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A tool for assessing life cycle CO_2 emissions of buildings in Sri Lanka

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ABSTRACT

The critical role of buildings in overcoming global environmental challenges is evident from their high contribution to global energy use and carbon dioxide (CO_2) emission. This study was aimed at developing a life cycle CO_2 emission estimator tool for buildings in Sri Lanka. First, system requirements and system boundary were identified. Then CO_2 emission calculation method for each life cycle stage was established, which was followed by development of building life cycle CO_2 emission database and program. The applicability of developed tool was evaluated by a case study of a multi-storey building in Sri Lanka. In the case study, operation and maintenance stage contributed to 55.47% of life cycle CO_2 emission, which was followed by material production stage (42.09%). Ready-mixed concrete, reinforcement steel, cement and clay bricks contributed to nearly 90% of CO_2 emission at material production stage. To the best of our knowledge, this study is the first-ever attempt at developing a building life cycle CO_2 emission estimator tool for Sri Lanka. The limited availability of local data for some life cycle stages was the main challenge faced by researchers, as national data inventories for building life cycle CO_2 emissions are still not fully developed in Sri Lanka. The tool can be used to compare life cycle CO_2 emissions of different buildings as well as providing means of assessing compliance of life cycle CO_2 emissions of buildings to CO_2 emission standards specified by green building certification bodies in Sri Lanka, thus promoting sustainable construction practices in the country.

1. Introduction

As stated in a recent report of Intergovernmental Panel on Climate Change [1], buildings account for 32% of global energy use and 19% of energy related CO_2 emissions as well as 57% of global electricity consumption. Therefore the importance of their role in overcoming global environmental challenges is evident. The energy use and associated CO_2 emissions are expected to rise significantly in future due to key global trends such as population growth, migration to cities, household size changes and increasing level of wealth and lifestyle changes [1]. If the targets for reducing CO_2 emissions are to be met, decision makers need to pay attention to buildings and buildings must be the focus of every national climate change mitigation strategy [2]. On the other hand, buildings offer immediately available, cost-effective opportunities to reduce energy consumption and CO_2 emissions [1]. With proven and commercially available technologies, energy consumption in both new and existing buildings can be reduced by an estimated 30–50% without significant increase of investment cost [3]. According to the energy sector scenario 2050 forecasted by International Energy Agency [4], CO_2 emissions of buildings are expected to be reduced by two-thirds through low-carbon electricity, energy efficiency and the shift to low and zero carbon technologies.

In order to identify mitigation strategies, it is essential to evaluate the current building performance in terms of energy consumption and CO_2 emissions. As CO_2 emission is a process which takes place throughout the whole life cycle of a building, life cycle assessment (LCA) is considered to be the best approach in evaluating impacts of CO_2 emissions. Researchers and organizations, mainly in developed countries, have introduced a number of building life cycle CO_2 emission assessment systems. In developing these, various data sources such as existing databases, standards, codes and reports of the country concerned were used. Although these systems can be applied to any country, they have limited validity outside the specific country or region due to climatic, geographical, technological, economic and sociocultural differences between countries [5].

Similar to other developing countries, Sri Lanka is currently facing many environmental challenges. Construction is one of the major industries and buildings contribute to more than half of value and raw material usage in the construction sector [6]. According to the current energy scenario of the country, rapidly expanding building sector consumes about 35% of national energy, thus contributing to a significant portion of CO_2 emissions [7]. Although buildings are identified

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as a priority sector in reducing energy use and CO_2 emissions, national data inventories and systems needed for the assessment of energy and CO_2 emissions are currently lacking in the country.

This study was aimed at developing a building life cycle CO_2 emission estimator tool in the context of Sri Lanka, which includes a CO_2 emission estimator program and an integrated life cycle database. The applicability of the developed CO_2 emission estimator tool was evaluated using a case study of a multi-storey building in a Sri Lankan university. With predictions of increasing energy use and rise of CO_2 emissions in the building sector of Sri Lanka in future, this type of tool will be highly useful in assessing life cycle CO_2 emissions of buildings and identifying appropriate strategies for mitigating CO_2 emissions throughout building life cycle.

2. Literature review

Life cycle CO_2 emission assessment (LCCO2A) is a technique to quantitatively assess CO_2 emissions associated with all stages of building life cycle [8] which include material production, transportation, construction, operation, maintenance and end-of-life. Many countries have been developing systems to evaluate life cycle CO_2 emissions of buildings that incorporate the unique characteristics of their construction industries [5]. Table 1 outlines some of these systems with their specific evaluation features.

Apart from the above national and organization-based life cycle CO_2 emission assessment systems, researchers around the globe have been developing and modifying similar systems based on building certification systems, life cycle databases, standards and codes of the respective countries in order to achieve optimum representation of existing conditions of their construction industries.

Roh et al. [9] developed a design program (SUSB-OPTIMUM) to assess life cycle CO_2 emission of an apartment house in South Korea, which included a database of CO_2 reducing performance and costs of environmentally-friendly construction technologies, an interpretation program based on a simplified technique for assessing life cycle CO_2 emissions and unit costs based on inter-industry relation table. A Building materials Embodied GHG Assessment criteria and System (BEGAS) for newly revised Korea Green Building Certification System (G-SEED) was established [14]. Li et al. [15] developed an automated estimator of life cycle carbon emission for residential buildings in China. The Building Life cycle Carbon Emission Assessment Program (BEGAS 2.0) that evaluates carbon emission quantity in Korea's Green Building Index Certification System (GBI Certification System) was developed by Roh et al. [16]. Lee et al. [17] established an integrated building LCA model that allows an interlinked application of LCA results of building materials, components and the whole building. They proposed a method for stepwise application of the integrated building LCA model to Green Standard for Energy and Environmental Design (G-SEED), a Korean green building certification system. A LCA tool for buildings which was integrated in TRNSYS environment and has the ability to perform 'cradle to cradle' LCA studies was presented by Cellura et al. [18]. The authors developed a database including the specific impacts due to Global Energy Requirement (GER) and Global Warming potential (GWP) of building materials, energy carriers, transport and end-of-life processes.

Roh and Tae [19] developed a web-based integrated assessment system to periodically evaluate and manage life cycle CO_2 emissions of a building. It included models for simple assessment (SAM), detailed assessment (DAM), construction site assessment (CAM) and results analysis (RAM). In a similar study, the same authors developed a Building Simplified LCCO2 emissions Assessment Tool (B-SCAT) for the application in the early design phase of low-carbon buildings in South Korea [20]. Dong and Ng [21] developed a LCA model, namely the Environmental Model of Construction (EMoC) to help decision makers assess environmental performance of building construction projects in Hong Kong. Li et al. [22] developed a dynamic model for calculating

Table 1
Building life cycle CO_2 emission assessment systems [5,9–13].

System	Country developed	Organization	Year	Features
SUSB-LCA	Korea	Sustainable Building Research Center, Hanyang University	2007	Assesses life cycle energy consumption, CO_2 emission and cost. The system update is relatively easy.
AIJ-LCA	Japan	Japan Architectural Society	2003	Composed of Excel worksheet type. Assesses building life cycle CO_2, NO_x, SO_x emissions, energy use and cost. Wide assessment range with industry specific analysis method.
GEM-21P	Japan	Shimizu construction	2008	Uses statistical data to assess life cycle CO_2 and estimates energy input per unit area. CO_2 unit data of Japan Architectural Society is used. Users can review alternatives for saving energy.
Carbon Navigator	Japan	Daisei construction	2009	Composed of 5 software; PAL-navi, ERR-navi, aurora, CarbonCalc and PAL-auto calculation. Interlinked with BIM, it can assess each life cycle stage and promotes efficient assessment by simulation of CO_2 reduction measures.
LISA	Australia	BHP Research Center and University of New Castle	2003	Composed of simple design interface and processes data in checklist form. Provides efficient material production analysis using life cycle inventory database.
BeCost	Finland	VTT Research Center	2003	Web based assessment offers easy access to users. Assessment and analysis of results are conducted in stages. Processes various data such as structure type, materials, land type and endurance period.
ENVEST2	UK	Building Research Establishment (BRE)	2003	Assesses building life cycle CO_2 and cost. Offers high accessibility through web based assessment. Uses Eco Point, the unique indicator of the system.
LCA-MCDM	USA	International Energy Agency (IEA)	1999	Reflects weighted value on standard proposals through general designing assessment program.
Eco-Quantum	The Netherlands	W/E Sustainable Building	1996	The first computer program based on building LCA. Capable of assessing various conditions such as effects of energy consumption through building life cycle.
K-LCA	Korea	Korea Institute of Construction Technology	2004	Uses CO_2 emission rates per basic unit on the basis of inter-industry analysis table.

carbon emissions in construction phase based on Building Information Modelling (BIM), incorporating basic BIM model of a building, real-time material consumption schedule and carbon emission estimation system. The model was expected to achieve an optimal construction scheme to guide low-carbon construction. The requisite for an LCCO2 assessment program that is based on technical elements of Global Environmental Model/Management-21P (GEM-21P) system was identified by Baek et al. [10].

LBNL China building LCA model for conducting life cycle assessment of residential and commercial buildings in Beijing was developed by Aden et al. [23]. A BIM-based building CO_2 emission quantity assessment method to analyze reduction of energy consumption and CO_2 emission was presented in which accuracy of BIM based quantity estimation according to major building materials was examined [24]. Fu et al. [25] introduced a LCA tool to calculate and compare embodied carbon and energy for different building plans in construction stage. A program-level management system for life cycle environmental and economic assessment of a complex building project was developed by Kim et al. [26]. A systematic model for developing sustainable building assessment tools and a related performance assessment framework was established by Kang et al. [27]. Stephan et al. [28] Introduced a framework that considered energy requirements at building and city scales. It was implemented through the development of a software tool which allowed rapid analysis of life cycle energy demand of buildings at different scales.

