Embodied Carbon Mitigation Strategies in the Construction Industry

M.N.N. Rodrigo,
Western Sydney University, Australia
(email: n.rodrigo@westernsydney.edu.au)
Srinath Perera,
Western Sydney University, Australia
(email: Srinath.Perera@westernsydney.edu.au)
Sepani Senaratne,
Western Sydney University, Australia
(email: S.Senaratne@westernsydney.edu.au)
Xiaohua Jin,
Western Sydney University, Australia
(email: Xiaohua.Jin@westernsydney.edu.au)

Abstract

The building sector contributes up to 36% of carbon emissions emphasizing the importance of carbon management. Carbon emissions in buildings are classified into two main types; embodied carbon and operational carbon. Operational carbon refers to emissions, which occur during the operational phase of a building. Embodied carbon is the fuel and process related carbon emitted during material extraction, transportation, manufacturing, distribution, construction, disposal and reuse. Creating zero carbon projects, where the operational carbon is reduced to zero, has become a trend, which may intern reduce operational carbon by adding to embodied carbon. Therefore, reducing the overall carbon emissions in construction projects, has become intricately important. Hence, the study aims at identifying embodied carbon mitigation strategies to reduce the embodied carbon emissions in construction projects.

Initially, a comprehensive literature review was carried out to identify the embodied carbon mitigation strategies recognised by various researchers. The literature findings and the data gathered from a roundtable expert forum was analysed to derive at conclusions in this regard. 36 experts attended the expert forum, who actively participated in discussion and contributed to the findings. A total of 22 embodied carbon mitigation strategies were identified through literature and the expert forum. These mitigation strategies can be implemented by the industry practitioners to reduce the embodied carbon emissions in the construction projects.

Keywords: Embodied carbon, mitigation strategies, construction industry, expert forum.

1. Introduction

Building construction is one of the major sources contributing to carbon emissions as it consumes a significant amount of energy that results in the release of large amounts of carbon emissions into the atmosphere (González & Navarro 2006; Shafiq et al. 2015). Precisely, Intergovernmental Panel on Climate Change (2001) and Nässén et al. (2007) found that in the industrialised countries, the building sector accounts for 40% of primary energy use and 36% of the energy related carbon emissions. In addition to that, Chau et al. (2012) opined that buildings are responsible for about 36% of the total carbon emissions worldwide. In United Kingdom (UK), the building sector contributes to 50% of its total CO_2 emissions (Dowden 2008). The Australian building sector accounts for about 36% of the overall carbon emissions (Huang, B, Xing & Pullen 2017). Australia's capital cities, such as Sydney, Canberra, Melbourne, Adelaide and Perth have already understood their responsibility in reducing their community's carbon emissions, as a result, strategies and targets have been established to achieve climate goals (Harrington 2018). When reducing carbon emissions, it is important to highlight that carbon emissions occur throughout the life cycle of a building/ product/ service.

Life Cycle Carbon (LCC) emissions comprise of two main components; operational and embodied carbon. Operational Carbon (OC) emissions occur during the operational and maintenance phases of a structure (Giesekam et al. 2014) while Embodied Carbon (EC) refers to the carbon emissions that occur during the production phase of a product/service within the system boundaries (Hammond & Jones 2011; Victoria, Perera & Davies 2016). As the novel trend is to reduce the OC of typical projects to create more energy efficient buildings known as zero-carbon projects, it has become intricately important to look at the remaining EC component (Ashworth & Perera 2015; RICS 2014). Therefore, this research paper aims at identifying and discussing the EC mitigation strategies in order to reduce the EC emissions in construction. Furthermore, this paper discusses the research findings of a project that was showcased and discussed at a roundtable expert forum.

