CARBON EMISSIONS OPTIMISATION IN PREFABRICATION CONSTRUCTION: A REVIEW OF CURRENT DESIGN INTEGRATED APPROACHES

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The construction industry is the overarching energy consumer and contributes to significant carbon emissions globally. Prefabricated construction has been adopted to alleviate the industry's pressure on the environment. Thus, the number of scientific publications about the realisation of a sustainable built environment through prefabricated design has followed an exponential trend since 2015. However, it is still not a common practice to implement sustainability during the design stage. Therefore, this study critically reviewed relevant literature on current design tools to evaluate the remaining challenges. The general area of investigation in this research was embodied carbon emissions optimisation in the design phase. Its findings showed that, although assessing sustainability in the design stage had become a hotpot recently, current design assistant tools were ineffective for the designers to generate a sustainable design. Their limited reliability, creativity, and user-unfriendly process were claimed as barriers. In the end, this study proposed a framework for implementing carbon emissions' optimisation in the design phase and concludes by setting out the direction for further work in this area.

Keywords: carbon emissions; prefabrication; design integrated optimisation

INTRODUCTION

Approximately 48% of energy is consumed by buildings during their construction and operation phases (Dixit 2019), out of which 29% can be potentially reduced (Liu *et al.,* 2019). As a response to it, prefabrication is increasingly being adopted worldwide (Hao *et al.,* 2020) as it has the potential to reduce 20% construction Carbon Emissions (CE) compared to conventional methods (Gao *et al.,* 2018). Although the design process generates nearly no CE, decisions in this stage determine key impacts on the projects' environmental performance (Li *et al.,* 2020). Generally, the earlier decisions are made, the more significant influence they may have (Basbagill *et al.,* 2013).

As a result, a number of studies (Basbagill *et al.,* 2014; Roberts *et al.,* 2020) have put considerable effort into integrating environmental analysis in the early design stage (Jusselme *et al.,* 2020). However, a contradiction has been widely found that a large amount of necessary data for the environmental assessment is typically not available in the design stage (Marsh 2016). Additionally, little attention has been paid to prefabrication, the construction type with the unique characteristic of assembling building elements. Merely adopting a material-based approach in prefabrication

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analysis can overestimate the benefit of efficient material utilisation but ignore the side-effect of lower transport and hanging efficiency. Since there is a logarithmic trade-off between the environmental impact and cost (Hester *et al.,* 2018), actions on the novel field produce more benefit than mature ones. Compared with reducing energy consumption during the production or operation procedure, optimizing CE in the construction process (e.g., transport and assembly) is an untapped topic. A critical review that considers this part helps to highlight the neglected hotpot for sustainability studies. Moreover, it offers the industry and the government a new direction to invest in sustainable construction.

This paper aims to determine the current research gaps in the CE optimisation of prefabrication through a review of academic literature. It culminates with a proposed framework for design integrated CE optimisation. As a preliminary stage of the study focusing on reducing CE of prefabricated construction through parametric design, its result works as background knowledge to support further research design. At this stage in the research, the prefabrication CE optimisation will be generally defined as reducing Embodied Carbon Emissions (ECE) in the production, transportation, and assembly procedure of prefabricated buildings.

LITERATURE REVIEW

Construction Carbon Emissions Analysis

Generally, there are three common approaches to evaluate CE, i.e., Life Cycle Assessment (LCA), economic integration analysis, and direct measurement. The categories of this part were, however, sometimes confused with the CE calculation method (Zhao *et al.,* 2018) or LCA method (Lim *et al.,* 2016). Therefore, terms with the minor cross citation were adopted in Table 1 for their classification.

