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Abstract

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Keywords

whole-life, australia, method, energy, uncertainty, analysis, net-zero, materials, building, (co2-e), emissions, carbon, embodied

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A method of uncertainty analysis for whole-life embodied carbon emissions (CO_2-e) of building materials of a net-zero energy building in Australia

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Highlights

- A net-zero educational building in Australia is considered for embodied CO_2-e analysis.
- A method for building embodied CO_2-e analysis based on Monte Carlo simulation was developed.
- Sensitivity analyses were employed to quantify uncertainties in building materials embodied CO_2-e.
- A significant level of uncertainty is associated with four building materials.

Abstract

The construction of new buildings requires the use of a substantial amount of materials, which have an associated embodied energy for manufacturing, transport, construction and end-of-life disposal. A number of inventories have been developed to collate the typical embodied energy or carbon emissions associated with different building materials and activities, and these can be used to quantify the environmental impacts of different construction methods. However, uncertainty exists in the estimation of embodied CO_2-e emissions and other environmental impact results, due to i) inconsistencies in typical embodied carbon emissions values in inventories; ii) errors in estimations of material quantities; iii) assumptions regarding building lifetimes, and iv) errors in estimations of transport distances.

This current study quantified the uncertainties associated with the calculation of lifetime CO_2-e emissions in a case study net-zero, in terms of operational energy, educational building. This study examined the lifetime impacts of building materials for the building based on a detailed Life Cycle Assessment (LCA) that had been previously undertaken for this site. The study considered the 19 building materials which most heavily influenced the total, transport and recurring embodied carbon footprint of the building and a probability distribution was generated to represent the variability for each of the following uncertain parameters: Lifetime, Embodied CO_2-e and transport distance over the building's life. Random sampling was used to generate input variables (1000 samples) based on a probability distribution of each uncertain parameter relative to the building materials. Through the use of a Monte Carlo simulation, the environmental impact for each construction material for a 50-year building lifetime was predicted. Unlike the conventional LCA approach, which provides a single deterministic value, cumulative Monte Carlo distribution curves were used to provide a range of embodied CO_2-e emissions for each construction material, and the whole building, through the lifetime of the building. The obtained results revealed a distribution of the total embodied CO_2-e of a building which ranged from 2,951 tCO_2-e to 5,254 tCO_2-e. This variation in the life cycle carbon emissions highlights the importance of considering an uncertainty analysis in the LCA analysis.

Keywords: Life cycle analysis, CO_2-e emissions, Monte Carlo simulation, Uncertainty Analysis, net-zero educational building.

1. Introduction

The construction industry is a major consumer of renewable and non-renewable natural resources. The construction of new buildings has substantial environmental costs; it is estimated that worldwide, buildings are responsible for the use of 40% of total primary energy, 40% of natural materials, 15% of the world's freshwater resources and 40–50% of greenhouse gas emissions (GHG) (Ding 2014; Lehne & Preston 2018; Mokhlesian & Holmén 2012; Ramesh et al. 2010). In Australia, the construction and demolition industry account for a significant amount of waste generated and disposed in a landfill (Crawford 2011; Yu et al. 2017).

The use of appropriate building materials to minimise the industry's environmental impact has received increasing research attention. A holistic approach to the selection of sustainable building materials should consider the life cycle of a building, including building performance and embodied energy (Berge 2009; Franzoni 2011; Hester et al. 2018; Le, Khoa N. et al. 2018). The life cycle of a building material includes the extraction of raw materials, manufacturing processes, transportation to the construction site, construction processes, the operational phase, and the end of life recycling and potential for reuse (Ding 2014).

As buildings become more energy efficient, the operational phase of a life cycle assessment will make an increasingly smaller contribution to the total environmental impact, while material selection will become relatively more important (Davies & Trabucco 2018; Hammad et al. 2018; Oldfield 2012). However, selecting sustainable building materials is a challenging task (Saghafi & Teshnizi 2011; Tam et al. 2018), because it requires an analysis of building materials embodied environmental impact at all stages of the life cycle, as well as the energy performance of the material as part of the operation of buildings. This is an ongoing area of research due to a large number of variables and the uncertainty involved in the assessment process (Hester et al. 2018; Paolo et al. 2018).

Several studies attempted to quantify the risks associated with the whole-life environmental performance of buildings (Beltran et al. 2016; Crawford 2011; Dixit et al. 2010; Mendoza Beltran, M. A. et al. 2018). For instance, Mendoza Beltran, M. A. et al. (2018) categorised those risks into the uncertainties associated with methodological choice, model uncertainty, lack of knowledge on system behaviour, and simplification characteristics of LCA (inclusion and exclusion in the system boundaries). Meanwhile, a review by Pomponi and Moncaster (2016) showed that different methods and techniques have been developed to analyse uncertainties and variations in LCA including: stochastic modelling (Hong et al. 2017; Miller et al. 2013), fuzzy theory (Egilmez et al. 2016), possibility theory (André & Lopes 2012), Tylor series expansions (Hoxha et al. 2014), data quality indicators (Wang & Shen 2013) as well as expert judgements and/or combinations of the methods. Despite the previous studies for addressing the uncertainties and variabilities associated with LCA study, there is still a significant gap in current research related to the uncertainty with the embodied energy of materials in the processing, manufacturing, and construction of low operational energy buildings, relative to operational impacts and uncertainty.

This study aimed to determine the uncertainties associated with the life cycle assessment of a net-zero energy educational building in Australia. Section 2 summarises uncertainty associated with lifetime CO_2-e emissions analysis in the building industry. Section 3 describes the methodological approach used to analyse the uncertainty associated with life cycleCO_2-e emissions of the net-zero energy educational building of this study. Section 4 provides results on the embodied CO_2-e emissions intensity for different building materials and products, followed by a discussion of the key role of four important materials selected in the overall embodied CO_2-e emissions of the case study building.

2. Life cycle assessment in buildings

Life cycle analysis is a method for identifying and evaluating the environmental aspects of a product during its life (ISO14040 2006); this method assesses the impacts from the materials used and energy released by the system into the environment. Applying a life cycle analysis to the building sector is a particularly complex life cycle analysis problem (Ortiz et al. 2009; Taborianski & Prado 2004) due in part to the complexity, size, and intensive use of natural resources in all stages of a building's life (Sharma et al. 2011). The following factors introduce further complexity to LCA in this sector:

- Buildings have a particularly long lifetime, often more than half a century, so it is difficult to predict the whole of lifetime behaviour of the project from cradle-to-grave (Cabeza et al. 2014; Paolo et al. 2018);
- During the lifetime of a project, the building may undergo many changes in terms of form and function, changes which can be as significant as the original construction (Stephan & Crawford 2014). Future changes can potentially be considered at an early stage of design to minimise the environmental effects of changes (Crawford 2011);
- There are many stakeholders and shareholders involved in the building industry. Stakeholders comprise professionals and non-professional who are involved in the conceptions, design, constructions, post constructions and end of life of projects (Oke & Aigbavboa 2017).

The European Standard EN15978 (EN15978 2011) has proposed a number of methods for assessing the environmental performance of buildings. The standard calculation method involves the following four stages in an LCA of buildings: the product stage (raw materials extraction, transportation and manufacturing); the construction process (transportation to the site, construction and installation process); the use stage (usage, maintenance, repair, replacement and refurbishment), and the end of life (deconstruction, demolition, transportation, waste processing and disposal). The system boundary includes the extraction of raw materials, production processes, transportation, and use and disposal.

A number of studies have found that the use stage (operational energy) accounts for 80% to 85% of the life cycle energy consumption in buildings (Richman et al. 2009; Robati et al. 2017; Sharma et al. 2011). The energy inputs for the production of building products, the extraction and processing of raw materials, and manufacturing and transportation to construction sites are responsible for the remaining 15% to 20% of whole life cycle energy usage of a building (Asdrubali et al. 2013). The contribution made by construction activities, and final demolition and disposal at the end of life is deemed negligible, at level of approximately 1% (Ruuska & Häkkinen 2015; Sartori & Hestnes 2007).

