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Holistic Review of Construction Process Carbon-Reduction Measures: A Systematic Literature Review Approach

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Abstract: The fragmented nature of construction operations makes it challenging to implement carbon-reduction strategies. However, attaining a holistic construction sector decarbonisation hinges upon ensuring all aspects of a construction project's lifecycle are decarbonised, including the construction process stage. Therefore, to mitigate the implementation challenge of reducing the levels of carbon involved in construction processes, this study attempts to synthesise and categorise carbon-reduction strategies that could be employed to decrease the carbon footprint during a construction projects' delivery. To achieve the aim of this study, a systematic literature review approach was adopted. Based on this technique, a total of 26 relevant articles within the built environment research area were eligible for the study, and their analysis revealed 56 carbon minimisation measures, which were summarised into nine distinct categories to ease their application and overcome the construction operations' complexities. The nine categories include material transport, waste transport, materials and equipment, waste, materials, on-site office, on-site lighting, on-site transportation of material and equipment, and construction methods. The findings of this study provide contractors with a suite of measures that can be deployed to reduce the carbon impact of construction project delivery.

Keywords: carbon-reduction strategies; sustainable construction; construction process carbon reduction; low carbon construction; sustainable project delivery

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1. Introduction and Theoretical Background

The construction sector has been identified to be a significant contributor to global greenhouse gas (GHG) emissions [1]. According to a report by the Global Alliance for Buildings and Construction, the sector emitted about 40% of the world's total carbon dioxide (CO_2) emissions in 2018 [2]. This might continue to worsen as the authors of [3] estimated that between 2017 and 2060, about 230 billion square meters of floor area will be developed, and by 2050, half of the entire carbon footprint of new construction will be embodied carbon. This embodied carbon includes emissions linked with the construction, renovation, and end-of-life stage of a built environment project [4]. These emissions are categorised into four major stages, namely the product stage, construction process stage, use stage, and end-of-life stage (Figure 1) [5]. The focus of this study is on the construction process stage emissions. This is because the authors of [6] highlighted that this stage has been largely ignored in construction carbon emission research. This lack of attention has been attributed to the low emissions associated with the construction process stage [7], which might be due to the unavailability of data on on-site activities like plant and equipment usage since these data are utilised for carbon measurement calculation [8]. Additionally, the authors of [9] argued that the output of carbon assessments is influenced by numerous factors such as data source, estimation method, scope of analysis, and system boundary. This was proven by the seminal work developed by the authors of [10], who discovered an additional emission of 385 tCO_2e by extending the system boundary of the construction stage of a building project to capture the emissions related to human activities. This demonstrates the uncertainty related to construction phase emission. This uncertainty is exacerbated by the fragmented nature of construction operations [11], making it problematic to deploy carbon minimisation strategies. However, due to the consistent push to decarbonise the construction sector to attain net zero carbon by 2050 [12], there is a need to devise efficient ways to implement strategies to reduce the carbon footprint associated with the construction process in order to ensure that this goal is achieved. Hence, to contribute to the realisation of this ambition and mitigate the uncertainty explained above, this study attempts to synthesise and categorise carbon-reduction strategies that could be employed to decrease the carbon footprint associated with construction project delivery.

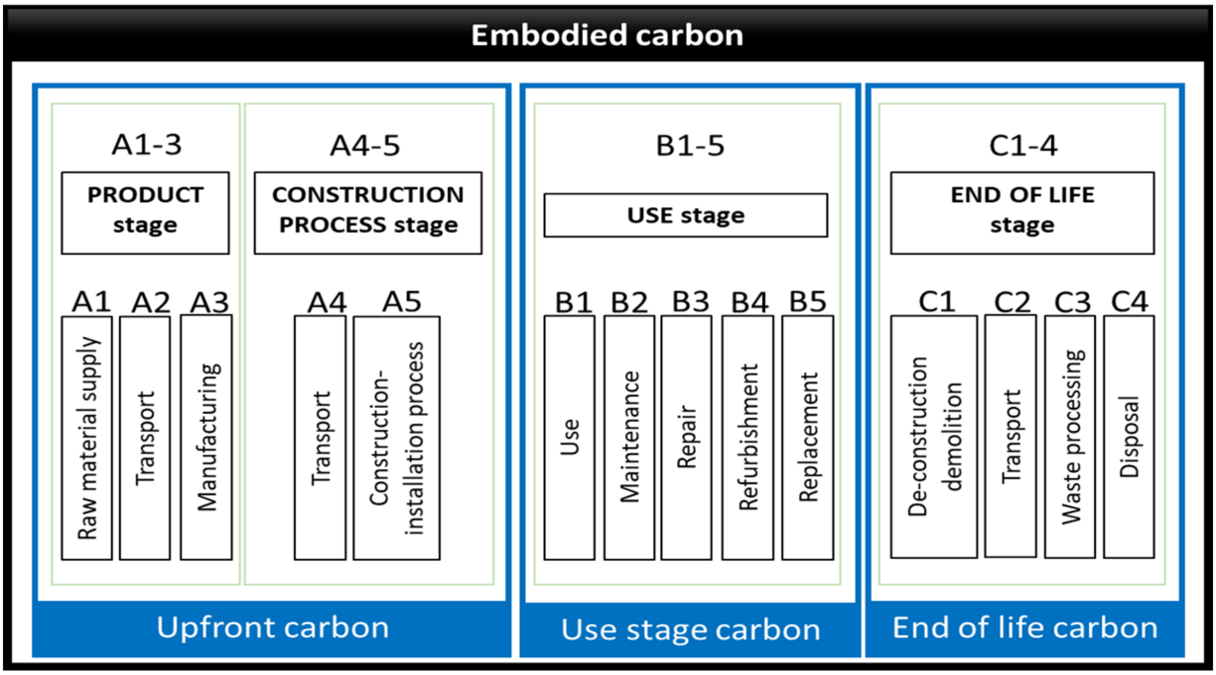

Figure 1. Embodied carbon lifecycle stages for a construction project (adapted from [5]).

