Prabodani, M.K.M., Ranasinghe, S.S. and Halwatura, R.U., 2024. Lifecycle carbon emissions: Adaptive reuse vs new buildings in Sri Lanka. In: Sandanayake, Y.G., Waidyasekara, K.G.A.S., Ranadewa, K.A.T.O. and Chandanie, H. (eds). *Proceedings of the 12th World Construction Symposium*, 9-10 August 2024, Sri Lanka. pp. 734-746. DOI: https://doi.org/10.31705/WCS.2024.58. Available from: https://ciobwcs.com/papers/

LIFECYCLE CARBON EMISSIONS: ADAPTIVE REUSE VS NEW BUILDINGS IN SRI LANKA

M.K.M. Prabodani[1], S.S. Ranasinghe[2] and R.U. Halwathura[3]

ABSTRACT

The building construction sector stands out as a significant contributor to carbon emissions (CE). Among the sustainable practices available to mitigate this impact, adaptive reuse of historic buildings (ARHB) emerges as a viable option. In tropical developing countries, there is no quantitative research on ARHB and CE to evaluate the effectiveness of the use of ARHB as a solution. This study addresses this gap by conducting a comparative analysis of lifecycle CE between ARHB and an envisioned new building with an identical building envelope. Notably, this is the pioneering case study of its kind in Sri Lanka. A historic building within Galle Dutch Fort serves as the chosen case study, repurposed as a homestay to align with current local trends. Results indicate that annual carbon emission from the ARHB is 37.35 kg.CO_2/m^2, while from the envisioned new building amounting to 48.64 kg.CO_2/m^2, showcasing the significantly reduced environmental impact of ARHBs. In both scenarios, operational energy accounted for the highest proportion of CE, at 73.8% and 62.3% respectively. Subsequently, material production emerged as the next critical stage for both cases. Consequently, this study concludes that ARHB presents a more environmentally friendly option than new building construction. Moreover, the research suggests a focus on operational and material production stages to diminish environmental impact further. Strategies such as altering user behaviour, implementing microclimatic approaches, and embracing circular economic principles are recommended to achieve this objective. This study underscores the potential for ARHB to contribute significantly to sustainability efforts within the building construction sector.

Keywords: *Adaptive Reuse; Carbon Emissions; Historic Buildings; Tropical Developing Countries.*

1. INTRODUCTION

Amidst the global environmental crisis, numerous international agreements have been established since the 1970s to combat global warming and climate change, with a primary objective of reducing carbon emissions (CE) across all industries (Tae et al., 2011). The construction sector plays a pivotal role in realising the objectives set forth by the Paris Agreement, given its substantial contribution to energy consumption and greenhouse gas (GHG) emissions. Recent data from 2022 reveals that the building sector accounted for

[1] Department of Civil Engineering, University of Moratuwa, Sri Lanka, methsi.praba@gmail.com
[2] Department of Agricultural Engineering, University of Ruhuna, Sri Lanka, subashasranasinghe@gmail.com
[3] Department of Civil Engineering, University of Moratuwa, Sri Lanka, rangikauh@gmail.com

34% of total energy consumption and 37% of GHG emissions (International Energy Agency [IEA], 2023; Intergovernmental Panel on Climate Change [IPCC], 2024). Tracking the progress of building sector decarbonisation since 2015, the Global Buildings Climate Tracker (GBCT) highlights a substantial 40-point gap between the current state and the necessary decarbonisation levels to meet Paris Agreement targets (United Nations Environment Programme [UNEP], 2024). Currently, global building construction encompasses an expansive area of 250 billion square meters, with residential spaces occupying 80% of this land (IEA, 2023). Factors such as population growth, evolving lifestyles, changes in household sizes, and urbanisation exert pressure, and energy usage and carbon emissions are expected to witness a notable surge (IPCC, 2014). These trends escalate the urgent need for comprehensive strategies to mitigate environmental impacts and foster sustainable practices within the building construction sector.

The foundational stage in identifying mitigation strategies for GHG emissions and energy usage involves an assessment of current performance. These evaluations serve as the basis for selecting low CE methods, materials, and systems. The implementation of the Kyoto Protocol has promoted numerous studies focused on evaluating building energy usage and GHG emissions (Kumanayake & Luo, 2018). These investigations provide critical insights into the existing state of affairs, guiding the development of effective and targeted solutions to align with sustainability goals.

Throughout their lifecycle, buildings exert substantial environmental impacts, highlighting the critical need to prioritise higher energy efficiency and reduced CE in their design and planning. The significance of material production has attracted particular attention, with numerous studies shedding light on this aspect. For example, a study analysing 78 office buildings in China found that a staggering 75% of CE occurred during the material production stage is from major construction materials (Luo et al., 2016).

