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Comparative life cycle carbon emission assessment of a residential building: a case study of Cambodia

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SUMMARY
This paper studies life cycle assessment (LCA) of a townhouse in Cambodia as a case study and compares carbon emission (CE) of green building scenarios generated with two types of LCA: screening and simplified. The research methodology is based on the building modelled in SimaPro software using ecoinvent 3 databases to assess life cycle CE of case study and different selected scenarios. The simplified LCA result show that the building produced a CE of 1276 kg CO_2-eq/m^2 and the average difference between the screening result and that of the simplified LCA is 2.8%, ranging from 1.9% to 4.9% according to the design scenario studied. The combination of the four tested strategies reduced the building's CE by 42% compared to the existing house. The results show the potential for integrating LCA into green building design in Cambodia. The screening LCA can be a useful tool to pre-size the GHG emissions produced by building and test different decarbonization options during the design stage.

Keywords: carbon footprint, screening LCA, residential building.

1. INTRODUCTION

In Cambodia, with a rising urban population and a construction sector growing at 18.1% between 2014 and 2019, GHG emissions from buildings are expected to increase rapidly (GGGI, 2021). To minimize the environmental impact (EI) of the building sector and promote green building design, the approach of LCA helps estimate the EI generated by a building throughout its whole life cycle. While the building LCA has reached an advanced stage of development in many developed countries, there remains a considerable need to enhance its adoption in developing countries, especially in Southeast Asia (Jayawardana et al., 2023). LCA has recently been introduced in Cambodia, primarily applied to sectors such as hydropower plants, cement production plants, and food production system to assess the EI, emissions to air pollution, and CO_2 emissions, respectively (Chhun et al., 2021; Chea et al., 2022; Hor et al., 2021). However, the application of LCA to buildings has not yet been implemented in the country. This study constitutes a valuable innovation for the local construction sector, providing a representative benchmark for developing green building guidelines and a practical method for simplifying LCA.

The ISO 14040 describes principles and framework of LCA and ISO 14044 describe the requirements and guidelines of LCA (ISO, 2006a; ISO 2006b). The European Standards for LCA of buildings: EN 15978 and EN 15804 provide guidance on how to apply LCA to buildings, divide the life cycles of building into five stages, define system boundaries, and allocation methods (CEN, 2012a; CEN, 2012b). Architects and planning professionals recognized LCA in supporting decision-making process in building design and assisting in materials selection (Mateus et al., 2011). Decisions made during the early design stages critically determine a building's EI, and LCA helps designers, faced with many decisions, choose those that are significant regarding the building's EI (Basbagill et al., 2013).

For building LCA, there are two types of simplification to facilitate the completion of a LCA study, used by stakeholder and practitioners for the early design stage of a building: screening and simplified LCA (Wittstock et al., 2012). The simplified LCA was conducted to obtain a more detailed and thorough assessment compared to the screening LCA. Full LCA can be hardly accomplished since it is time-consuming and resource-intensive, and often faces a lack of data, so that it is recommended to use simplification in LCA (Hochschorner et al., 2003; Gradin et al., 2021). The simplification of LCA methods is essential if practitioners aim to include environmental aspects in an early stage of product development and improvement.

SimaPro software is particularly suitable for estimating the global warming potential (GWP) of a building during production phase and is considered the most widely used LCA database-software combination in the building sector (Gu et al., 2024; Emami et al., 2019). The software includes several databases, among which ecoinvent is the most widely utilized in building sector. Furthermore, SimaPro allows users to modify input data to reflect regional conditions not explicitly included in the default database options. The environmental LCA of a single house in India was modeled in SimaPro using the ecoinvent database, which integrated the European Life Cycle Database (Pinky and Palaniappan, 2012). A similar study, analysing the EI of a residential building in Malaysia, was conducted using LCA in SimaPro and the Malaysian Life Cycle Inventory Database, adapted from ecoinvent database (Abd Rashid et al., 2017).