2. Literature Review

2.1 Life Cycle Carbon

LCC emissions refer to all the carbon equivalent emissions from a building within different phases of its life cycle (Chau, Leung & Ng 2015). Schwartz, Raslan and Mumovic (2018) declared that LCC emissions refer to the carbon dioxide emitted from all processes in buildings throughout their life cycle. Similarly, De Wolf et al. (2017) opined that LCC includes OC for heating, cooling, lighting, ventilating and EC for material supply, production, transport, construction and disassembly. However, Schwartz, Raslan and Mumovic (2018) categorised LCC to occur in three different categories; (1) EC emitted during raw material extraction, transportation, construction, maintenance and refurbishment; (2) OC emitted during the process of maintaining comfortable environmental conditions in building related to heating, cooling, domestic hot water and lighting; and (3) demolition related carbon emitted during demolition of building and transportation of waste to dump sites. The carbon emissions associated with construction can be distinguished as either operational or embodied emissions (Giesekam et al. 2014; Mohammed, Mustapha & Mu'azu 2011).

OC is considered as the "carbon emissions caused by energy consumed during the use of buildings, such as space cooling and heating, ventilation, lighting, hot water and running electrical equipment" (Teng et al. 2018, p. 126). Similarly, RICS (2014) identifies OC as the carbon emissions associated with energy consumptions while the building is occupied including the regulated load (i.e. heating, cooling, ventilation, lighting) and unregulated load (i.e. ICT equipment, cooking and refrigeration appliances). OC emissions can be classified into (1) building emissions associated with built-in appliances for heating, lighting and others; (2) occupant emissions related to the occupant provided appliances such as kettles, microwaves, washing machines and the like; and (3) renovation emissions resulted by repair and restoration of the building related to recarpeting, repainting among others

(Riedy, Lederwasch & Ison 2011; Teh et al. 2015). In addition, Foxell (2014) stated that 40% of the OC is emitted due to space heating while 14% and 12% of OC emissions are resulted by water heating and lighting of buildings respectively. Though OC emissions occur only during the use stage of the building, EC emissions can occur during the entire life cycle of the building.

Hitchin (2013, p. 2) defined EC as "the carbon dioxide (and equivalent global warming potential of other gases) emitted as a result of embodied energy." EC, also known as capital carbon, is associated with the initial production of a structure, which includes emissions from raw material acquisition, transportation, processing and manufacturing of building materials, distribution of materials to site, assembly at site, deconstruction and disposal at site (Giesekam et al. 2014). Similarly, EC emissions can be considered as a combination of (1) fossil carbon emissions, generated during material production and (2) process carbon emissions, generated due to chemical reactions inherent to industrial production process (Chau, Leung & Ng 2015; Hammond & Jones 2011). Ibn-Mohammed et al. (2013) classified EC emissions into (1) initial embodied emissions, which are occurred during the initial construction of the building and (2) recurring embodied emissions, which are incurred to maintain, repair, restore, refurbish or replace materials, components or systems during the effective life of the building. Peters (2010) stated EC also known as embedded carbon or virtual carbon, refers to the emissions that occur along the supply chain of a functional unit (i.e. building element). Similarly, EC emissions can occur within different system boundaries.

2.2 Importance of reducing EC

When considering the LCC of a building, approximately 70-80% is associated with the OC in the use phase, while the remaining is associated primarily with the EC (RICS 2012). However, the ratio between the OC and EC depend on the type of the building as illustrated in Figure 2.5 (RICS 2012, 2014). As an example, low specification buildings such as a warehouse, which may not require any heating and cooling, will contribute to very less amount of OC (Ashworth & Perera 2015), making the remaining EC component in that building quite high. Therefore, controlling EC in such buildings is extremely important.