Operational use emerges as a critical stage with the highest environmental impact, as highlighted by Pomponi and Moncaster (2017). Despite existing benchmarks for operational energy performance, scholars stress the necessity of a comprehensive Life Cycle Assessment (LCA) to provide a holistic evaluation of environmental impacts (Izaola et al., 2023; Mastrucci et al., 2017). These findings collectively highlight the complex interplay of different lifecycle stages in influencing environmental impacts associated with buildings. They emphasise the importance of considering these factors in the context of sustainable building practices. A predominant proportion of researchers have conducted their investigations employing CE as a primary metric for quantifying environmental impact, owing to its direct association with climate change and global warming phenomena (Izaola et al., 2023; Tae et al., 2011).

The adaptive reuse buildings (ARB) stand out as a sustainable method that the construction sector can adopt to mitigate the environmental impact (Foster & Saleh, 2021; Pomponi & Moncaster, 2017). ARB presents a solution that significantly reduces energy usage and CE across various lifecycle stages, including demolition, material transportation, and waste disposal (Mansfield, 2009). Further highlighting the advantages of rehabilitation over new construction, Erlandsson and Borg (2003) utilised parameters such as acidification and global warming potential to demonstrate the environmental superiority of rehabilitation projects.

The majority of research on ARHB and its environmental impacts has been conducted in developed countries, where building design, energy use, and climate differ significantly from those in many tropical developing nations (Atmaca & Atmaca, 2015).

The findings derived from non-tropical developed countries cannot be directly applied to decision-making processes in tropical developing countries due to distinct differences in energy use and CE. In tropical developing countries, energy consumption is predominantly driven by cooling needs, often without proper insulation methods. Additionally, the energy sources available in these regions tend to have higher CE compared to those in developed countries (Ramesh et al., 2010). Furthermore, inefficient material production technologies prevalent in these areas contribute to increased embodied energy and CE.

Consequently, this research aims to clarify the current state of CE reduction in tropical developing countries, with a specific focus on Sri Lanka, through the application of ARHB. This study intends to conduct a comprehensive comparison of the carbon emissions associated with ARHB and those of a new building constructed using contemporary materials and methodologies. As the first case study of its kind in Sri Lanka, this research seeks to provide valuable insights into the advantages of ARHB in tropical developing regions facing similar challenges and conditions.

2. MATERIALS AND METHODS

2.1 SCOPE OF THE STUDY

The research will comprehensively analyse the whole lifecycle. The Life Cycle Assessment (LCA) framework adopted in this study follows the guidelines outlined in BS EN 15978:2011 (British Standards Institution, 2011). A consistent building lifespan of 50 years will be applied for comparative analysis, with the functional unit measured as square meters per annum. It is noteworthy that this study represents a pioneering effort in directly comparing CE between ARHB and newly constructed counterparts. By providing a quantitative assessment of environmental impact, this research aims to contribute significantly to the understanding of the sustainability implications associated with the ARHB.

2.2 CASE STUDY

This study focuses on the Galle Dutch Fort area, distinguished as the most prominent surviving Dutch colonial city outside Europe, showcasing a unique blend of European and South Asian architectural styles (Refer to Figure 1).

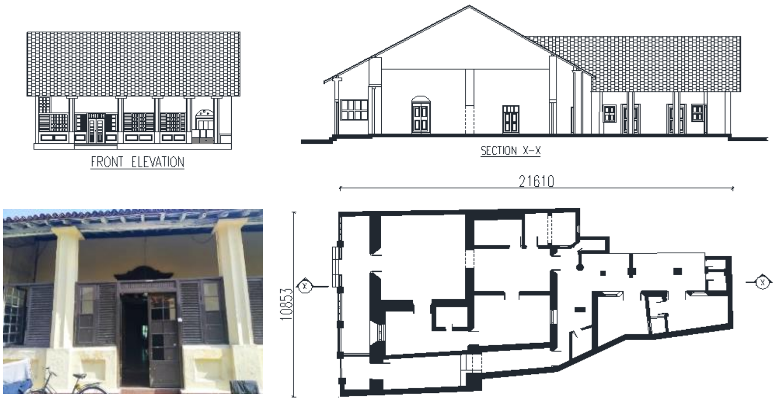

Figure 1: Selected House in Galle Fort

Designated as a UNESCO World Heritage site in 1988, Galle Fort has experienced notable functional transitions attributed to the thriving tourism industry accompanied by shifts in lifestyles and resident requirements (Rajapakse & Silva, 2020).