Even though the study conducted by the authors of [13] considered the full spectrum of embodied carbon reduction (that is, the four categories described above), the identified carbon mitigation strategies detailed by their study are broad and did not focus on specific measures that capture the distinct clusters of the construction process. Thus, this study gains importance as it is the first, to the authors' knowledge, to systematically investigate construction process carbon minimisation strategies with the aim of contributing to the scientific body of knowledge. Furthermore, due to the anticipated growth in new construction at a global level [3], the identification of strategies capable of lessening construction-phase carbon becomes vital in ensuring that sustainable practices are incorporated into these expected developments. Additionally, the findings of this study will provide contractors with a collection of measures to minimise the carbon impact within their control. The following section (Section 2) details the method, while the carbon-reduction measures identified from the systematic review are presented and extensively discussed in Section 3. The conclusion, limitations, and implications of the study are then highlighted in Section 4.

2. Method

The research method used in this study is a systematic review of the literature approach using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). This technique was utilised due to its wide usage in built environment studies as well as its ability to ensure objectivity, rigour, and thoroughness [13]. Additionally, since the aim of this study is to synthesise construction process carbon-minimisation strategies to facilitate the decision-making of contractors and influence practice, a systematic review of the literature was chosen, as it has been noted to be the most suitable technique for accomplishing this goal [14].

The systematic review was carried out following a four-step process (Figure 2) adapted from [15]. The database utilised is Scopus due to its enormous archive of business, management, construction management, and engineering publications [16] as well as its reputation of being the largest warehouse of publications globally [17,18]. Upon choosing a suitable database, keywords were utilised to identify relevant articles linked to the study's focus [19]. Even though keyword selection was challenging and assumptions were made as required [15,20,21], such an assumption is noted to be permissible by scholars as they have argued that no single study can solely address all potential complexities connected to research keywords while exploring a subject matter [16]. In line with this, the keywords used in this study are as follows:

i. *"construction phase"* OR *"construction stage"* OR *"construction process"*
ii. *"carbon emission reduction"* OR *"carbon reduction"* OR *"greenhouse gas emission reduction"* OR *"ghg reduction"* OR *"ghg emission reduction"* OR *"embodied carbon reduction"* OR *"embodied carbon emission reduction"*

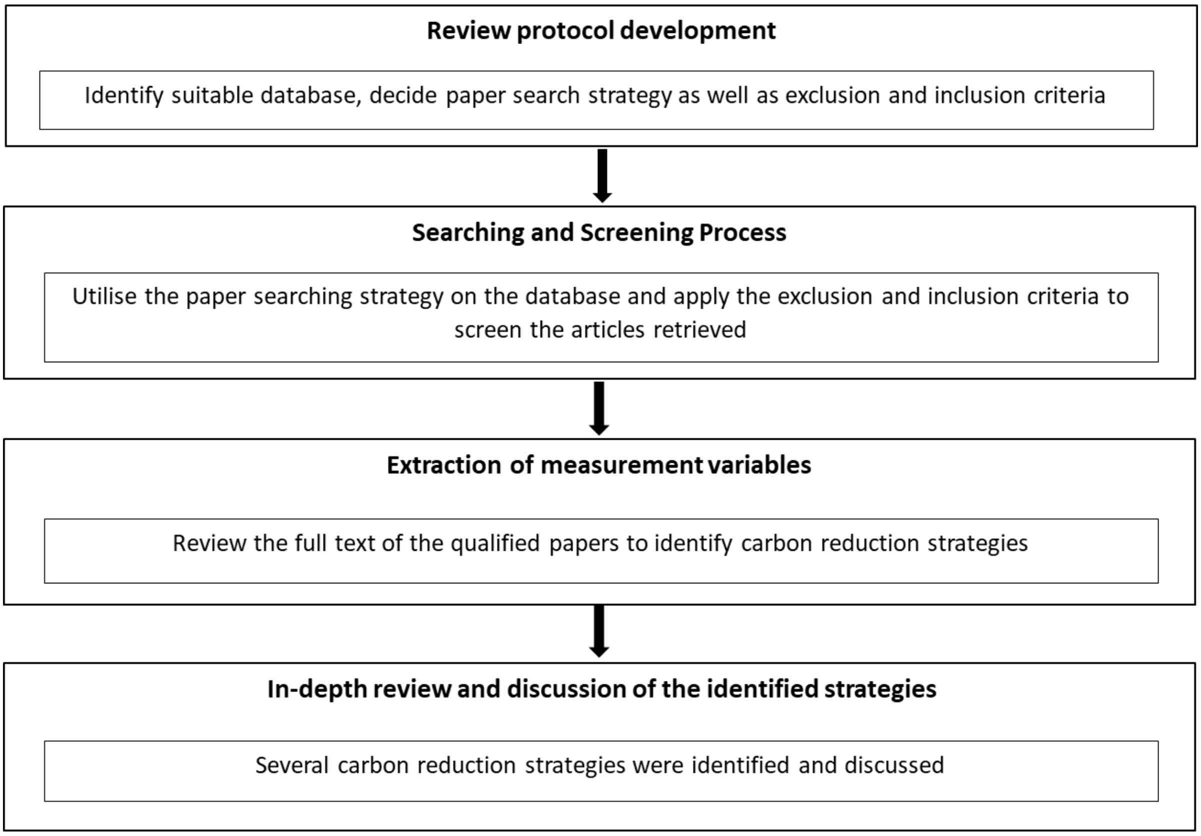

Figure 2. Systematic study process step.

