Building Life Cycle Carbon Emissions: A Review

TENG Yue[a], PAN Wei[b]

[a] *The University of Hong Kong, Hong Kong SAR, tengyue@hku.hk*
b The University of Hong Kong, Hong Kong SAR, wpan@hku.hk

ABSTRACT

Buildings are responsible for a substantial percentage of energy use related carbon emissions that contribute to global warming. Examination of buildings' carbon emission has been one of the key issues for the sustainability. As a high-density city, Hong Kong has increasingly advocated the use of prefabrication for high-rise residential buildings. However, although life cycle carbon emission assessment has been widely applied to buildings, its implications on high-rise prefabricated buildings remain unclear. Therefore, this paper aims to contribute to a better understanding of the life cycle carbon emission assessment of high-rise prefabricated buildings in Hong Kong.

The review was carried out through a meta-analysis of relevant previous studies and a more focused examination of research in the context of Hong Kong. The meta-analysis was conducted from the temporal, spatial, functional and methodological dimensions using seven variables, namely, life span, life cycle phase, research area, research scope, building type, building height, and life cycle assessment method. The focused examination reveals a severe gap in knowledge of the life cycle carbon emissions of high-rise prefabricated buildings in Hong Kong. A lack of understanding was also identified of the operational stage and indirect implications of prefabricated buildings. Furthermore, there is absence of consistent life cycle carbon assessment method in addressing the gaps. A systemic model of examining the carbon emissions of high-rise buildings is suggested to address the full building life cycle.

Keywords: *life cycle assessment, carbon emission, high-rise prefabricated building, Hong Kong*

1. INTRODUCTION

The excessive releasing of greenhouse gases (GHGs) is the largest cause of global warming, which has created risks worldwide (Soetanto et al., 2014). Carbon dioxide (CO_2), produced by consumed energy, has been the primary component of the GHG (Li et al., 2016). According to Sadineni et al. (2011), buildings are responsible for almost one third of the energy-related CO_2 emissions. In Hong Kong, this figure can be as high as 60% (EPD, 2010). Research into the environmental impact of buildings is thus important to Hong Kong.

Being a high-density city, Hong Kong has increasingly advocated prefabrication for high-rise buildings. Although relevant studies have widely applied life cycle carbon assessment ($LCCO_2A$) method for evaluating carbon emissions from the construction industry, the use of this method for high-rise prefabricated buildings remains unclear. Therefore, it is vital to explore consistent method of $LCCO_2A$ for prefabricated high-rise buildings. This paper aims at contributing to a systematic understanding of $LCCO_2A$ of buildings in Hong Kong. There are three research objectives: (1) to reveal the profiles of previous studies on $LCCO_2A$ of buildings; (2) to investigate the implications of $LCCO_2A$ for high-rise prefabricated buildings in Hong Kong; and (3) to explore the research gaps and recommendations.

2. THE CONCEPT OF LCA AND $LCCO_2A$

According to International Organization for Standardization (ISO, 2006), life cycle assessment (LCA) was defined as "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system through its life cycle". As a simplified version of LCA, $LCCO_2A$ only focuses on CO_2 relevant emissions (Chau et al., 2015). The building's life cycle can be divided into four main phases: production, construction, operation and end-of-life (Kamali and Hewage, 2016). However, previous studies examined the building's life cycle carbon emissions in different interpretations of the building life cycle: e.g. from "cradle to gate" (Din and Brotas, 2016), from "cradle to site" (Gardezi et al., 2016), from "cradle to grave" (Blengini, 2009), and from "cradle to cradle" (Sinha et al., 2016). Subsequently, the various concepts of $LCCO_2A$, coupled with inconsistent data collection methods, boundaries, and calculation methodologies, call for a critical review of previous research.

3. REVIEW METHODS

The research was carried out through a meta-analysis of previous relevant studies and a focused examination of research within the Hong Kong context.

