Engineering Journal issn: 0125-8281

Article

Life Cycle Carbon Dioxide Emissions Assessment in the Design Phase: A Case of a Green Building in Vietnam

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Abstract. Buildings are responsible for about 30% of the total CO_2 emissions globally. To reduce this amount of CO_2, developing green buildings is one of the best approaches. However, this approach is undeveloped in Vietnam due to lacking methods to evaluate design alternatives to meet the criteria of green buildings. This paper presents a life-cycle CO_2 analysis ($LCCO_2A$) as a tool to support the decision-making process in the design phase of a 75-year-lifespan green building in Vietnam. The study conducts $LCCO_2A$ for two design alternatives (with different bricks usage and glass types) and points out the reasons for the differences. Comparing the first alternative with the second one, the results show slight variations in the amount of CO_2 emissions in the erection and demolition phases (with an increase of 21.81 tons and a reduction of 106.1 tons of CO_2eq, respectively), and a significant difference in the operation phase (10,631.52 tons of CO_2eq or 58.34% reduction). For the whole life-cycle, the second design scenario, which uses "greener" materials shows a great decrease of 10,715.81 tons of CO_2eq or 37.54%. By comparing its results with the findings in the literature, this research proves the environmental dominance of green buildings over other building categories.

Keywords: $LCCO_2A$, green buildings, decision-making tool, Vietnam, construction design.

ENGINEERING JOURNAL Volume 25 Issue 7
Received 10 June 2021
Accepted 8 July 2021
Published 31 July 2021
Online at https://engj.org/
DOI:10.4186/ej.2021.25.7.121

This article is based on the presentation at The Construction Digitalization for Sustainable Development (CDSD 2020) International Conference in Hanoi, Vietnam, 24th-25th November 2020.

DOI:10.4186/ej.2021.25.7.121

1. Introduction

The climatic conditions are becoming more and more severe worldwide, pushing many countries, including Vietnam, to face risks of global warming and sea-level rise. According to a report of Climate Central [1], by the year 2050, the majority of the Red River and Mekong River Delta provinces' land in Vietnam may be under sea level. Consequently, more than 31 million Vietnamese people in these localities may be impacted [1]. The emissions of greenhouse gases (GHG), which include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3) have been reported in the literature as one of the primary causes for negative climate changes [2], including global warming and sea-level rise. Regarding the amount of GHG emissions in general and in particular carbon dioxide emissions, which is one of the most harmful GHG [3], nearly one-third of the total GHG [4, 5] and about 30% of the total CO_2 emissions [6-8] globally are attributed to buildings sector. There have not been many statistics available on carbon emissions by sectors of the economy in Vietnam yet. However, it is reported that only the construction materials industry was responsible for about 55 million tons of CO_2 equivalent (CO_2eq) per year [9]. If taking all stages of a buildings' lifetime into consideration, the result may be much higher than that. Therefore, to minimise the climate crisis today, Vietnam needs to target the reduction of CO_2 emissions from the buildings sector.

A popular approach that has been taken for this target globally, and Vietnam is not an exemption, is to develop green buildings, which should be accredited by one of the building rating systems. Currently, Vietnam adopts several internationally widely-used green building rating systems, such as LEED (Leadership in Energy and Environmental Design – developed by the U.S. Green Building Council), Green Mark (Singapore Green Building Council), EDGE (developed by IFC - International Finance Corporation, the World Bank Group), and also a local one (LOTUS). LOTUS was first introduced to the country in 2010 by the Vietnam Green Building Council (VGBC) [10]. In Vietnam, although the government has issued a series of documents and policies for implementing the national commitment to sustainable development [11] along with many campaigns and training that have been delivered in the country to promote green buildings, until August 2020, there are only 114 green buildings accredited, yet most of them are industrial factories [12]. For instance, among the number of green buildings accredited by the LEED system, which accounts for about two-thirds (the largest share) of green buildings accreditation, over 60% are industrial manufactories [12]. Several factors could be blamed for the underdevelopment of green buildings in Vietnam. Yet, the determining factor would be the limitation of the mindset of decision-makers and investors regarding the development of this building type due to lacking facts and figures on the impact of the buildings that are not "green" on the environment [13].

Green buildings development requires excellent attention from the design stages. "Greener" design alternatives will have more sustainable materials and solutions with more negligible environmental impacts. Hence specific tools for assisting the selection processes will be helpful. Life cycle assessment (LCA) is one of the tools used for this purpose [14]. LCA is a group of methods for assessing the environmental impact using different indicators such as waste and gas emissions. Among several LCA methods, life cycle carbon dioxide emissions analysis (LCCO_2A) is very suitable to indicate the environmental effect of buildings with regards to CO_2 emissions. By analyzing the total amount of CO_2 that a building releases to the environment throughout its lifetime for each design scenario, this method equips decision-makers with a comprehensive perspective to compare and select the best alternative architectural design. However, LCCO_2A has not been widely practiced in Vietnam. This tool has not been introduced officially to the practitioners and experts in the construction industry of the country, who are more familiar with the "traditional buildings" and focus more on functions and costs of the design. Also, formulas used in other countries for estimating CO_2 emissions in a building's lifetime may need to be revised to reflect the indigenous conditions and customs for this type of estimation, e.g. the lack of standard data as input for the calculation process. A step-by-step guide for LCCO_2A which introduces solutions for dealing with insufficient data will surely be useful when applying LCCO_2A to support decision-making in choosing design alternatives.

