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Review

Estimation and Minimization of Embodied Carbon of Buildings: A Review

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Abstract: Building and construction is responsible for up to 30% of annual global greenhouse gas (GHG) emissions, commonly reported in carbon equivalent unit. Carbon emissions are incurred in all stages of a building's life cycle and are generally categorised into operating carbon and embodied carbon, each making varying contributions to the life cycle carbon depending on the building's characteristics. With recent advances in reducing the operating carbon of buildings, the available literature indicates a clear shift in attention towards investigating strategies to minimize embodied carbon. However, minimizing the embodied carbon of buildings is challenging and requires evaluating the effects of embodied carbon reduction strategies on the emissions incurred in different life cycle phases, as well as the operating carbon of the building. In this paper, the available literature on strategies for reducing the embodied carbon of buildings, as well as methods for estimating the embodied carbon of buildings, is reviewed and the strengths and weaknesses of each method are highlighted.

Keywords: carbon footprint; embodied carbon; greenhouse gas emissions; buildings

1. Introduction

The building and construction industry is responsible for up to 30% of annual global greenhouse gas (GHG) emissions, placing it among the top seven major contributors to the enhanced global warming effect [1]. It is estimated that, without major improvements in the energy efficiency of buildings, the current surge in urbanization may lead to a doubling of GHG emissions associated with the building and construction industry in the next 20 years [2]. GHGs mainly include six gases with proven global warming effects, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6) [3]. Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) make considerably higher contributions to global warming than the other GHGs and account for about 97% of the total global warming potential [4]. To facilitate comparison and reporting, an aggregate measure, known as carbon equivalent, is usually used to quantify and report the overall global warming impact caused by various greenhouse gases emitted during a process. Carbon equivalent is estimated by converting the quantity of various GHGs to an equivalent quantity of carbon dioxide that leads to the same global warming impact [5]. Throughout this paper, the term "carbon emissions" is used to refer to "carbon equivalent emissions".

The energy use and carbon emissions occur in all different stages of a building's life cycle, which may be defined as (I) material extraction; (II) material processing and component fabrication; (III) construction and assembly; (IV) operation and service phase; and (V) end-of-life phase (Figure 1) [6]. Furthermore, the transition between these phases generally involves considerable transportation-related emissions, which should be considered in the estimation of the carbon footprint. In another particular categorization, carbon emissions may be divided into two general groups, embodied carbon and operating carbon emissions. The operating carbon comprises of carbon emissions incurred during the service life of a building and includes the carbon emissions incurred in maintaining the indoor environment through processes such as heating, cooling, lighting and the operation of appliances [7]. The embodied carbon, on the other hand, has been conventionally defined to comprise carbon emissions incurred in stages I to III of the building's life cycle (defined above), although it may be extended to include the end-of-life carbon emissions. As shown in Figure 1, to clarify the life cycle phases considered, the embodied carbon may be reported as "cradle to gate", "cradle to site", "cradle to service" or "cradle to grave" embodied carbon, which respectively comprise emissions incurred up until the onset of Phase II, Phase III, Phase IV, and Phase V of a building's life cycle, alongside the corresponding transportation emissions.

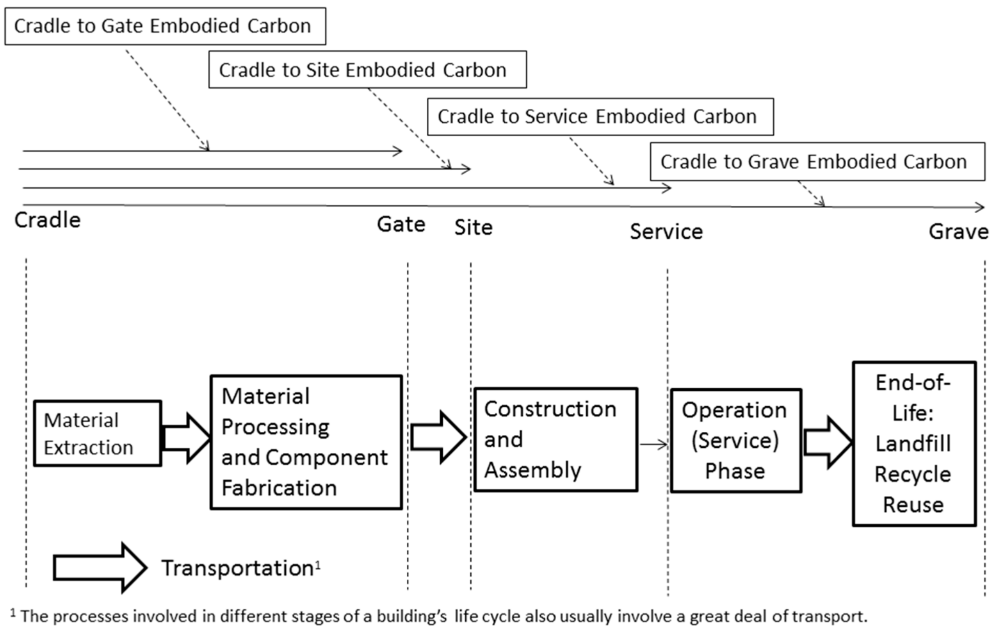

Figure 1. Different phases of a building's life cycle.

The relative contribution of embodied carbon and operating carbon to the total life cycle carbon of buildings may vary considerably depending on the type and function of the building [8], as well as factors including location, climate, fuel type used, orientation of building, massing of building, etc. [9]. In this regard, the share of embodied carbon in the life cycle carbon of conventional buildings has been reported to vary from as low as 20%, or lower, for conventional office and residential buildings to as high as 80%, or higher, for low-energy buildings such as washhouses [8,10–13]. On the other hand, with advances in the area of energy efficiency as well as more stringent energy efficiency requirements imposed by building regulations, the share of embodied carbon in the life cycle carbon of buildings has been on an increasing trend in new projects [8,14]. The share of embodied energy, closely related to embodied carbon, in the total life cycle energy of low-energy houses has been reported to be up to 40%–60% [15,16]. The reduced share of operating carbon and consequent increase in the relative contribution of embodied carbon to life cycle carbon has resulted in a clear shift in the focus of research towards investigating strategies to reduce the embodied carbon of buildings [7,17,18]. These common strategies include the use of low-carbon materials, material reuse, recycling and minimization, selection of optimal structural system and structural optimization, and optimization of construction operations [19–22]. However, while considerable effort has been put into developing strategies for reducing the embodied carbon of buildings, as well as models for quantifying the effectiveness of such strategies through estimating the resulting reductions in a building's embodied carbon, the available literature is highly scattered across different relevant disciplines and a lack of a comprehensive reference highlighting the options available to decision makers is apparent. This paper presents an extensive literature review on (i) the proposed strategies to reduce the embodied carbon of buildings and (ii) existing methods for estimating the embodied carbon of buildings. The focus is placed on strategies related to structural rather than non-structural elements of the building. However, the majority of the discussed concepts are general and could be applied to design and planning related to non-structural components of the building. The review was performed on relevant literature identified using a keyword search in different search engines, by limiting the publication date from 1990 to 2016, and a selection was carried out based on the focus of this paper. It should be noted that while the focus of this paper is on methods for reduction and estimation of embodied carbon, the ultimate decision to implement the proposed strategies should be made by considering the resulting reductions in the total life cycle carbon of the building, as well as the effects that implementation of embodied carbon reduction strategies may have on the other economic, environmental and social impacts of the building.