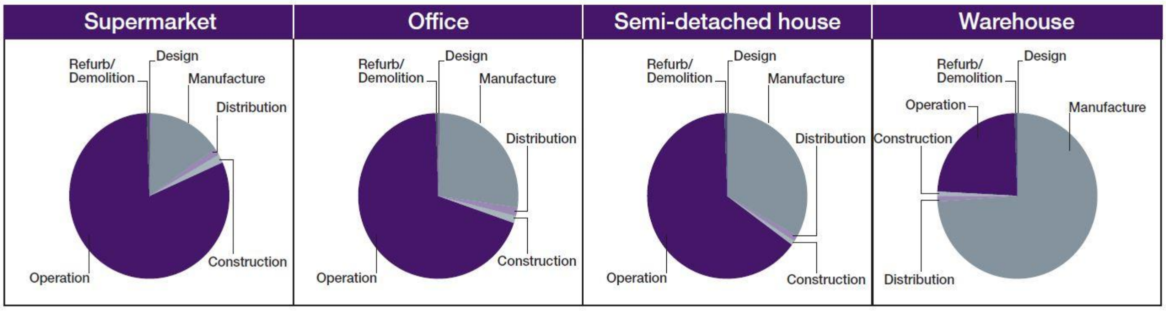

Figure 1: Carbon footprint in different lifecycle phases for different projects
Source: RICS (2012)

Kang et al. (2015, p. 326) opined that "OC is being continuously reduced via multipronged efforts related to technology and policy aspects, such as improvement of heating, ventilation, and air-conditioning performance, utilisation of new and renewable energy, adoption of the zero-energy building design, and the introduction of green building certification policies." Hence, according to the latest trend of reducing OC in typical projects to create more energy efficient buildings known as zero-carbon projects, the remaining EC component becomes almost 100% as illustrated in Figure 2.6 (Ashworth & Perera 2015; RICS 2014). Often, the minimisation of OC emissions of buildings is considered to be the desired goal (Airaksinen & Matilainen 2011), ultimately decreasing the EC emissions becomes intricately important.

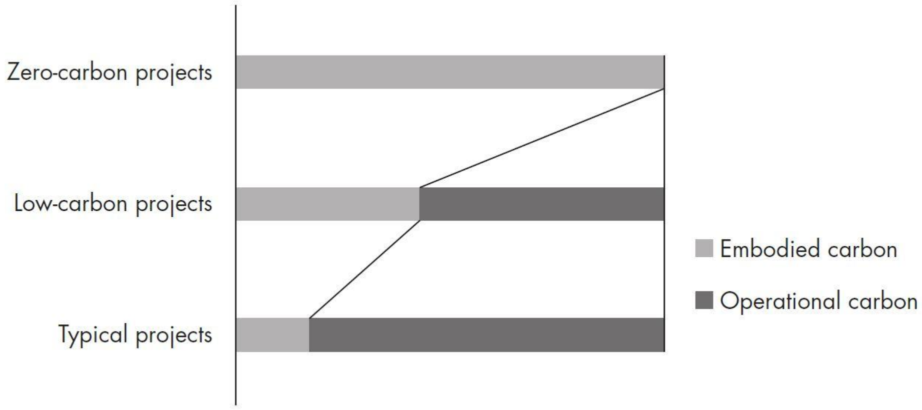

Figure 2: The ratio of EC to OC during implementation of energy efficient buildings
Source: Adapted from RICS 2014, Ashworth and Perera 2015

According to Koezjakov (2017, p. 9), "the reduction of operational energy use often leads to an increase in embodied energy use due to an increase in material use with higher energy intensities." In order to reduce the OC related to the air-conditioning system of a building, additional layers of insulation materials will be installed to improve insulation (Airaksinen & Matilainen 2011; Ashworth & Perera 2015) which would result in contributing more to the EC component. On the other hand, unlike the OC which can be reduced over time, EC emissions cannot be reversed (De Wolf et al. 2016). Hence, Innovation Growth Team (2010) highlighted that EC needs to be brought into appraisal of projects and for design decisions of projects.

On the other hand, investigating the dual currency concept, Victoria, Perera and Davies (2016) found that EC and cost of a building are perfectly correlated, which signifies the importance of reducing EC in order to accomplish reduced cost of buildings. Similarly, one can reduce the cost of a building to achieve reductions in EC emissions of that building. In addition to that, researchers have commenced looking for EC mitigation strategies to reduce the EC emissions in the building industry. The growth of literature outside academia (ASBP 2014; ICE 2015; RICS 2012) discussing the ways of mitigating EC emphasise the importance of reduction of EC. As strategies of reducing EC, use of low-carbon materials (González & Navarro 2006), material minimization (Akbarnezhad & Xiao 2017), local sourcing and transport minimization (Akbarnezhad & Xiao 2017), and construction optimization (Lewis, P, Leming & Rasdorf 2012) have been identified. Besides, 17 EC mitigation strategies were identified through a literature review carried out by Pomponi and Moncaster (2016). Further, Langdon (2009) opined that EC emissions in building materials are associated with material mass where reducing mass results in low carbon emissions. As there are many EC mitigation strategies which have been identified by various researchers, few of them have been summarised in Table 1.