This study considers all phases of a green building over its 75-year lifetime to illustrate a systematic analysis. The research study also shows the detailed calculations to provide a step-by-step guide to perform LCCO_2A considering the Vietnamese context. Two architectural designs for the case study building have been developed. Then with the results from conducting LCCO_2A for each, the better design is determined, which is the alternative with a lower amount of CO_2 emission. Through the calculation and comparison, solutions for reducing CO_2 emission are realized, then strategies to reduce CO_2 emissions of buildings can be proposed. Thus, this paper can be a good reference for practitioners in the construction industry in Vietnam or further studies on this topic.

2. Literature Review

Because of the importance of LCA methods, there are a plethora of related studies on the subject. Existing literature on LCCO_2A, on the other hand, has not attracted the same level of interest. LCA research papers may mention LCCO_2A as one of the assessing aspects for the buildings, but they rarely detail the LCCO_2A processes, particularly the estimation and assessment processes.

Extant literature show that the estimation of carbon dioxide emissions, the core job of an $LCCO_2A$, can be conducted manually, semi-automatic or automatic [15, 16], and artificial neural networks [17]. Regarding the approaches, $LCCO_2A$ can be categorized into a process-based method, input-output analysis, and hybrid method [3]. The system boundaries for $LCCO_2A$ need to be well defined to reduce the errors caused by imperfect definition [3]. LCA, as well as $LCCO_2A$, can be conducted for a stage, such as the materialization stage [18], a type of component, as a prefabricated component [19], or the entire building lifespan.

In terms of $LCCO_2A$ for the entire building lifetime, Atmaca A. et al. [5] have assessed two residential buildings in Gaziantep, Turkey. The results of their research show that the average amount of CO_2 emissions of the two buildings are from 5,221.9 to 6,484.9 kg CO_2eq per m^2, respectively. According to their research, the operation stage is responsible for 86-93% of the total CO_2 emissions, then becomes the stage with the largest share. In another study, Kofoworola, O.F. et al. [20] have indicated that nearly 52% of the GHG, including CO_2, is generated in the operation stage of a commercial office building in Thailand. While calculating the average amount of CO_2 per m^2 of a building in Hong Kong, Zhang, X. et al. [21] have figured out approximately 35,244.05 kg CO_2eq, and the operation stage is accounted for about 98.8% of this figure. When comparing the life-cycle CO_2 emissions for both standard and energy-efficient houses, Keoleian, G.A. et al. [22] have come up with a conclusion that the average houses generate a much more considerable amount (89 kg CO_2eq for one m^2 per year) than energy-efficient houses (32 kg CO_2eq for one m^2 per year).

Embodied CO_2 is another topic being found in the literature. Apart from CO_2 emissions in construction and operation stages, embodied CO_2 generated in the materials production, transport, etc., needs to be counted in the environmental impact of the buildings [23-25]. Hong, T. et al. [23] have detailed some formulas for assessing embodied GHG in South Korea in material manufacturing and transportation. Whereas, Kumanayake, R. et al. [24] have pointed out that concrete and clay bricks are among the materials with the most carbon emissions. For an office building in Sri Lanka, the average materials-related embodied CO_2 is estimated at 629.6 kg of CO_2eq/m^2, where concrete and clay bricks contribute to more than 70% of the total embodied carbon emissions.

For manipulating the CO_2 emission amounts when conducting an $LCCO_2A$, several types of data are essential inputs. Selected countries have developed carbon dioxide inventory of construction materials for a variety of reasons; this type of dataset can be utilized for this purpose. Hence, literature in $LCCO_2A$ shows a number of proofs on the usage of inventories for the inputs of the calculations. Nonetheless, the most popular inventory would be the Inventory of Carbon & Energy (ICE) developed by Bath University [26, 27]; and this database is constantly updated.

3. Methodology

The building lifetime can be staged as materials production, construction, operation, and demolition phases (Fig. 1) [28]. Throughout its service life, a building is responsible for a tremendous amount of CO_2 emissions, which links to (i) the use of materials and machinery in the construction phase, (ii) the usage of HVAC (heating, ventilation, and air conditioning), DHW (domestic hot water), lighting systems, and other household appliances during the operation stage, (iii) the consumption of materials and machines for repairing, retrofitting, and maintaining activities, and (iv) the utilization of machines for demolishing works and carrying wastes to landfills or recycling plants.

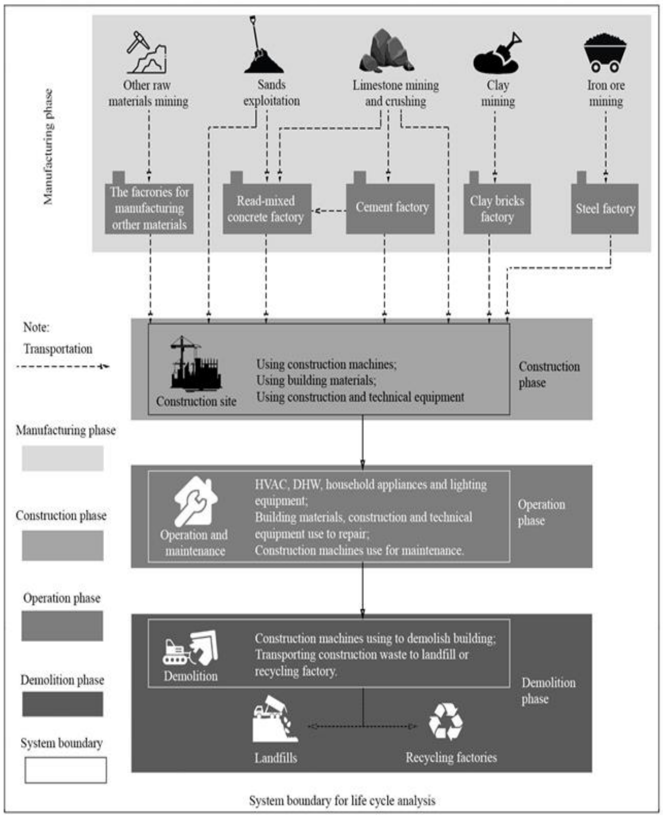

Fig. 1. The system boundary of the study (adapted from [28]).

