EVALUATION OF LIFE CYCLE CARBON IMPACTS FOR HIGHER EDUCATION BUILDING REDEVELOPMENT: AN ARCHETYPE APPROACH

D. Hawkins*, D. Mumovic

The Bartlett School of Environment, Energy and Resources, University College London,

14 Upper Woburn Place, London, WC1H 0NN, UK

david.hawkins.10@ucl.ac.uk

ABSTRACT

An archetype-based approach was taken to generalise findings on the life cycle carbon impacts of higher education building redevelopment, as a follow-up to a previous case study analysis. For each archetype, the life cycle operational and embodied carbon impacts of carbon reduction interventions and building redevelopment options were analysed.

A database of English and Welsh university buildings was constructed comprising energy and geometry data. Six archetypes for pre-1985 buildings were then determined based on academic activity and servicing strategy. Buildings were synthesised for each archetype using case study data and the database geometry data. Life cycle carbon models following the BS EN 15978:2011 standard were constructed, calibrated using the database energy data and used to simulate carbon reduction interventions and new-build schemes. Various material systems were considered and design stage uncertainty was factored in.

For new-build, average life cycle carbon savings ranged from 37 to 54%, exceeding the range of 25 to 33% for the best-case refurbishment options. However, in some cases the differences were only slight and within the range of uncertainty. Structural systems and building services dominated material impacts, the latter owing to replacement cycles. The generalised findings allowed guidance to be given on higher education carbon management.

Keywords: higher education, university, life cycle carbon, embodied carbon, retrofit, archetypes, uncertainty

1. INTRODUCTION

The context to this study was the management of operational and embodied carbon impacts in the UK higher education sector. As highlighted in a preceding study by the authors [1], operational carbon emissions in the higher education sector have grown since 1990 and currently stand at around 0.5% of UK carbon emissions [2]. The sector experiences specific challenges that impact its operational carbon emissions: high proportion of scientific research, irregular occupancy patterns, transient populations and ageing estates [3–6]. There are also a number of drivers for reduction of operational carbon through building redevelopment, such as utility costs, compliance with building energy legislation and environmental schemes, and institution reputational incentives [7].

Embodied carbon emissions– the emissions associated with the manufacture, transport, installation and disposal of materials used throughout a building's life cycle [8] - are also noted as an important area of consideration in higher education building redevelopment [3,6]. Whilst currently estimated to contribute around 18% of total life cycle carbon emissions on average, embodied carbon emissions are projected to increase in relative magnitude as operational carbon emissions are reduced through energy efficiency improvements [9–11]. Arguably then, the embodied carbon impact of new, energy-efficient buildings is proportionally higher in terms of life cycle impact than existing or even refurbished buildings where energy efficient measures have been introduced but material additions minimised. There are strong motivations to review the redevelopment options for higher education buildings in terms of total life cycle carbon performance.

The aim of this study was to build on the preceding study [1], which focused on the analysis of case study buildings, to achieve results on the life cycle carbon impact of building redevelopment applicable to the wider UK university stock. This might then provide generalised findings for application beyond the original case studies. For this purpose, an archetype-based method was developed and carried out. A number of life cycle carbon analyses has been carried out using real data from case studies, such as those that made static measures of life cycle carbon impacts for existing buildings [12–14] and those that assessed the redevelopment of case study buildings in terms of life cycle carbon impact [15,16]. Evidence has not been found of studies that use archetypes to transfer findings from building life cycle carbon impact case studies to a general building stock, particularly considering a broad variety of redevelopment scenarios.

Use of archetypes is a common method for generalisation of findings in building energy analysis. In the UK, building form-based classification was employed as the basis of the Non-Domestic Building Stock database [17] and the Community Domestic Energy Model [18], with both used to analyse energy use in large building stocks. Chidiac et al. [19] developed archetypes of Canadian office buildings with which to simulate the impact of retrofit measures on operational energy use. The office archetypes were classified based on construction era and type of building structure. An archetype approach was also taken for life cycle carbon analysis by Bull et al. [20]. They modelled the operational and embodied carbon impact of thermal improvements on four different UK school archetypes classified by period of construction. On this evidence, the archetype approach would appear to be valid for generalisation of the case study analysis.

As highlighted in Figure 1, the archetypes were developed in this study using high-level higher education building data and measured building data from the case study analysis. A database was built up accordingly using in-use energy and other data from the Display Energy Certificate (DEC) scheme together with measured building parameters using desktop methods. The archetypes were characterised as a having a minimum age considered suitable for redevelopment and were primarily distinguished by activity and primary environmental strategy. Operational and embodied carbon models following the BS EN 15978:2011 standard were built for each archetype and calibrated using energy data from the database and building data from the five case study buildings, which had different primary activities as follows: law, chemistry, art and design, medical research and administration. A series of redevelopment options were then simulated, including a method to measure the associated analysis uncertainty, building on investigations such as those by Basbagill et al. [14]. The method for data collection and analysis is summarised, followed by presentation of the life cycle carbon results. Further detail of the method is given elsewhere [1,21].