To understand the role that building materials have on an energy efficient design; the operational and embodied energy implications of building design options must be investigated. Since the operational energy offers the most opportunities for energy efficiency, the majority of previous research has focused on reducing it, and less research has been done on minimising the impacts from all the stages of a building’s life cycle.

Existing literature has highlighted the significance of building materials and embodied energy in a lifetime energy analysis of buildings (Akbarnezhad & Xiao 2017; Catherine et al. 2016; Tecchio et al. 2018). An appropriate choice of construction and building materials can reduce the embodied energy and embodied CO_2-e emissions by 17 % and 30 %, respectively, over the lifetime of buildings (González & García Navarro 2006; Thormark 2006). Asif et al. (2007) studied the life cycle embodied energy and the emissions associated with five commonly used materials (glass, aluminium, wood, ceramic tiles, and concrete) in a Scottish residential house. Concrete was responsible for 60% of the total embodied energy in those buildings. Similarly, Ximenes and Grant (2013) used the LCA method to determine the GHG emissions associated with several building materials in Australia and found that structural elements consisting of concrete and bricks are responsible for up to 31% and 17% of the total greenhouse gases impact, respectively. The authors also found that the use of timber in the sub-floor resulted in between 31% and 56% reductions in embodied GHG emissions. Aye et al. (2012) undertook LCA on three forms of common Australian building constructions and showed that steel structured buildings reduce the consumption of material by almost 78% by mass compared to a concrete structure. However, the steel structure resulted in a 50% increase in embodied energy compared to the concrete structure. They concluded that an efficient use of materials could result in energy savings of up to 81% of embodied energy, and 51% of the mass of materials.

A number of previous studies identified variations and inconsistencies in embodied energy estimation methodologies (Crawford 2013; Dixit et al. 2010; Huang et al. 2010; Langston & Langston 2008; Robati et al. 2016). Dixit et al. (2010) found these sources of uncertainty to be: variations in the method of analysis used in each assessment; different system boundaries; and the quality of data sources and input in the calculation of upstream processes. Accordingly, it is important to use methods to quantify the uncertainties associated with the LCA of buildings and construction materials. This study, therefore, aimed to quantify the uncertainty associated with the whole-life embodied carbon emissions of a net-zero energy case study building. The analysis of these uncertainties for the case study building will demonstrate the importance of uncertainty analysis within life cycle assessment.

3. Methodology

The uncertainty associated with whole-life embodied carbon impact was assessed for a case-study net-zero operational energy building, the University of Wollongong's Sustainable Buildings Research Centre (SBRC). The SBRC building is a 6 Star Green Star building (GBCA 2017), and can be considered as a best practice building for sustainability in Australia, both in terms of minimising operational energy consumption, and minimising embodied energy through design and material selection. A brief characterises of SBRC building is summarised in Table 1.

Table 1 a brief characterises of SBRC building.

Floor area	- 1700 m^2 of office and laboratory spaces - 900 m^2 of industrial research high-bay - 360 m^2 of roof-top testing space - 1700 m^2 of external breakout space
Fabric	- Fixed sunshade devices to control solar gain - Cross ventilation via opposing high- and low-level operable openings - Reused railway track structure - Reused brickwork applied to internally exposed thermally mass - Reused timber cladding to external insulating skin
Capacity	- 50 research staff, students and industry partners.
Sustainability targets	- first certified Living Building in Australia under the International Living Building Challenge™ Program - Ultra-low energy consumption of less than 60 kWh/m^2 per annum - The first 6 Star Green Star design rated building in the Illawarra.
Year of construction	- Construction commenced in April 2012 and completed in July 2013.
Location: One hour south of Sydney at the University of Wollongong's Innovation Campus	

The SBRC building was selected as a case study because it represented a critical case where the operational energy is minimised. The uncertainty associated with whole-life embodied carbon emissions analysis for this building was therefore anticipated to be relatively significant compared to typical construction. The boundary of this study considered the embodied CO_2-e emissions associated with construction materials from production, construction, replacement and at the end life activities (as shown in Figure 1).

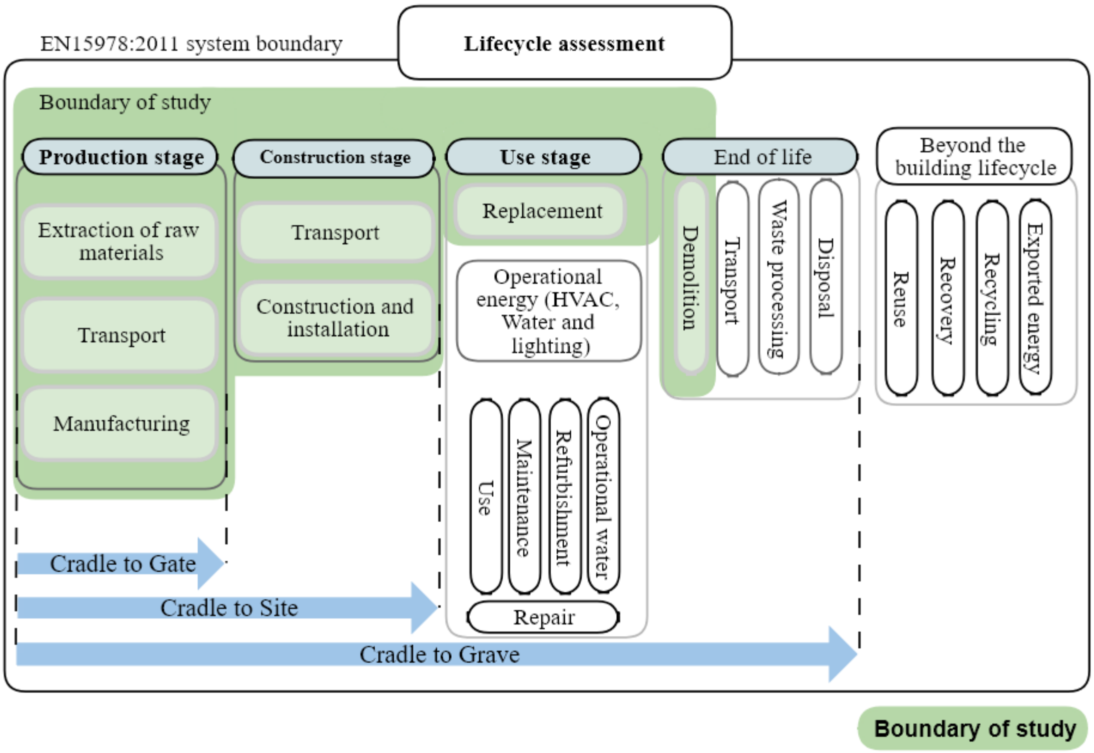


Figure 1. Boundary of study (EN15978 2011)

We employed a sensitivity-based method to determine the ranges of dependent parameters by considering the uncertainties associated with the independent parameters (the embodied carbon emissions of the building and the building materials are summarised in section 4). The Input parameters were: Material quantities, lifespan, embodied carbon emissions and transport distances and are summarised in Table 2. Sensitivity analysis methods can be grouped into a screening, local and global methods (Heiselberg et al. 2009). We undertook a global sensitivity and uncertainty analysis using the Monte Carlo simulation method. Monte Carlo is a statistical method that uses random values from input parameters and presents a distribution for the output parameter, and has been previously employed in numerous studies, e.g.(Bisinella et al. 2016;

Bojacá & Schrevens 2010; Grant et al. 2016; Mendoza Beltran, Angelica et al. 2018). Global sensitivity analysis methods have the advantage that all parameters are varied at the same time, and the effect of input parameter range and probability density function are considered (Bisinella et al. 2016; Silva & Ghisi 2014).

This study consisted of five major steps, namely:

1) Identify the relevant input parameters and define their probability density functions; The input parameters consist of the top 19 building materials which most heavily influenced the primary (production stage), transport and recurring embodied carbon footprint of the building (material quantities were extracted from a previously undertaken study for this site).
2) Define the appropriate probability density function of the input parameters using the embodied CO_2-e emissions, lifetime and the transport distance extracted from published literature;
3) Perform a random sampling, using, for example, Microsoft Excel's normal distribution function: the input parameters (embodied CO_2-e emissions, lifetime and transport distance) associated with each building material (Table 2) were randomly generated 1000 times to achieve more accurate results (Inyim et al. 2016).
4) Perform an uncertainty analysis: for each 1000 sample data, Equation 1 was used to generate the probability distribution of all the input parameters. The total result presents the global uncertainty analysis associated with the building.