During the literature search process in the Scopus database, no time restriction was applied due to the limited studies available in this area of research [6]. Regarding the exclusion and inclusion criteria, the study of [15,22] was utilised as a guide with some modifications. In this study, articles written in English and published in conference proceedings, journals, and industry reports were included due to the sparse number of studies related to this research area, as revealed by the systematic review study of [6] in mapping research done on building construction projects carbon minimisation. Additionally, papers whose focus is related to this study's objective in terms of title and abstract were included. At the same time, it excluded duplicates, studies disseminated in book chapters and books, and those without full-text availability. An in-depth text analysis of the qualified papers was done to achieve the study objective. In the course of the in-depth text review, the snowballing technique was adopted to improve the number of eligible papers. This resulted in including three additional papers in the study. Therefore, making the total number of eligible studies for this present research 26 (Figure 3). This number of papers is considered adequate for the study as it is higher than the 22 articles used in the systematic review research carried out by [23] on eye-tracking studies in construction safety and almost similar in quantity to the 30 and 34 papers included in the study of [21,24], respectively.

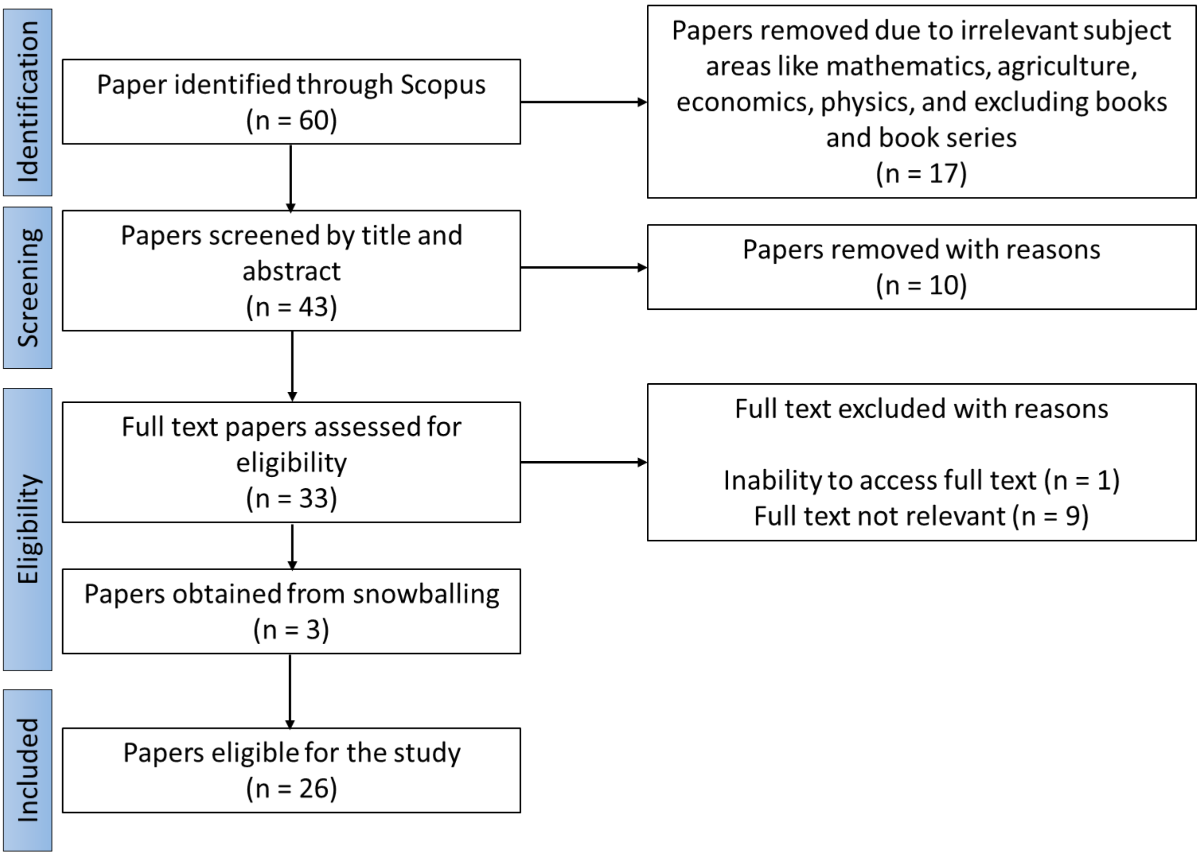

Figure 3. Flowchart for the systematic review.

3. Results and Discussion

The review of the literature revealed 56 carbon-reduction strategies that contractors could deploy in minimising the carbon footprint associated with construction activities. These strategies were grouped into the two phases of the construction process stage, namely construction installation and transportation, shown in Figure 1. Furthermore, the transportation stage was further divided into two categories, namely, material and waste transport, while the construction-installation stage was divided into seven categories, namely, machinery/equipment, waste, material, on-site lighting, on-site office, on-site transportation of material and equipment, and construction method (Table 1). The listed clustering, also presented in Table 1, was achieved through a thematic analysis process. This process was guided by the current study's boundary within the embodied carbon lifecycle stages for a construction project highlighted in Figure 1. That is, the clusters were closely related to the transportation (A4) and construction installation (A5) stages. This classification will enable a better understanding of the carbon-reduction strategies and assist with differentiating them [25]. The grouping and categories are extensively discussed in the next section.

