Front. Eng. Manag. 2018, 5(3): 381–393
https://doi.org/10.15302/J-FEM-2018055

RESEARCH ARTICLE

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Life cycle carbon emission assessment of a multi-purpose university building: A case study of Sri Lanka

Abstract Buildings are known to significantly affect the global carbon emissions throughout their life cycle. To mitigate carbon emissions, investigation of the current performance of buildings with regard to energy consumption and carbon emissions is necessary. This paper presents a process-based life cycle assessment methodology for assessing carbon emissions of buildings, using a multi-storey reinforced concrete building in a Sri Lankan university as a case study. The entire cradle-to-grave building life cycle was assessed and the life span of the building was assumed as 50 years. The results provide evidence of the significance of operation and material production stages, which contributed to the total carbon emissions by 63.22% and 31.59% respectively. Between them, the main structural materials, concrete and reinforcement steel made up 61.91% of the total carbon emitted at the material production stage. The life cycle carbon emissions of the building were found to be 31.81 $kg \cdot m^{-2}$ CO_2 per year, which is comparable with the values obtained in similar studies found in the literature. In minimizing the life cycle carbon emissions, the importance of identifying control measures for both building operation and material production at the early design stage were emphasized. Although the other life cycle stages only contributed to about 5.19% of the life cycle carbon emissions, they should also receive attention when formulating control strategies. Some of the recommended strategies are introducing energy efficiency measures in building design and operation, using renewable energy for building operation and manufacturing of materials, identifying designs that can save mass material quantities, using alternative materials that are locally available in Sri Lanka and implementing material reuse and recycling. This study is one of the first to undertake a life cycle carbon emissions assessment for a building in the Sri Lankan context, with the hope of facilitating environmentally-friendly buildings and promoting sustainable construction practices in the country.

Keywords carbon emission, life cycle assessment, buildings, sustainable construction, Sri Lanka

Received July 2, 2017; accepted October 31, 2017

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1 Introduction

Climate change is a major environmental concern globally and the increase in greenhouse gas (GHG) emissions is one of its main drivers. Global GHG emissions due to human activities have grown since the pre-industrial times, with an increase of 70% between 1970 and 2004 (Intergovernmental Panel on Climate Change, 2007). Annual emissions of carbon dioxide (CO_2), the most prominent GHG, grew by about 80% during the same period, mainly due to extensive fossil fuel usage and land use, both highly contributed to by the construction industry. Globally, buildings account for 30%–40% of total primary energy use and about one third of GHG emissions. Thus, the building sector can play a significant role in reducing carbon emissions and thereby contribute to the mitigation of global climate change (United Nations Environment Programme, 2010). Energy is used extensively throughout the life cycle of a building during material production, transportation, construction, operation, maintenance and demolition and as a result, a considerable amount of carbon is emitted. There is great potential in improving the energy efficiency of buildings and thereby reducing carbon emissions without significant increases in investment costs (Intergovernmental Panel on Climate Change, 2007).

As buildings have long lifespans, they should be planned and designed to have high energy efficiency and low carbon emissions over their entire life cycle.

Incorporating energy efficiency and low-carbon measures are now feasible during the early stages of building design. For any improvements to occur, assessment of current building performance is essential. In the recent decades, numerous studies have been conducted to analyze energy and carbon impacts of buildings. The full extent of the lifetime emissions of a building can best be understood by using life cycle assessment (LCA), which considers a range of environmental impacts throughout the life cycle of a building. Life cycle carbon emission assessment is a specialized form of LCA, which evaluates carbon emissions as an output across the building life cycle to facilitate the selection of low-carbon emitting materials, systems, and processes for buildings. It has become particularly significant due to the imminently threatening global warming problem caused by GHG emissions. The Kyoto Protocol has set binding targets to reduce the GHG emissions by an average of 5% to the 1990 levels between 2008 and 2012 (Kim et al., 2013). The ratification of Kyoto Protocol has led to many studies which aimed to evaluate impacts of energy use and carbon emissions of buildings.

In previous studies, the possibility of reducing CO_2 emissions by up to 30% during the construction phase was demonstrated through the selection of low environmental impact materials (González and García Navarro, 2006) and the environmental impacts of CO_2 emissions in building construction phase of single family detached houses in Spain were analyzed (Pacheco-Torres et al., 2014). Many studies have emphasized the dominance of the operation stage in life cycle carbon emissions assessment irrespective of the country in which the study was based (Kofoworola and Gheewala, 2008; Varun et al., 2012; Atmaca A and Atmaca N, 2015; Zhang et al., 2016). The carbon emissions at the material production stage have also been found to be significant by many researchers (Varun et al., 2012; Zhang et al., 2016). By investigating CO_2 emissions of 78 office buildings in China during the pre-use stage, it was found that material production accounted for 75% of the total CO_2 emissions and steel, concrete, mortar and wall materials made up over 80% of the emissions of material production stage (Luo et al., 2015). Most of the previous studies focused on reinforced concrete structures which gave evidence for the prominence of concrete and reinforcement steel in carbon emissions during the material production stage (Jeong et al., 2012; Luo et al., 2015; Sim et al., 2016). The life cycle GHG emissions and energy consumption of pre-fabricated reusable building modules have been compared with those of the conventional concrete construction methods (Aye et al., 2012). Gustavsson et al. (2010) studied the primary energy use and CO_2 emissions of a wood-framed apartment building. The concept of 'life cycle carbon efficiency' was introduced and it was applied to a 5-storey residential building in Nanjing, China (Li et al., 2013). Zhang and Wang (2015) established an analytical framework to assess the life cycle carbon emissions and to identify appropriate control measures, which emphasized the possibility of carbon control during the materialization stage, particularly for developing countries that are experiencing extensive construction works. Many researchers have used LCA models, frameworks and methodology to analyze energy consumption and GHG emissions throughout the building life cycle (Monahan and Powell, 2011; Wu et al., 2012; Biswas, 2014).

