EVALUATION OF LIFE CYCLE CARBON IMPACTS FOR HIGHER EDUCATION BUILDING REDEVELOPMENT: A MULTIPLE CASE STUDY APPROACH

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ABSTRACT

UK higher education institutions have strong drivers to reduce operational carbon emissions through building redevelopment. The life cycle carbon impact of buildings - operational and embodied carbon - is a developing area of consideration, particularly in redevelopment. A case study analysis was employed to assess how redevelopment interventions can reduce life cycle carbon impacts.

The five case study buildings covered a variety of activities, construction styles, systems and operational characteristics. Each building was monitored over a 12-month period and the data was combined with metered energy use to calibrate life cycle carbon base models following the BS EN 15978:2011 standard. The base models were modified to simulate a range of carbon reduction interventions and also new-build to current UK energy efficiency regulations. The design stage uncertainty was factored in.

The best-case refurbishment options showed average life cycle carbon savings of between 20 and 29%, with the most effective intervention varying by building. For new-build, the savings ranged from 32% of 64%, with the greatest being for conversion from mechanical to natural ventilation. The average contribution of embodied carbon to total life cycle carbon for the new-builds varied from 6% for the chemistry building to 23% for the law building.

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

1. INTRODUCTION

The UK higher education sector comprises over 150 higher education institutions (HEIs) and accommodates 2.5m students [1]. In total the sector contributes to approximately 0.5% of the UK's total emissions [2], with carbon emissions having risen by 33% from 1990 to 2005. In line with UK policy, there is a sector target to counter this expansion and to reduce emissions by 43% by 2020 and 83% by 2050 against a 2005 baseline [3].

The higher education sector has a number of distinct challenges with regards to carbon emissions: large proportions of estate area used for energy intensive scientific teaching and research [4]; irregular occupancy patterns owing to teaching and research demands [5]; transient populations requiring repeat behavioural reinforcement [3]; ageing estates with many buildings deteriorating and pre-dating modern energy efficiency standards [6]. Individual HEIs also have strong drivers to manage their carbon emissions, including utility cost and energy levy savings, building energy-related schemes and legislation such as Part L of the Building Regulations, participation in the EU Emissions Trading Scheme in certain cases, and demonstrating environmental stewardship as high-profile, thought-leading institutions [7].

Often implemented through senior and mid-level internal carbon management teams, UK HEIs have outlined a variety of technical measures to facilitate carbon management [3,7]. These measures can be broadly summarised as follows: end-use interventions such as space management, behaviour change programmes and ICT management; building alterations such as fabric upgrades and heating or lighting system upgrades; new building construction to high energy efficiency targets; energy supply modifications such as combined heat and power (CHP) systems and renewable energy. The Association of University Directors of Estates [6] note that the appropriate selection of such measures must be weighed against a variety of other economic, social and vision-related factors relevant to higher education building redevelopment.

Embodied carbon impact, which is associated with the manufacture, transport, installation and disposal of materials used in the building throughout its life, is also a significant part of the total carbon impact of a building and is gaining consideration in building design. Estimates for the contribution made by embodied carbon to total life cycle carbon emissions vary significantly between studies and building types, for example as found in studies by Sturgis and Roberts [8], Szalay [9] and Scheuer [10]. On average annually, about 18% of the total carbon impact associated with buildings relates to embodied carbon [11]. There are views that as buildings become more efficient in operation the embodied carbon impact will increase proportionally as a life cycle component [8,12,13]. The Green Construction Board has estimated that by 2050 embodied carbon will make up nearly 40% of the built environment's carbon emissions [14].

As new-build replacement offers an opportunity to extensively improve the operational efficiency of the building, whereas structural retention and refurbishment allows embodied carbon impacts to be mitigated, there can be a trade-off between these options in building redevelopment. AUDE [6] and HEFCE [3] assert that this trade-off should be considered when planning higher education building redevelopment.

As highlighted by Vukotic [15] and Moncaster [16], life cycle impact assessments have historically been based on different scopes, data and underlying assumptions, so it is often not practical to draw comparisons between them. To address this, BS EN 15978:2011 [17] is an EU-harmonised standard that provides a framework for assessing the environmental performance of buildings including embodied carbon analysis. The standard defines life cycle stages as "modules" and specifies the scope of the assessment that should be included in each module. The standard also defines the data that is suitable for use in the assessment. Despite this standard, there remain a number of uncertainties in the embodied carbon calculations owing to the degree of information available at the time of calculation and assumptions that need to be made, for example on refurbishment and maintenance cycles, building lifetime and end-of-life disposal options.