Among the three methods that can be used to compute the life-cycle CO_2 emissions of buildings, the hybrid method has been proven many advantages compared to the process-based and input-output approaches [5]. Thus, this study will adopt a hybrid approach as the principal methodology to analyze the life-cycle CO_2 emissions of the case study building. The amount of CO_2 released by a building throughout its entire lifetime can be mathematically computed using the following equation [5]:

$$CO_2 = CO_{2Extraction} + CO_{2Manufacture} + CO_{2Onsite} + CO_{2Operation} + CO_{2Demolition} + CO_{2Recycling} + CO_{2Disposal} \quad (1)$$

where CO_{2i} refers to the amount of CO_2 attributed to the i^{th} phase over the lifetime of buildings.

This formula covers the entire life-cycle of a building from the cradle to the grave. Although this formula looks very detailed and straightforward, it is not easy to apply in the Vietnamese context. The reasons include the lack of relevant data for CO_2 emissions during the stages, especially raw material extraction and material manufacture. For the ease of the calculation, along with the on-site stage, CO_2 emissions from raw material extraction and material manufacture are not separated but included in the amount for the construction phase in order to make use of the available comprehensive data, such as data from the Inventory of Carbon and Energy (ICE) Version 3.0 [29]. Data from this inventory, not showing detailed figures for each of the aforementioned stages, but general figures of CO_2 emissions for the usage of building materials in which embodied CO_2 is integrated can be used to compute all CO_2 emissions for building materials. Furthermore, construction and demolition waste (CDW) in Vietnam is mainly treated by dumping in landfills [30]. Hence the demolition and transportation processes should be considered as the leading sources for CO_2 emissions in the buildings' end-of-life stage. By combining stages with comprehensive data as discussed, this research considers only three main stages of construction, operation, and demolition, but the results can still show the life cycle CO_2 emissions. Mathematically, the life cycle CO_2 emissions of a building can be estimated with the simplified equation below [4, 5, 15]:

$$LCCO_2 = ERCO_2 + OPCO_2 + DCO_2 \quad (2)$$

where $LCCO_2$ refers to the CO_2 emissions throughout the entire lifetime of a building, $ERCO_2$ is the amount of CO_2 caused by the construction phase, $OPCO_2$ is the amount of CO_2 emissions attributed to the operational phase, and DCO_2 represents the amount of CO_2 emissions to the environment at the end of the building's life.

The following sections present the estimation of these categories of CO_2 emissions in detail.

3.1. Carbon Dioxide Emissions in the Construction Stage

The construction stage is associated with two forms of CO_2 emissions, including indirect and direct emissions. Specifically, the former refers to the amount of CO_2 contained in materials used to erect buildings ($MTCO_2$), which is computed based on the embodied CO_2 data referenced from the ICE database [29] and Eq. (3). Whereas the latter is attributed to machinery in the erection process ($OSCO_2$) which is calculated based on Eq. (4), linking the final demand emissions with relevant input-output data.

$$MTCO_2 = \sum m_i * ECO_{2(i)} \quad (3)$$

where m_i is the quantity of the i^{th} material, $ECO_{2(i)}$ is the average amount of CO_2 contained in one unit of the i^{th} material.

$$OSCO_2 = \sum F_i * EQCO_{2(i)} \quad (4)$$

where F_i is the amount of the i^{th} fuel consumed by machinery for on-site processes, $EQCO_{2(i)}$ is the CO_2 emissions equivalent to one unit of the i^{th} fuel.

The total carbon dioxide emissions in the erection phase are comprised of these two categories, hence it can be determined based on Eq. (5).

$$ERCO_2 = MTCO_2 + OSCO_2 \quad (5)$$

3.2. Carbon Dioxide Emissions in the Operation Stage

The operation phase of buildings is responsible for two categories of CO_2 emissions. These are (i) the emissions by maintenance or refurbishment activities and (ii) the emissions caused by using electricity and other fuels to deliver the building services. The first category refers to the amount of CO_2 that buildings release during regular annual maintenance via materials and machines (RCO_2). In contrast, the second one links to the usage of HVAC, DWH, lighting systems, and other energy-consumed devices to provide better living and working conditions (OCO_2).

These types of CO_2 can be calculated using Eq. (6) and Eq. (7), respectively.

$$RCO_2 = \sum m_i * ECO_{2(i)} * (B_{LP}/M_{LP} - 1) \quad (6)$$

where m_i and $ECO_{2(i)}$ are the same as Eq. 3, B_{LP} is the building's lifespan, and $M_{LP(i)}$ is the lifetime of the i^{th} material.

$$OCO_2 = OACO_2 * B_{LP} \quad (7)$$

where $OACO_2$ is the CO_2 emissions caused by the operation of a building annually, B_{LP} is the same as Eq. (6).

Hence, the total amount of carbon dioxide emissions attributed to the operational stage can be computed using Eq. (8).

$$OPCO_2 = RCO_2 + OCO_2 \quad (8)$$

3.3. Carbon Dioxide Emissions at the End-of-Life Stage

When buildings end their lives, the demolishing process and construction waste transportation to disposal places required a tremendous amount of energy, especially fossil fuel, to operate machines. Consequently, these activities produce a certain amount of CO_2 (DCO_2), and its determination can use Eq. (9) as follow:

$$DCO_2 = MDCO_2 + CRCO_2 \quad (9)$$

where MDO_2 is the CO_2 emissions generated by machinery used in the demolition stage, and $CRCO_2$ is the quantity of CO_2 produced by trucks needed to carry waste to landfills and recycling manufactories. Nonetheless, the stage of recycling or disposing of wastes is excluded in this study.