Most of the past research on building energy and carbon emissions has focused on developed and temperate climate countries and only a few examples from developing tropical countries exist (Kofoworola and Gheewala, 2008; Ramesh et al., 2012; Varun et al., 2012; Paulsen and Sposto, 2013; Pinky Devi and Palaniappan, 2014; Wen et al., 2015). The linkage between building design, energy use and carbon emissions is dependent on and sensitive to climate and the socio-demographic characteristics that are geographically and culturally variable (Atmaca A and Atmaca N, 2015). Therefore, the results of life cycle studies can vary extensively for countries in different regions of the world. There are several characteristics that distinguish energy use and carbon emission of developing tropical countries from the rest of the world. In these countries energy is extensively used for cooling and electricity is the main energy source, which usually has higher carbon emissions than other sources used in developed countries (Ramesh et al., 2010). Although the traditional buildings in the tropical countries are naturally ventilated, with increased access to air conditioning as a result of increasing disposable income, the energy demand of developing countries are steadily rising (Chirarattananon and Hien, 2011). Despite the extensive use of air conditioning in buildings, a little or no insulation is currently used, resulting in inefficiencies in the life cycle energy performance and increased carbon emissions. Also, inefficient material production technologies result in increased embodied energy and carbon emission (Chirarattananon et al., 2012). The parameters to be focused on energy and carbon emissions studies in the developing tropical countries were identified as; level of operational energy use, transition from traditional to modern building materials, role of insulation, role of advanced building systems, technology of material production, energy production methods and energy carriers (Ruuska, 2013). In some studies, the existing data was adjusted to reflect the differences in the above parameters for a particular country (González and García Navarro, 2006; Chau et al., 2007; Abeysundara et al., 2009).

Most of the building life cycle energy and carbon emission studies in the existing literature are based on typical residential or office buildings (González and García Navarro, 2006; Dimoudi and Tompa, 2008; Kofoworola and Gheewala, 2009; Ramesh et al., 2012; Pacheco-Torres et al., 2014; Pinky Devi and Palaniappan, 2014; Wen et al., 2015). Only a few studies can be found for university buildings which have special characteristics; usually these are multi-purpose buildings consisting of offices, class rooms, laboratories and in some cases residential facilities. Therefore their energy and carbon emission characteristics are found to be complex and differ substantially from case to case (Scheuer et al., 2003; Varun et al., 2012; Wu et al., 2012; Biswas, 2014).

Construction is the second largest industry in Sri Lanka. As buildings contribute to more than 50% of value of work done and the raw material use in the construction sector of the country (Department of Census and Statistics Sri Lanka 2013, 2015), assessment of environmental implications of buildings should be given priority. At present, there is a significant lack of country-specific research and related data inventories on building energy and carbon emissions in Sri Lanka. Some authors described a computerized relational database management system to determine energy contents and carbon emission coefficients for a variety of Sri Lankan building materials (Dias and Pooliyadda, 2004). In some studies, the environmental burdens of building elements were analyzed using typical school buildings in Sri Lanka as case studies (Abeysundra et al., 2007; Abeysundara et al., 2009).

This study aimed at assessing life cycle carbon emissions of a university building in Ratmalana, a suburb of Colombo in Sri Lanka. Due to unavailability of energy and carbon related data in the context of Sri Lanka, internationally recognized databases, relevant Sri Lankan and international reports and recent research literature, preferably studies based on the developing Asian countries were used as data sources. In identifying the most relevant data for Sri Lanka, current construction practices of the country were considered. No previous research on life cycle carbon emissions of buildings in Sri Lanka is found in literature and this study can be considered as the first-ever such study for Sri Lankan buildings, which is timely and highly relevant to the current requirements of the country. The proposed methodology can be used by building planners, designers, owners and certification bodies to assess life cycle carbon emissions of Sri Lankan buildings, hence facilitating environmentally-friendly construction decision making and strategy formulation to promote sustainable construction practices in Sri Lanka.

2 Materials and methods

2.1 Methodological framework for life cycle assessment

This study was based on the LCA approach and the four stages of the LCA methodological framework as identified in ISO 14040 on Environmental Management; goal and scope definition, inventory analysis, impact assessment and interpretation were followed (International Organization for Standardization, 1997). The LCA was process-based where input data, in the form of energy and materials were utilized in assessing life cycle carbon emissions of the building.

2.1.1 Goal and scope of the study

The cradle-to-grave life cycle carbon emissions of a multi-storey university building in Sri Lanka were investigated in this study. Both spatial and life cycle process boundaries were included within the system boundary. The spatial boundary was defined as the closed three-dimensional space bounded by the foundation, roof and the façade of the building. The cradle-to-grave life cycle phases; material production, transportation, construction, operation, maintenance, demolition and waste disposal were included in the life cycle process boundary. The life span of the building was taken as 50 years and the functional unit for the study was considered as one square meter (m^2) of gross floor area of the building per year.

2.1.2 Life cycle inventory analysis

The inputs (materials and energy) and outputs (carbon emissions) during building life cycle were considered in the life cycle inventory. The inputs were obtained from design drawings, bills of quantities, technical specifications, reports of relevant Sri Lankan and international bodies and recent research literature. In selecting the appropriate data, values that best match the current construction practices in Sri Lanka were considered and in the case of insufficient data, suitable assumptions were made with consultation of experienced construction professionals.