Although not always specific to higher education, several studies have been carried out that explore phenomena related to life cycle carbon analysis using case study buildings. Scheuer et al. [10] conducted a detailed life cycle study for a new-build university building, making use of construction data. Cole and Kernan [18] calculated life cycle embodied energy for a case study office building, highlighting the significance of recurring embodied carbon impacts. Basbagill et al. [19] explored early design uncertainty in embodied carbon analysis owing to variation in the selection and quantification of building materials. Gaspar and Santos [20], Badea and Badea [21] and Bull et al. [22] have carried out retrofit case studies largely comparing thermal efficiency improvements with embodied carbon inputs and for the purpose of simulations made assumptions regarding the operational characteristics of the study buildings. Although focusing on operational energy only, Suh et al. [23], Zhu [24] and

Pisello et al. [25] all carried out site investigations with which to calibrate energy models to simulate retrofit options.

The above studies have all investigated a number of areas concerned with measuring life cycle carbon impacts of redevelopment. There is a need, as addressed in this study, to bring these principles together and to consider in life cycle carbon impact terms the wider range of redevelopment scenarios available, following the BS EN 15978 standard. The key aims of the study were to develop and implement a method to measure the effect of redevelopment scenarios – both refurbishment and new-build – on the life cycle operational and embodied carbon impact of a selection of case study buildings. Furthermore, to factor in analysis uncertainties that might be associated with early stage assessment.

The following sections describe the key elements of the method for analysing carbon impacts and the results, presented following the BS EN 15978 format. The detailed methodology is given elsewhere [26].

2. METHOD

2.1. Case study buildings

Five case study buildings were selected from leading UK HEIs for analysis, as summarised in Table 1. The buildings were all over 40 years old, so considered appropriate for redevelopment considerations and were diverse in terms of activity, building construction style – architecture, fabric thermal performance, form - and energy use.

Table 1 Summary of the case study buildings

Building	Year built	Gross internal floor area (m^2)	Annual heating fuel use (kWh/m^2)	Annual electricity use (kWh/m^2)	Environmental strategy	Envelope
Law building	1958	5,000	91	96	Natural ventilation throughout except lecture theatres.	Stone and brickwork, uninsulated. Mostly single glazing.
Chemistry building	1968	12,551	224	348	Mechanically-ventilated labs. Air-conditioned server rooms, specialist labs and lecture theatres.	Pre-cast concrete cladding, uninsulated. Mostly single glazing.

Art and design building	1962	14,578	165	105	Natural ventilation throughout except lecture theatres, gallery and local workshop and kitchen exhaust.	Cavity brickwork, uninsulated. Double glazing.
Medical research building	1907	8,462	224	287	Mechanically-ventilated/air-conditioned labs and some offices.	Stone and brickwork, uninsulated. Mostly single glazing.
Administration building	1960	13,903	98	150	Mechanical ventilation and adiabatic cooling throughout.	Brickwork and cement panel cladding, uninsulated. Mostly single glazing.

2.2. Redevelopment scenarios

2.2.1. Scenario selection

A variety of demand-related carbon interventions and building redevelopment scenarios were considered for each building, as listed in Table 2. The interventions were developed in line with those recommended by HEFCE [3] and those considered generally by HEIs [7]. The interventions were grouped into categories of system/management, refurbishment and new-build, and paired combinations of interventions in different categories were also considered. 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. 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.

Table 2 Redevelopment scenarios for each case study building

Reference	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 [27]	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 [27]	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^2K 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 [28]: 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 [27].	5% lower heating and cooling efficiency. Systems 20% improvement	5% higher heating and cooling efficiency. Systems 60% improvement

Note: where changes to specific building systems or materials are not described for particular interventions or refurbishment options they remained the same as in the existing scenario.

2.2.2. New building elements

For the new-build and, where appropriate, refurbishment scenarios, the embodied carbon impacts were assessed separately by element: structure, external walls, floor finishes, ceiling finishes etc. In order to evaluate the sensitivity of carbon impact to material selection, a number of different typical material options were considered for each element. Typically two to four different types of material were considered, as follows:

- Structural frame: concrete frame; concrete frame using pulverised fuel ash as 35% cement replacement; steel frame with concrete decking; steel frame with timber decking
- Partitions: plasterboard – skimmed/painted; blockwork – skimmed/paint; glass partitions (office areas only)
- Floor finishes: carpet; vinyl sheet; porcelain tiles; unfinished (screed only)
- Ceiling finishes: suspended mineral wool tiles; suspended plasterboard ceilings; wet plaster/paint; unfinished
- Facades: steel curtain walling with stone cladding, steel curtain walling with aluminium cladding, steel curtain walling with timber cladding and brickwork
- Glazing: triple glazing in aluminium frame (1.1 $W/m^2/K$ was set for the glazing and a G-value of 0.54)

