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Review

Environmental Impacts of Construction in Building Industry—A Review of Knowledge Advances, Gaps and Future Directions

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Abstract: The building-and-construction industry has been researched extensively over its life cycle regarding green and sustainable processes and techniques due to its major contributions towards energy consumption and its environmental impacts. Over the past decade, the construction stage of a building is often criticized for overlooking or approximating the environmental impacts as compared to other life-cycle stages of a building. This is evident through strong research findings regarding other building life-cycle stages in building-emission-assessment studies. With the drive towards digitization, the construction industry is receiving significant research attention in order to minimize environmental impacts at the construction stage. Despite these research initiatives, only a handful of recent review studies have systematically furnished current advances, gaps and future directions in environmentally sustainable building-construction techniques. The current study represents a systematic literature review of the environmental impacts at the building-construction stage with the objective of identifying the current findings, gaps and future research scopes. A bibliometric assessment revealed key author contributions, key research areas and collaboration aspects of research works related to environmental impacts of construction in building projects. Four major barriers and knowledge gaps in conducting a comprehensive assessment at the construction stage of a building were identified, including the lack of definition of a generic system boundary, difficulties in data collection, complex modeling issues and complications in the classification and analysis of emissions. The findings would provide key knowledge for passionate construction-industry stakeholders who are keen to benchmark green and sustainable construction practices in the building industry.

Keywords: construction; buildings; emissions; sustainability; environmental impacts



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1. Introduction

Buildings are one of the seven foremost contributors to resource consumption and environmental emissions, with studies demonstrating the contemporary requirement to identify the emission-reduction practices [1,2]. Statistics and previous studies have emphasized that buildings account for one-sixth of the world's freshwater withdrawals, one quarter of the wood harvested and two-fifths of its materials, which indicates its intensive resource consumption [3–6]. In addition, they are also known as significant emission contributors with statistics suggesting buildings as one of the seven dominant sectors that contribute greatly towards environmental emissions [7]. Researchers across the globe have undertaken several attempts to minimize these adverse effects across the life cycle of a building [8–11]. Due to considerable material utilizations and large emission contributions during other life cycle stages, emissions and impacts at the construction stage of a building have often been approximated as compared to other life-cycle stages [2,12,13]. However, a handful of studies have highlighted the importance of accurate modeling and estimation of construction-stage emissions at distinct levels in order to benchmark short-term impacts on surrounding environments [14]. This will also help to address the contem-

porary requirement of analyzing, predicting, and minimizing short-term and long-term environmental impacts.

Life-cycle assessment (LCA) is known to be one of the most comprehensive assessment tools for the analysis and prediction of environmental impacts of a product or process [15]. Recent research findings of building LCA studies have led to significant changes in the built environment, with directions for emissions and energy reductions. However, the construction stage of a building is given minimum consideration in these building LCA studies and have been the least-considered life cycle of building-emission studies [1,16]. With the current digitization drive in the building-construction industry and the introduction of Industry 4.0, studies have stressed the importance of comprehensively assessing the building-construction stage's environmental impacts [17]. Attaining environmental impacts of each life-cycle stage at the early stages would enable the project team to obtain collective decisions on green and sustainable designs. However, understanding the current knowledge advances and barriers is the key initial step that would lead to comprehensive assessment of the construction-stage's environmental impacts. Thus, there is a contemporary requirement of a study to inform and educate the research field on the recent knowledge developments and current trends related to environmental impacts of the building-construction stage. The current review study aims to identify current trends and barriers to conducting studies on construction-stage emissions and impacts. The findings of the study aim to facilitate passionate researchers who are keen on conducting research on environmental impacts at the construction stage and have intentions to benchmark the life-cycle impacts of buildings.

2. Research Methodology

The research methodology corresponds to the sequential procedure as shown in Figure 1. To facilitate a comprehensive review, the current study initially focused on identifying the current trends of using waste products in concrete manufacturing by conducting a bibliometric assessment (BA) using the "Bibliometrix" software. A BA uses a statistical approach to determine relations between key research data such as the research topic, authors, keywords, publication year and publishing country. Using the key data elements, this method facilitates the analysis and interpretation of current research trends and knowledge gaps [18,19]. Related research publications were selected from the "Web of Science (WoS)" scientific database using the key words "construction", "emissions", and "buildings" with the "AND" operator, and the keyword "impact" using the "OR" operator. The time span was set from 1991 to 2021 in order to capture two decades of related research articles. WoS was selected as it could effectively capture related scientific articles and due to its compatibility with the "Bibliometrix" software [20,21]. The selected research articles in the search string included journal articles, conference publications, books, and book chapters corresponding to construction-stage emissions and impacts. Duplicate and non-related articles were removed from the list through a manual inspection of titles and topic content. Following the bibliometric assessment, a focused review was conducted on major LCA studies on the construction stage of a building, mathematical models, and current advancements. Using the review findings, barriers and knowledge gaps related to a comprehensive emissions assessment at the construction stage of a building were identified. Key findings would also enable the researchers to focus on transitional research by addressing the current impediments.

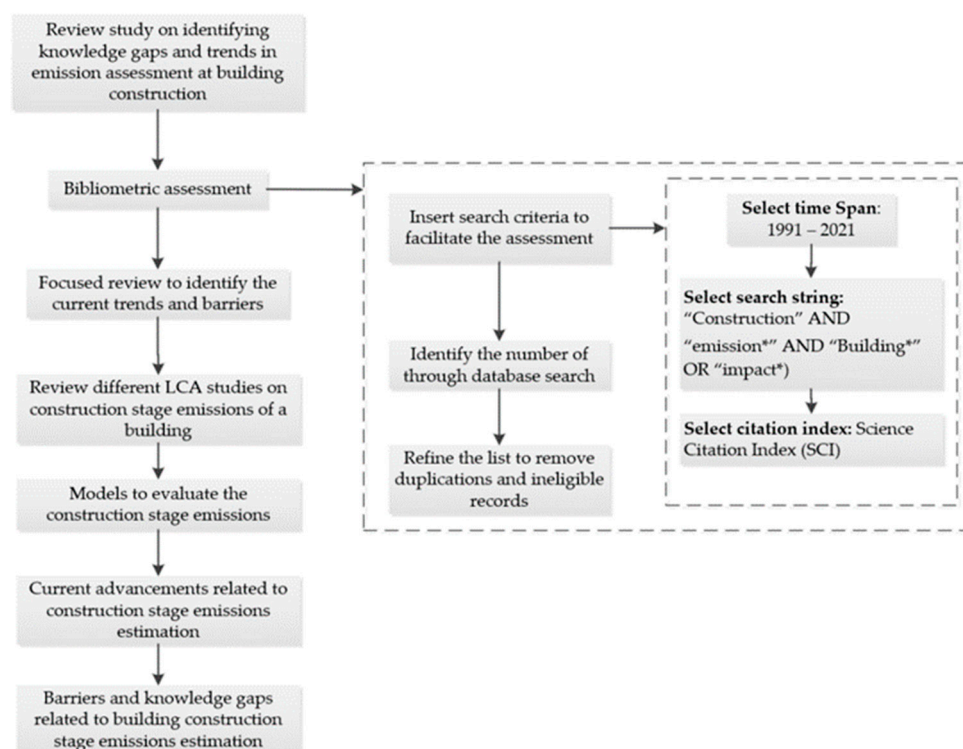


Figure 1. Research methodology.

3. Bibliometric Analysis Results

The results corresponding to two decades of research from 1991 and 2021 are highlighted in Table 1. These results were extracted from the bibliometric reference data of the input data file of the related articles through the “Bibliometrix (accessed through www.bibliometrix.org, accessed on 28 December 2021)” web-based application. Based on the results, it is evident that there are no significant average citations or average citations per year per document. This corresponds to the lack of new research publications in the area. Moreover, a relatively high number of published single-authored documents (130 publications from the total population) during the time indicates limited collaboration between authors. The relatively under-researched nature and the approximations of environmental impacts during building construction could be a major factor contributing to less collaboration among researchers. The bibliometric analysis featured 2976 authors and 3563 author appearances. These facts also provide an understanding of the author and co-author distribution in the building-construction stage’s environmental impacts. The “authors per document” (2.74) parameter indicated that on average, one article is authored by approximately three authors. However, after accounting for single-authored documents, this value is a relatively higher, which could indicate that the limited studies conducted in this area are clustered in groups. The “collaboration index” is an indicative term that calculates the number of authors in a multi-authored article per multi-authored article published. This provides a good indication of the level of collaboration for each published article. The collaboration-index value of “3” further justifies the previous claim of various research teams working in groups in several areas of the building-construction stage’s environmental impacts.