Table 1: EC mitigation strategies identified in literature

Nr	Mitigation Strategy	Identified Study									
		R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
1	Use of materials with lower embodied energy and carbon	✓	✓		✓	✓	✓	✓	✓	✓	
2	Better design	✓		✓	✓	✓	✓	✓		✓	
3	Reduction, recycle, reuse and recovery of EE/EC intensive construction materials	✓	✓	✓	✓	✓	✓	✓	✓	✓	
4	Tools, methods and methodologies	✓			✓		✓				
5	Government policy and regulations	✓		✓		✓	✓	✓			
6	Refurbishment of existing buildings and adaptive reuse of buildings	✓		✓		✓		✓			
7	Decarbonisation of energy supply/ grid	✓		✓	✓			✓	✓		
8	Inclusion of waste, by-product, and used	✓			✓	✓	✓		✓		

Nr	Mitigation Strategy	Identified Study									
		R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
	materials into building materials										
9	Increased use of local materials and components	✓	✓						✓		
10	Construction sector policy and regulations	✓		✓			✓	✓			
11	People-driven change	✓						✓	✓		
12	More efficient construction process/ techniques	✓		✓		✓	✓	✓			
13	Carbon mitigation offsets, emissions trading, and carbon tax	✓		✓	✓		✓	✓			
14	Carbon sequestration	✓			✓						
15	Extending the building's life	✓			✓			✓			
16	Increased use of prefabricated elements/ off-site manufacturing	✓									
17	Demolition and rebuild	✓									
18	Construction optimisation		✓						✓		✓
19	Reduction of transportation		✓					✓		✓	
R1- Pomponi and Moncaster (2016); R2- Akbarnezhad and Xiao (2017); R3- Li and Colombier (2009); R4- Tingley and Davison (2011); R5- Giesekam et al. (2014); R6-Ariyaratne and Moncaster (2014); R7- Ma et al. (2015); R8- Reddy (2009); R9- González and Navarro (2006); R10- Lewis, Leming and Rasdorf (2012)											

3. Research Methodology

The project on developing a methodology for estimating EC using a blockchain platform for construction supply chains was showcased at a roundtable based expert forum, consisting of collaborative audience of industry and academia. There were 6 tables, each comprising of 4 industry practitioners such as engineers, quantity surveyors, architects, manufacturers, project managers; and 2 academics representing a real life construction eco-system, where a total number of 36 participants engaged. During the engagement activity which was carried out, an open ended question was asked to identify EC mitigation strategies in order to reduce EC in construction projects. The experts in each table were to come up with different ideas and list down the strategies. Afterwards, a discussion was carried out where each table demonstrated their findings and all other tables actively participated in the discussion. The findings of this engagement activity have been discussed in the following section.

4. Research Findings

The experts opined of different aspects on mitigation strategies to reduce the EC in construction projects. The six tables (T1, T2, T3, T4, T5 and T6) conversed 27 mitigation strategies and after carrying out an analysis on the findings, most of the identified strategies could be grouped together and furthermore they could be aligned with the mitigation strategies identified in the literature review which were illustrated in Table 1. As a result, a total of 22 strategies were identified through literature and the roundtable expert forum as demonstrated in Table 2. Through the literature review 19 mitigation strategies were identified while the experts additionally identified 3 other mitigation strategies; use of short supply chains; reduction of wastage; and development of a database of materials and carbon. Though few mitigation strategies were identified in literature; such as tools, methods and methodologies; government policy and regulations; decarbonisation of energy supply/grid; construction sector policy and regulations; more efficient construction process/techniques; carbon mitigation offsets, emissions trading, and carbon tax; carbon sequestration; demolition and rebuild; and construction optimisation, they were not identified by the experts.