Through extensive site visits and interviews with experts and residents, No. XX in Galle Fort was identified as an ideal case study subject (Figure 1). This historic building, erected in 1680 and with a floor area of 181 m^2, has retained its original features over the centuries. The necessary information was collected from the Galle Heritage Foundation, the Divisional Archaeological Department, and residents of the area. Noteworthy findings from our investigations revealed a prevailing trend wherein many residential buildings in the area have transitioned into homestays. Subsequent analysis and discussions with construction experts led to the decision to propose homestay as the adaptive reuse option for No. XX, Galle Fort building. The following are the two cases considered in this research.

Case 1: Adaptive reuse of the selected house as homestay (Old Building)

Case 2: Envisioned new building with the same building envelope with the same purpose (New Building)

2.3 ESTIMATING LIFE CYCLE CARBON EMISSIONS

According to the LCA and carbon emissions coefficient (CEC) method, the total CE can be calculated using Equation 01 (Chau et al., 2015). The CE for each specific lifecycle component mentioned in Equation 01 will be further detailed in Equation 02 through 06.

$$C_{LC} = C_M + C_T + C_c + C_{O\&M} + C_D \qquad \textit{(Eq. 01)}$$

Where C_{LC} is the Total Lifecycle CE ($kgCO_2$), C_M is the CE in Material Production ($kgCO_2$), C_T is the CE in Transportation ($kgCO_2$), C_C is the CE in Construction ($kgCO_2$), $C_{O\&M}$ is the CE in Operation and Maintenance ($kgCO_2$), and C_D is the CE in Demolition ($kgCO_2$)

2.3.1 Material Production

Equation 02 gives the CE at the material production stage (Li et al., 2016). Using Equation 2, the carbon emissions (CE) for both the old building and the new building were calculated. The building blueprint was obtained from the Galle Heritage Foundation. Subsequently, the two buildings were modelled using Autodesk Revit software to extract the quantity of materials.

$$C_M = \sum_{i=1}^{n} (m_i \times f_{m,i}) \qquad \textit{(Eq. 02)}$$

n is the number of materials; m_i is the quantity of material of type i (kg or m^3), and $f_{m,i}$ is the embodied CEC of material type i ($kgCO_2kg^{-1}$ or $kgCO_2m^{-3}$). Sri Lanka does not have a dedicated database for CEC. Consequently, well-accepted databases and relevant literature were utilised for this study (Kumanayake & Luo, 2018; University of Bath UK, 2019).

2.3.2 Transportation

Equation 03 presents the formula for calculating CE from material transportation for the new building. T_i is the number of trips of the transport vehicle, D_i is the average two-way travel distance (km)and $f_{t,i}$ is the CEC for transporting the material type i ($kgCO_2km^{-1}$). Except ready-mixed concrete, other materials were transported using 8-ton trucks (Kumanayake & Luo, 2018). Emission coefficients were extracted from literature and other acceptable databases (Sri Lanka Sustainable Energy Authority, 2015). CE due to transportation for the old building was considered null, as manual methods were predominantly utilised for transportation during that era.

$$C_T = \sum_{i=1}^{n} (T_i \times D_i \times f_{t,i}) \qquad \textit{(Eq. 03)}$$

2.3.3 Construction

CE due to construction work was calculated using the methodology developed by Pinky Devi and Palaniappan (2014). Construction sector experts were interviewed to gather information on the general practices of the construction sector in Sri Lanka. Using Equation 04, CE from construction activities was calculated, for the new building. This value is considered as zero for the old building, as manual methods were used for construction activities during that time.

$$C_C = \sum_{i=1}^{k} (Q_i \times R_i \times f_{c,i}) \qquad \textit{(Eq. 04)}$$

When the number of construction activities is equal to k, Q_i is the quantity of on-site construction activity (m^3, m^2 or kg), R_i is the fuel/electricity usage rate for construction activity (Lm^{-3}, $kWh\ kg^{-1}$ or $kWh\ m^{-2}$) and $f_{c,i}$ is the CEC for the energy source used for the construction activity ($kg\ CO_2L^{-1}$ or $kg\ CO_2kWh^{-1}$).

2.3.4 Operation and Maintenance (O&M)

Two separate Design Builder models were used to calculate the operational energy for Case 1 and Case 2. There, energy requirements for cooling and lighting were extracted. In Sri Lanka, households generally get their energy requirement from the national grid. The method used by Roh and Tae (2016) was adopted, and Equation 05 was used to calculate the CE from the operational and maintenance of the building.

$$C_{O\&M} = (Q_e \times f_e \times Y) + \left(\sum_{i=1}^{j} \left(m_i \times r_i \times f_{m,i} \times \frac{Y}{R}\right)\right) \qquad \textit{(Eq. 05)}$$

Q_e is the electricity consumption per annum (kWh yr^{-1}), f_e is the CEC of the Electricity (kg CO_2 kWh^{-1}), and Y is the lifespan in years. j is the number of material types needed for maintenance and repair. m_i is the quantity of i^{th} material (kg or m^3), r_i is the rate of repair, f_{mi} is the CEC of the i^{th} material ($kgCO_2kg^{-1}$ or $kgCO_2m^{-3}$) and R is the repair intervals (years).