4. The Case Study

4.1. The Case Study Building Description

The research takes into account a green building in Hanoi, Vietnam, as the case study. This building contains three basements, 17 office floors, and one attic. The building's key features are presented in Table 1.

Table 1. Key features of the building.

Contents	Detailed descriptions
Underground floors	3
Above-ground floors	17 office floors and 1 attic
Lifetime	75 years
Total floor area	14,112m^2
Columns, beams, and slabs	Reinforced concrete
Bored piles, foundation	Reinforced concrete
Internal wall	Brickwall
External wall	Brickwall and glass curtain wall
Floor finish	Concrete, ceramic tiles, gypsum board
Doors	Fire-resistant steel, Ironwood, MDF, and Aluminium glass doors
Roof	Flat roof, concrete

This project is the first project funded by the state budget in Vietnam to be awarded silver LOTUS green building certification in 2020, after one year since it was completed [31]. At the design phase of the building, several alternative architectural scenarios were proposed then compared to select the best one. LCA methods, particularly life cycle cost analysis, life cycle energy analysis, and life cycle carbon dioxide emissions assessment methods, have been used for comparing the design alternatives to make decisions. Nevertheless, in this research, two design plans are given to demonstrate the use of $LCCO_2A$ to provide an indicator to support the decision-making process. These two options differ in the use of some materials, energy-consumed appliances and are described in Table 2.

Table 2. Two given design alternatives [32].

Materials/ equipment	Alternative 1	Alternative 2
Brick	Clay burnt brick	Concrete unburnt brick
Glass	Heat absorbing glass	Low-E glass with two layers
Sanitary equipment	Normal toilets and faucets	Water-saving toilets and faucets
Air-conditioner system	Daikin VRV	VRF Panasonic Multi V
Lighting system	Difference in number of lights	Difference in number of lights

With the aim to save energy, both alternatives use the same set of architectural solutions. These are: (i) placing louvers along the south facade as sun-light-preventing panels outside the building; and (ii) reducing the window/wall area ratio to the West, North, and East sides of the building. Moreover, renewable energy with 8kwp solar panels and solar hot water systems with 37kw heating capacity have been included in the design. The building also reuses treated sewage to meet 100% of irrigation needs.

As in the equations (from 1 to 9 which have been discussed above), in order to carry out a life-cycle CO_2 emissions assessment, a lot of data is required, for instance:

- the quantity of the ith material to be consumed to erect the building (Eq. 3);

- the amount of embodied CO_2 of the ith material (Eq. 3);

- the equipment types and their utilization during the construction stage, that are required to figure out Fi in Eq. 4;

- the amount of energy being used in the operation period, and the approach to convert it to CO_2 equivalent;

- and, data to calculate demolition CO_2.

No publication has been publicly found in Vietnam regarding the data in the above list. Therefore, in order to perform an $LCCO_2A$, this research study looks for overseas sources to get relevant data that has been previously published, such as the ICE databases and adapted historical figures as well as commercial databases, such as standardized estimating data (cost norms published by the Ministry of Construction and provincial departments of construction) available in Vietnam.

Moreover, the research study also needs to adopt several assumptions as below:

- the annual energy consumption throughout the operational stage of the building is constant;

- the lifespans of structural elements and brick walls are equal to the building's service life.

4.2. Life Cycle Carbon Dioxide Emissions Assessment of Design Options

The process for the $LCCO_2$ emissions determination of the case study building is illustrated in Fig. 2.

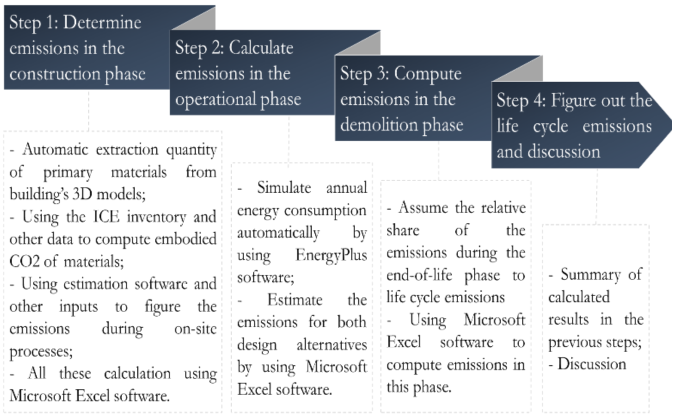

Fig. 2. The life-cycle CO_2 emissions determination process for the case study building.

This process separates the calculations of CO_2 emissions for each of the stages in the life-cycle of the building then sums up the results to get the life-cycle emissions. Step 1 starts the process with the determination of CO_2 emissions in the construction phase. In this study, the $LCCO_2A$ of the case study is performed in a BIM-enabled project. Therefore quantities of primary materials can be extracted from the building's 3D models. Data extracted from the models and the available databases (as discussed in Section 4.1) are input into Microsoft Excel for easy calculation. Step 2 uses EnergyPlus software to simulate the energy consumption for the whole operation period, which is used to figure out the CO_2 emissions in this stage. Demolition CO_2 emissions are estimated as a percentage of the total life-cycle emissions.

4.2.1. Carbon emissions in the construction phase

The construction stage of the building is responsible for a remarkable amount of CO_2 emissions, and this figure can be calculated using Eq. (3), Eq. (4), and Eq. (5).