Table 1. Construction process carbon-reduction measures.

Category	Carbon-Reduction Strategies	References
	Transportation	
Material Transport	Transport distance optimisation and reduction	[26–28]
	Operational optimisation of transport vehicle (e.g., ensuring the vehicle is loaded to capacity)	[27]
	Utilisation of rail or water transport where possible	[26,29]
	Ensuring material transport fuel is from renewable source	[30]
	Adoption of driving techniques that maximise transport vehicle's engine efficiency during material transportation to site	[30]
	Adoption of lightweight material	[31]
	Purchasing materials locally	[29]
	Utilisation of locally available material	[26]
	Reusing and recycling material on-site	[29]
Waste Transport	Adoption of driving techniques that maximise transport vehicle's engine efficiency during construction waste transportation	[30]
	Ensuring fuel utilised during waste transport is from renewable source	[30]
	Construction	
Machinery and Equipment	Utilisation of wind or solar energy for powering equipment	[32,33]
	Utilisation of alternative fuels such as hydrogen and vegetable oils	[30,34]
	Usage of low-emission machinery	[32]
	Utilisation of multi-purpose and work-specific construction equipment to reduce operation time	[26,30,33,35,36]
	Reducing machinery idle time through work scheduling	[26,27,30,36,37]
	Reduce number of machinery/equipment through work sequencing	[33]
	Provision of training to machine operators on carbon reduction	[33]
	Maintaining machinery regularly	[26,30,36]
	Selection of fuel-efficient machinery	[30]
	Reducing machinery fuel consumption	[38]
	Replacing diesel oil machineries with electric ones	[39]
	Reducing the usage of cranes on-site	[37]
Waste	Reusing waste material on-site	[26,30,33,40]
	Utilisation of the correct construction equipment for specific work to reduce waste generated	[26]
Material	Reusing materials (including carbon-intensive material) on-site	[26,29,39,41]
	Reusing formworks and temporary structure on-site	[26]
	Replacing some cement with ground-granulated blast-furnace slag	[26,29,33,36,42–46]
	Replacing some cement with coal fly ash	[26,29,36,42–46]
	Selection of geopolymer-based cement	[26,29,36,44–46]
	Reduction in material consumed (e.g., by optimising structural component)	[28,44,47]
	Utilisation of recycled material	[27,29,33]
	Adequate material resources planning and allocation	[27]
	Utilisation of cement in bulk instead of in bags	[39]
	Efficiently use temporary construction material on-site	[26]
	Purchase of construction materials with carbon labelling scheme	[26]
On-site Lighting	Usage of biodiesel, electricity from renewable sources, etc., for lighting on-site	[41]
	Reducing the usage of transformer boxes	[37]
	Managing night-time electricity	[37]
	Usage of light-emitting diode (LED) illuminance control appliances	[39]
	Minimising festoon lighting through the use of large stand-alone LED lights	[37]
On-site Office	Utilisation of energy-efficient site accommodation	[30]
	Switching off office equipment when not in use	[30,37]
	Usage of occupant sensor to minimise electricity usage	[30,37]
	Utilisation of timer to control heating usage	[37]
On-site Transportation of Material and Equipment	Usage of biodiesel, electricity from renewable sources, etc., for machinery/equipment transportation on-site	[41]
	Utilisation of intelligent signal lamp (e.g., smart traffic signal)	[39]
	Optimise logistics process on-site through adequate work planning	[48]
	Optimisation of site management (e.g., by using construction management software)	[26,33]
Construction Method	Proper planning of construction work sequence	[42]
	Utilisation of prefabrication method of construction	[28,35,42,44,46,49,50]
	Adoption of low-emission installation processes minimising waste generation	[43]
	Usage of new construction process like modular construction technique	[26,45]
	Reducing thickness of the wall	[44]
	Usage of energy-measurement management system during construction	[30,39]
	Earlier connection of construction site to the grid	[30]

3.1. Construction Process Carbon-Reduction Strategies

3.1.1. Transportation Stage

The construction process stage transportation carbon emission has been a subject of debate amongst scholars, and the work of [48] has dealt with the argument in detail. The result of the systematic literature review revealed two major categories, which are material and waste transport. As regards material transport, its carbon emissions during the construction process are of two types. One is the emission related to material transport from the manufacturers to a dedicated area on the construction site or contractor's preferred storage point, and the other is the carbon emission linked to the transportation of materials within the construction site. The former will be discussed in this section, while the latter will be discussed in Section 3.1.2. This segregation is important due to the complex nature of the construction supply chain because the responsibility of transporting material to a site might be totally different from its transportation within the construction site. Therefore, affecting the emission calculation boundary while also shifting the likely obligation for carbon reduction. Additionally, worthy to note is that a few papers [31,51–53] highlighted the process of capturing and measuring carbon emissions during equipment and human transportation to construction sites. However, their carbon emission reduction strategies are not included in the categories to be discussed in this section largely due to their omission from the result of the systematic literature review. Despite that, it was found that some of the tactics proposed in the reviewed literature to reduce carbon emission from material and waste transport can be adopted in minimising the emission related to both human and equipment transport to the site.

Having established this boundary, we will now discuss the two categories found in the literature, which are associated with transportation carbon emission, alongside their minimisation approaches.

Material Transport

The construction industry is overly dependent on material importation, with the consumption of energy taking up almost 20% of the sector's total energy consumption during its transportation [48]. According to the case study research conducted by [27] in Australia, the authors reported that in constructing the foundation and structure of a 15-story commercial building in the central business district of Melbourne, material transportation GHG emission alone was responsible for more than half (55.4%) of the total direct GHG emission. A similar result was obtained during two case studies where [50] explored the utilisation of prefabrication and conventional approach to the construction process carbon emission during two residential building constructions in Melbourne, Australia.