Table 2: EC mitigation strategies identified through roundtable expert forum

Nr	Mitigation Strategies	Literature Findings	T1	T2	T3	T4	T5	T6
1	Use of materials with lower embodied energy and carbon	✓	✓	✓		✓	✓	
2	Better design	✓	✓		✓	✓	✓	✓
3	Reduction, recycle, reuse and recovery of EE/EC intensive construction materials	✓			✓	✓		✓
4	Tools, methods and methodologies	✓						
5	Government policy and regulations	✓						
6	Refurbishment of existing buildings and adaptive reuse of buildings	✓				✓		
7	Decarbonisation of energy supply/ grid	✓						
8	Inclusion of waste, by-product, and used materials into building materials	✓				✓		
9	Increased use of local materials and components	✓			✓			
10	Construction sector policy and regulations	✓						
11	People-driven change	✓		✓				
12	More efficient construction process/ techniques	✓						
13	Carbon mitigation offsets, emissions trading, and carbon tax	✓						
14	Carbon sequestration	✓						
15	Extending the building's life	✓	✓					
16	Increased use of prefabricated elements/ off-site manufacturing	✓					✓	
17	Demolition and rebuild	✓						
18	Construction optimisation	✓						
19	Reduction of transportation	✓	✓	✓				✓
20	Use of short supply chains			✓	✓			
21	Reduction of wastage		✓				✓	✓
22	Development of a database of materials and carbon				✓			

The mitigation strategies identified by the experts in the roundtable expert forum have been further elaborated in this section as discussed below.

Use of materials with lower embodied energy and carbon

This was found in literature as well as the experts. Tables T1, T2, T4 and T5 opined that during selection of construction materials, it is indeed important to analyse the embodied energy and EC emissions of them and select materials which have a lower EC contribution to the atmosphere. T4 highlighted that it is better to use carbon friendly materials such as timber and at the same time, to reduce highly carbon intensive materials such as cement. T2 further mentioned the importance of introducing sustainable initiatives to achieve good results with regards to this aspect.

Better design

All the tables except T2, were of the opinion that a better design would be a good mitigation strategy to reduce the EC emissions. T5 opined that energy efficient designs are to be implemented in projects to improve energy efficiency and ultimately reduce the EC emissions. On the other hand, T6 mentioned that by getting rid of inefficient designs or over designs, would also contribute in reducing the EC emissions. According to T3, it is important for the designers to be aware of the carbon intensive materials in order to contribute to better designs.

Reduction, recycle, reuse and recovery of EE/EC intensive construction materials

Reduction of EE/EC intensive construction materials, is one of the most important mitigation strategies of reducing EC. Furthermore, T3, T4 and T6 agreed on this aspect where T3 suggested getting rid of concrete and blocks would be a greater way to reduce the EC emissions while T4 conversed of reducing the usage of paper to contribute to sustainability. Similarly, T6 mentioned of reducing concrete, plastic, bricks and glass in construction would be ideal as these materials are identified as carbon intensive materials. T6 further added that if certain carbon intensive materials cannot be avoided, it is a good option to recycle, reuse and recover them rather than disposing them completely. Tables T1, T2, T3 and T5 also agreed on this aspect where T5 insisted the importance of using recycled products for construction projects as much as possible.

Refurbishment of existing buildings and adaptive reuse of buildings
Adaptive reuse of buildings has become the latest trend in many countries as demolition of buildings is considered as a waste of energy and material. Therefore, T4 opined that repurposing structures after use would be a good strategy to reduce the EC emissions in certain ways.

Inclusion of waste, by-product, and used materials into building materials
Inclusion of waste, by-product and used materials is considered as a good mitigation strategy to reduce EC emissions related to building materials. As disposal of waste consumes a considerable amount of energy resulting in carbon emissions, use of waste will reduce the EC emissions. T4 agreed on this by opining that reuse/ recycle of waste/by-products would enable to reduce EC emissions.