Table 1: Classification of construction carbon emissions analysis approach

Approach		Method	Application	Input Data
LCA	Process-based LCA	CE factor	Specific Operation	Construction quantity
	Input-output LCA	Mass balance	Material Level	Material Consumption
	Hybrid LCA	Mass balance	Specific Operation	Material Consumption
Economic Analysis		Mass balance	Economies and Industry	Material Consumption
Direct Measurement		Measurement	All	None

LCA is the approach that evaluates the environmental impacts through the project's life cycle (ISO 2006). It can be further divided into three sub-approaches: 1) process-based LCA, 2) input-output LCA, and 3) hybrid LCA (Liu *et al.,* 2019). The process based LCA is appropriate for evaluating CE of specific construction methods as it directly evaluates CE attributable to construction items (e.g., equipment, labour, and material) (Lim *et al.,* 2016). Fang *et al.,* (2018) employed an approach to calculate the CE distribution among construction operations and equipment. Liu *et al.,* (2020) established a construction CE monitoring system based on real-time process based LCA. In contrast, the input-output LCA is used on a broad scale, such as exploring the CE driving factors in the construction sector (Cui *et al.,* 2019). It is also adopted when considering the material as the primary contributor to calculate CE based on the bill of quantities (Cang *et al.,* 2020; Lu *et al.,* 2019). Specific cases compared CE of different materials (Zhang *et al.,* 2020) and CE reduction through material selection and quantity optimisation (Basbagill *et al.,* 2014; Basic *et al.,* 2019; Marsh 2016). As a combination of these two approaches, hybrid LCA can be considered transforming the detailed CE list of process-based LCA to a bill of quantities used in input-output LCA (Liu *et al.,* 2019).

The strong relationship of a nation's energy to its Gross Domestic Product (GDP) is the basis of the economic analysis approach (Dixit *et al.,* 2013). Compared to LCA, it is employed at a macro level to evaluate the sustainability of economies (Han *et al.,* 2020) or industry (Chen *et al.,* 2019). These aimed to address suggestions for policy or regulation, which is different from this research. As for the direct measurement, Liu *et al.,* (2020) reported its application in construction CE monitoring. Technologies they mentioned (e.g., GIS, video camera) are mainly adopted for visualization rather than calculation or analysis. However, Christen *et al.,* (2011) put forward the thought to employ direct eddy-covariance measurements in urban-scale CE calculation. Their model, promising at the scale between 100m (size of the construction site) - 10km, pointed to the potential for construction applications.

Design Integrated Optimisation

Optimising CE in the design stage is to evaluate the sustainability of design alternatives and guide designs to less CE. Research on the open-source UK (Ekundayo *et al.,* 2019) and wider-rage (De Wolf *et al.,* 2017) tools pointed out the lack of precise, up to date, open-source, and user-friendly tools. A vital issue to this challenge is the insufficient information interaction between stages (Jusselme *et al.,* 2020), especially at two ends of the design integrated optimisation, i.e., the process of design data input and assessment result output.

At the former end, dealing with uncertain data is inevitable when estimating CE with early design files because of wide-spread uncertainties in the design stage (Marsh 2016). Generally, previous studies solved the issue through data refining or model simplification. The data refining refers to using information from the later phase to gain a relatively accurate calculation of CE post design (Hao *et al.,* 2020; Li *et al.,* 2016; Lin *et al.,* 2019), and adopting assumed or empirical values to replace the uncertain data (Dixit 2019). Obviously, it is hysteretic or inaccurate in these scenarios. Therefore, more studies selected the other choice, i.e., simplifying and adjusting the model to accommodate data quality. Kanafani *et al.,* (2019) classified model simplification methods into the horizontal approach (i.e., reducing the number of parameters in analysis) and the vertical approach (i.e., reducing data quality and allowing generic data). As an example of the horizontal approach, Victoria and Perera (2018) suggested to design following the carbon intensity and focused on the carbon hotpot (elements contribute to more than 80% of the total CE). Rodrigues *et al.,* (2018) strengthened this approach by predicting a robust environmental performance with less than ten design attributes. Although the horizontal approach claims to be effective and efficient, its application was less observed than the vertical approach as the latter evaluates more design alternatives and produces more comprehensive results (e.g., 14630112 alternatives were evaluated in the research of Shadram and Mukkavaara, (2018)). On the contrary, the vertical approach accepted the uncertainty and formed the alternative space by distributing uncertain design parameters. It generates results by exploring the optimized parameter sets. For instance, Hester *et al.,* (2018) established a design space by distributing parameters like building geometry, occupant behaviour, and material selection. Their design guidance, an optimised scale of crucial attributes, was extracted by quasi-optimum solutions (i.e., alternatives possessed 75% of the maximum potential) exploration. A similar idea was adopted but not limited to the research of Basbagill *et al.,* (2013) and Feng, Chen and Lu (2019).