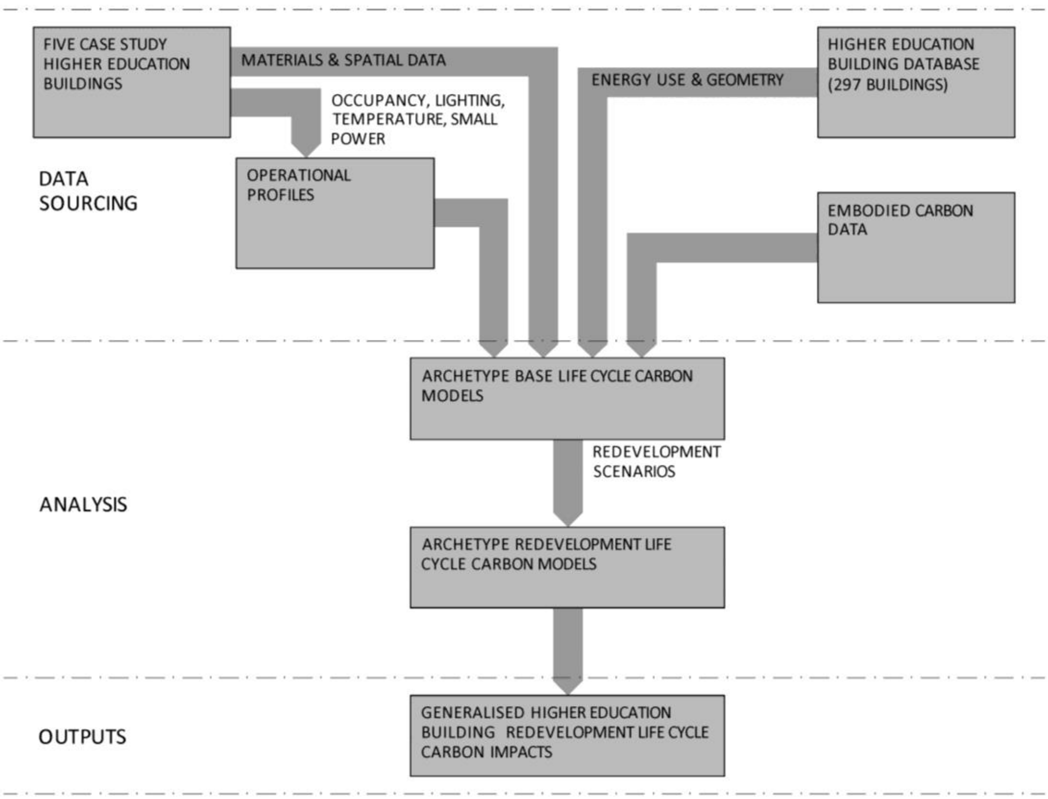

Figure 1 Flow diagram showing the key stages in the archetype analysis

2. METHOD

2.1. Building data collection

The archetypes were defined for academic higher education buildings that were deemed appropriate for redevelopment, selected using a cut-off in terms of the initial construction era. The chosen cut-off construction year was 1985, the year that energy efficiency standards were introduced in the UK Building Regulations [22]. For compliance with this, minimum levels of insulation and glazing performance were required, typically requiring double-glazing.

The main aim of the archetype definition, as described later, was to determine categories of university buildings that were considered discrete in terms of their energy performance. A database of appropriate UK higher education buildings was built with which to define the archetypes. The main source of data for the database was the UK Display Energy Certificate (DEC) scheme [24]. The DEC data was provided by the Chartered Institute of Building Services Engineers (CIBSE), obtained from the UK Government and the database compilers, Landmark

[25]. The complete dataset was understood to contain all records submitted in England and Wales from the start of the scheme in October 2008 to the end of July 2012. The principal energy use figures used were actual electricity (EuiElec) and thermal fuel use (EuiHtg) in total annual kWh/m^2 gross internal floor area. A number of steps were carried out on the dataset to isolate the DEC data for English and Welsh higher education buildings and to filter out unsuitable and erroneous records. This included all steps to 'clean up' the data and select university occupiers described by Hawkins et al. [26].

A section of the resulting database, which included 1,951 records in total, was enhanced with a number of other fields, principally related to building geometry, using desktop methods. Table 1 lists the key fields populated for each building and a summary of the methods used for data collection, which are described in detail elsewhere [27]. From the enhanced database section, a sample of 234 pre-1985 period academic buildings (67% of all academic buildings) was extracted to be used for the archetype definition.

Table 1 Key fields in the building database used for archetype definition

Field	Values / units	Data collection method
Electricity use	Total annual kWh/m^2	From DEC data
Heating fuel use	Total annual kWh/m^2	From DEC data. Corrected for annual heating degree days and onsite renewables use.
Primary activity type	Art and design, performance, general academic, chemistry, physics, medical science/biology, library, administration, engineering/workshop, lecture theatre	Classified manually using university website information.
Primary environmental strategy	Air conditioning, mechanical ventilation, natural ventilation	Fields condensed from DEC data
Gross internal floor area	m^2	From DEC data
Context	Urban, rural	Assigned using postcode density as a proxy, defined as the number of neighbouring postcodes within a 1km radius.
Construction year		From university websites or historical maps (to closest decade)
Building height	m	From GIS data
Glazing ratio	%	Measured using images from the Google Earth application
Aspect ratio	%	Ratio of shortest to longest dimensions. Measured using digital Ordnance Survey maps

Adjacency shading factor: south, west, north, east	%	Defined as the elevation angle from the mid-height of the building to top of the adjacent building. Measured using GIS mapping data.

2.2. Archetype definition

2.2.1. Activity classification

The archetypes were initially defined in terms of building activity. As discussed by Bruhns et al [28], university-specific building activities are not clearly designated in the DEC scheme and the assignments made have not always been reliable. Accordingly, each building was classified manually using information obtained from the respective university's website or other internet searches. Previous studies on DEC energy data carried out by the authors [26,29] have found high variation in median annual electricity and heating fuel uses between classes separated into laboratory, workshop and general academic-type activities. In this study, the buildings were therefore grouped into these major academic activity classes based on their primary activities, as follows:

- Archetype A - Science/lab: Chemistry, physics, medical science/biology

- Archetype B - Engineering/workshop: Engineering or workshop

- Archetype C - General academic: Art and design, general academic, performance, administration, lecture theatre, library or learning centre

These classes showed strong distinction in terms of both electricity and heating fuel use. Median annual electricity use was found to be significantly different between all three classes. Median annual heating fuel uses for the science/lab and engineering/workshop classes were found to be significantly different to that for the general academic class (significance measured with 95% confidence in all cases).

2.2.2. Primary environmental strategy classification

The buildings were also separated by primary environmental strategy, which was found to be another key energy use determinant. Two categories were used: "naturally-ventilated" and "mechanically-ventilated", with the latter being all primary environmental strategy classes not using natural ventilation. The median energy use values for each archetype is shown in Table 2. Significant differences in electrical energy performance were found for each archetype by strategy (with 95% confidence), however not for heating fuel use so common values were used for each activity class. These median energy values were used as the basis for calibrating the models in the life cycle analysis described in the following section.

Table 2 Median annual energy use for each archetype (both context types)

Major activity class	Primary environmental strategy	Archetype code	Median annual electricity use (kWh/m^2)	Median annual heating fuel use (kWh/m^2)
Science/lab	Naturally-ventilated	A-NV	145	215
	Mechanically-ventilated	A-MV	247	
Engineering/ workshop	Naturally-ventilated	B-NV	111	146
	Mechanically-ventilated	B-MV	198	
General academic	Naturally-ventilated	C-NV	72	119
	Mechanically-ventilated	C-MV	96	

2.2.3. Geometry

There was found to be a strong relationship between building context – urban or rural - and the building geometry factors in the database, as shown by the mean values and associated 95% confidence intervals in Table 3. At 95% significance, the urban buildings in the dataset were found to be greater in floor area, taller and more shaded, and to have higher glazing and aspect ratios than rural counterparts. Owing to a lower observed impact of context on energy use, separate archetypes based on context were not developed. However, to explore the impact of building geometry, each archetype was modelled in two different contexts with different geometries to develop a range of results accordingly.