2.1.3 Life cycle impact assessment and interpretation

In this phase, the significance of the potential environmental impacts was evaluated using the results of the life cycle inventory analysis. In the present study, life cycle carbon emissions were considered as the potential environmental impact and the final results were presented as annual carbon emissions per unit gross floor area ($kg \cdot m^{-2}$ CO_2) of the case study building. The life cycle interpretation phase combined the findings of inventory analysis and the impact assessment in order to draw conclusions and suggest recommendations within the defined goal and scope of the study.

2.2 Methodology followed for life cycle carbon emissions assessment

2.2.1 Estimation of life cycle carbon emissions

Based on the carbon emission coefficient method and the LCA approach, total lifecycle carbon emissions of a building were calculated as given in Eq. (1) (Chau et al., 2015).

$$C_{LC} = C_M + C_T + C_C + C_{O\&M} + C_D \tag{1}$$

where C_{LC} represents the total lifecycle carbon emissions of a building and C_M, C_T, C_C, $C_{O\&M}$ and C_D represent carbon emissions at the material production, transportation, construction, operation and maintenance and demolition stages (kg CO_2) respectively. The carbon emissions attributable to each life cycle stage are presented by Eqs. (2)–(6).

2.2.2 Carbon emissions at the material production stage

The carbon emissions at the material production stage (C_M) includes the raw materials extraction and building material production and can be estimated as given in Eq. (2) (Li et al., 2016).

$$C_M = \Sigma_{i=1}^{n}(m_i \times f_{m,i}) \tag{2}$$

where n is the total number of material types, m_i is quantity of material type i (kg or m^3) and $f_{m,i}$ is the embodied carbon emission coefficient ($kg \cdot kg^{-1}$ or $kg \cdot m^{-3}$ CO_2) of type i material. Due to current unavailability of carbon emission data inventories for Sri Lanka, appropriate values of $f_{m,i}$ were taken from existing literature and globally recognized databases such as Inventory of Carbon and Energy (ICE) (University of Bath UK, 2011) and Korea LCI DB Information Network (Korea LCI DB Information Network, 2017).

2.2.3 Carbon emissions at the material transportation stage

The carbon emissions during the material transportation (C_T) stage was computed based on the amount of carbon emitted by the type of vehicles used to deliver materials to the construction site. C_T is given by Eq. (3) which was developed using the methodology suggested in literature (Pinky Devi and Palaniappan, 2014).

$$C_T = \Sigma_{i=1}^{n}(T_i \times D_i \times f_{t,i}) \tag{3}$$

where T_i is number of trips of trucks required for transporting type i material, D_i is the average two-way travel distance (km) for transporting type i material to the construction site and $f_{t,i}$ is the carbon emission coefficient for transporting type i material ($kg \cdot km^{-1}$ CO_2). The means of material transportation that are commonly used in Sri Lanka were investigated and transit-mixer trucks (6 m^3) for ready-mixed concrete, 20-ton trailers for reinforcement steel and 20-ton and 8-ton trucks for other building materials were identified. The carbon emission coefficients for various types of transportation were calculated using the data obtained from research literature and local and international reports such as Common Carbon Metric (United Nations Environment Programme, 2010), IEA Statistics (International Energy Agency, 2015) and Sri Lanka Energy Balance (Sri Lanka Sustainable Energy Authority, 2015).

2.2.4 Carbon emissions at the building construction stage

The carbon emissions at the construction stage were estimated by using fuel/electricity usage rates for typical construction activities at site such as earthworks, pouring and lifting of ready-mixed concrete, concrete compaction, rebar and reinforcing, lifting of materials by tower crane and material hoist and site lighting. The energy sources used were taken as diesel and electricity. Carbon emissions during building construction (C_C) are given by Eq. (4) which was developed using the methodology suggested in the literature (Pinky Devi and Palaniappan, 2014).

$$C_C = \Sigma_{i=1}^{j}(Q_i \times R_i \times f_{c,i}) \tag{4}$$

where j is total number of on-site construction activities, Q_i is the quantity of on-site construction activity i (m^3, m^2 or kg), R_i is fuel/electricity usage rate for construction activity i ($L \cdot m^{-3}$, $kWh \cdot kg^{-1}$ or $kWh \cdot m^{-2}$) and $f_{c,i}$ is carbon emission coefficient for the energy source used for the construction activity i ($kg \cdot L^{-1}$ or $kg \cdot kWh^{-1}$ CO_2). The data related to typical construction activities of a reinforced concrete building were obtained from research literature, technical specifications and consultation with construction professionals in Sri Lanka.

2.2.5 Carbon emissions at the operation and maintenance stage

In assessing carbon emissions during building operation, the energy consumption due to air conditioning, ventilation, lighting and equipment use (mainly computers) was considered. Electricity from the national grid was taken as the energy source for building operation. Electricity generation in Sri Lanka is the result of a unique mix of energy sources; hydro (37.5%), coal (33.9%), fuel oil (17.4%), and non-conventional renewable energy (11.2%). The carbon emission factor for grid electricity was computed based on emission factors of the relevant primary energy sources and their contribution to the electricity generation mix. According to Sri Lanka Energy Balance 2015 (Sri Lanka Sustainable Energy Authority, 2015), current carbon emission factor for electricity in Sri Lanka is about 0.6896 $kg \cdot kWh^{-1}$ CO_2. The carbon emissions for building maintenance were computed using repair cycle and rate of repair for each material type i (Roh et al., 2016). The carbon emissions in the operation and maintenance stage ($C_{O\&M}$) were estimated as given in Eq. (5).