In developing a life cycle CO_2 emission estimator tool for buildings in Sri Lanka, the existing systems which were developed in other countries with attention to their specific features and adaptability in the context of Sri Lanka were taken into consideration. The national building life cycle CO_2 emission data inventories, which are available in some countries, are not yet developed in Sri Lanka. To the best of our knowledge only a number of related research literature in the context of Sri Lanka exist, the relevant data from which were used in the present study. Dias and Pooliyadda [29] developed a computerized relational database management system and the embodied energy and carbon of building materials were calculated using an aggregation-decomposition hierarchy. Pooliyadda [30] estimated the embodied energy content and carbon emission of building materials commonly used in Sri Lanka. In these studies, the country-specific factors such as type and quality of raw materials, energy sources and material manufacturing technologies prevailing at the time of the respective studies were taken into account. The developed tool is expected to fill an existing gap in the CO_2 emission assessment of buildings sector in Sri Lanka to a certain degree and will also provide opportunities for future improvements.

3. Materials and methods

Life cycle CO_2 emission assessment is a specific form of LCA where carbon emission is evaluated throughout the building life cycle. In the present study, for life cycle CO_2 emission assessment, system boundaries and assumptions were established and CO_2 emission was calculated through life cycle inventory (LCI) and life cycle impact assessment (LCIA), which are the phases identified in the LCA methodological framework of ISO 14040- Environmental Management-Life Cycle Assessment [31]. In order to develop the CO_2 emission estimator tool, CO_2 emission calculation method and database were established based on life cycle stages of material production, construction, operation, maintenance and end-of-life as classified by ISO 21931–1: Sustainability in building construction [32].

3.1. System boundary

The system boundary of the study included both spatial boundary and lifecycle process boundary for the estimation of CO_2 emissions. The spatial boundary was defined as the closed 3-dimensionsl space constituted by the foundation at the bottom, the highest point and the façade of the building. All phases in the cradle-to-grave lifecycle process were included in the process boundary as illustrated in Fig. 1. The

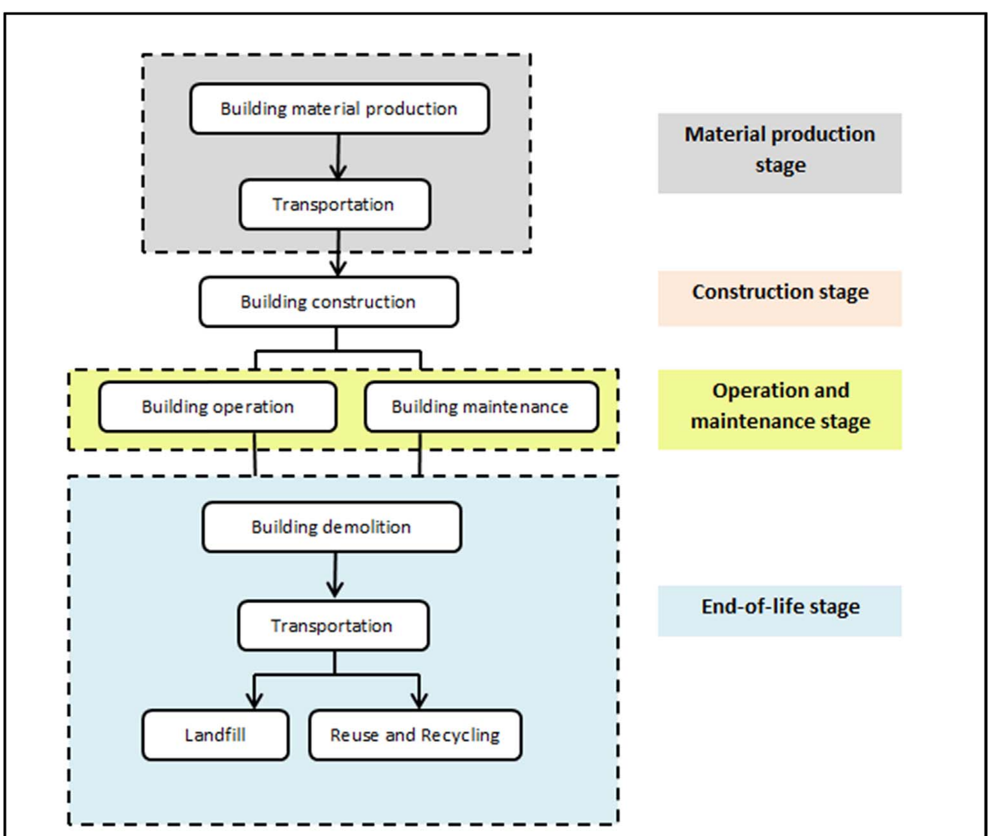

Fig. 1. Life cycle process boundary of study.

functional unit for the study was considered as 1 m^2 of the gross floor area of the building per year.

3.2. Estimation of building life cycle CO_2 emissions

Based on the LCA approach, total life cycle CO_2 emissions of a building can be calculated as given in equation (1)[33].

$$C_{LC} = C_M + C_C + C_O + C_E \tag{1}$$

where C_{LC} = total life cycle CO_2 emissions ($kgCO_2$) and C_M, C_c, C_o, C_E = CO_2 emissions at material production, construction, operation and maintenance and end-of-life stages ($kgCO_2$). The CO_2 emissions at each life cycle stage are presented by equations (2)–(5).

3.2.1. CO_2 emission at material production

Material production stage includes both material production and transportation to the building site. CO_2 emissions at material production stage, C_M can be calculated as [34]:

$$C_M = \sum_{i=1}^{n} (m_i \times f_{m,i}) + \sum_{i=1}^{n} [(m_i/T) \times d_i \times f_{t,i}] \tag{2}$$

where n = total number of material types, m_i = quantity of material type i (m^3 or kg), $f_{m,i}$ = carbon emission coefficient of type i material ($kgCO_2/m^3$ or $kgCO_2$/kg), T = capacity of transportation vehicle (m^3 or kg), d_i = two-way distance between material supply point to construction site (km) and $f_{t,i}$ = carbon emission factor for material transported over unit distance ($kgCO_2$/km).

3.2.2. CO_2 emission at construction

CO_2 emission at construction stage, C_C is due to the operation of construction machinery and equipment during on-site construction activities, which is given as:

$$C_c = \sum_{i=1}^{j} (Q_{c,i} \times U_i \times f_{c,i}) \tag{3}$$

where j = total number of construction activities, $Q_{c,i}$ = quantity of construction activity i (m^3 or kg), U_i = fuel/electricity use rate for the construction activity i (l/m^3, kwh/kg etc.) and $f_{c,i}$ = carbon emission factor for fuel/electricity used for the construction activity i ($kgCO_2$/l or $kgCO_2$/kwh).

3.2.3. CO_2 emission at building operation and maintenance

CO_2 emission at this stage C_O, includes emissions due to building operation, repair and replacement of materials and components which can be calculated as [34]:

$$C_O = \sum_{i=1}^{k} \left(E_i \times f_{e,i} \times Y\right) + \sum_{i=1}^{n} \left[m_i \times f_{m,i} \times \left(Y/R_i\right) \times r_i\right] \tag{4}$$

where k = total number of energy sources, E_i = average annual consumption of energy type i (kWh, l etc.), $f_{e,i}$ = carbon emission factor of energy type i ($kgCO_2$/kWh, $kgCO_2$/l etc.), Y = life span of building (years), R_i = average life span of building material i (years) and r_i = repair/replacement rate for material i. m_i and $f_{m,i}$ are same as defined in equation (2). The value (Y/R_i) is the repair/replacement factor of material i.

3.2.4. CO_2 emission at end-of-life

CO_2 emission at end-of-life stage, C_E can be regarded as the summation of CO_2 emissions due to building demolition, transportation to landfill site and disposal in landfill. As reuse and recycling of demolition waste is not very common in the current construction industry of Sri Lanka and relevant data is not available, it was assumed that the total amount of demolished material is disposed in landfill. The total CO_2 emission at end-of-life stage is given by equation (5).

$$C_E = \sum_{i=1}^{m} (Q_{d,i} \times f_{d,i}) + [(M_d/T) \times d_i \times f_{t,i}] + (M_d \times f_d) \tag{5}$$

where m = total number of demolition activities, $Q_{d,i}$ = quantity of demolition activity i (m^3 or kg), $f_{d,i}$ = carbon emission factor of demolition activity i ($kgCO_2/m^3$ or $kgCO_2$/kg), M_d = total quantity of demolished material (kg), and f_d = carbon emission factor for landfill operation ($kgCO_2$/kg). T, d_i and $f_{t,i}$ are the same as defined in equation (2).

3.3. Development of building life cycle CO_2 emission estimator tool

3.3.1. Conceptual model

In order to understand how the real world (problem) relates to the computer model (CO_2 emission estimator tool) a conceptual model was developed. It includes three components; input, analysis and results. For identifying the inputs to the model, a number of assumptions related to materials, construction activities, climate, energy sources, building life span, maintenance cycle, energy uses, user behaviour and

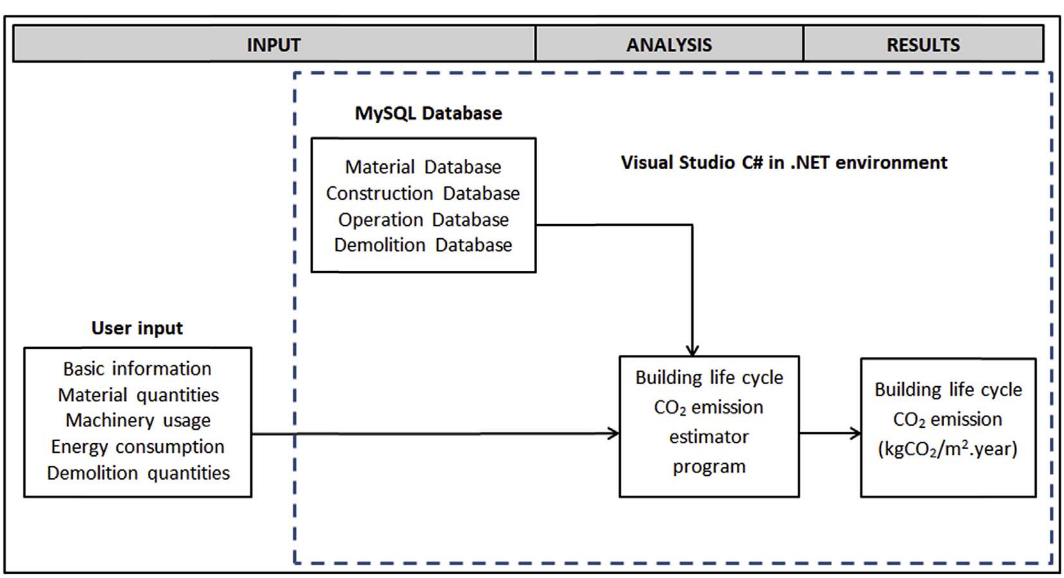

Fig. 2. Conceptual model for developing building life cycle CO_2 emission estimator tool.

demolition practices were taken into consideration. For example, only the identified major CO_2 emitting materials were considered in the material input. The assumptions made were fully explained in Section 3.3.2. The conceptual model for the development of the tool is illustrated in Fig. 2.