2. METHODOLOGY

An LCA model was developed and analysed using SimaPro V9.4.0.2 software due to its popularity and leading LCA software used as a decision tool (Herrmann et al., 2015). The ecoinvent 3 database is selected to model the inventory of the housing unit, considering all inputs of material manufacturing (gradle-to-gate) and energy involved in life cycles, as no database specific to materials in Cambodia has yet been developed. This database was chosen for the study due to its status as the largest transparent unit-process Life Cycle Inventory database globally, distinguished by its integrity, usability, and completeness (Wernet et al., 2016; Martínez-Rocamora et al., 2016). The CE in this study is the amount of GHG produced throughout the building life cycle and it was calculated in kg CO_2-eq/m^2.

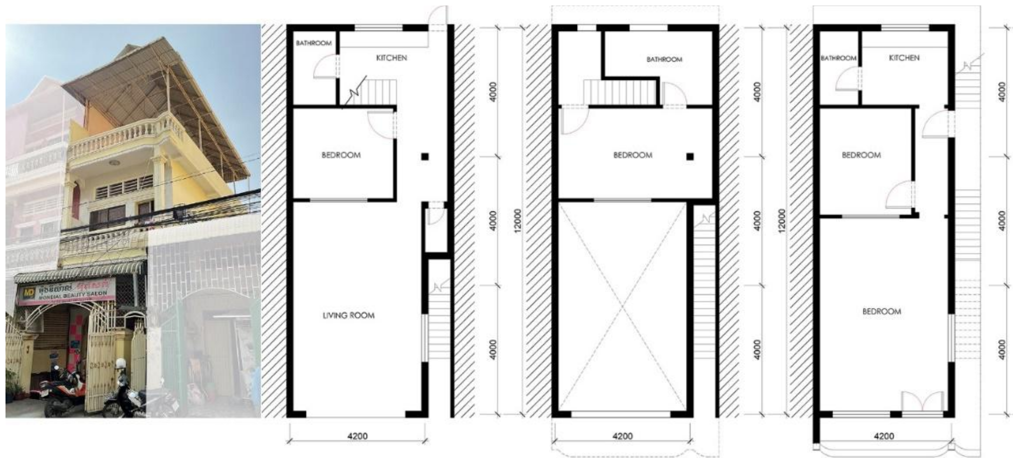

Figure 1. Streetview photo and floor plans of the building case study.

The selected building case study is a three-storey townhouse with a gross floor area (GFA) of 157 m^2 as shown in Fig. 1 and located in Cambodia, a hot and humid tropical climate. The construction techniques and materials are common in Cambodia: reinforced concrete structural frames and brick masonry walls without insulation. The annual electricity and water consumption is 6,480 kWh and 1,200,000 liters. The case study was selected based on the fact that this housing type is mostly built in urban areas, an important part of current city development and suitable for the Cambodian context (Taing et al., 2023; Khoan et al., 2022). The number of constructions this townhouse type increased by more than 34% from 2020 to 2021 in Cambodia (Choun et al., 2022).

This study follows the LCA method standardised by ISO 14040 and 14044 standards, using the screening and simplified LCA based on EN 15978, which includes four stages as follows: goal and scope definition, life cycle inventory, life cycle impact assessment, interpretation. The two simplification types of LCA studies are applied on the one hand to the reference building, selected as a case study, and on the other hand to five environmental improvement strategies described below.

2.1. Goal and scope definition

The goal of this study was to evaluate the CE of a townhouse in Cambodia using two types of LCA: screening and simplified LCA, taking into account the production and use phase within specific system boundaries as shown in Table 1. Other LCA impact categories were not considered, as there is an urgent need for research on embodied carbon in developing countries, where the CE is the most widely recognized emission indicator (Nawarathna et al., 2021). Additionally, the selected impact method focuses exclusively on CO_2 emissions. The construction and end of life phase were not taken into account due to the study's system boundary, building's data, and references limitation. Although waste processing and disposal are defined as mandatory modules, they were excluded from the assessment due to the absence of data and information regarding the building's end of life phase. Neglecting the end of life phase is acceptable because their impacts are very low compared to the CE on its entire life cycle (Sharma et al., 2011). The building functional unit selected was 1 m^2 of GFA and its lifespan assumed to be 50 years as recognized in building industry (Abd Rashid and Yusoff, 2015).

Table 1. Life cycle phases to be considered for screening and simplified LCA type (based on EN 15978).