2.3. BS EN 15978:2011 definitions and scope

In accordance with the BS EN 15978 standard, the study definitions and scope were as follows:

- Purpose of the assessment: to compare carbon impacts of redevelopment options for an existing building
- Object of assessment: the whole building excluding its foundations and any external works
- Functional equivalent: "A building to accommodate the respective university function with the existing pattern of operation."
- Functional unit: gross internal floor area in m^2.
- Reference period: 60 years
- BS EN 15978 life cycle stages: Product/Construction (A), Use (B) and End of Life (C) for refurbishment and new-build scenarios; Use (B) and End of Life (C) only for existing scenarios
- Systems included: superstructure, roof, floor finishes, ceiling finishes, partitions, façade, glazing, doors, building services (major plant, lifts, ductwork, pipework and cabling), operational energy use: building systems and equipment

Although not strictly covered by BS EN 15978, it was deemed pertinent to the decision-making process to include also the operational energy use associated with building equipment (small power for laboratories, server rooms, offices, social areas etc.), although for clarity the results for these were totalled separately.

2.4. Building data collection

To feed into the life cycle carbon analysis, the target outputs from the building data collection were a set of information to describe the building construction and technical systems, a room data schedule that described energy and material characteristics, and measured energy profiles for representative rooms. A thorough site walk-round was first undertaken to establish the existing materials and energy use characteristics of each room. After this, rooms were also categorised into standard space categories based on activity.

From the space categorisation, a sample of around 10-15 representative spaces in each building was developed for monitoring. The following operational characteristics of these sample spaces were measured: occupancy using HOBO UX90 series loggers; equipment and lighting electrical use using Current Cost EnviR energy use loggers; space temperature using TinyTag Ultra 2 devices. Each space was monitored during three discrete monthly periods within a 12-month period between July 2013 and June 2014 to build typical profiles for use in the model calibration, as follows:

- Law and Administration spaces – October 2013, February 2014 and May 2014
- Chemistry spaces – June 2013, November 2013 and March 2014
- Art and Design spaces – August 2013, December 2013 and April 2014

Medical Research spaces – September 2013, January 2014 and June 2014Other supplementary data was also collected, such as zone mechanical plant power use, where deemed appropriate. Annual electrical and heating energy use was also determined from the building utility bills, installed building incoming meters and sub-meters for the same period for use in the model calibration (following the method described below).

2.5. Modelling life cycle carbon impacts

2.5.1. Model construction

The information collected during the monitoring period and building plans were used to construct and calibrate dynamic thermal simulation (DTS) models and embodied carbon models of each building. The IES Virtual Environment (IESVE) application (version 2014.1.0.0) was selected for this purpose. As well as DTS, the suite includes the EnviroImpact module (version 2) for embodied carbon assessment. It is understood that the methods used and materials database of the module meet the requirements of BS EN 15978 and BS EN 15804:2012 respectively [29].

Models for equivalent new buildings were also developed in accordance with the modern fabric and system standards given in Table 2. For comparison purposes, the geometry used for the new building was identical to that of the existing building.

2.5.2. Operational carbon impact

To assess the life cycle operational carbon impact, the annual energy demands by end use were determined from the DTS results and multiplied by the respective fuel carbon factors (based on CIBSE values [30]). The annual carbon emissions were then projected over the building lifetime to obtain the life cycle impact. For simplification, the analysis did not consider future changes in building efficiency and operation nor external factors such as fuel supply changes, grid decarbonisation or climate effects.

To build the base DTS models initially, thermal templates were constructed in the IESVE Apache module based on the monitoring data. The templates varied by space conditioning strategy and defined the characteristics of the heating, cooling, ventilation and hot water systems used in the existing and new buildings. Corresponding systems data described the heating, cooling and ventilation efficiency, obtained from guidance values for existing [31] and new [27] buildings where not measured directly. Profiles were set for each template using the monitoring data which described temporal variation in the mechanical ventilation flow rates, heating setpoint and system operation, cooling setpoint, lighting use, occupancy and equipment electricity and gas use. Air infiltration rates were included in each model to estimate the associated thermal loads based on values for existing and new buildings given in CIBSE Guide A [32]. Estimations were made of the annual energy consumption of lifts used in the existing and new buildings following the calculation method described in CIBSE Guide D [33].