- Input: Input data is of two types; (1) data stored in the database (related to materials, construction activities, energy sources and end-of-life activities) (2) data entered by user (material quantities, energy consumption, quantities of construction activities and basic information such as location, type of building, type of structure, gross floor area, number of floors and building life span). The input data is linked to each stage of life cycle for computation of CO_2 emissions.
- Analysis: Using input data and life cycle CO_2 emission formulae within the program, the life cycle CO_2 emission of each life cycle stage as well as CO_2 emission of materials are estimated.
- Results: Life cycle CO_2 emission results of the building is given for each life cycle stage in both tabular and graphical form. An assessment report is generated which can be either printed or saved as a PDF file for further use.

The development of the building CO_2 emission estimator tool was carried out in two stages (1) development of CO_2 emission database (2) development of estimator program and user interface.

3.3.2. Development of building life cycle database

The building life cycle database is composed of four sub-databases; material database, construction database, operation database and demolition database. MySQL database management software was used to create the building life cycle database which can be easily integrated with the estimator programme. In developing the life cycle database, a number of data sources were used as given in Table 2.

Table 3
Major CO_2 emitting building materials.

Material	Percentage of CO_2 emission	
	Residential buildings	Commercial buildings
Ready-mixed concrete	39.1	38.7
Steel-reinforcement	20.8	20.4
Cement	14.4	14.2
Rubble	2.8	2.3
Clay bricks	2.0	1.6
Concrete blocks	1.9	1.7
Steel-structural	1.3	1.6
Ceramic tiles	1.3	1.8
Aluminium	0.8	1.4
Paint	1.0	1.1
Total	85.4	84.8

realistic to focus on a fewer number of high carbon impact materials (‘carbon hotspots’) [44]. Therefore, material database was made up of materials which contribute together to more than 85% of total CO_2 emission of typical Sri Lankan buildings. These were identified by analysing bills of quantities of a number of residential and commercial buildings in Sri Lanka. The major CO_2 emitting building materials used in this study are shown in Table 3. A similar approach of considering major CO_2 emitting materials was followed by several previous studies [12,14,16,17,19,45].

As given in Table 3, ten major CO_2 emitting materials in the context of Sri Lanka were identified for this study; ready-mixed concrete, reinforcement steel, clay bricks, cement, rubble, concrete blocks, structural steel, ceramic tiles, aluminium and paint. According to their strength characteristics, ready-mixed concrete and concrete blocks were further categorised into seven and four sub-categories respectively. Therefore, in the material database, a total number of 19 detailed building materials for all ten major CO_2 emitting materials were considered. As much as possible, the values of carbon emission coefficients of materials were taken from the existing Sri Lankan literature [29,30]. When the available data from these sources did not match with the material specifications considered in the present study (such as compressive strength of ready-mixed concrete), relevant data were referred from international databases [35–37].

Table 2
Data sources used for developing building life cycle database.

Life cycle stage	Variables	Data sources
Material manufacturing	Carbon emission coefficients of materials	Existing Sri Lankan literature [29,30] International databases [35–37]
Transportation	Type and capacity of transportation vehicle, fuel type, mileage, transportation distance	Records of material suppliers and contractors in Sri Lanka, technical specifications
	Fuel carbon emission coefficients	International data sources [3]
Construction	Types of machinery used, energy sources, energy use rate	Records of machinery suppliers and contractors in Sri Lanka, technical specifications
	Fuel/electricity carbon emission factors	For electricity Sri Lankan data sources [38], for other fuels International data sources [3]
Operation	Types of energy sources, fuel/electricity carbon emission factors	For electricity Sri Lankan data sources [38], for other fuels International data sources [3]
Maintenance	Repair/replacement factor and repair/replacement rate of materials	Discussions with building contractors in Sri Lanka, Existing research literature [39–41]
End-of-life	Demolition activities, machinery used, fuel use rates	Existing research literature [9,12,19,42,43]

- Material database

The material database was composed of manufacturing, transportation and maintenance data related to the major building materials. Rather than considering hundreds of materials used in a building, most of which have negligible overall carbon impact, it was considered more

Data related to transportation of building materials to construction site such as types and capacity of vehicles, fuel used, average distance of transportation and mileage were gathered from previous records through discussions with several material suppliers and contractors in Sri Lanka. Transit-mixer truck (6 m^3) for ready-mixed concrete, 20-ton truck for steel reinforcement and 8-ton truck for all other materials were designated for material transportation. The fuel specific CO_2 emission factors were taken from international data sources [3].

The maintenance related data included repair/replacement factor and repair/replacement rate for each building material as shown in Table 4. These were identified by discussions with several building contractors in Sri Lanka as well as using previous research literature [39–41]. In identifying repair/replacement rates, four materials and related activities were considered; cement (needed for repairing tiling and plastering), ceramic tiles (replacing of tiles), aluminium (repair of doors and windows) and painting. Other materials, which were used for building structure and envelope, were considered to have repair/replacement factor of 1.0.

Table 4
Repair/replacement data for materials.

Material	Repair/Replacement factor[a]	Repair/Replacement rate (%)
Ready-mixed concrete	1.0	–
Steel-reinforcement	1.0	–
Rubble	1.0	–
Clay bricks	1.0	–
Concrete blocks	1.0	–
Steel-structural	1.0	–
Cement (mortar and plaster)	5.0	0.25
Ceramic tiles	5.0	0.25
Aluminium	5.0	0.25
Paint	10.0	1.00

[a] Repair/replacement factor = (life span of a building/average life span of building material).

- Construction database

For the development of the construction database, CO_2 emission due to the use of machinery and equipment during the process of on-site building construction was considered. The activities needed to install the major CO_2 emitting materials such as excavation and removal, backfilling, ready-mixed concrete placing and compaction, rebar and reinforcing, lifting of materials and site lighting were included in the database. For these construction activities, types of machinery used, energy use rate and CO_2 emission factor of energy sources were identified. The data required for the construction database were obtained from previous records through discussions with several machinery suppliers and contractors in Sri Lanka. The carbon emission factors of electricity and other fuels were taken from Sri Lanka Energy Balance 2015 [38] and relevant international data sources [3] respectively.

- Operation database

It was assumed that in the building operation stage energy was required for lighting, air conditioning, ventilation, operation of lifts, hot water generation and equipment use (mainly computers) only. As Sri Lanka is a tropical country with a warm climate throughout the year, space heating is not required. The building life span is a user input and depends on the particular building assessed. The operation database includes data related to energy sources used for building operation; types of energy sources and their CO_2 emission factors. The most common types of energy sources used in Sri Lankan buildings such as national grid electricity, diesel, kerosene and LP gas were considered in developing the database. The annual electricity consumption which is assumed to be constant throughout the building life span is a user input and was calculated using monthly electricity bills. The CO_2 emission factors for energy sources commonly used in Sri Lanka are given in Table 5.

Table 5
CO_2 emission factors of energy sources.

Energy source	CO_2 emission factor	Unit	Data source
Electricity	0.6896	$kgCO_2/kWh$	[38]
Diesel	2.68	$kgCO_2/l$	[3]
Kerosene	2.52	$kgCO_2/l$	[3]
LP gas	1.61	$kgCO_2/l$	[3]

- Demolition database

The quantity of demolished materials was assumed to be the same as the quantity of materials used for building construction. Due to the unavailability of demolition data in Sri Lanka, relevant data from research literature were considered in developing this database [9,12,19,42,43]. Three main demolition activities were considered; removal of individual elements, ground levelling and crane handling for which CO_2 emission factors were taken from previous research [43]. It was assumed that a 20-ton dump truck is used to transport the demolished waste for a distance of 15 km from building site to landfill site. As reuse and recycling of demolished waste is still not practiced much in Sri Lanka and the relevant data is unavailable, the total amount of demolished material was assumed to be landfilled. It was assumed that waste material was landfilled using bulldozers and compactors for which a standard fuel usage rate was taken by referring previous research [9].

3.3.3. Development of CO_2 emission estimator program

The CO_2 emission estimator programme was developed using Visual Studio C# programming language in .NET environment. The system architecture is composed of three interactive layers; user interface layer, calculation layer and database layer as shown in Fig. 3. After entering the program, a user has to provide two types of input through user interface layer; (1) basic information of the project such as project name, location, type of building, type of structure, number of floors, gross floor area, land area, building life span and an image of the building (2) building life cycle information such as quantities of major CO_2 emitting materials and construction activities, annual energy consumption and demolition information. Once all user input was given, the calculation process commences. The request for calculation prompts the calculation layer to analyze the given data and with the use of relevant data from integrated database, CO_2 emissions of each life cycle stage are calculated by using the programmed CO_2 emission formula given in section 3.2.