Production			Const-ruction		Use							End of life				Benefits and loads beyond the system boundaries
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material acquisition**	Transportation**	Manufacturing**	Transportation to the site	Construction and installation	Use	Maintenance	Repair	Replacement*	Refurbishment	Operational energy use**	Operational water use	Demolition	Transportation	Waste processing*	Disposal*	Reuse, recovery or recycling potential

Legend:
* Mandatory for simplified LCA
** Mandatory for screening and simplified LCA
☐ System boundary

2.2. Life cycle inventory (LCI)

2.2.1 Production phase

The inputs for the production phase were obtained from on-site measurements and survey with house owner. Following detailed measurements of each building component, the construction materials used for each component were estimated with the assistance of construction engineers, as no technical drawings or plans were available for the building. The ratio of each building material's component was divided per m^2 of GFA. The LCI data for the production phase were modelled by calculating the detailed build-up elements of the building components, and are presented in Table 2.

Table 2. LCI of materials in production phase.

Components	Materials	Amount	Unit	Ratio (kg/m^2 or m^3/m^2)
Internal walls	Ceramic tile	1225.35	kg	7.80
	Clay brick	2839.2	kg	18.08
	Cement mortar	2028	kg	12.92
	Base plaster	930	kg	5.92
External walls	Ceramic tile	1278.83	kg	8.15
	Clay brick	14196	kg	90.42
	Cement mortar	5371	kg	34.21
	Base plaster	2580	kg	16.43
Structures (slab, column, and beam)	Ceramic tile	4761.40	kg	30.33
	Normal concrete	31.75	m^3	0.20
	Reinforcing steel	2715.28	kg	17.29
	Base plaster	1670	kg	10.64
	Cement mortar	716.22	kg	4.56
Stairs	Steel	69	kg	0.44
	Alkyd paint	2.5	kg	0.02
	Normal concrete	1.36	m^3	0.01
	Reinforcing steel	16.74	kg	0.11
Roof shelter	Zinc	300	kg	1.91
	Steel	412.80	kg	2.63
Doors	Polyvinylchloride	27	kg	0.17
	Wood	4.8	m^2	0.03

	Alkyd paint	3.2	kg	0.02
	Steel	92	kg	0.59
	Coated flat glass	30.8	kg	0.20
Windows	Aluminum frame	4.95	m^2	0.03
	Coated flat glass	84.24	kg	0.54
	Steel	200.82	kg	1.28
	Alkyd paint	3.6	kg	0.02

The main building components to be considered in the screening LCA included exterior walls, windows, roof and floor slab, and load-bearing walls and structure (Hollberg, 2016). For simplified LCA, foundations, interior walls, building services, and finishing are added to the components listed in the screening LCA.

The transportation of virgin materials to the factory gate was taken into account in the production phase and the average distance per trip was assumed to be 130 kilometers (Decorte et al., 2020).

2.2.2. Use phase

The inputs for the use phase were obtained from bills of electricity and water consumption given by the house owner. Electricity is the only form of energy consumed during the building's use phase, as no active mechanical systems are installed. It is mainly used for cooling (electrical and ceiling fan), lighting, and appliances. Energy for water heating is not required, as hot water is not provided within the building. The electricity and water consumption were modelled by the total amount of electricity (kWh) and water (kg) consumed per year, multiplied by 50 years and expressed by m^2 of GFA. The CE associated with these operational phases were calculated based on the embodied emissions resulting from the building operation, included electricity and water use.

Maintenance inputs were modelled based on the potential of replacement, reapplying, and change of each component. Painting, windows, and solar PV panels were considered in the use phase maintenance. The replacement of roofing materials, floor tiles, and electrical and plumbing fixtures was not included. The number of replacements in 50 years of painting and windows are 4 times and 1 time, respectively (Abd Rashid et al., 2017; Ortiz-Rodríguez et al., 2010). The used PV panels will be replaced 1 time in 50 years due to their lifetime of 25 years (Chowdhury et al., 2020). The CE calculation for this phase accounts for all modules within the production phase of the selected components.