5) Perform a sensitivity analysis to quantify the magnitude of the change in the estimated embodied CO_2-e emissions of the building and building materials. In this last step, the range of embodied carbon emissions for each construction materials was quantified and

compared against the total embodied CO_2-e emissions of the building. The results of this stage quantified the relative importance of each building material by considering their relative impact at each individual iteration over the total iterations (1000) on the overall CO_2-e emissions of the building.

Table 2 quantity and assumed distributions of analysed parameters.

Number	Parameter (i)	Unit	Quantity	Distribution					
				Lifetime (years) I		Embodied CO_2-e emissions (kg/unit of material) II		Distance (km) III	
				Mean	SD	Mean	SD	Mean	SD
1	Solar PV Panels (Polycrystalline)	m^2	983	22.50	2.08	249.00	0.00	67.32	55.77
2	Windows (Aluminium Framed; Double Glaze)	m^2	1,017	25.00	10.80	245.12	34.12	150.00	72.24
3	Concrete (Structural; 40 MPa;60% BFS*)	m^3	461	135.00	60.20	398.39	80.60	12.00	7.07
4	Concrete (Walls, floor topping 40 MPa,30% BFS)	m^3	370	135.00	60.20	300.80	158.53	12.00	7.07
5	Steel (General)	kg	55,091	115.90	42.23	1.45	1.14	8.72	4.95
6	Steel (Hot Rolled	kg	56,362	105.00	10.00	1.18	0.98	8.72	4.95
7	Insulation (Loose Fill; Cellulose Fibre)	m3	390	22.50	2.88	335.22	0.00	108.00	0.00
8	Aluminium	kg	16,838	69.38	58.64	13.10	5.79	9.50	7.56
9	Windows with Aluminium Framed and Single Glaze	m^2	308	42.40	28.21	202.61	0.00	2.04	1.13
10	Plaster and Gypsum Derived Products	m^2	3,488	46.25	21.74	5.36	4.63	4.20	2.86
11	Bulk Aggregates Sands and Soils	m^3	177	87.00	83.56	95.05	127.54	7.00	2.91
12	Bricks, Blocks and Pavers	kg	257,915	150.00	39.52	0.31	0.25	19.50	14.72
13	Rubber, Synthetic	kg	3,434	47.22	40.31	3.43	1.08	5.50	2.38
14	Plastics (HDPE**)	m^3	2.80	116.66	54.48	6,681.12	1,615.28	5.15	4.55
15	Carpets and Floor Coverings	m^2	622	10	3.80	22.54	12.36	6.98	6.39
16	Plastics (Polycarbonate)	kg	991	18.75	2.98	17.45	16.19	5.15	4.55
17	Electrical Goods (Electrical Equipment)	#	40,000	10.00	1.58	0.41	0.00	5.15	4.55
18	Plastics (General)	kg	1,814	40.00	26.55	5.93	2.93	5.15	4.55
19	Electrical Goods (Inverter)	kg	271	20.00	4.08	51.54	14.05	5.15	4.55

References:

I.Materials lifetime (Cabeza et al. 2014; Ding 2004; Ding 2008; eTool 2014; Furuta et al. 2014; Thormark 2006);

II.Embodied CO_2-e emissions (Alcorn 2003; BPIC 2014; Crawford 2011; Hammond et al. 2011; Moussavi Nadoushani & Akbarnezhad 2015; Robati et al. 2016); III.Online mapping tools.

*BFS: Blast Furnace Slag | **HDPE: High Density Polyethylene

The overall embodied CO_2-e emissions was calculated by adding the magnitude of each parameter through the use of Equation (1). Equation (1) represents lifetime (Cradle to Grave) environmental impacts (embodied CO_2-e emissions) associated with selection of the building materials which was adopted from previous studies (Akbarnezhad & Xiao 2017; Crawford 2011).

$$T_{CO_2-e} = \sum_{i=1}^{n=19} \left(\frac{L_t}{L_i} \times ((Q_i \times I_i) + (\frac{Q_i}{C_t} \times I_t \times D_i\,))\right) \qquad (1)$$

Where:

- T_{CO_2-e} is the total embodied CO_2-e emissions of the building (kg CO_2-e emissions); This study considers the impacts of the top 19 materials ranked in terms of quantity used in the case study building (n=19).
- i is the building material number as shown in Table 2;
- L_t represents the total lifetime of the building, assumed to be 50 years (AS3600 2009);
- L_i is the lifetime associated to the i^{th} building material (number of years); for a material's lifespan higher than 50 years (such as concrete, steel reinformance, timber), the lifetime ratio $\left(\frac{L_t}{L_i}\right)$ is equal to 1;
- Q_i represents the quantity of the *i*th building material (based on Table 2);
- I_i is the embodied CO_2-e emissions associated with the i^{th} building material (kg CO_2-e /unit of material);
- C_t is related to the truck capacity, which can carry a 20ft container (volume 39 m^3);
- I_t is the embodied CO_2-e emissions associated with the truck used to transport materials (excluding concrete). This is assumed here as 0.07155 (kg CO_2-e /tonne per km) (Moussavi Nadoushani & Akbarnezhad 2015).
- D_i is the travelling distance the i^{th} building material (Table 2) was transported from the supplier to the counstruction site (km).

Figure 2 summarises the workflow and the methodology used to quantify the uncertainty associated with a lifetime environmental assessment of the SBRC building.

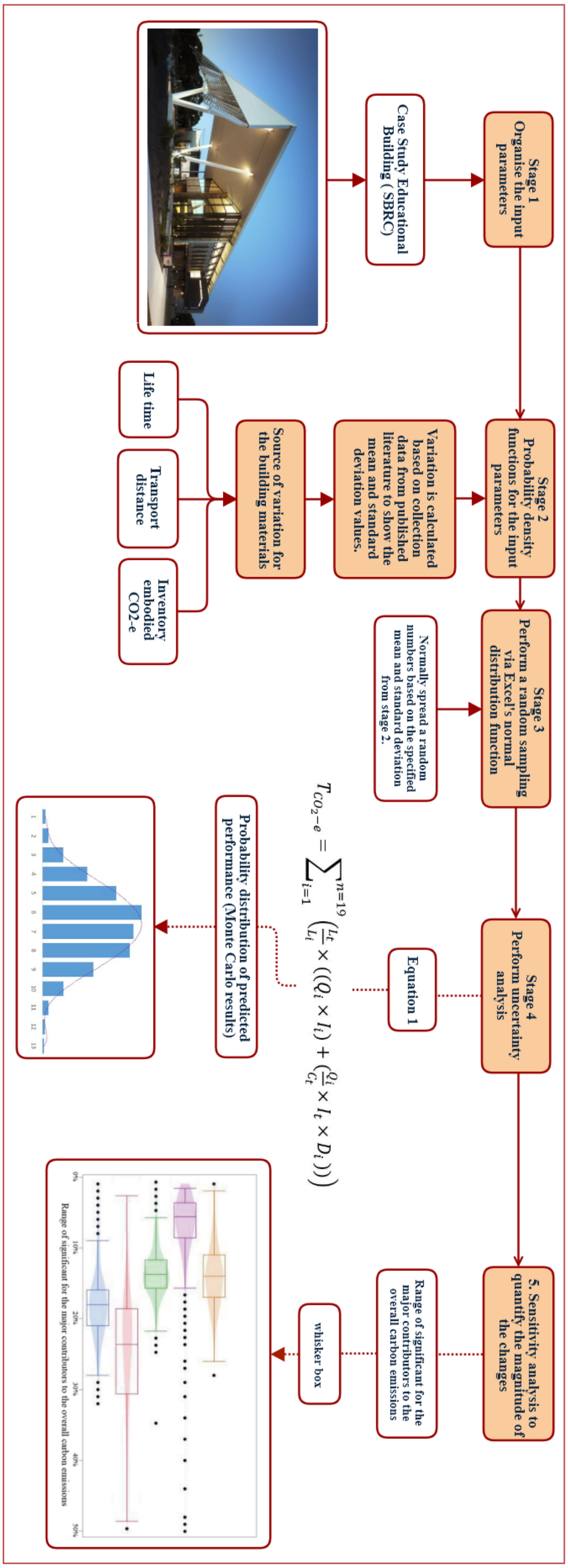


Figure 2. The workflow and methodology used in this study

Stage 2 of methodology considers the variations associated with the lifetime of materials, embodied CO_2-e emissions, and the travel distance. The amount of variation is calculated based on collecting data from published literature to represent the mean and standard deviation values.