Upon the request for calculation results, the CO_2 emissions of each life cycle stage can be viewed in the assessment results interface. Some of the user interfaces of the program; input of basic information, life cycle information and calculation of results are given in Fig. 4. After completion of the computation, a report of the building life cycle CO_2 emission is generated that can be either printed or can be saved as a PDF file. The report includes the following information: basic building information, CO_2 emission of each life cycle stage (in $kgCO_2$) both numerically and as percentages of total CO_2 emission, total life cycle CO_2 emission (in $kgCO_2/m^2$ and $kgCO_2/m^2$.year). The summary of CO_2 emissions of life cycle stages and material types can be viewed both in tabular and graphical forms, facilitating easy understanding and comparison of results.

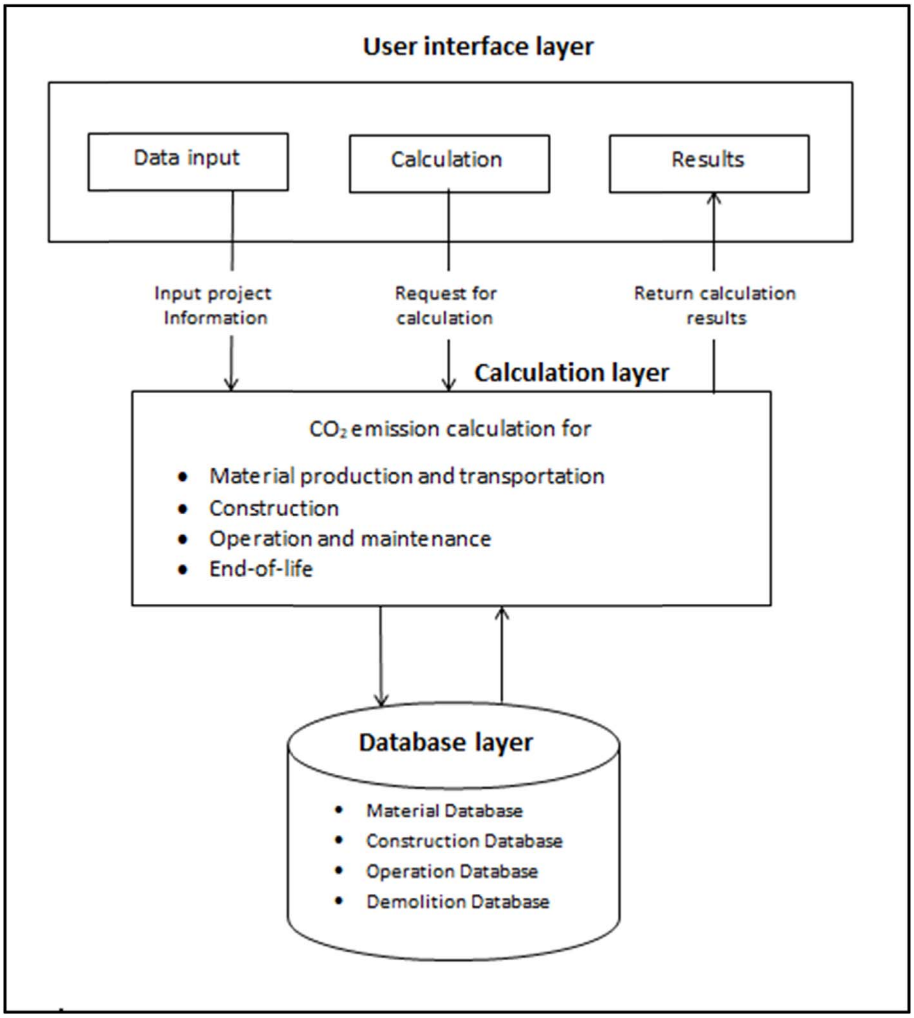

Fig. 3. System architecture of developed tool.

3.4. Case study

To evaluate the applicability of the CO_2 emission estimator tool developed in this study, life cycle CO_2 emissions were assessed for a 7-storey university building in Sri Lanka. It is a multi-purpose building containing class rooms, examination halls, conference room, auditorium, computer laboratories, cafeteria, offices and residential facilities for visiting faculty. An overview of the case study building is given in Table 6.

3.4.1. Application of developed CO_2 emission estimator tool

The basic information interface and the material production stage interface for case study building are given in Figs. 5 and 6. Similarly, data was input for other life cycle stages; construction, operation and end-of-life.

After the completion of data input, the calculation of life cycle carbon emissions of each stage was carried out in the assessment results interfaces. The assessment result interface for material production and end-of-life stages are given in Figs. 7 and 8. By using 'calculate' function in the user interface, carbon emission at each stage was displayed.

After computation of CO_2 emissions of all life cycle stages, a results report was generated as shown in Fig. 9, which can be either printed or saved as a PDF file.

3.4.2. Assessment results

The total life cycle CO_2 emission of the building over the assumed life span of 50 years was found to be 7,015,358.39 $kgCO_2$. The annual emission was 140,307.17 $kgCO_2$ and CO_2 emission per unit gross floor area per year was 23.51 $kgCO_2/m^2$.year. The summary of CO_2 emissions at each life cycle stage as taken from the assessment report is given in Table 7.

The highest contribution is from operation (52.24%), which was followed by material production at 41.76%. Material transportation only contributed to 0.78% of CO_2 emission at material production stage. Construction and maintenance contributed to 1.61% and 3.23% of total CO_2 emission respectively. In the construction stage, activities which highly contributed to CO_2 emission were excavation and removal (53.45%) and lifting of materials (28.59%). The maintenance contributed to 5.83% of CO_2 emission of operation and maintenance stage. The end-of-life stage shared only 0.83% of total life cycle CO_2 emission.

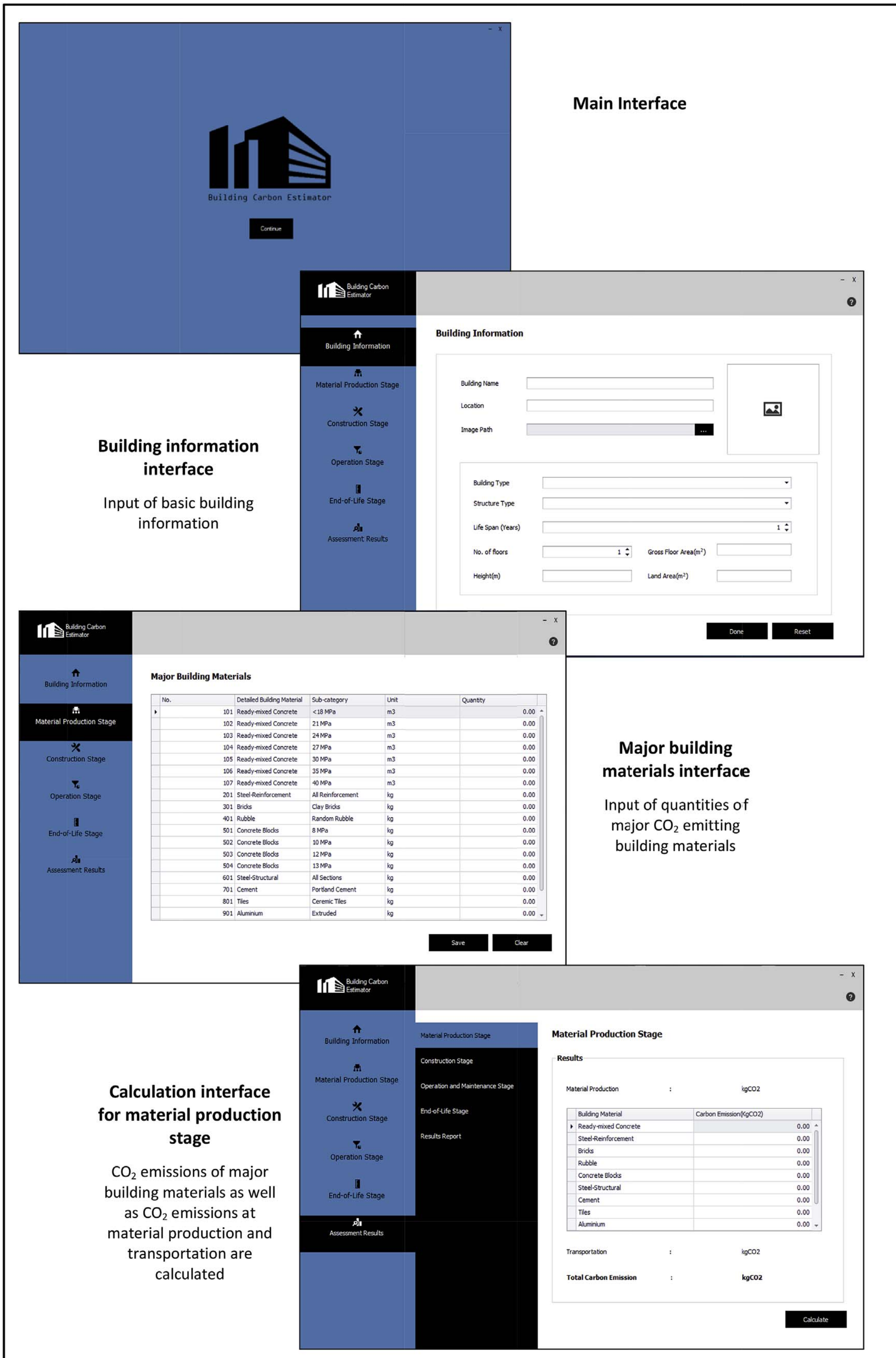

Fig. 4. User interfaces of CO_2 emission estimator program.

Table 6
Overview of case study building.