While the transportation of construction material is inevitable, scholars [26,29] have opined that the usage of low-carbon transport mechanisms like rail or water should be prioritised, especially if the importation of material is to be done, as is the case in Sri Lanka where imported cement has low lime content and contractors prefer to use the imported cement instead of the locally available ones [26]. Although, local purchase of materials has equally been identified to minimise carbon emissions associated with material transport [26,29]. This was exemplified in the study of [41], where the authors ran different scenarios as regards the purchase and utilisation of construction materials for a highway project locally within 5–40 km of the project location in Spain, at 800 km in Northern Spain and that imported from China and France. The authors [41] found out that relative to the base case scenario, which was the usage/purchase of material locally, the material bought from Northern Spain added 0.3% to the construction stage emission, and those imported from France and China added 3.3% to the carbon emission of the highway project construction. Hence, it is evident that transportation distance plays a key role when trying to reduce transport-related emissions, even when another method of construction, like prefabrication, is utilised [28].

For instance, in the study carried out by [50] described above, the authors discovered that the little gain in emission reduction was eroded due to the transportation distance of the prefabrication components, which was double compared to the transportation distance related to the conventional approach. Although, it is worth noting that the study has some limitations. The authors [50] mentioned that the building contractor for both projects is the same, thereby assuming that the project management skills remain the same, but the two buildings have different total floor areas and number of floors. The difference in their floor area is about 850 m^2, and the difference in floors is four, and the semi-prefabrication building is the one that has the highest floor area and number of floors. This could have impacted the carbon emission calculation. However, in general, reducing and optimising transport distance for the delivery of material is crucial in minimising transportation carbon emissions, irrespective of the construction method adopted [26–28]. Reference [29] equally suggested the reuse and recycling of materials on-site as a strategy for achieving this, while [31] noted that the utilisation of lightweight material could make up for the emission associated with long-distance travel. Reference [31] demonstrated this in their research where they compared the carbon emission linked to the construction of a pedestrian bridge with a lightweight glass-fiber reinforced polymer (GFRP), reinforced concrete (RC), and steel in Taiwan. The authors found out that even though the GFRP had to be transported from a farther distance (160 km) compared to RC (158.6 km) and steel (88.4 km), the transportation carbon emission was much lower (64 kgCO_2eq.) relative to RC (787 kgCO_2eq.) and steel (90 kgCO_2eq.). Albeit, it could be argued that the distance for the RC and GFRP material is almost similar, but in terms of their respective carbon emission, RC is about 1230% higher than GFRP because of the material weight of both components [31].

Lastly, [30] recommended that if drivers are trained in fuel-efficient driving to maximise the vehicle's engine efficiency during material transportation and the fuel sourced from renewables, this can assist the construction industry in the UK to reduce transportation carbon emission by almost 3%. Therefore, for contractors to minimise the carbon footprint of their activities during construction, the transportation carbon emission cannot be ignored [48].

Waste Transport

Similar to material transport, ref. [30] opined that the utilisation of renewable fuel for waste transport and the adoption of driving techniques that maximises transport vehicles' engine efficiency during construction waste transportation could help to minimise carbon emission by about 1.5% in the UK. This is because it has been argued that the burning of fossil fuels leads to the emission of GHG, giving rise to a negative environmental impact where [54,55] reported that in transporting 530 tons of waste to the landfill during a building construction project in Korea, 1.4 tCO_2 emission was generated. This emission could likely be minimal if the fuel used were from a renewable source. Furthermore, in conjunction with using renewable fuel for waste transportation, there is a possibility that if large disposal trucks are utilised in transporting the waste to the landfill, thereby reducing the number of trips, this could also help in minimising the emission associated with construction waste transportation. Such a claim was supported by [26], who highlighted that number of trips is one of the key factors that affect transportation carbon emission.

3.1.2. Construction-Installation Stage

During construction activities on-site, the usage of fossil fuels and consumption of electricity is quite huge, thereby leading to a substantial amount of carbon emission [55,56]. According to [38], in 2007, about 1755.94 Gigagrams of CO_2eq. was generated during construction site operations in Australia. These emissions can be attributed to the several activities which go on on-site and various activity contributes differently to the overall carbon emission produced during construction. The study conducted by [57] in Korea gives a good example of how different construction activities contribute to the overall carbon emission generated on a construction site (see Table 2). This shows that carbon reduction efforts should be spread across all activities undertaken on a construction site, and some of these will be discussed below.

Table 2. Carbon emission for various construction work types (Source: [57]).

Construction Work Type	Carbon Emission (tCO_2)	Percentage (%)
Civil Engineering	73.4	39.7
RC	45.5	24.6
Steel Frame/Metal and Window/Glazing	10.1	5.5
Interior and Exterior Finishing	9.6	5.2
Ground heat	46.4	25.0

