Building Material Recycling

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Construction is amongst the leading sectors contributing to global economic growth whilst having a huge adverse impact on resource consumption, GHG emission, solid waste generation, and global warming. One of the main strategies to deal effectively with demolished building materials or components at the end of a building's useful service life is recycling. Recycling is defined as the process of converting construction and demolition waste into new material.

Keywords: embodied carbon ; recycling

1. Introduction

Globally, there is a growing awareness of the need to limit greenhouse gas (GHG) and mitigate climate change. The most recent annual UN climate change conference—Conference of the Parties (COP26) summit held in the United Kingdom and attended by delegates from regional, national, and international levels—underscores the global commitment to reduce GHG.

Construction is amongst the leading sectors contributing to global economic growth whilst having a huge adverse impact on resource consumption, GHG emission, solid waste generation, and global warming [1][2][3]. Globally, buildings are responsible for 39% of carbon emissions, up to 36% of energy and natural resources consumption and almost 50% of the solid waste disposed of in landfills [2][4]. Previously, however, most effort was focused on reducing the operational carbon of buildings rather than the embodied carbon (*EC*) [5][6]. Without a comparable effort on the reduction of the *EC* of buildings and construction materials, efforts towards net-zero-emission buildings and GHG emissions reduction to mitigate climate change would be compromised. According to UK Green Building Council (UKGBC) [7], *EC*, also referred to as carbon capital, can be defined as follows: 'the total greenhouse gas emissions generated to produce a built asset'. This encompasses carbon emission emitted during extraction of raw material, processing and manufacturing of building material, transporting and assembling of building product, and deconstruction or demolition of building material and its disposal. Furthermore, Akbarnezhad and Xiao [8] observed that the whole-life *EC* can be reduced by considering the carbon footprint implications of the chosen strategy to deal with the end of life (EoL) of a building. Thus, the whole lifecycle of a building should be taken into account in an attempt to achieve net-zero buildings and reduce the built environment's impact on climate change. Whilst past research carried out by Mohebbi et al. [9] on the role of *EC* coefficients databases in the estimation of *EC* accuracy at the cradle to gate revealed that the use of a comprehensive database compared to a generic database can lead to a 35.2% reduction of carbon emissions, very little is currently known about the impact of different databases on EoL phase *EC* calculation. Reliable and credible databases provide useful information for a transparent calculation of carbon emissions.

2. Recycling

One of the main strategies to deal effectively with demolished building materials or components at the end of a building's useful service life is recycling [8][10]. Recycling is defined as the process of converting construction and demolition waste into new material [11]. While the process of recycling may result in carbon emissions, it is encouraged as an alternative strategy to raw material extraction to deal with construction and demolition waste [12]. It is therefore essential these emissions are assessed when selecting recycling as a strategy for carbon emission minimisation. Factors influencing the quantity of carbon emission during the recycling process are the materials being recycled and the level of technological advancement of the recycling process [13]. Akbarnezhad and Xiao [8] claimed that the initial *EC* invested in building materials during the production and construction processes can be released during the process of recycling at the end of the building's useful life. The authors, therefore, suggested that in the absence of data, the initial carbon can be used to estimate the emissions of recycling structural elements or materials.

Notwithstanding, the environmental benefits of recycling demolished building materials at end of the service life in an attempt to reduce carbon emissions have been documented [5][14]. For instance, Hopkinson et al. [14] observed that due to the challenges to reclaiming concrete, much emphasis has been on recycling instead of reuse. Yuan [15] further highlighted that recycling diverts waste materials from being sent to landfills and removes the need for virgin materials. Reducing waste production through recycling is a key factor in material resource efficiency. Wu et al. [5] asserted that recycling has now become the common EoL management strategy for concrete, and the proportion of concrete being recycled keeps increasing year on year. For instance, according to the British Ready-Mixed Concrete Association [16], in the UK, approximately 90% of concrete can be recycled or recovered. Hence, recycling as an EoL management strategy promotes effective resource utilisation by extending the life span of the building materials, thus improving the building and construction sector in an ecologically friendly way. Nevertheless, there is no current study that examines the impact of different databases on EoL-phase embodied carbon calculation.

3. Embodied Carbon and Operational Carbon

The total carbon emissions generated during the whole life cycle of a building are usually classified into operational emissions and embodied emissions. Operational carbon emissions are the result of energy used during the use phase of the building and represent approximately 28% of the global energy consumption [2], while embodied carbon is the total amount of emissions of GHG emitted over the life cycle of the building accounting for almost 11% of the energy used [6]. The initial *EC* is a product-based emission that occurs prior to the construction of the building and involves raw materials extraction, manufacturing, and transporting of products to a construction site. The construction *EC* is related to the construction stage of the building, whilst the recurring *EC* emission is associated with maintenance, replacement, deconstruction, demolishing, and disposal of the building materials.

