Analysis of embodied carbon and cost profiles of school buildings in Australia

Srinath Perera, Sepani Senaratne, M.N.N. Rodrigo and Luke Brady
Centre for Smart Modern Construction,
School of Built Environment, Western Sydney University,
Sydney, Australia

Received 8 March 2020
Revised 18 June 2020
18 September 2020
Accepted 20 December 2020

Abstract

Purpose – In recent years, there has been an increased focus on creating sustainable buildings that have a reduced carbon footprint. The primary method to achieve this has been through reducing operational carbon of buildings. However, as the industry aims to produce “carbon neutral” buildings with extremely low operational carbon through measures such as insulation, embodied carbon (EC) component could get increased. As such, it is equally important to understand the state of EC emissions in buildings. The aim of this research was to analyse typical EC and cost profiles of school buildings within Australia to understand which building elements need more attention.

Design/methodology/approach – The research involved measuring EC of five classroom blocks in schools in Sydney through a case study research approach and document survey. Bills of quantities from these projects were analysed to estimate the EC and cost profiles of the buildings.

Findings – Results indicated that some elements such as roof, site works, upper floors and substructure had a higher cost also demonstrating an increased EC indicating a possibility of a relationship between carbon and cost. Accordingly, these elements were identified as the typical carbon hotspots within school buildings in Australia, which need greater attention in reducing EC.

Originality/value – The study explores the carbon–cost profile of Australian school buildings and highlights the importance of reducing EC in carbon hotspots.

Keywords Embodied carbon, Operational carbon, Embodied carbon estimating, Carbon and cost profile, Carbon hotspots, School buildings

Paper type Research paper

1. Introduction

Australia must reduce CO_2 emissions by 26–28% based on 2005 levels by the year 2030 to meet the targets set in the Paris Agreement (Government, 2017). One important step to achieve this could be a reduction of CO_2 emissions from the construction industry (ASBEC, 2016). The construction industry is an enormous contributor to Australian CO_2 emissions accounting for 18.1% of total life cycle carbon emissions in 2013 (Yu *et al.*, 2017).

Life cycle carbon of a building encompasses two types, operational carbon (OC) and embodied carbon (EC) (Zhou and Azar, 2019). OC is the carbon emitted during the operational phase of a building, whereas EC refers to the carbon emitted during the production process of various products (Gan *et al.*, 2018). Typically, around 70–80% of emissions are produced in the operational phase of the building, leaving the remaining emissions to be released from EC during the materials manufacturing process (RICS, 2014). However, the ratio between OC and EC could depend on the type of the building. For example, warehouse being a low specification building produces less OC as it has low heating and cooling requirements compared to a residential or office building, making it have a higher EC component (Ashworth and Perera, 2015; Rodrigo *et al.*, 2019b).

This paper presents the research findings of a research project carried out at the Centre for Smart Modern Construction in the School of Built Environment, Western Sydney University.

Built Environment Project and Asset Management
Vol. 11 No. 4, 2021
pp. 660-672
© Emerald Publishing Limited
2044-124X
DOI 10.1108/BEPAM-02-2020-0031

Many developed countries such as Sweden, France, United Kingdom, Italy, Germany, among others, have reduced their carbon emissions approximately by 30–40% with the introduction of climate policies and consequent changes in energy profiles (Canadell *et al.*, 2020). The increased focus on reducing the environmental footprint of buildings has led to lowering OC by introducing zero carbon buildings (Kang *et al.*, 2015; Zhao and Pan, 2017; Athapaththu and Karunasena, 2018). For example, Stephan *et al.* (2013) discussed that passive houses generally incorporate increased insulation and triple glazed windows to achieve energy savings. These result in adding more materials to achieve greater insulation increasing the EC in the building (Stephan *et al.*, 2013). Thus, reducing OC alone will not necessarily reduce the net emissions. Sartori and Hestnes (2007) recommended that, when aiming to reduce the life cycle carbon of a building, the focus should be paid not only on reducing the OC, but also the EC. According to the carbon road map introduced by Green Building Council Australia (2018), the main target is to reduce OC by 100% and the EC by 10% by the year 2028. RICS (2012) and Perera and Victoria (2017) emphasised the importance of identifying the carbon hotspots and reducing the EC in such carbon-intensive elements of a building. While there are limited studies such as Victoria *et al.* (2016), which identify carbon hotspots for office and residential buildings in the United Kingdom, studies on school buildings and in Australia are lacking.

On the other hand, clients are more interested in reducing the cost of a project. From their perspective, it would be more beneficial to identify building elements or materials that have both low EC and cost, where they could gain economic advantages as well as higher green star ratings and for consultants, it would be easier to convince clients on lower EC options. Langston *et al.* (2018) carried out a study on new-build and refurbished projects in Hong Kong and Melbourne. Their results revealed that there is a strong relationship between EC and cost. Similarly, studies carried out by Victoria *et al.* (2017), Jiao *et al.* (2012), Copiello (2016) in the United Kingdom, China and Italy, respectively, revealed the existence of carbon–cost relationship in certain building elements or materials. Similarly, it is important to explore the possibility of a cost–carbon relationship in school buildings of Australia. Within the year 2019, housing construction has increased by 0.7% in NSW, while school buildings and other non-residential have increased by 0.4% (Australian Bureau of Statistics, 2020). Though there is an increase of construction in school buildings and a scarcity of studies in Australian context in particular, the carbon–cost relationship in school buildings has not been explored even elsewhere. This research aims to analyse the elemental EC and cost profile of school buildings in Australia in order to recommend building elements, which needs more attention in the planning stage to reduce their EC and cost simultaneously.