Project Name	Faculty of Graduate Studies, General Sir John Kotelawala Defence University
Location	Ratmalana, Sri Lanka
Purpose	Educational
Structure	Reinforced concrete
No. of floors	7
Gross floor area	5967 m^2
Site area	2031 m^2
Life span	50 years

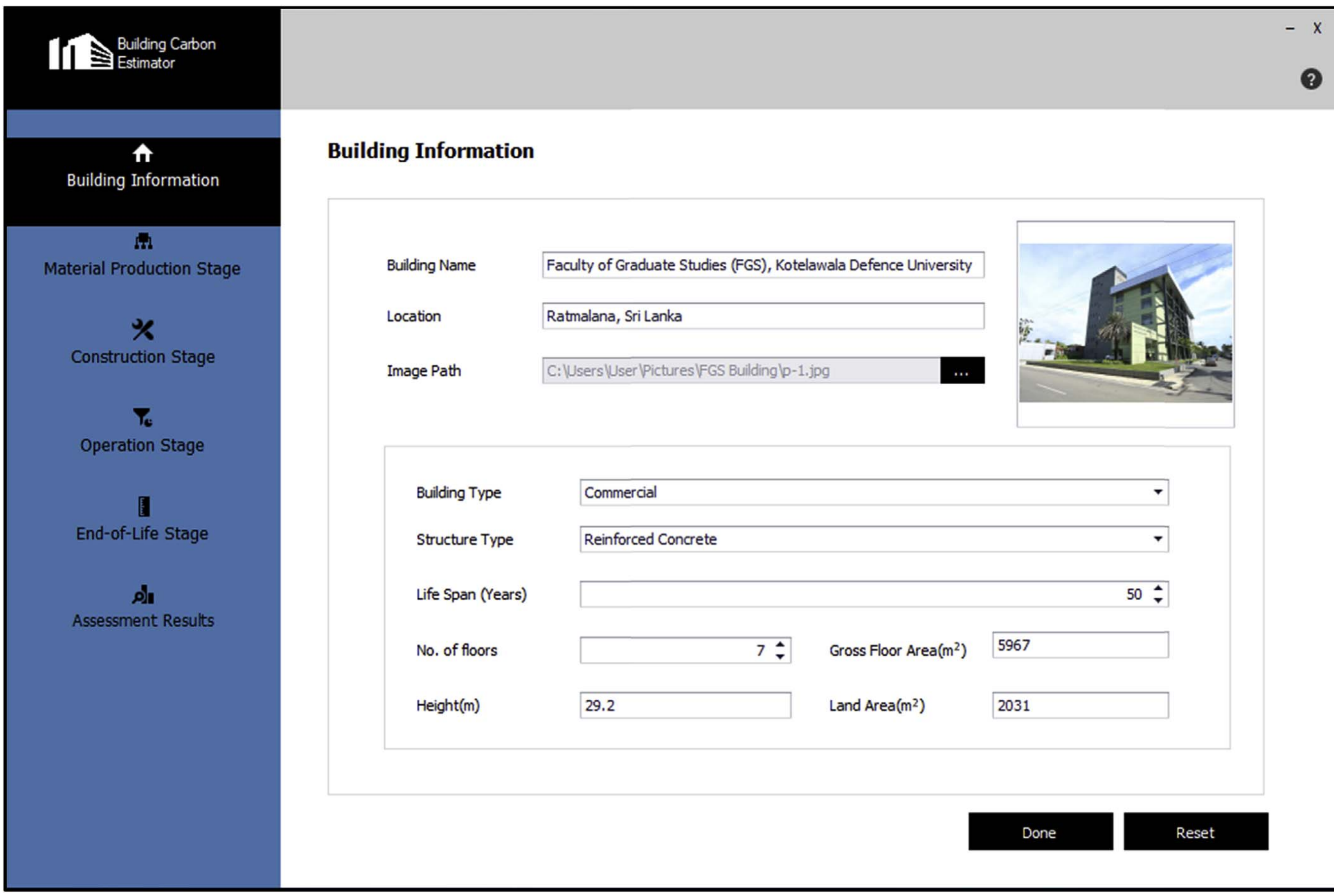

Fig. 5. Building information interface.

From total CO_2 emissions of end-of-life stage, demolition had the highest contribution of 82.25% and transportation to landfill and disposal in landfill contributed to 10.46% and 7.28% of end-of-life CO_2 emissions respectively. The contributions of each life cycle stage to the total CO_2 emission are shown in Fig. 10.

By analyzing the contribution of building materials to the CO_2 emission at the material production stage, it was found that ready-mixed concrete has the highest contribution of 41% followed by cement (18%) and reinforcement steel (17%). Many previous carbon emission studies of reinforced concrete buildings had shown a similar trend [40,46–50]. The main envelope material, clay bricks also has a high share of 13%. As illustrated in Fig. 11, the top four mass materials; ready-mixed concrete, reinforcement steel, cement and clay bricks emitted about 90% of carbon at material production stage. The materials used for building finishes such as aluminium, tiles and paint contributed to 4% of CO_2 emission at material production stage.

Although there are many previous studies available in literature on building life cycle CO_2 emission, their results highly vary. Dixit [51] highlighted several methodological and data quality parameters causing variations across life cycle assessment studies such as system

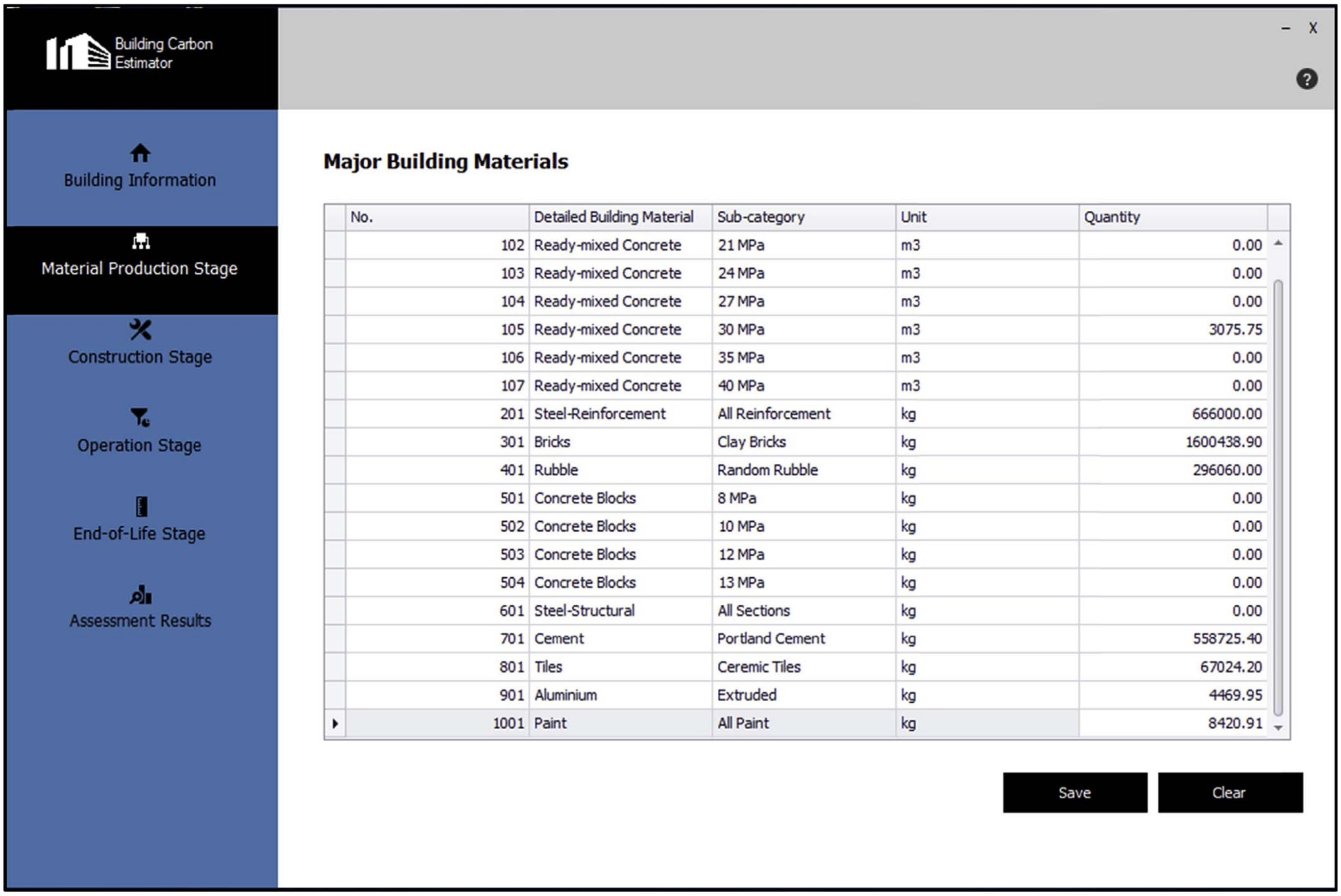

Fig. 6. Material production stage interface.

boundary, methodological approaches, energy inputs, use of primary/secondary data, data incompleteness, and data representativeness. The unique and complex nature of buildings makes the comparisons more difficult.

4. Discussion

This study established a computerized life cycle CO_2 emission estimator tool with an integrated life cycle database to assess life cycle CO_2 emissions of buildings in the context of Sri Lanka. The life cycle process boundary was identified as 'cradle-to-grave' where material production, construction, operation, maintenance and end-of-life stages were considered. The study was composed of four man components; (1) identifying system requirements and system boundary (2) establishing calculation method for CO_2 emissions at each life cycle stage (2) development of building life cycle CO_2 emission database (3) development of CO_2 emission estimator program. The applicability of the developed tool was evaluated by assessing the life cycle CO_2 emissions of a multi-storey reinforced concrete building in a Sri Lankan university. It was found that over the assumed life span of 50 years, the building emits a total of 7,015,358.39 $kgCO_2$. The CO_2 emission per unit gross floor area per year was 23.51 $kgCO_2/m^2$.year. The CO_2 emission at operation and maintenance stage had the highest contribution of 55.47%, which was followed by material production stage having 42.09% of CO_2 emission. The four major CO_2 emitting materials; ready-mixed concrete, reinforcement steel, cement and clay bricks contributed to nearly 90% of CO_2 emission in the material production stage. The construction and end-of-life stages contributed 1.61% and 0.83% respectively to the total life cycle CO_2 emission.