Machinery and Equipment

As seen in Table 2 and based on the case study carried out by [57], three work types (civil engineering, RC, and ground heat) contributed the most (around 90%) to the total carbon emissions released on-site during the construction of a building complex in Korea. Reference [57], therefore, argued that this emission is related to the energy consumed by the construction machinery and equipment used for the stated work types. This claim is corroborated by [55], who stated that almost all the carbon (99.8%) available in the fossil fuel used up by an excavator is passed out as carbon emission. Additionally, in profiling construction machineries used for various activities on-site, ref. [32] highlighted that those used for civil engineering and RC works had the highest carbon emission. Hence, adopting strategies such as the usage of alternative fuels, regular maintenance of machinery, and utilisation of low-emission machineries that can minimise the usage of fossil fuels and construction machineries emission is crucial [26,30,32,36]. For instance, during an ongoing highway construction project in Taiwan in 2017, ref. [36] reported that replacing gasoline with biodiesel optimised equipment efficiency and reduced carbon emission by 13,088.2 $kgCO_2eq$, while according to some construction experts, regularly maintaining equipment could also reduce fuel consumption and improve efficiency [26]. In the same vein, 'replacing diesel oil machineries with electric ones' could assist in minimising the usage of fossil fuels and drive down emissions, especially if the source of the electricity in powering the equipment is from renewables like wind or solar. This was demonstrated in the work of [32], where the authors analysed two buildings' construction process carbon emissions in China. They discovered that the construction equipment with the lowest carbon emissions utilised on-site was all those using electricity (emission factor was 0.6101 $kgCO_2/kWh$), and the authors stated that in China, the emissions associated with power generation are decreasing due to the application of solar and wind for power generation [32].

Similarly, the reduction of equipment idle time has been noted by researchers [27,37] to lessen the carbon impact linked with machinery usage. In a building construction project in the West of Ireland, ref. [37] carried out an action research study that lasted for 48 weeks and noticed that by reducing some equipment (diggers, teleporters, and dumpers) idling time by 5%, carbon emission reduced by 9.60 tCO_2. Although [58] argued that minimising the idle time of machineries during construction is a simple action that might not amount to much emission reduction, ref. [26] claimed that it is a good practice globally in reducing carbon emissions. The authors [26] further supported this claim during a case study research done in Sri Lanka, where it was discovered that contractors handling all four project sites used as case studies have ensured that no idle time of equipment occurs. This was achieved, as narrated by one of the participants in the case study, by ensuring proper work scheduling [26]. Reference [55] also suggested that carbon emissions emerging from equipment idle time can be minimised through the usage of some technologies like automatic engine shut-off devices and direct-fire heaters, to mention a few.

Furthermore, the provision of training to machine operators has been pointed out by [33] to reduce carbon emissions. In understanding the extent to which different green technologies can aid carbon reduction during the construction of infrastructure projects, ref. [33] did a survey with construction industry experts who have the ability to make key decisions on a construction project from the planning to the construction phase. The analysis of the survey showed that the experts believed that guidance on machine usage could reduce carbon emission by 22% during earthwork, and 38% of them claimed that they would adopt this strategy (i.e., training machine operators) during project execution even though it might increase construction time by 10% [33]. Reference [37] also found out in their action research study that when crane operators change their work practice by minimising the usage of the crane by two hours in a day instead of the usual 11 h when possible, 10.2 tCO_2 was saved. This can be achieved through work sequencing [26,59], which could also assist in reducing the number of machinery required during construction.

Lastly, the selection of work-specific and appropriate matching of machinery has been cited to improve productivity and efficiency and reduce carbon [26,58,59]. In a field study carried out in the UK by [59] to explore the minimisation of construction equipment GHG emission, the authors found that adequate matching vis à vis selection of equipment could result in a 40% reduction in emissions of machinery during construction projects.

Waste

Just as the selection of work-specific and multi-purpose equipment has been suggested to improve work efficiency and decrease the carbon emission of machinery on construction sites, this strategy has equally been mentioned by [26] to minimise wastage of material on-site. Once there is reduced waste generation, then carbon emission associated with waste transportation from a construction site will diminish as well as the embodied carbon of the material that turned into waste. In addition, the 'provision of separate skips for reusable, recyclable, and landfill waste' can aid the reduction of carbon linked to construction waste. This will also ensure that inert materials (e.g., concrete and soil) are separated from non-inert ones (e.g., packaging and wood), thus limiting the waste that is sent to the landfill [54], again saving waste transportation emissions. This will equally boost the re-usage of waste material on-site [30,33,40], thereby contributing to embodied carbon reduction. The reuse of waste on-site is important not only because of the enormous quantity being generated during construction—1.13 billion tons/annum in China, 890 million tons/annum in Europe, and 31 million tons/annum in Brazil [54]—but also due to the associated carbon emission. For example, during the construction of an 83 m^2 semi-detached modular timber frame three-bedroom house, the emission related to the waste generated equated to 4.9 tCO_2 [55]. Likewise, of the more than 13 million tCO_2eq. emission released during the construction of a residential tower made of concrete steel in Tehran, 14% (>1.8 million tCO_2eq.) was connected to construction waste [55]. Reusing some of these waste materials generated on-site has the potential of reducing embodied carbon emission by 6.2%, and some of the ways in which they are reused include utilising concrete waste to make paving blocks and lintels, to mention but a few [26]. In general, ref. [60] noted that the effective management of construction waste is pertinent in attaining the construction sector's emission minimisation goals.

Material

The huge consumption of material resources by the construction industry has been identified as one of the major contributors to climate change [1]. This is due to the enormous consumption of energy during the production of construction materials, which results in corresponding high emissions of GHGs [1,61]. Reference [61] noted that steel, concrete, and aluminium are amongst the highest emitters of carbon within the sector. Similarly, in the review of literature done by [44] on the assessment of embodied carbon ('cradle-to-end of construction') of high-rise buildings, the authors discovered that most of the reviewed articles stated that steel and concrete are responsible for the highest carbon emitted when it comes to consumption of materials. This finding was further proved by the authors' [44] empirical study on a semi-prefabricated 30-floor high-rise building in Hong Kong, where they found out that during construction activities on-site, emission related to 'cast in situ concrete' (49.8%) and steel (12.6%) alone were responsible for about 63% of the total carbon emitted on-site, while other materials (timber, ceramic tiles, aluminium, etc.) consumed contributed almost 26%. Hence, the opportunity to reduce, reuse, or even replace some of these materials and, indeed, any other construction material on-site needs to be explored and embraced in order to reduce their accompanying emission.