2. Embodied carbon estimating methods and tools

The early-stage estimation describes measuring EC during the preliminary design of the building, where there is a lack of detailed information. At this stage, RICS (2014) recommended to measure EC, by multiplying the gross floor area of the building measured in m^2 with an EC rate in $kgCO_2e/m^2$. The design development stage is where more details of the building become known providing more accurate EC estimates. This would be the ideal stage to complete EC estimates. However, due to a lack of accurate elemental EC rates, this is often forgone (Ashworth and Perera, 2015).

Measurement of the EC of a building material is highly complicated, and there is often variation and inconsistency within the results (Jackson and Brander, 2019; Rodrigo *et al.*, 2019a). The geographical location and system boundaries (cradle-to-gate, cradle-to-site, cradle-to-end of construction, cradle-to-grave and cradle-to-cradle) that each study chooses to measure will affect the EC estimates (Dixit *et al.*, 2010). De Wolf *et al.* (2017) further support the notion that lack of transparency within methodologies, varying carbon data sets and calculators used and varying life cycle phases measured result in inconsistent results between studies.

Dixit *et al.* (2010) concluded that to improve the accuracy and validity of results from studies measuring the EC, a uniformed method should be introduced for future research. Rodrigo *et al.* (2019a) proposed a new methodology for estimating EC in construction supply chains using the value chain concept and blockchain technology to mitigate the existing issues in EC estimating. This study used the EC database, Blackbook (Franklin and Andrews, 2010; Ekundayo *et al.*, 2019), as it was the most appropriate EC estimating method based on available tools currently in the practice.

Crawford and Stephan (2015) discussed that estimating EC within Australia is difficult due to lack of published data. To determine the most popular data sets for estimating EC, they conducted a survey for 46 different construction companies within Australia. The results from this study indicate that "SimaPro" followed by "eTool" were the most popular software used in Australia to estimate EC (Crawford and Stephan, 2015). EC rates for materials can be derived from international databases such as WRAP, a UK-based carbon calculator (WRAP, 2018), Inventory of Carbon and Energy (ICE), an online carbon database (ICE, 2015), the Green Guide Calculator another online database used in the United Kingdom and Blackbook (Franklin and Andrews, 2010), which is an online and hard copy carbon data set (Ashworth and Perera, 2015). There are certain limitations within most of these carbon data sets and carbon calculators that affect the accuracy of the EC estimates (Victoria *et al.*, 2017). These need to be addressed to provide more accurate EC measurement results.

Even though "eTool" is a popular Australia-based carbon data set, it was not used in this study. "eTool" is better suited in providing an overview of life cycle carbon emissions in the early design stages of a project, and it does not provide detailed EC emission factors for all the items in the bills of quantities (BOQs) as provided in Blackbook. Few Australia-based EC and LCA databases, such as ECE Tool, The Footprint Calculator and The Greenbook 2020, have been released recently (Rodrigo *et al.*, 2020). These tools are not freely available; however, any user who requires to use them can obtain a subscription-based licence. There were no studies which had used these tools, most probably, as they were only launched in 2019. However, Blackbook has been used by various studies to estimate EC, analyse its findings and derive at conclusions (Menzies, 2011; Victoria *et al.*, 2015).

Ekundayo *et al.* (2012) discussed that Blackbook has been developed from the ICE database based on UK data, which is internationally recognised and accredited. ICE database provides EC emission factors for various construction materials. In order to estimate EC using ICE, the project BOQ has to be converted to a bill of materials, which is a time-consuming process. Unlike other tools, Blackbook comprises of EC rates in a BOQ format (Ekundayo *et al.*, 2019) considering the system boundary, cradle-to-end of construction. Hence, calculations could be easily carried out as the project data were also in a BOQ format. Blackbook consists of location factors to convert UK EC rates to Australian EC rates, which was lacking in many other international databases such as WRAP, ICE, GaBi and Athena. It also allows cost and EC rates to be measured and compared in parallel, which supports the aim of this study. It also enables to present the carbon profile of the building in an elemental format.

3. Research method

Case studies have been implemented in this research to gather and quantify results, while conducting a detailed investigation on the specific context. Case studies are more appropriate for this study compared to other methods as they offer a closer in-depth investigation into real-life contexts. For similar studies carried out by Victoria *et al.* (2017) and Fernando *et al.* (2018), a case study approach has been used to estimate EC in various buildings in the United

Kingdom. Five school projects handled by a commercial mid-tier building organisation in Sydney were selected through purposive sampling due to the time and funding constraints and further based on the factors, comparable size; similar cost; similar materials; similar number of storeys; and similar level of finishes. Data for this research was obtained through a document review. The details of selected case studies are outlined in Table 1.

EC estimation for each building element was carried out by multiplying the quantity of the element with the EC rate related to that element as illustrated in Equation (1).

$$EC_E = Q_E \times E_E \tag{1}$$

(where EC_E = embodied carbon emitted in element; Q_E = quantity of the element; E_E = embodied carbon rate related to that element)

The quantity of each element could be directly obtained from the BOQ and the EC rate of that element was obtained from Blackbook, which was adjusted for location and compatibility for the item measured. According to Blackbook, the location adjustment factor to convert UK EC emission rates to Sydney was 1.06. Therefore, the EC emission rates obtained from Blackbook were multiplied by this factor. After every item under all the trades in the BOQ had been multiplied by an appropriate EC rate, the carbon estimation was complete. Subsequently, the total carbon of each "trade" was calculated using Equation (2) followed by preparation of a trade breakup summary for carbon and cost values, which comprised of the various trades in the BOQ.