At the other end, assessment results are provided in four approaches (Roberts *et al.,* 2020): 1) cooperation of BIM and LCA software (Basbagill *et al.,* 2014); 2) BIM integrated plug-in tool (Basic *et al.,* 2019); 3) calculation based on bill of quantity (Cang *et al.,* 2020); and 4) parametric approach (Chen *et al.,* 2018). When employing approaches 1 and 2, architects can evaluate sustainability and aesthetics requirements simultaneously (Hollberg 2016). Specifically, Shadram and Mukkavaara (2018) transferred the design data from BIM to numeric parameters and re-instantiated them in Revit after the mathematic optimisation to visualize results. Basic *et al.,* (2019)'s method realized a real-time CE calculation within the design software. A novel expression was reported by Basbagill, Flager and Lepech (2014), who represented the probability distribution of remaining alternatives after each decision was made. It directs the decision to considering both design flexibility and sustainability. In contrast, although weak in visualisation, approaches 3 and 4 are software-independent and conveniently implemented. For instance, Lu *et al.,* (2019) calculated CE in Excel and no software was specifically noted in the study of Chen *et al.,* (2018).

Adjustment for Prefabrication Construction

Prefabrication construction is an approach to assemble off-site-produced elements to form the final project (Li *et al.,* 2014). Compared with the conventional method, a prefabricated element (the physical entity with specific geometric size) is manipulated rather than the material. Obvious distinctions exist in the unit element and research boundary when applying CE analysis on prefabrication. A primary approach to consider these differences is counting the material reduction in manufacture. Abey and Anand (2019) differed material-level CE of conventional and prefabrication through adopting various CE factors. Hao *et al.,* (2020) reported a 15% material CE reduction due to less waste.

However, this approach ignored the concomitant weakness in construction efficiency. As a more realistic approach, Cang *et al.,* (2020) replaced the material with the prefabricated element as the evaluation unit. Although no significant variance was observed in material CE (91.80 % compared with the conventional approach), it provides the possibility in detailed construction analysis where potential gaps exist. Comparing the result of the element-based approach (Gao *et al.,* 2018) and material-based approach (Hao *et al.,* 2020), they have a similar percentage of the material contribution (88% and 90%), but a significant difference in transport (10% and 1 %). The variance was also observed in the comparison between life cycle accumulative CE, where a more significant increase in the construction appeared in element-based analysis (Liu *et al.,* 2020) than the material approach (Hao *et al.,* 2020). Besides providing precise details, the element approach was also recommended by Lützkendorf, (2019) as a simplified method for quantity determination and is advantageous in the parallel determination of design performance. It, therefore, has great potential in prefabrication optimisation.

METHOD

As a preliminary stage of sustainable construction research, this study conducted a critical literature review to evaluate CE optimization application in prefabrication, especially in the design stage. Compared to systematic review (Roberts *et al.,* 2020) or comprehensive review (Evins 2013), this approach emphasises on the conceptual contribution of previous research and provides the starting point for further evaluation (Grant and Booth 2009). Web of Science was selected as the main database since it is a comprehensive database. An exploratory approach was adopted with keywords selection. CE, design optimisation, and prefabrication were used as the original keywords. Sub-keywords for each one included “Carbon Footprint” “Green House Gas”, “LCA”, and “Embodied Energy” for “CE”, “Design Integrated”, “Early Design Stage”, “Parametric Approach” for “Design Optimisation”, and “Prefabricated Building”, “Prefabricated Construction”, and “Building Element” for “Prefabrication”. They were developed after a thorough review of phased paper iteratively. Table 2 shows contents of the most relevant literature concerning design stage CE reduction.