Table 3 Geometry parameters used for the two archetype forms

Parameter	Urban form			Rural form		
	95% confidence interval lower limit	Mean	95% confidence interval upper limit	95% confidence interval lower limit	Mean	95% confidence interval upper limit
Observed parameters						
Gross internal floor area	5,690m^2	6,730m^2	7,910m^2	4,420m^2	5,270m^2	6,600m^2
Building height	19.4m	21.0m	22.8m	12.4m	13.7m	14.9m
Glazing ratio	25.1%	27.4%	29.9%	19.4%	21.8%	24.4%
Aspect ratio	33.4%	38.1%	42.4%	24.8%	29.5%	34.4%
Adjacency shading factor - north	28.0%	33.3%	38.6%	12.1%	16.4%	21.9%
Adjacency shading factor – east	30.7%	36.7%	42.6%	17.3%	23.3%	30.1%
Adjacency shading factor – south	24.1%	29.8%	35.1%	8.1%	12.1%	17.3%
Adjacency shading factor - west	28.3%	33.6%	38.7%	13.7%	19.2%	25.5%
Derived parameters						
Number of floors		7 (6+1)			5 (4+1)	
Average floor height (slab-to-slab)		3.6m			3.4m	
Building length		50m			60m	
Building width		19m			18m	

2.3. Redevelopment scenarios

The same redevelopment scenarios were considered for the archetype buildings as those for the case study buildings [1], as listed in Table 4. The original selection was made in accordance with interventions recommended by HEFCE [3] and those that higher education institutions reported considering or implementing in their Carbon Management Plans [30]. The interventions were grouped into system/management, refurbishment and new-build types and where appropriate pairs of interventions from different groups were also considered. Design stage uncertainty was also factored in, defined by calculation of the upper (higher energy use) and lower (lower energy use) limits around the standard intervention, based on observed typical variations

[21]. For each scenario, the total life cycle carbon impact was determined in terms of any initial embodied carbon impact plus future recurring embodied carbon impacts and operational carbon impact over the building lifetime.

Table 4 Redevelopment scenarios

Ref-erence	Summary	Standard intervention	Upper uncertainty limit	Lower uncertainty limit
Existing				
X1	As existing	Baseline scenario with no alterations	None	None
Systems and management interventions				
S1	Boiler upgrade	Replacement with boiler to current Building Regulations Part L standards [31]	Boiler efficiency five percentage points lower	Boiler efficiency five percentage points higher
S2	Chiller upgrade	Replacement with chiller to current Building Regulations Part L standards [31]	5% lower chiller seasonal efficiency	5% higher seasonal chiller efficiency
S3	Demand-led ventilation	70% turndown of ventilation systems outside of occupied periods. Excluding specialist laboratories and workshops with high heat gains	60% turndown	80% turndown
S4	Lighting control	Reduction of base lighting load during unoccupied periods by 75%	50% reduction	100% reduction
S5	Switch-off campaign	Reduction of base equipment load during unoccupied periods by 75%. Excluding research laboratories and heat-based workshops	50% reduction	100% reduction
S6	Set point adjustment	Reduction of space heating temperature and increase of cooling temperature by 1 ° C	0.5 ° C change	1.5 ° C change
S7	All management and system changes: S1 to S6	As S1 to S6	As S1 to S6	As S1 to S6
Refurbishment interventions				
R1	Insulation and glazing upgrade	Addition of 100mm mineral wool insulation to façade and 150mm polystyrene insulation to roof insulation. Upgrade to triple glazing with 1.1W/m^{2}K U-value	Insulation 20% thinner. Glazing U-value 20% higher	Insulation 20% thicker. Glazing U-value 20% lower
R2	External shading devices	Addition of external shading devices to south-facing facades	None	None
R3	Façade replacement	Replacement of the existing façade with a new façade to current efficiency standards: U-value 0.21 W/m^2/K, airtightness 8 m^3/m^2/hr. Roof insulation included.	Insulation U-value and infiltration 20% higher	Insulation U-value and infiltration 20% lower
New-build scenarios				

N1	New-build	Replacement with a new building in line with Building Regulations Part L 2013 energy efficiency standards [32]: 40% U-value improvement on limiting values; airtightness 5 $m^3/m^2/hr$; lighting 2.5 $W/m^2/100$ lux. Building systems as 40% improvement on Part L standards [31].	5% lower heating and cooling efficiency. Systems 20% improvement	5% higher heating and cooling efficiency. Systems 60% improvement

2.4. BS EN 15978:2011 scope and definition

The scope and definitions for the life cycle assessment in terms of BS EN 15978 were the same as those for the case study analysis [1]. Key characteristics were as follows: the reference period was 60 years; the material systems included were the superstructure, roof, floor finishes, ceiling finishes, partitions, façade, glazing, doors and building services; operational energy use for both the building systems and equipment were included. The embodied carbon of building services is presented separately to the BS EN 15978 life cycle totals in the results as it was calculated using a separate database: the German national product life cycle impact database, Ökobau.dat[1]. Operational energy use for equipment is outside the scope of the standard so this is also totalled separately.

2.5. Modelling life cycle impacts

2.5.1. Model construction

The archetypes were modelled as simple rectilinear forms. Two different forms were considered representing the average "urban" and "rural" geometry factors shown in Table 3. Adjacent forms were also added for shading purposes.

Space and operational data from seven 'base' buildings was used as the basis for the construction and configuration of the models used for each archetype. Five of these buildings were the case study buildings; a geography building and a civil engineering building were used additionally for archetype B, engineering/workshop. The space equipment use, occupancy and temperature profiles determined for the respective case study buildings were also assigned to the archetype models. For archetype B,

[1] Available at http://www.nachhaltigesbauen.de/oekobaudat/

engineering/workshop, where specific profiles were not measured in the case studies, appropriate profiles were selected from the other case study buildings. Individual models were constructed for each base building in the rural and urban forms (fourteen models in total) with room types and corresponding floor area proportions matching those measured in the base building. In each model, the room distribution matched that found in the corresponding base building.

2.5.2. Operational carbon impact

The operational carbon impact analysis was carried out using the IES Virtual Environment (IESVE) application (version 2014.1.0.0). Specific zone templates were developed for each archetype major activity class and primary environmental strategy internal to describe the building systems according to the conditioning strategy and the operational characteristics (occupancy, temperature and internal gains). Each template was based on an equivalent for the corresponding base building, using the same profiles, although separate building systems were defined. A common conditioning strategy was used for each space type to suit the overall building servicing strategy and based on the typical conditioning strategies observed in the case study buildings. For example, naturally-ventilated offices were applied in naturally-ventilated archetypes and vice versa. Exceptions were laboratory and workshop areas where some mechanical ventilation was used even for the predominately naturally-ventilated archetypes. System efficiencies were assigned based on guidance values [31,33].