The developed tool can be used to compare life cycle CO_2 emissions of different buildings. Also it can be used to assess the compliance of buildings to the CO_2 emission criteria specified in green building certification systems of Sri Lanka. Most of the existing building life cycle CO_2 emission systems which were discussed under literature review used currently available data inventories developed by recognized authorities of the particular country for the computations [17,19,34,52,53]. But Sri Lanka at present lacks such national databases which had been a major challenge in developing a CO_2 emission estimator tool for the country. Hence, in developing the life cycle database for the tool, the researchers had to rely on the limited number of available Sri Lankan literature as well as international databases. Some of the data related to life cycle stages such as material transportation, construction and maintenance were collected through discussions with construction industry professionals in Sri Lanka. The data related to end-of-life stage were taken from existing literature due to the current unavailability of such data in Sri Lanka. The current scenario of the UK

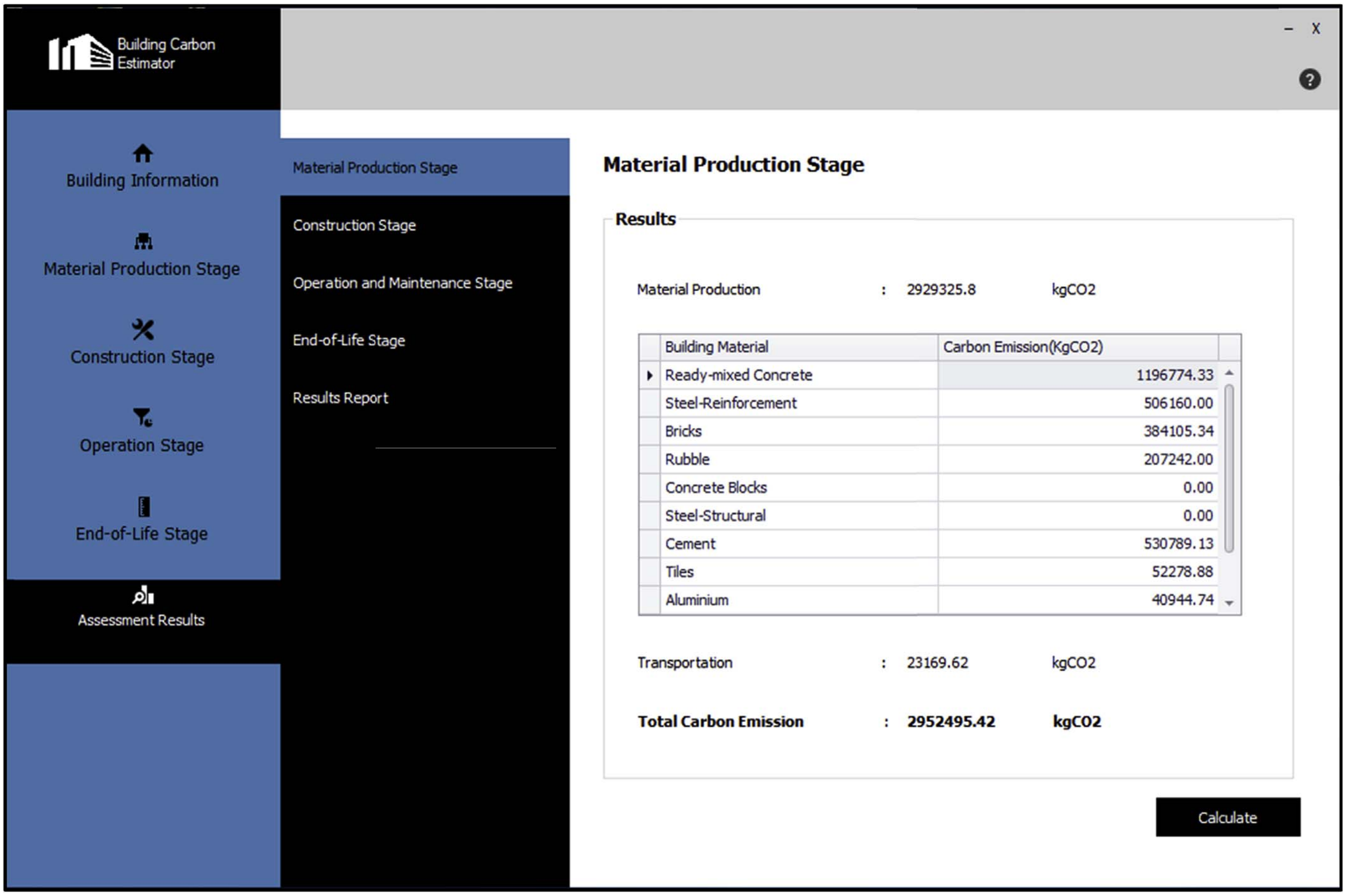

Fig. 7. Assessment results for material production stage.

construction industry pointed out by Moncaster and Symons [53] is more or less the same for Sri Lanka. There is no culture of construction material manufacturers estimating and publishing the whole life environmental impacts of their products and the use of sub-contractors for different construction packages and a culture of commercial confidentiality make data of on-site construction and building demolition and waste disposal scarce.

According to Dixit [51], geological relevance of data causes the largest variations in LCA results. As building life cycle data can highly vary from one country to another due to a wide range of factors such as climate, geographical location, available technology, construction processes, building materials used, energy sources, electricity generation mix and socio-economic conditions, using data which were based on a different country may lead to inaccuracies in the results. Therefore, the database developed in the study should be periodically updated with newly available Sri Lankan data. With the increased awareness of the importance of assessing building life cycle CO_2 emissions, more realistic and accurate data inventories are expected to be available in Sri Lanka in future, which will enable the improvement of the existing database within the tool. Most of the previous studies used national life cycle data inventories which were developed under government authority of the particular country. For Sri Lanka also, development and maintenance of national life cycle inventory databases (LCI DB) need to be accomplished by recognized government authorities for the promotion of building LCA research.

The calculation of energy consumption in the operation stage for the case study considered was based on the input of annual average energy consumption which is manually calculated from monthly electricity bills. In case of newly constructed buildings, where these data are not available, suitable energy simulation tools can be used to estimate the energy consumption based on building characteristics and expected use. In several previous studies, energy simulation software were integrated with CO_2 emission assessment tools for this purpose [9,16,53]. Kang [27] suggested using a specialized energy simulation program such as EnergyPlus for the computation of the operational energy consumption. GEM-21P program includes an energy simulation program namely the Heating, Air conditioning and Sanitary Engineering Program (HASP) for calculating the amount of CO_2 emissions in the building operation stage [10]. In the developed tool the material quantities which are given as initial input to the program are manually calculated from bills of quantities, which is time consuming and also may lead to human errors. Several previous studies used quantity take-off software which were integrated with the CO_2 emission estimator tool to make the quantity estimation process fully automated, hence

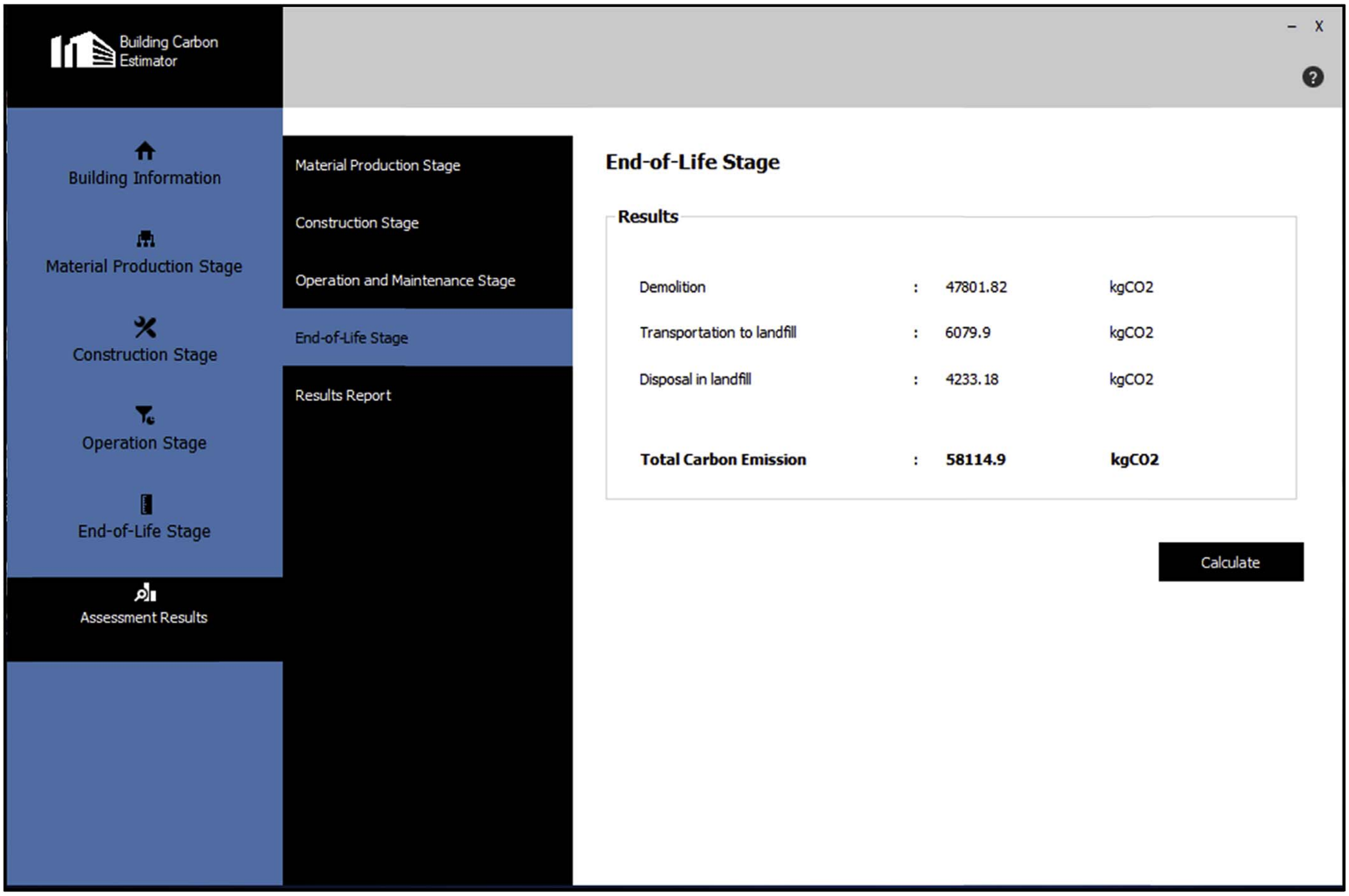

Fig. 8. Assessment results for end-of-life stage.