2.3. Life cycle impact assessment (LCIA)

The CE of the case study were assessed using the IPCC 2021 GWP100 method considering and quantifying only the Global Warming Potential indicator for a timeframe of 100 years (GWP100) with climate change factors of IPCC (PRé Sustainability-SimaPro, 2023).

2.4. Interpretation

The LCIA results were interpreted according to the goal and scope of the study and made it possible to identify the significant potential of improvements of the studied scenarios.

2.5. Building studied scenarios

The studied scenarios were designed to reduce the CE of the case study and other residential buildings in Cambodia. LCA modelling of the scenarios applied to the case study are carried out and analysed, following the same methodological framework as for the existing house's LCA. The description and aim of each scenario are listed in Table 3.

Table 3. Building studied scenarios and their descriptions.

Scenario	Description
Reference	• Existing situation of the building case study
Strategy 1: removing unnecessary materials	• Removing ceramic tiles from the external walls and steel bars from exterior windows and doors, aiming to minimize the excessive materials consumption for decoration
Strategy 2: using environmental manufacturing and bio-based materials	• Replacing of normal reinforced concrete by lean concrete and aluminum window frames by wooden frames
Strategy 3: using lightweight timber frames	• Replacing brick masonry walls by lightweight timber frames for the external walls only
Strategy 4: installing solar PV panels	• Implementing the solar panels on the existing roof shelter, generating solar energy that cover about 51% of the annual energy consumption. This value was calculated based on the installation of 24 solar panels, each with a power output of 380 W and an efficiency of 20%, at a location receiving an average of 5 peak sun hours per day.
Strategy 5: combined strategy	• Combination of the four studied strategies to find the potential of improvement and green building solutions

3. RESULTS

Fig. 2 shows the CE comparison of the reference and four studied scenarios corresponding to the production phase by building component. The following scenarios, reference, strategy 1, strategy 2, strategy 3, and strategy 4, accounted for 175, 170, 148, 140, and 188 kg CO_2-eq/m^2 in the production stage, respectively. Among all scenarios, strategy 3 shared a lower CE than others while strategy 4 generated a higher emission.

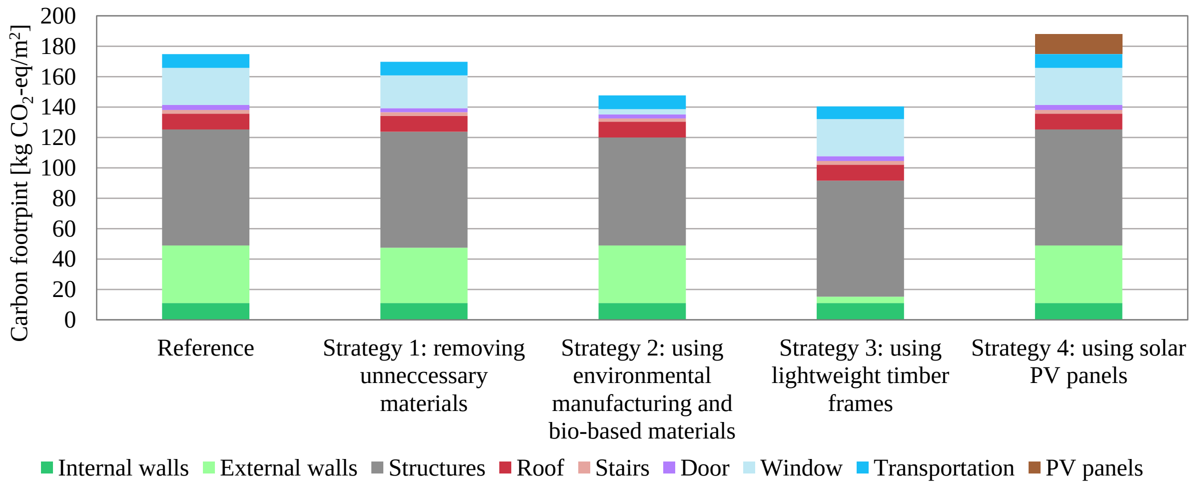

Figure 2. Carbon emission of the reference and four studied scenarios during the production phase, presented by building component.