School project	Description including elemental specification	Gross floor area (GFA) (m^2)	Project cost (AUD)	Documentation	Year
Case study 1	A single storey irregular-shaped classroom block. Combination of brick work and metal wall cladding. Metal sheet roofing, aluminium windows	894	2,145,753	BOQ	2015
Case study 2	A two-storey high classroom block with an undercover COLA. Featuring a mix of metal roof and wall sheeting. Aluminium windows and timber doors with carpet and vinyl floors. External works comprising of steel gates, fencing, concrete paving and the like	1,708	3,906,039	BOQ	2017
Case study 3	A single-story classroom block. Metal roof sheeting with brickwork to external walls and acoustic wall panels for internal walls. Large total floor area and external works comprising of concrete roads, steel gates, steps, ramps and fences	1,238	4,074,444	BOQ	2014
Case study 4	A two-storey classroom block. Sheet metal roofing with timber trusses. Metal wall cladding, aluminium framed windows, timber doors and carpet and vinyl flooring	1,695	770,069	BOQ	2016
Case study 5	A two-storey classroom block with a COLA underneath. Sheet metal roofing, brick, block, concrete used external walls, steel stud framed timber wall panels for internal walls and aluminium framed windows	1,496	1,141,512	BOQ	2014

Table 1. Description of case studies

$$EC_{\mathrm{Trade},j} = \sum_{i=1}^{n} EC_{E,i} \tag{2}$$

(Where $EC_{\mathrm{Trade},j}$ = embodied carbon emitted in the jth trade; $EC_{E,i}$ = embodied carbon emitted in ith element)

However, the trade breakdown format was not ideal to present and compare the carbon and cost profiles of the building elements. This is because there is a lack of consistency amongst trades and each trade varies with items in different buildings. Building elements offer same function irrespective of the building, and therefore, an elemental breakdown offers better comparisons, which is also the reason for using cost analyses. The standard elemental breakdown based on the Australian Institute of Quantity Surveyors was employed. Firstly, the items with similar functions were grouped together and were coded with the initials of the relevant building element. For example, wall tiling, plasterboard wall lining, joinery and painting were measured under four trades in the BOQ; however, in the elemental breakup all four trades could be measured as "wall finishes" because all their functions are decorative finishes to internal walls and the group, "wall finishes", was given the code, WF.

Once this had been completed for all the items, the total carbon of building elements was calculated. To develop the element unit rate for carbon, the total carbon was divided by the total area (m^2) for each element. This could be used to determine carbon per m^2 of each building element. Next, the element rate was calculated by dividing the total carbon by the gross floor area (GFA) of the building. The GFA is the total floor area within a building. This determined the average carbon amount per m^2 of the total building area. Subsequently, the same method was followed to estimate the elemental unit cost along with the average cost per m^2 of the GFA. The results are presented and discussed in Section 4.

Cross-case analysis was carried out to analyse the five case studies and compare the similarities and dissimilarities among them related to cost and carbon profiles as explained in Section 4.1. The average element rates for cost and carbon of each building element were calculated to further examine the cost and carbon profiles of the case studies. This was achieved by adding the element rate cost/carbon of each building element from case studies 1 to 5 and then dividing the total by 5. However not every case study featured every building element, for example, case studies 1 and 3 were single storey, therefore these buildings did not feature, columns, upper floors or staircases, so for these elements the average of only three case studies could be taken. Similarly, only case studies 1 and 5 featured internal screens, therefore, the average for this element was only taken from two values.

Subsequently, an analysis was carried out to compare the overall case study findings related to cost against results of Rawlinsons' Australian Construction Handbook and findings related to carbon with existing literature. Moreover, the existence of carbon–cost relationship for certain elements was compared with the findings of other similar studies to derive at conclusions.

4. Discussion of results

The following results demonstrate the findings from the five case studies. For each case study, the EC and cost profiles were created. Subsequently, the most carbon-intensive building elements and the highest costing elements could be observed. Further analysis of these results was carried out to determine if there was a relationship between a higher costing element having an increased amount of EC. Distribution of the EC within these case studies was also highlighted through identifying the "carbon hotspots", demonstrating the patterns of EC within school buildings. The results of the five case studies are depicted in Figure 1–5 respectively. Each dot point in Figure 1–5 has a value for cost per m^2 from x axis and a value