2.3.5 Demolition

In the context of demolition, Case 1 considered the demolition of the building at the end of its lifespan. In contrast, Case 2 involved the demolition of the old building at the beginning and the demolition of the new building at the end of its lifespan. Here, under demolition part CE in the demolition activities, transportation of demolished materials and disposal as landfilling was considered (Equation 06).

$$C_D = \sum_{i=1}^{r}\left(Q_{d,i} \times f_{d,i}\right) + \left[\left(T \times D \times f_{t,i}\right) + \left(M \times f_i\right)\right] \quad \textit{(Eq. 06)}$$

In demolition, $Q_{d,i}$ is the quantity of r type demolition, $f_{d,i}$ is the CEC of the r type demolition procedure, T is the number of trips to transport demolished waste, D is the Two-way distance between the building site and the landfill (km), $f_{t,i}$ is the CEC Transporting waste (kg CO_2 km^{-1}), M is the demolished material quantity (kg) and fi is the CEC of the used landfilling machinery ($kgCO_2kg^{-1}$).

3. RESULTS AND DISCUSSION

3.1 MATERIAL PRODUCTION

The predominant materials utilised in the old building are clay, granite, limestone, timber, glass, sand, and limestone. In contrast, the principal building materials in the new constructions consist of clay bricks, concrete, reinforcement, mortar, clay tiles, paint, and granite. Table 1 provides details on the CE values during the material production stage for the old building, while Table 2 presents corresponding values for the new building within the same phase. These tables offer a comparative overview of the environmental impact associated with material production, shedding light on the CE attributed to different construction materials used in the respective buildings.

Table 1: CE at the material production of the old building

Material	Weight	Weight %	f_{mi}	Carbon Emission	Carbon Emission
	kg	%	$kgCO_2/kg$	$kgCO_2$	%
Clay	130,634	16.2	0.255	33,312	35.2
Granite	466,441	58.0	0.079	36,849	38.9
Limestone	150,387	18.7	0.09	13,535	14.3
Timber	3,336	0.4	0.306	1,021	1.1
Glass	125	0.0	1.44	180	0.2
Sand	41,040	5.1	0.007	287	0.3
Lime	12,239	1.5	0.78	9,546	10.1
Total	**804,202**	**100**		**94,729**	**100**

Table 2: CE at the material production of the new building

Material	Weight kg	Weight % %	f_{mi} $kgCO_2/kg$	Carbon Emission $kgCO_2$	Carbon Emission %
Clay Bricks	193,500	35.7	0.24	46,440	57.0
Concrete	24,567	4.5	0.123	3,022	3.7
Reinforcement	319	0.1	1.45	463	0.6
Mortar	21,173	3.9	0.2	4,235	5.2
Clay Tiles	6,411	1.2	0.255	1,635	2.0
Ceramic Tiles	1581	0.3	0.78	1,233	1.5
Paint	418	0.1	2.91	1,216	1.5
Granite	293,858	54.2	0.079	23,215	28.5
Total	**541,827**	**100**		**81,458**	**100**

The material weight of the old building was measured as 4443.1 kg/m², whereas the material weight of the new building was 2993.5 kg/m². This discrepancy primarily arose from the greater weight of granite in the old building. The material weight of the new building aligns with findings from previous studies (Kumanayake & Luo, 2018; Pinky Devi & Palaniappan, 2014). In the material production stage, the CE of the old building amounted to 523.37 $kg.CO_2/m^2$, whereas the corresponding value for the new building was 450.04 $kg.CO_2/m^2$. Once more, this variance was attributable to the higher mass of granite in the old building. Notably, in the old building, granite accounted for the highest percentage of CE, whereas in the new building, clay bricks exhibited the highest emissions.

3.2 MATERIAL TRANSPORTATION

During ancient times, construction materials were typically transported to the construction site via canal or manual means, as indicated by gathered historical data. The calculation of material transportation emissions for the new building is presented in Table 3. Notably, the highest CE was attributed to clay brick transportation, accounting for 74.5% of the total emissions related to transportation in the new building. The CE due to transportation amounted to 1.05 $kg.CO_2/m^2$ in the new building, while this value was assumed to be negligible in the case of the old building.