Increased use of local materials and components
Usage of local materials and components in construction projects would reduce EC emissions. T3 conversed that usage of local manufactured products would reduce the EC emissions and contribute to the benefit of local and national economy as well. Rather than importing products from abroad, usage of local manufactured products would reduce the EC emissions immensely as the EC emissions related to transportation can be reduced.

People-driven change
Reducing EC emissions cannot be just done by reducing carbon intensive materials or other means, but it has to be a collective effort of all parties to move towards achieving sustainability holistically. The construction activities carried out at site need to be pre-planned and managed well, in order to achieve good construction performance. Therefore, people driven change is essential socially, culturally and environmentally in order to improve sustainability in every manner. T2 agreed with this mitigation strategy and claimed that future focused decisions are quite important to reduce EC emissions and ultimately create sustainable construction.

Extending the building's life
Extending the life span of a building would reduce the EC emissions related to demolition, disposal and reconstruction. On the other hand, expanding the life span of a building cannot be an instant decision as it requires a considerable amount of attention through investigations, testing and monitoring to decide whether a particular building's life span can be extended or not. Therefore, it is important to design the building, considering this aspect and make the building future ready with flexibility to adapt to this requirement if needed. In addition, T1 stated that usage of durable materials/components would contribute and assist in extending the building's life.

Increased use of prefabricated elements/ off-site manufacturing
Unlike on-site manufacturing which contributes to wastage due to over ordering of materials, off-site manufacturing completely resolves this issue as it will manufacture only the quantity ordered. Off-site manufacturing uses much lower resource inputs and contributes to much lower waste outputs compared to on-site manufacturing. These will ultimately result in reduction of unnecessary EC emission contributions. Experts in T5 were of a similar opinion and suggested increasing off-site manufacturing in order to reduce the EC emissions in construction projects.

Reduction of transportation
Transportation directly contributes to EC emissions. Therefore, when supplying materials or components to site, the distance between suppliers and sites needs to be considered while disposing construction and demolition waste, the distance between site and the off-site location for disposal

need to be considered. By reducing these distances, the EC emissions related to transportation can be reduced immensely. In addition to that, Tables T1, T2 and T6 were of the opinion that reduction of logistics can be considered as a good mitigation strategy to reduce EC emissions.

Use of short supply chains
Shorter supply chains result in shorter production circles and shorter logistics. Therefore, it can result in reducing EC emissions. However, though this mitigation strategy was not found in literature, Tables T2 and T3 opined that this would reduce EC emissions in construction projects.

Reduction of wastage
Construction and demolition wastage in construction projects is a contribution to waste of energy. Therefore, reduction of wastage can contribute to reduction of EC. Tables T1, T5 and T6 also agreed on this stating that wastage needs to be disposed, which would contribute in EC emissions and further wastage simply mean that it is a waste of resources and energy which would have also contributed to unnecessary EC emissions.

Development of a database of materials and carbon
T3 suggested developing an updated database including materials and their carbon values could be beneficial for industry practitioners as it can be used as a guidance in selecting materials for construction projects. This would enable the practitioners to select low carbon materials by carrying out a material comparison by themselves.

5. Conclusion

A comprehensive review of the previous studies carried out on EC mitigation strategies and the opinions of the roundtable participants regarding identification of possible EC mitigation strategies that could be implemented to reduce the EC emissions in construction were discussed in this paper. Though 19 EC mitigation strategies were identified through literature, some of them were not identified by the experts in the roundtable. Those strategies were tools, methods and methodologies; government policy and regulations; decarbonisation of energy supply/grid; construction sector policy and regulations; more efficient construction process/techniques; carbon mitigation offsets, emissions trading, and carbon tax; carbon sequestration; demolition and rebuild; and construction optimisation. However, experts identified three new mitigation strategies, use of short supply chains; reduction of wastage; and development of a database of materials and carbon, that can be used to reduce EC emissions in construction projects. The mitigation strategy identified by most of the experts in tables was ‘better design’ followed by ‘use of materials with lower embodied energy and carbon’. Besides, ‘reduction, recycle, reuse and recovery of EE/EC intensive construction materials’, ‘reduction of transportation’ and ‘reduction of wastage’ were few other strategies which was recognised by at least 3 experts in tables. Apart from these strategies, few other strategies were identified by one or two experts in tables. As discussed in the paper, EC mitigation strategies can be implemented in order to reduce the EC emissions in construction projects.