The spread of random numbers in stage 3 was determined by the specified mean and the specified standard deviation of each input parameter from stage 2 (as shown in Table 2). A normal distribution is recommended for modelling the variations associated with each input variable because the maximum and minimum CO_2-e emissions values were not clear enough to define them (Inyim et al. 2016; Peña-Mora et al. 2009). It was therefore assumed that all the parameters (lifetime, embodied CO_2-e emissions and travel distance) associated with the building materials are distributed normally along the standard deviation (SD). So, the lifetime, the embodied CO_2-e emissions of materials, and the travel distance between the material suppliers to the construction site are distributed separately because each variable comes from different sources of data. A normal distribution is used because when that other distribution (rectangular, triangular) is combined it often yields a net distribution which is close to normal (Farrance & Frenkel 2014).

An existing life cycle assessment for the case study building had been completed prior to the current study, and the result presented a single deterministic embodied CO_2-e emissions value for the building (Cradle to Grave). This study extended the existing LCA to include a risk analysis to quantify uncertainties associated with the calculation of CO_2-e emissions. The material quantity from the existing LCA was used for the calculation, as they were based on as-built documentation; however, it is acknowledged that this assumption could be an additional source of uncertainty which was unexplored in this study. The system boundary of the existing LCA study was the same as the current study in this paper (Figure 1). Stage 2 of methodology considers the variations associated with the lifetime of materials, embodied CO_2-e emissions, and the travel distance. The amount of variation is calculated based on collecting data from published literature to represent the mean and standard deviation values for each of the top 19 dominantly used materials by quantity in the building. The variations in the material's lifespan came from published literature (Cabeza et al. 2014; Ding 2004; Ding 2008; eTool 2014; Furuta et al. 2014; Thormark 2006). The embodied CO_2-e emissions coefficient associated with the building materials came from six inventory databases: BPIC (BPIC 2014), ICE (Hammond et al. 2011), eTools (eTool 2014), Alcon (Alcorn 2003), AusLCI (AusLCI 2016), Crawford (2011), and other published literature (Moussavi Nadoushani & Akbarnezhad 2015; Robati et al. 2016). The mean travel distance value from the potential manufacturing companies to the site was measured using online mapping tools (Poinssot et al. 2014; Robati et al. 2018). The values assumed for the study parameters (top 19 building materials) are included in Table 2.

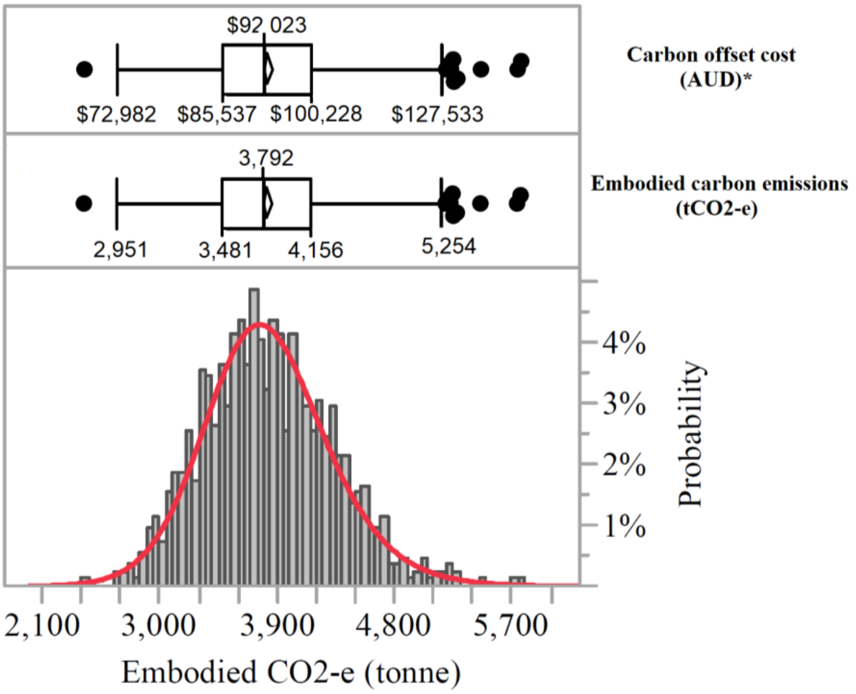
One of the considerable limitations of this study is the inability to precisely determine the distributional form and number of samples in the Monte Carlo analysis. Also, Monte Carlo analysis demands more data (Miller et al. 2013), and there is not a certain agreement on the minimum size of samples (iterations) that are required to be carried out (Pomponi et al. 2017). Increasing the sample size adds to computational time and complexity of the analysis(Lloyd & Ries 2007). By considering these limitations, we used 1000 sample size (Gantner et al. 2018; Inyim et al. 2016) by using a selected combination of the inputs which were taken from several studies (as outlined in Table 2). Besides these limitations, Monte Carlo analysis still is the most widely implemented method to assess uncertainties associated with various LCA studies (Hong et al. 2018; Pomponi et al. 2017). Another limitation relates to the quantity of the building materials extracted from an existing LCA data, which based on as-built documentation.

4. Results and discussion

This section presents the results of the global uncertainty and sensitivity analysis for the LCA of the whole building, and a targeted consideration of parameters which have a particularly large influence on the LCA results.

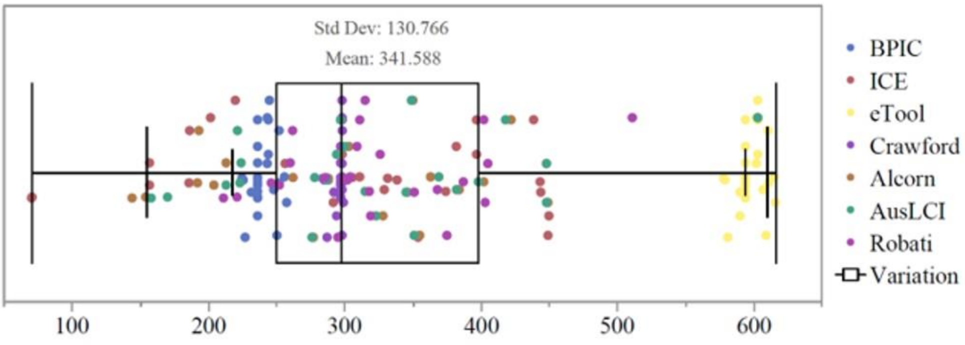
4.1 Uncertainty for the whole-life CO_2-e emissions analysis

The results of the Monte Carlo uncertainty analysis that were generated using Equation 1 are displayed in Figure 3. The results were generated from 1000 iterations (as recommended by Inyim et al. (2016)) of each parameter generated independently using normal distributions with the mean and the standard deviations from Table 2. For instance, Figure 4 presents the variations associated with the embodied CO_2-e emissions coefficients for two grades of concrete (N32 and N40); for concrete N32 and N40, the standard deviation and mean values are obtained from 203 and 175 datasets, respectively. By summing up the embodied CO_2-e emissions of the building materials, the total embodied CO_2-e emissions of the SBRC building was calculated.