2. Embodied Carbon Reduction Strategies

A great deal of research has been conducted to investigate various strategies to reduce the embodied carbon of buildings. These strategies can be generally divided into six categories: (1) low-carbon materials; (2) material minimization and material reduction strategies; (3) material reuse and recycling strategies; (4) local sourcing and transport minimization; and (5) construction optimization strategies. The recent advances in each of these areas are reviewed in the following.

2.1. Low-Carbon Materials

Designers are usually obliged to select from a limited number of alternative materials available for each structural and non-structural element in a building by considering their performance against technical requirements [23]. The material options shortlisted after screening based on technical and performance requirements may have considerably different embodied carbon implications for the buildings [24,25]. The embodied carbon of materials may vary significantly depending on the type of the raw material constituents, the location of material quarries and mode of transport required, carbon intensiveness of extraction and processing operations, carbon intensiveness of applicable construction methods to install the materials, carbon intensiveness of recycling and reuse operations, if applicable, and distance to disposal sites accepting the resulting waste [25]. The important effect that material selection can have on the carbon footprint of structures has been studied in several previous studies [19,26,27]. González and Navarro showed that a decrease of about 30% in CO_2 emissions was achieved when conventional materials were replaced with lower embodied carbon material alternatives in the case building considered, highlighting the importance of material selection in reducing the carbon footprint of buildings [27]. The selection of materials for low embodied carbon buildings should ideally be performed by comparing the effect of the material type on cradle to grave embodied carbon of the building, which also accounts for variations in the transport, construction, and end-of-life processing requirements of different materials [28]. Furthermore, due to the important effect that material type may have on the operating energy requirements of some building, the effect of material changes on the operating carbon of a building should be assessed and considered in the selection process [29].

The effects of material types on the embodied carbon of buildings and the possibility of minimizing the carbon footprint of building through the selection of low-carbon materials have been widely studied in the literature [19,26,30]. By evaluating the embodied carbon of a number of office buildings made with different materials, Dimoudia and Tompa reported that the highest share of embodied energy belonged to the structural materials (concrete and reinforcement steel), which accounted for about 59% to 66% of the total embodied energy of the building [31]. Ji et al. indicated that small variations in the type of material could considerably affect the embodied carbon of a structure and showed that, depending on the grade of the concrete and reinforcing rebar used, the embodied carbon of a concrete structure can change by up to 40% [32]. Furthermore, Cole showed that the use of different structural materials including wood, steel and concrete can result in significantly different embodied energy and carbon [33]. Moussavi et al. showed that the embodied carbon of a structure not only changes with the type of the material selected but also by other design parameters including, but not limited to, the type of structural system selected and the height of the structure, which affect the quantity of the material required [29]. In addition, the results of this study showed that the selection of low-carbon materials and building systems for a building based on minimum cradle to gate or cradle to site embodied carbon estimates may be misleading and may not result in the lowest life cycle carbon footprint. It was therefore recommended that the selection of the best structural material and system to reduce the carbon footprint should be based on the effects of the structural system on the life cycle carbon footprint rather than the carbon footprint of individual life cycle phases [29].

Several previous studies have advocated the use of wood as a more sustainable and low-carbon construction material than conventional concrete and steel [34–36]. Buchanan and Levine claimed that, due to the considerably less energy-intensive manufacturing process of structural wood compared to other construction materials, wood structures tend to have considerably lower embodied carbon than buildings made with other construction materials, including brick, steel and concrete [34]. These authors indicated that a 17% increase in the use of wood in New Zealand's building industry may result in a 20% reduction in carbon emissions due to the manufacturing of construction materials and, thus, about a 1.5% reduction in the country's total carbon emissions [34].

Apart from comparing the embodied carbon of materials when selecting the material from conventional alternatives for a building, the available literature suggests two other common strategies to reduce the embodied carbon of buildings. These include reducing the embodied carbon of existing materials by increasing the content of recycled, waste or byproduct materials in their composition [37] and developing new low-carbon materials [38]. Among various construction materials, a great deal of attention has been paid to cement and concrete, where considerable effort has been made to (1) reduce the embodied carbon of cement and concrete through a partial use of waste/byproduct cementitious materials and (2) find alternative low-carbon materials for cement and concrete [39]. The considerable attention paid to cement and concrete is partly due to the significant contribution of cement production to worldwide emissions, accounting for up to 7% [40,41]. The possibility of reducing the embodied carbon of concrete structures by substituting Portland cement fully or partially with supplementary cementitious materials (SCMs), including fly ash, ground granulated blast furnace slag (GGBFS), and amorphous silica (silica fume), has been investigated by several studies [42,43]. Table 1 shows the effect of different percentages of fly ash, as a representative SCM, substitution for Portland cement on the embodied carbon of different grades of concrete as reported by the ICE carbon inventory [24]. As shown, partial replacement of Portland cement with fly ash can result in a considerable reduction in the embodied carbon of concrete, with reductions as high as 17% achievable at 30% replacement. However, the replacement of Portland cement with SCMs has been shown to result in a slower development of concrete properties and, thus, the extent of SCM substitution for Portland cement in concrete should be determined by considering such negative effects and project requirements [44]. Numerous studies have been conducted to evaluate the effect of SCM content on the mechanical properties and durability of concrete [45]. The relationships between SCM content and the properties of concrete established in such studies provide a useful basis for evaluating the trade-off between a reduction in the embodied carbon of concrete achievable through the use of varying amounts of SCMs and the loss of mechanical properties of concrete.

Table 1. Effect of fly ash replacement for Portland cement on embodied carbon of concrete.

Concrete Grade	Embodied Carbon (kg CO_2-e/kg)		
	Cement Replacement with Fly Ash (%)		
	0%	15%	30%
RC 20/25 (20/25 MPa)	0.132	0.122	0.108
RC 25/30 (25/30 MPa)	0.140	0.130	0.115
RC 28/35 (28/35 MPa)	0.148	0.138	0.124
RC 32/40 (32/40 MPa)	0.163	0.152	0.136
RC 40/50 (40/50 MPa)	0.188	0.174	0.155

In a different approach to reducing the embodied carbon of buildings, alternative low-carbon materials to replace Portland cement have been studied in the literature. In this regard, hydraulic cements and geopolymer concrete have been widely advocated as replacements for Portland cement [46,47]. The production of geopolymer concrete has been reported to result in up to 80% fewer carbon emissions than Portland cement concrete [39,47]. Geopolymer concrete is formed by a reaction of silicon and aluminium in byproduct materials such as fly ash, ground granulated blast furnace slag and rice husk ash with an alkaline liquid, which leads to the formation of a cement-like binder [48–50]. Numerous studies have been conducted to investigate the mechanical properties and durability of geopolymer concrete to explore its suitability as a replacement for Portland cement concrete and to assess its competitive performance in terms of compressive strength, tensile strength and modulus of elasticity as well as shrinkage, creep, corrosion resistance, sulphate resistance, fire resistance and acid resistance [47,51–66].