Table 2: Content of relevant literature

Author	CE Approach	Design Approach	Design parameter	Scale
Basic *et al.,* (2019)	Input-output LCA	BIM plug-in	Geometry, Material, HVAC	Material ECE + Operational CE (OCE)
Feng, Chen and Lu (2019)	Process-based LCA	Parametric Approach	Element size, Construction plan	Construction ECE
Hester *et al.,* (2018)	Input-output LCA	Parametric Approach	Geometry, Behaviour, Material, Thickness	Material ECE + OCE
Shadram and Mukkavaara (2018)	Input-output LCA	BIM software cooperation	Material, Thickness	Material ECE + OCE
Marsh (2016)	Input-output LCA	Parametric Approach	Mid variable	Material ECE + OCE
Hollberg (2016)	Input-output LCA	BIM plug-in	Geometry, Material, Thickness	Material ECE + OCE
Basbagill, Flager and Lepech (2014)	Input-output LCA	BIM software cooperation	Geometry, Material, Thickness	Material ECE + OCE

ANALYSIS AND DISCUSSION

Most research and policy initiatives are inclined to reduce OCE (Fernandez-Sanchez and Rodriguez-Lopez 2012), because 80% of energy is currently consumed during the operational phase (Lim *et al.,* 2016). Consequently, the embodied impact of buildings has been ignored for a long while (Pomponi and Moncaster 2016). This unbalanced focus leads to the result that the share of ECE is to exceed 60% in the future (Roberts *et al.,* 2020). In fact, ECE and OCE are related logarithmically in sustainable designs (Shadram and Mukkavaara 2018), therefore deserve equal consideration. But ECE itself suffers an inconsistent research interest as well. Only 20-40% stages, often production stages, were included in current LCA as shown in the Table 2. (De Wolf *et al.,* 2017). Although they are believed to contribute the most ECE by materials, their reduction potential is limited. The maximum impact reduction of the framework and exterior walls is 4.50% and 0.97%, through material selection, respectively (Basbagill *et al.,* 2013). In contrast, that of the construction phase is 22% (Feng *et al.,* 2019), which indicates a great significance to consider all stages comprehensively.

Regarding design integrated CE optimisation, despite achievements in the improvement of sustainability, the implementation of environmental assessments remains a challenge (Azzouz *et al.,* 2017). There has been a wide-spread misperception of sustainability analysis (Alsaadani and Bleil De Souza 2018), based on which estimation is understood more as design validation than a source of creativity. Therefore, results are usually in the form of a separate statistic table with final CE values, which is hard to understand and interpret by the architects (Jusselme *et al.,* 2020). Although the BIM integrated parametric approach (Basic *et al.,* 2019) realizing a real-time analysis, their parameter selection remains at a preliminary stage, represented by terms like orientation, dimensions, window area, material, and HVAC system as shown in Table 2. Design at this stage is still far from a complement building and is possibly misled in the opposite direction during further design. The error of some results (Cavalliere *et al.,* 2019) is considered unacceptable in the end. Basbagill, Flager and Lepech (2014)'s framework is the only tool that supports sequential decision making, giving an example of guiding the designer to a sustainable preference. Nevertheless, the appropriate expression of decision support, considering the requirement of both analysis and design, deserves further exploration.