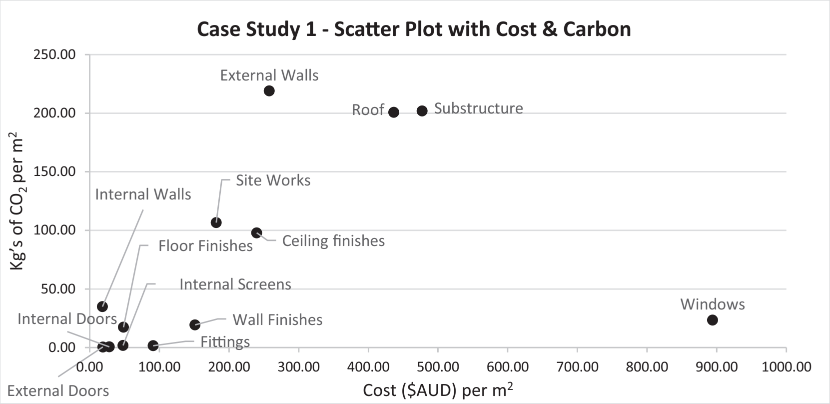

Figure 1.
Case study 1 building elements cost versus carbon

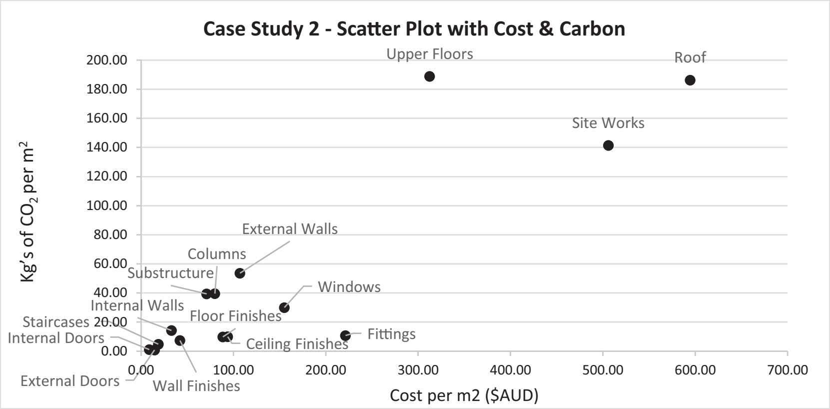

Figure 2.
Case study 2 building elements cost versus carbon

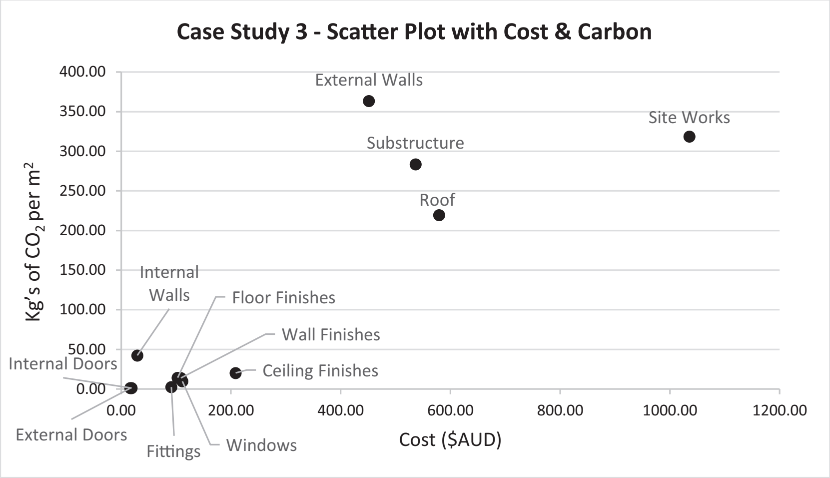

Figure 3.
Case study 3 building elements cost versus carbon

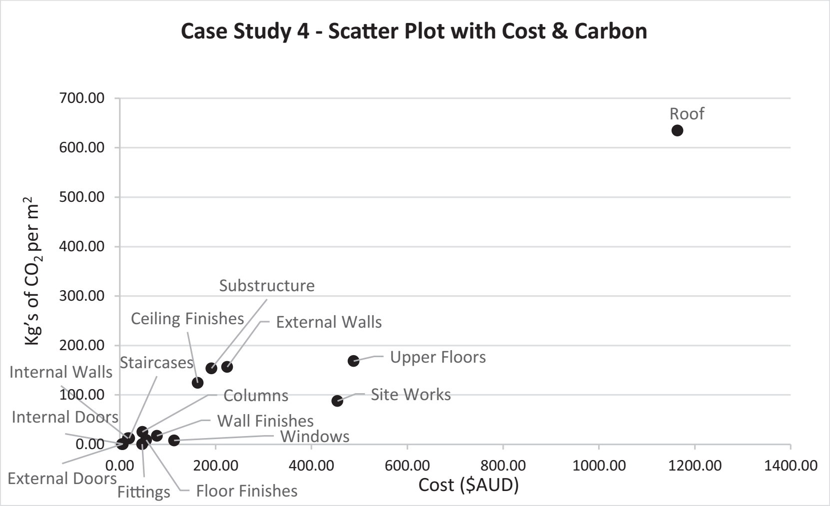

Figure 4.
Case study 4 building elements cost versus carbon

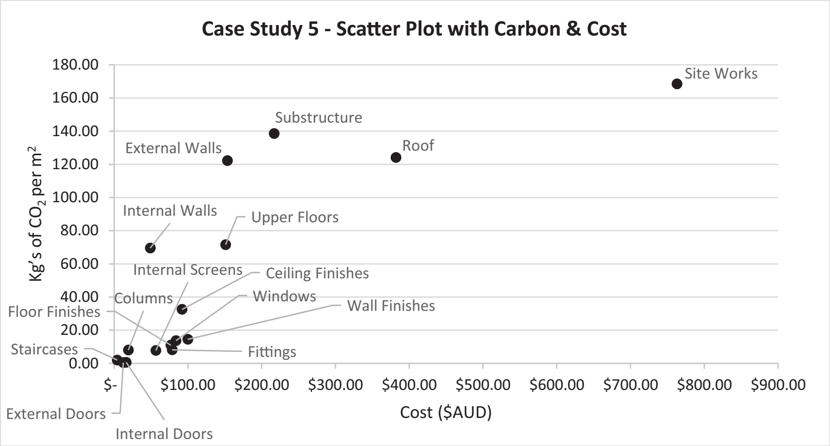

Figure 5.
Case study 5 building elements cost versus carbon

for carbon per m^2 from *y* axis. As an example, in Figure 1, the dot point for substructure demonstrates a cost of $477.32 per m^2 and a carbon rate of 201.97 kg's of CO_2 per m^2.