In the past, a large amount of effort has been concentrated on optimising operational carbon. However, due to the whole lifecycle of the buildings, carbon emissions extend beyond the use of the building. Additionally, with the race to net-zero carbon intensified, there could be no operational carbon for buildings in the future, and all carbon emissions will be assigned to embodied carbon [17]. Therefore, the key to reducing the impact of buildings on climate change is to minimise *EC* emissions, and the whole lifecycle of a building should be taken into consideration in order to reap long-term benefits.

4. Life Cycle Assessment

One way to ensure the environmental impact of construction activities is minimised to a reasonable level, whilst providing the needed economic and social infrastructure, is the application of the life cycle assessment (LCA) tool [18][19]. LCA is a dynamic tool that can be employed to assess the consumption of raw material and energy, carbon emission, and waste associated with the whole useful life of a product or a system [19][20]. It is a well-recognised quantification tool that allows the comparison of different materials used in a project and their choice of management strategies [21].

As a multipurpose and useful environmental impact assessment tool, LCA can be employed at a single-product level to calculate the carbon emission arising from the product across its useful lifespan or to determine the environmental impacts of several products and processes over their entire life cycle [22][23]. It is an internationally accepted approach that provides a standardised methodological basis for quantifying carbon emission, consumption of energy, depletion of natural resources, and other environmental impacts throughout the whole lifecycle of buildings [24][25][26].

The LCA methodology follows the four-stage framework (goals and scope definition, life cycle inventory (LCI), LCA, and interpretation recommended by [20]. The EN 15978 [27] for buildings environmental performance assessment provides guidelines for the sustainability of construction activities. **Figure 1** illustrates the structure and definition of stages in the life cycle of buildings.

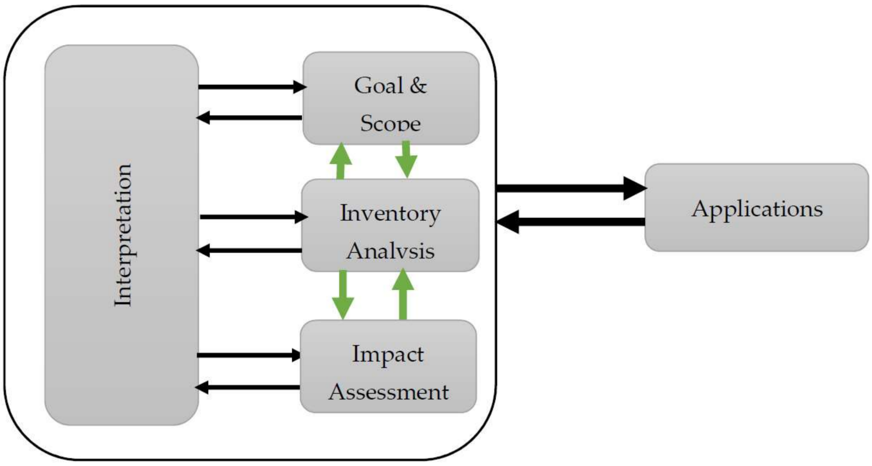

Figure 1. Life cycle assessment stages, reproduced [20].

LCA scope is EoL (C1–C4), as shown in **Figure 2**. Module C1 encompasses all the activities and processes in the deconstruction or demolition of the building at the end of its useful service life and includes carbon emissions associated with the use of equipment, fuel consumption, and related emissions. Module C2 activities include the transportation of the deconstructed or demolished building materials to the storage site for reuse, recycling plants, waste treatment plants, or landfill sites. The carbon emissions associated with C2 depend on the mode of transport and fuel consumption as well as the distance travelled. Module C3 includes all the activities associated with the waste treatment plant, while Module C4 encompasses the carbon emissions of the processes associated with the final disposal of building materials.