The base models were calibrated based on the monthly electricity and heating fuel consumption by making bulk adjustments to standard settings for the ventilation, equipment, lighting and chiller efficiencies and the building infiltration rates. An iterative approach was followed similar to that described by Hubler et al. [34] where the systems with less certainty were adjusted first. Following targets given in ASHRAE Guideline 14 [35], total annual energy values were matched exactly and, to allow for discrete monitoring periods throughout the year, the quarterly energy use was also matched using a target maximum CV-RMSE of 15%. Weather files used for calibration were local Actual Meteorological Year (AMY) files corresponding to the building meter data periods. Once calibrated, all base and redevelopment scenarios were run using the closest AMY that represented a standard weather year (based on 2021 heating degree days as reported by CIBSE TM46 [30]), which was the year ending February 2014.

To simulate interventions and new-build scenarios further templates and system and gain variation profiles were created based on those for the existing building except with alterations appropriate to the scenario being considered. In the N1 new building scenarios all system and gain profiles were identical although new system settings were applied.

2.5.3. Embodied carbon impact

The life cycle embodied carbon impact was calculated following the BS EN 15978 method [17]. The quantity of each material introduced (by volume or weight as appropriate) during each life cycle stage was multiplied by its carbon loading factor in the database; then the aggregate carbon impact for the stage was determined. The calculation was carried out using the EnviroImpact module of the IESVE suite. Constructions were developed using materials in the Impact generic UK materials database (version 2) and were assigned to the model geometry to determine the material quantities and corresponding total carbon loadings for each BS EN 15978 life stage module. To assist with these calculations, data provided in the EnviroImpact database included typical transport distance, site wastage and services life for each material.

Separate structural calculations using rule-of-thumb guides [36–39] were carried out for the new buildings to estimate the quantity of materials in structural flooring, roofs, shear walls, beams and columns.

Outline design calculations were also carried out based on the CIBSE design guides [40–42] to estimate the quantities of relevant products for the building services systems: heating, cooling, ventilation, hot and cold water, gas distribution, drainage, low voltage electrical distribution, lighting and data distribution. Owing to insufficient embodied carbon data for building services products in the UK [43], data was taken from the German national product life cycle impact database, Ökobau.dat[1] and combined with service life lengths taken from the Building Cost Information Service (BCIS) [44]. As a different data source was used, the calculated embodied carbon impacts for building services were not included in the main BS EN 15978 totals but in separate totals.

2.5.4. Scenario simulation and uncertainty

Each scenario was simulated by making appropriate adjustments to the geometry, systems and profiles of the base IESVE model according the specifications for each scenario. The corresponding changes to operational and embodied carbon impacts were analysed.

A key feature of the method was the measurement of the sensitivity of the overall lifetime carbon impacts owing to design uncertainties. The method employed adopted principles for assessing uncertainty in design stage energy calculations set out in CIBSE TM54 [45]. For the operational carbon impact, the medium intervention impact was first calculated by simulation based on the standard figures given for each scenario in Table 2. To establish the associated uncertainty range, higher and lower operational carbon impacts were then calculated around each medium value. The higher carbon impact was calculated by simulation based on the 'upper' figures given in Table 2, based on the lower limit of carbon performance for the intervention. Conversely, the lower carbon impact was calculated based on the 'lower' limit in the same table.

For embodied carbon, the medium impact was first calculated for the material using its standard properties in the EnviroImpact database. To establish the uncertainty range, the embodied carbon was then calculated for five versions of the same material with randomly adjusted values for quantity, service life and transport distance parameters. For quantity, each material was assigned a range of 2%, 10% or 20%, based on the likelihood of the material having high, medium or low construction tolerance respectively. For transport, the transport distance was varied in the range 50%. For service life, a range of short, medium and long service lives were obtained for each material from the BCIS [44]. The standard deviation of the five randomly adjusted versions was then determined and used to construct 95% confidence limits around the medium impact to give the uncertainty range. . The uncertainty range for each building system was then obtained by summing the low, medium and high values for all of the constituent materials.