The annual publication rates of related publications from 1991 to 2021 are listed in Figure 2. The observed distribution can be discussed based on three timeline stages. The initiation stage from 1991–2006 is the time frame that can be closely related to the research interests that were facilitated through the introduction of the carbon-emission-reduction targets in the Kyoto Protocol (KP) published on 11th December 1997 [22]. The development stage ranging from 2006–2011 can be identified as the as the continuous development of the research findings that were initiated from the initiation stage. The growth stage since

2012 can be attributed to the large uptake of innovative construction techniques such as prefabrication and 3D printing. The requirement to benchmark sustainable benefits over these smart and novel construction practices have amplified the research interest in the construction stage, especially in construction techniques. The top five publishing sources with the number of related publications on construction-stage impacts were identified (see Figure 3). The results illustrated that since 2015, multidisciplinary journals such as the “Journal of Cleaner Production” and “Sustainability” have published significantly more studies, outweighing the other three journals. This could be related to the multidisciplinary scope and objectives of these journals, which often covered studies with a wide scope. “Building and Environment” and “Energy and Buildings” are mainly focused on building-related construction and therefore are placed third and fourth, respectively. “International Journal of Life Cycle Assessment” is placed fifth on the list due to having a more specific scope, i.e., life-cycle assessment and related studies. The findings also suggests that the journal title could influence the selection of publication source.

Table 1. Main information from the bibliometric assessment.

Attribute	Result
Timespan	1991–2021
Average years from publication	5.84
Average citations per documents	1.278
Average citations per year per doc	0.1673
References	3795
Author’s Keywords (DE)	387
Authors	2976
Author Appearances	3563
Authors of single-authored documents	130
Authors of multi-authored documents	2846
Documents per Author	0.365
Authors per Document	2.74
Co-Authors per Documents	3.28
Collaboration Index	3

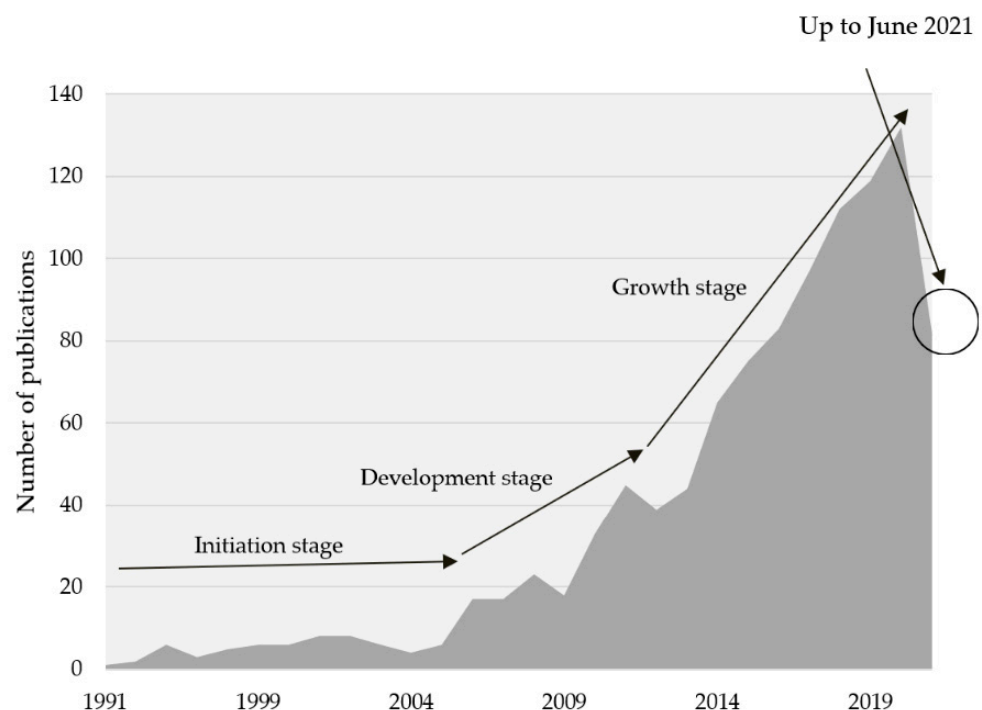


Figure 2. Annual scientific publications on environmental impacts in construction.

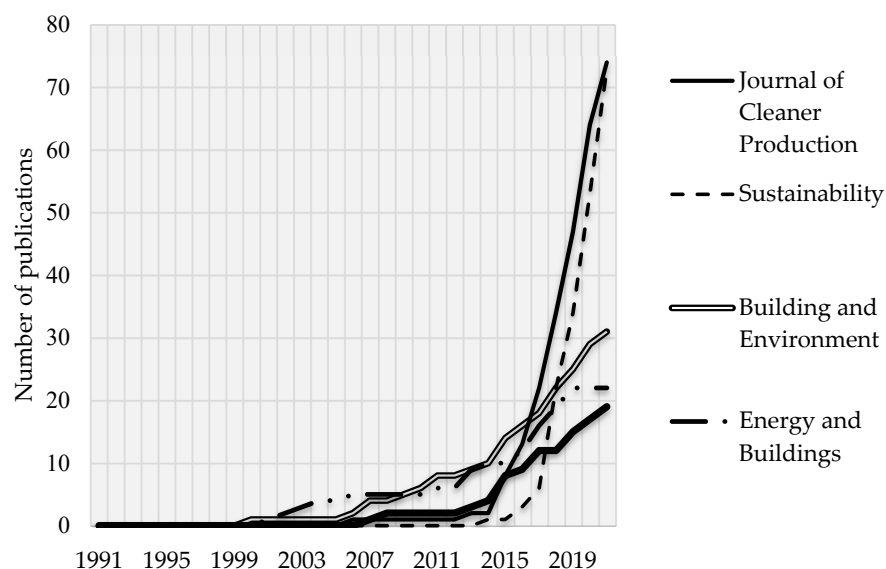


Figure 3. Annual publications in the top five journals related to environmental impacts in construction.

The three-plot diagram, including country of publication of the corresponding author, topic area and keywords are illustrated in Figure 4. The three-plot diagram provides a visualization of the three main selected items and how they are related through a Sankey diagram [19]. The indicative topic-area-term results of “LCA” and “life-cycle assessment” indicate that the life-cycle assessment is widely adopted as a methodology for assessing environmental impacts and greenhouse-gas emissions. The results also indicate that several studies have focused on the urban-level-sustainability and energy-performance-assessment aspects of buildings. A strong linkage between “energy efficiency”, “buildings” and “residential” suggest that energy consumption and performance evaluation have been the major focus in building-construction-emission studies. Besides, a relatively strong relationship between the keywords, “construction” and “greenhouse-gas emissions (GHG)” also indicate that the majority of these studies have focused on GHG emissions at the construction stage of a building. However, the high number of topic areas in the diagram indicates the broader scope considered in building-construction-stage-emission studies from the house level to the urban level. The United States of America (USA) exhibited a strong research focus on the active living of buildings, which indicated that the construction research was more focused on improving the operational level of buildings. Australia had a strong research focus on the climate change of infrastructure construction while European countries such as Italy had more research focus on energy efficiency at the urban level. These findings facilitate the understanding of the current research directions and research focuses across the globe.

Publication-evolution timelines of the top twenty authors and their publishing countries are highlighted in Figure 5. Each line in the figure corresponds to the evolution timeline for each author with the starting year corresponding to the start of each line. The circle presented in each line corresponds to the number of related articles in the corresponding year considered. If the circle is relatively large, that corresponds to more related research work in that year for the corresponding author. Madelyn Marrero heads the list with strong recent-research outputs in the related topic. Her research expertise and focus areas mainly include the environmental and economic impacts of construction waste [23]. Her vast research skills on sustainable construction, green buildings, climate change, building materials and construction technology are a major reason for the significant researcher impact on the related field [24,25]. Her collaborative publications with Jaime Solís-Guzmán and Alba-Rodríguez, who also make the top list of authors, might have contributed to her high impact record [26,27]. Vivian Tam and Guomin Zhang are the other two top authors who have made significant research contributions since 2019 to the environmental impacts

at the construction stage of buildings [28–36]. This includes both construction materials and impacts on the construction-activity level. Martin Skitmore is a world-renowned researcher who has undertaken research over the past two decades in several research areas including construction risk and safety, procurement, and stakeholder management. Recently, he has published research outputs in sustainable construction and the life-cycle-impact assessment of building and transportation-infrastructure projects, which is evident from Figure 5. This further signifies the importance of the research focus on the construction stage of a project. The author-collaboration cluster analysis shown in Figure 6 indicates that several research groups in several countries have extensively worked on different research areas of the construction stage of buildings. The biggest collaboration network was observed between Madelyn Marrero, J. Solís-Guzmán and M. D. Alba-Rodríguez, mainly in the areas of construction waste materials, as well as the economic and environmental impacts of housing construction [23,25,27]. Collaborative work between Vivian W. Y. Tam, Khoa N. Le and C. N. N. Tran also exhibited a strong network with a wide scope of environmental management of construction projects and green-rating tools [37]. However, their research group has also extensively worked on the life-cycle assessment of recycled, coarse-aggregate incorporated concrete and construction waste [38,39]. A notable collaboration was also discerned between Guomin Zhang and Malindu Sandanayake, in which their research focused mainly on assessing environmental impacts at the construction-activity level [13,31,32,40–42].