As an alternative to the low-carbon concrete discussed above, rammed earth has been also highlighted as a potential low-carbon construction material [26]. Rammed earth may be categorised into non-stabilized rammed earth and stabilized rammed earth, where the main difference lies in the use of cement or lime additives in the latter to stabilize the soil, sand and gravel [67,68]. Non-stabilized rammed earth has considerably lower embodied carbon than concrete. This is mainly because the main source of emissions in the production of non-stabilized rammed earth structures is the compaction operation. However, non-stabilized rammed earth is not generally suitable for structural applications and the addition of stabilizing additives is usually required. The embodied carbon and embodied energy of rammed earth tends to increase proportionally with the binder content as rammed earth is stabilized through the addition of cement. Reddy and Kumar showed that the embodied energy of a non-stabilized rammed wall may increase from 0.33–0.36 MJ/m^3 to 0.4–0.5 GJ/m^3 range when about 6%–8% cement is added to stabilize the wall [67].

Low-carbon brick containing solid waste materials has been also investigated in previous studies as an alternative low-carbon construction material [69]. Jiao et al. studied bricks made with four types of solid waste including dredged mud, steel slag, fly ash and calcium carbide sludge and identified the maximum content of the waste that ensures adequate quality. Furthermore, stabilized mud blocks have been promoted as an alternative low-carbon material, with an estimated 60%–70% lower embodied energy, for the clay brick [67]. Non-fired clay bricks made with lime and Portland cement as activators for GGBFS to stabilize kaolinite clay have been shown to have considerably lower embodied carbon than conventional clays [70].

While highlighting various low-carbon material alternatives, previous studies also note that the selection of materials for reduction of embodied carbon of building should be conducted by also considering the performance of the material with respect to other performance criteria [23,29]. With this in mind, the use of multi-attribute decision making methods including TOPSIS and AHP for selection of building materials for sustainable buildings has been studied in several previous studies [23,71–74]. In particular, in a study focused on embodied carbon of structures, Moussavi et al. showed that the selection of building material for a structure should be performed by accounting for the effect such selection may have on the operating carbon of a building [29]. Ahmadian et al. assert that a variety of other environmental, technical and logistic factors should be considered in the selection of materials for sustainable buildings and developed a framework for the selection of building materials where embodied carbon is one of the selection criteria alongside other technical and performance criteria [23].

2.2. Material Minimization

The total embodied carbon of a structure is directly proportional to the quantity of the material used in the building [75]. Therefore, comparing the alternative materials should be performed by considering the total embodied carbon, which is the product of the unit embodied carbon rate and the total quantity of the material used [29,75]. The quantity of the material used in a structure may be affected by various factors including the type of materials used, the structural system selected for the building, and the height of the structure [29]. Optimal design, and thus avoiding overdesign, may result in considerable reductions in the total quantity of materials and, thus, the embodied carbon of the structure. Avoiding overdesign has been advocated for decades as one of the main principles of engineering design to minimize the costs, weight and material use of structures [21]. It should be noted that minimizing the material usage, and thus the embodied carbon, should be performed while maintaining the ability of the structure to meet all other technical and performance requirements [21]. Yeo and Gabbi showed that the structural optimization of a beam cross section can result in a decrease in the embodied energy of the beam on the order of 10% at the expense of about a 5% increase in the cost relative to a cost-optimized member. The total amount of materials used in a structure, and thus the embodied carbon of the structure, has also been shown to be considerably affected by the amount of waste produced during component manufacturing, on-site construction and installation process [76,77]. Therefore, minimizing the waste generated during production and construction can be considered a potential strategy for minimizing the embodied carbon of structures. Moussavi et al. showed through a case study that minimizing the trim loss in cutting reinforcing steel rebars resulted in a decrease of about 7.7% and 49.6% in the total amount of material used and generated waste, respectively [76].

2.3. Material Reuse and Recycling

Figure 2 schematically shows the increase in the embodied carbon of the building as it goes through different stages of its life cycle. As shown, the embodied carbon of a structure increases gradually as additional energy is consumed in every step of the project to turn construction materials into structural elements, individual structural elements into structural frames and modules through assembly, and modules into an integrated structure [29]. Therefore, it can be assumed that a given amount of carbon is gradually invested in the element as a material moves through different stages of processing, manufacturing, installation and assembly. However, when the building reaches the end of its service life, this invested carbon is at risk of being lost, as determined by the end-of-life strategy selected to deal with the building at the end of its service life [20,78]. Common strategies to deal with buildings at the end of their service life include "demolition and landfilling", recycling and reuse (of components or materials) [79,80]. The cradle to grave embodied carbon of buildings can be reduced by accounting for carbon emission implications when selecting the end-of-life strategy. As shown in Figure 2, demolition and landfilling strategy, if adopted, not only does not preserve the embodied carbon invested to convert the material into an integrated structure but also results in additional carbon emissions during the demolition of the building and the transportation of debris to remote landfills [20]. The recycling strategy is, on the other hand, one of the oldest sustainable strategies to deal with construction and demolition waste [81–88]. Concrete recycling has been highlighted as an effective strategy to reduce carbon emissions and costs incurred in transporting and dumping of debris at remote landfills, reducing the need for the landfill space and providing a sustainable source of alternative aggregate [75,88,89]. The recyclability of materials and implementation of a recycling strategy may considerably affect the embodied carbon of the buildings in different ways and should be considered in the selection of materials for low-carbon buildings.

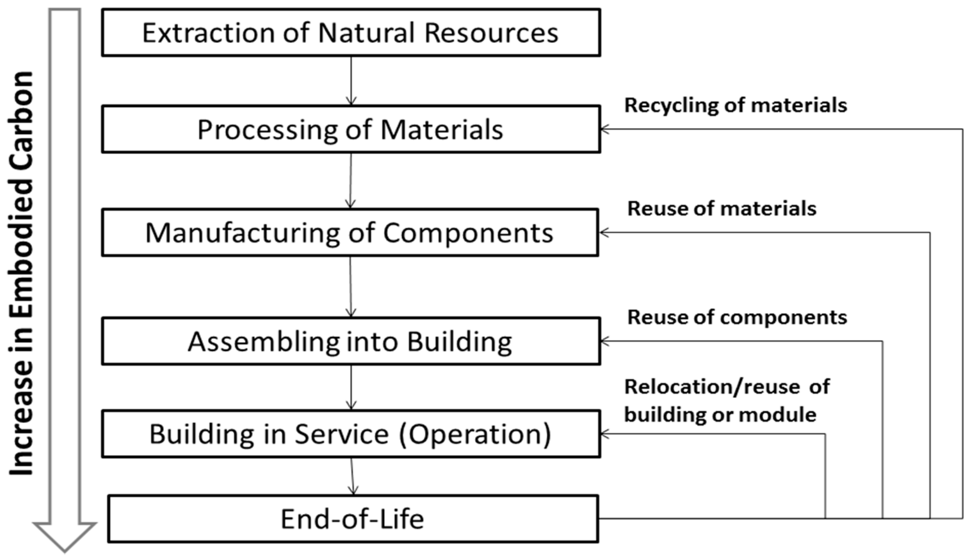

Figure 2. Increase in embodied carbon of a structure as it moves through different stages of its life cycle; and capability of different end-of-life strategies in preserving the invested embodied carbon.