The archetype locations were selected using the mean postcode grid reference for the corresponding urban and rural buildings in the database, with both being based close to Coventry. Actual Meteorological Year weather data was obtained accordingly to achieve total annual degree-days close to the average value, 2021 used for normalisation of the DEC data [34].

Each base model was calibrated to the respective median annual energy figures following the same iterative method used for the case study analysis, based on Hubler et al. [35]. Owing to limited data resolution, the models were only calibrated to the annual total energy use. The annual energy of the lifts was also included following the CIBSE Guide D [36] method.

2.5.3. Embodied carbon impacts

The embodied carbon impacts were measured using the IESVE EnviroImpact module together with the Impact generic materials database (version 2) and results were determined by building construction system. A range of systems was assessed for the new buildings as used in the case study analysis [1]. To also generalise the assessment of the base buildings a range of construction systems was analysed, based on the materials existing in the case study buildings. These existing materials included the following: plasterboard, blockwork and glass partitions; suspended plasterboard, wet plaster and tiled ceilings; carpet, vinyl and timber flooring. New structural systems and building services were also included in the archetype analysis following the same calculation method as for the case studies.

2.5.4. Model uncertainty analysis

Operational and embodied carbon uncertainty analysis were carried out following the same approach as for the case studies [1]. By this approach, the operational carbon models were rerun to assess the upper and lower values in Table 4. Also, the materials used in the embodied carbon analysis were randomly adjusted in terms of quantity used, transport distance and service life, and a range of embodied carbon impacts was determined.

3. RESULTS AND DISCUSSION

3.1. Life cycle carbon impact of redevelopment scenarios

Table 5 and Figure 2 summarise the findings from the life cycle carbon analysis for the main redevelopment scenarios for each archetype. The results in Table 5 comprise the following values: the operational energy associated with the building systems ("Systems energy"); the total life cycle carbon in accordance with the BS EN 15978 standard, which includes building systems energy and building materials ("BS EN 15978 total"); the embodied carbon of the building services ("Building services"); the operational energy associated with the building equipment ("Equipment energy"); the total life cycle carbon including BS EN 15978 totals, the building services and the equipment energy ("Total").

Figure 2 compares the embodied carbon component of the results with the operational carbon component for key redevelopment scenarios for each archetype. It also shows as crosshairs the range of measured uncertainty for each result.

Life cycle carbon reductions were found for collective management and system changes (X1/S7) for all archetypes, although these decreased in magnitude from the science/lab, A archetypes (24 to 26%) to the general academic, C archetypes (18 to 20%), indicating greater responsiveness for science and engineering buildings. For both the mechanically and naturally-ventilated science/lab archetypes, most of this reduction was associated with demand-led ventilation (X1/S3). For the remaining archetypes, demand-led ventilation only offered a significant reduction for the mechanically-ventilated versions, B-MV and C-MV. Both engineering/workshop archetypes showed the greatest reductions for switch-off campaigns (X1/S5), owing to these having the greatest proportion of user-controlled equipment loads. Lighting control (X1/S4) was found to be most significant for the naturally-ventilated general academic archetype, A-NV, because the lighting load was dominant for this archetype. This archetype also had the highest response to setpoint changes (S6): indeed setpoint changes were generally found to be more effective in the naturally-ventilated archetypes.

Further reductions owing to façade replacement (R3/S7) were observed for all archetypes, with total life cycle carbon reductions ranging from 25% for the mechanically-ventilated engineering/workshop archetype, B-MV to 33% for the naturally-ventilated general academic archetype, C-NV. This intervention was found to be more effective generally for naturally-ventilated versions of the archetypes, with a range for standalone façade replacement (R3) going from 8% for the science/laboratory archetype, A-NV to 18% for the general academic archetype, C-NV. This would indicate that interventions to improve façade performance are of greater benefit for less intensively serviced buildings,

For the new-build scenario without management changes (N1), improvements against the best-case refurbishment option (R3/S7) were only found for two of the archetypes: the mechanically-ventilated versions of the science/lab and engineering/workshop archetypes (B-MV and C-MV). For these archetypes, the new-build options also introduced the most substantial changes in the servicing strategy. The addition of management changes to the new-build scenario (N1/S7) resulted in the further reductions for all archetypes and clear improvement on the best refurbishment case, with peak life cycle carbon reductions ranging from 37% for the naturally-ventilated engineering/workshop archetype to 54% for the mechanically-ventilated general academic archetype, C-MV. With the exception of the chemistry building, reductions found for new-build were not as great for the archetypes as those found for the equivalent case study buildings in the previous study [1]. This suggests that whilst new-build may be more favourable in specific cases, in the general case it is less effective and actually closer to refurbishment.

Table 5 Life cycle carbon results for each archetype (total tCO_2e/m^2 over a 60-year lifetime). All values are averages to 2 significant figures to reflect the data precision. "E" = Embodied carbon, "O" = Operational carbon, "EO" = Embodied and operational carbon

