, still the number is much too far from the 7-8% suggested by Steadman et al. (2000a) (Table A4). It cannot therefore be overlooked and curtain walling is one of the options considered in this study. Such an assumption is supported by the findings from Ebbert (2010), who identified three major types of façades in the UK each accounting for around 20%, one of which is curtain wall.

Table A5 - Glazing systems and their percentage according to structural systems (interpolation from Gakovic, 2000)

Structural System	Glazing System	Percentage	Diagram (Gakovic, 2000)
Load Bearing	Light or ventilation window	84.11%	
	Horizontal strip light or ventilation window	4.78%	
Framed	Glazed curtain wall (full or partial)	79.11%	
	Horizontal strip light or ventilation window	10.67%	
	Light or ventilation window	8.33%	

Within Gakovic's glazing systems (Table A5), those related to ground floor openings have been omitted, for they are insignificant to the present research – hence totals do not sum up to 100%.

Table A6 - Glazing ratios according to the structural system (Gakovic, 2000)

Structural System	Windows to floor ratio	Windows to wall ratio	Wall to floor ratio
Traditional (load bearing)	0.13	0.14	0.94
Framed (curtain wall)	0.29	0.60	0.49
Framed (deep plan)	0.08	0.15	0.52

All the ratios in Table A6 show very strong correlation coefficients (Gakovic, 2000).

Table A7 - Average No. of Storeys coupled with built forms and size bands (interpolation from Steadman et al., 2000a)

	Cellular Side-lit built forms		Deep open-plan built forms	
Size band [m²]	Roof to Floor ratio	Equivalent No. of Storeys	Roof to Floor ratio	Equivalent No. of Storeys
0-100	0.70	1.4	0.62	1.6
100-300	0.55	1.8	0.51	2.0
300-1000	0.40	2.5	0.40	2.5
1000-3000	0.30	3.3	0.30	3.3
3000-10000	0.21	4.8	0.20	5.0
10000-30000	0.11	9.1	0.13	7.7

For this research it is assumed to have buildings at least three storey high, which is consistent with previous research on UK office benchmarks (Korolija et al., 2013) in order to have a reliable representation of the existing stock. Korolija et al. (2013) also suggested a floor to ceiling height equal to 3.5 m to be used as average value, which also conforms well to spot checks done for this research.

Table A8 - Number of storey, built forms, size bands, and floor height for the models developed – values have been converted into an integer

	Cellular side-lit built forms	Deep open-plan built forms	
Size band [m²]	Number of Storeys for the generic model	Number of Storeys for the generic model	Floor to ceiling height [m]
< 1000	3	3	3.5
1000 - 3000	4	4	3.5
3000 - 10000	5	5	3.5
10000 - 30000	9	8	3.5

Felt/asphalt flat roof is the most representative category in both built forms (50% for the cellular and 65% for the open plan) (Steadman et al., 2000a). When analysing and simulating buildings with DSFs, the assumption of having a felt/asphalt flat roof is a reasonable scenario compared to DSF buildings observed in reality.

Table A9 - Age bands and U-values

Age band	Building Regulations	U-values [W/m² K]			
		Wall	Roof	Windo ws	Ground Floor
1965-1976	(DCLG, 1965, DCLG, 1972)	≤ 1.7	≤ 1.42	≤ 5.7	≤ 1.42
1976-1985	(DCLG, 1976)	≤ 1.0	≤ 0.6	≤ 5.7	≤ 1.0
1985-1990	(DEWO, 1985)	≤ 0.6	≤ 0.6	≤ 5.7	≤ 0.6
1990-1995	(DEWO, 1990)	≤ 0.45	≤ 0.45	≤ 5.7	≤ 0.45
1995-2002	(DEWO, 1995)	≤ 0.45	≤ 0.45	≤ 3.3	≤ 0.45

Appendix B – Step-by-step procedure to obtain 3D models of the benchmarks

Table C1 – Step-by-step procedure developed

Steps	Tasks	Details
#1	Calculate total treated floor area	By dividing the floor area of the size band by the number of storeys, the floor area for each storey is identifiable. The upper bound within each size band is used for this purpose, which implies that the benchmark developed will be characterised by the largest floor area in its size band. This assumption holds true for all but the last size band as reviews of existing buildings have shown the upper bound is not really representative.
#2	Determine internal layout	The floor-to-ceiling height (assumed as a fix parameter equal to 3.5 m) determines the depth for the amount of daylighting to be reasonable (Baker and Steemers, 2000). The authors suggest a value of 2h (where h is the room height) for the room depth in the case of a double-sided wholly day-lit plan with a central corridor. This provides one of the two dimensions of the floor area of the cellular office. For open plan models dimensions for reference can be found in Musau and Steemers (2008) and in Korolija et al. (2013). There exists different approaches about the daylighting design such as the one suggested by Gregg (2003) who states that the depth of daylighting penetration is 2.5 times the window height. To use this approach, however, more reliable information is needed about windows' dimensions and layout but such data are harder to collect and more often subject to change from one building to another. This is why the floor to ceiling height has been used, where a relatively lower variance is expected. Corridor width has been assumed to be 2m as in Baker and Steemers (2000) and Korolija et al. (2013).