Some elements demonstrate a relationship between carbon and cost as shown in Figure 1. External walls have a cost of $257.76 per m^2 with an element rate of 219.14 kg's of CO_2 per m^2. Similarly, roof and substructure illustrate a similar relationship. Roof has a cost of $436.47 per m^2 and a carbon rate of 200.64 kg's of CO_2 per m^2, while substructure depicts a cost of $477.32 per m^2 and a carbon rate of 201.97 kg's of CO_2 per m^2. The cost per m^2 is significantly higher than the EC per m^2 in multiple building elements. Windows, being made of aluminium, have an extremely high cost of $403.29 per m^2, as a result of current inflated prices within the greater Sydney region, whilst having a relatively low EC rate of 23.48 kg's of CO_2 per m^2, due to usage of recycled material.

According to Figure 2, the roof being a steel trussed roof showed both high cost and EC, with the cost at \$594.59 per m^2 and EC at 186.32 kg's of CO_2 per m^2. Similarly, for site works the cost was \$506.01 per m^2 and EC rate was 141.36 kg's of CO_2 per m^2 due to comprising of items related to steel gates, fencing, concrete paving and the like. Concrete and steel being two of the most carbon-intensive materials, it was very likely for site works to have a higher EC rate. However, due to the quantities of items and materials used, the expected output was not demonstrated. Furthermore, upper floors comprising of post-tensioned and concrete slabs and beams, showed a cost of \$312.46 per m^2 and a carbon value of 188.90 kg's of CO_2 per m^2. On the other hand, internal doors and external doors demonstrated a lower cost and EC, as most doors were timber doors, whereas timber is one of the least carbon-intensive materials. However, between most of the building elements, the cost and carbon per m^2 were not similar. Examples of such building elements are, fittings, which cost \$221.35 per m^2 with a carbon value being only 10.79 kg's of CO_2 per m^2, and windows, which cost \$155.15 per m^2 and the carbon was 30.33 kg's of CO_2 per m^2.

According to the results illustrated in Figure 3, the external walls being constructed using brick and concrete have demonstrated a cost of \$451.46 per m^2 of the GFA and an EC rate of 363.55 kg's of CO_2 per m^2, while the internal walls, being constructed with acoustic wall panels that are cheap in cost and low in EC rate, have demonstrated a cost of \$29.27 per m^2 of the GFA and 42.40 kg's of CO_2 per m^2. Site works show a higher cost per m^2 and a higher EC rate per m^2 due to comprising of concrete roads, steel gates, steps, ramps and fences. Similarly, the steel trussed roof and substructure comprising of expensive and carbon-intensive materials, concrete and brick are showing higher costs of \$579.63 and \$536.44 per m^2 and higher EC rates of 219.57 and 283.51 per m^2 respectively. The similar rates of the building elements can be observed in Figure 3, which demonstrates that for some building elements as the cost increases, the EC also increases, that is, external and internal walls. However, for other building elements this relationship does not occur. This can be seen within fittings, windows, ceiling finishes, wall finishes and floor finishes, where a higher cost does not also show an increased amount of EC.

The results from the carbon and cost profiles for this case study as illustrated in Figure 4 represent a similar pattern to other case studies. There are some elements, where the higher cost also sees an increased amount of EC. For example, steel trussed roof has a cost of \$1164.03 per m^2 of GFA and an element carbon rate of 635.07 kg's of CO_2 per m^2. On the other hand, some elements have a similar cost and similar carbon rate. The substructure has a cost of \$191.45 per m^2 of GFA and an element carbon rate of 153.91 kg's of CO_2 per m^2. External doors resulted in lowest elemental cost and EC rate as they were constructed using one of the lowest carbon-emitting materials, timber. However, there were multiple elements, where an increased cost did not result in an increasing amount of EC. The windows demonstrate a cost of \$113.27 per m^2, with only an element carbon rate of 8.02 kg's of CO_2 per m^2. Also, the fittings had a cost of \$46.66 per m^2 with only 0.71 kg's of CO_2 per m^2. As similar to previous cases, timber windows and joinery are the reason for demonstrating lower EC values.

The cost of the building elements is typically greater than the EC within the building elements as shown in Figure 5. There are some elements, where the higher cost also sees an increase in EC. For example, site works demonstrated the highest cost per m^2 and highest EC rate per m^2, due to comprising of concrete roads, steel gates and fences. However, though the external walls showed a higher EC rate, elemental rate cost was comparatively lower as the materials used for wall construction were bricks, blocks and concrete. Concrete being one of the most carbon-intensive materials used in building construction resulted in higher EC rate. Similarly, the element rate cost of internal walls is \$48.80 per m^2 of GFA and the element rate carbon is higher at 69.50 kg's of CO_2 per m^2 as the internal walls were constructed of steel stud framed timber wall panels. As steel is a carbon-intensive material, the EC rate of internal wall panels has demonstrated a higher amount. However, the cost is greater than the EC for the majority of elements such as windows, with a cost of \$83.90 per m^2 of GFA and only 13.71 kg's of CO_2 per m^2. This was reflected in other case studies as well, where the fittings indicated a cost of 78.57 per m^2 of GFA; however, its carbon value was only 8.1271 kg's of CO_2 per m^2.