$$C_{O\&M} = (Q_e \times f_e \times Y) + \left(\Sigma_{i=1}^{k} m_i \times r_i \times f_{m,i} \times \frac{Y}{R}\right) \tag{5}$$

where Q_e is the average annual electricity consumption of the building ($kWh \cdot yr^{-1}$), f_e the carbon emission coefficient of electricity ($kg \cdot kWh^{-1}$ CO_2) and Y lifespan of the building (years). The average annual electricity consumption was calculated based on monthly electricity bills and it was assumed to be uniform throughout the building life cycle. For the maintenance stage, k is the total number of material types required for repairs and replacement, m_i is the amount of the original building material i which is needed for repair or replacement (kg or m^3), r_i is the rate of repair for the construction material i, $f_{m,i}$ is the carbon emission coefficient of type i material ($kg \cdot kg^{-1}$ or $kg \cdot m^{-3}$ CO_2), Y is the lifespan of the building (years) and R is the repair interval (years) of material i. The value (Y/R) is the repair cycle for the material i (Chau et al., 2007). Only standard maintenance activities such as painting and replacement of ceramic tiles were considered in the study.

2.2.6 Carbon emissions at the demolition stage

The carbon emissions at the demolition stage (C_D) can be regarded as the summation of carbon emissions of demolition activities, transportation of demolished waste and disposal as given by Eq. (6).

$$C_D = \Sigma_{i=1}^{p}(Q_{d,i} \times f_{d,i}) + [(T \times D \times f_{t,i}) + (M \times f_l)] \quad (6)$$

where p is the total number of demolition procedures, $Q_{d,i}$ is the engineering quantity of p type demolition procedure and $f_{d,i}$ is the carbon emission factor of demolition procedure p. T is the number of trips of 20-ton trucks required to transport the demolition waste to the landfill site, D the two-way distance between demolition site to landfill site (km) and $f_{t,i}$ is the carbon emission coefficient of trucks transporting waste ($kg \cdot km^{-1}$ CO_2). M is the total quantity of demolished materials (kg) and f_l is the carbon emission factor of machinery used for landfill operation ($kg \cdot kg^{-1}$ CO_2).

The carbon emissions during building demolition were computed considering three main demolition activities; removal of individual elements, ground levelling and crane handling, for which carbon emission factors were obtained from literature (Zhang and Wang, 2015) as 7.8 $kg \cdot m^{-2}$ CO_2 (gross floor area), 0.62 $kg \cdot m^{-2}$ CO_2 (site area) and 2.85×10^{-3} $kg \cdot kg^{-1}$ CO_2, respectively. The weight of construction waste was taken as approximately the same as the total weight of building materials. The carbon emissions attributable to transporting waste to the landfill site were computed using the same method as for material transportation in Eq. (3). It was assumed that a 20-ton truck is used to transport the waste for a distance of 15 km from the building site to the landfill site. As the relevant data for recycling of construction waste is not currently available for Sri Lanka, recycling was not considered in the study. The total amount of demolished material was assumed to be land filled using bulldozers and compactors for which a standard fuel usage rate of 0.15×10^{-3} $L \cdot kg^{-1}$ was obtained from the literature (Roh and Tae, 2016).

2.3 Case study building

The newly constructed, multi-storey building for Faculty of Graduate Studies of General Sir John Kotelawala Defense University, Ratmalana, Sri Lanka was considered as the case study. It is a multi-purpose building consisting of offices, laboratories, class rooms and guest apartments. The ground floor and first floor consist of reception area, auditorium, cafeteria and offices. The second to fourth floors include examination halls, conference room, lecture halls and the computer laboratory. The fifth floor has three guest apartments and the roof terrace. The sixth and seventh floors consist of the machine room and the water tank. The basic parameters and the pictorial view of the case study building are given in Table 1 and Fig. 1, respectively.

3 Results and discussion

3.1 Building material production

A building usually comprises of hundreds of materials, and therefore, in order to increase the efficiency of the assessment, the concept of major building materials, which has been used in several previous studies (Tae et al., 2011; Roh et al., 2014a; Roh and Tae, 2016) was adopted. The major building materials for a typical reinforced concrete framed building in Sri Lanka were taken as those which account for more than 1% of total material weight or total material carbon emission. Using a pilot survey conducted on several reinforced concrete buildings in Sri Lanka, the major building materials were identified as ready-mixed concrete, reinforcement steel, clay bricks, random rubble, cement, sand, aluminum, ceramic tiles and paint. The percentage contribution of the building materials to total weight and carbon emissions are presented in Table 2. The material flow per unit floor area was found to be 2417.68 $kg \cdot m^{-2}$ which is comparable with previous studies (Shukla et al., 2009; Pinky Devi and Palaniappan, 2014). As shown in Table 2, the structural materials; concrete, rubble and reinforcement steel contributed to about 57.84% of total material mass whereas clay bricks, cement and sand used for brick masonry contributed to about 41.6%. The share of other materials such as aluminum, ceramic tiles and paint to the total mass was negligible.

The main structural material (reinforcement concrete) had the highest contribution to total material related carbon, which was 30% for concrete and 31.91% for reinforcement steel. The results of many previous studies on reinforced concrete structures agree with the significant contribution of concrete and reinforcement steel to carbon

Table 1 Basic parameters of the case study building

Building parameter	Specification
Number of floors	7 floors
Land area	2031 m^2
Gross floor area	5967 m^2
Total height	29.2 m
Service life	50 years
Structure	Reinforced concrete
Envelope	Brick masonry
Foundation	Reinforced concrete and random rubble masonry
Walls	Brick masonry for external and internal walls, gypsum board partition walls
Roof	Reinforced concrete slab and steel truss with Zn-alum coated steel roofing sheets
Ceiling	Gypsum board suspended ceiling on galvanized iron frame
Doors and windows	Timber, plywood, aluminum and glass
Finishes	Ceramic and granite tiles, cement sand rendering, cement plaster, painting, carpeting

Fig. 1 Pictorial view of the case study building

emission in the material production stage (Asif et al., 2007; Dimoudi and Tompa, 2008; Kofoworola and Gheewala, 2008; Biswas, 2014; Hong et al., 2015). Although the quantity of sand was relatively high, its contribution to carbon emission was negligible, whereas aluminum with a negligible mass contributed significantly to carbon emissions at this stage. The comparison of percentage weight and embodied carbon for the major construction materials is illustrated in Fig. 2. The embodied carbon per unit area of the building was found to be 507.19 $kg \cdot m^{-2}$ CO_2.