Steps	Tasks	Details
#3	Define occupied spaces	Report form the British Council for Offices (2009) provide occupancy figures per m^2 of floor area, which for cellular offices is 13 m^2 for a single workspace. This value conforms to recommendations from CIBSE (2006) that specify a maximum occupancy density of 12 m^2 per person. It is assumed that a cellular office is shared between two people as often observed in practice hence a total area of the room of 26 m^2. One of the two dimensions of the room is already known due to knowing both the depth of the building and the corridor width hence the other one can be calculated since the room area is known, too.
#4	Draw the floor plan	Draw the entire floor plan (if needed consider the built forms sketched in Steadman et al. (2000b)).
#5	Calculate openings	Since both the floor area and the wall area are known at this stage, glazed areas can be calculated by using either window to floor ratio or window to wall ratio. Evidently slightly different figures are expected depending on which ratio is used. The window to wall ratios as they appear in Gakovic (2000) seem to be a more reliable choice as that study is specifically focused on glazing and openings in the non-domestic building stock.
#6	Draw the envelope	Measured surveys of few UK offices indicated that the average windowsill height of 1m above floor level. Once the area of opening, its system, and its sill height are determined, openings can be drawn by centring them within the external wall of the room.
#7	Draw the roof	The roof type, as indicated in Table 2, completes the drawing.

Appendix C – Large sample of buildings with DSFs in the UK

No.	Building's Name	City	Firms involved	Address	DSF Type	Storeys	Source
1	Library building (University of Bath)	Bath	Alec French Partnership	BA2 7AY (Quarry Road)	Corridor	5	(Hernandez Tascon, 2008)
2	BT Brentwood	Brentwood	Arup Associates	1 London Road, Brentwood,Essex	Multi-storey	3	(Hernandez Tascon, 2008)
3	Amex Building (1, John St.)	Brighton	Gartner - Permasteelisa/EPR Architects	1 John Street	Multi-storey Corridor	7	(Gartner, 2013)
4	Pavilion Surgery Building	Brighton	///	2 Old Steine	Box	4	/
5	History Faculty Cambridge	Cambridge	James Stirling	West Road	Box	7	(Banham, 2010)
6	Ashcroft International Buisiness School (Anglia Ruskin University)	Chelmsford	Wilkinson Eyre Architects	Bishop Hall Lane	Multy-Storey	5	(Hernandez Tascon, 2008)
7	Briarcliff House	Farnborough	Ove Arup Associates	Kingsmead/ Eastmead	Multi-storey	4	(Compagno, 2002), (Poirazis, 2004)
8	BRE (Building Research Establishment)	Garston	Fielden Clegg	Bucknalls Lane	Corridor/ Multi- s	3	(Lee et al., 2002), (Poirazis, 2004)
9	BBC Scotland	Glasgow	David Chipperfield Architect	Pacific Quay	Box	5	(Mignat, 2008)
10	Glaxo Wellcome	Greenford	RMJM London Ltd., Arup Façade Engineering	891-995 Greenford Road, Middlesex	Corridor	4	(Hernandez Tascon, 2008)
11	The Shard	London	Renzo Piano/ Permasteelisa/Gartner/WSP Cantor Seinuk	32 London Bridge Street	Multi-storey	72/87	(Spring, 2010)
12	30 St Mary Axe (The Gerkin)	London	Foster & Partners/Arup/Schmidlin Ltd (Façade)	14-34 St Mary Axe	Spiral spaces that wrap the building	40	(Hernandez Tascon, 2008)
13	BBC Televition Centre	London	///	White City, Wood Lane	Multi-storey	3	/
14	W London Leicester Square	London	McAleer & Rushe Group/ Jestico + Whiles Architects/ Cladwell Consulting	10 Wardour Street	Multi-storey	14	/
15	One Plantation Place Building	London	Arup Associates	31-35 Fenchurch Street	Multi - Storey	16	(Hernandez Tascon, 2008)