making the performance of the CO_2 emission assessment tool more efficient [9,26]. Roh et al. [14] established an automated quantity input technique using the standard work codes of Korea Public Procurement Service (PPS) as a medium. Lee et al. [17] proposed linking of LCA programs with data from a Building Information Model (BIM), so a user of a BIM program can perform LCA using quantity takeoff and energy simulation functions inherent in the BIM programs. Adopting similar practices will help to make the developed building life cycle CO_2 emission estimator tool fully automatic in relation to quantity estimation and energy simulation. It will greatly enhance the present capabilities of the tool, making it more efficient as well as more convenient and less time consuming to use by various stakeholders for building CO_2 emission estimation at different stages of construction.

5. Conclusions

This study was aimed at developing a building life cycle CO_2 emission estimator tool in the context of Sri Lanka. The tool can be used to compare life cycle CO_2 emissions of different buildings as well as to assess the compliance of buildings to the CO_2 emission criteria specified in green building certification systems of Sri Lanka. A database for life cycle CO_2 emissions of buildings in the context of Sri Lanka was established, which was integrated with a CO_2 emission estimator program. As much as possible, life cycle data were collected from Sri Lankan literature and building industry. For life cycle stages where appropriate local data is not available, international data sources were referred.

The applicability of the developed tool was evaluated by using a case study of a multi-storey university building in Sri Lanka. It was found that the operation and maintenance stage contributed most (55.47%) to life cycle CO_2 emission, whereas material production stage followed at 42.09%. The contribution of major CO_2 emitting building materials; ready-mixed concrete, reinforcement steel, cement and clay bricks to the total CO_2 emission at material production stage was found to be about 90%. Finishing materials such as aluminium, paint and ceramic tiles contributed to about 4% of CO_2 emission at material production. The tool can be used to identify low-carbon building materials by comparing alternative building material options, hence supporting material related decision making.

To the best of our knowledge, this study is the first-ever attempt to develop a much needed building life cycle CO_2 emission estimator tool for Sri Lanka and there is much room for improvements. The integrated database should be updated periodically and with the increasing awareness of the country towards low-carbon buildings, it is expected that in future more accurate and relevant local data will be available for improving the database. Also, integration of the tool with quantity take-

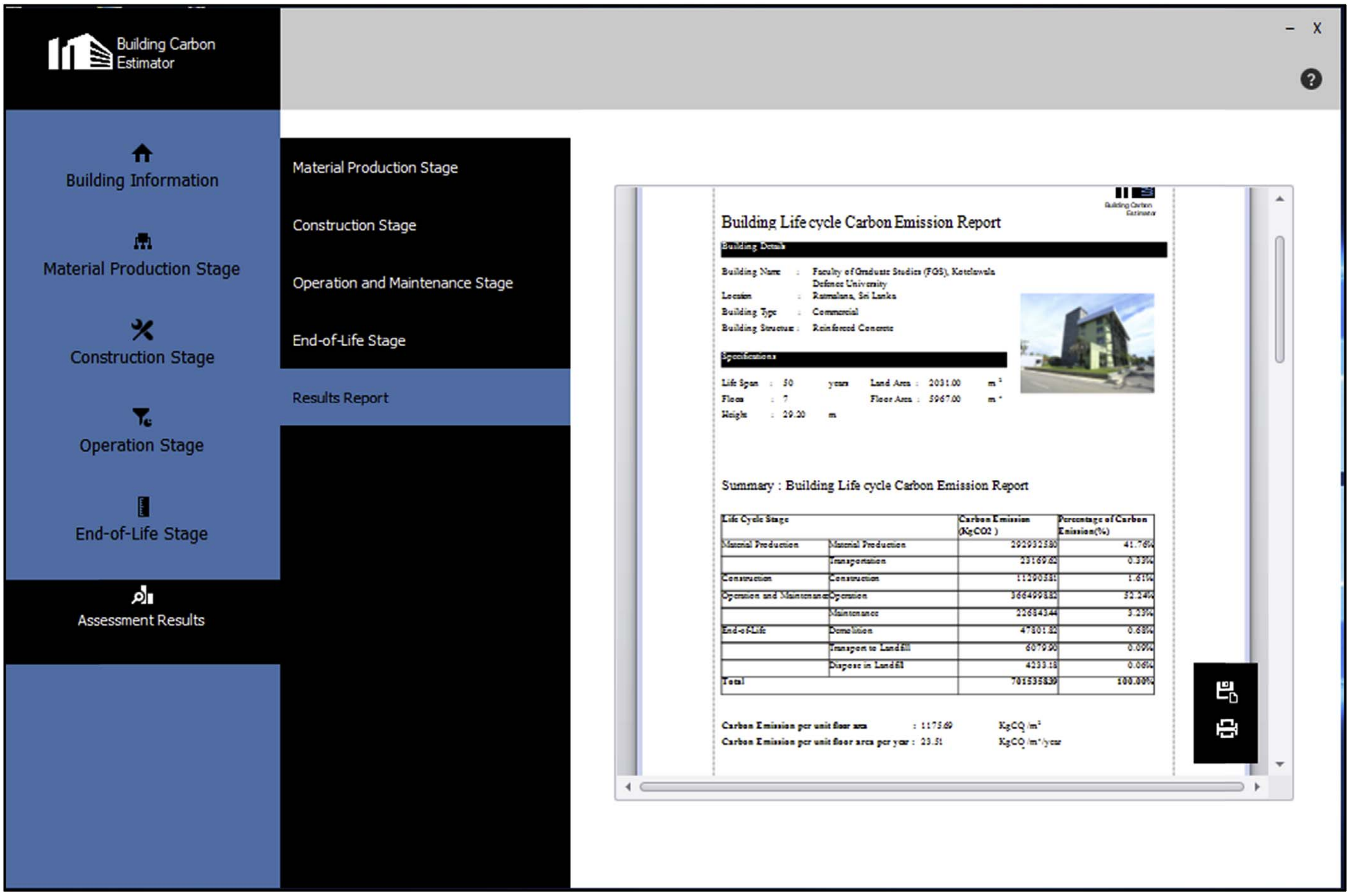

Fig. 9. Report of the CO_2 emission assessment.

Table 7
CO_2 emissions at building life cycle stages.

Life cycle stage		CO_2 emission ($kgCO_2/kg$)	Percentage of CO_2 emission (%)
Material production	Material production	2929325.80	41.76
	Transportation	23169.62	0.33
Construction	Construction	112905.81	1.61
Operation and maintenance	Operation	3664998.82	52.24
	Maintenance	226843.44	3.23
End-of-life	Demolition	47801.82	0.68
	Transportation to landfill	6079.90	0.09
	Disposal in landfill	4233118	0.06
Total		7015358.39	100.00

off software and energy simulation software will make it more efficient and accurate compared to manual input of material quantities and energy consumption data used at present.

The applicability of the tool was evaluated by using a single case study building. The study can be expanded by using the tool on different types of buildings, both residential and commercial so that the limitations of the tool can be identified and suitable measures for further improvement can be devised. As a milestone study, this will initiate the practice of assessing life CO_2 carbon emissions of Sri Lankan buildings, which is a timely requirement towards achieving sustainable goals of the construction industry in Sri Lanka.

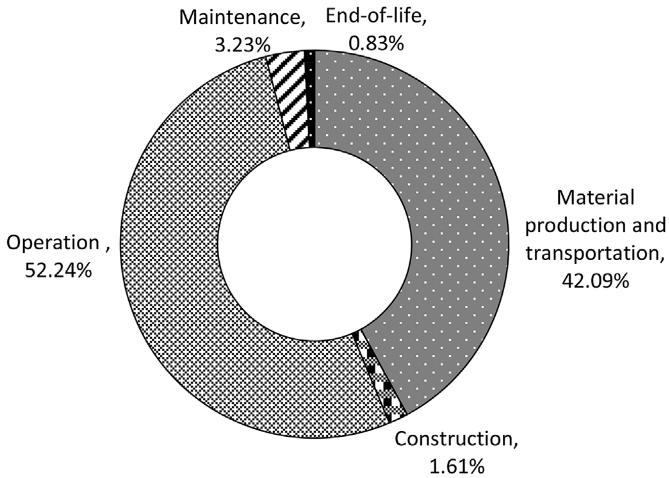

Fig. 10. CO_2 emissions of building life cycle stages.

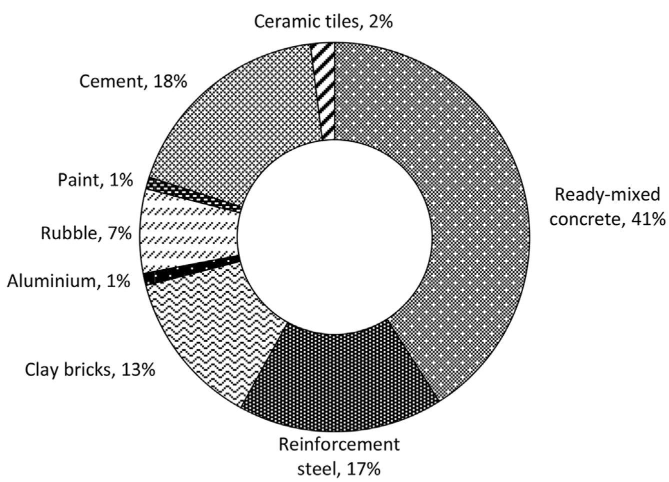

Fig. 11. Contribution of materials to production stage carbon emission.