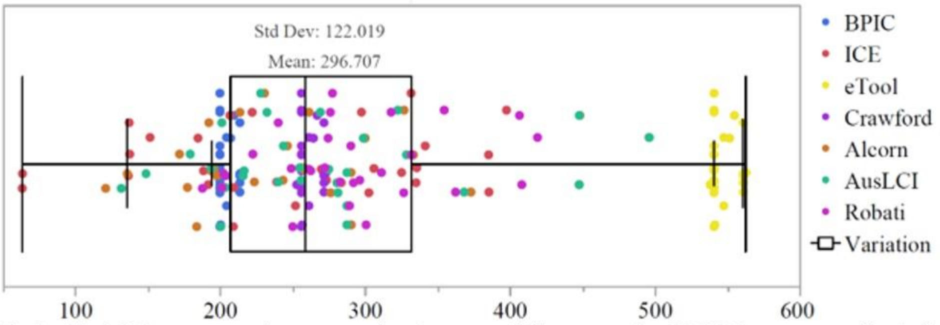


* The price of CO_2-e emissions is based on the Robati et al. (2018) method and the Australia Emissions Trading Scheme (Combet 2012).

Figure 3. Probability distribution of LCA from global uncertainty analysis sampling



a.Embodied CO_2-e across inventory databases and literature for 40 MPa concrete (kg/m^3)

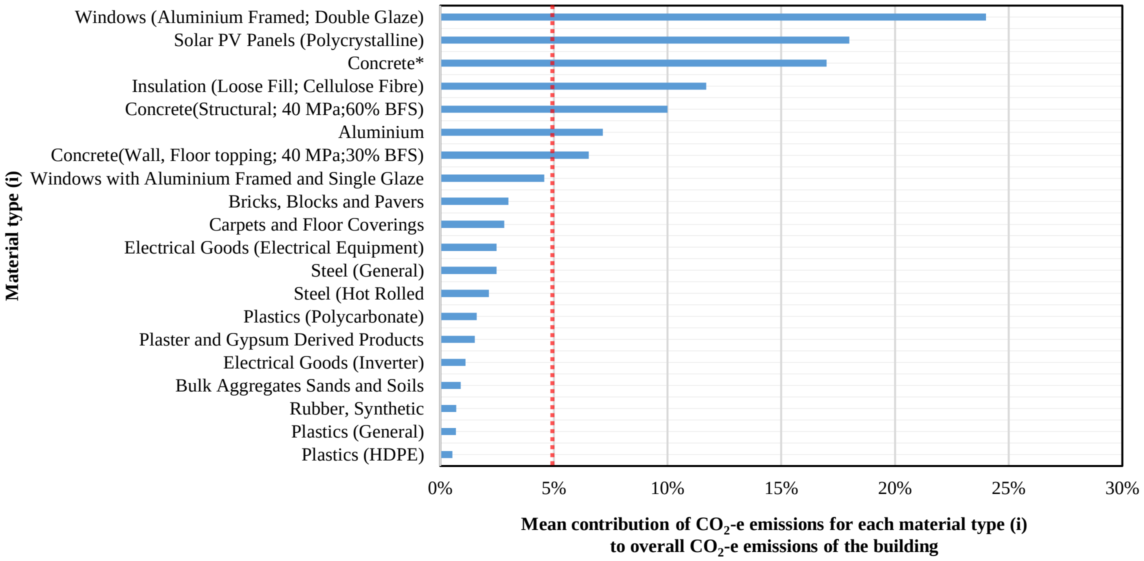


b.Embodied CO_2-e across inventory databases and literature for 32 MPa concrete (kg/m^3)

Figure 4. Embodied CO2-e emissions variations for two grades of concrete (a.N32 and b.N40)

Figure 3 summarises the global uncertainties associated with the whole-life carbon emissions analysis results of the SBRC building. The distribution of the total embodied CO_2-e was found between 2,951 tCO_2-e to 5,254 tCO_2-e using a range of reasonable inputs taken from previous studies. The mean value was found to be 3,828 tCO_2-e (median value was 3,792 tCO_2-e), with a standard deviation of 502 tCO_2-e. Accordingly, the carbon offset cost (voluntary market in Australia) to compensate the carbon emissions for the low carbon analysis would be $72,982; while, the high value offset would be $127,533 by considering a 95% confident interval (as shown in Figure 3). This variation in the embodied emissions and carbon offset cost highlights the importance of considering an uncertainty analysis in the LCA analysis.

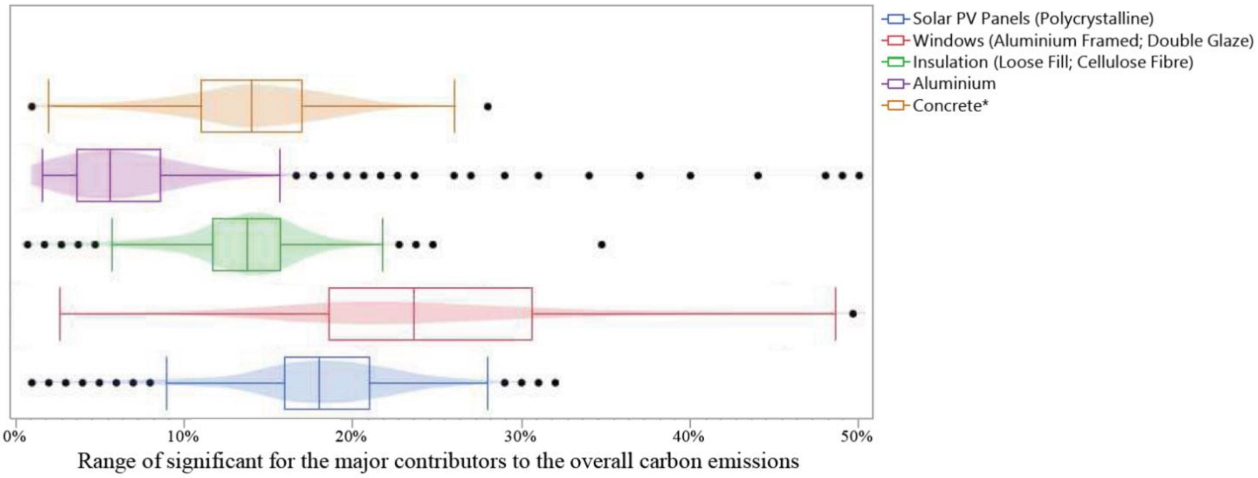
The relative importance of the analysed materials is shown in Figure 5. It can be seen that the windows, PV system and concrete as a structural material have the largest mean impact on total embodied CO2-e emissions of the building. The top six materials, each contributing greater than 5% of the total mean embodied carbon emissions, were responsible for 75% of the total embodied CO_2-e emissions.



* represents the combinations of both types of concrete (material number 3 and 4 in Table 2).
BFS: Blast Furnace Slag│HDPE: High Density Polyethylene.

Figure 5. Ranking of mean contribution of CO_2-e emissions of construction materials for the SBRC building.

Further analysis revealed the range of uncertainty associated with the construction materials that have the highest contributions in terms of carbon emissions as shown in Figure 6. It can be seen that there is a particularly significant level of uncertainty associated with Solar PV Panels, Windows, Insulation, Aluminium and Concrete. These sources of uncertainty associated with these materials are explored in the following sections.



* Concrete includes a combination of Structural Concrete (40 MPa;60% Blast Furnace Slag) and Concrete for Walls, floor topping (40 MPa,30% Blast Furnace Slag).

Figure 6. Range of significant for the major contributors to the overall carbon emissions.