In the meta-analysis, a commonly applied search engine, Scopus, was firstly selected to identify relevant articles published in peer-reviewed journals during the period from 1996 to 2016. The keywords were identified as: "Life Cycle" and "Carbon Emission" and "Building" in undertaking the analyses. Papers with these specific terms included in the Title/Abstract/Keyword were considered to have fulfilled the requirement of this review. The search was further limited to subject areas such as "engineering", "environmental science", "energy", "social and management" with the document types of articles. Through the process, the search limited the data sources to a list of representative 13 journals. Subsequently, a total of 173 articles were identified (Table 1).

	Journal	Number of articles
1	Applied Energy (AE)	14
2	Building and Environment(BE)	31
3	Building Research and Information (BRI)	8
4	Energy (EN)	7
5	Energy and Buildings(EB)	44
6	Energy Policy (EP)	6
7	Environmental Impact Assessment Review(EIAR)	4
8	Habitat International (HI)	2
9	International Journal of Life Cycle Assessment(IJLCA)	21
10	Journal of Cleaner Production(JCP)	21
11	Journal of Environmental Management (JEM)	3
12	Renewable Energy (RE)	4
13	Renewable and Sustainable Energy Reviews(RSER)	8
	Total	173

Table 1: Selected journal and articles for analysis

The meta-analysis method, prompted by Pan and Ning (2015), was then applied to the 173 articles identified to investigate the $LCCO_2A$ of buildings. Seven variables were selected drawing on literature, from temporal, spatial, functional and methodological dimensions (Table 2).

Dimensions	**Variables**	**Description of variables**
Temporal	Life span	The service life of the buildings
	Life cycle phase	Full life cycle or not
Spatial	Research area	Location of the buildings
	Research scope	Building as a whole; components; materials; system; others
Functional	Building type	Residential buildings; non-residential buildings
	Building height	High-rise; medium-rise; low-rise buildings
Methodological	LCA Methods focus	Input-output; process based; hybrid method

Table 2: Dimensions and variables for review

In the focused examination, six papers focusing on $LCCO_2A$ of buildings in Hong Kong were identified. The analysis was carried out from the dimensions of case study, building type, life cycle phase, LCA method, research method and key data input.

4. REVIEW RESULTS AND ANALYSIS

4.1 Results of meta-analysis

4.1.1 Profile of research in the temporal dimension

- Buildings' life cycle phase examined

Among the 173 articles, 134 indicated the life cycle phase of the cases studied, of which 43.3% (58) focused on the examination of LCCO2A from the full life cycle. The other LCCO2A studies of the partial life cycle (76; 56.7%) mainly included those articles examining the “cradle to end of construction” (23.7%; 18), “cradle-to-gate” (19.7%; 15), and the “operation” (18.4%; 14). There were also some articles addressing “cradle to site” or “cradle to grave” (both of 13.2%; 10), and some others studying “cradle to operation” (10.5%; 8).

- Buildings’ life span studied

Among the 173 articles examined, 69.9% (121) addressed particular building cases and clearly specified the service life span of the cases. However, the life spans addressed in these 121 articles were inconsistent: falling in three groups (1) between 25 (exclusive) and 50 years (inclusive) (50.4%), (2) 25 years or less (22.3%), and (3) greater than 50 years (27.3%). In particular, 27.3% and 19.0% of the 121 articles adopted 50-year and 100-year life span, respectively.

4.1.2 Profiles of research in the spatial dimension

- Research area studied

The majority (89%; 154) of the identified articles specified the cases’ locations in text, whereas the rest did not explicitly describe them. Among these 154 articles, the largest category (26.6%; 41) addressed the examination of LCCO2A in Europe, followed by the categories addressing U.S. (13.6%; 21), Mainland China (12.3%; 19) and Korea (10.4%; 16). However, only a few (3.9%; 6) examined the cases in Hong Kong. For the 41 articles focused on the Europe, Sweden was the most researched (31.7%; 13). These results reveal a lack of studies into the life cycle carbon emissions of buildings in Hong Kong.