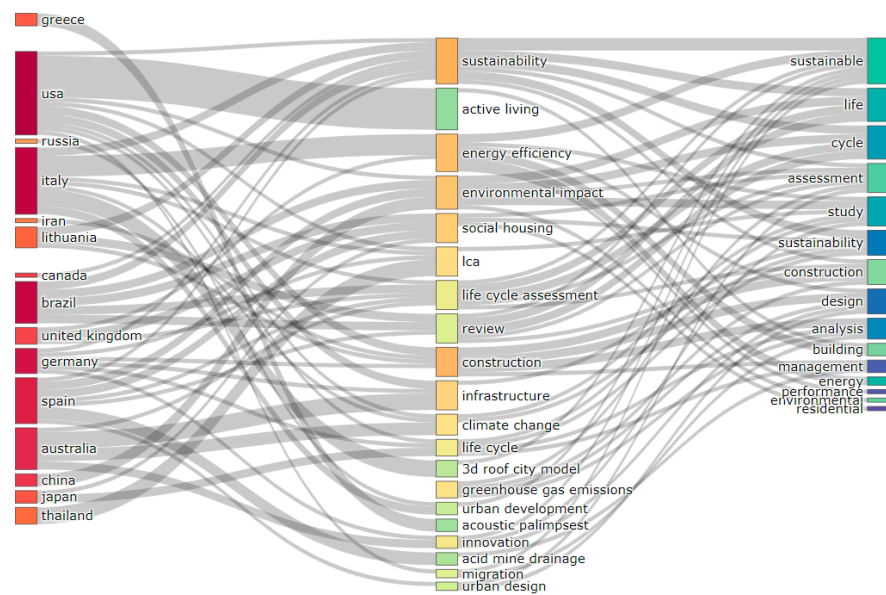


Figure 4. Relationship between countries, topic area and keywords in previous studies.

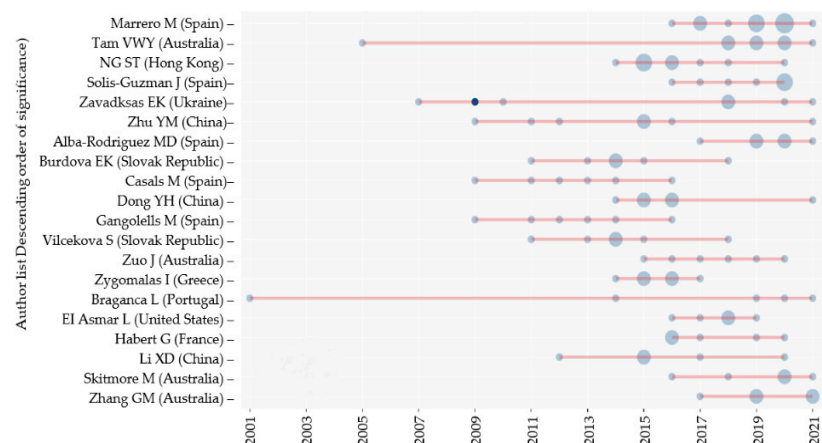


Figure 5. Top twenty author evolutions across the timeline.

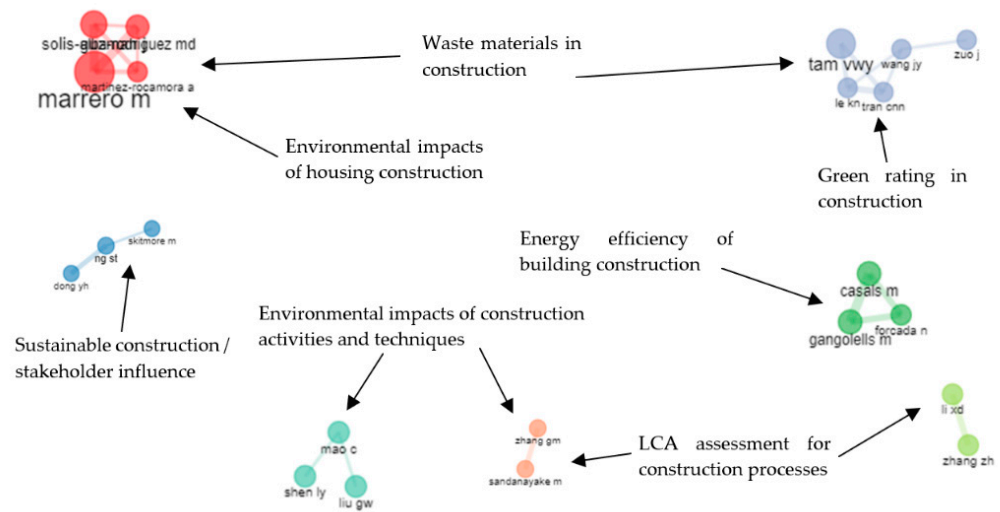


Figure 6. Author collaborations in studies related to construction-stage impacts.

4. Critical Review of Studies on Construction Stage Environmental Impacts

4.1. Major LCA Studies at Construction Stage of a Building

Guggemos et al. outlined the importance of emissions at the construction stage at an aggregate level in their study [3]. They argued that focusing only on the use phase will eliminate the opportunity to reduce the life-cycle emissions of a building. Consequently, the research significance of emission studies at the construction stage is highly important when considering the total emissions of a building. An effective method of compressively assessing emission studies at the construction phase is to categorize them into low-rise- and high-rise-building constructions. This is because there is a significant difference in the material and machine usage at the construction stage for low-rise and high-rise buildings. Suzuki and Oka [43] estimated the energy consumption and CO₂ emissions at the construction stage of an office building in their life-cycle-emission study using input/output (I/O) and process methods to determine the energy consumption and CO₂ emissions, respectively. CO₂ emissions in the office building were estimated with respect to five emission sources: temporary works, structure, finishing, equipment and general expenditure. The results indicated that the operation and the construction stages of the building are responsible for the highest emissions, with a respective contribution of 82% and 15%, while the demolition stage has a minimum impact on CO₂ emissions. Moreover, Suzuki et al. also conducted the same emission study on the construction phase of a residential building [44]. The results concluded that structural works are responsible for the most CO₂ emissions. Mao et al. compared GHG emissions of conventional and semi pre-fabrication construction methods in their emission study using a high-rise residential-building construction in China [10]. The study defined five emission sources for the construction process including the embodied emissions of building materials, transportation of building materials, construction waste, soil and prefabricated components, and operation of equipment. Data corresponding to all five emission sources were collected for both of the construction methods. A process-based quantitative model was developed to evaluate the emissions. The results indicated GHG emissions of 336 and 368 kg/m² for conventional and semi pre-fabrication construction, respectively. The findings further highlighted the dominance of material emissions at the construction stage with around 80% of the total emissions. The study concluded by stating that the use of prefabrication materials can reduce the total GHG emissions by 15%.

A case study conducted in Hong Kong estimated the greenhouse-gas emissions of a commercial building [7]. The study defined a system boundary to include GHG emissions from the manufacture and transportation of building materials, the energy consumption of construction equipment and the processing resources and emissions due to the disposal of construction waste. The results illustrated that around 93% of emissions are due to the manufacture and transportation of materials, whereas emissions due to equipment and the disposal of construction waste are responsible for 6% and 1%, respectively. It also indicated that steel and concrete are responsible for around 95% of the material emissions. The study recommends the use of recycled materials, the transportation of materials by sea, and that adopting energy-saving construction technology can lower emissions at the construction phase by 10%. A comparative study in Japan was conducted for the environmental assessment of wood and reinforced-concrete (RC) house construction [45]. They considered energy use and selected air emissions such as CO₂, NO_x, SO₂ and PM₁₀, and used an I/O-based hybrid model that was developed to evaluate emissions. The comparative results showed that CO₂ emissions govern the total emissions at the construction stage over other emission substances considered, with an overwhelming 93% contribution. However, the emission-comparison results at various life-cycle stages revealed different outcomes. The paper highlighted that CO₂ emissions are dominant in the operation stage compared to the construction, maintenance and disposal stages, while other air pollutants such as NO_x, SO₂ and PM are significant at the construction stage for both types of buildings. Of the four considered impact categories, GWP remained the most important impact category, whereas acidification, eutrophication, and human toxicity were less important. Overall, it was found that reinforced-concrete houses have more emissions compared to timber houses, and the authors also concluded that a higher design life can reduce emissions by 14%.