Archetype		X1 Existing	X1/S1 New boiler	X1/S2 New chiller	X1/S3 Demand vent.	X1/S4 Lighting control	X1/S5 Power switch-off	X1/S6 Set-point change	X1/S7 All man. & systems	R1 Insul-ation & glazing	R2 External shading	R3 Replace façade	R3/S7 Facade & man. & systems	N1 New-build	N1/S7 New-build and all man.
A-MV	Systems energy (O)	6.6	6.4	6.6	5.2	6.1	6.7	6.4	4.3	6.4	6.6	6.3	4.0	3.5	2.4
	BS EN 15978 total (EO)	6.7	6.5	6.7	5.3	6.2	6.7	6.5	4.4	6.5	6.7	6.5	4.2	3.9	2.8
	Building services (E)	0.25	0.26	0.25	0.25	0.25	0.25	0.25	0.26	0.25	0.25	0.25	0.26	0.32	0.32
	Equipment energy (O)	4.0	4.0	4.0	4.0	4.0	3.7	4.0	3.7	4.0	4.0	4.0	3.7	4.1	3.8
	Total (EO)	**11**	**11**	**11**	**9.6**	**10**	**11**	**11**	**8.3**	**11**	**11**	**11**	**8.2**	**8.3**	**6.9**
A-NV	Systems energy (O)	5.5	5.2	5.4	4.6	5.0	5.5	5.3	3.7	5	5.5	4.8	3.2	2.7	1.8
	BS EN 15978 total (EO)	5.5	5.3	5.5	4.6	5.1	5.5	5.3	3.8	5.1	5.5	5.0	3.3	3.1	2.2
	Building services (E)	0.23	0.24	0.23	0.23	0.23	0.23	0.23	0.24	0.23	0.23	0.23	0.24	0.32	0.32
	Equipment energy (O)	1.5	1.5	1.5	1.5	1.5	1.4	1.5	1.4	1.5	1.5	1.5	1.4	1.6	1.4
	Total (EO)	**7.3**	**7**	**7.3**	**6.4**	**6.8**	**7.2**	**7.1**	**5.4**	**6.9**	**7.3**	**6.7**	**5.0**	**4.9**	**4.0**
B-MV	Systems energy (O)	5.0	4.8	4.9	4.5	4.4	5.0	4.8	3.6	4.6	5.0	4.6	3.3	1.8	1.5
	BS EN 15978 total (EO)	5.0	4.9	5	4.6	4.5	5.0	4.9	3.7	4.8	5.1	4.7	3.4	2.2	1.9
	Building services (E)	0.23	0.24	0.23	0.23	0.23	0.23	0.23	0.24	0.23	0.23	0.23	0.24	0.19	0.19
	Equipment energy (O)	3.2	3.2	3.2	3.2	3.2	2.8	3.2	2.8	3.2	3.2	3.2	2.8	3.2	2.7
	Total (EO)	**8.5**	**8.3**	**8.5**	**8.1**	**7.9**	**8.1**	**8.4**	**6.7**	**8.2**	**8.5**	**8.2**	**6.4**	**5.6**	**4.8**
B-NV	Systems energy (O)	3.4	3.2	3.4	3.4	3.0	3.4	3.2	2.6	2.9	3.4	2.7	2.0	1.6	1.3
	BS EN 15978 total (EO)	3.5	3.3	3.5	3.5	3.1	3.5	3.3	2.7	3.0	3.5	2.8	2.2	2.0	1.7
	Building services (E)	0.17	0.18	0.17	0.17	0.17	0.17	0.17	0.18	0.17	0.17	0.17	0.18	0.19	0.19
	Equipment energy (O)	2.0	2.0	2.0	2.0	2.0	1.7	2.0	1.7	2.0	2.0	2.0	1.7	1.9	1.7
	Total (EO)	**5.6**	**5.4**	**5.6**	**5.6**	**5.2**	**5.3**	**5.4**	**4.5**	**5.1**	**5.6**	**5.0**	**4.0**	**4.1**	**3.5**
C-MV	Systems energy (O)	3.8	3.6	3.7	3.5	3.4	3.8	3.6	2.9	3.3	3.8	3.2	2.4	1.1	0.95
	BS EN 15978 total (EO)	3.8	3.7	3.8	3.6	3.5	3.9	3.7	3.0	3.4	3.9	3.3	2.6	1.5	1.3
	Building services (E)	0.19	0.2	0.19	0.19	0.19	0.19	0.19	0.2	0.19	0.19	0.19	0.2	0.18	0.18
	Equipment energy (O)	0.91	0.91	0.91	0.91	0.91	0.76	0.91	0.76	0.91	0.91	0.91	0.76	0.91	0.75
	Total (EO)	**4.9**	**4.8**	**4.9**	**4.7**	**4.6**	**4.8**	**4.8**	**4.0**	**4.5**	**4.9**	**4.4**	**3.5**	**2.6**	**2.3**
C-NV	Systems energy (O)	2.8	2.6	2.8	2.8	2.5	2.8	2.7	2.2	2.2	2.8	2.0	1.6	1.1	0.95
	BS EN 15978 total (EO)	2.9	2.7	2.9	2.9	2.6	2.9	2.8	2.3	2.3	2.9	2.2	1.7	1.5	1.3
	Building services (E)	0.14	0.15	0.14	0.14	0.14	0.14	0.14	0.15	0.14	0.14	0.14	0.15	0.18	0.18
	Equipment energy (O)	0.9	0.9	0.9	0.9	0.9	0.75	0.9	0.75	0.9	0.9	0.9	0.75	0.91	0.75
	Total (EO)	**3.9**	**3.8**	**3.9**	**3.9**	**3.6**	**3.8**	**3.8**	**3.2**	**3.4**	**3.9**	**3.2**	**2.6**	**2.6**	**2.3**

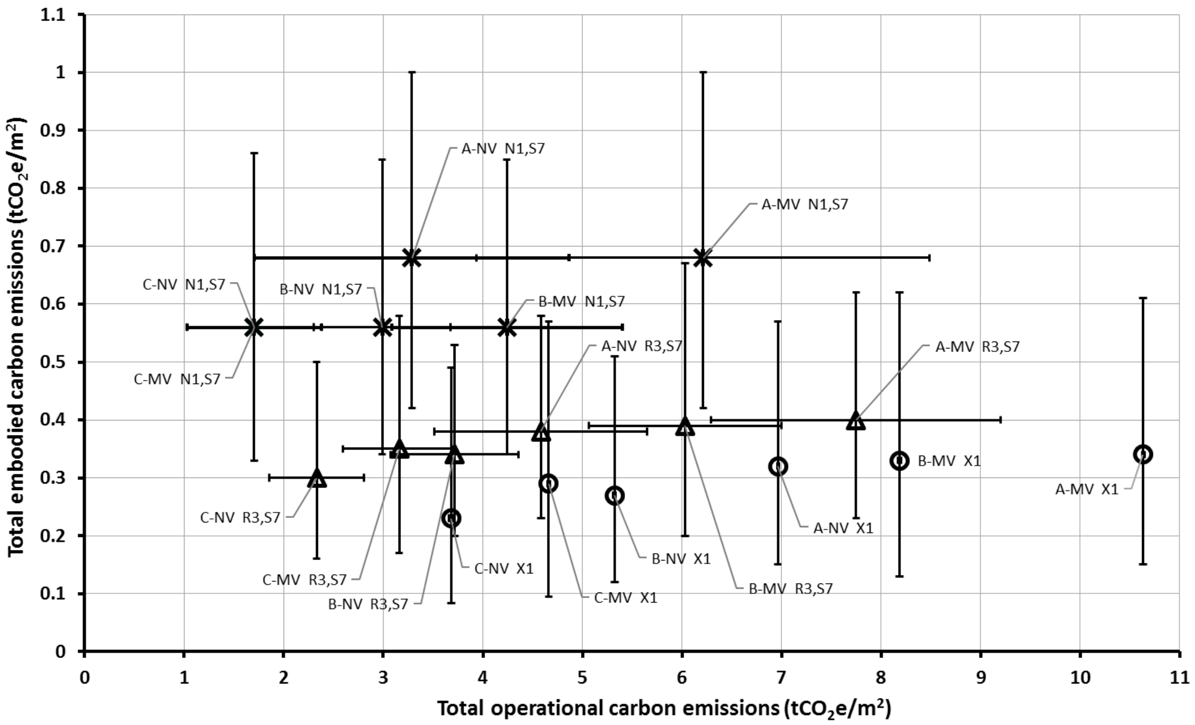

Figure 2 Comparison of ranges of operational and embodied carbon impacts (over 60 years) for the main redevelopment scenarios for each archetype. Crosshairs show the measured uncertainty. Labels indicate archetype and redevelopment scenario.