In reducing material consumption on-site, several scholars [28,44,47] have noted that optimising structural components, building schemes, and the ingredient and process of production (of concrete especially) can assist in achieving this. As a means of optimising ingredients during concrete production, ref. [39] highlighted that during two different highway construction projects in China, between 6,696.9 and 29,356.6 tCO_2 was saved when cement was obtained in bulk rather than in bags. In contrast, it can be argued that optimising structural components or building schemes does not fall under the purview of contractors, who are the stakeholders in charge of carrying out construction activities on-site, as this optimisation would have been done during the design stage. Hence, utilising this technique might not lead to the reduction of material consumption and its associated carbon emission on-site. However, if contractors were involved early during the planning stage of a construction project, they might be able to suggest strategies that could lead to reduced consumption of material once the project execution commences. In exemplifying the benefit of early contractor involvement (ECI) in minimising material and associated GHG emissions during a road construction project in Australia, ref. [62] reported that even though the involvement was late as the preliminary design had been concluded, the ECI team was still able to reduce the haulage of about 600,000 m^3 of material from a total of two million cubic metres that was to be hauled initially by making changes to regrading and re-alignment of a section of the road.

Reusing materials is another strategy that has been identified to minimise carbon emissions during construction activities [29,41]. Reference [26] indicated that embodied carbon could be reduced by almost 6.2% if construction materials are reused in a construction project. In the study conducted by [63] (p. 22) in investigating the emission reduction potential of 'five different material use options over a 60-year lifespan of a high-rise concrete office buildings' in Hong Kong, it was discovered that about 17% of savings in carbon emission could be achieved if between 15 and 30% of the existing non-structural and structural components are reused while around 3% emission savings could be achieved if between 5 and 10% of the existing material resources are reused. Furthermore, materials such as plywood, windows, and glass could be reused in making temporary structures on a construction site, while formworks could be re-utilised a number of times (up to 30 times as reported by one of the participants in the study of Kumari and his colleagues) within a site [26]. Additionally, the utilisation of recycled materials such as reinforcing steel, post-consumer timber, roof tiles, aggregates, and concrete, to mention but a few, could contribute to construction stage carbon reduction [27,29,33]. This was demonstrated by the scenario analysis done by [27] in understanding the impact of recycled material used during the construction stage of a building. The researchers [27] found that using 15% recycled reinforcing steel could lead to about 12% reduction in carbon. In the study carried out by [33], the authors reported that utilising 30% recycled aggregate for structural and pavement work during road construction projects could result in an 18% decrease in carbon emission.

Perhaps, most of the savings on carbon emission that can be achieved during construction projects could come from either 'replacing some cement with ground-granulated blast-furnace slag (GGBFS)' or coal fly ash or 'selection of geopolymer-based cement' for concrete production [26,29,33,36,42–46] since most scholars opined that concrete is the highest emitter of carbon during construction activities. According to [45], if fly ash is used to replace 30% of cement during the production of ready-mix concrete, there could be a GHG emission saving of around 25%, and based on some studies in Western Australia, about 30–40% of cement can be replaced with fly ash and the structural and physical performance of the concrete will still be intact. Although transportation emissions related to procuring the fly ash might be much, the authors reported that according to another study done in Australia, there will still be a net saving in GHG emissions when used instead of cement [45]. Likewise, in a study conducted by [36], about a 40% reduction in carbon emission was achieved when GGBFS and coal fly ash were used to partially replace cement. Additionally, the use of geopolymer-based cement in replacing Portland cement could result in a 75–90% decrease in carbon emissions [29].

Finally, refs. [26,27] noted that 'adequate material resources planning and allocation' is crucial in decreasing construction material carbon emission, and so is the purchase of construction materials with a carbon labelling scheme where possible [64].

On-Site Lighting

During the execution of construction projects, having suitable lighting is inevitable. However, the source and management of the lighting on-site is essential in ensuring minimal wastage of electricity supply as well as reduction of its associated carbon emission. In the research done by [37], the authors highlighted three strategies that could be adopted in managing lighting on-site, namely, reduction of the usage of transformer boxes, night-time electricity management, and minimising 'festoon lighting bulbs'. Each of these approaches saved 16.52 tCO_2, 19.64 tCO_2, and 3.55 tCO_2, respectively, during the action research study carried out by the authors [37]. Furthermore, 'usage of light emitting diode (LED) illuminance control appliances' can assist in regulating electricity usage on-site, thereby reducing the emission linked to the used electricity [39]. Reference [39] reported that the application of this strategy reduced 8233.1 tCO_2 during the construction of a highway project in Western China. Similarly, ref. [65] reported that LED light usage has the potential to reduce electricity fees while equally limiting carbon emissions.

In general, obtaining electricity from renewable sources such as solar and wind (generated on-site or from the grid) could have a positive impact on carbon emission savings during construction projects [32].