In the reference scenario, the structure (floor slab, column, and beam) was the dominant contributor to CE, external wall ranked second, and windows ranked third compared to other components. The 35%, 22%, and 14% were shared to the total CE by the structure, external walls, and windows, respectively. Strategy 1, aiming to remove ceramic tiles from interior of the external walls, gives a slight reduction of 3% compared to the reference scenario. While strategy 2, using lean concrete in place of normal concrete and using wooden window frames in place of aluminium frames, gives a reduction of 16% compared to the reference and reduces significantly the impact of windows on the total CE. Strategy 3 replacing the masonry external walls by lightweight timber frames brings a reduction of 20% compared to the reference. This strategy generates a significant improvement in the CE of external walls and shifts its rank from the second most influential to a less dominant position. However, strategy 4, implementing solar PV panels on the roof, led to an increase of approximately 7% in CE compared to the reference.

Fig. 3 presents the overall CE comparison of the reference and four studied scenarios, calculated using screening LCA and simplified LCA. The reference scenario showed a CE of 1248 and 1276 kg CO_2-eq/m^2 for the screening and simplified LCA, respectively, with a 2.2% difference. For strategy 1, CE were 1244 (screening LCA) and 1271 kg CO_2-eq/m^2 (simplified LCA), yielding a 2.2% difference. Strategy 2 showed CE of 1226 (screening) and 1249 kg CO_2-eq/m^2 (simplified), resulting in a 1.9% difference. In strategy 3, total CE were 1214 (screening) and 1242 kg CO_2-eq/m^2 (simplified), with a 2.3% difference. Strategy 4 resulted in CE of 794 (screening) and 835 kg CO_2-eq/m^2 (simplified), with a 4.9% difference. Overall, the differences between the screening and simplified LCA across all scenarios ranged from 1.9% to 4.9%.

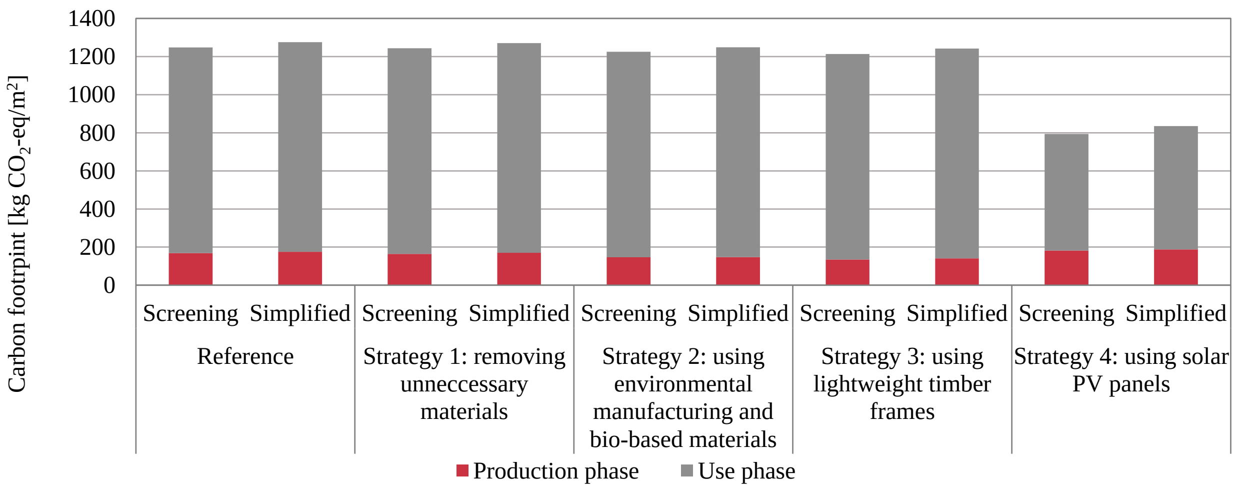

Figure 3. Carbon emission results comparison based on all the scenarios by two types of LCA.

Using screening LCA, the results of strategy 1, strategy 2, strategy 3, and strategy 4 accounted for 0.35%, 1.79%, 2.75% and 36.39% reduction in CE compared to the reference, respectively. Using simplified LCA, these scenarios accounted for 0.39%, 2.13%, 2.69%, and 34.57% reduction in CE compared to the reference, respectively. Thus, there is about 1% to 2% difference between CE reduction percentage results from the screening and simplified LCA of the reference and studied scenarios comparison. Strategy 4 generated a significantly greater reduction in CE than the other strategies.