In another study, Raymond Cole evaluated energy and greenhouse emissions due to the on-site construction of wood, steel and concrete structural assemblies [46]. A total of 15 wood types, 12 steel and 12 concrete assemblies were used to form a total 39 assemblies for comparative study and emissions were categorized into the three major categories of transportation, energy use, and supporting processes. The transportation stage was further classified into equipment, labor, and material transportation, whereas supporting processes included formwork and temporary heating for concrete mixing and curing. The results of the study illustrated that concrete assemblies are responsible for the highest emissions, whereas steel assemblies exhibit the lowest emissions. The overwhelming high emissions of concrete assemblies are equally due to contributions from on-site equipment use, equipment/material transportation and worker transportation. Table 2 highlights the major LCA-based emission studies that were conducted on the construction stage of buildings.

4.2. Models to Estimate Emissions at Building-Construction Stage

The accuracy and efficiency of the mathematical models play a pivotal role in conducting a comprehensive emission assessment at the construction stage of a building as it leads to a better outcome [47–49]. These mathematical models can be of different forms based on the type of analysis, scope, and purpose of the study. The lack of consistency and accuracy of these mathematical models can also lead to distorted results. A mathematical model in an LCA study can be either developed based on the requirement or adopted from previously developed models with necessary modifications to match the scope and the system boundary of the study. The development of a detailed mathematical model solely depends on the scope and the objectives of the analysis. The following section reviews the mathematical models that are available for the estimation of emissions at the building-construction stage, embodied emissions from materials, emissions from construction-equipment usage, emissions from transportation and emissions from construction waste.

Mathematical models for emission and energy estimation from construction materials can facilitate input/output (I/O)-, process-, and hybrid-based LCA approaches. The input/output analysis is a top-down methodology that evaluates the effects of different

industry sectors considering the economy as a whole [50,51]. This method is an effective way of estimating emissions when process specific data is not available, especially in the case of obtaining upstream process data of construction materials [52,53]. The process-based analysis is a bottom-up methodology to evaluate environmental emissions considering unit processes of the activities within the system boundary of the product or process. The quality of the results of the process-based approach depends on acquiring high-quality data. The process-based approach is the most widely used and most suitable method to evaluate emissions if quality data are available. The hybrid-based approach is a more comprehensive analysis that uses a combination of the two above approaches. Many previous emission studies on the construction stage of a building have given more significance to embodied energy and emissions from construction materials [12,54,55]. One major reason is the larger quantities of construction materials used provide greater opportunities to reduce emissions [10]. Several studies have opted for I/O-based models to quantify emissions from materials due to the unavailability of upstream process data for a building [6,52,53,56,57]. The focus of most of the I/O models has been to model CO₂ emissions. A typical I/O model to estimate CO₂ emissions from building materials is as follows:

$$\text{Emissions} = [W * E_{in} * (I - A)^{-1}]$$

where W is the CO₂ conversion coefficient, E_{in} is the energy-input vector, I is the unit matrix and A is the I/O table, which is the transaction matrix between industry sectors. W is the converted energy type, which can be determined from Equation (2) in Table 2. Most of the I/O models are either a derivation or a representation of Equation (1). Process-based mathematical models have been the most frequently used models to evaluate embodied emissions from building materials. Several studies used a similar type of process-based algebraic equation to quantify embodied energy and emissions from materials [7,12,46]. The equation estimated the total embodied GHG emissions from construction materials from the quantity of materials and the material-emission factors. According to the study, these material quantities can be obtained from daily delivery reports and bills of quantities (BOQs). However, the use of BOQ data often suffers from approximations. Moreover, care should be taken to avoid double calculation in the case of using actual material quantities from daily delivery reports. Several other studies modified the previous equation by incorporating a waste factor such as in Equation (4) in Table 2 [10,58,59]. This waste factor is a dimensionless factor and can be either developed or adopted from previous studies. Even though it is an approximation, this model overcomes the double calculation of emissions. Treloar et al. used a similar model to measure emissions from recycled materials in an attempt to highlight the reduction in emissions from construction materials [60]. Embodied emissions in the model were represented in terms of the material quantities, wastage rates and emission factors. The model excluded emissions and energy consumption during the material-installation stage. Shukla et al. used another type of process-based model to calculate the embodied energy of an adobe house [61]. They used the volume and density of the material to calculate the weight of the material. Crawford proposed a process-based hybrid model to estimate embodied emissions from construction materials [62]. In his equation, I/O models were used to calculate the emissions for the missing data paths of the material life cycle, and then these values were added to the known process-based result to obtain the total embodied emissions of a basic material (Equation (7) in Table 2). The known process-based emissions were then added to the I/O models to obtain a process-based hybrid model to evaluate the total embodied emissions from materials, as shown in Equation (9) in Table 2. This model is considered one of the best models to estimate the life-cycle emissions of a construction material.

Construction-equipment emissions, which are often categorized as stationary equipment emissions, are a result of the combustion of fuel during the operation of the equipment [63]. As a result of partial combustion, almost all of the equipment generates non-GHG emissions such as CO, NO_x, PM and SO₂ in addition to GHG emissions [64]. Numerous studies have employed various mathematical models to estimate both these GHG and non-GHG emissions from equipment usage. Millstein and Harley [65] used a model to quantify emissions (E_i) from fuel combustion in their study on emissions from construction activities. The model incorporated the fuel consumed (S) in kilograms per day (kg/day) and was multiplied by an emission factor (F_i), which provided the grams of emissions per kg of fuel combusted (g/kg). One drawback of this model is that it used the actual fuel consumption in terms of kilograms, which is not readily available for most construction sites. Often at construction sites, the fuel-consumption quantities are recorded in liters (L); therefore, using a slight modification (Equation (11) in Table 2) by introducing fuel consumption in terms of liters per day (L/day) and the density of the fuel, a straightforward calculation of equipment emissions due to fuel combustion can be provided. Another study on estimating GHG emissions in building construction used a similar approach to estimate GHG emissions from the fuel combustion of construction equipment [7]. According to the study, GHG emissions from fuel combustion included CO₂, CH₄ and N₂O emission, and the GHG-emission factor should be calculated by the summation of all the emission factors according to the formula provided in the following equation. Mao et al., in a comparative study on estimating GHG emissions between prefabrication and conventional construction methods, employed a model to estimate GHG emissions from the resource consumption of construction equipment [10]. According to the model, the total GHG emissions can be calculated in terms of tons of CO₂-eq by knowing the resource or energy utilized (R_r) of the corresponding construction technique. The study further stated that construction equipment usually uses diesel, electricity and water as fuel resources. Sihabuddin and Ariaratnam used a different approach to calculate emissions from construction equipment in their emission study [66]. They argued that emissions from construction equipment are dependent on the machine characteristics rather than the combusted fuel. Consequently, they used a model that determined GHG and non-GHG emissions based on machine characteristics such as power, usage and deterioration. The model is useful to quantify non-GHG emissions from construction equipment.

Transportation emissions are due to fuel combustion and are significant due to both the short- and long-term environmental impacts based on distance of travel and the mode of transportation [41]. One study estimated emissions due to fuel combustion of transportation in terms of the amount of material transported [7]. The model uses the travel distance of materials both by land and sea to evaluate emissions. The equation is useful to measure emissions and impacts from both local and imported construction materials. Mao et al. adopted a similar model in their study to estimate emissions due to the transportation of building materials and prefabricated components [10] (Equation (17) in Table 2), and both of these models considered only the GHG emissions due to transportation. Chen and Zhu [58], in their analysis of environmental impacts on construction phase of a concrete building, used a different type of model to estimate emissions from transportation. The significance of this model is that it employed the vehicle deterioration in its emission model (Equation (18) in Table 2). The equation considered the emission levels of vehicles at the zero-kilometer level and the total emissions were estimated based on deterioration levels, total usages and total distances traveled. However, the assumption of total distance to be equal to twice the one-way distance is not always accurate, as the departure distance can be different from the return distance in practical conditions.

Table 2. LCA mathematical models for construction-emissions estimation.