3.2. Embodied carbon contribution and uncertainty

As read from Figure 2, life cycle total embodied carbon emissions for the existing archetype scenarios (X1) were in the range 240 to 340kgCO_2e/m^2 on average and these only formed about 3 to 6% of total life cycle carbon emissions when set against total operational carbon emissions. For the new-build options (N1), the average embodied carbon emissions were found to range from 570 to 690kgCO_2e/m^2. It is also shown that peak embodied carbon emissions were found for the science/laboratory archetypes of 1.0tCO_2e/m^2, which was slightly higher than the peaks for other archetypes owing to the building services component. Allowing for the ranges of uncertainty in both the embodied and operational carbon values, it can be derived that in specific situations, such as the new-build options for the general academic archetypes, C-MV and C-NV, the embodied carbon emissions exceeded 40% of the total life cycle carbon impact. This approach of embodied carbon emissions towards parity with operational carbon emissions would appear to support assertions made by the UK Green Building Council [11] that embodied carbon emissions will start to dominate as buildings become more efficient in operation. However, it should be noted that this was still only at the extremes of the archetypes considered.

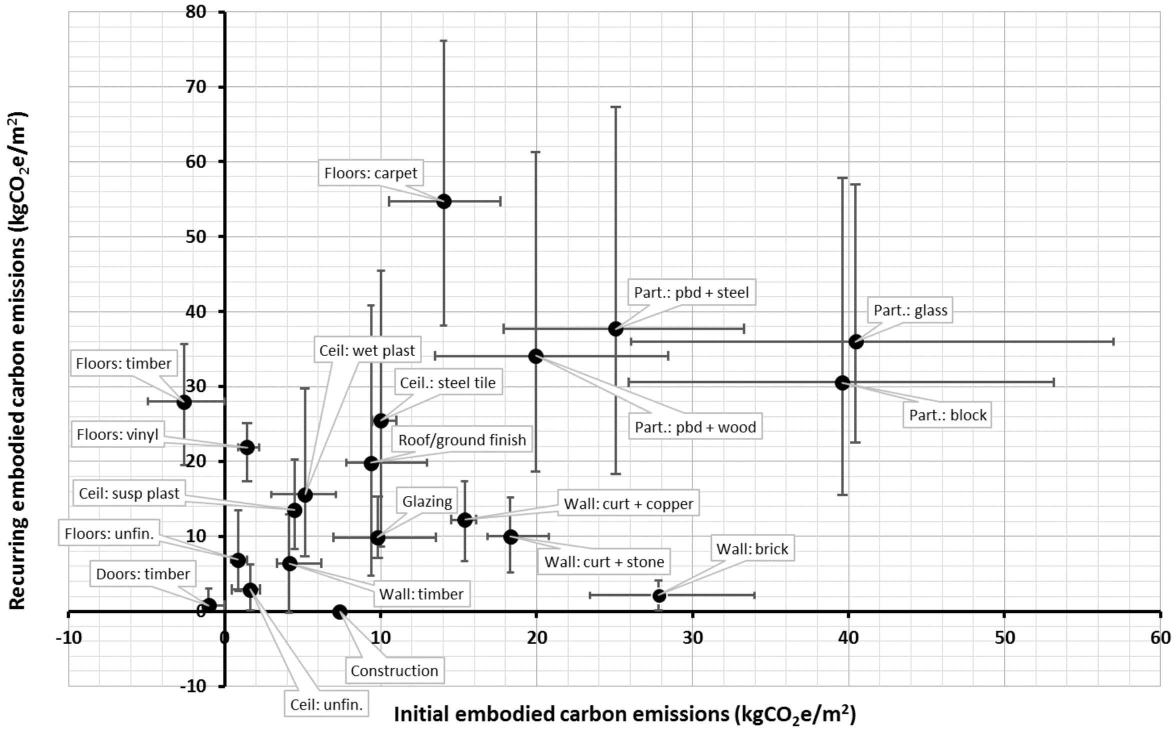

Figure 3 Initial and recurring embodied carbon impacts by building system material scheme (over 60 years) - small scale. Crosshairs shows the measured variation in results.

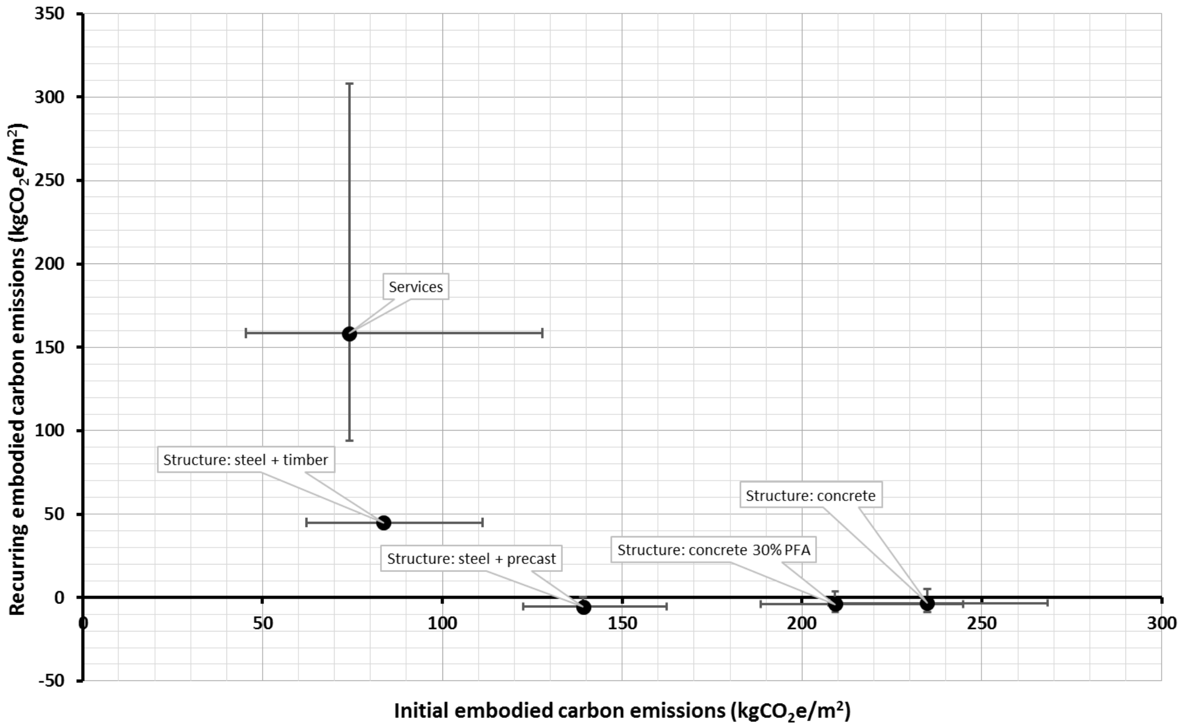

Figure 4 Initial and recurring embodied carbon impacts by building system material scheme (over 60 years) - large scale. Crosshairs shows the measured variation in results.