Fig. 4 presents the overall CE comparison of the refence and combined scenarios using the screening and simplified LCA methodologies. The combination of four strategies demonstrates a significant reduction in total life cycle CE, approximately 42% of the reference building's CE. The combined strategy showed a total CE of 722 and 749 kg CO_2-eq/m^2 for the screening and simplified LCA, respectively, with a 3.6% difference. The combined strategy generates overall 42.13% and 41.67% less CE compared to the reference scenario, resulted from screening and simplified LCA, respectively.

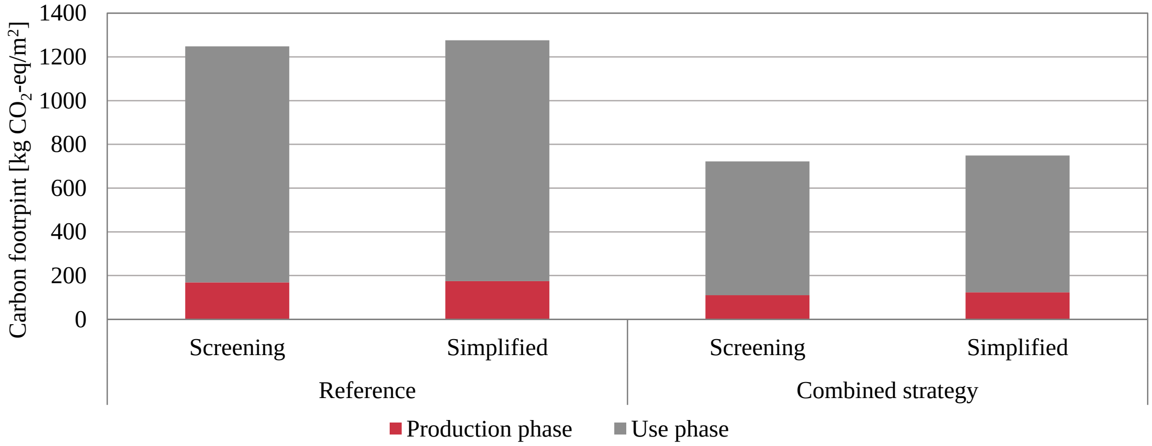

Figure 4. Carbon emission results comparison based on the reference and combined strategy.

4. DISCUSSION

The studied townhouse in Cambodia generates the highest CE during the use phase which is similar to other residential building case studies in Southeast Asia (Abd Rashid et al., 2017; Le et al., 2021) and in other developing countries (Morsi et al., 2020). Strategy 4 implementing solar PV panels is a particularly relevant solution for buildings in Southeast Asia, as there is significant potential for renewable solar energy resources in this region (Lai et al., 2023). Incorporating a broader range of energy conservation measures in future research, such as building envelope improvements, energy-efficient electrical appliances, behavioural controls, and advanced technologies, could provide valuable insights. In terms of production phase, the scenarios of removing unnecessary materials and using more environmental manufacturing and biogenic materials show a significant reduction of CE and reflect the needed effort to select more sustainable materials and minimize materials consumption to achieve sustainable building in Cambodia (Durdyev et al., 2018). However, the main drivers of the significantly reduced CE for the combined strategy are primarily related to use phase, followed by the production phase.

This study compares the CE result of the reference and combined strategy to results from the literature review on building LCA in Southeast Asia and in Egypt, another developing country, by phases of life cycle included in the LCA and its entire lifespan, as shown in Fig. 5. The CE of these cases: Morsi et al. (2020), Le et al. (2021), and Abd Rashid et al. (2017) varied at 1062, 1335, and 3327 kg CO_2-eq/m^2, respectively. The reference result of this study calculated by the simplified LCA is 1276 kg CO_2-eq/m^2, which is comparable to the case of Le et al. (2021) in Vietnam, while the other cases produced a lower and higher emission. However, the second design scenario using greener materials in the study of Le et al. (2021) produced 834 kg CO_2-eq/m^2 of CE based on production and use phase, which is a higher CE reduction than the combination of the first 3 strategies related to greener materials in this study, but is a lower CE reduction than the combined strategy of this study considering greener materials and PV panels, which produces 749 kg CO_2-eq/m^2. The different CE results of all scenarios from the screening and simplified LCA studies vary minorly in a range from 1.9% to 4.9%, representing a slight difference. With these percentage values, the results of a screening LCA are reliable and results from these two types of LCA simplification are comparable.