Table 3: CE at the transportation stage

Material	Type of Vehicle	No of Trips	Distance km	Mileage l/km	Fuel Factor $kg\ CO_2/l$	$f_{(t,i)}$ $kgCO_2/km$	Carbon Emission $kgCO_2$
Clay Bricks	8-ton truck	24	5	0.22	2.68	0.59	141.50
Reinforcement	8-ton truck	1	5	0.32	2.68	0.86	8.58
Mortar	8-ton truck	3	5	0.29	2.68	0.78	23.32
Clay Tiles	8-ton truck	3	5	0.17	2.68	0.46	13.67
Ceramic Tiles	8-ton truck	1	2	0.17	2.68	0.46	1.82
Paint	8-ton truck	1	2	0.09	2.68	0.24	0.96
Total							**190**

3.3 CONSTRUCTION ACTIVITIES

The construction activities considered for the new building included concrete mixing, concrete compaction, rebar works, and site lighting. Consultation with industry experts was conducted to gather construction norms specific to Sri Lanka. Notably, site lighting emerged as the activity contributing the highest percentage to the CE, accounting for 99% of the total emissions. The calculation summary is shown in Table 4.

Table 4: CE from construction activities

Activity	Energy use rate		Quantity of Work		Amount of Energy		f $kgCO_2$/ l or kg CO_2 /kWh	Carbon Emission $kgCO_2$
Site mixed concrete	0.5	l/m^3	10.24	m^3	5.12	l	2.58	13.20
Concrete Compaction	0.21	l/m^3	10.24	m^3	2.15	l	2.58	5.55
Rebar and reinforcement	2	$kWh.MT^{-1}$	0.319	MT	0.64	kWh	0.6896	0.44
Site Lighting	26	$kWh.m^{-2}$	181	m^2	4706	kWh	0.6896	3245.26
Total								**3,264**

The CE due to construction activities for the new building was calculated at 18.04 $kg.CO_2/m^2$. For the old building, emissions in the construction stage were assumed to be negligible.

3.4 OPERATION AND MAINTENANCE

3.4.1 CE due to Operational Activities

For the two cases, two separate buildings were modelled using DesignBuilder software to assess their energy requirements. The results indicated that for the new building, the estimated energy requirement for the entire lifespan was 488,700 kWh, whereas for the old building, it was 470,600 kWh. The total Carbon Emission (CE) from the new building was calculated in 1862 $kg.CO_2/m^2$, while for the old building, it was 1793 $kg.CO_2/m^2$. The Carbon Emission Coefficient (CEC) of the electricity grid in Sri Lanka was considered to be 0.6896 $kg.CO_2/kWh$ according to the Sri Lanka Sustainable Energy Authority (2015).

3.4.2 CE due to Maintenance

During the maintenance stage of the new building, both painting and tile replacement were taken into account. However, painting work was only considered for the old building, as it is equipped with granite tiles that do not require replacement within the next 50 years. The painting frequency was set at five years, with a repair rate of 1. For tile replacement, the repair frequency was set at ten years, with a repair rate of 0.1 (Kumanayake & Luo, 2018). The Carbon Emissions (CE) associated with maintenance were evaluated at 56 $kg.CO_2/m^2$ for the new building and 54 $kg.CO_2/m^2$ for the old building.

3.5 DEMOLITION

In the demolition phase, only deconstruction, waste transportation, and landfilling were considered. For deconstruction, it was assumed that a Backhoe (1 m^3) and a Giant Breaker (0.7 m^3) were utilised. Additionally, transportation was assumed to employ a 20-ton dump truck, while landfilling involved the use of a Dozer and a Compactor. The calculated CE for demolition were 60.13 kg.CO_2/m^2 for the old building and 18.54 kg.CO_2/m^2 for the new building. The higher CE value for the old building is attributed to its greater material weight, whereas the new building is assumed to be constructed on top of the old wall foundation.

3.6 TOTAL CARBON EMISSION

The carbon emissions (CE) at each stage for both cases are presented, with the total carbon emission percentages illustrated in Figure 2. In both cases, operational energy accounted for the highest percentages, representing 73.8% for Case 1 and 62.3% for Case 2. The second-largest contributions were from the material production stage, comprising 21.5% for Case 1 and 32.6% for Case 2. In Case 1, construction and transportation emissions were assumed to be zero, while in Case 2, transportation emissions were almost negligible in percentage terms. For Case 2, the construction stage's CE was primarily due to site lighting.

The percentages of CE in the maintenance stage were very similar between the two cases. A difference in this stage was observed as the old building did not have ceramic floor tiles, and the available granite tiles did not require replacement or repair even within the next 50 years. In the demolition stage, the main difference was the need to demolish the new house in addition to the demolition of the old house in the initial stage. These findings are consistent with previous studies (Kumanayake & Luo, 2018).