To observe the nature of the embodied carbon impacts in more detail, Figure 3 and Figure 4 compare the average initial and recurring embodied carbon impacts for each material scheme considered for each system in the archetype new-build options (in separate charts owing to the varying scale of results). The initial embodied carbon emissions were those owing to the original construction and recurring embodied carbon emissions were those over the remaining life cycle owing to replacement and maintenance. Total embodied carbon emissions were the summation of both. Crosshairs show the measured variation in the results owing to the uncertainty analysis and the variation of finishes in each archetype.

Key observations are as follows:

- With a total average embodied impact of 230kgCO_2e/m^2, the embodied carbon impact of building services across the life cycle was found to be the same as that of the most-intensive (concrete) structure. Although the initial impact was relatively low, and in some cases close to the 15% of total building initial carbon impact proposed by the RICS [37], high recurring impacts averaging around two replacements over the 60-year lifetime contributed to the significant total life cycle impact. These findings support the inclusion of building services in comprehensive building life cycle carbon assessments and also the need to overcome the limited availability of system-level data, as noted by Hitchin [38].

- Other systems apart from structure and building services had much lower embodied carbon impacts, with the next highest impact being 76kgCO_2e/m^2 for glass partitions.
- Recurring impacts over the life cycle were found to be the dominant component of total embodied carbon impact in a number of cases, for example owing to replacement of carpets, painting of plasterboard walls and varnishing of timber floors. In this sense, unfinished floor and ceiling options were shown to perform particularly well over the life cycle.
- As highlighted by the extent of the crosshairs, high variation was found owing to the analysis uncertainty. As well uncertainty owing to material quantities, service lives and transport distances, this was attributed to variations in design amongst the archetypes, for example the choice between mechanical and natural ventilation systems and the degree of open-plan arrangements. This demonstrates a need to consider the degree of uncertainty owing to generic material selection at early design stages in order to give confidence in the calculations and outputs.

3.3. Higher education estates carbon management

As highlighted in section 2.1, two-thirds of all buildings in the original sample taken were found to be pre-1985 area. When extrapolated to the whole stock, this indicates that a large number of buildings in the higher education sector in the UK pre-dates regulations on energy efficient construction. Building redevelopment would be essential in order to meet operational carbon targets in the sector, such as the 43% reduction in sector carbon emissions by 2020 set by HEFCE [3]. The values in Table 5 suggest that on average this scale of reduction would not typically be achieved using the refurbishment and management/systems changes alone, even where a number of interventions were applied together: the peak average operational carbon reduction for these interventions was 37%. In practice, greater savings might be achieved by applying the interventions more extensively, by adding other interventions or by combining a mixture of refurbishment and new-build schemes.

The variation in results by archetype highlights how the approach to managing carbon and achieving carbon targets needs to be tailored to a particular building, and in turn the building composition of the particular higher education institution. From the results in Table 5 and Figure 2, principal guidance for developing an appropriate approach to managing life cycle emissions is summarised as follows:

- For science/lab buildings, irrespective of the ventilation strategy, fabric improvements are unlikely to be effective although interventions to improve the building systems or replacement of the building altogether can offer significant operational carbon savings. As operational carbon emissions are generally very high for these buildings such interventions remain favourable also in life cycle terms.
- For mechanically-ventilated buildings generally, where opportunities exist to revert to a naturally-ventilated solution by new construction this is typically favourable in life cycle terms.
- For naturally-ventilated engineering/workshop buildings, improvements in the building operation, such as switch-off campaigns may prove to be effective.
- For naturally-ventilated general academic buildings, except science/lab buildings, collective refurbishment and system improvements may have a similar impact in life cycle terms as new-build. In these cases, careful estimation of the relative operational and embodied carbon impacts might be required, taking into account the impact of the likely analysis uncertainty.

4. CONCLUSION

In response to drivers to manage life cycle carbon impact in the redevelopment of higher education estates, an archetype analysis was carried out to generalise findings on the operational and embodied carbon impact of higher education building redevelopment. Data from a buildings database and case study buildings was combined to develop six archetype buildings, based on building activity and environmental strategy. The life cycle carbon impacts of a selection of building redevelopment options were then simulated.

The impact of interventions varied significantly for the different archetypes, highlighting how the approach to carbon management in higher education estates needs to suit the particular estate composition. In certain circumstances embodied carbon was found to be an influential factor in the building redevelopment. In these cases, the life cycle carbon impact should be carefully analysed in the decision-making process and analysis uncertainties, such as those relating to material selection, should be considered.

The archetype approach appeared to show success in developing general findings for the sector based on case study and database data. The method that was developed might itself be the key contribution of the study. It is important to note the principal limitations owing to the scope and available data. Firstly, the archetypes were defined principally as pre-1985 whereas further resolution by construction era would be appropriate. Secondly, the scope could be extended to include non-academic buildings, particularly student residences. Thirdly, the embodied carbon data was generic rather than product or system-specific. Fourthly, the analysis was simulation-based rather than measured. Finally, only a selection of possible new-build designs and redevelopment schemes was considered. These limitations highlight opportunities for further research.

5. ACKNOWLEDGEMENTS

This study was delivered under the UCL-FCBS Educational Building Design and Performance Research Programme. This programme is jointly funded by the Engineering and Physical Sciences Research Council (EPSRC) via the UCL EngD Centre in Virtual Environments, Imaging and Visualisation and Feilden Clegg Bradley Studios architectural practice.

6. REFERENCES

[1] D. Hawkins, D. Mumovic, Evaluation of life cycle carbon impacts for higher education building redevelopment: a multiple case study approach, Energy Build. This issue (2016).

[2] HESA, Higher Education Statistics Agency - Environmental Management Statistics 2013/14, (2013). https://www.hesa.ac.uk/component/content/article?id=2093 (Accessed 31 January 2016).

[3] HEFCE, Carbon reduction target and strategy for higher education in England, 1 (2010). http://www.hefce.ac.uk/pubs/year/2010/201001/ (Accessed 31 January 2016).

[4] L. Hopkinson, P. James, N. Lenegan, T. Mcgrath, M. Tait, Energy Consumption of University Laboratories : Detailed Results from S-Lab Audits, (2011). http://www.goodcampus.org/files/files/60-S-Lab_Energy_Audits_of_HE_Labs_final_v15_4_7_11.pdf (Accessed 31 January 2016).