Acknowledgement

The authors wish to acknowledge Western Sydney University, Australia for providing the funding support and furthermore, the participants of the roundtable expert forum for providing their opinions which was incorporated in producing this research paper.

References

Airaksinen, M & Matilainen, P 2011, 'A Carbon Footprint of an Office Building', *Energies*, vol. 4, no. 8, pp. 1197-210.

Akbarnezhad, A & Xiao, J 2017, 'Estimation and Minimization of Embodied Carbon of Buildings: A Review', *Buildings*, vol. 7, no. 4.

Ariyaratne, CI & Moncaster, AM 2014, 'Stand-alone Calculation Tools are not the Answer to Embodied Carbon Assessment', *Energy Procedia*, vol. 62, pp. 150-9.

ASBP 2014, *Embodied Carbon Industry Task Force Recommendations - Proposals for Standardised Measurement Method and Recommendations for Zero Carbon Building Regulations and Allowable Solutions*, The Alliance for Sustainable Building Products, London.

Ashworth, A & Perera, S 2015, 'Economics of Sustainability and Carbon Estimating', in *Cost Studies of Buildings*, Routledge, New York, pp. 491-529.

Chau, CK, Hui, WK, Ng, WY & Powell, G 2012, 'Assessment of CO2 emissions reduction in high-rise concrete office buildings using different material use options', *Resources, Conservation and Recycling*, vol. 61, pp. 22-34.

Chau, CK, Leung, TM & Ng, WY 2015, 'A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings', *Applied Energy*, vol. 143, pp. 395–413.

De Wolf, C, Cerezo, C, Murtadhawi, Z, Hajiah, A, Al Mumin, A, Ochsendorf, J & Reinhart, C 2017, 'Life cycle building impact of a Middle Eastern residential neighborhood', *Energy*, vol. 134, pp. 336-48.

De Wolf, C, Yang, F, Cox, D, Charlson, A, Hattan, AS & Ochsendorf, J 2016, 'Material quantities and embodied carbon dioxide in structures', *Proceedings of the Institution of Civil Engineers: Engineering Sustainability*, vol. 169, no. 4, pp. 150-61.

Dowden, M 2008, *Climate chang and sustainable development: law, policy and practice*, Estates Gazette, London.

Foxell, S 2014, *A Carbon Primer for the Built Environment*, Routledge, New York.

Giesekam, J, Barrett, J, Taylor, P & Owen, A 2014, 'The greenhouse gas emissions and mitigation options for materials used in UK construction', *Energy and Buildings*, vol. 78, pp. 202-14.

González, MJ & Navarro, JG 2006, 'Assessment of the decrease of CO2 emissions in the construction field through the selection of materials: Practical case study of three houses of low environmental impact', *Building and Environment*, vol. 41, no. 7, pp. 902-9.

Hammond, GP & Jones, CI 2011, *Embodied Carbon: The Inventory of Carbon and Energy (ICE)*, University of Bath and BSRIA, UK.

Harrington, P 2018, *Leading the Way – Low Carbon Policies and Measures in Australia's Capital Cities*, Cooperative Research Centre for Low Carbon Living, Australia.

Hitchin, R 2013, *Embodied Carbon and Building Services*, CIBSE.

Huang, B, Xing, K & Pullen, S 2017a, 'Carbon assessment for urban precincts: Integrated model and case studies', *Energy and Buildings*, vol. 153, pp. 111-25.

ICE 2015, *Energy Briefing Sheet: Embodied Energy and Carbon*, Institution of Civil Engineers.

Innovation Growth Team 2010, *Low Carbon Construction Final Report*, UK.

Intergovernmental Panel on Climate Change 2001, *Climate Change 2001: Mitigation, Contribution of Working Group III to the Third Assessment*, Intergovernmental Panel on Climate Change, UK.

