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The life cycle carbon footprint of refurbished and new buildings – A systematic review of case studies

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ABSTRACT

CO_2 is emitted throughout the lifespan of buildings—from construction through to operation, and eventually, demolition. Life Cycle Carbon Footprint calculations (LCCF) can be employed to provide useful evaluation metrics for the analysis and comparison of their environmental impact. This paper brings together, for the first time, a systematic review of the LCCF of 251 case study buildings from 19 different countries. This review focuses on the comparison of the LCCF of refurbished and newly constructed buildings, through the synthesis of the overall outcomes of these studies, to identify whether refurbishment or replacement design alternatives achieve better performance.

The results highlight that the average embodied, operational-related and demolition-related CO_2 is responsible for 24%, 75% and 1%, respectively, of LCCF. Furthermore, this review indicates that while the type of heating and energy supply system can significantly impact overall LCCF (when normalised to kgCO_2/60 years/m^2 floor area), other factors, such as building floor area or number of storeys, have minimal effect. A comparison between the LCCF of refurbished and new buildings showed that while most refurbishments had lower LCCF than most new buildings, some new buildings performed better than refurbished ones. Thus, findings suggest that on the basis of current evidence, it is still not possible to conclusively determine which of the alternatives is preferred. Finally, the paper highlights the current state of buildings LCCF, in particular in terms of the analysis scope and limitations, illustrating how these terms were interpreted differently in the examined case studies, and subsequently highlighting the need for a unified protocol to be developed for building LCCF analysis.

1. Introduction

The built environment is responsible for 40% of global energy consumption [1]. The global construction industry is also responsible for approximately 40% of overall raw aggregate consumption and 25% of the world's wood consumption [1–4]. The United Kingdom (UK) is one of the world's highest CO_2-emitting countries [5]. Following the 1992 Kyoto protocol and the 2015 Paris UN Climate Change Conference, the UK Government's Climate Change Act aimed to achieve a minimum 80% reduction commitment in the UK's CO_2 emissions [6,7].

The UK building stock includes an estimated 28 million properties. These include approximately 22 million residential and 6 million non-residential buildings, which are responsible for around 26% and 18% of the UK's total CO_2 emissions, respectively [8,9]. While around 75% of the UK housing stock that will exist in 2050 has already been built [10], much of the effort for improving energy efficiency is focused on new buildings, which only add around 1% to the UK building stock every year [11]. Legislation and assessment tend to focus on operational stage building performance—while the building is built and used [12]. CO_2 emissions, however, also occur during other building life cycle stages such as construction, maintenance, use and demolition.

Two alternatives are often examined to analyse if the aforementioned CO_2 emissions can be achieved, namely the refurbishment of existing buildings or their demolition and replacement with new, more energy-efficient buildings. In order to understand which of the alternatives may result in the lowest (i.e. minimal) environmental impact, a comparison between the Life Cycle Carbon Footprint (LCCF) of refurbished and new buildings should be undertaken. Despite the recent increase in the number of LCCF studies, evidence supporting the

Abbreviations: Bath ICE, Bath Inventory of Carbon and Energy; BRE, Building Research Establishment; EC, embodied CO_2; EOL, end of life; EPD, Environmental Product Declaration; EPSRC, Engineering and Physical Sciences Research Council; ISO, International Organisation for Standardisation; LCA, life cycle analysis; LCCF, life cycle carbon footprint calculations; LCE, life cycle energy; ORCE, operations-related CO_2 emissions

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benefits of either refurbishment or replacement is still considered to be uncertain and any performance advantages or either approach remain unclear [11–14].

This study aims to investigate the LCCF of refurbished and new buildings to determine whether the environmental impact of one design alternative outperforms that of the other.

In addressing this, the objectives of this study are:

a. To collect data of the LCCF of a series of case study buildings and, for the first time, present their results.
b. To synthesise the data and examine various factors that might contribute to the LCCF of refurbished and new buildings.
c. To compare the LCCF of new and refurbished case study buildings.

As a meta-analysis of the LCCF of case study buildings has never before been presented, a main contribution of this paper is the collection and analysis, for the first time, of the life cycle environmental impact of the built environment.

This paper is structured as follows:

Section 2 discusses the life cycle of buildings and presents the concept of life cycle analysis. The different elements of CO_2 flows in buildings and how these are taken into account in the evaluation of the life cycle performance of buildings is detailed.
Section 3 discusses existing literature examining the current 'building carbon footprint' debate, in relation to refurbishment versus replacement.
Section 4 presents the systematic literature review methodology and outlines the study scope, search technique, the case study stock and study limitations.
Section 5 includes a synthesis of review findings and presents the LCCF of the whole case study stock. Influential LCCF environmental and design-related factors are examined and a comparison between the performance of refurbished and new residential buildings in the UK is presented.
Section 6 sums up review findings and presents a set of conclusions based on the work.