- Research scope examined

The research scope in relation to the LCCO2A of buildings exists at four layers: materials, components, systems, and buildings as a whole. Nearly three quarters (130; 75.1%) of the 173 identified articles clearly pointed out their research scopes. For the 130 articles, the largest category (57; 43.8%) studied LCCO2A of buildings from the perspective of “Materials”, followed by 28 articles (21.5%) studying “Components of buildings” (Table 3). The number of articles examined from the perspective of “Systems” (23; 17.7%) and “Buildings as a whole” (22; 16.9%) nearly remains the same.

Group	Description	Number
Materials	Focusing on the materials (concrete, cement, wood, steel, etc.) in the buildings	57
Components	Focusing on components (envelope, floor, foundation, interior, etc.) in buildings	28
Systems	Focusing on the system (fuel and heating system; household biogas system; rainwater systems, thermal system, etc.) in the buildings	23
Buildings as a whole	Focusing on the whole buildings	22
Others	Macro analysis; No case studies; Not concentrating on specific buildings, etc.	43

Table 3: Articles of buildings’ $LCCO_2A$ by research scope

4.1.3 Profiles of previous research in the functional dimension

- Building type studied

Buildings are divided into residential and non-residential buildings (e.g. industrial, commercial, educational and health buildings) (Wong et al., 2000). Among the identified 173 articles, only 61.3% (106) definitely showed the buildings’ types of the cases. The results illustrate that the majority of the articles (73; 68.9%) studied the LCCO2A of residential buildings, whereas merely 33 articles (31.3%) addressed that of no-residential buildings. Under the category of non-residential buildings, nearly half (16; 48.5%) studied office buildings, followed by those studying educational buildings (8; 24.2%) and commercial buildings (7; 21.2%); very few examined the cases of health buildings (1; 3.0%) and historic buildings (1; 3.0%). The salience of research on residential buildings illustrates the clear focus of previous research on examining the life cycle carbon emissions of domestic buildings.

- Building height examined

According to Jan et al. (2004), buildings are divided into four types based on the stories: low-rise (less than 3 stories), medium-rise (4 to 6 stories), medium-to-high-rise (7 to 9 stories), and high-rise (greater than 10 stories). Among the identified 173 articles, only 97 articles specified the height of the cases. The majority of the LCCO2A articles (43; 44.3%) studied low-rise buildings, followed by the group addressing medium-rise (22; 22.7%) and high-rise buildings (25; 25.8%), with a marginal amount of studies addressing medium-to-high-rise buildings (7; 7.2%).

4.1.4 The Profile of previous research in the methodological dimension

Three LCA methods, i.e. process-based analysis, input-output analysis and hybrid analysis, have been advocated by previous studies to calculate the carbon emissions of buildings (Ries and Mahdavi, 2001). Only 41.6% (72) of the identified 173 articles implemented the calculation process and adopted one of the three methods. The results show the majority of the studies adopted input-output and process-based methods in their LCCO2A examination, namely 34 (47.2%) and 31 (43.1%) of the articles. Only about one in ten (7; 9.7%) used hybrid analysis method.

4.2 Results of focused examination within the Hong Kong context

Despite several studies have examined LCCO2A of buildings, little research has been undertaken into high-rise prefabricated buildings in Hong Kong. To address this gap, six identified papers which are relevant to Hong Kong were investigated thoroughly (Table 4).

	Authors	Case study	Building type	Life cycle phase	LCA method	Research method	Key data input
1	Chau et al. (2012)	CB [a]	HR office	cradle-to-end of construction	process-based	Monte Carlo method	First hand data; Reference; Published information.
2	Zhang et al. (2013)	CB	a thirty-story commercial	Full life cycle	process-based	inventory analysis; case study	Report by the Electrical Mechanical Service Department of Hong Kong; Literatures.
3	Chiang et al. (2014)	CB	residential	cradle to site	NA	NA	ICE database
4	Jaillon and Poon (2014)	review	HR residential	deconstruction phases	NA	Questionnaire survey	Questionnaire survey; Face-to-face interviews; Site observations.
5	Dong et al. (2015)	CB and PB	HR residential	cradle-to-end of construction	process-based	SimaPro	Questionnaire survey; Semi-structured interview; Ecoinvent.
6	Pan et al. (2016)	NA	PRH	NA	Simulation	BEA software	Literature review; Technical analysis; Case study;

[a] CB means the conventional buildings and PB means the prefabricated buildings.