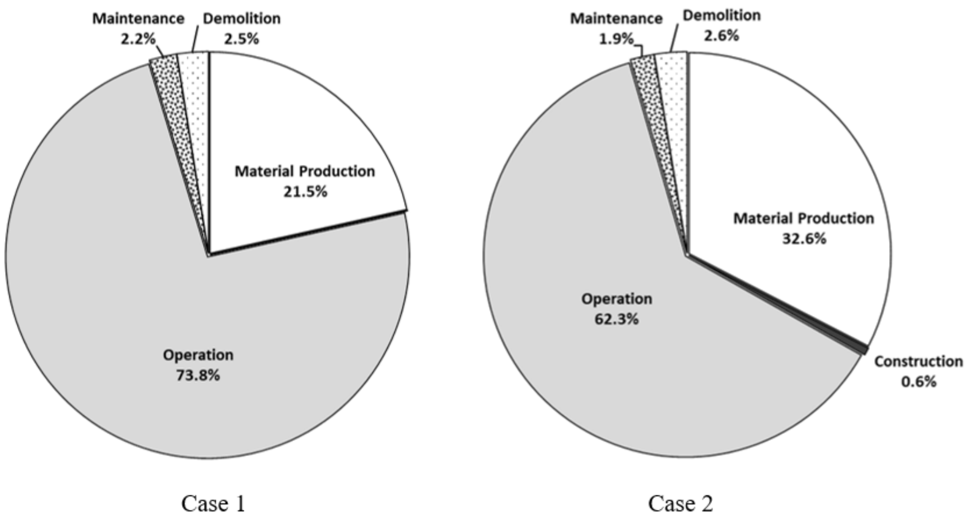

Figure 2: CE percentages for each lifecycle stages

For Case 1, the total CE was 2430 kg.CO_2/m^2, while for Case 2, it was 2989 kg.CO_2/m^2, resulting in a difference of 559 kg.CO_2/m^2. Further analysis was conducted considering the lifespan of the buildings. In this analysis, the material production for the old building was considered from 1680. It was found that the CE of material production after 50 years of lifespan is nearly zero per annum in the old building. For Case 1, the total CE per annum was 37.35 kg.CO_2/m^2, and for Case 2, it was 48.64 kg.CO_2/m^2. These results provide insights into the environmental impact of the buildings over their lifespan, highlighting the significance of operational energy and material production in contributing to carbon emissions. This study provides a quantitative analysis, demonstrating that each life cycle stage of ARHB exhibits lower CE compared to new buildings.

In the Sri Lankan context, there are no directly comparable results. However, Kumanayake and Luo (2018) conducted a study on a university building, which resulted in 31.8 kg CO2/m² per annum. This building was a reinforced structure with seven floors. A similar study in Turkey on a residential building calculated the CE to be 48.87 kg CO2/m² per annum (Atmaca & Atmaca, 2022). Additionally, research in Spain and Portugal reported CE values of 49.33 kg CO_2/m² per annum and 43.34 kg CO_2/m² per annum, respectively (Ortiz-Rodríguez et al., 2010; Rossi et al., 2012).

3.7 CARBON EMISSION REDUCTION MEASURES

Previous studies have also shown a similar pattern of CE for each lifecycle stage, with the operational phase often yielding the highest impact, followed by material production. Notably, building operational energy consumption, particularly for thermal and visual comfort, is significant (Pathirana et al., 2019). Properly applied passive design principles can substantially reduce building energy requirements before considering mechanical systems (Bai et al., 2015). Studies have highlighted that occupants' positive attitudes can significantly reduce operational carbon emissions (Delzendeh et al., 2017). Furthermore, microclimatic modifications achieved through landscaping, natural ventilation, and other passive design strategies (Rajapaksha & Halwatura, 2020) can be utilised to decrease energy consumption during the operational phase.

Replacing conventional materials with mass timber in half of new constructions can reduce global emissions by 9% (Himes & Busby, 2020). Utilising wooden frames instead of aluminium can cut emissions by half and additionally lowers energy demand due to wood's lower heat transmittance properties (Saadatian et al., 2021).

In light of traditional linear economic principles prevalent in the building sector, there is a growing need to transition towards circular economic principles that promote the 3R concept: reduce, reuse, and recycle (Pomponi & Moncaster, 2017). Additionally, incorporating energy-efficient building materials can further diminish the environmental impact of the construction industry. These insights highlight the multifaceted approaches needed to foster a more sustainable and environmentally conscious building sector.

4. CONCLUSIONS

This study aimed to compare the CE of ARHB versus newly constructed buildings. The selected case study building, situated in Galle Dutch Fort, underwent two scenarios: Case 1 involved repurposing the existing building into a homestay. In contrast, Case 2 envisioned constructing a new building with contemporary materials and technology for the same purpose. The CE of both cases was then compared.