4.1 Comparative analysis of cost and embodied carbon

The average element rate cost and average element rate carbon of each building element were produced in a clustered column graph and a line chart respectively, as illustrated in Figure 6, to examine whether there was a relationship between the higher costing building elements having a higher amount of EC.

Majority of building elements indicated that there is no clear relationship between carbon and cost. However, there are some elements, where both cost and carbon being high such as roof, site works, upper floors and substructure. The highest element rates for both cost and carbon are demonstrated in the element, roof, with \$631.36 per m^2 and 273.15 kgCO_2 of GFA, respectively. The roof in all cases consisted of steel trussed roofs, whereas steel is one of the most expensive and most carbon-intensive building materials. Site works have a cost of \$588.17 and an element rate carbon of 164.56 kgCO_2 per m^2. Upper floors have an element rate cost of \$317.17 with an element rate carbon of 142.99 kg's of CO_2 per m^2 of GFA. The substructure has an element rate cost of \$298.61 per m^2 and an element rate carbon cost of 163.45 kg's of CO_2 per m^2. These results indicate that for the roof, site works, upper floors and substructure, there is a relationship between cost and carbon. However, due to the limited number of case studies used in this study, it is difficult to conclude and generalise the findings.

Rawlinsons' Australian Construction Handbook, a popular cost guide book within Australia, was reviewed to conduct a comparison between the typical cost profiles from this research and standard industry rates. Rawlinsons (2017) presents the elemental rates per GFA for educational buildings as an average value. These average values were used to carry out the comparison of the costs as demonstrated in Table 2.

The cost comparison within Table 2 illustrated that some building elements showed a relatively similar cost, for example, columns, external walls, external doors, internal screens and floor finishes. There were several building elements where the average element cost of the selected case studies was significantly higher than Rawlinsons (2017) such as substructure, upper floors, roof, wall finishes and ceiling finishes. This could have been

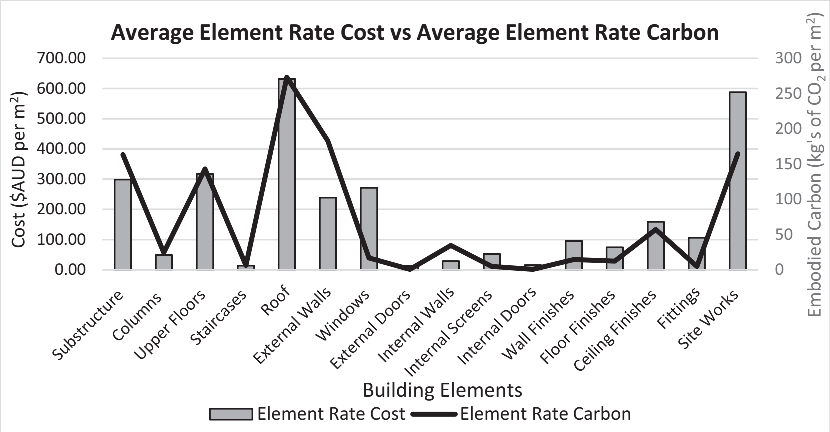

Figure 6.
Comparative analysis of average cost and embodied carbon

Building element	Rawlinson's (2017) cost (AUD per m^2 of GFA)	Average cost in this study (AUD per m^2 of GFA)	Difference between average cost and Rawlinson's cost
Substructure	76.50	298.61	222.11
Columns	35.25	48.73	13.48
Upper floors	178.00	317.17	139.17
Staircases	32.00	14.14	−17.86
Roof	149.00	631.36	482.36
External walls	244.50	238.81	−5.69
External doors	10.75	13.45	2.70
Internal walls	76.50	29.26	−47.24
Internal screens	47.00	52.16	5.16
Internal doors	26.25	15.78	−10.47
Wall finishes	28.25	95.87	67.62
Floor finishes	64.50	74.39	9.89
Ceiling finishes	79.00	159.29	80.29
Fittings	197.25	105.79	−91.46
Total	1805.00	2094.80	289.80

Table 2. Cost comparison of building elements

due to the limitations of the study mainly related to the selected sample being only five case studies, which were obtained from one building organisation in Sydney. There were also some building elements where Rawlinsons (2017) had a higher cost for elements such as staircases, external walls, internal walls, internal doors and fittings. The difference of the total element cost rates is $289.80 and as a percentage, it is 16% higher than Rawlinsons (2017), which is quite a considerable difference, which again would have been resulted due to the limitations of the study.

The elements with highest EC emissions in all case studies were identified as roof, external walls, site works, substructure and upper floors. Similarly, Victoria *et al.* (2017) found that substructure, frame and services were recognised as the carbon hotspots in their study. Having identified that within multiple building elements, there is a relationship between a high cost ensuing an increase of EC, efforts to reduce EC should be focussed on these elements where there is also a greater opportunity to achieve cost savings. This notion of a relationship between carbon and cost is supported by a study conducted in the United Kingdom, which analysed two office buildings and found that substructure, frame and services were both carbon and cost-critical elements (Victoria *et al.*, 2017). Another study by Jiao *et al.* (2012) examined two commercial building projects in China and one in New Zealand. Findings from this research concluded there was a positive relationship between total EC and total cost for each building; however, it existed for some individual building components only. Further, research carried out in Italy suggests a relationship between EC and cost exists, however, only for some materials and elements within a building (Copiello, 2016). In being consistent with these previous studies, specific findings within this research indicated that there is a possibility of a positive relationship between cost and carbon for elements roof, site works, upper floors and substructure for similar school buildings in Australia. As the five case studies are not statistically sufficient to prove the co-relationship between carbon and cost, it can be further researched to prove the findings of this study.