Table 4: Previous studies of buildings' LCCO2A in Hong Kong

Chau et al. (2012) conducted Monte Carlo method to predict CO2 emissions of the superstructure of thirteen high-rise office buildings in Hong Kong. It provided a method to evaluate the emissions reduction impacts by using different materials. However, operational stage was not considered in this research. Zhang et al. (2013) analysed a thirty-story high commercial building to examine eight types of air emissions in Hong Kong, using an inventory analysis method. It contributed to identify the optimal solution of minimizing the air emissions in early stage. However, this paper used a second data that needed to be improved in further studies. Chiang et al. (2014) proposed an optimization model from environmental, economic, and social criterions. A residential building, with a 75 years' life span in Hong Kong, was used as the case study. It helped decision makers choose a reduction method both from economic and social aspects. However, the operational stage was not included in this analysis. Jaillon and Poon (2014) proposed a review on design for deconstruction and a case study on industrialized building.

Findings from the case studies shows there are several advantages when adopting prefabrication in Hong Kong. However, this article just focused on the deconstruction phases. Dong et al. (2015) compared the carbon emissions of precast and traditional construction methods from the "cradle-to-end of construction" life cycle phase, based on a high-rise private residential building in Hong Kong. Results showed reduction of carbon emission could be 10% due to precast concrete. Pan et al. (2016) developed strategies for modelling carbon emissions in 40-story public residential buildings in Hong Kong. It helped to achieve efficient and accurate building energy simulation and carbon emission estimation of high-rise buildings in Hong Kong. These studies show LCCO2A of traditional high-rise buildings have been carries on by some scholars, whereas very few studies worked on LCCO2A of prefabricated buildings in Hong Kong.

5. DISCUSSION

The results of the meta-analysis reveal some general trends of previous studies. First, it reflects the inconsistent of cases' service life span. In the identified articles, 50-year and 100-year life span are the relatively most widely accepted life span. Second, despite some studies have emphasised the analysis from the full life cycle aspect, the non-full life cycle was carried on by more scholars, especially the phase of "cradle to end of construction", "cradle-to-gate", and the "operation". The reason may lay in the statements by some researchers that carbon emissions in the use and end-of-life phases were insignificant and could be neglected (Flower and Sanjayan, 2007). Third, although there are abundant LCCO2A articles in Europe, U.S., Mainland China and Korea, very few studies have been conducted in Hong Kong, which reveals the demand for further research. Fourth, the majority of articles addressed the LCCO2A studies from the materials' aspect, which manifested the importance of changing materials for reducing the carbon emission (Wu et al., 2014, Ingrao et al., 2015). Fifth, residential buildings were demonstrated as the main research objectives of previous LCCO2A cases. This finding supports the statement of Li et al. (2013) that residential buildings' carbon emissions are rather prodigious. Among the no-residential buildings, nearly half of them studied office buildings. However, the majority of LCCO2A analysis just focused on low-rise buildings. Therefore, the lack of understanding on the mid high-rise and high-rise buildings needs to be optimised in further research. Sixth, the input-output and the process-based methods have been widely advocated in previous research. Nevertheless, the articles adopting hybrid method are inadequate, albeit the demonstrated efficiency of it (Zhang and Wang, 2016).

The in-depth examination of the identified six articles reveals research problems. First, although studies on the carbon emissions from the upstream phase of buildings are abundant, the operation phase has been overlooked in Hong Kong. This finding is in line with the observation of Kamali and Hewage (2016) that the evaluation of CO2 emissions from the upstream phase was increasingly common in recent years. However, the operational phase can occupy 80% of all life cycle carbon emissions (Mao et al., 2013), which should not be ignored. Second, studies on high-rise prefabricated buildings in Hong Kong are inadequate. One reason might be that prefabrication has not yet been a recognised phase in the building life cycle. Another reason appeared to be the insufficient adoption of precast concrete components within the precast yard (Dong and Ng, 2015), which leads to the limited applications and analyses using real projects. Third, the direct implications were considered while the indirect ones were ignored. For example, the improved quality of buildings can reduce the carbon emission from full life cycle aspect, which should be taken into consideration in the calculation of carbon emissions.