Kang, G, Kim, T, Kim, Y-W, Cho, H & Kang, K-I 2015, 'Statistical analysis of embodied carbon emission for building construction', *Energy and Buildings*, vol. 105, pp. 326-33.

Koezjakov, A 2017, *The Effect of an Increase in Energy Efficiency on Embodied Energy use: A Scenario Analysis for Dutch Residential Buildings*, Master of Science thesis, Utrecht University.

Langdon, D 2009, *Embodied CO2 and CO2 emissions from new buildings and the impact of possible changes to the Energy standards*, Building Standards Division, Scottish Government, Livingston.

Lewis, P, Leming, M & Rasdorf, W 2012, 'Impact of Engine Idling on Fuel Use and CO2 Emissions of Nonroad Diesel Construction Equipment', *Journal of Management in Engineering*, vol. 28, no. 1, pp. 31-8.

Li, J & Colombier, M 2009, 'Managing carbon emissions in China through building energy efficiency', *Journal of Environmental Management*, vol. 90, no. 8, pp. 2436-47.

Ma, J-J, Liu, L-Q, Su, B & Xie, B-C 2015, 'Exploring the critical factors and appropriate polices for reducing energy consumption of China's urban civil building sector', *Journal of Cleaner Production*, vol. 103, pp. 446-54.

Mohammed, A, Mustapha, A & Mu'azu, N 2011, 'Energy efficient buildings as a tool for ensuring sustainability in the building industry', paper presented to *International Conference on Multimedia Technology*, Hangzhou, China, 26-28 July 2011.

Nässén, J, Holmberg, J, Wadeskog, A & Nyman, M 2007, 'Direct and indirect energy use and carbon emissions in the production phase of buildings: An input–output analysis', *Energy*, vol. 32, no. 9, pp. 1593-602.

Peters, GP 2010, 'Carbon footprints and embodied carbon at multiple scales', *Current Opinion in Environmental Sustainability*, vol. 2, no. 4, pp. 245-50.

Pomponi, F & Moncaster, A 2016, 'Embodied carbon mitigation and reduction in the built environment - What does the evidence say?', *Journal of Environmental Management*, vol. 181, pp. 687-700.

Reddy, BVV 2009, 'Sustainable materials for low carbon buildings', *International Journal of Low-Carbon Technologies*, vol. 4, no. 3, pp. 175-81.

RICS 2012, *Methodology to calculate embodied carbon of materials*, RICS, UK.

RICS 2014, *Methodology to calculate embodied carbon*, 1st edn, RICS, London.

Riedy, C, Lederwasch, A & Ison, N 2011, *Defining Zero Emission Buildings: Review and Recommendations*, Australian Sustainable Built Environment Council.

Schwartz, Y, Raslan, R & Mumovic, D 2018, 'The life cycle carbon footprint of refurbished and new buildings – A systematic review of case studies', *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 231-41.

Shafiq, N, Nurrudin, MF, Gardezi, SSS & Kamaruzzaman, AB 2015, 'Carbon footprint assessment of a typical low rise office building in Malaysia using building information modelling (BIM)', *International Journal of Sustainable Building Technology and Urban Development*, vol. 6, no. 3, pp. 157-72.

Teh, SH, Wiedmann, T, Schinabeck, J, Rowley, H & Moore, S 2015, 'Integrated Carbon Metrics and Assessment for the Built Environment', paper presented to *22nd CIRP conference on Life Cycle Engineering*, Sydney, Australia, 7-9 April 2015.

Teng, Y, Li, K, Pan, W & Ng, T 2018, 'Reducing building life cycle carbon emissions through prefabrication: Evidence from and gaps in empirical studies', *Building and Environment*, vol. 132, pp. 125-36.

Tingley, DD & Davison, B 2011, 'Design for deconstruction and material reuse', *Proceedings of the Institution of Civil Engineers - Energy*, vol. 164, no. 4, pp. 195-204.

Victoria, MF, Perera, S & Davies, A 2016, 'Design Economics for Dual Currency Management in Construction Projects', paper presented to *RICS COBRA 2016*, Toronto, Canada, 20-22 September 2016.