Results revealed that Case 1, the ARHB scenario, exhibited a lower annual CE of 37.35 kg.CO_2/m^2 compared to Case 2's CE of 48.64 kg.CO_2/m^2 per annum, demonstrating the reduced environmental impact of ARHB over demolition and new construction. Notably, the analysis of the building's entire lifecycle addressed a previous argument regarding historic buildings' operational energy impact, revealing that the selected building's operational energy was lower than that of the newly constructed building, likely due to its thick walls (approximately 1m).

Furthermore, the study highlighted the operational phase as the most critical in a building's lifecycle concerning CE. Material production stages were also identified as crucial, suggesting that reusing old buildings can significantly reduce CE in both material production and demolition stages. The reuse of historic buildings goes beyond preservation for heritage and architectural significance. These buildings hold personal and cultural identities for communities. However, poorly designed ARHB projects can jeopardise the social and cultural values of these buildings. Hence, it is imperative to assess a building's significance before opting for reuse. To mitigate environmental impacts, the study suggests employing passive building design strategies, fostering positive occupant attitudes, introducing circular economic strategies, utilising locally available energy-efficient materials, and promoting the 3R (Reduce, Reuse, Recycle) concept.

The limitations of this research include the scarcity of recognised literature, challenges in locating building drawings, and potential difficulties in information collection due to the migration of native people. A major limitation of this research was the absence of a national database for CEC, necessitating the use of coefficients from regional literature and global databases. Therefore, there is a strong recommendation to develop a national database for CEC in Sri Lanka to enhance the quality and reliability of future research in this area.

5. ACKNOWLEDGEMENTS

The authors would like to thank the owner of the No. XX, Galle Fort Building.

6. REFERENCES

Atmaca, A., & Atmaca, N. (2015). Life cycle energy (LCEA) and carbon dioxide emissions (LCCO2A) assessment of two residential buildings in Gaziantep, Turkey. *Energy and Buildings, 102*, 417–431. https://doi.org/10.1016/j.enbuild.2015.06.008

Atmaca, A., & Atmaca, N. (2022). Carbon footprint assessment of residential buildings, a review and a case study in Turkey. *Journal of Cleaner Production, 340*. https://doi.org/10.1016/j.jclepro.2022.130691

Bai, G., Gong, G., Yu, C. W., & Zhen, O. (2015). A combined, large, multi-faceted bulbous façade glazed curtain with open atrium as a natural ventilation solution for an energy efficient sustainable office building in Southern China. *Indoor and Built Environment, 24*(6), 813–832. https://doi.org/10.1177/1420326X15602048

British Standards Institution. (2011). *BS EN 15978:201: Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method*. British Standards Institution, London. https://knowledge.bsigroup.com/products/sustainability-of-construction-works-assessment-of-environmental-performance-of-buildings-calculation-method?version=standard

Chau, C. K., Leung, T. M., & Ng, W. Y. (2015). A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. *Applied Energy, 143*, 395-413. https://doi.org/10.1016/j.apenergy.2015.01.023

Delzendeh, E., Wu, S., Lee, A., & Zhou, Y. (2017). The impact of occupants' behaviours on building energy analysis: A research review. *Renewable and Sustainable Energy Reviews, 80*, 1061–1071. https://doi.org/10.1016/j.rser.2017.05.264

Erlandsson, M., & Borg, M. (2003). Generic LCA methodology applicable for buildings, constructions and operation services—Today practice and development needs. *Building and Environment, 38*(7), 919–938.https://doi.org/10.1016/S0360-1323(03)00031-3

Foster, G., & Saleh, R. (2021). The circular city and adaptive reuse of cultural heritage index: Measuring the investment opportunity in Europe. *Resources, Conservation and Recycling, 175*, 105880. https://doi.org/10.1016/j.resconrec.2021.105880

Himes, A., & Busby, G. (2020). Wood buildings as a climate solution. *Developments in the Built Environment, 4*, 100030. https://doi.org/10.1016/j.dibe.2020.100030

International Energy Agency (IEA). (2023). *Tracking clean energy progress 2023*. International Energy Agency. https://www.iea.org/reports/tracking-clean-energy-progress-2023

Intergovernmental Panel on Climate Change (IPCC). (2014). *AR5 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 University Press, Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/report/ar5/wg3/

Izaola, B., Akizu-Gardoki, O., & Oregi, X. (2023). Setting baselines of the embodied, operational and whole life carbon emissions of the average Spanish residential building. *Sustainable Production and Consumption, 40*, 252–264. https://doi.org/10.1016/j.spc.2023.07.001