Equation No.	Type	Model	Variable Definition and Method Explanation	Evaluation Basis	LCA Method	References
(1)	Material	$E_m = (I - A)^{-1} E_{in}$	W is the CO ₂ conversion coefficient, E _{in} is the energy input vector, I is the unit matrix and A is the I/O table, which is the transaction matrix between industry sectors.	Embodied energy	I/O	[6,56,57]
(2)	Material	$W = \sum E_{ts} * \theta_{ts}$	E _{ts} is the energy type t consumed in the industry sector s and θ_{ts} is the conversion coefficient.	Carbon dioxide	I/O	[6]
(3)	Material	$E = \sum Q_i * f_i$	E is the total emissions (kg) from material type i, Q _i is the quantity of material i (kg) and f _i is the emission factor for the material i in (kg of emissions/kg).	Impacts from materials	Process	[13,41]
(4)	Material	$E = (Q_i + \mu) * f_i$	E is the total emissions (kg) from material type i, Q _i is the quantity of material i (kg) and μ is the waste factor and f _i is the emission factor for the material i in (kg of emissions/kg).	Impacts from materials	Process	[3,16,59,67]
(5)	Material	$EE = \sum_{e=1}^E \sum_{m=1}^M [Q_{em} \times W_{em} \times EE_m]$	EE is the embodied energy of the material, Q _{em} is the quantity of material m in the element e, W _{em} is the wastage rate and EE _m is the embodied energy of the material excluding installation effects.	Embodied energy	Process	[60]
(6)	Material	$EE = \sum_{i=1}^n V_i * \rho_i * E_i$	EE is the embodied energy of the material, V _i is the volume of material used in m ³ , ρ_i is the density of the material kg/m ³ and E _i is the embodied-emission factor for material i in kg of CO ₂ -eq/kg	Embodied energy	Process	[61]
(7)	Material	$EI_M = PEI_M + (TEI_n - TEI_M) * \xi_M$	PEI _M is the process-based hybrid emissions of the material, TEI _n is the emissions of the sector n, TEI _M is the emissions representing the basic material M and ξ_n is the total price of the material i.	Energy intensity	Hybrid	[62,68]
(8)	Material	$CE_{mat} = \sum_{i=1}^n m_i * EF_{mat,i}$	CE _{mat} is the carbon emissions from materials, m _i is the weight of the material i in kg, EF _{mat,i} is the emission factor for material in kg CO ₂ -eq/kg	Carbon emissions	Process	[69]
(9)	Material	$EE_t = Q_M * W * EI_M + (TEI_n - TEI_M) * \xi_M$	EE _t is the total embodied emissions from process-based hybrid analysis; Q _M is the quantity of the total materials M and W is the wastage factor of the respective material.	Total environmental impacts	Hybrid	[62,68]
(10)	Equipment	$E_i = S * F_j$	E _i is the GHG emissions from equipment i and S is the fuel consumed in liters and F _j is the emission factor for the fuel j in kg/liter	GHG emissions	Process	[59,70,71]
(11)	Equipment	$E_i = S' * \rho * F_i$	ρ is the density of the material in kg/m ³ , S' is the volume of the fuel consumed in m ³ and F _i is the emission factor in kgCO ₂ -eq/kg	GHG emissions	Process	[59]
(12)	Equipment	$E = \sum \frac{F * f}{1000}$	The amount of fuel j consumed by the construction equipment in liters; f is the greenhouse gas emission factor for fuel j consumed by construction equipment (in kg CO ₂ -eq/liter)	GHG emissions	Process	[67,72]
(13)	Equipment	$E = \sum_{r=1}^r \sum_{v=1}^v \frac{R_r * P_v}{1000}$	Emissions from equipment in kg, R _r is the power of the equipment in kW and P _v is the emission factor for r th equipment in kg of CO ₂ /kW	GHG emissions	Process	[8,59,67]

Table 2. Cont.

Equation No.	Type	Model	Variable Definition and Method Explanation	Evaluation Basis	LCA Method	References
(14)	Equipment	$Emissions_i = EF_i * HRS * HP * LF * 0.01$	Emissions _i is the total emissions of emission substance i in grams, HRS is the hours of use in hours, HP is the power of machine in hp, LF is the load factor is the ratio between operation and maximum rated outputs and 0.01 is the conversion of percent to fraction.	Non-GHG and GHG emissions	Process	[3,16,66,73]
(15)	Equipment	$EE = \sum_{i=1}^3 \sum_{j=1}^m (T_{mac,i} \times EU_{mac,ij}) \times EF_{ej}$	T _{mac,i} is the working time of type i machinery, EU _{mac,ij} is the consumption of type j energy for type i machinery working unit time, and EF _{e,j} is the emission factor for type j energy	GHG emissions	Process	[69]
(16)	Transport	$E_{ii} = \sum \frac{M_j^{ii} * (T_j^l + f_j^{ii} + T_j^s + f_k^{ii})}{1000}$	E _{ii} is the total GHG emissions due to fuel combustion from transport vehicles, M _j ⁱⁱ is the total quantity of material j, T _j ^l and T _j ^s are the total distances of transportation for building materials j by land and sea in km and f _j ⁱⁱ , f _k ⁱⁱ are the GHG emission factor for transportation by land sea in kg CO ₂ -e/(ton km), respectively.	GHG emissions	Process	[72]
(17)	Transport	$E = \sum \sum \frac{M_j * L_j^m + f_k}{1000}$	E is the emissions from transport and M _j is the weight of the material j transported, L _j ^m is the distance traveled in km and f _k is the emission factor in kg/ton-km	GHG emissions	Process	[72]
(18)	Transport	$I_i = (Z_i + r_i * M) \sum d$	“I” is the impact from i th vehicle in kg, Z _i is the zero-level emissions of the i th vehicle in kg/km, r _i is the emission factor of i th vehicle in kg/ton-km, M is the total weight of the vehicle in tons and d is the distance traveled by the vehicle in km	GHG and non-GHG emissions	Process	[41]
(19)	Transport	$CE_{tran} = \sum (m_i \times s_i) \times EF_{tran,i}$	CE _{tran} is the carbon emissions from transportations in kg, m _i is the material weight in tons and s _i is the distance traveled in km. EF _{tran,i} is the emission factor for the transport vehicle in kg/tons-km	GHG emissions	Process	[69]
(20)	Unit Process	$E_u = \sum_{i=1}^n \sum_{j=1}^6 M_i \mu_{ij} GWP_j$	Eu is the GHG emissions in kg CO ₂ -eq, μ _{ij} is the emission factor for the j th GHG emission pollutant and i th emission substance, and M _i is the mass of the emission substance in kg	GHG emissions	Process	[74]

5. Barriers and Knowledge Gaps

Based on this review, the following knowledge-specific observations are highlighted for further discussion and future considerations. The observations and issues identified are summarized based on the review conducted on emissions at the construction stage of a building.

5.1. Lack of Definition for a Generic System Boundary

The lack of a generic and standard system boundary is a major issue that restricts comprehensive emission assessment at the construction stage of a building [41,75]. The controversial opinion of including the embodied emissions of construction materials in the same system boundary is an important issue that needs to be addressed. Most of the recent emission studies on construction have included material emissions in the construction stage, citing their influence on the downstream impacts of material handling and construction techniques [10,48]. For instance, the environmental impacts due to material transportation, curing and handling processes directly affect emissions at the construction stage of a building. Moreover, the material type directly affects the type of technique used for construction [16]. For instance, using a green concrete material such as geo-polymer concrete will require additional machine and technical expertise to maintain workability,

transportation and storage. This will directly affect emissions from equipment usage and transportation, which will then influence the total emissions at the construction stage. Thus, from this point of view, the consideration of material emissions at the construction stage is meaningful. However, the argument for excluding embodied emissions from the building-construction system boundary cannot be completely discarded. High upstream energy consumptions and emissions, including material processing and production, has no direct relation to the construction-related emissions [3,76]. This often overrepresents the construction-stage emissions and the comparisons and interpretations therefore become distorted. Thus, there is a contemporary requirement to standardize a well-defined system boundary that can facilitate comprehensive emission assessment at the building-construction stage. A generic definition will enable uniform emissions comparisons across different construction practices and facilitate meaningful interpretations.

5.2. Difficulties in Data and Information Collection

The unavailability of comprehensive data and information is a typical issue that hampers the quality of any emission assessment [11,41]. Especially in the case of building-construction-emission studies, data collection is even more difficult because of the continuous variations and the uniqueness of the construction works. Therefore, capturing quality data specific to each construction technique or practice is often time consuming and labor intensive. Due to strict timelines and budget constraints, project team members are often unable to allocate additional resources for case-specific data collection, which results in the approximation of emissions and environmental impacts at the construction stage. The commercial sensitivity of data and information is another reason that was observed during the review of building-emission studies that leads to difficulty in data collection [10,13,72]. This also results in data approximation, which results in distorted outputs. Sub-contractors and suppliers are often hesitant to provide project-specific information due to the transparency issues. Moreover, in certain situations the main contractor is also tentative to reveal all the required information for studies due to the worry of receiving criticism or revealing innovations to their construction practices and techniques [13]. Collaborative information-sharing platforms that are facilitated through building-information modeling (BIM) can be identified as an effective methodology to overcome this issue [77]. At present, BIM-enabled collaborative platforms expedite information management at both the organization and project levels. Using existing information (bills of quantities and project timelines) and integrating it with other relevant information (transportation and equipment specific) can facilitate the data-acquisition process and enable the comprehensive building-construction-emission assessment. Future research on collaborative BIM platforms can also focus on improving communication, data integration, and the collaboration and transparency aspects related to capturing construction practices at the organizational level [78]. This can remove all the silos and introduce an integrated system for capturing quality data in order to facilitate the effective emission assessment at the construction stage of a building. Moreover, future research can also focus on integrating machine learning and other smart technologies in order to automate the data-capture process.