With respect to the CO_2 contents in construction materials, the research only takes 20 main materials into account due to several reasons. The reasons include: (i) these materials are used in load-bearing elements of the building such as foundations, columns, beams, slabs, walls, and other finishing works, (ii) the quantity of these materials can be easily extracted and estimated from the building's 3D models and the design drawings at the design phase, and (iii) due to the lack of figures on embodied CO_2 for the other materials. Using relevant data and Eq. (2), the amount of CO2 emissions for both design scenarios is calculated and presented in Table 3 and Table 4.

Because the two alternatives differ only in the usage of bricks and types of glass, their total CO_2 amount contained in materials are quite similar, with 9,083,878 kg CO_2eq for the first alternative and 9,062,069 kg CO_2eq for the second one, with a reduction of 21,809 kg CO_2eq. Regarding the relative contribution of the materials for both alternatives, ready-mixed concrete is responsible for the largest share of more than 37%, followed by rebars and PVC with just under 28% and more than one-tenth of this category, respectively (Fig. 3 and Fig. 4).

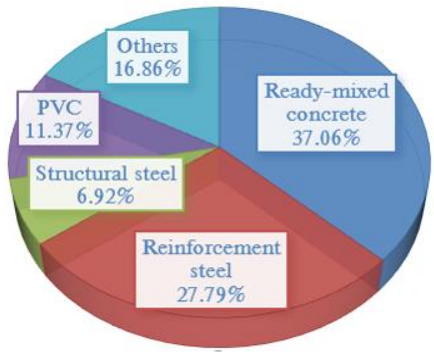

Fig. 3. The relative share by types of material to the embodied CO_2 of materials of the 1st design alternative.

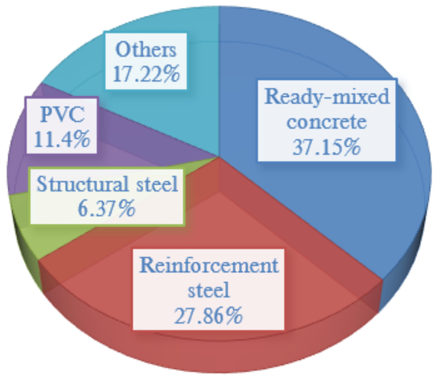

Fig. 4. The relative share by types of material to the embodied CO_2 of materials of the 2nd design alternative.

Carbon dioxide emissions caused by machinery used during the construction processes can be estimated using relevant data sets. These are: (i) the total number of working shifts of each of the equipment, (ii) the type and amount of fuel needed for one working shift of machine, and (iii) the amount of CO_2 equivalent of each type of fuel, which has been collected and manipulated. The kinds of machinery and their number of working shifts are identified based on the volume of tasks related to 20 critical materials in Table 3 and the current machinery norms in Vietnam. The categories and amount of fuel each machine consumes per shift on average are referenced from the databook issued with the Decision 1134/QD-BXD of the Ministry of Construction of Vietnam dated October 8, 2015. Although petrol, diesel, and electricity are three major sources of energy to be used in the construction stage, the amount of CO_2 equivalent per unit of petrol equal to diesel. Thus, this research only sorts them into two categories as fossil fuel and electricity. The calculated consumptions for these categories are 96,678 liters and 822,897 kWh, respectively. The figures about the CO_2 equivalent of these fuels are referenced in the publication of Atmaca, A. et al. [5], with about 6.003 kg CO_2eq per litter for fossil fuel and 0.475 kg CO_2eq per kWh for electricity. Putting all relevant data into Eq. (3), the total amount of on-site CO_2 emissions of the case study building is 974,401 kg CO_2eq for both alternatives due to the difference in terms of using machinery is insignificant.

According to Eq. (5), the total amount of CO_2 emissions of the building caused by the erection phase for both design scenarios were calculated as 10,036,470 kg CO_2eq for the first alternative and 10,058,279 kg CO_2eq for the second one. In terms of the average figures per one m^2, they equal 711.2 kg CO_2eq and 712.75 kg CO_2eq per m^2, respectively, which are slightly higher than figures proposed in several publications [24, 25].

Table 3. Embodied CO_2 of materials of the first design alternative.

Materials	Quantity	Unit	Embodied CO_2 (Kg/unit) [26, 29][c]	Total amount (Kg CO_2eq)	Relative share (%)
Ready-mixed concrete	21,717,356	kg	0.155	3,366,190	37.06
Reinforcement steel	1,268,635	kg	1.99	2,524,583	27.79
Structural steel	255,350	kg	2.46	628,160	6.92
Sand	970,777	kg	0.00493	4,786	0.05
Aggregate	454,511	kg	0.00493	2,241	0.02
Cement	363,859	kg	0.832	302,731	3.33
Cement mortar	422,736	kg	0.2	84,547	0.93
Bricks[a]	1,704,795	kg	0.21	358,007	3.94
Galvanised steel	44,552	kg	3.03	134,991	1.49
Plasterboard	56,845	kg	0.39	22,170	0.24
Glass[b]	277,315	kg	1.44	399,334	4.40
Paint	9,810	kg	1.31	12,852	0.14
Ceramic tiles	78,805	kg	0.7	55,164	0.61
Marble stone	36,328	kg	0.13	4,723	0.05
Wood	140,979	kg	0.263	37,077	0.41
PVC	319,809	kg	3.23	1,032,983	11.37
Steel doors	2,213	kg	3.06	6,772	0.07
MDF (doors)	626	kg	0.856	535	0.01
Timber (doors)	3,688	kg	0.306	1,129	0.01
Doors and windows (Aluminium Framed)	376	m^2	279	104,904	1.15
Total				9,083,878	100.00

Table 4. Embodied CO_2 of materials of the second design alternative.