First, a great deal of carbon emissions may be produced in the recycling process that should be accounted for when evaluating the carbon reduction value of the recycling strategy. The level of carbon emission depends on the type of material recycled and the sophistication of the recycling process [90]. In a recent study, Akbarnezhad et al. showed that carbon emissions associated with the recycling process may vary considerably depending on the target quality of the recycled aggregates/products and thus the recycling technology selected [20]. It was found that there is generally a trade-off between the quality achieved and the carbon footprint of the recycled products. Second, the recycling strategy does not fully preserve the energy and carbon initially invested in the element during the construction and manufacturing processes. The recycled products may be of considerably lower embodied carbon value than the original structural elements recycled and, thus, a great deal of invested carbon is lost during the process. We propose that the carbon value of the recycled material may be estimated by considering the embodied carbon of the original material which is intended to be replaced by recycled material. For instance, we propose that the carbon value of recycled concrete aggregates (RCA) produced by recycling of concrete should be considered to be equal to that of, usually low/medium quality, natural aggreagtes intended to be replaced by RCA.

Reuse of materials and components has been highlighted as an effective alternative end-of-life strategy to preserve materials, as well as some or all of the costs, energy and embodied carbon invested into the structure [22,91]. The technical aspects, benefits and costs of reuse of materials and building components, through design for disassembly/deconstruction, have been widely studied in the available literature [92–95]. If designed properly, many of the elements used in a typical building could be in good enough condition, at the end of the service life of the building, to be reused for similar or other applications [78,91,96]. As shown in Figure 2, reuse of components not only can preserve the energy, carbon and capital initially invested into making the components but also preserves the materials used. Akbarnezhad et al. proposed a framework to estimate and compare the embodied carbon of designed for disassembly concrete buildings with that of buildings designed using conventional concrete elements. The authors indicated that a similar methodology can be used during the design phase to compare the effects of various end-of-life strategies on a building's embodied carbon.

2.4. Local Sourcing of Materials and Components

The impact of transportation as an important contributor to the embodied carbon of buildings has been emphasized in the literature [27,97]. The main factors affecting transport emissions include the quantity of material to be transported, the size of the material, the transportation distance, and the mode of transport [98,99]. Due to the significant impact of such factors, the importance of accounting for transport requirements in the selection of materials for a building has been highlighted in the literature [23].

The supply chain structure of materials may considerably affect the transport requirements and thus the transport emissions associated with the material [23]. In a general categorization, materials may be classified into Made-To-Stock (MTS), Assembled-To-Order (ATO), Made-To-Order (MTO), and Engineered-To-Order (ETO) products, which have been shown to have considerably different supply chain structures and thus different emissions implications [100]. The main factors affecting the transport emission of materials, including the number of trips, the mode of transport and travel distance requirements, should be considered in selecting materials for low-carbon buildings. However, it should be noted that the final decision on choice of material and supplier should be made by accounting for other important economic, social and environmental factors affected by the selection of the material supplier [23,27].

2.5. Construction Optimization Strategies

One of the contributors to embodied carbon that can be regulated to reduce the embodied carbon of a building is the construction emissions associated with the operation of construction equipment and the use of temporary construction materials [101–104].

The carbon emissions of the construction phase can be minimized through different approaches including optimizing the construction operations to reduce the idle time of equipment, selection of optimal equipment for a construction operation, optimizing the operation of equipment, and minimizing the on-site transport including both horizontal and vertical transport [105–112]. Among the different construction operations, earthmoving, concerting, and lifting operations have been identified as the primary contributors to carbon emissions in the construction phase [5,103,104]. Guggemos and Horvath reported that these three operations account for 83% of the overall construction phase emissions of the structure studied in their work [104,113]. Several previous studies have focused on quantifying and minimizing the environmental impacts of earthmoving operations through optimizing operational parameters such as fleet size [114–116]. Kaboli and Carmichael showed that for earthmoving operations, placing the focus on minimizing costs could also lead to minimizing the carbon emissions associated with the process [117].

There is currently a lack of sufficient literature on optimizing other important construction operations including concreting, lifting and onsite transport operations to minimize carbon emissions. This is despite the fact that a great deal of literature exists on multi-objective optimization of concreting and lifting operations to minimize various conventional objectives including costs, and other sustainability objectives including safety and security [110,111]. Addition of carbon emission minimization objective to conventional objectives considered in the optimization of construction operations can provide a new approach to minimizing the carbon emissions of the construction phase. Optimizing the concreting operation to minimize the idle time of trucks and pumps on a construction site could result in a reduction in carbon emissions incurred during construction. Similarly, a considerable reduction in the carbon emissions of construction may be achievable through optimizing the location of supply and demand points on a construction site to minimize the operation time of the crane [111]. Apart from this, minimizing the on-site transport on a construction site through optimizing the layout of construction facilities on a construction site, which has been widely investigated previously as a potential cost reduction strategy, is likely to result in considerable carbon emission reductions [110].

3. Estimation of Carbon Emissions

One of the most important skills required for the implementation of sustainable strategies in practice is the ability to evaluate the effectiveness of such strategies in the context of a project. Quantifying the embodied carbon reductions achievable by the adoption of different embodied carbon reduction strategies may provide key insight into the design of low-carbon buildings. The estimated achievable reduction in the embodied carbon of a building can be added to the estimated operating carbon to calculate the life cycle carbon of the building. The estimated life cycle carbon reductions can then be used as the main selection criterion for identifying the best strategy or best combination of applicable strategies by considering the effects of an embodied carbon reduction strategy or strategies on other important economic, environmental and social impacts of the building.