2. Building life cycle

Although both refurbishing or replacing an existing building has the potential to significantly improve its overall life cycle impact [11,12,15], each option offers performance improvements at different stages. While refurbishment allows the retention of some parts of existing structures, new buildings often offer a higher potential for integrating passive and active climate-control improvements, which could potentially lead to a reduction in CO_2 emissions. A holistic life cycle approach is recommended for comparing the overall benefits of each alternative [11].

2.1. Life cycle analysis

To carry LCCF calculations, the Life Cycle Analysis (LCA) methodology is often used [16]. LCA is an environmental assessment and management framework that offers a holistic approach to evaluating the potential environmental impact of products and process throughout their lives [17]. LCA compares the performance of different 'system units' (a product or service, or a building in the case of the built environment). The main comparative component in an LCA is the functional unit, this a reference unit that helps quantify the performance of the product. In the built environment, a commonly used functional unit is 1 m^2 floor area. According to ISO 14040 — one of the most widely used LCA frameworks [18] — LCA studies consist of four steps (Fig. 1).

There are currently no standardised measures that address embodied CO_2 calculation methods. Yet, two approaches, referred to as 'top-down' and 'bottom-up', are often used. The top-down approach refers to pre-calculated databases of embodied energy or CO_2 values, summarising the outputs of the production processes of various generic building materials, from cradle to factory gate [19]. These include databases such as the Building Research Establishment (BRE) IMPACT, Bath Inventory of Carbon and Energy (Bath ICE), the Swiss Ecoinvent and others.

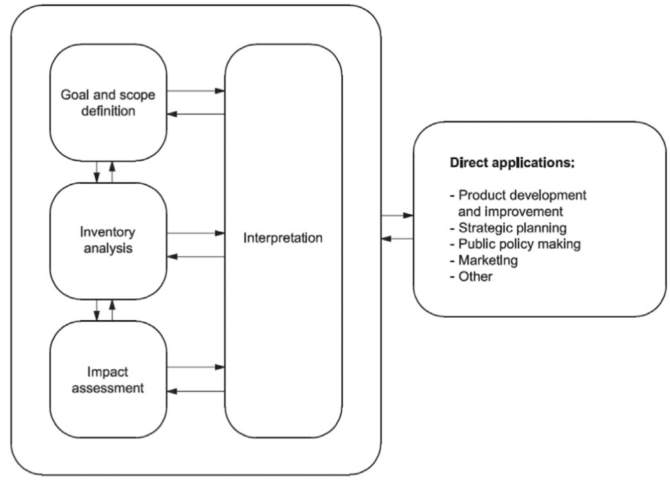

Fig. 1. LCA framework (ISO 14040, 2006).

The bottom-up approach describes the embodied CO_2 calculation of individual materials, products or processes (sometimes referred to as input-output LCA). Bottom-up protocols such as the Environmental Product Declaration (EPD) or EN 15804 [20] have been established in recent years, however an accurate assessment greatly relies on the availability of these types of certificate. As there is still no binding legislation in regard to EPDs, their availability is still scarce.

2.2. CO_2 flows in buildings

LCCF is a measurement that accounts for all the processes that involve CO_2 inputs or outputs in buildings throughout their life cycle. According to life cycle energy analysis ([2,16,21]), CO_2 emissions flow in and out of building systems during the following life cycle stages (Fig. 2):

- *Embodied CO_2 (EC):* the sum of CO_2 emissions due to the extraction of raw materials, transportation to and from factories, building construction, maintenance and refurbishment.
- *Operations-related CO_2 emissions (ORCE)*: CO_2 emitted in the process of maintaining comfortable environmental conditions in the building: heating, cooling, domestic hot water and lighting.
- *Demolition: End of life (EOL)*: CO_2 emissions due to the demolition of the building and transportation of waste to dump sites.

Other CO_2-related processes have gained increasing attention in recent research [22–24]. These are:

- *Renewables*: the generation of energy that has the potential of reducing energy use and CO_2 emissions during the operational phase of the building.
- *Recycling:* the re-use of some building components and materials and potential saving of CO_2. This might require the engagement of a novel approach towards design (cradle-to-cradle, circular economy) that emphasises the importance of considering recycling at the earliest stages of design of a product or service [25].

According to the BRE Green Guide, the life cycle stages are assessed over an assumed building life span of 60 years [26,27]. Since there is no