Materials	Quantity	Unit	Embodied CO_2 (Kg/unit) [26, 29][c]	Total amount (Kg CO_2eq)	Relative share (%)
Ready-mixed concrete	21,717,356	kg	0.155	3,366,190	37.15
Reinforcement steel	1,268,635	kg	1.99	2,524,583	27.86
Structural steel	255,350	kg	2.46	628,160	6.93
Sand	970,777	kg	0.00493	4,786	0.05
Aggregate	454,511	kg	0.00493	2,241	0.02
Cement	363,859	kg	0.832	302,731	3.34
Cement mortar	422,736	kg	0.2	84,547	0.93
Bricks[a]	1,704,795	kg	0.0931	158,716	1.75
Galvanised steel	44,552	kg	3.03	134,991	1.49
Plasterboard	56,845	kg	0.39	22,170	0.24
Glass[b]	277,315	kg	2.08	576,815	6.37
Paint	9,810	kg	1.31	12,852	0.14
Ceramic tiles	78,805	kg	0.7	55,164	0.61

Materials	Quantity	Unit	Embodied CO_2 (Kg/unit) [26, 29][c]	Total amount (Kg CO_2eq)	Relative share (%)
Marble stone	36,328	kg	0.13	4,723	0.05
Wood	140,979	kg	0.263	37,077	0.41
PVC	319,809	kg	3.23	1,032,983	11.40
Steel doors	2,213	kg	3.06	6,772	0.07
MDF (doors)	626	kg	0.856	535	0.01
Timber (doors)	3,688	kg	0.306	1,129	0.01
Doors and windows (Aluminium Framed)	376	m^2	279	104,904	1.16
Total				9,062,069	100.00

[a] the first alternative uses clay burnt brick and the second one uses concrete unburnt brick
[b] the first alternative uses heat-absorbing glass and the second one uses temper clear Pilkington Energy Advantage Low-E light green glass.
[c] embodied carbon dioxide of almost all materials is extracted from ICE database V3.0 except for doors and windows referenced from ICE database V1.6a.

4.2.2. Carbon emissions in the operational phase

Two sorts of CO_2 emissions are attributed to the operational period. In which, the first category is caused by the use of HVAC, DHW, lighting systemsto ensure comfortable conditions for users, whereas the second one is the consequence of the maintenance or retrofitting activities of the building

The first category associated with electricity-consumed systems and equipment is estimated based on Eq. (7). The building's service duration for both design alternatives is 75 years long, whereas $OACO_2$ is determined according to the annual energy consumption, which is simulated using EnergyPlus software based on the 3D model of the building. The simulated results for both alternatives are presented in Table 5.

Table 5. The annual energy consumption of two alternative architectural designs.

Design alternatives	Net site energy (MWh)	Net source energy (MWh)
The 1st alternative	294.624	482.360
The 2nd alternative	122.958	181.440

Because the CO_2 equivalent of electricity is 0.475 kg CO_2eq per kWh [5], this category of CO_2 emissions is determined as 17,184,091.03 kg CO_2eq and 6,463,831.71 kg CO_2eq for the first and the second alternative, respectively. Looking at the results, there is a big difference between the two given options, and the primary reason for this is the change in terms of using energy-consumed systems and appliances in the second alternative.

The last sort of CO_2 emissions in the operational period is caused by the maintenance or retrofitting of the building. During maintenance or retrofitting activities, the CO_2 emissions are attributed to materials and machinery. However, due to the difficulty of estimating the number of working shifts of machines used for these activities at the design stage, the CO2 emissions associated with the use of them are assumed not included in the scope of this research. Thus, the research adopts Eq. (6) and related information such as (i) the building's lifespan (75 years), (ii) the main materials' lifetimes, and (iii) the amount of CO_2 contained in the i^{th} material to estimate this category. Because the building has just started its operation stage, the statistics on materials' service life and the proportion of each type that needs to be replaced are still blank, causing difficulty when conducting a life cycle assessment. This research aims to provide a comprehensive analysis, historical data from previous publications have been used for calculation. The results for both alternatives are displayed in Table 6 and Table 7.

The use of different types of glass brings in a difference in CO_2 emissions of the two design options. Even though the DWH, HVAC, lighting systems, and other energy-consumed equipment also require to be replaced throughout the building lifetime, their contribution to CO_2 emissions is excluded in this research due to the unavailability of their embodied CO_2 related data. Although considering only primary materials, both the comprehensiveness and reliability of this study are acceptable due to the outstanding contribution of the discussed materials.

Calculating the total amount of CO_2 emissions in the operation stage using Eq. 8 for the first and second alternative architectural designs brings in two results of 18,224,349 kg CO_2eq and 7,592,831 kg CO_2eq, respectively. These figures differ significantly due to the difference in the use of energy-consumed systems and appliances. It proves that although using saving-energy equipment may cause a high investment cost, the amount of energy consumption, the energy expenses as well as the CO_2 emissions over the entire life cycle can be reduced remarkably with "greener" buildings. This finding could convince decision-makers and designers or even policymakers regarding green building development.

4.2.3. Carbon dioxide emissions in the demolition stage

In this stage, the building produces CO_2 through using machinery to demolish the building and trucks to transport waste to recycling factories or landfill areas. Relying on the context of the construction industry in Vietnam, the demolishing process of buildings mostly uses heavy machines like excavators, loaders, and trucks. Therefore, diesel is the primary source of energy to be used in this stage. However, in Vietnam, due to the lack of data relevant to the demolition activities, this sort of CO_2 cannot be accurately and systematically determined. Nonetheless, aiming to provide a holistic $LCCO_2A$, the study will conduct the estimation of CO_2 emissions in this category relatively using the rule of thumb. According to a study by Atmaca, A. et al. [5], the demolition process is only responsible for about 1% of the total life-cycle CO_2 emissions of the building. This study assumes that CO_2 emissions in the demolition stage account for 1% of the total CO_2 of previous phases. Consequently, the first and second design alternatives bring in 282,608.19 kg CO_2eq and 176,511.09 kg CO_2eq, respectively.