3.2 Material transportation

In calculating carbon emissions during the material transportation stage, current material transportation practices in Sri Lanka were considered. The average distances for transporting each material were estimated and the two-way transportation distances were used in the calculations. The carbon emission factors for the type of transportation were calculated using data obtained from relevant literature, especially based on Asian countries (Tae et al.,

Table 2 Contribution of major construction materials to total weight and carbon emissions

Material	Quantity	Weight/kg	Weight/%	$f_{m,i}$/(kg·kg^{-1} CO_2)	carbon emission/(kg CO_2)	Carbon emission/%
Ready-mixed concrete	3075.75 m^3	7,381,800.00	51.17	0.123	901,961.40	30.00
Reinforcement steel	666,000.00 kg	666,000.00	4.62	1.45	965,700.00	31.91
Random rubble	128.70 m^3	296,060.00	2.05	0.70	207,207.00	6.85
Clay bricks	695,843.00	1,600,438.90	11.09	0.24	384,105.34	12.69
Cement	558,725.40 kg	558,725.40	3.87	0.759	424,072.58	14.01
Sand	1715.82 m^3	3,843,436.80	26.64	0.0051	19,601.53	0.65
Aluminum	4469.95 kg	4469.95	0.03	9.16	40,944.74	1.35
Ceramic tiles	6571.00 m^2	67,024.20	0.46	0.78	52,278.88	1.73
Paint	18,526.00 m^2	8420.91	0.06	2.91	24,504.85	0.81
Total		14,426,326.16			3,026,376.31	

Note: [a]values of material carbon emission coefficients extracted from studies (University of Bath UK, 2011; Tae et al., 2011; Roh and Tae, 2016)

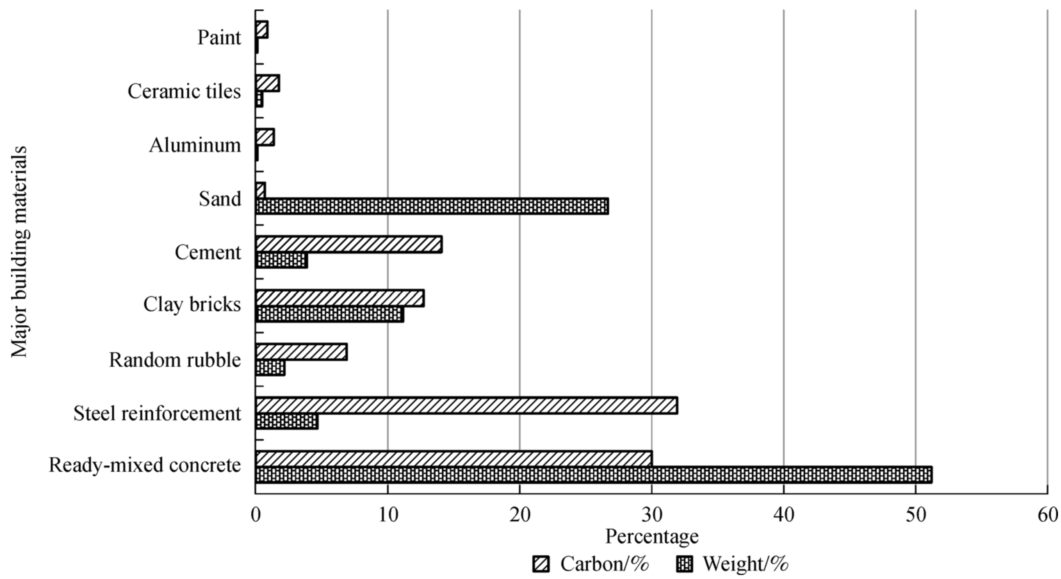

Fig. 2 Comparison of percentage weights and embodied carbon of major building materials

2011; Pinky Devi and Palaniappan, 2014; Sim et al., 2016) and international reports. The construction professionals and material suppliers in Sri Lanka were also consulted. A summary of the carbon emissions at the material transportation stage is given in Table 3. The main factor that affected the carbon emissions in this stage was the material quantity as evidenced from ready-mixed concrete which contributed to 76.47% of total transportation carbon, followed by sand (10.14%). As the average material transportation distances were not high for this particular construction site, transport distance did not play a significant role in the production of carbon emission. The carbon emissions of material transportation were found to be 7.41 kg·m^{-2} CO_2.

3.3 Building construction

In calculating carbon emissions, typical construction activities of a reinforced concrete building were considered. The energy use rates for construction activities were determined from technical specifications and by consulting experienced professionals in the construction industry of Sri Lanka. Whenever data was not available, recent literature from South Asian countries were referred. The summary of carbon emissions in the construction stage is given in Table 4. Earthworks contributed to 39.87% of the carbon emissions at the construction stage followed by site lighting (21.2%) and lifting of materials by tower crane (19%). The carbon emissions per unit area at the construction stage were found to be 15.61 kg·m^{-2} CO_2.