4.2 Uncertainty associated with Aluminium, insulation and windows

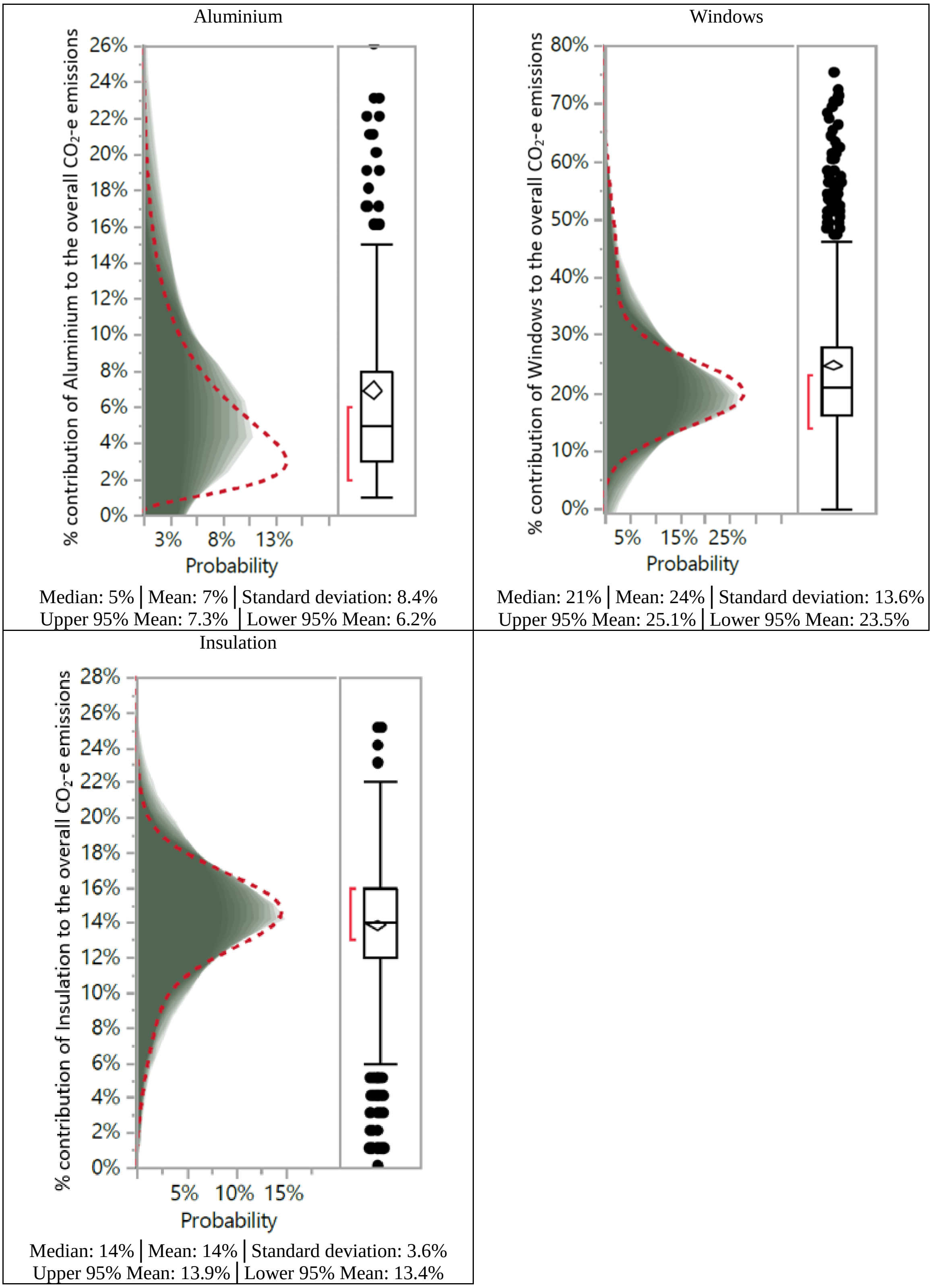
Aluminium (general use), windows (double glazed and aluminium framed) and insulation materials had a high impact on total embodied CO_2-e emissions of the building. The mean percentage contribution to the overall embodied CO_2-e emissions of the building was 7% for aluminium, 12% for insulation and 24% for windows (Figure 7).

The embodied CO_2-e emissions contribution associated with aluminium ranged from 1% to 15% of the overall embodied CO_2-e emissions from the building when assuming a 95% confidence interval. The respective embodied CO_2-e emissions related to the insulation materials varied from 6% to 22%, while for the aluminium double-glazed windows, they varied from 3% to 46%.

For these materials, the uncertainties mainly result from the variations in embodied CO_2–e emissions coefficient as proposed by different inventory databases. For instance, the amount of the embodied CO_2-e emissions for aluminium, which is a material with high energy content, ranged from 8 to 22.8 (kg CO_2-e/kg) in the existing databases. The respective embodied CO_2-e emissions associated with insulation changes from 0.63 to 1.05 (kg CO_2-e/kg); for the windows, the carbon emissions factor was sourced as 216 to 279 (kg CO_2-e)/m^2 (eTool 2014; Hammond et al. 2011).

Additionally, it was found that the short lifetime for insulation materials and windows contributed to 23% and 38% of their embodied carbon emissions, respectively. Similarly, the shipping distance constitutes 4% of the windows and 5% the insulation materials total embodied carbon emissions.

As both, insulation and windows, have a lower lifetime than other materials, they required more maintenance and refurbishments over the lifetime of the building. Moreover, the type of shipping and transport distance have a significant impact on intensity of embodied CO_2-e emissions of the windows (Dowdell et al. 2016; Macintosh 2007).



Aluminium

Median: 5% | Mean: 7% | Standard deviation: 8.4%
Upper 95% Mean: 7.3% | Lower 95% Mean: 6.2%

Windows

Median: 21% | Mean: 24% | Standard deviation: 13.6%
Upper 95% Mean: 25.1% | Lower 95% Mean: 23.5%

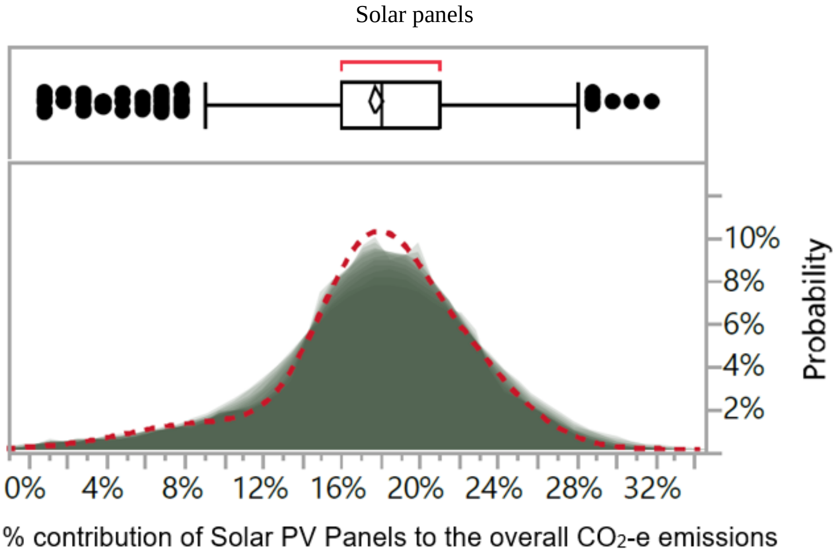
Insulation

Median: 14% | Mean: 14% | Standard deviation: 3.6%
Upper 95% Mean: 13.9% | Lower 95% Mean: 13.4%

Figure 7. Probability distribution for the percentage contribution of Aluminium, Windows and Insulation to the overall embodied CO_2-e emissions

4.3 Uncertainty associated with Solar PV Panels:

The cumulative probability variation of output data showed that the solar PV panels had the second highest impact on total embodied CO_2-e emissions of the building. The uncertainty analysis of output data showed that solar PV panels were responsible for 18% (mean value) of total embodied CO_2-e emissions of the building (as shown in Figure 8).