Table 6. CO_2 emissions caused by the maintenance of the building of the 1st design alternative.

Material	Quantity	Unit	Embodied CO_2 (kg CO_2eq/unit)	Materials' service life (year) [33, 34]	Embodied CO_2 (kg CO_2eq)
Plasterboard	56,845	kg	0.39	30	33,254
Paint	9,810	kg	1.31	10	83,536
Ceramic tiles	78,805	kg	0.7	25	110,327
Mortar	422,736	kg	0.2	50	42,274
Doors and windows	376	m^2	279	50	52,452
Timber doors	3,688	kg	0.306	25	2,257
Glass	277,315	kg	1.44	50	199,667
PVC	319,809	kg	3.23	50	516,492
Total					1,040,258

Table 7. CO_2 emissions caused by the maintenance of the building of the 2nd design alternative.

Material	Quantity	Unit	Embodied CO_2 (kg CO_2eq/unit)	Materials' service life (year) [33, 34]	Embodied CO_2 (kg CO_2eq)
Plasterboard	56,845	kg	0.39	30	33,254
Paint	9,810	kg	1.31	10	83,536
Ceramic tiles	78,805	kg	0.7	25	110,327
Mortar	422,736	kg	0.2	50	42,274
Doors and windows	376	m^2	279	50	52,452
Timber doors	3,688	kg	0.306	25	2,257
Glass	277,315	kg	2.08	50	288,408
PVC	319,809	kg	3.23	50	516,492
Total					1,128,999

4.2.4. Life cycle carbon dioxide emissions

Based on the computed results of CO_2 emissions for all the building's stages and Eq. 1, the total life cycle CO_2 emissions of the building was calculated as 28,543,426.93 kg CO_2eq for the first alternative and 17,827,620.23 kg CO_2eq for the second one. When taking the average figure per square meter into account, the results for both alternatives are 1,263.3 kg CO_2eq and 2,022.64 kg CO_2eq for the first and second ones respectively over the whole lifespan, which is much lower than the proposed figures by Atmaca, A. et al. [5]. Similarly, these figures equal to 15.55 kg CO_2eq/(m^2 year) and 28.09 kg CO_2eq/(m^2 year), and they are also lower than the results in [22]. The determining reason for these differences is that two alternative architectural designs in the study are proposed to target green building. For instance, the usage of saving-energy systems and equipment can influence directly the life cycle CO_2 emissions of the building. The detail of the calculation and the relative proportion by stages of the life cycle CO_2emissions for both are presented in Table 8.

Looking closely at the results present in Table 8, the relative share of CO_2 emissions by phases of the first

DOI:10.4186/ej.2021.25.7.121

design plan differs largely from that of the second one, especially in terms of the contribution of the construction and operation stages. In the first scenario, the operation phase is responsible for the most significant percentage of CO_2 with 63.85%, which nearly double the second-largest contributor, the construction stage, with a figure of 35.16% (Fig. 5). On the contrary, the greatest distributor to the life cycle CO_2 in the second scenario is the construction phase with 56.42%, followed by the operation period with 42.59% (Fig. 6). The comparison of CO_2 emissions by stages of two alternatives is illustrated in Fig. 7. The primary factors for this significant difference are the changes in terms of using energy-consumption systems and equipment as well as the building's envelope. Specifically, the second scenario using saving-electricity systems and lighting equipment, and low-E glass. Hence its annual energy consumption is only nearly 41.7 % compared to the first one's figure. As a result, the CO_2 equivalent related to energy consumption during the operation stage of the first alternative is doubled that of the second scenario. This could be convincing evidence for either designers or decision-makers to take into account when evaluating a design scenario or adjusting design alternatives to achieve the target. By comparing the total life cycle CO_2 emissions of two given alternatives, designers and decision-makers can easily choose the most suitable one. Of course, to select the design plan, several different factors should be taken into consideration such as the financial capability of investors, the life cycle cost of each design scenario, etc. However, the amount of CO_2 emissions throughout the entire life is also the most crucial basis for this process.

Table 8. Life cycle CO_2 emissions of two alternatives and the relative share by stages.

Phases	CO_2 emissions (Tone CO_2eq)		Relative share (%)	
	1st scenario	2nd scenario	1st scenario	2nd scenario
Erection	10,036.47	10,058.28	35.16	56.42
Operation	18,224.35	7,592.83	63.85	42.59
Demolition	282.61	176.51	0.99	0.99
Life cycle CO_2	28,543.43	17,827.62	100.00	100.00

However, the contribution by phases to life cycle CO_2 emissions of both design alternatives in this research differs mainly from the results proposed in the previous studies [5, 20, 21, 35]. The determining factor for this difference is that both suggested design scenarios meet green building design standards, although the first option is not as good enough as the second one. It indicates that green buildings are far more environmentally friendly than other building categories. Thus, the findings in this study can become a good reference source for decision-makers or policymakers when considering the environmental impact of buildings to select the design option and propose policies towards the sustainable construction industry in Vietnam.

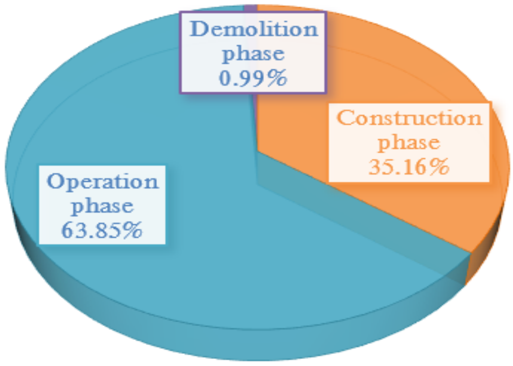

Fig. 5. The share by phases of the life cycle CO_2 emissions of the 1st scenario.