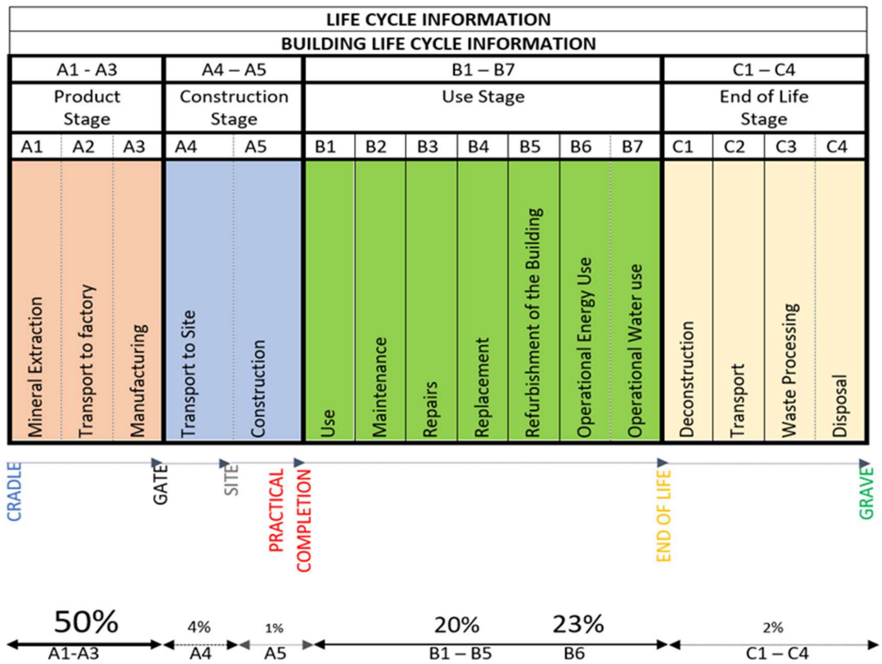

Figure 2. Life cycle stages and modules with split carbon emission across all building elements, adapted [28].

The life cycle of a building is divided into stages, and the carbon emission boundary of each stage is determined. The carbon source of each stage is quantified according to the material quantities and the emission factors of various materials that are determined. Regarding the carbon footprint of building material, however, the whole life cycle or an isolated life cycle stage can be selected as a boundary system. The ISO 14067 [29] specifies the assessment method for the carbon footprint of a product by providing some specific requirements on the selection of system boundary and the simulation of other phases but cradle to gate. This document specifies that the construction phase can be used as the system boundary for carbon emission calculation only when:

- Information on a specific stage such as EoL of the products is unavailable, and reasonable scenarios cannot be modelled, or
- The other phases have insignificant impact on the calculation of the carbon emissions of the product.

Therefore, for certain materials/products' whole lifecycle estimation, the EoL stage may be left out only if its results are considered insignificant. Hence, the need to investigate the impact of ECF databases on the calculation of EoL embodied carbon.

5. Databases and Embodied Carbon Factors State of the Art

One of the crucial data requirements in the assessment of *EC* of buildings is the materials and components emission coefficients or embodied carbon factors (ECFs). Accurate carbon emission coefficients are vital for reliable *EC* estimation. These factors can be obtained from various secondary sources including national data, industry data, commercial lifecycle database, PAS 2050 compliant carbon footprint, aggregated or derived from the literature, and Environmental Product Declarations (EPDs). The accuracy and reliability, however, differ from one database to another. Consequently, EN 15978 [28] requires that the most recently updated data be used and verified with the provisions of EN 15804 [30][31]. According to Gervasio and Dimova [32], emission coefficients can be obtained from two main sources—generic and specific. Generic refers to datasets that are based on material quantities production and construction processes specific to the geographical area where the structure is built. These data sources may include national data and data derived from the literature. Therefore, any amendments in these details can have a significant impact on the results of the estimation. Generic databases should be used with caution, as they cannot be assumed to possess similar features as those of other geographic regions where both material production and construction processes differ [33]. The data should fit conditions of the geographical area of production and construction procedures. Hence, the use of a specific data source can enhance the accuracy of lifecycle assessment.

Specific data, on the other hand, are supplied by producers and manufacturers in the form of EPDs and externally validated to certify the environmental impact of the product in accordance with the requirements of BS EN 15804 [34]. Additionally, the EPDs production process must meet the standard of ISO 14044 [20]. The goal of EPDs is to share building materials or products' environmental impacts with users [31]. According to Gelowitz and McArthur [35], EPDs provide freely available environmental data. Ibáñez-Forés et al. [36] have also observed that one of the important features of EPDs is to act as a valuable source of transparency to understand the environmental impacts of construction materials and processes. In addition, the availability of EPDs affords assessors more certainty in their findings; therefore, they are noted as an effective way of transmitting products' environmental performance [37]. The aforementioned demonstrate that EPDs are a useful data source to gain an accurate picture of building materials' environmental performance which can aid the assessment of *EC*.

However, EPDs are not mandatory for all the lifecycle stages except the A1–A3 boundary [34]. Although EPDs are currently a progressively growing source of the environmental database for the built environment, they are still limited in number [37]. The available literature suggests there are various reasons why EPDs are not currently well-positioned to aid whole lifecycle assessment and for comparison [37][38]. Andersen et al. [37] suggested that EPDs are presently accessible for a limited number of building materials, whilst Hunsager et al. [38] pointed out the challenge of the distrust of users concerning inadequate transparency and validity. Additionally, Bhat and Mukherjee [39] discussed the issue of reliability in EPDS.

Currently, in the UK, the Inventory of Carbon and Energy (ICE) is recognised as the most reliable database for carbon factors. It was developed in the late 1990s by the University of Bath and summarises embodied carbon coefficients for most common construction materials [40]. This database contains more than 500 building materials commonly used in construction but provides only cradle-to-gate carbon factors. Therefore, the number of available databases providing ECFs for the EoL phase is limited.

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