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

3. RESULTS AND DISCUSSION

3.1. Existing building life cycle carbon performance

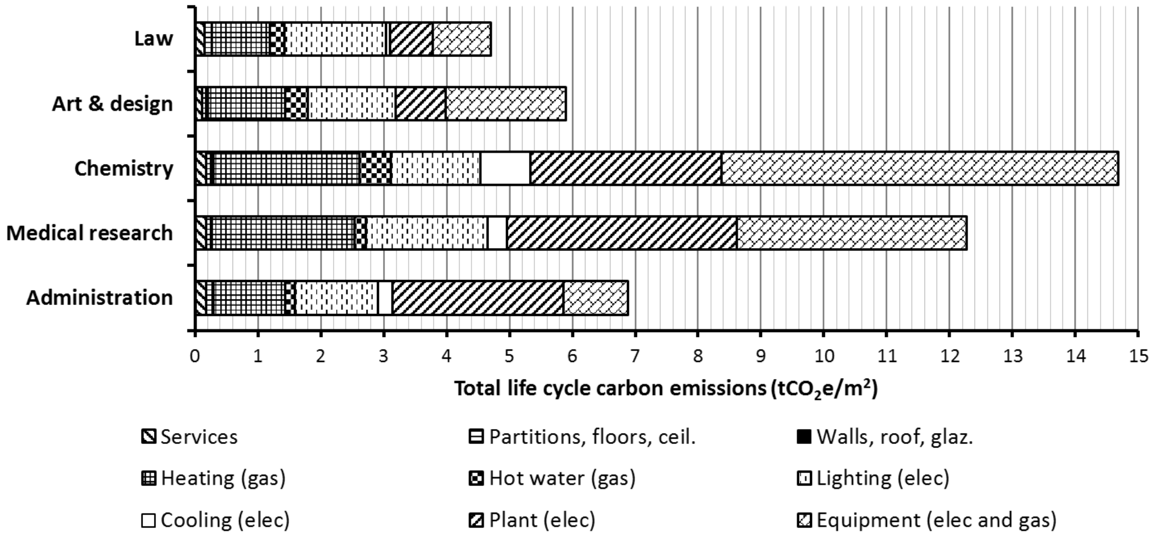

Figure 1 Breakdown of life cycle carbon impacts (over 60 years) by system for the existing buildings

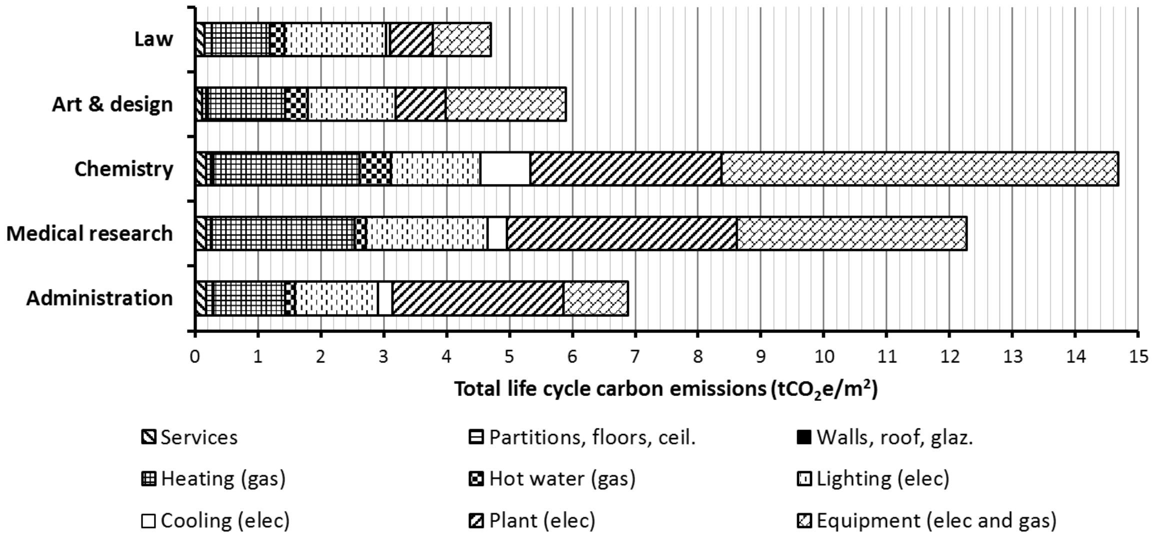

Figure 1 gives the existing life cycle carbon performance of each case study building projected over 60 years, broken down into the main impacts.

For the law building, the dominant existing impact was found to be lighting, owing to high out-of-hours use, particularly in circulation spaces and lecture theatres. Equipment in use in the building was largely PCs for office use and the out-of-hours base use was relatively low. Mechanical plant systems were limited mostly to lecture theatres and accordingly the building heating loads related mostly to the local space heat emitters.