5.3. Complex-Modeling Issues and Lack of Decision-Making Aspects

This review of the current modeling tools and software highlights that most of the tools either lack a comprehensive database or involve complex-modeling methods [39,79]. For instance, studies have shown that the emissions from construction equipment are dependent on factors such as age, deterioration, and usage. According to authors' best knowledge, none of the tools can analyze emissions by incorporating these factors. Moreover, the complex modeling in most of the LCA software restricts the capability of a dynamic comparison of different options for reducing emissions during the construction stage. With the limited time availability, it is important to have a simple decision-making tool that has the capability to estimate, compare and optimize emissions at the construction stage of a building. Another issue with most of these tools is the lack of capacity to consider regional

variations. Especially in the case of Australia, the lack of a tool that is able to consider the regional variations is a major issue in the comprehensive assessment of emissions and environmental impacts of building construction. Some studies have made attempts to develop frameworks to conduct in-depth emissions analyses of building construction [41,58]. An in-depth analysis using such methodologies can identify the significant construction activities and equipment with high emissions and eventually highlight environmentally friendly construction strategies and assets. However, contractors are hesitant to invest in such strategies due to the associated additional costs of procurement and implementation. Therefore, decision-making tools should focus on optimizing both the construction cost and environmental impact. This will help contractors to obtain green and sustainable construction methods and selections without significantly compromising the cost aspects. Moreover, such a decision-making tool will also help project contractors to recognize the overall long-term benefits at early design stages and to improve the market value in order to secure indirect financial benefits.

5.4. Complications in Classification and Analysis of Emissions

It was observed that the majority of the building-construction-emission studies have concentrated on estimating GHG emissions, while only a handful of studies have made attempts to quantify non-GHG emissions [10,13]. The omission of non-GHG emissions from these studies is justifiable from a whole-life-cycle perspective of the building due to large quantities of GHG emissions compared to non-GHG emissions at the usage stage [1,80]. However, several studies have highlighted the importance of non-GHG emissions and their corresponding short-term impacts from a contractors' perspective, which cannot be neglected [16,41]. The necessity of analyzing the environmental impacts of non-GHG emissions could be a major concern for the contractors who are keen on maintaining an environmentally friendly construction site. Moreover, the presence of other emissions in smaller quantities such as particulate matter (PM₁₀) and carbon monoxide (CO) can have adverse health impacts [81]. Therefore, accurate guidelines should be developed for selecting the most-important emission substances to improve the comprehensiveness of the emission study.

6. Conclusions, Future Research Focuses and Directions

Despite the short-term and severe environmental impacts of the usage level, environmental impacts at the construction stage of a building are often neglected or approximated. Despite a handful of previous case studies capturing and comparing the environmental impacts at the construction stage and considering all the emission sources or selected sources, a systematic literature review was absent. Therefore, the current study presented a review using a three-step methodology to highlight the current trends and barriers to conducting studies, as well as future research focuses on construction-stage impacts.

Initially, a bibliometric assessment was conducted to identify the current research trends, focuses and author contributions related to the research of environmental impacts at the construction stage of a building. The results indicated that major studies focused on construction materials while a handful of studies focused on environmental impacts at the construction-activity level. The findings also highlighted that enormous research interest in environmental impacts at the construction stage has been observed since 2010. This is mainly due to the increased industry drive towards sustainable construction and environmentally friendly construction-site operations. The bibliometric assessment also represented research collaborations and research evolutions of key research authors of studies that evaluated construction-stage emissions and impacts. The results also indicated that research focuses were mainly concentrated on either material emissions or construction-activity emissions. A focused review of past studies revealed several barriers and impediments related to the comprehensive assessment of environmental impacts at the construction stage of a building. These barriers were mainly categorized into four groups, including the lack of definition of a systematic system boundary, difficulties in data collec-

tion, complex-modeling issues, and complications in classifying emissions. Some of these issues are partially addressed by basic applications in current studies with the introduction of concepts such as building-information modeling (BIM) and the use of collaborative tools and techniques [82,83]. With the introduction of Industry 4.0, the construction industry is rapidly progressing towards digitization [17].

Several basic studies have undertaken both the assessment of environmental impacts of smart-construction techniques and the use of smart technologies to capture environmental impacts at the construction stage of a building [84–88]. However, these systems often lack integration, data security and decision-making options. Therefore, future studies can focus on improving the usability and decision-making options by incorporating machine-learning techniques. Moreover, this study focused only on the environmental impacts at the construction stage of a building. Further studies can focus on comparing developed and developing countries in order to identify the gap in more detail. The findings of this study aim to facilitate passionate researchers who are keen on conducting research on environmental impacts at the construction stage and have intentions to benchmark the life-cycle impacts of buildings.

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References

1. Buyle, M.; Braet, J.; Audenaert, A. Life cycle assessment in the construction sector: A review. *Renew. Sustain. Energy Rev.* **2013**, *26*, 379–388. [[CrossRef](#)]
2. Zhang, X.; Shen, L.; Zhang, L. Life cycle assessment of the air emissions during building construction process: A case study in Hong Kong. *Renew. Sustain. Energy Rev.* **2013**, *17*, 160–169. [[CrossRef](#)]
3. Guggemos, A.A.; Horvath, A. Comparison of environmental effects of steel-and concrete-framed buildings. *J. Infrastruct. Syst.* **2005**, *11*, 93–101. [[CrossRef](#)]
4. Chau, C.K.; Hui, W.K.; Ng, W.Y.; Powell, G. Assessment of CO₂ emissions reduction in high-rise concrete office buildings using different material use options. *Resour. Conserv. Recycl.* **2012**, *61*, 22–34. [[CrossRef](#)]
5. Sartori, I.; Hestnes, A.G. Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy Build.* **2007**, *39*, 249–257. [[CrossRef](#)]
6. Seo, S.; Hwang, Y. Estimation of CO₂ emissions in life cycle of residential buildings. *J. Constr. Eng. Manag.* **2001**, *127*, 414–418. [[CrossRef](#)]
7. Yan, H.; Shen, Q.; Fan, L.C.H.; Wang, Y.; Zhang, L. Greenhouse gas emissions in building construction: A case study of One Peking in Hong Kong. *Build. Environ.* **2010**, *45*, 949–955. [[CrossRef](#)]
8. Hong, J.; Shen, G.Q.; Feng, Y.; Lau, W.S.-t.; Mao, C. Greenhouse gas emissions during the construction phase of a building: A case study in China. *J. Clean. Prod.* **2015**, *103*, 249–259. [[CrossRef](#)]
9. Liu, G.; Chen, R.; Xu, P.; Fu, Y.; Mao, C.; Hong, J. Real-time carbon emission monitoring in prefabricated construction. *Autom. Constr.* **2020**, *110*, 102945. [[CrossRef](#)]
10. Mao, C.; Shen, Q.; Shen, L.; Tang, L. Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: Two case studies of residential projects. *Energy Build.* **2013**, *66*, 165–176. [[CrossRef](#)]
11. Sandanayake, M.; Zhang, G.; Setunge, S.; Thomas, C.M. Environmental Emissions of Construction Equipment Usage in Pile Foundation Construction Process—A Case Study. In *Proceedings of the 19th International Symposium on Advancement of Construction Management and Real Estate*; Shen, L., Ye, K., Mao, C., Eds.; Springer: Berlin/Heidelberg, Germany, 2015; pp. 327–339.
12. Chau, C.K.; Yik, F.W.H.; Hui, W.K.; Liu, H.C.; Yu, H.K. Environmental impacts of building materials and building services components for commercial buildings in Hong Kong. *J. Clean. Prod.* **2007**, *15*, 1840–1851. [[CrossRef](#)]
13. Sandanayake, M.; Zhang, G.; Setunge, S. Environmental emissions at foundation construction stage of buildings—Two case studies. *Build. Environ.* **2016**, *95*, 189–198. [[CrossRef](#)]
14. Sandanayake, M.; Zhang, G.; Setunge, S. A comparative method of air emission impact assessment for building construction activities. *Environ. Impact Assess. Rev.* **2018**, *68*, 1–9. [[CrossRef](#)]
15. Bribián, I.Z.; Uson, A.A.; Scarpellini, S. Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. *Build. Environ.* **2009**, *44*, 2510–2520. [[CrossRef](#)]
16. Sandanayake, M.; Zhang, G.; Setunge, S.; Luo, W.; Li, C.Q. Estimation and comparison of environmental emissions and impacts at foundation and structure construction stages of a building—A case study. *J. Clean. Prod.* **2017**, *151*, 319–329. [[CrossRef](#)]
17. Oesterreich, T.D.; Teuteberg, F. Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. *Comput. Ind.* **2016**, *83*, 121–139. [[CrossRef](#)]