3.4 Building operation and maintenance

As the case study building has been in operation for less than two years, the first complete year of operation (2016) was considered in calculating electricity consumption. The

Table 3 Carbon emissions in material transportation

Material	Type of vehicle	No. of trips	Distance /km	Mileage /($L \cdot km^{-1}$)	Fuel factor /($kg \cdot L^{-1}$ CO_2)	$f_{(t,i)}$ /($kg \cdot km^{-1}$ CO_2)	Carbon emission /(kg CO_2)
Ready-mixed concrete	transit-mixer (6 m^3)	513	30	0.41	2.68	1.099	33,796.35
Reinforcement steel	20-ton trailer	33	25	0.32	2.68	0.858	1427.90
Random rubble	20-ton truck	15	15	0.29	2.68	0.777	690.18
Clay bricks	20-ton truck	80	20	0.22	2.68	0.590	1887.24
Cement	20-ton truck	28	50	0.22	2.68	0.590	1647.12
Sand	20-ton truck	192	15	0.29	2.68	0.777	4480.68
Aluminum	8-ton truck	1	35	0.22	2.68	0.590	23.06
Ceramic tiles	8-ton truck	8	30	0.17	2.68	0.456	229.02
Paint	8-ton truck	1	25	0.09	2.68	0.241	12.69
Total							44,194.24

Note: No. of trips = (Material quantity/Truck capacity) and ($f_{(t,i)}$ = Mileage × Fuel factor)

Table 4 Carbon emissions in construction

Activity	Energy use rate	Quantity of work	Amount of fuel/Electricity	Carbon emissions/(kg CO_2)
Earthworks	3.53 $L \cdot m^{-3}$	3927.00 m^3	13,862.31 L	37,150.99
Pouring and lifting concrete	0.77 $L \cdot m^{-3}$	3075.75 m^3	2368.33 L	6347.12
Concrete compaction	0.21 $L \cdot m^{-3}$	3075.75 m^3	645.91 L	1731.04
Rebar and reinforcing	2 $kWh \cdot MT^{-1}$	666.00 MT	1332.00 kWh	918.55
Lifting of materials-tower crane	10 $kWh \cdot MT^{-1}$	2566.92 MT	25,669.20 kWh	17,701.48
Lifting of materials-hoist	3.1 $kWh \cdot MT^{-1}$	4477.61 MT	13,880.59 kWh	9572.05
Site lighting	26 $kWh \cdot m^{-2}$	1101.68 m^2	28,643.68 kWh	19,752.68
Total				93,173.91

Note: [a]Values of energy use rates are extracted from studies (Pinky Devi and Palaniappan, 2014; Sim et al., 2016).

Table 5 Summary of building life cycle carbon emissions

Life cycle phase	Sub-phase	Carbon emission/(kg CO_2)	Carbon emission/%
Material production	Material production	3,026,376.31	31.59
Transportation	Transportation	44,194.24	0.46
Construction	Construction	93,173.91	0.97
Operation and maintenance	Operation	6,057,239.59	63.22
	Maintenance	271,187.89	2.83
Demolition	Demolition	77,963.25	0.81
	Transportation	6177.15	0.06
	Landfill	4254.31	0.04
Total		9,580,566.58	

total annual electricity consumption was 175,674 kWh. Considering the life span of the building as 50 years, total carbon emissions during building operation were estimated to be 6,057,239.52 kg CO_2. The carbon emissions per unit area at the operation stage were 1015.12 $kg \cdot m^{-2}$ CO_2. In calculating the carbon emissions from building maintenance, only routine maintenance work such as painting and replacement of tiles were considered. The repair interval of tiles and paint were taken as 10 years and 5 years respectively, whereas the repair rates were taken as 0.1 and 1.0, respectively. The total carbon emissions due to maintenance activities over a 50 years life span were calculated as 271,187.89 kg CO_2 and the value for unit floor area was estimated at 45.45 $kg \cdot m^{-2}$ CO_2.

3.5 Building demolition and waste disposal

In calculating carbon emissions attributable to the demolition stage, previous literature was referred (Roh et al., 2014b; Zhang and Wang, 2015) due to the lack of demolition data of Sri Lankan buildings. Only building demolition, transportation of the demolished material and disposal to landfill were considered in determining carbon emissions in the demolition phase. Recycling of construction waste was excluded from the study due to the lack of reliable data. The total carbon emissions from the demolition phase were estimated to be 88394.71 kg CO_2. The carbon emission per unit floor area was 14.81 kg·m^{-2} CO_2. Of the total carbon emissions of this phase, building demolition, transportation and landfill contributed 88.2%, 7% and 4.8%, respectively.

3.6 Building Life cycle carbon emissions

The building life cycle carbon emissions refer to the summation of carbon emissions throughout all the life cycle stages; material production, transportation, construction, operation and maintenance and demolition as given in Eq. (1) in section 2.2.1. The summary of carbon emissions at each life cycle stage is presented in Table 5. The results revealed that the operation and maintenance stage accounted for about 66.06% of life cycle carbon emissions and the cumulative proportion of the operation, maintenance and material production stages were found to be above 97%. The combined contribution of material transportation, construction and demolition stages was 2.35% of the total life cycle carbon emission. This result is comparable with the results of several previous studies (Gustavsson et al., 2010; Li et al., 2013; Zhang et al., 2016). The carbon emission of the building was normalized to 'kg·m^{-2} CO_2 per year' based on its gross floor area and assumed lifespan of 50 years. The life cycle carbon emission of the building was found to be 31.81 kg·m^{-2} CO_2 per year. The carbon emissions of life cycle stages as percentages of the total life cycle carbon emissions are illustrated in Fig. 3.