Life cycle assessment (LCA) has been widely used to estimate the embodied carbon of different building materials and components, as well as the carbon emissions rates of different machineries and operations involved in the construction and operation of the building [7]. LCA provides a holistic approach for quantifying the environmental impacts, including associated emissions and energy use, of the buildings. The common LCA approaches may be categorized into statistical analysis, process based analysis, economic input-output analysis and hybrid analysis methods [97,118]. While providing a detailed and reliable assessment, the statistical-analysis-based LCA is generally difficult to perform due to its high reliance on availability of comprehensive statistics, and thus has had limited use in previous studies [118]. The process-based analysis, on the other hand, is a commonly used bottom-up method, which involves identifying all materials and energy flows associated with different activities involved in the production of a material or provision of a service and quantifying the corresponding environmental impacts [113,118]. The results of process-based LCA are detailed and process-specific and thus may be used to compare specific products and processes or identify areas for process improvement. However, performing a detailed process-based LCA may be time-consuming and costly. To alleviate these issues and difficulties in collection of detailed data on all the processes involved, process-based LCA is generally performed by defining boundaries for the environmental impacts to be evaluated, as well as the material and energy flows to be monitored in the study. However, defining the boundary may be subjective. Furthermore, it has been noted that applying the results of process-based LCA to a new process design is generally difficult [113,119]. Contrary to the process-based LCA, economic input–output analysis (EIO–LCA) is a top-down LCA method. The strength of this method lies in its ability to account for all indirect impacts involved in the supply chain of a product or service on top of the direct environmental impacts [97]. To achieve this, in the EIO–LCA method, the aggregate national economic data available for different products and services are analysed to quantify the associated environmental impacts. The EIO–LCA, however, has a number of drawbacks including the need to link the monetary values with physical units, and difficulties in application to an open economy with substantial non-comparable imports. Furthermore, EIO–LCA may not adequately account for project-specific differences, which are essential in comparing the impacts of different buildings. Alternatively, a hybrid approach developed by combining the top-down and bottom-up methods has been used in a number of studies to evaluate the life cycle environmental impacts of the buildings, taking advantage of the strengths of both methods [103,113]. The LCA methods reviewed above have been used in various forms, combined by computational approaches in some cases, to estimate the embodied carbon of buildings. The proposed methods for the estimation of embodied carbon of buildings are reviewed in the following sections. It should be noted that the LCA methods reviewed are focused on carbon emissions from fossil sources and exclude biogenic carbon emissions. The exclusion of biogenic carbon from LCA models has been criticized by a number of authors, and models to account for biogenic carbon have been proposed [120,121].

3.1. Cradle to Gate Embodied Carbon of Materials

The cradle to gate embodied carbon of materials should ideally account for three types of carbon emissions: (i) carbon emissions incurred during the material manufacturing and processing operations [18]; (ii) emissions due to the release of carbon compounds in the raw material [46]; and (iii) emissions due to a depreciation in the embodied carbon value of the equipment used to process materials, i.e., the gradual loss of carbon invested into manufacturing of equipment [30]. The second type of carbon can be estimated through evaluating the composition of the material, whereas the first type requires a detailed evaluation of the processes involved in manufacturing and processing of materials into their final form, leaving the gate of the manufacturer's site [46]. The third type of embodied carbon highlighted above, which has received considerably less attention in the literature, accounts for the fact that a great deal of carbon emissions have been incurred during the manufacturing of the equipment and machinery used to process materials, which is reflected in the embodied carbon of equipment. Due to the limited service life of each equipment, a given portion of its embodied carbon is depreciated each time it is used to process materials. This depreciation in the embodied carbon should be added to the embodied carbon of the materials processed by the equipment [30].

A great deal of effort has been made in previous studies to investigate the cradle to gate embodied carbon of building materials and develop embodied carbon inventories for use in evaluating the carbon footprint of buildings [122,123]. Examples of such efforts include studies conducted by Hammond and Jones [24,25] as a part of the Carbon Vision Buildings Program at the University of Bath, England, which led to the development of a comprehensive inventory of the embodied carbon of building materials, which has since been used in several studies. Similarly, the studies conducted by the Centre for Building Performance Research in New Zealand [118,124] led to the development of an "Embodied Energy and CO_2 Coefficients for NZ Building Materials" inventory.

When available, carbon inventories can be used as the basis for estimating the cradle to gate embodied carbon. However, it should be noted that the embodied carbon of materials can be significantly affected by the manufacturing processes used. On the other hand, the manufacturing process used to produce a particular material can vary considerably from one manufacturer to another, depending on the technology used and the properties of the raw material sources available to the manufacturer. Furthermore, the transport requirements may vary considerably from one manufacturer to another depending on the location of the processing sites, location of material quarries and suppliers, and layout of the facilities, leading to considerably different transport-related carbon emissions for different manufacturers. With this in mind, in the literature the emphasis is generally placed on using local carbon inventories or, when possible, modifying the data provided by inventories to reflect actual manufacturing conditions [24,122].

After calculation through LCA or identifying a reliable local estimate of cradle to gate embodied carbon emission factor for construction materials (f_j^{c-g}), the total cradle to gate embodied carbon of building can be estimated by multiplying the quantity of each material used in the building by its corresponding cradle to gate embodied carbon factor and summing up all the calculated values. Alternatively, the cradle to gate embodied carbon factor can be used as the basis for estimating the cradle to site embodied carbon factor (f_j^{c-s}) by accounting for the impact of transportation, which can then be used to estimate the total cradle to site embodied carbon of the building.

3.2. Cradle to Site Embodied Carbon—Impact of Transportation

The cradle to site embodied carbon factor of materials is commonly used as a basis for the estimation of embodied carbon of buildings. The cradle to site embodied carbon can be estimated by adding the material transport emissions to the cradle to gate embodied carbon estimated through analysing the manufacturing process. Construction generally involves a great deal of transportation including (i) transport of materials and equipment from the supplier's site to the construction site; (ii) transport of materials, equipment and workers between different facilities on the construction site; and (iii) transport of project personnel to and from the construction site. The importance of accounting for transport emissions has been emphasized in the literature [33]. The United States Environmental Protection Agency reports that the construction industry is responsible for 6% of total light on-road truck use and 17% of medium/heavy truck use, which together account for 28%

of the total transport-related emissions in the United States [125,126]. The Motor Vehicle Emission Simulator (MOVES) and EMFAC models have been commonly used to estimate the carbon emissions associated with on-road vehicles used in construction. MOVES was originally developed by the United States Environmental Protection Agency (EPA) to estimate air pollution emissions from cars, trucks and motorcycles. MOVES was designed to replace its predecessor, i.e., the MOBILE model, by providing a more comprehensive and scientific emission analysis tool that covers a wider range of spatial applications [127,128]. MOVES is categorised as a modal emissions model that derives emission estimates from predicted second-by-second vehicle performance in various driving modes. Due to its modal form, MOVES is capable of providing relatively accurate estimates of emissions at different scales, ranging from individual transportation projects to large regional emission inventories [129]. The input data used by MOVES include vehicle feet composition, traffic activities, fuel information and meteorology parameters. By relying on a number of modal equations, MOVES starts by estimating the modal-based vehicle emission rates, which are then used to generate emission factors for the desired geographic scale and temporal resolution (year, day and hour) [129].

EMFAC is another emission model commonly used in previous studies to estimate transport-related emissions associated with construction projects. EMFAC uses the latest data and statistics on California's car and truck fleets to estimate emissions [130]. EMFAC applies a methodology similar to that used by MOVES to estimate emissions, where total emissions are estimated as a product of vehicle activities and base emission rates after a number of adjustments. The main difference between MOVES and EMFAC is, however, mainly related to the methodologies adopted for quantifying and pairing vehicle activities and measurement of emission rates [129].