18. Liu, J.W.; Huang, L.C. Detecting and Visualizing Emerging Trends and Transient Patterns in Fuel Cell Scientific Literature. In Proceedings of the International Conference on Wireless Communications, Networking and Mobile Computing, Dalian, China, 19–21 September 2008.
19. Aria, M.; Cuccurullo, C. *Bibliometrix: An R-tool for comprehensive science mapping analysis*. *J. Informetr.* **2017**, *11*, 959–975. [[CrossRef](#)]
20. Van Eck, N.J.; Waltman, L. *Visualizing Bibliometric Networks in Measuring Scholarly Impact*; Springer: Berlin/Heidelberg, Germany, 2014; pp. 285–320.
21. Synnestvedt, M.B.; Chen, C.; Holmes, J.H. *CiteSpace II: Visualization and Knowledge Discovery in Bibliographic Databases in AMIA Annual Symposium Proceedings*; American Medical Informatics Association: Bethesda, MD, USA, 2005; pp. 724–728.
22. Kyoto Protocol UNFCCC Website. Available online: http://unfccc.int/kyoto_protocol/items/2830.php (accessed on 28 December 2021).
23. Solís-Guzmán, J.; Marrero, M.; Montes-Delgado, M.V.; Ramírez-De-Arellano, A. A Spanish model for quantification and management of construction waste. *Waste Manag.* **2009**, *29*, 2542–2548. [[CrossRef](#)]
24. Martínez-Rocamora, A.; Solís-Guzmán, J.; Marrero, M. LCA databases focused on construction materials: A review. *Renew. Sustain. Energy Rev.* **2016**, *58*, 565–573. [[CrossRef](#)]
25. Solís-Guzmán, J.; Marrero, M. Ramírez-de-Arellano, A. Methodology for determining the ecological footprint of the construction of residential buildings in Andalusia (Spain). *Ecol. Indic.* **2013**, *25*, 239–249. [[CrossRef](#)]
26. González-Vallejo, P.; Marrero, M.; Solís-Guzmán, J. The ecological footprint of dwelling construction in Spain. *Ecol. Indic.* **2015**, *52*, 75–84. [[CrossRef](#)]
27. Alba-Rodríguez, M.D.; Martínez-Rocamora, A.; González-Vallejo, P.; Ferreira-Sánchez, A.; Marrero, M. Building rehabilitation versus demolition and new construction: Economic and environmental assessment. *Environ. Impact Assess. Rev.* **2017**, *66*, 115–126. [[CrossRef](#)]
28. Tan, Y.; Luo, T.; Xue, X.; Shen, G.Q.; Zhang, G.; Hou, L. An empirical study of green retrofit technologies and policies for aged residential buildings in Hong Kong. *J. Build. Eng.* **2021**, *39*, 102271. [[CrossRef](#)]
29. Li, D.; Huang, G.; Zhang, G.; Wang, J. Driving factors of total carbon emissions from the construction industry in Jiangsu Province, China. *J. Clean. Prod.* **2020**, *276*, 1–14. [[CrossRef](#)]
30. Tushar, Q.; Bhuiyan, M.; Sandanayake, M.; Zhang, G. Optimizing the energy consumption in a residential building at different climate zones: Towards sustainable decision making. *J. Clean. Prod.* **2019**, *233*, 634–649. [[CrossRef](#)]
31. Sandanayake, M.; Zhang, G.; Setunge, S. Impediments affecting a comprehensive emission assessment at the construction stage of a building. *Int. J. Constr. Manag.* **2019**, 1–11. [[CrossRef](#)]
32. Sandanayake, M.; Zhang, G.; Setunge, S. Estimation of environmental emissions and impacts of building construction—A decision making tool for contractors. *J. Build. Eng.* **2019**, *21*, 173–185. [[CrossRef](#)]
33. Illankoon, I.M.C.S.; Tam, V.W.; Le, K.N.; Shen, L. Key credit criteria among international green building rating tools. *J. Clean. Prod.* **2017**, *164*, 209–220. [[CrossRef](#)]
34. Senaratne, S.; Lambrousis, G.; Mirza, O.; Tam, V.W.Y.; Kang, W.-H. Recycled Concrete in Structural Applications for Sustainable Construction Practices in Australia. *Procedia Eng.* **2017**, *180*, 751–758. [[CrossRef](#)]
35. Tam, V.W.; Butera, A.; Le, K.N.; Li, W. Utilising CO₂ technologies for recycled aggregate concrete: A critical review. *Constr. Build. Mater.* **2020**, *250*, 118903. [[CrossRef](#)]
36. Wang, J.; Li, Z.; Tam, V.W. Identifying best design strategies for construction waste minimization. *J. Clean. Prod.* **2015**, *92*, 237–247. [[CrossRef](#)]
37. Tam, V.W.Y.; Le, K.N.; Tran, C.N.N.; Illankoon, I.M.C.S. A review on international ecological legislation on energy consumption: Greenhouse gas emission management. *Int. J. Constr. Manag.* **2021**, *21*, 631–647. [[CrossRef](#)]
38. Xing, W.; Tam, V.W.Y.; Le, K.N.; Hao, J.L.; Wang, J. Life cycle assessment of recycled aggregate concrete on its environmental impacts: A critical review. *Constr. Build. Mater.* **2022**, *317*, 125950. [[CrossRef](#)]
39. Ding, Z.; Zhu, M.; Tam, V.W.Y.; Yi, G.; Tran, C.N.N. A system dynamics-based environmental benefit assessment model of construction waste reduction management at the design and construction stages. *J. Clean. Prod.* **2018**, *176*, 676–692. [[CrossRef](#)]
40. Sandanayake, M.; Zhang, G.; Setunge, S. Toolkit to capture environmental emissions in construction phase of buildings in the Australian context. In Proceedings of the 31st Annual ARCOM Conference, Association of Researchers in Construction Management (ARCOM), Lincoln, UK, 7–9 September 2015; pp. 247–256.
41. Sandanayake, M.; Zhang, G.; Setunge, S.; Li, C.-Q.; Fang, J. Models and method for estimation and comparison of direct emissions in building construction in Australia and a case study. *Energy Build.* **2016**, *126*, 128–138. [[CrossRef](#)]
42. Sandanayake, M.; Yang, W.; Chhibba, N.; Vrcelj, Z. Residential building defects investigation and mitigation—A comparative review in Victoria, Australia, for understanding the way forward. *Eng. Constr. Archit. Manag.* **2021**. *ahead of print*. [[CrossRef](#)]
43. Suzuki, M.; Oka, T. Estimation of life cycle energy consumption and CO₂ emission of office buildings in Japan. *Energy Build.* **1998**, *28*, 33–41. [[CrossRef](#)]
44. Suzuki, M.; Oka, T.; Okada, K. The estimation of energy consumption and CO₂ emission due to housing construction in Japan. *Energy Build.* **1995**, *22*, 165–169. [[CrossRef](#)]
45. Gerilla, G.P.; Teknomo, K.; Hokao, K. An environmental assessment of wood and steel reinforced concrete housing construction. *Build. Environ.* **2007**, *42*, 2778–2784. [[CrossRef](#)]