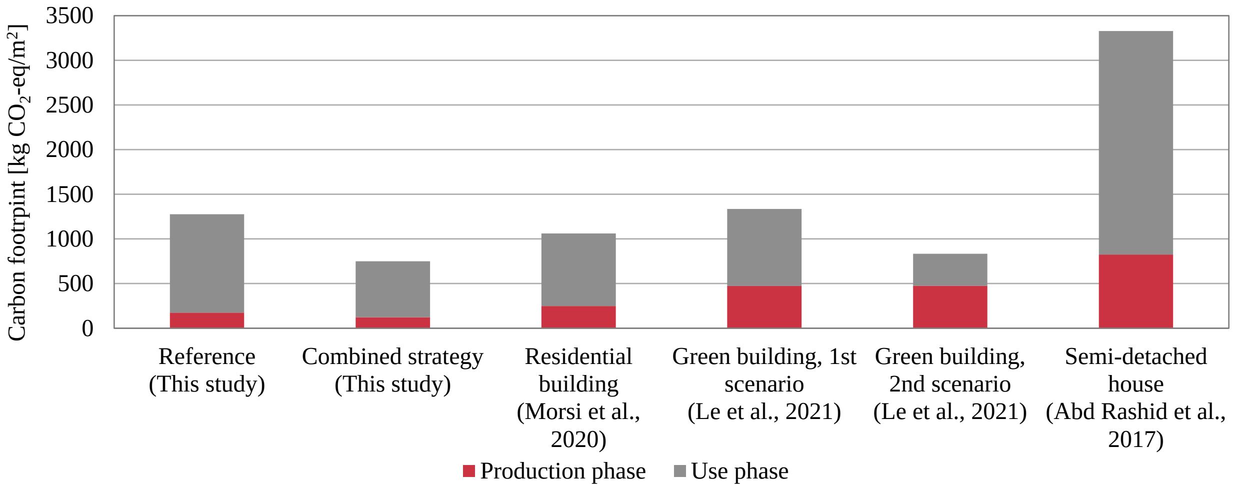

Figure 5. Carbon emission results comparison of this case study in Cambodia with other LCA studies.

The limitations of this study are related to assumptions made regarding the materials database, system boundaries, and the assessment of only a single impact category. It would be valuable to test the results obtained using the same regional database or other LCA software for comparison. Moreover, mandatory modules for the end of life phase were not included due to the lack of data on all activities and energy consumption during the building's demolition. The end of life phase of buildings is becoming critical in circular economy policies aimed at extending building service life and promoting component reuse or recycling (Giorgi et al. 2018). While using a single impact indicator may be sufficient for a specific study, it is not recommended for the holistic optimization of building designs, as it may result in suboptimal solutions (Hollberg, 2016).

5. CONCLUSION

The average difference between results of the screening and simplified LCA studies is 2.8% according to the results comparison from 6 different scenarios. All studied scenarios show a different reduction value of CE. Strategy 3 using lightweight timber frames walls in place of masonry walls presents the highest CE reduction during the production phase with approximately 20% of CE reduction during the building's production phase, while strategy 4 presents about 36% CE reduction in terms of overall life cycle compared to the reference. The combined strategy allows a significant reduction of 42% throughout its life cycle compared to the existing house. The results of this study demonstrate the potential of integrating the life cycle perspective into green buildings design in Cambodia and highlight the best strategies that should be used for future renovation and design of new residential buildings. Furthermore, this study proves that a screening LCA is a useful tool to pre-size the GHG emissions produced by a building and test different decarbonization design options during the building design phase. However, the future study should study several environmental impacts to check the variability and accuracy of the screening LCA results concerning the total building environmental footprint compared to those of a simplified LCA.

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