Regardless of the model used, once the emission factors for different type of vehicles are determined or deduced from emission inventories, the carbon emissions due to transportation of building materials or equipment can be calculated using the following equation:

$$EC_T = \sum_j \sum_k Q_j^k \times (T_j^k \times f_k^T)/1000, \tag{1}$$

where EC_T is the total carbon emissions due to transport of materials, waste and equipment (in tons CO_2); Q_j^k is the amount of building material, waste or equipment j (in tons) to be transported by vehicle k; T_j^k is the total transport distance for item j using vehicle k (in km); and f_k^T is the carbon emission factor for transport using vehicle k (in kg CO_2-e/ton·km). Alternatively, a transportation emission factor can be calculated for each material by considering its transport requirements:

$$f_j^T = \sum_k X_k^j f_k^T, \tag{2}$$

where f_j^T it the aggregate transport emission factor for material j, f_k^T is the emission factor associated with transportation mode k, and X_k^j is the percentage of total travel of material j that is completed by transport mode k. Furthermore, the estimated aggregate transport mode can be added to the cradle to gate embodied carbon factor of the material to estimate an aggregate cradle to site embodied carbon factor, which can then be used directly as the carbon factor for estimation of total cradle to site embodied carbon of the building using material quantity estimates:

$$f_j^{c-s} = f_j^{c-g} + f_j^T, \tag{3}$$

where f_j^{c-s}, f_j^{c-g} and f_j^T are cradle to site, cradle to gate and transport emission factors for material j, respectively. The total cradle to site embodied carbon of building can then be estimated by multiplying the quantities of each material by its estimated cradle to site carbon factor:

$$EC_B^{c-s} = \sum_j Q_j f_j^{c-s}, \tag{4}$$

where EC_B^{c-s} is the total cradle to site embodied carbon of the building (kg CO_2-e/ton), and Q_j is the quantity of material j (in tonnes) as estimated using common quantity takeout methods.

3.3. Cradle to Service Embodied Carbon—Impact of Construction Operations

The increasing interest in evaluating and comparing the environmental impacts of different construction scenarios has led to several studies aimed at developing methods for quantitative estimation of energy use and carbon emissions of the construction phase. Cole estimated the energy and GHG emissions associated with the construction of alternative wood, steel, and concrete structural systems [33]. Guggemos and Horvath developed a Construction Environmental Decision-Support Tool (CEDST) to evaluate the environmental impacts of the construction of commercial buildings [104,113]. CEDST follows a predefined detailed process diagram to quantify the energy use and carbon emissions of the construction stage based on the designer's and builder's choice of structural materials, temporary materials, and operating equipment. Through a case study, Guggemos and Horvath showed that a planning decision, such as using a concrete mixer truck with a 335 hp engine rather than a 565 hp engine (with the same capacity), can lead to up to 12% reduction in energy demand of the project [113]. A number of quantitative methods to estimate the carbon emissions of the construction phase have been developed by relying on actual site data [97,118]. However, the need for the availability of actual site data such as amount of fuel, electricity, water and various materials used by different contractors is a limiting factor for such methods, rendering them incapable of predicting carbon emissions before the completion of the activity. To address this issue, Hong et al. [5] proposed a model to assess the energy consumption and carbon emissions of the construction phase by using the available information on type and energy efficiency of equipment, amount of materials used and characteristics of the building project and construction site.

The use of visualisation-based methods for progressive monitoring and estimation of construction emissions has been also investigated by several previous studies [131–133]. Enhancing the operational efficiency of equipment on site has been highlighted as one of the most feasible and effective methods to mitigate the carbon emissions of construction equipment [107,131,134,135]. Ahn and Lee introduced the concept of Operating Equipment Efficiency (OEE) as the ratio of the valuable operating time to the total operating time [107]. Using this concept and discrete event simulation, they investigated the trade-off between the OEE of the equipment and resulting carbon emissions of the earthmoving activity. The results indicated that managerial planning decisions such as fleet size not only affect a project's cost and schedule but also its environmental impacts.

Based on findings and recommendations from previous studies, in this paper we propose that a systematic approach to the estimation of the carbon emissions of the construction phase should consider two main emission sources: (i) indirect emissions due to the depreciation in the embodied carbon value of construction equipment and temporary materials and (ii) direct emissions due to the operation of construction equipment [113,118]. A framework for estimation of the total construction-induced carbon emissions by considering the above two main sources of emissions is depicted in Figure 3 and explained in the following sections.

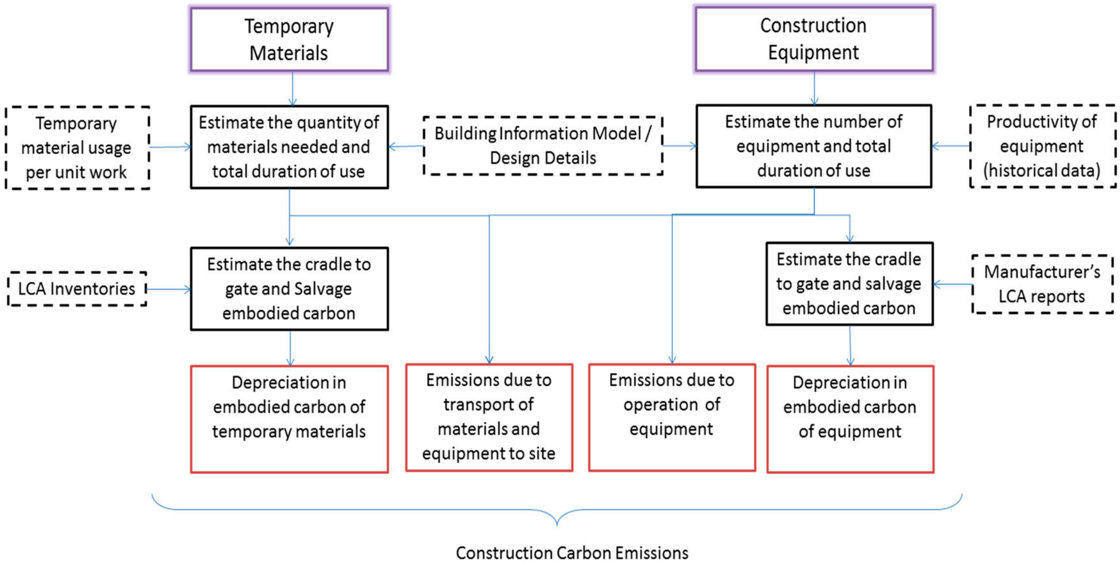

Figure 3. A framework for the estimation of carbon emissions incurred during the construction phase.