No.	Building's Name	City	Firms involved	Address	DSF Type	Storeys	Source
16	Arup HQ - Fitzrovia Building	London	Sheppard Robson/ Arup Associates	13 Fitzroy Street	Multi - Storey	7	(Chadwick, 2003), (Gissen, 2005)
17	One Triton Square	London	Arup Associates	1 Triton Square, Camden	Multi - Storey	5	(Hernandez Tascon, 2008)
18	Watling House	London	Arup Associates	31-37 Cannon Street	Shaft- Box	7	(Hernandez Tascon, 2008)
19	Greater London Authority(GLA)	London	Arup Associates/Norman Foster	The Queen's Walk/TooleyStreet	Box	11	(Hernandez Tascon, 2008)
20	Helicon Building	London	Sheppard Robson/Arup & Partners/ Permasteelisa	Finsbury Pavement/South Place	Multi - Storey/ Corridor	8	(Lee et al., 2002), (Kragh, 2000), (Poirazis, 2004), (Hernandez Tascon, 2008), (Chadwick, 2003)
21	The Darwin Centre	London	HOK International/Arup Associates/Arup Façade Engineering	Natural History Museum, Cromwell Road	Multi-Storey	10	(Hernandez Tascon, 2008)
22	The Wellcome building	London	Micheal Hopkins/Arup Associates	189 Euston Road	Corridor	15	(Hernandez Tascon, 2008)
23	Portcullis House	London	Micheal Hopkins/Arup	Bridge Street	Shaft- Box	6	(Hernandez Tascon, 2008)
24	The Willis Building	London	Foster & Partners/ MERO-Schmidlin (UK) for the façade	51 Lime Street	Shaft- Box	23 (average)	(Hernandez Tascon, 2008)
25	One Blackfriars	London	Ian Simpson Architects/ SimpsonHaugh and Partners	1 Blackfriars Road London	Multi-Storey	52	(BerkleyGroup, 2015)
26	DZ Bank Building	London	Carillion PLC/ Micheal Aukett Architects Ltd	150 Cheapside	Multi-Storey	9	(Maris-Interiors, 2014)
27	338 Euston Road	London	Sheppard Robson	338 Euston Road	Multi-storey	9	(Chadwick, 2003)
28	One New Change	London	Gartner - Permasteelisa/ Ateliers Jean Nouvel & Sidell Gibson Architects	1, New Change	Multi-storey	6	(Gartner, 2015)
29	20 Gresham Street	London	Gartner - Permasteelisa/ Kohn Pedersen Fox Associates	20 Gresham Street	Corridor	6	(Gartner, 2014)
30	Riverbank House	London	Gartner - Permasteelisa/ EPR Architects/ David Walker Architects/ ARUP Façade Engineering	Upper Thames Street/Swan Street	Corridor (TBC)	10	(Permasteelisa, 2013)

No.	Building's Name	City	Firms involved	Address	DSF Type	Storeys	Source
31	The Broadgate Tower	London	Gartner - Permasteelisa/ Skidmore, Owings & Merrill Architects/ Gartner (façade)	201 Bishopgate	Multi-storey	34	(Moore, 2009)
32	Watermark Place	London	Gartner - Permasteelisa/ Fletcher Priest Architects/ Sir Robert McAlpine Ltd./ Waterman Group	90 Upper Thames Street	Corridor	12	(Lane, 2009)
33	Chapel for the Salvation Army	London	Sheppard Robson/Arup & Partners	101 Queen Victoria Street	Multi-storey	6	(Chadwick, 2003)
34	ITN (Independent Television News) Headquarters	London	Foster & Partners	200, Gray's Inn Road	Shaft- Box	6	(Allison and Thornton, 2003)
35	Regent Street Block - W4	London	AHMM Architects	New Burlington Mews, Regent Street Block W4	Multi-storey	7	(AHMM, 2013)
36	One Angel Square	Manchester	3DReis Architects/ Buro Happold Engineer/ Waagner Biro(façade)	1 Angel Square	Multi-storey	14	(BREEAM, 2014)
37	No. 1 Deansgate	Manchester	Ian Simpson Architects/ Martin Stockley Associates	1 Deansgate Street	Corridor	17	(Hernandez Tascon, 2008)
38	Beetham Tower	Manchester	Ian Simpson Architects/ Carillion Construction	301 Deansgate	Box	47	(Hernandez Tascon, 2008)
39	Urbis (Exibition Centre)	Manchester	Ian Simpson Architects/ Martin Stockley Associates	Cathedral Gardens/ Fennel Street	Corridor	6	(Hernandez Tascon, 2008)
40	Manchester Civil Justice Centre	Manchester	Gartner - Permasteelisa/ Denton Corker Marshall Architects	Left Bank/ Bridge Street	Both Corridor & Multi-Storey	14/16	(Shahin and Chandler, 2011)
41	M&S Corporation Street	Manchester	ARUP/ Hodder + Partners	Corporation Street	Multi-storey	4	/
42	Inland Revenue Centre	Nottingham	Micheal Hopkins & Partners	Howard House/ Castle Meadow Road	Multi-storey	5	(Lee et al., 2002), (Poirazis, 2004)
43	British Sugare Office	Peterborough	///	Sugar Way	Multi-storey	2	(Crowley, 1975)

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