The operational characteristics were found to be similar for the administration building, although the lighting impact was lower there owing to use of presence detection in cellular offices. Equipment was also mainly office-type, although the base use was found to be high, particularly in the shared open plan offices typically used for university administration. The most significant difference with the law building was the use of mechanical ventilation throughout, which resulted in a much higher plant carbon contribution, and space heating load accordingly.

In the art and design building, plant energy patterns similar to the law building were found. Mechanical ventilation systems were only local workshop extract and kitchen exhaust systems, although these typically operated continuously day and night. The contribution of office equipment was low, although overall equipment impact was high owing to workshop areas such as metal and woodworking. The equipment use was also found to be relatively sporadic, likely reflecting the seasonal use of the building and changing demands in art and design. As with the law building, lighting use was found to be high owing to patterns of continuous use.

Energy use characteristics for the chemistry and medical research buildings showed some similarities and were found to be markedly different to the other three case study buildings. Both buildings exhibited continuous mechanical ventilation in extensive laboratory areas with high air volumes and high specific fan power. This contributed to high electrical and heating fuel-related ventilation loads. Equipment loads were also high in both buildings, although for varying reasons. The chemistry building had significant isolated loads such as the x-ray and electron microscope, whilst in the medical research building equipment load more comprised general laboratory equipment such as refrigerators and centrifuges. Computational demands were also high in both buildings, with research IT clusters and servers contributing to the equipment electrical load, and in turn the space cooling load. In both buildings, similar continuous lighting characteristics to the other buildings were observed, although with less overall impact.

3.2. Life cycle carbon impact of redevelopment scenarios

Table 3 Life cycle carbon results for each case study building (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

Building		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.
Law	Systems energy (O)	3.5		3.5	3.4	3	3.5	3.4	2.8	3		2.9	2.2	1.3	1.1
	BS EN 15978 total (EO)	3.6		3.6	3.5	3.1	3.6	3.5	2.9	3.2		3.1	2.4	1.7	1.5
	Building services (E)	0.15		0.15	0.15	0.15	0.15	0.15	0.15	0.15		0.15	0.15	0.21	0.21
	Equipment energy (O)	0.92		0.92	0.92	0.92	0.77	0.92	0.77	0.92		0.92	0.77	0.91	0.76
	Total (EO)	**4.7**		**4.7**	**4.5**	**4.2**	**4.6**	**4.6**	**3.8**	**4.3**		**4.2**	**3.3**	**2.9**	**2.5**
Chemistry	Systems energy (O)	8.1		8	6.2	7.6	8.1	7.9	5.6	8	8.1	8	5.4	4.9	3.5
	BS EN 15978 total (EO)	8.2		8.1	6.4	7.7	8.2	8	5.7	8.1	8.2	8.1	5.6	5.3	3.8
	Building services (E)	0.18		0.18	0.18	0.18	0.18	0.18	0.19	0.18	0.18	0.18	0.19	0.24	0.24
	Equipment energy (O)	6.3		6.3	6.3	6.3	5.9	6.3	5.9	6.3	6.3	6.3	5.9	6.3	6
	Total (EO)	**15**		**15**	**13**	**14**	**14**	**15**	**12**	**15**	**15**	**15**	**12**	**12**	**10**
Art and design	Systems energy (O)	3.8	3.6	3.8	3.5	3.4	3.8	3.6	2.9	3.3		3.2	2.4	1.9	1.6
	BS EN 15978 total (EO)	3.9	3.7	3.9	3.6	3.5	3.9	3.7	3	3.4		3.3	2.6	2.4	2
	Building services (E)	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12		0.12	0.12	0.16	0.16
	Equipment energy (O)	1.9	1.9	1.9	1.9	1.9	1.8	1.9	1.8	1.9		1.9	1.8	1.9	1.8
	Total (EO)	**5.9**	**5.7**	**5.9**	**5.6**	**5.6**	**5.8**	**5.8**	**4.9**	**5.5**		**5.4**	**4.5**	**4.4**	**3.9**
Medical research	Systems energy (O)	8.4		8.3	6.4	7.6	8.4	8.2	5.5	8.3	8.5	8.4	5.4	4.4	2.9
	BS EN 15978 total (EO)	8.4		8.4	6.5	7.7	8.4	8.3	5.6	8.5	8.6	8.6	5.6	4.8	3.3
	Building services (E)	0.18		0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.23	0.23