3.3.1. Construction Carbon Emissions Due to Depreciation

Apart from permanent building materials, which are the building blocks of the structure and envelope of the building, the construction industry also consumes a considerable amount of temporary materials to support and facilitate different construction activities [29]. For example, in the construction of a typical concrete structure, apart from reinforcing steel bars and concrete, which form the permanent materials of the structural elements, a number of temporary materials including formworks and propping elements are usually required to support the concrete elements while being cured to gain enough strength to support their own weight. Temporary materials are usually reusable several times before they turn into waste and need replacement. Therefore, the embodied carbon of temporary materials gradually depreciates over time as they are used to support construction activities. The same concept applies to equipment used during construction, where the initial embodied carbon of equipment gradually depreciates as it approaches the end of its service life. The depreciated embodied carbon of temporary materials and equipment should be taken into account when estimating the carbon footprint of construction [91]. The following equation can be used to estimate the amount of construction carbon emissions due to a gradual reduction in the remaining service life of temporary materials and equipment:

$$C_C^{TM/E} = \sum_i (EC_i^{M/E} - EC_i^S) d_i^u / D_i^S, \tag{5}$$

where $C_C^{TM/E}$ is the construction carbon emissions due to depreciation in the embodied carbon of construction equipment or temporary materials (in ton or kg CO_2), $EC_i^{M/E}$ is the embodied carbon of equipment or temporary material i as reported by inventories or manufacturer (in ton or kg CO_2), EC_i^S is the salvage embodied carbon of equipment or temporary material i at the end of its service life (in ton or kg CO_2), d_i^u is the duration of operation of equipment or temporary material i during the project (in hours, days, years, etc.), D_i^S is the total service life of equipment or temporary material i (in hours, days, years, etc.). The salvage embodied carbon of temporary materials and equipment at the end of their service life can be estimated by investigating the final usability, or fitness for use, of the remaining components. For instance, if all the elements of the equipment are to be recycled, the following equation may be used:

$$EC_i^S = \sum_j (EC_{ij}^R - C_{ij}^{RP}), \tag{6}$$

where EC_{ij}^{R} is the embodied carbon of the recycled product obtained after the recycling of component j of equipment/or temporary material i, and C_{ij}^{RP} is the carbon emissions due to operations involved in the recycling of component j of equipment or temporary materials i.

3.3.2. Construction Carbon Due to Equipment Operations

The other major contributor to carbon emissions incurred during construction is the operation of fossil-fuelled equipment used to perform or support various construction activities. The carbon emissions factors for on-site transport equipment used to transport materials between different facilities can be estimated using the transport emission models reviewed earlier. Furthermore, the estimation of the carbon emissions factor of other, non-road, equipment has been studied previously and a number of models have been proposed in the literature. These models include NONROAD, OFFROAD, URBEMIS, and the Road Construction Emissions (RCEM) model [136].

The NONROAD model, developed by the Environmental Protection Agency of the United States, has been designed to estimate the emission factors associated with the non-road equipment used in construction and other industries [137]. The carbon inventory used by the NONROAD model comprises more than 80 basic and 260 specific types of non-road equipment, classified according to their type, horsepower rating and age. The reported emissions include hydrocarbons (HC), NO_x, carbon monoxide (CO), carbon dioxide (CO_2), sulphur oxides (SO_x), and particulate matter (PM), which are estimated using the following equation:

$$E = EP \times OT \times ER \times LF \tag{7}$$

where E is the emissions incurred due to operation of equipment, EP is the available engine power (hp) of the equipment, OT is the duration of operation, ER is the emission factor (g·hp^{-1}·h^{-1}) for the specific equipment and fuel type used and LF is the load factor [107,138]. The load factor refers to the fraction of the maximum rated engine power that is actually utilized. In the NONROAD model, an average load factor, which accounts for idling and partial loading, is used. The LFs used for common construction equipment include 0.21 for backhoes and 0.59 for bulldozers, excavators, motor graders, off-road trucks, track loaders, and wheel loaders [105,139].

The OFFROAD model, developed by the California Air Resources Board (CARB), estimates the emissions caused by the operation of non-road vehicles in the state of California [140]. The emissions inventory of OFFROAD model uses a number of variables including the location of operation, air basins, engine type, fuel type, equipment group and horse power group to categorise the emission factor. The same equation as that of the NONROAD model, i.e., Equation (7), is then used to estimate the emissions. The OFFROAD model comprises three main modules. These include (i) a population module, which accounts for the addition of new equipment and/or the elimination of old equipment from the fleet; (ii) an activity module, which accounts for seasonal and temporal effects on emissions by relying on monthly, weekly and daily usage pattern statistics for each information; and (iii) an emissions module, which provides emission factors considering the fuel type, horsepower group, and model year of the equipment. The emission factors of equipment are adjusted based on duty cycle and the estimated rate of engine deterioration of the equipment. The main difference between NONROAD and OFFROAD models is their geographical boundaries. In particular, while the NONROAD model relies on national-level inventories in the United States, the OFFROAD model has been designed mainly for use within the state of California [136,140]. Both models have, however, been developed based on the results of engine dynamometer testing rather than the monitoring of actual emissions of equipment on a construction site and should be used with caution by considering the unique site conditions of the project and conditions of the actual equipment used. The precision of the NONROAD and OFFROAD models in estimating the emissions incurred during construction has been investigated by a number of studies [107,136,138].

3.3.3. Accounting for Uncertainty and Site-Specific Conditions

The need to account for site-specific and project-specific conditions in estimating the carbon emissions of the construction phase has been recognised in previous studies, leading to the development of a number of specialized models for specific types of projects. The URBEMIS model, developed by the Sacramento Metropolitan Air Quality Management District (SMAQMD), was developed to estimate the construction emissions associated with land development projects [141]. URBEMIS estimates the NO_x, CO, PM_{10}, $PM_{2.5}$, CO_2, reactive organic gases (ROG), and sulphur oxides (SO_x) emissions that occur in seven phases of a typical land development project: demolition, fine site grading, mass site grading, trenching, building construction, architectural coating, and paving. The parameters used in making such estimates include the project size, equipment type, and emission factor of the equipment. The emission factors used by URBEMIS are based on an OFFROAD emissions inventory for non-road emissions and an EMFAC emissions inventory for highway emissions [136].

Another specialized model developed for the estimation of construction emissions is the Road Construction Emissions Model (RCEM), developed by the Sacramento Metropolitan Air Quality Management District. RCEM is conceptually similar to URBEMIS, but has been optimized for linear projects including roadway construction and levee repair [142]. The construction phases considered in RCEM include grubbing and land clearing, grading and excavation, drainage and sub-grade, and paving. The input information include equipment type (which is selected from an existing database of equipment), project type (which includes new road construction, road widening and bridge construction), construction duration, soil type, project size (length of the road), project area, amount of soil imported or exported daily, and average capacity of trucks.