3.7 Comparison of results with previous studies

The life cycle carbon emissions across different studies are affected by various factors such as the assumptions made for the estimations, life cycle methodology applied, climate, materials utilized, energy sources and technologies used, uniqueness of each building and applicable socio-economic factors. As shown in Table 6, these differences result in a wide range of life cycle carbon emissions (318.64–7.68 kg·m^{-2} CO_2 per year) for selected case studies of various types of buildings in different regions of the world. The life cycle carbon emissions of the present study (31.81 kg·m^{-2} CO_2 per year) are comparable to the values obtained for India (9.0 kg·m^{-2} CO_2 per year), Thailand (20.0 kg·m^{-2} CO_2 per year) and Colombia (17.2 kg·m^{-2} CO_2 per year) which are also developing

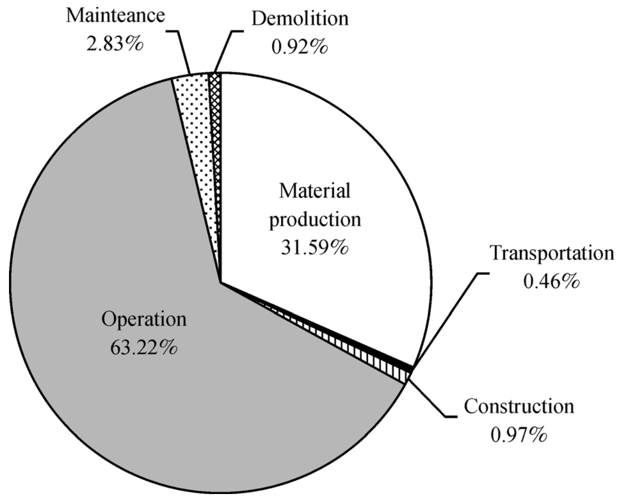

Fig. 3 Carbon emissions from the various building life cycle stages

countries with a similar tropical climate. Even in the same country, carbon emission values can vary highly across different regions (Liaoning and Nanjing in China have values of 318.64 kg·m^{-2} CO_2 per year and 19.0 kg·m^{-2} CO_2 per year, respectively). The life cycle carbon emissions for China (Liaoning), USA, Singapore and Turkey are relatively higher. There seems to be a wide difference among the values of university buildings in the five countries considered (318.64–9.0 kg·m^{-2} CO_2 per year). Due to the vast range of variables involved in building life cycle studies, more detailed comparisons are necessary in order to arrive at valid conclusions.

3.8 Possible measures for life cycle carbon emissions reduction

To reduce life cycle carbon emissions of buildings, several measures were identified. The carbon emissions from the operation stage contributed the largest proportion (63%) within the total life cycle carbon emissions of the building assessed. Carbon emissions at the material production stage were also significant at 32% of total carbon emissions. Hence, the simultaneous control of carbon emissions in both operation and material production stages is critical to achieving low-carbon buildings. As behavior of a building is highly influenced by the initial design, appropriate measures for energy efficient and low-carbon buildings should be taken at the early design stages (Wu et al., 2012). Optimized designs aimed at reducing carbon emissions should be set as a control index and optimization can include carbon emission assessment, identifying high-emission sections, provision of possible optimization schemes and evaluation of outcomes (Zhang and Wang, 2015).

Introducing no-cost energy saving measures in buildings

Table 6 Comparison of studies on life cycle carbon emissions

No.	Reference	Type of building	Location	Life span/year	Gross floor area/m^2	GHG/Carbon emissions /($kg \cdot m^{-2}$ CO_2 per year)
1	(Zhang et al., 2016)	Residential	Tianjin, China	50	4443.3	28.10
2	(Varun et al., 2012)	University	Hamirpur, India	50	3960.0	9.00*
3	(Biswas, 2014)	Uuniversity	Western Australia	50	4020.0	70.80*
4	(Scheuer et al., 2003)	University	Michigan, USA	75	7300.0	246.58*
5	(Kofoworola and Gheewala, 2008)	Office	Bangkok, Thailand	50	60,000.0	20.00*
6	(Wu et al., 2012)	University	Liaoning, China	50	36,500.0	318.64
7	(Atmaca A and Atmaca N, 2015)	Residential	Gaziantep, Turkey	50	7445.0	104.40
8	(Roh et al., 2016)	Residential	Seoul, South Korea	40	208,393.0	51.22
9	(Li et al., 2016)	Residential	Nanjing, China	50	1837.7	19.00
10	(Kua and Wong, 2012)	Commercial	Singapore	30	52,094.0	108.30*
11	(Rossi et al., 2012)	Residential	Belgium	50	192.0	28.71
			Sweden	50	192.0	7.68
			Portugal	50	192.0	43.34
12	(Ortiz-Rodríguez et al., 2010)	Residential	Spain	50	160.0	49.33*
			Colombia	50	140.0	17.20*
13	(Aye et al., 2012)	Residential	Australia	50	3943.0	54.97*
14	Current study	University	Ratmalana, Sri Lanka	50	5967.0	31.81

Note: *GHG values are given ($kg \cdot m^{-2}$ CO_{2eq} per year).

such as controlling the set point temperature of air conditioning and load shedding have been shown to be beneficial in reducing the carbon emissions of buildings at the operation stage. By changing the set point room temperature from 24°C to 26°C, 1.14×10^6 $kWh \cdot yr^{-1}$ of electrical energy can be saved and a corresponding reduction of 820 tons of CO_2 per year can be expected in an office building in Thailand (Kofoworola and Gheewala, 2008). Some authors have pointed out that through load shedding by switching off office equipment and lighting during daily lunch breaks, energy use and carbon emissions can be reduced by about 2050 $MJ \cdot m^{-2}$ per year and 451 $kg \cdot m^{-2}$ per year, respectively in office buildings (Wu et al., 2012). Also, encouraging positive attitudes among building occupants toward saving energy can be considered as a highly effective step toward operational carbon reduction (Delzendeh et al., 2017).