Things are even more challenging when it comes to prefabrication because it demands professional and detailed management during both the manufacture and design stage. As lacking the knowledge of sustainability (De Wolf *et al.,* 2017) and construction (Jaillon and Poon 2014), architects consider the design and optimization from an abstract perspective. As mentioned before, the concept of prefabricated element supports not only detailed prefabrication design but also process-based LCA. However, the term "element" seldom refers to the prefabricated products (Cang *et al.,* 2020) but building components defined by function (Basic *et al.,* 2019; Ham and Golparvar-Fard 2015). This definition ignores the difference in manufacture and construction. Sebaibi and Boutouil's (2020) research shows that even adopting emission data of conventional material in manufacture could cause significant variance due to unique prefabrication operations (e.g., steam curing). However, specific and reliable information is hard to obtain (De Wolf *et al.,* 2017). More specifically, the emission coefficient of either materials or components employed in approaches except for direct measurement is not accurate all the time for various index values (Zhao *et al.,* 2018). The uncertainty of this part can lead to serious inaccuracy of the final result as that of De Wolf, Pomponi and Moncaster, (2017). Apart from a standardized database, the need for a consistent methodology to obtain precise quantities is also put forward by Moncaster and Symons (2013). Liu *et al.,* (2020) provided a novel framework of real-time quantity measurement, which was distinct from relying on the bill of Construction Quantity (CQ) (Jafary Nasab *et al.,* 2020; Li *et al.,* 2016; Lu *et al.,* 2019). However, it was only tested on a single element and cannot be accessed in the design stage. Fortunately, construction simulation, especially Discrete Event Simulation (DES), proved high accuracy in pre-construction quantity analysis (Feng *et al.,* 2019; Vidalakis *et al.,* 2013). Therefore, a combination of these two approaches is considered a promising solution.

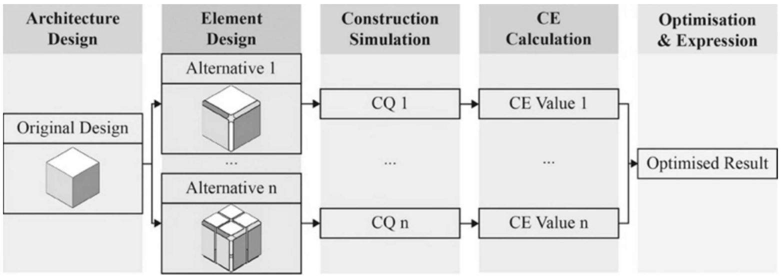

Fig 1: Flowchart of the proposed framework

These findings highlight the direction of the ongoing study on carbon emissions optimisation in prefabrication construction. A proposed approach is formed based on the hypothesis that schematic design rather than concept design contributes the most to the ECE of prefabrication. As shown in Fig 1, it assumes the geometric model as the input file. Design alternatives concerning different element design are automatically generated by distributing key parameters to a given range. The model will generate CQ for every single alternative by DES. After calculating CE with process based LCA, an optimising algorithm will be employed to generate the final result. The proposed output will be a set of key parameters (i.e., size of structure elements). These parameters can be adopted in the construction design process to determine the division of elements, the selection of construction equipment, etc.

CONCLUSIONS

This paper critically reviewed the academic literature on sustainable prefabrication construction optimisation with a design integrated approach. The reviewed articles focused on construction CE analysis, design integrated sustainability optimisation, and prefabrication application. It was found that previous research provided abundant CE analysis and calculation approaches. Although the uncertainty in the design data led to challenges of accurate evaluation, it helped to generate design alternatives for optimisation. However, research gaps exist in the research scale and prefabrication application. The sustainability analysis is biased at the operational stage and works as an extra validation process in the design phase. Limited studies reported ECE reduction approach apart from the material selection. Designers were left a narrow scale after analysis in most research and caused the ineffective implementation of the design integrated approach. Although a primary element approach realized its prefabrication application, it did not fill the demand thoroughly. Therefore, a framework aiming at reducing construction CE by design optimisation is proposed. Further research will include a larger amount of previous work to eliminate potential interpretative bias and focus on the framework development and implementation.

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