[5] EEBPP, Energy Consumption Guide 54: Energy efficiency in further and higher education - cost-effective low energy buildings, 1997.

[6] AUDE, The Legacy of 1960's University Buildings, (2008). http://www.aude.ac.uk/resources/1960s_project/ (Accessed 31 January 2016).

[7] H. Altan, Energy efficiency interventions in UK higher education institutions, Energy Policy. 38 (2010) 7722–7731. doi:10.1016/j.enpol.2010.08.024.

[8] G. Hammond, C. Jones, E.F. Lowrie, P. Tse, A BSRIA guide: Embodied Carbon - The Inventory of Carbon and Energy (ICE), BSRIA, 2011.

[9] S. Sturgis, G. Roberts, RICS Research: Redefining Zero, Building. (2010). http://sturgiscarbonprofiling.com/wp-content/uploads/2010/05/RICS.RedefiningZero.pdf (Accessed 31 January 2016).

[10] T. Ibn-Mohammed, R. Greenough, S. Taylor, L. Ozawa-Meida, A. Acquaye, Operational vs. embodied emissions in buildings—A review of current trends, Energy Build. 66 (2013) 232–245. doi:10.1016/j.enbuild.2013.07.026.

[11] UK Green Building Council, Building Zero Carbon - the case for action, (2014). http://www.ukgbc.org/resources/publication/uk-gbc-task-group-report-building-zero-carbon-—-case-action (Accessed 31 January 2016).

[12] R.J. Cole, P.C. Kernan, Life-cycle energy use in office buildings, Build. Environ. 31 (1996) 307–317. doi:10.1016/0360-1323(96)00017-0.

[13] C. Scheuer, G. a Keoleian, P. Reppe, Life cycle energy and environmental performance of a new university building: modeling challenges and design implications, Energy Build. 35 (2003) 1049–1064. doi:10.1016/S0378-7788(03)00066-5.

[14] J. Basbagill, F. Flager, M. Lepech, M. Fischer, Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts, Build. Environ. 60 (2013) 81–92. doi:10.1016/j.buildenv.2012.11.009.

[15] P.L. Gaspar, A.L. Santos, Embodied energy on refurbishment vs. demolition: A Southern Europe case study, Energy Build. (2014). doi:10.1016/j.enbuild.2014.11.040.

[16] N. Badea, G.-V. Badea, Life cycle analysis in refurbishment of the buildings as intervention practices in energy saving, Energy Build. 86 (2015) 74–85. doi:10.1016/j.enbuild.2014.10.021.

[17] P. Steadman, H.R. Bruhns, P.A. Rickaby, An introduction to the national Non-Domestic Building Stock database, Environ. Plan. B Plan. Des. 27 (2000) 3–10. doi:10.1068/bst2.

[18] S.K. Firth, K.J. Lomas, A.J. Wright, Targeting household energy-efficiency measures using sensitivity analysis., Build. Res. Inf. 38 (2010) 25–41. doi:10.1080/09613210903236706.

[19] S.E. Chidiac, E.J.C. Catania, E. Morofsky, S. Foo, A screening methodology for implementing cost effective energy retrofit measures in Canadian office buildings, Energy Build. 43 (2011) 614–620. doi:10.1016/j.enbuild.2010.11.002.

[20] J. Bull, A. Gupta, D. Mumovic, J. Kimpian, Life cycle cost and carbon footprint of energy efficient refurbishments to 20th century UK school buildings, Int. J. Sustain. Built Environ. 3 (2014) 1–17. doi:10.1016/j.ijsbe.2014.07.002.

[21] D. Hawkins, EngD thesis: Life cycle carbon impact of higher education building redevelopment, University College London, 2016.

[22] HM Government, The Building Regulations 1985, HMSO, London, 1985. http://www.legislation.gov.uk/uksi/1985/1065/pdfs/uksi_19851065_en.pdf (Accessed 31 January 2016).

[23] BCIS, The Building Cost Information Services, (2015). http://www.rics.org/us/knowledge/bcis/ (Accessed 31 January 2016).

[24] CIBSE, TM47: Operational Ratings and Display Energy Certificates, 2009.

[25] Landmark, Landmark: non-domestic energy performance register, (2014). https://www.ndepcregister.com/ (Accessed 31 January 2016).

[26] D. Hawkins, S.M. Hong, R. Raslan, D. Mumovic, S. Hanna, Determinants of energy use in UK higher education buildings using statistical and artificial neural network methods, Int. J. Sustain. Built Environ. 1 (2012) 50–63. doi:10.1016/j.ijsbe.2012.05.002.

[27] D. Hawkins, Applying artificial neural networks to estimate building energy use in architectural design, Masters dissertation. University College London, 2011.

[28] H. Bruhns, P. Jones, R. Cohen, B. Bordass, H. Davies, CIBSE review of energy benchmarks for Display Energy Certificates - analysis of DEC results to date, (2011). http://www.cibse.org/Knowledge/CIBSE-Technical-Symposium-2011/CIBSE-Review-of-Energy-Benchmarks-for-Display-Ener (Accessed 14 September 2015).

[29] D. Hawkins, D. Mumovic, Evaluating determinants of energy use in higher education buildings using artificial neural networks – an enhanced study, in: Port. SB13, 2013: pp. 311–318.

[30] CMP, Collective Carbon Management Plans for King's College London, Imperial College, LSE, UCL, Oxford, Cambridge, Bristol, Southampton, Manchester Metropolitan University, Bath, Brighton, Kent and York. As published on individual websites, March 2012., (2012).

[31] HM Government, Non-Domestic Building Services Compliance Guide, NBS, London, 2013.

[32] HM Government, Approved Document L2A: Conservation of fuel and power 2013, (2013). https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/441420/BR_PDF_AD_L2A_2013.pdf (Accessed 31 January 2016).

[33] DCLG, Non-Domestic Heating, Cooling and Ventilation Compliance Guide, First, NBS, London, 2006.

[34] CIBSE, TM46: Energy benchmarks, 2008.

[35] D. Hubler, K. Tupper, E. Greensfelder, Pulling the Levers on Existing Buildings: A Simple Method for Calibrating Hourly Energy Models, ASHRAE Trans. 116 (2010).

[36] CIBSE, CIBSE Guide D: Transportation systems in buildings, 2010.

[37] RICS, Methodology to calculate embodied carbon of materials, RICS, London, 2012.

[38] R. Hitchin, Embodied Carbon and Building Services, (2013) 1–16. http://www.cibse.org/getmedia/4f1e4d9c-ddc7-4074-9faa-a944dc465fff/Research-Report-9-Embodied-Carbon-b.pdf.aspx (Accessed 31 January 2016).