Median: 19% | Mean: 18% | Standard deviation: 4.06% | Upper 95% Mean: 18.24% | Lower 95% Mean: 17.73%

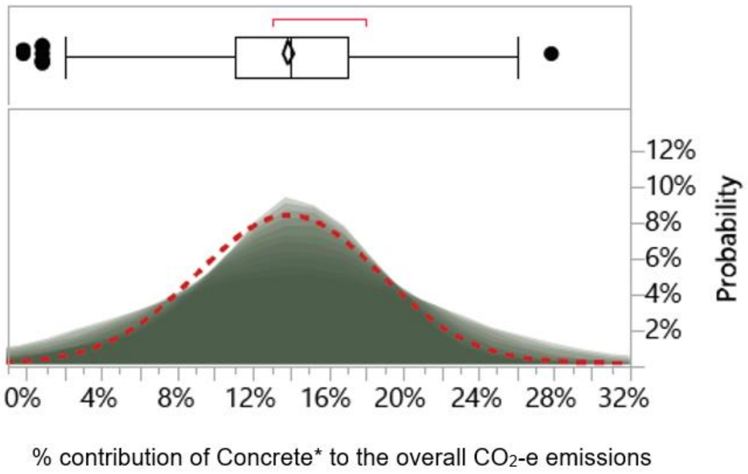
Figure 8. Probability distribution for the percentage contribution of solar PV panels to the overall embodied CO_2-e emissions of the building

Similarly to the previous section, the variation of the results are largely due to differences in the inventory databases and the lifetime of PV solar panels. The embodied CO_2-e emissions related to the production of the PV system ranged from 12 to 569 g CO_2-e/kWh (Wong et al. 2016). The uncertainty related to the embodied CO_2-e emissions coefficient has been affected due to the changes in efficiency of PV panel, levels of solar irradiation, technology associated with manufacturing of PV panel as well as the application of PV panel (residential, commercial or power plant) (Kim et al. 2014; Wong et al. 2016). The results of Sherwani et al. (2010) study on LCA of commonly used solar PV showed that carbon emissions of panels have been dependent on type of solar cell, for instance, amorphous solar cells (thin film modules) emit less carbon energy while its efficiency was lower than other cells (mono-crystalline and poly-crystalline).

Additionally, it was found that the overall embodied CO_2-e emissions of PV system was significantly influenced (up to 50%) by having a lower lifespan in comparison with the assumed building life and therefore they require maintenance and refurbishment after a certain period (every 25 years) (Ma et al. 2014).

4.4 Uncertainty associated with Concrete materials

The difference in the amount of embodied CO_2-e emissions for two types of concrete that were used in the building was quantified. The mean embodied carbon emissions associated with the concrete used in the structural components that had higher cement substitution (Case a: 40 MPa with 60% Blast Furnace Slag-in Figure 9) were 7% of the overall CO_2-e emissions of the building. On the other hand, the mean embodied carbon emissions for the concrete used in the walls and floors systems with a lower cement substitution material (Case b: 40 MPa with 30% Blast Furnace Slag-in Figure 9) were 10% of the total CO_2-e emissions; 3% higher than the Case a. The overall magnitude impacts of concrete (for both cases) in terms of CO_2-e emissions ranged from 4% to 28% (assuming a 95% confidence interval) of the total CO_2-e emissions from the building (Figure 9).

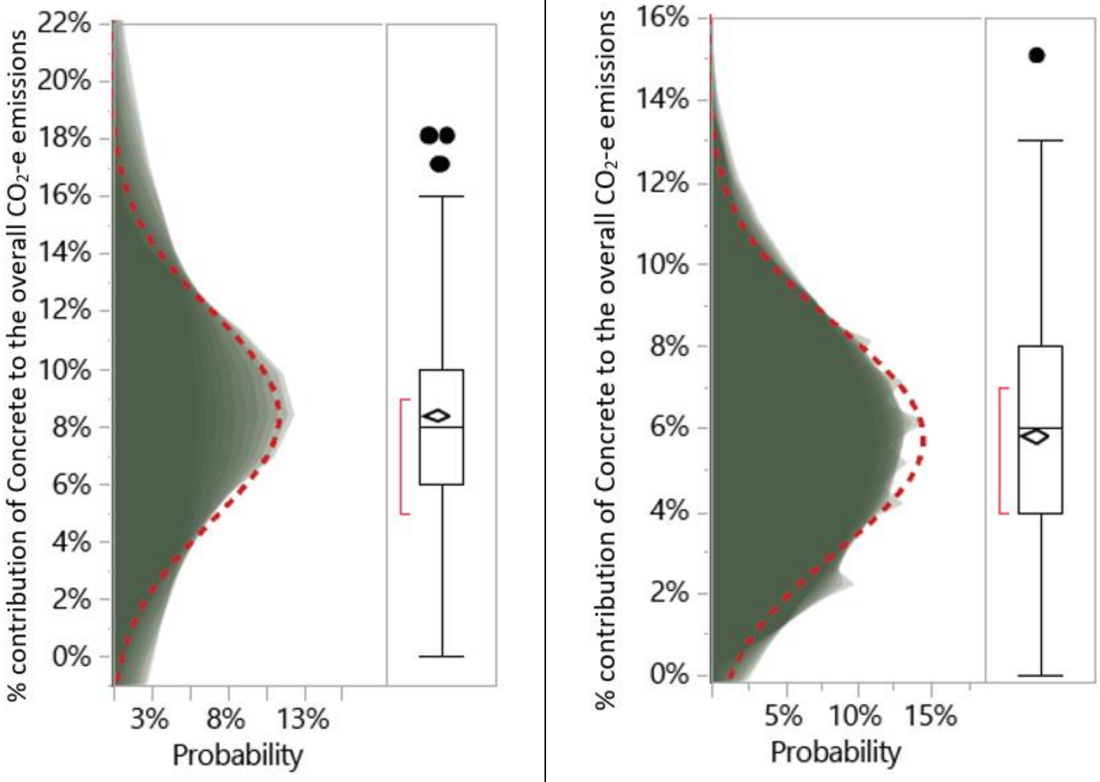


Median: 14% | Mean: 14% | Standard deviation: 4.85% | Upper 95% Mean: 14.4% | Lower 95% Mean: 13.8%

* Concrete includes a combination of Structural Concrete (40 MPa;60% Blast Furnace Slag) and Concrete for Walls, floor topping (40 MPa,30% Blast Furnace Slag).

Concrete (a)
Structural; 40 MPa;60% BFS*

Concrete (b)
Walls, floor topping 40 MPa,30% BFS*



Median: 7% | Mean: 7% | Standard deviation: 3.03%
Upper 95% Mean: 7.16% | Lower 95% Mean: 6.78%

Median: 10% | Mean: 10% | Standard deviation: 3.85%
Upper 95% Mean: 10.32% | Lower 95% Mean: 9.84%

*BFS: Blast Furnace Slag

Figure 9. Probability distribution for the percentage contribution of different types of concrete used in the building to the overall embodied CO_2-e emissions

The resulted concrete greenhouse emissions were mainly influenced by the variations across the different inventory databases. These recorded variations in embodied CO_2-e emissions are due to the different methods of analysis used in the different databases, the source of data and quality of input data (related to the upstream process) in the calculation (Illankoon et al. 2018; Le, Khoa N et al. 2018; Robati et al. 2016).

For instance, the embodied CO_2-e emissions values across Alcorn, Crawford, eTool, ICE and AusLCI databases vary from 75 to 600 kg CO_2-e/m^3 (Robati et al. 2016). The embodied CO_2-e emissions from transportation and lifetime of concrete contributed to 10% of the total impact of concrete over the lifetime of the building.

4.5 Impact of the building’s lifetime on whole-life embodied carbon emissions.

The total life cycle assessment considers the whole-life of the building, from pre-use process, operational phase and end of life. Through the use of on-site renewable generation technologies, the SBRC produces more energy than it consumes over an annual operational phase (as shown in Figure 10), making the SBRC building a net exporter of energy to the grid over a year. This trend in energy consumption points out the significance of embodied carbon emission in a net-zero building and raises a question about the impact of assumption made regarding the building’s life, as disused below.