Many previous studies have emphasized the use of passive solar building design (Varun et al., 2012) and it was found that about 77% reduction of life cycle energy of a residential building in Ahmedabad, India was achieved by using solar panels and a wind turbine (Ramesh et al., 2012). As both these renewable energy sources are abundant in a tropical island like Sri Lanka, the same strategy can be recommended in order to reduce life cycle energy and subsequent carbon emissions of Sri Lankan buildings. At the time of data collection, installation of solar panels in the case study building was in progress. Therefore, in future, carbon emissions at the operation stage of the building are expected to reduce due to the proposed use of solar energy.

Also, carbon emissions can be controlled by reducing energy and resource consumption of a building by innovative technologies and management, such as optimizing design schemes and construction methods and enhancing 3R (reduction, reuse and recycle) principles at each stage. Emphasis of 3R should be placed on high carbon impact materials such as concrete, reinforcement steel and aluminum due to their high contribution to carbon emissions at the material production stage as shown in Table 2. Cleaner production technologies for building materials and use of green building materials are already being promoted in Sri Lanka through GREEN^{SL} Rating System and green labeling system (Green Building Council Sri Lanka, 2015).

Previous research in the Indian context has shown that total embodied energy of a building can be reduced by 50% when energy efficient and alternative building materials are used (Venkatarama Reddy and Jagadish, 2003). Similarly, in Sri Lanka, use of locally available, alternative building materials should be encouraged. In the present study, total demolished waste was assumed to be disposed in landfill, which resulted in an additional carbon emission. The results of a study on an office building in Thailand indicated that 8.9% of initial embodied energy can be recovered though recycling and the recycling potential is about 1.5% of the total energy use of the building (Kofoworola and Gheewala, 2009). The analysis of a residential building in Italy provided further evidence of recycling potential of 29% and 18% in terms of life cycle energy and GHG emissions respectively (Blengini, 2009). Sri Lanka can also benefit by introducing recycling processes in the construction waste disposal.

4 Conclusions

The building life cycle carbon emission study presented was based on a university building in the suburbs of Colombo, Sri Lanka. The entire life cycle of a building; material production, transportation, construction, operation, maintenance and demolition was considered in a process-based study in which the existing LCA methodology for estimation of building life cycle carbon emissions was modified for the Sri Lankan context. The proposed methodology was applied to a multi-storey reinforced concrete university building located in Ratmalana, Sri Lanka. With an assumed building life span of 50 years, life cycle carbon emissions per unit gross floor area were estimated to be 31.81 $kg \cdot m^{-2}$ CO_2 per year. The results of this study were compared with previous studies based in different regions of the world as well as referring to different types of buildings. The values for life cycle carbon emissions obtained in the present study are comparable with those of other developing and tropical countries such as India, Thailand and Colombia. Due to a wide range of diverse factors, building life cycle carbon emissions vary highly between different studies.

Carbon emissions were found to be the highest in the operation phase, contributing to 63.22% of the total carbon emissions. Concrete and steel reinforcement were found to be the most significant materials contributing to 62% of the total carbon emissions at the material production stage. Clay bricks and cement used for brick masonry shared about 27% of the carbon emissions. In reducing embodied carbon emissions, two types of materials were identified as significant; materials used in mass quantity such as concrete and materials with high embodied carbon coefficient value such as aluminum. Both types are important in identifying carbon emissions reduction strategies for the material production stage. Reduction, reuse and recycling of materials, use of alternative materials which are available locally as well as introducing clean manufacturing technologies are expected to enhance the possibility of carbon emission reduction at the material production stage.

As evidenced by the study, life cycle carbon emissions are mainly attributable to the operation stage of the building. This strongly correlates with the operational energy requirement of the building. Significant reduction of carbon emissions can be achieved by the practice of simple, no-cost energy conservation measures such as using the building's air conditioning system at an appropriate set point temperature and the practice of load shedding. Also, encouraging positive attitudes toward energy saving among the building users is important in reducing building carbon emissions. The use of renewable energy sources such as solar and wind power to produce energy for building operation was also proved to have a beneficial effect in reducing building carbon emission. Incorporation of environmental LCA into the current building code and building certification systems is also proposed. Although material transportation, construction and demolition only contributed to 2.35% of the total life cycle carbon emission they also present possibilities of carbon emission reduction. As recycling of construction waste is currently not practiced much in Sri Lanka and there is a lack of reliable data on recycling, the present study assumed that all demolished materials were disposed to landfill. By increasing the share of recycling as a method of construction waste disposal, carbon emission at the demolition stage can be reduced significantly.

As no previous building life cycle carbon emission studies exist in the literature for Sri Lanka, or life cycle data inventories in the specific context of the country, the main challenge in conducting the study was the difficulty in accessing appropriate data for some life cycle stages such as material production, maintenance, demolition and recycling. Due to the unavailability of country-specific data inventories at present, international databases and previous literature were referred in identifying appropriate data for the study. The development of country-specific data inventories is necessary for ensuring the reliability and accuracy of building life cycle carbon emission studies in the future. To have a better understanding of the life cycle carbon emissions of Sri Lankan buildings, future studies should extend to different areas of the country and encompass different types of buildings. This study laid the much needed groundwork for future building life cycle carbon emission assessments and presented a methodology that can be used by building planners, designers, owners and certification bodies to assess life cycle carbon emissions of Sri Lankan buildings, which is essential in order to form strategies for carbon mitigation and to promote low-carbon buildings in Sri Lanka.

Acknowledgements The authors gratefully acknowledge the authorities of the General Sir John Kotelawala Defense University, Sri Lanka and the Central Engineering Consultancy Bureau (CECB), Sri Lanka for providing the valuable information needed for this research work.

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