6. CONCLUSIONS

Drawing the results and discussion, this paper concludes that uncertainties and inconsistency in the adoption of LCCO2A methods contribute to a fragmented understanding of the LCCO2A of high-rise prefabricated buildings. These uncertainties and inconsistency are caused by the differences in system boundaries, assumptions, chosen life span, building types and locations in LCCO2A. The paper also concludes that there is a lack of understanding of LCCO2A relevant to the building's operational stage and prefabricated buildings' indirect implications. There is a severe gap in the knowledge of the LCCO2A of high-rise prefabricated buildings in Hong Kong. To bridge this gap, a systemic model of examining the carbon emissions of high-rise buildings is suggested, which addresses the inconsistency of LCCO2A method. By this systemic model, the carbon emissions generated from the full life cycle will be accounted. The life cycle will cover eight phases: cradle-to-gate (P1), transportation (P2), prefabrication (P3), construction (P4), operation (P5), maintenance and refurbishment (P6), deconstruction (P7) and recycling/landfill (P8). First, data in the phase of cradle-to-gate (P1) will be primarily collected from Carbon Labelling of Construction Products in Hong Kong and Life Cycle Inventory worldwide, being calculated using process-based method. Second, carbon emissions in prefabrication (P2- P3) and construction (P4) phases will be examined using data from resource and energy consumption during transportation and installation in the construction yards and site. Third, operational carbon emissions (P6-P8) will be determined using EnergyPlus software, based on the simulated energy consumption. Last, data in the after-use phase (P9-P10) will be obtained through LCA inventories and literature review subject to their compatibility with available LCA inventories. The adoption of this systemic model will help to achieve a better understanding of the life cycle carbon emissions of buildings within high-rise contexts.

ACKNOWLEDGMENT

The work described in this paper was supported by a grant from the General Research Fund of the Hong Kong Research Grants Council (RGC GRF Project No.: 17207115).

REFERENCES

[1] BLENGINI, G. A. 2009. Life cycle of buildings, demolition and recycling potential: a case study in Turin, Italy. Building and Environment, 44, 319-330.
[2] CHAU, C., HUI, W., NG, W. & POWELL, G. 2012. Assessment of CO 2 emissions reduction in high-rise concrete office buildings using different material use options. Resources, Conservation and Recycling, 61, 22-34.
[3] CHAU, C., LEUNG, T. & NG, W. 2015. A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. Applied Energy, 143, 395-413.
[4] CHIANG, Y., ZHOU, L., LI, J., LAM, P. & WONG, K. 2014. Achieving sustainable building maintenance through optimizing life-cycle carbon, cost, and labor: Case in Hong Kong. Journal of Construction Engineering and Management, 140, 05014001.
[5] DIN, A. & BROTAS, L. 2016. Exploration of life cycle data calculation: Lessons from a Passivhaus case study. Energy and Buildings, 118, 82-92.
[6] DONG, Y. H., JAILLON, L., CHU, P. & POON, C. 2015. Comparing carbon emissions of precast and cast-in-situ construction methods–A case study of high-rise private building. Construction and Building Materials, 99, 39-53.
[7] DONG, Y. H. & NG, S. T. 2015. A life cycle assessment model for evaluating the environmental impacts of building construction in Hong Kong. Building and Environment, 89, 183-191.
[8] EPD, E. A. 2010. Guidelines to Account for and Report on Greenhouse Gas Emissions and Removals for Buildings in Hong Kong. The HKSAR Government, Hong Kong.
[9] ERBERIK, M. A. 2008. Fragility-based assessment of typical mid-rise and low-rise RC buildings in Turkey. Engineering Structures, 30, 1360-1374.
[10] FLOWER, D. J. & SANJAYAN, J. G. 2007. Green house gas emissions due to concrete manufacture. The international Journal of life cycle assessment, 12, 282-288.
[11] GARDEZI, S. S. S., SHAFIQ, N., ZAWAWI, N. A. W. A., KHAMIDI, M. F. & FARHAN, S. A. 2016. A multivariable regression tool for embodied carbon footprint prediction in housing habitat. Habitat International, 53, 292-300.
[12] INGRAO, C., GIUDICE, A. L., BACENETTI, J., TRICASE, C., DOTELLI, G., FIALA, M., SIRACUSA, V. & MBOHWA, C. 2015. Energy and environmental assessment of industrial hemp for building applications: A review. Renewable and Sustainable Energy Reviews, 51, 29-42.
[13] ISO, I. 2006. 14040: Environmental management–life cycle assessment–principles and framework. London: British Standards Institution.
[14] JAILLON, L. & POON, C. 2014. Life cycle design and prefabrication in buildings: A review and case studies in Hong Kong. Automation in Construction, 39, 195-202.
[15] JAN, T. S., LIU, M. W. & KAO, Y. C. 2004. An upper-bound pushover analysis procedure for estimating the seismic demands of high-rise buildings. Engineering Structures, 26, 117-128.
[16] KAMALI, M. & HEWAGE, K. 2016. Life cycle performance of modular buildings: A critical review. Renewable and Sustainable Energy Reviews, 62, 1171-1183.
[17] LI, D., CHEN, H., HUI, E. C., ZHANG, J. & LI, Q. 2013. A methodology for estimating the life-cycle carbon efficiency of a residential building. Building and environment, 59, 448-455.