	Equipment energy (O)	3.7	3.7	3.7	3.7	3.3	3.7	3.3	3.7	3.7	3.7	3.3	3.7	3.3
	Total (EO)	**12**	**12**	**10**	**12**	**12**	**12**	**9**	**12**	**12**	**12**	**9.1**	**8.8**	**6.9**
Admin-istration	Systems energy (O)	5.6	5.5	4.8	5.2	5.6	5.4	4.3	5.4	5.5	5.3	4	1.4	1.2
	BS EN 15978 total (EO)	5.7	5.7	4.9	5.3	5.7	5.5	4.4	5.6	5.6	5.5	4.1	1.9	1.6
	Building services (E)	0.18	0.18	0.18	0.18	0.18	0.18	0.19	0.18	0.18	0.18	0.19	0.16	0.16
	Equipment energy (O)	1	1	1	1	0.71	1	0.71	1	1	1	0.71	1	0.71
	Total (EO)	**6.9**	**6.9**	**6.1**	**6.5**	**6.6**	**6.7**	**5.3**	**6.8**	**6.8**	**6.7**	**5**	**3.1**	**2.5**

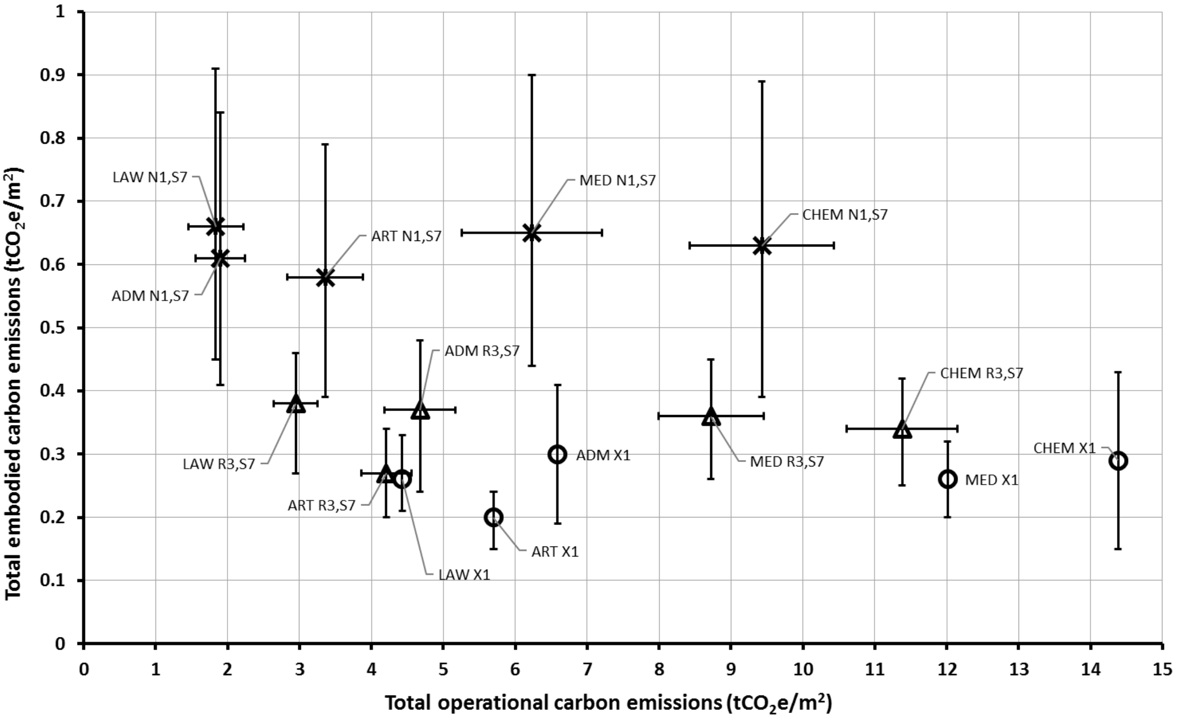

Figure 2 Comparison of ranges of operational and embodied carbon impacts (over 60 years) for the main redevelopment scenarios for each case study building. Crosshairs show the measured uncertainty.

Table 3 summarises and compare the results from the life cycle carbon analysis for the main redevelopment options for each case study building. The results 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 shows the measured operational and embodied carbon uncertainty for the key redevelopment scenarios.