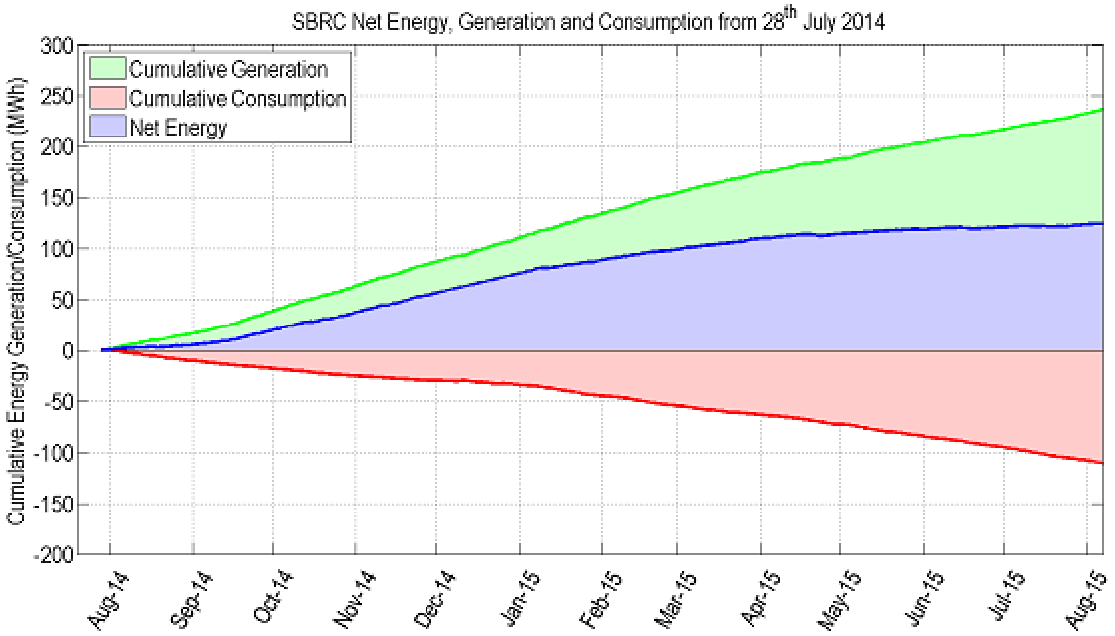


Figure 10. SBRC cumulative energy performance

The results of uncertainty analysis in Figure 11 show that the assumed length of a building's life could have a considerable effect on the overall results of embodied CO_2-e emissions calculation, the other variable remained the same (similar to the previous sections). The results show that by increasing the building lifetime from 50 to 150 years, the mean overall environmental impact of the building in terms of CO_2-e emissions will be increased by 185% (from 3,828 to 10,936 tCO2-e), as shown in Figure 11. This is mainly caused by the increased impact of the operational phase of the building as a result of replacing materials and interior finishes. The probability trends of the output data were consistent across all five different lifetime scenarios. However, it has to be mentioned that to fully understand and quantify the uncertainty associated with products' lifetime requires considerations of the materials durability, service conditions, materials properties, maintenance and occupants' behaviour during the operational phase of the buildings. The ongoing developments in the durability of construction materials could also reduce maintenance and replacement requirements.

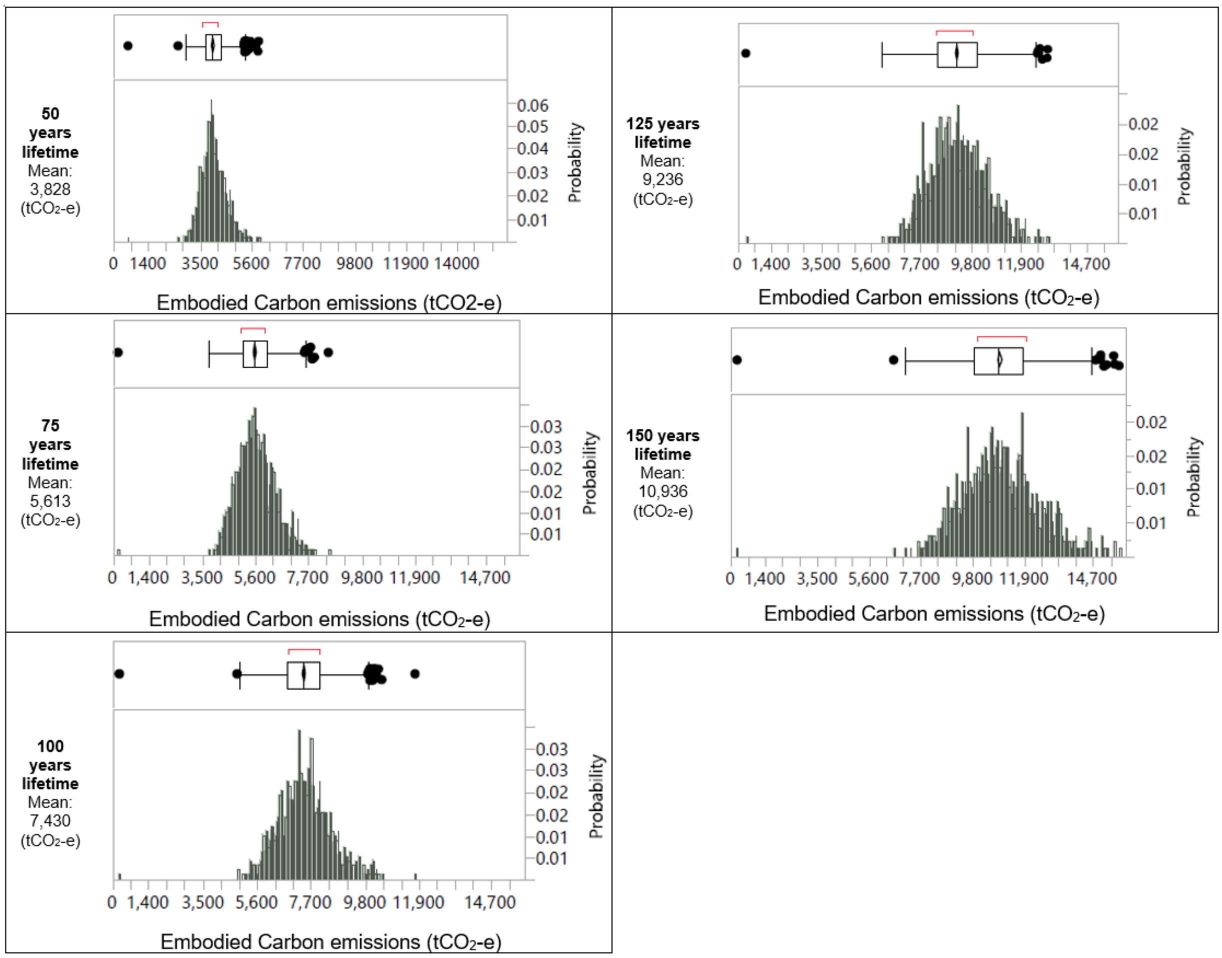


Figure 11. Impact of building's lifespan on the life cycle embodied CO_2-e

5. Conclusion

A Monte Carlo simulation method was employed to predict the ranges of the embodied CO_2-e emissions associated with a net-zero energy University building. The probability distributions of the most influential building materials (input data) were obtained in order to estimate the mean (expected) embodied CO_2-e emissions value of each of the building materials. The embodied carbon emissions associated with each input parameter was used into the Monte Carlo simulation to produce the mass function for the whole life embodied carbon emission of the building. The total embodied energy of the case study building was found to be highly sensitive to input assumptions and varied by order of magnitude from lowest to highest possible calculated value, using reasonable inputs from previously published research. The mean CO_2-

e emissions value for the building was calculated at 3,828 tCO_2-e, (with standard deviation of 502 tCO_2-e). This study highlighted the contribution and variation of most carbon-intensive construction materials during the lifetime of the building. It was found that solar PV panels, double glazed windows with aluminium frame, concrete (two types of concrete) and insulation are the key parameters that should be given due attention. These four components contribute to 78% (mean contribution) of total CO2-e emissions of the building. Considering reasonable assumptions, the mean embodied CO_2-e emissions impacts were estimated as 18% for Solar PV panel, 24% for double glazed windows with aluminium frame, 14% for Insulation, 7% for Aluminium and 14% for concrete.

The ranges in these results were mainly due to differences in the carbon inventory datasets. For the solar PV panels and the windows, the assumed lifespan of the materials had a considerable impact on their overall embodied CO_2-e emissions. Transporting materials to the site was a significant contributing factor to the embodied CO_2 emissions for the cases of concrete and windows as these two components involved relatively high quantities and long distances, respectively. It was also noticed that the total embodied CO_2-e emissions of the building were increased by assuming longer building lifetimes that ranged from 50 to 150 years. This study emphasises the need for considering uncertainties associated with LCA analysis to avoid misrepresentation of the final results at the decision-making processes.

The findings of this study can be used as a guideline for future comparison of environmental impacts associated with buildings materials and systems. This work integrates the embodied CO_2-e emissions associated with the building performance during its lifetime and highlights the importance of ensuring appropriate input assumptions are employed in a life cycle assessment.

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