On-Site Office

Having an office on a construction site is close to the norm, and the utilisation of energy within the on-site office will contribute to construction-stage carbon emissions, even if they are minimal. Therefore, it is vital to consider its energy usage and not exclude it so it does not serve as a loophole in the carbon-reduction effort being engaged in on-site. This could possibly be responsible for the suggestion made by [30] that existing site cabins should be retrofitted to be more energy-efficient before being deployed to the site, and all new ones should, as a standard, be energy-efficient. In addition, [30] further reported that an energy-efficient site accommodation could lessen carbon emission by 50% or more when juxtaposed with a traditional site office, and within its lifetime, it could save 4.9 million tCO_2. Some of the measures highlighted in decreasing the on-site office carbon emission, apart from having appropriate glazing and insulation, include utilisation of occupant sensors to reduce electricity usage, a lighting delay switch, deploying timers to control heating usage, turning off the equipment in the office when not in use, and occupant behaviour change [30,37,66]. In line with this, [37] noted that the utilisation of occupant sensors, controlling heating usage, and turning off equipment rather than putting them to sleep reduced on-site carbon emissions by 14.23 tons, 6.86 tons, and 12.71 tons, respectively.

On-Site Transportation of Material and Equipment

During a construction project, both equipment and materials are moved around on-site to achieve different tasks. Adequate site management [26,33] and planning of construction activities will ensure that work is performed sequentially and that the movement of materials and machinery needed for these activities are optimised [48]. Thus, impacting the carbon emission related to the movement of these important resources on-site. The lesser the distance needed to travel by machinery, especially those used to transport materials on-site, the lesser its energy consumption, therefore, the lesser the carbon likely to be emitted and vice versa. For example, during the construction of a four-story high building in Southern China covering 2189.29 m^2 area, out of the 34 types of machinery noted to be utilised for the construction, an electric hoist which is employed for vertical transportation within a 20 m distance on-site was responsible for about 26% (1979.61 $kgCO_2$) of the total (7726.32 $kgCO_2$) emissions and this was the highest amongst all the equipment [48]. Possibly, this was why one of the interviewees in the [26] study stated that in locating the crane on-site, distance in reaching the rebar yard and every area of the site was considered, and another interviewee mentioned that the placement of the hoist within the site was done in such a way that material handling would be easy, thereby assisting them to minimise carbon emission that could have resulted from 'additional operating hours of the hoist'. For the machinery utilising electricity for their movement on-site, procuring energy from a renewable source (whether on-site or from the grid) has been argued to reduce their carbon emission [32], while those using fossil fuel, especially diesel, could switch to biodiesel B20, which could reduce emission by about 9% [41].

Additionally, ref. [39] opined that the usage of smart traffic signals could assist in reducing carbon emissions within a construction project, and this was evident from the highway construction case study conducted by the researcher in China, where this strategy saved about 21,569.1 tCO_2.

Construction Method

Reference [61] described the construction method as a practice that dictates construction activities, tools to be used, construction material optimisation, as well as waste to be generated on-site. Consequently, the construction work sequence should be properly planned to realise lower carbon emissions [42]. Based on this, ref. [67] suggested that contractors can reduce emissions within their control via the on-site practices they decide to adopt. Therefore, utilisation of new and improved construction processes, along with the 'adoption of low-emission installation processes' and energy-management systems, should be explored and prioritised by contractors [26,30,39,43,45]. For example, ref. [39] reported that the usage of a management system to measure energy minimised carbon emission to the tune of 20,006.2 tons during the construction of a highway project in Eastern China.

Several studies [28,42,44,46,49,50] have equally proposed—albeit with some reservation—the uptake of the prefabrication method of construction as a means of reducing construction-stage carbon emission. To move towards the adoption of the prefabrication method, however, there seems to be uniformity in the call to pay attention to the type of material to be used, its transportation distance, and its installation method on-site if the carbon reduction gain is to be maximised [42–44]. Furthermore, the ECI approach is also crucial in implementing prefabrication since clients and designers would need to be involved in the decision-making of employing the prefabrication method. For an extensive understanding of the prefabrication method of construction, including its carbon reduction potential or otherwise, see [49]. Similar to prefabrication, minimising the thickness of the wall as a means to decrease carbon emission during construction, as advanced by [44], will require ECI.

Another strategy linked to the construction method in lessening carbon emission during construction is the on-site generation of energy from renewable sources rather than from fossil fuel or early connection to the grid (especially if the grid power generation is from a renewable source) by a large construction site in particular [30].

4. Conclusions, Limitations, and Contribution of the Study

This study highlights various carbon-reduction strategies that could be adopted to decrease the construction process's carbon footprint through the synthesis of the literature. These strategies were summarised into nine different categories, namely, material transport, waste transport, materials and equipment, waste, materials, on-site office, on-site lighting, on-site transportation of material and equipment, and construction method. The material and waste transport are related to the transportation stage (A4) of the construction process phase of a project-embodied carbon lifecycle, while the remaining seven categories are linked to the construction-installation stage (A5). The result of this literature synthesis could provide a foundational base for further study within the construction process carbon emission reduction research area. Additionally, it can serve as a framework to guide contractors in adopting suitable measures or a suite of measures in minimising carbon impact during construction project delivery. Moreover, the findings of this study explicate the intricacies shrouding the construction process and suggest appropriate strategies that could be utilised in tackling them. This could equally enable policymakers to develop programmes targeted at the identified construction process cluster areas to accelerate their decarbonisation. For instance, in the UK, there are legislations targeted at the management of construction waste [68]. These legislations have been in existence for decades and were enacted from a resource and pollution management perspective [69,70], albeit beneficial for decreasing construction waste carbon. Hence, the adoption of such an approach by policymakers for each construction process phase cluster might be valuable in driving down their associated carbon emission.

Lastly, it is noteworthy to mention that the eligible papers that underpin this study were generated as a result of the keywords utilised. Hence, the number of relevant literature found for the keyword used might be influenced by the type of adopted keywords. Thus, this should be considered when interrogating the study findings.

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