Each building showed a significant response to combined management and system changes (X1/S7), with average life cycle carbon reductions in the range 17 to 26%, however the nature of this varied. For the law building, most of the reduction was associated with lighting control improvements (X1/S4) to reduce overnight use, owing partly to the relatively low contribution of the other loads. For all mechanically-ventilated buildings – chemistry, medical research and administration - the largest individual management and system change related to demand-led ventilation (X1/S3), reflecting the trends of continuous out-of-hours ventilation in all these buildings. The impacts of setpoint changes (X1/S6) were highest in the non-laboratory buildings, likely owing to the lower equipment loads and associated casual gains in these buildings leading to a greater sensitivity to the space heating system output. Reductions for switch-off campaigns (X1/S5) were greatest in the law building and the administration building. This may be related to these buildings having the greatest proportions of office space and also that research areas such as research laboratories and heat-based workshops were excluded from the switch-off campaign analysis. As the total equipment loads were large in the other buildings, it would suggest that where research equipment could be managed to allow additional downtimes the potential energy savings would be significant.

The additional façade replacement option (R3/S7) offered substantial further savings for the law building and art and design buildings and a relatively small saving for the administration building, although further life cycle savings were not observed for the chemistry building or the medical research building. Reductions for intermediate measures such as insulation and triple glazing (R1) followed similar proportions. Three principal reasons are proposed for the reduced impact of fabric improvements for the latter two buildings: high fresh air ventilation heating loads in the laboratory buildings; high casual gains reducing the impact of the space heating system as above; increased base cooling requirements offsetting savings in heating. It should be noted that improved fabric may still be beneficial for other reasons such as improved occupant comfort and better environmental stability.

A large range in reductions was observed associated with the new-build option excluding management changes (N1): from 19% for the chemistry building to 56% for the administration building. For the chemistry building the reduction was actually lower than the best refurbishment option (R3/S7) and for the art and design and medical research buildings the margins relative to refurbishment were small. Also, for these buildings, the equipment loads were the highest proportionally, suggesting the lowest sensitivity to the performance of the building fabric and systems. Additionally, these buildings had the greatest amount of mechanical ventilation – for laboratories, kitchens and workshops – retained in the new schemes. The large reduction for the administration building, owing to the near total conversion to natural ventilation, is notable.

Where management changes were included in the new-build schemes (N1/S7), further reductions were observed and this option outperformed refurbishment in all cases. This highlights the importance of ensuring good building management to realise successful reductions in operational carbon emissions. Overall, the range of peak life cycle carbon reductions was significant, from 32% for the chemistry building to 64% for the administration building.

3.3. Embodied carbon as a life cycle component

For all buildings, the embodied carbon in the existing scenarios (X1) was found to be between 200 and 290 $kgCO_2e/m^2$ on average, which at up to only 6% of the total life cycle carbon impact was low relative to the operational carbon impacts. With the new-build options (N1), the embodied carbon associated with the initial building construction was measured to range from 180 to $520kgCO_2e/m^2$ depending on the building type and material selection. This appeared to be broadly in line with RICS benchmark values [46] that start at around 400 $kgCO_2e/m^2$, particularly given that structural foundations were not included and the low-end of range allowed for low embodied carbon options, such as timber.

With recurring impacts included, the total life cycle embodied carbon impact increased to between 570 and 660 $kgCO_2e/m^2$ on average. On average, this typically contributed to between 6% (for chemistry) and 23% (for law) of the total life cycle carbon impact for new-build, although for the most efficient new-build options for the law and administration buildings the potential was found for embodied carbon to rise to between 30 and 40% of the total life cycle carbon impact. This suggests that, as building operational carbon performance improves, the embodied carbon impact could achieve parity in some cases. This appears to support assertions by the UK Green Building Council [13] that in order to achieve the UK’s 2050 target for 80% reduction in carbon emissions, the embodied carbon impact of buildings will also need to be mitigated.

4. CONCLUSION

In response to drivers to manage life cycle carbon impact in the redevelopment of higher education estates, a case study analysis was carried out to measure the effect of redevelopment scenarios on the operational and embodied carbon impact of higher education buildings. The approach was novel by the use of monitoring data to simulate life cycle carbon impacts in line with the BS EN 15978 standard for a variety of redevelopment scenarios and the inclusion of analysis uncertainty.

The findings showed that all of the carbon reduction interventions considered were effective, although their impact varied by circumstance. Achieving substantial reductions in operational carbon emissions might therefore require a multilateral approach. Interventions addressing the building systems appeared most effective for laboratory-type buildings, whilst building fabric-related interventions were more effective for naturally-ventilated buildings and buildings with low equipment energy intensity. Building management-related interventions were shown to have impact and to be influential in the success of low-carbon new-build developments. On average, the embodied carbon impact of new development was found to be relatively low, although in highly efficient new-build scenarios there was potential for it to be close to life cycle operational impact.

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