Kumanayake, R., & Luo, H. (2018). Life cycle carbon emission assessment of a multi-purpose university building: A case study of Sri Lanka. *Frontiers of Engineering Management, 5*(3). https://doi.org/10.15302/J-FEM-2018055

Li, D., Cui, P., & Lu, Y. (2016). Development of an automated estimator of lifecycle carbon emissions for residential buildings: A case study in Nanjing, China. *Habitat International, 57*, 154–163. https://doi.org/10.1016/j.habitatint.2016.07.003

Luo, Z., Yang, L., & Liu, J. (2016). Embodied carbon emissions of office building: A case study of China's 78 office buildings. *Building and Environment, 95*, 365–371. https://doi.org/10.1016/j.buildenv.2015.09.018

Mansfield, J. (2009). Sustainable refurbishment: Policy direction and support in the UK. *Structural Survey, 27*(2), 148–161. https://doi.org/10.1108/02630800910956470

Mastrucci, A., Marvuglia, A., Leopold, U., & Benetto, E. (2017). Life cycle assessment of building stocks from urban to transnational scales: A review. *Renewable and Sustainable Energy Reviews, 74*, 316–332. https://doi.org/10.1016/j.rser.2017.02.060

Ortiz-Rodríguez, O., Castells, F., & Sonnemann, G. (2010). Life cycle assessment of two dwellings: One in Spain, a developed country, and one in Colombia, a country under development. *Science of The Total Environment, 408*(12), 2435–2443. https://doi.org/10.1016/j.scitotenv.2010.02.021

Pathirana, S., Rodrigo, A., & Halwatura, R. (2019). Effect of building shape, orientation, window to wall ratios and zones on energy efficiency and thermal comfort of naturally ventilated houses in tropical climate. *International Journal of Energy and Environmental Engineering, 10*, 107–120. https://doi.org/10.1007/s40095-018-0295-3

Pinky Devi, L., & Palaniappan, S. (2014). A case study on life cycle energy use of residential building in Southern India. *Energy and Buildings, 80*, 247–259. https://doi.org/10.1016/j.enbuild.2014.05.034

Pomponi, F., & Moncaster, A. (2017). Circular economy for the built environment: A research framework. *Journal of Cleaner Production, 143*, 710–718. https://doi.org/10.1016/j.jclepro.2016.12.055

Rajapakse, A., & Silva, K. D. (2020). *Transient heritage values, conflicting aspirations, and endangered urban heritage in the Historic Galle Fort, Sri Lanka.* In K. D. Silva (Ed.), *The routledge handbook on historic urban landscapes in the Asia-Pacific* (pp. 462–475). Routledge, London.

Rajapaksha, M., & Halwatura, R. U. (2020). Poro-therm clay wall panel system for indoor cooling. *2020 From innovation to impact (FITI)*, 1–6. https://doi.org/10.1109/FITI52050.2020.9424896

Ramesh, T., Prakash, R., & Shukla, K. K. (2010). Life cycle energy analysis of buildings: An overview. *Energy and Buildings, 42*(10), 1592–1600. https://doi.org/10.1016/j.enbuild.2010.05.007

Roh, S., & Tae, S. (2016). Building simplified life cycle CO2 emissions assessment tool (B-SCAT) to support low-carbon building design in South Korea. *Sustainability, 8*(6), 567. https://doi.org/10.3390/su8060567

Rossi, B., Marique, A.F., Glaumann, M., & Reiter, S. (2012). Life-cycle assessment of residential buildings in three different European locations, basic tool. *Building and Environment, 51*, 395–401. https://doi.org/10.1016/j.buildenv.2011.11.017

Saadatian, S., Freire, F., & Simões, N. (2021). Embodied impacts of window systems: A comparative assessment of framing and glazing alternatives. *Journal of Building Engineering*, *35*, 102042. https://doi.org/10.1016/j.jobe.2020.102042

Sri Lanka Sustainable Energy Authority. (2015). *Sri Lanka energy balance 2015: An analysis of energy sector performance.* Sri Lanka Sustainable Energy Authority. https://www.scribd.com/document/447373758/2015-Energy-Balance

Tae, S., Shin, S., Woo, J., & Roh, S. (2011). The development of apartment house life cycle CO2 simple assessment system using standard apartment houses of South Korea. *Renewable and Sustainable Energy Reviews*, *15*(3), 1454–1467. https://doi.org/10.1016/j.rser.2010.09.053

United Nations Environment Programme (UNEP). (2024). *Global status report for buildings and construction - beyond foundations: Mainstreaming sustainable solutions to cut emissions from the buildings sector*. https://doi.org/10.59117/20.500.11822/45095

University of Bath UK. (2019). *Embodied carbon - The ICE database.* Circular Ecology. https://circularecology.com/embodied-carbon-footprint-database.html