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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

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ABSTRACT

An archetype-based approach was taken to generalise case study findings on the life cycle carbon impacts of higher education building redevelopment. For each archetype, the life cycle operational and embodied carbon impacts of carbon reduction interventions and building redevelopment options were analysed. The contribution of embodied carbon to total life cycle carbon impact was also evaluated.

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 25–33% 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 were used to provide guidance on higher education carbon management.

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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 sector have grown since 1990 and currently stand at around 0.5% of UK carbon emissions [2]. Higher education institutions (HEIs) experience specific challenges that impact their operational carbon emissions: high proportions of scientific research, irregular occupancy patterns, transient populations, and ageing estates [3–6]. There are also a number of drivers in the sector 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 in the UK [9], embodied carbon emissions are projected to increase in relative magnitude as operational carbon emissions are reduced through energy efficiency improvements [10–12]. The greater embodied carbon impact but potentially higher operational carbon efficiency of new-build schemes can lead to trade-offs when comparing them with refurbishment alternatives for redevelopment of higher education buildings. There are strong motivations then to evaluate redevelopment options for higher education buildings in terms of total life cycle carbon performance.

Life cycle carbon analyses have been carried out using real data from case studies, such as those that made static measures of life cycle carbon impacts for existing buildings [13–15]. Further studies, for example those by Gaspar and Santos [16] and Badea and Badea [17], also assessed the redevelopment of case study buildings in terms of life cycle carbon impact. To provide more generalised life cycle carbon findings, Bull et al. [18] applied an archetype approach. They modelled the operational and embodied carbon impact of thermal improvements on four different UK school archetypes classified by period of construction. Use of archetypes is a common

* Corresponding author.
E-mail address: david.hawkins.10@ucl.ac.uk (D. Hawkins).

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method for generalisation of findings in building energy analysis more broadly. In the UK, building form-based classification was employed as the basis of the Non-Domestic Building Stock database [19] and the Community Domestic Energy Model [20], with both used to analyse energy use in large building stocks. Chidiac et al. [21] 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. Despite being a common method generally, evidence has not been found of studies that use archetypes to transfer life cycle carbon findings from real building case studies to a general building stock, particularly considering a broad variety of redevelopment scenarios.

The aim of this study was to develop generalised findings on the life cycle carbon impact of building redevelopment applicable to the wider UK higher education building stock. Furthermore, there was an aim to use these results to evaluate the magnitude of embodied carbon impacts both in terms of contribution to total life cycle carbon impact and in terms of breakdown by constituent building material schemes. The study built on previous case study analyses by the authors [1] and used an archetype-based method to achieve generalised results applicable beyond the scope of the original case studies.

As highlighted in Fig. 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 that was considered appropriate for redevelopment and were mainly 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. [15]. The method for data collection and analysis is summarised, followed by presentation and discussion of the life cycle carbon results. Further detail of the method is given elsewhere [1,22].

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 year. The chosen cut-off construction year was 1985, the year that energy efficiency standards were introduced in the UK Building Regulations [23]. For compliance with these standards, minimum levels of insulation and glazing performance were needed, 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.

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] 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 was 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 use were found for each archetype by strategy (with 95% confidence), however not for heating fuel use so common values for this were used for each major activity class. The median energy values were used as the basis for calibrating the models in the life cycle analysis as described later.

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

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