While the use of specialized methods may alleviate the issues related to the effects of project-specific conditions on the emissions, another common drawback that remains to be dealt with is the reliance of emission models on deterministic industry-average or country-average inventory data, which may not precisely represent the actual specifications and condition of the equipment used in a particular project [5,97,143]. Furthermore, the operation parameters including duration of activities, and thus duration of operation of equipment, are, in practice, subject to uncertainty [143]. A common approach adopted in the literature to account for uncertainty and project-specific conditions in planning and analysis is discrete-event simulation (DES). DES has been used widely in previous studies to experiment with different construction processes [144–149]. Furthermore, DES has been used in several studies to estimate the carbon emissions of a number of construction operations including earthmoving [107,138,150], asphalt paving operation [151], tower crane swing operation [152] and highway construction projects [134]. Zhang performed a field investigation on the load factors of some pieces of equipment used in earthmoving operations and showed that the load factor of equipment is variable during the duty cycle of various activities [138]. He proposed an emissions calculation model based on the NONROAD model and used it to develop a DES method for estimating the construction emissions and noise that accounts for uncertainty, randomness, and dynamic nature of load factor. Discrete Event Simulation may serve as a reliable tool for evaluating various emission-reduction strategies in construction. The most frequently used simulation tools in previous studies include Simphony [153] and Stroboscope [154].

3.3.4. Direct Measurement of Equipment Emissions

When required, a more accurate estimation of the carbon emissions factor of equipment at different working conditions can be obtained through direct measurement. A number of direct emission measurement devices including Portable Emission Measurement Systems (PEMS) such as Axion R/S are commercially available. However, while enabling the direct measurement of exhaust emissions, PEMS instrumentation and maintenance is usually costly [133]. Alternatively, in situations where direct measurement is not feasible, indirect emissions monitoring methods including accelerometer-based approaches, and vision-based approaches can be used to provide an estimate of the actual emissions incurred during construction [133,155].

3.4. Cradle to Grave Embodied Carbon

Estimating the cradle to grave embodied carbon requires estimation of the carbon emissions incurred in the end-of-life (EOL) phase of a building's life cycle. The most common strategies for dealing with a building at the end of its service life include "demolition and landfilling", recycling, and reuse. The choice of end-of-life strategy can considerably affect the end-of-life carbon emissions and other environmental impacts of the building [156]. Accordingly, factors affecting the end of life emissions and, thus, the methodology for estimating the end-of-life emissions vary with the choice of EOL strategy [20]. The optimal EOL strategy for a building depends on a variety of parameters including type of the materials used, the original design of building components, availability of required local technologies for reuse and recycling, availability of local market for the products of such processes, and availability of local landfills for disposal of debris.

When compared to other phases of building life cycle, considerably less attention has been paid to estimating the carbon emissions of EOL phase. Vitale et al. [156] performed a detailed LCA to investigate the environmental impacts of the end-of-life phase of a number of residential buildings in southern Italy. In this study detailed modelling of material and energy consumption and the emissions of different on-site and off-site activities involved in common EOL strategies was performed based on a detailed quantification of mass and energy flows over each of the involved systems [156]. Akbarnezhad et al. presented a simplified methodology for estimating the carbon emissions of recycling and landfilling end-of-life strategies for a concrete building [20]. The proposed method for estimating the carbon emissions of the recycling strategy involves (i) estimating the total amount of materials available for recycling using quantity take-off tools including building information modelling; (ii) identifying potential recycling methods by considering available local recycling technologies; (iii) identifying the individual recycling operations involved in each recycling method; (iv) identifying the carbon emission factors for each operation using methodologies similar to those described previously for the estimation of construction emissions and estimating the carbon emissions incurred in each operation by considering the quantity of the materials to be processed; and (v) estimating the equivalent embodied carbon value of the final recycled product, which is then compared with the total emissions of the recycling process to evaluate the carbon emissions implications of the recycling strategy [20]. It was indicated that applying the proposed methodology to calculate the carbon emissions of different recycling strategies can be used as an optimization method to select the optimal recycling strategy for a particular project.

When compared to recycling and landfilling strategies, the reuse strategy can lead to considerable reductions in the embodied carbon of the building by preserving the embodied carbon invested in the manufacturing of components and processing of materials into their final form. With this in mind, Akbarnezhad et al. developed a methodology for estimating the embodied carbon of reusable, designed for disassembly (DfD) structural elements. The authors also noted that the implementation of a reuse strategy requires additional support operations and changes to the design of components, which may lead to additional carbon emissions. For instance, designing structural concrete elements for disassembly may require the use of additional embedded steel connections to facilitate assembly and disassembly operations. Furthermore, construction using disassembleable components may require a number of non-traditional services during the assembly and disassembly processes that may lead to additional carbon emissions and costs. These may include selective removal of cover concrete for access to connections as well as additional propping and lifting [91]. Moreover, the reuse strategy may require storage of components and involve increased transport of components and materials between facilities, which should be considered in estimating the carbon emissions. The end-of-life emissions estimated using the methods proposed in the above studies can then be added to the previously calculated cradle to service embodied carbon to estimate the cradle to grave embodied carbon of the building.

4. Conclusions

A comprehensive review of previous studies on methods for the estimation and minimization of embodied carbon of buildings was presented in this paper, with a focus on the embodied carbon of the structure. A recent shift in attention towards minimizing the embodied carbon of buildings was shown, which can be attributed to the increase in the relative share of embodied carbon in the life cycle carbon emissions of buildings due to recent advances in minimizing the operating emissions. Five different areas—use of low-carbon materials, material minimization, material reuse and recycling, local sourcing and transport minimization, and construction optimization—have been highlighted in previous studies as potential avenues for minimizing the embodied carbon of buildings. Among these, particular attention has been paid to the use of low-carbon materials. However, one major gap in the literature in this area is the focus on selection of materials with low cradle to gate embodied carbon without considering the effects that such low-carbon materials may have on the carbon emissions of the construction and end-of-life phases as well as the operating carbon emissions of the building. Apart from accounting for overlapping effects on carbon emissions in different phases of the building life cycle, accounting for the effects of carbon reduction strategies on other economic, environmental and social impacts of buildings was found to be a new approach promoted in the literature, which is in line with the emphasis of sustainable development strategies. The review of previous studies presented in this paper also highlighted the lack of sufficient literature on methods for minimizing construction and end-of-life carbon emissions, when compared to cradle to gate embodied carbon. The importance of reliable methods for the estimation of embodied carbon of buildings as a prerequisite for evaluating the effectiveness of carbon reduction strategies has been emphasized in previous studies. The methods proposed in previous studies were compiled in this paper to provide a systematic approach to the estimation of the embodied carbon incurred in the different phases of a building's life cycle. The review of previous studies also indicated that considerably less attention has been paid to the estimation of carbon emissions from the construction and end-of-life phases when compared to other phases of a building's life cycle. Furthermore, the need to verify the accuracy of the proposed estimation methods, as well as modifying the existing methods to account for project-specific conditions and uncertainty, were highlighted. Discrete event simulation was identified as a potential approach to address such limitations. It should be noted that the carbon reduction strategies reviewed in this paper should be evaluated by considering the ultimate reduction achievable in the life cycle carbon of the building, which requires evaluating the effects that such strategies may have on the operating carbon of the building. Furthermore, the potential effects of carbon reduction strategies on other economic, environmental, and social impacts of the project should also be taken into consideration in the selection of embodied carbon reduction strategies. While the present study provides an overview of the previous research in the area of embodied carbon estimation and minimization, further research, including a more detailed scientometric analysis, is required to achieve a better understanding of trends and their alignment with advances in other related disciplines.

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