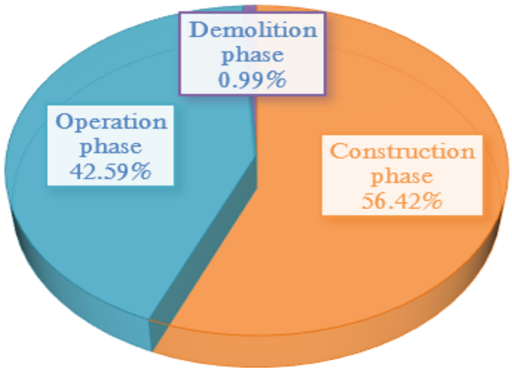

Fig. 6. The share by phases of the life-cycle CO_2 emissions of the 2nd scenario.

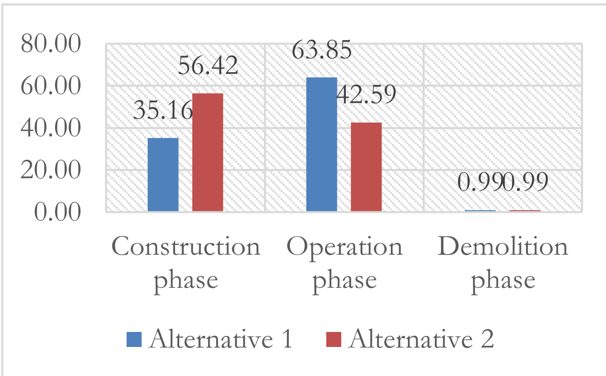

Fig. 7. The comparison of the life cycle CO_2 emissions of two scenarios by phases.

5. Discussion

It is easy to formulate a formula to calculate the amount of carbon dioxide emissions, detailing each of the stages of the building life-cycle, but it is challenging to apply the formula in practice due to the lack of detailed data for each of the stages in terms of typical CO_2 emissions values. Typically, GHG inventories only show the combined data for the selected stages. The total values take into account all the activities that may generate GHG, such as raw material extraction, material process and manufacture, and transportation to the sites. Therefore, this research proposes an approach to simplify the calculation while making use of the available comprehensive data by combining seven stages in Eq. (1) into three major stages. This revision facilitates Vietnamese users by considering the local context and the calculation habits of practitioners in the construction industry in Vietnam.

The study demonstrates a semi-automatic approach to carry out an $LCCO_2A$, making use of Building Information Modelling to estimate quantities of key materials by extracting data from the 3D models and EnergyPlus software for stimulating energy consumption directly. This application is specifically practical when developing design alternatives by reducing the manual re-calculations, which may need performing due to the continuous changes during the design in progress.

By proposing two different design scenarios, then determining the life cycle CO_2 emissions for each, this research shows an example in which decision-makers who are either clients or designers take into consideration the environmental impacts when selecting a design plan. Doing the same in their projects, while comparing the two design alternatives, decision-makers can figure out the major affecting factors to the total CO_2 emissions of the building, especially in terms of the materials' usage. This helps them make better changes in the designs at the early stage for greener future buildings. In this case study, the calculated figures show that the share of CO_2 emissions by phases to the life cycle CO_2 of the building is significantly different with dissimilar materials. Specifically, in the first scenario, the share of the operation phase is the largest while it is the construction stage to have the most significant share in the second design alternative. This change is caused by using different types of brick and glass, resulting in the change in energy-consumption systems and equipment in the second alternative. Therefore, a great reduction in the annual electricity consumption has been identified for the second alternative, which is only about one-third of the first one. The changes then lead to a vast difference in the CO_2 emissions in the operational phase and the life cycle CO_2 of the two options. Apparently, alternative architectural designs are available for the buildings to be more environmentally friendly.

6. Conclusion

Green buildings development requires careful review of design alternatives to get the "greener" design, where $LCCO_2A$ can be of use. To promote the use of $LCCO_2A$, which has not been widely practiced in Vietnam, this research introduces a step-by-step guide in a semi-automatic approach using BIM and spreadsheet software such as Microsoft Excel. To reflect the indigenous conditions of lacking relevant data and the calculation habits of practitioners in the construction industry in Vietnam, the calculation equations have been revised accordingly. The research results show that, with the use of greener materials, CO_2 emission has reduced a lot in the case study building's operation phase and for the whole life cycle.

This research study has some limitations. Firstly, only 20 primary materials were taken into consideration. Secondly, the life cycle inventory used to compute embodied CO_2 emissions of the building was not developed based on the Vietnam construction industry context. Even though these may limit the research outcomes, the results are good references for investors and decision-makers to consider building's environmental impacts when choosing construction materials and design scenario.

Although the life-cycle CO_2 assessment plays a vital role in the design phase, it could be better if the assessment is simultaneously considered with the life-cycle energy and life-cycle cost analyses. Future research should consider the combination of those assessments for a more comprehensive and practical assessment of the sustainability of green buildings.

Acknowledgments

Thanks are due to National University of Civil Engineering for funding this project (67-2021/KHXD-TD). Opinions or recommendations expressed in this paper do not necessarily reflect the views of the supporting organization.

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Dinh-Linh Le, photograph and biography not available at the time of publication.

The-Quan Nguyen, photograph and biography not available at the time of publication.

Khoa Do Huu, photograph and biography not available at the time of publication.