5. Conclusions

The research aimed at analysing the EC and cost profiles of school buildings within Australia. A review into literature discovered that carbon estimation is very complex and the accuracy of estimates is greatly affected by multiple variables. Previous studies had considered different stages of the building life cycle, where varying carbon data sets are used, thus, the practice is immensely unregulated and the results can differ greatly between buildings. The available carbon estimating methods were reviewed and after considering time–cost constraints, availability of data and type of data, the Blackbook was selected for the study.

Primarily, this was a qualitative study with an in-depth analysis of case studies. However, the data analysis incorporated elements of a quantitative study, where EC calculations were carried out. The cost data of each case study was available within the BOQ of the respective project, which was obtained through a document survey. The results that were produced through the carbon estimation were presented alongside the cost to develop the carbon and cost profiles in the elemental breakdowns.

The building elements with the greatest amount of EC were the roof, external walls, site works, substructure and upper floors and were identified as the carbon hotspots within all of the case studies. Building elements with the highest cost were the roof, site works, upper floors, substructure and windows. It was determined that for some building elements such as external walls, columns, internal walls and substructure, there was a possibility of a clear relationship between the cost and carbon. However, in other building elements, a higher cost did not result in increased EC. EC reduction of the elements that indicate a possibility of a relationship between carbon and cost could reduce the cost of those elements, which will be highly attractive to investors to achieve savings, while contributing towards sustainability. According to the carbon road map introduced by Green Building Council Australia, it is targeted to reduce 10% of EC emissions by the year 2028. In order to achieve this type of reductions, building designers can target carbon hotspots identified in this research. As certain elements are indicating possible carbon–cost relationship, this information can also help in reducing building cost while achieving carbon reduction as well.

The research further recommends establishment of a standard method of assessing EC in buildings within green star rating system to assess the EC that buildings will emit. This could be examined early within the design stages, so if required design changes could be made in buildings to lower EC and achieve a better star rating. Moreover, incorporating EC data rates into popular Australian cost indices such as Rawlinson's Construction Cost Guide and Cordell's Cost Guide could enable to prepare preliminary EC estimates during early design stages.

Since this study used EC of five case studies, the results cannot be statistically generalised over the entire population. Further, selection of case studies from one organisation may affect with organisation-specific contextual factors. However, the results could be theoretically generalised and could form the basis of a baseline data set for further similar studies. This method could be replicated by construction companies, who undertake repetitive projects such as banks, hotels, hospitals, among others, to identify carbon hotspots specific to those types of buildings.

References

ASBEC (2016), *Low Carbon, High Performance, How Buildings Can Make a Major Contribution to Australia's Emissions and Productivity Goals*, Climate Works.

Ashworth, A. and Perera, S. (2015), *Cost Studies of Buildings*, 6th ed., Taylor and Francis, Oxon.

Athapaththu, K.I. and Karunasena, G. (2018), "Framework for sustainable construction practices in Sri Lanka", *Built Environment Project and Asset Management*, Vol. 8 No. 1, pp. 51-63.

Australian Bureau of Statistics (2020), *Australian Producer Price Indexes*, March 2020, Australian Bureau of Statistics, available at: https://www.abs.gov.au/ausstats/abs@.nsf/Latestproducts/6427.0Main%20Features2Mar%202020?opendocument&tabname=Summary&prodno=6427.0&issue=Mar%202020&num=&view= (accessed 1 June 2020).

Canadell, P., Le Quere, C., Peters, G., Korsbakken, J.I. and Andrew, R. (2020), "Eighteen countries showing the way to carbon zero", available at: https://theconversation.com/eighteen-countries-showing-the-way-to-carbon-zero-112295 (accessed 1 June 2020).

Copiello, S. (2016), "Economic implications of the energy issue: evidence for a positive non-linear relation between embodied energy and construction cost", *Energy and Buildings*, Vol. 123, pp. 59-70.

Crawford, R. and Stephan, A. (2015), "The Australian construction industry's approach to embodied carbon assessment: a scoping study", *Living and Learning: Research for a Better Built Environment: 49th International Conference of the Architectural Science Association 2015*, Melbourne.

De Wolf, C., Pomponi, F. and Moncaster, A. (2017), "Measuring embodied carbon dioxide equivalent of buildings: a review and critique of current industry practice", *Energy and Buildings*, Vol. 140, pp. 68-80.

Dixit, M.K., Fernández-Solís, J.L., Lavy, S. and Culp, C.H. (2010), "Identification of parameters for embodied energy measurement: a literature review", *Energy and Buildings*, Vol. 42 No. 8, pp. 1238-1247.

Ekundayo, D., Perera, S., Udeaja, C. and Zhou, L. (2012), "Carbon review and qualitative comparison of selected carbon counting tools", *RICS COBRA Research Conference*, Las Vegas, Nevada.

Ekundayo, D., Babatunde, S.O., Ekundayo, A., Perera, S. and Udeaja, C. (2019), "Life cycle carbon emissions and comparative evaluation of selected open source UK embodied carbon counting tools", *Construction Economics and Building*, Vol. 19 No. 2, pp. 220-242.