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References

[1] Intergovernmental Panel on Climate Change (IPCC), Climate Change 2014: Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA.
[2] United Nations Environmental Programme Sustainable Buildings and Climate Initiative: Summary for Decision Makers, (2009).
[3] United Nations Environment Programme (UNEP), Common Carbon Metric: Protocol for Measuring Energy Use and Reporting Greenhouse Gas Emissions from Building Operations, (2010).
[4] International Energy Agency, Energy Technology Perspectives: Scenarios & Strategies to 2050, (2010).
[5] A. Haapio, P. Viitaniemi, A critical review of building environmental assessment tools, Environ. Impact Assess. Rev. 28 (2008) 469–482.
[6] Department of Census and Statistics Sri Lanka, Survey of Construction Industries-2013, (2015).
[7] Sri Lanka Sustainable Energy Authority, Innovative, Energy Efficient Building Concepts, (2017) http://www.energy.gov.lk/your-business/building-energy/energy-efficient-building-design Accessed September 26 2017.
[8] A. Forsberg, F. von Malmborg, Tools for environmental assessment of the built environment, Build. Environ. 39 (2004) 223–228.
[9] S. Roh, S. Tae, S. Shin, J. Woo, Development of an optimum design program (SUSB-OPTIMUM) for the life cycle CO_2 assessment of an apartment house in Korea, Build. Environ. 73 (2014) 40–54.
[10] C. Baek, S.H. Park, M. Suzuki, S.H. Lee, Life cycle carbon dioxide assessment tool for buildings in the schematic design phase, Energy Build. 61 (2013) 275–287.
[11] K. Lee, S. Tae, S. Shin, Development of a life cycle assessment program for building (SUSB-LCA) in South Korea, Renew. Sustain. Energy Rev. 13 (2009) 1994–2002.
[12] S. Tae, S. Shin, J. Woo, S. Roh, The development of apartment house life cycle CO_2 simple assessment system using standard apartment houses of South Korea, Renew. Sustain. Energy Rev. 15 (2011) 1454–1467.
[13] G.K.C. Ding, Sustainable construction-The role of environmental assessment tools, J. Environ. Manage 86 (2008) 451–464.
[14] S. Roh, S. Tae, S. Shin, Development of building materials embodied greenhouse gases assessment criteria and system (BEGAS) in the newly revised Korea Green Building Certification System (G-SEED), Renew. Sustain. Energy Rev. 35 (2014) 410–421.
[15] D. Li, P. Cui, Y. Lu, Development of an automated estimator of life-cycle carbon emissions for residential buildings: a case study in Nanjing, China, Habitat Int. 57 (2016) 154–163.
[16] S. Roh, S. Tae, S.J. Suk, G. Ford, S. Shin, Development of a building life cycle carbon emissions assessment program (BEGAS 2.0) for Korea's green building index certification system, Renew. Sustain. Energy Rev. 53 (2016) 954–965.
[17] N. Lee, S. Tae, Y. Gong, S. Roh, Integrated building life-cycle assessment model to support South Korea's green building certification system (G-SEED), Renew. Sustain. Energy Rev. 76 (2017) 43–50.
[18] M. Cellura, F. Guarino, S. Longo, M. Mistretta, Modeling the energy and environmental life cycle of buildings: a co-simulation approach, Renew. Sustain. Energy Rev. 80 (2017) 733–742.
[19] S. Roh, S. Tae, An integrated assessment system for managing life cycle CO_2 emissions of a building, Renew. Sustain. Energy Rev. 73 (2017) 265–275.
[20] S. Roh, S. Tae, Building simplified life cycle CO_2 emissions assessment tool (B-SCAT) to support low-carbon building design in South Korea, Sustain 8 (2016).
[21] Y.H. Dong, S.T. Ng, A life cycle assessment model for evaluating the environmental impacts of building construction in Hong Kong, Build. Environ. 89 (2015) 183–191.
[22] B. Li, F.F. Fu, H. Zhong, H.B. Luo, Research on the computational model for carbon emissions in building construction stage based on BIM, Struct. Surv. 30 (2012) 411–425.
[23] N. Aden, Y. Qin, D. Fridley, Lifecycle Assessment of Beijing - Area Building Energy Use and Emissions: Summary Findings and Policy Applications, China Energy Group, Energy Analysis Department, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, 2010.
[24] H. Jun, N. Lim, M. Kim, BIM-based carbon dioxide emission quantity assessment method in Korea, J. Asian Archit. Build. Eng. 14 (2015) 569–576.
[25] F. Fu, H. Luo, H. Zhong, A. Hill, Development of a carbon emission calculations system for optimizing building plan based on the LCA framework, Math. Probl. Eng. 2014 (2014).
[26] C.-J. Kim, J. Kim, T. Hong, C. Koo, K. Jeong, H.S. Park, A program-level management system for the life cycle environmental and economic assessment of complex building projects, Environ. Impact Assess. Rev. 54 (2015) 9–21.
[27] H.J. Kang, Development of a systematic model for an assessment tool for sustainable buildings based on a structural framework, Energy Build. 104 (2015) 287–301.
[28] A. Stephan, R.H. Crawford, K. De Myttenaere, Towards a comprehensive life cycle energy analysis framework for residential buildings, Energy Build. 55 (2012) 592–600.
[29] W.P.S. Dias, S.P. Pooliyadda, Quality based energy contents and carbon coefficients for building materials: a systems approach, Energy 29 (2004) 561–580.
[30] S.P. Pooliyadda, Energy Content and Carbon Emission Audit of Building Materials, M.Phil. thesis Department of Civil Engineering, University of Moratuwa, Sri Lanka, 2000.
[31] International Organization for Standardization, ISO 14040-Environmental Management - Life Cycle Assessment - Principles and Framework, International Organization for Standardization, 1997.
[32] ISO 21931-1, Sustainability in Building Construction – Framework for Methods of Assessment of the Environmental Performance of Construction Works – Part 1: Buildings, (2010) https://www.iso.org/standard/45559.html Accessed September 26 2017.
[33] C.K. Chau, T.M. Leung, W.Y. Ng, A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings, Appl. Energy 143 (2015) 395–413.
[34] D. Li, P. Cui, Y. Lu, Development of an automated estimator of life-cycle carbon emissions for residential buildings: a case study in Nanjing, China, Habitat Int. 57 (2016) 154–163.
[35] University of Bath UK, Inventory of Carbon and Energy (ICE) Version 2, (2011).
[36] Centre for Building Performance Research (CBPR), Embodied Energy Coefficients, School of Architecture, Victoria University of Wellington, Newzealand, 2007.
[37] Korea LCI DB Information Network, http://www.epd.or.kr/en/lci/lci_intro.asp (Accessed May 29 2017).
[38] Sri Lanka Sustainable Energy Authority, Sri Lanka Energy Balance 2015– an Analysis of Energy Sector Performance, (2015).
[39] T. Chen, J. Burnett, C. Chau, Analysis of embodied energy use in the residential building of Hong Kong, Energy 26 (2001) 323–340.
[40] C.K. Chau, F.W.H. Yik, W.K. Hui, H.C. Liu, H.K. Yu, Environmental impacts of building materials and building services components for commercial buildings in Hong Kong, J. Clean. Prod. 15 (2007) 1840–1851.

[41] R.H. Crawford, Post-occupancy life cycle energy assessment of a residential building in Australia, Archit. Sci. Rev. 8628 (2013) 1–11.

[42] S. Roh, S. Tae, Building simplified life cycle CO_2 emissions assessment tool (B-SCAT) to support low-carbon building design in South Korea, Sustainability 8 (2016) 567.

[43] X. Zhang, F. Wang, Life-cycle assessment and control measures for carbon emissions of typical buildings in China, Build. Environ. 86 (2015) 89–97.

[44] RICS, Methodology to Calculate Embodied Carbon of Materials, RICS Information Papers, (2012) QS and Construction Standards IP 32/2012.

[45] X. Li, F. Yang, Y. Zhu, Y. Gao, An assessment framework for analyzing the embodied carbon impacts of residential buildings in China, Energy Build. 85 (2014) 400–409.

[46] H.J. Wu, Z.W. Yuan, L. Zhang, J. Bi, Life cycle energy consumption and CO_2 emission of an office building in China, Int. J. Life Cycle Assess. 17 (2012) 105–118.

[47] J. Hong, G.Q. Shen, Y. Feng, W.S. Lau, C. Mao, Greenhouse gas emissions during the construction phase of a building: a case study in China, J. Clean. Prod. 103 (2015) 249–259.

[48] Y.S. Jeong, S.E. Lee, J.H. Huh, Estimation of CO_2 emission of apartment buildings due to major construction materials in the Republic of Korea, Energy Build. 49 (2012) 437–442.

[49] A. Dimoudi, C. Tompa, Energy and environmental indicators related to construction of office buildings, Resour. Conserv. Recycl 53 (2008) 86–95.

[50] A. Atmaca, N. Atmaca, Life cycle energy (LCEA) and carbon dioxide emissions (LCCO2A) assessment of two residential buildings in Gaziantep, Turkey, Energy Build. 102 (2015) 417–431.

[51] M.K. Dixit, Life cycle embodied energy analysis of residential buildings: a review of literature to investigate embodied energy parameters, Renew. Sustain. Energy Rev. 79 (2017) 390–413.

[52] C. Baek, S.H. Park, M. Suzuki, S.H. Lee, Life cycle carbon dioxide assessment tool for buildings in the schematic design phase, Energy Build. 61 (2013) 275–287.

[53] A.M. Moncaster, K.E. Symons, A method and tool for “cradle to grave” embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards, Energy Build. 66 (2013) 514–523.