[18] LI, D., CUI, P. & LU, Y. 2016. Development of an automated estimator of life-cycle carbon emissions for residential buildings: A case study in Nanjing, China. Habitat International, 57, 154-163.

[19] LUO, Z., YANG, L. & LIU, J. 2016. Embodied carbon emissions of office building: A case study of China's 78 office buildings. Building and Environment, 95, 365-371.

[20] MAO, C., SHEN, Q., SHEN, L. & TANG, L. 2013. Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: two case studies of residential projects. Energy and Buildings, 66, 165-176.

[21] PAN, W. & NING, Y. 2015. The dialectics of sustainable building. Habitat International, 48, 55-64.

[22] PAN, W., QIN, H. & ZHAO, Y. (2016) Challenges for energy and carbon modeling of high-rise buildings: The case of public housing in Hong Kong. Resources, Conservation & Recycling, doi:10.1016/j.resconrec.2016.02.013.

[23] RIES, R. & MAHDAVI, A. 2001. Integrated computational life-cycle assessment of buildings. Journal of Computing in Civil EngiSneering, 15, 59-66.

[24] SADINENI, S. B., MADALA, S. & BOEHM, R. F. 2011. Passive building energy savings: A review of building envelope components. Renewable and Sustainable Energy Reviews, 15, 3617-3631.

[25] SINHA, R., LENNARTSSON, M. & FROSTELL, B. 2016. Environmental footprint assessment of building structures: A comparative study. Building and Environment, 104, 162-171.

[26] SOETANTO, R., ZHANG, S., PAN, W. & KUMARASWAMY, M. 2014. A multi-criteria decision framework for the selection of low carbon building measures for office buildings in Hong Kong. International Journal of Energy Sector Management, 8, 456-476.

[27] WONG, L., CHOW, W. & KWAN, E. C. 2000. A brief review on fire regulations for old highrise commercial buildings in Hong Kong. International Journal on Engineering Performance-Based Fire Codes, 2, 153-160.

[28] WU, P., XIA, B. & ZHAO, X. 2014. The importance of use and end-of-life phases to the life cycle greenhouse gas (GHG) emissions of concrete–a review. Renewable and Sustainable Energy Reviews, 37, 360-369.

[29] ZHANG, X., SHEN, L. & ZHANG, L. 2013. Life cycle assessment of the air emissions during building construction process: a case study in Hong Kong. Renewable and Sustainable Energy Reviews,s 17, 160-169.

[30] ZHANG, X. & WANG, F. 2016. Hybrid input-output analysis for life-cycle energy consumption and carbon emissions of China's building sector. Building and Environment, 104, 188-197.