Fernando, N.G., Ekundayo, D.O. and Victoria, M.F. (2018), "Embodied carbon emissions of buildings: a case study of an apartment building in the UK", *7th World Construction Symposium 2018: Built Asset Sustainability; Rethinking Design, Construction and Operation*, Colombo.

Franklin and Andrews (2010), *Hutchins UK Building Blackbook: The Capital Cost and Embodied CO2 Guide*, Major Works, Vol. 2, Franklin and Andrews, London.

Gan, V.J., Tse, M.D.K.T.T., Chan, C.M., Lo, I.M.C. and Cheng, J.C.P. (2018), "Holistic BIM framework for sustainable low carbon design of high-rise buildings", *Journal of Cleaner Production*, Vol. 195, pp. 1091-1104.

Government (2017), "Paris agreement department of environment and energy", available at: http://www.environment.gov.au/climate-change/international/paris-agreement (accessed 15 March 2017).

Green Building Council Australia (2018), *A Carbon Positive Roadmap for the Built Environment*, Green Building Council Australia.

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

Jackson, D.J. and Brander, M. (2019), "The risk of burden shifting from embodied carbon calculation tools for the infrastructure sector", *Journal of Cleaner Production*, Vol. 223, pp. 739-746.

Jiao, Y., Lloyd, C. and Wakes, S. (2012), "The relationship between total embodied energy and cost of commercial buildings", *Energy and Buildings*, Vol. 52, pp. 20-27.

Kang, G., Kim, T., Kim, Y.-W., Cho, H. and Kang, K.-I. (2015), "Statistical analysis of embodied carbon emission for building construction", *Energy and Buildings*, Vol. 105, pp. 326-333.

Langston, C., Chan, E.H.W. and Yung, E.H.K. (2018), "Embodied carbon and construction cost differences between Hong Kong and Melbourne buildings", *Construction Economics and Building*, Vol. 18 No. 4, pp. 84-102.

Menzies, G.F. (2011), *Embodied Energy Considerations for Existing Buildings*, Heriot-Watt University, Edinburgh.

Perera, S. and Victoria, M.F. (2017), "The role of carbon in sustainable development", in Brandon, P.S., Lombardi, P. and Shen, G.Q. (Eds), *Future Challenges in Evaluating and Managing Sustainable Development in the Built Environment*, John Wiley and Sons, New Jersey, pp. 125-154.

Rawlinsons (2017), *Australian Construction Handbook*, 35th ed., Rawlinsons Publishing, Perth.

RICS (2012), *Methodology to Calculate Embodied Carbon of Materials*, RICS Professional Information, London.

RICS (2014), *Methodology to Calculate Embodied Carbon*, 1st ed., RICS, London.

Rodrigo, M.N.N., Perera, S., Senaratne, S. and Jin, X. (2019a), "Conceptual model on estimating embodied carbon in construction supply chains using value chain and blockchain", *AUBEA 2019*, AUBEA, Noosa.

Rodrigo, M.N.N., Perera, S., Senaratne, S. and Jin, X. (2019b), "Embodied carbon mitigation strategies in construction industry", *CIB World Building Congress 2019*, CIB, Hong Kong.

Rodrigo, M.N.N., Perera, S., Senaratne, S. and Jin, X. (2020), "Potential application of blockchain technology for embodied carbon estimating in construction supply chains", *Buildings*, Vol. 10 No. 8, p. 140.

Sartori, I. and Hestnes, A.G. (2007), "Energy use in the life cycle of conventional and low-energy buildings: a review article", *Energy and Buildings*, Vol. 39 No. 3, pp. 249-257.

Stephan, A., Crawford, R.H. and De Myttenaere, K. (2013), "A comprehensive assessment of the life cycle energy demand of passive houses", *Applied Energy*, Vol. 112, pp. 23-34.

Victoria, M.F., Perera, S. and Davies, A. (2015), "Developing an early design stage embodied carbon prediction model: a case study", *31st Annual ARCOM Conference*, Lincoln.

Victoria, M., Perera, S. and Davies, A. (2016), "A pragmatic approach for embodied carbon estimating in buildings", *International Conference on Sustainable Built Environment*, Torino.

Victoria, M.F., Perera, S., Davies, A. and Fernando, N. (2017), "Carbon and cost critical elements: a comparative analysis of two office buildings", *Built Environment Project and Asset Management*, Vol. 7 No. 5, pp. 460-470.

WRAP (2018), *WRAP – Embodied Carbon Database*, WRAP, available at: http://ecdb.wrap.org.uk/About.aspx (accessed 2 August 2018).

Yu, M., Wiedmann, T., Crawford, R. and Tait, C. (2017), "The carbon footprint of Australia's construction sector", *International High Performance Built Environment Conference – A Sustainable Built Environment Conference 2016 Series (SBE16)*.

Zhao, X. and Pan, W. (2017), "Co-productive interrelations between business model and zero carbon building: a conceptual model", *Built Environment Project and Asset Management*, Vol. 7 No. 4, pp. 353-365.

Zhou, H. and Azar, E.R. (2019), "BIM-based energy consumption assessment of the on-site construction of building structural systems", *Built Environment Project and Asset Management*, Vol. 9 No. 1, pp. 2-14.

Corresponding author
M.N.N. Rodrigo can be contacted at: navomail@gmail.com