46. Cole, R.J. Energy and greenhouse gas emissions associated with the construction of alternative structural systems. *Build. Environ.* **1998**, *34*, 335–348. [[CrossRef](#)]
47. Abanda, F.H.; Tah, J.H.M.; Cheung, F.K.T. Mathematical modelling of embodied energy, greenhouse gases, waste, time–cost parameters of building projects: A review. *Build. Environ.* **2013**, *59*, 23–37. [[CrossRef](#)]
48. Li, X.; Zhu, Y.; Zhang, Z. An LCA-based environmental impact assessment model for construction processes. *Build. Environ.* **2010**, *45*, 766–775. [[CrossRef](#)]
49. Ortiz, O.; Castells, F.; Sonnemann, G. Sustainability in the construction industry: A review of recent developments based on LCA. *Constr. Build. Mater.* **2009**, *23*, 28–39. [[CrossRef](#)]
50. Hawdon, D.; Pearson, P. Input-output simulations of energy, environment, economy interactions in the UK. *Energy Econ.* **1995**, *17*, 73–86. [[CrossRef](#)]
51. Su, B.; Huang, H.C.; Ang, B.W.; Zhou, P. Input–output analysis of CO₂ emissions embodied in trade: The effects of sector aggregation. *Energy Econ.* **2010**, *32*, 166–175. [[CrossRef](#)]
52. Acquaye, A.A.; Duffy, A.P. Input-output analysis of Irish construction sector greenhouse gas emissions. *Build. Environ.* **2010**, *45*, 784–791. [[CrossRef](#)]
53. Chang, Y.; Ries, R.J.; Wang, Y. The embodied energy and environmental emissions of construction projects in China: An economic input–output LCA model. *Energy Policy* **2010**, *38*, 6597–6603. [[CrossRef](#)]
54. Hammond, G.P.; Jones, C.I. Embodied energy and carbon in construction materials. *Proc. Inst. Civ. Eng.-Energy* **2008**, *161*, 87–98. [[CrossRef](#)]
55. Huberman, N.; Pearlmutter, D. A life-cycle energy analysis of building materials in the Negev desert. *Energy Build.* **2008**, *40*, 837–848. [[CrossRef](#)]
56. Treloar, G.J. Extracting embodied energy paths from input–output tables: Towards an input–output-based hybrid energy analysis method. *Econ. Syst. Res.* **1997**, *9*, 375–391. [[CrossRef](#)]
57. Crawford, R.H.; Treloar, G.J. Proceedings of the Validation of the Use of Australian Input Output Data for Building Embodied Energy Simulation. In Proceedings of the Eighth International IBPSA Conference, Eindhoven, The Netherlands, 11–14 August 2003.
58. Chen, Y.; Zhu, Y. *Analysis of Environmental Impacts in the Construction Phase of Concrete Frame Buildings*; Department of Construction Management, Tsinghua University: Beijing, China, 2008.
59. Guggemos, A.A. Environmental impacts of on-site construction processes: Focus on structural frames. Ph.D. Thesis, University of California, Berkeley, CA, USA, 2003.
60. Treloar, G.J.; Gupta, H.; Love, P.E.; Nguyen, B. An analysis of factors influencing waste minimisation and use of recycled materials for the construction of residential buildings. *Manag. Environ. Qual. Int. J.* **2003**, *14*, 134–145. [[CrossRef](#)]
61. Shukla, A.; Tiwari, G.; Sodha, M. Embodied energy analysis of adobe house. *Renew. Energy* **2009**, *34*, 755–761. [[CrossRef](#)]
62. Crawford, R.H. Validation of a hybrid life-cycle inventory analysis method. *J. Environ. Manag.* **2008**, *88*, 496–506. [[CrossRef](#)] [[PubMed](#)]
63. Frey, H.; Rasdorf, W.; Lewis, P. Comprehensive Field Study of Fuel Use and Emissions of Nonroad Diesel Construction Equipment. *Transp. Res. Rec. J. Transp. Res. Board* **2010**, *2158*, 69–76. [[CrossRef](#)]
64. USEPA; Environmental Protection Agency; Air and Radiation Office USA; Office of Transportation and Air Quality. Crankcase Emission Factors for Non-Road Engine Modeling-Compression-Ignition. 2010. Available online: <https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockkey=P100UXEN.txt> (accessed on 21 November 2021).
65. Millstein, D.E.; Harley, R.A. Revised estimates of construction activity and emissions: Effects on ozone and elemental carbon concentrations in southern California. *Atmos. Environ.* **2009**, *43*, 6328–6335. [[CrossRef](#)]
66. Sihabuddin, S.S.; Ariaratnam, S.T. Methodology for estimating emissions in underground utility construction operations. *J. Eng. Des. Technol.* **2009**, *7*, 37–64. [[CrossRef](#)]
67. Ji, Y.; Li, K.; Liu, G.; Shrestha, A.; Jing, J. Comparing greenhouse gas emissions of precast in-situ and conventional construction methods. *J. Clean. Prod.* **2017**, *173*, 124–134. [[CrossRef](#)]
68. Crawford, R.H.; Czerniakowski, I.; Fuller, R.J. A comprehensive framework for assessing the life-cycle energy of building construction assemblies. *Archit. Sci. Rev.* **2010**, *53*, 288–296. [[CrossRef](#)]
69. Zhang, X.; Wang, F. Assessment of embodied carbon emissions for building construction in China: Comparative case studies using alternative methods. *Energy Build.* **2016**, *130*, 330–340. [[CrossRef](#)]
70. Peng, C. Calculation of a building’s life cycle carbon emissions based on Ecotect and building information modeling. *J. Clean. Prod.* **2016**, *112*, 453–465. [[CrossRef](#)]
71. Sim, J.; Sim, J.; Park, C. The air emission assessment of a South Korean apartment building’s life cycle, along with environmental impact. *Build. Environ.* **2016**, *95*, 104–115. [[CrossRef](#)]
72. Sandanayake, M.S. Models and Toolkit to Estimate and Analyse the Emissions and Environmental Impacts of Building Construction. Ph.D. Thesis, RMIT University, Melbourne, Australia, 16 December 2016.
73. Zhang, G.; Sandanayake, M.; Setunge, S.; Li, C.; Fang, J. Selection of emission factor standards for estimating emissions from diesel construction equipment in building construction in the Australian context. *J. Environ. Manag.* **2017**, *187*, 527–536. [[CrossRef](#)] [[PubMed](#)]

74. Li, L.; Chen, K. Quantitative assessment of carbon dioxide emissions in construction projects: A case study in Shenzhen. *J. Clean. Prod.* **2017**, *141*, 394–408. [[CrossRef](#)]
75. Guggemos, A.A.; Horvath, A. Decision-support tool for assessing the environmental effects of constructing commercial buildings. *J. Archit. Eng.* **2006**, *12*, 187–195. [[CrossRef](#)]
76. Treloar, G.J.; Love, P.; Faniran, O.; Iyer-Raniga, U. A hybrid life cycle assessment method for construction. *Constr. Manag. Econ.* **2000**, *18*, 5–9. [[CrossRef](#)]
77. Chi, H.-L.; Kang, S.-C.; Wang, X. Research trends and opportunities of augmented reality applications in architecture, engineering, and construction. *Autom. Constr.* **2013**, *33*, 116–122. [[CrossRef](#)]
78. Rowlinson, S.; Rowlinson, S. Building information modelling, integrated project delivery and all that. *Constr. Innov.* **2017**, *17*, 45–49. [[CrossRef](#)]
79. Sandanayake, M.; Gunasekara, C.; Law, D.; Zhang, G.; Setunge, S.; Wanijuru, D. Sustainable criterion selection framework for green building materials – An optimisation based study of fly-ash Geopolymer concrete. *Sustain. Mater. Technol.* **2020**, *25*, e00178. [[CrossRef](#)]
80. Eldridge, C. Lcaid™ Software: Measuring Environmental Performance of Buildings. In Proceedings of the 9th International Conference on Durability of Building Materials and Components, Brisbane, Australia, 17–20 March 2002.
81. Luo, W.; Sandanayake, M.; Zhang, G. Direct and indirect carbon emissions in foundation construction—Two case studies of driven precast and cast-in-situ piles. *J. Clean. Prod.* **2019**, *211*, 1517–1526. [[CrossRef](#)]
82. Hao, J.L.; Cheng, B.; Lu, W.; Xu, J.; Wang, J.; Bu, W.; Guo, Z.J. Carbon emission reduction in prefabrication construction during materialization stage: A BIM-based life-cycle assessment approach. *Sci. Total Environ.* **2020**, 723. [[CrossRef](#)]
83. Cheng, B.; Li, J.; Tam, V.W.Y.; Yang, M.; Chen, D. A BIM-LCA approach for estimating the greenhouse gas emissions of large-scale public buildings: A case study. *Sustainability* **2020**, *12*, 685. [[CrossRef](#)]
84. Sandanayake, M.; Li, C.; Zhang, G.; Setunge, S. Environmental emissions in building construction—two case studies of conventional and pre-fabricated construction methods in Australia. In Proceedings of the Fourth International Conference on Sustainable Construction Materials and Technologies, Las Vegas, NV, USA, 7–11 August 2016.
85. Zhang, G.; Sandanayake, M. BIM and optimisation techniques to improve sustainability in green certification submission of construction projects. In Proceedings of the 7th World Construction Symposium, Colombo, Sri Lanka, 29 June–1 July 2018.
86. Alhumayani, H.; Gomaa, M.; Soebarto, V.; Jabi, W.J. Environmental assessment of large-scale 3D printing in construction: A comparative study between cob and concrete. *J. Clean. Prod.* **2020**, *270*, 122463. [[CrossRef](#)]
87. Yao, Y.; Hu, M.; Di Maio, F.; Cucurachi, S.J. Life cycle assessment of 3D printing geo-polymer concrete: An ex-ante study. *J. Ind. Ecol.* **2020**, *24*, 116–127. [[CrossRef](#)]
88. Han, Y.; Yang, Z.; Ding, T.; Xiao, J.J. Environmental and economic assessment on 3D printed buildings with recycled concrete. *J. Clean. Prod.* **2021**, *278*, 123884. [[CrossRef](#)]