Embodied Carbon in Commercial Office Buildings: Lessons Learned from Sri Lanka

Amalka Nawarathna [a,*], Zaid Alwan [a], Barry Gledson [a], Nirodha Fernando [b]

[a] Northumbria University, Faculty of Engineering and Environment, Newcastle Upon Tyne, NE1 8ST, UK

[b] University of Salford, School of Science, Engineering and Environment, Salford, M5 4WT, UK

Abstract

Growing concerns over the importance of reducing the embodied carbon (EC[1]) of buildings have led to a greater focus on EC-related research and policymaking. Nevertheless, the Sri Lankan building sector is currently lagging behind on this issue. While a few studies have been conducted on the EC impacts of different buildings, further research is needed on impact estimation in order to inform policies and guidelines on EC reduction, with assessment or estimation being the main driver towards reduction. Thus, this study aims to present, evaluate, and discuss EC assessment methodology and the assessment results drawn from twenty case studies in Sri Lanka, including low-, medium-, and high-rise office buildings. The results indicated that the EC extent of buildings ranged between 384.45 and 677.39 kgCO2e/m^2. The average EC extent of each building category was valued at 522.18 kgCO2e/m^2 (low-rise buildings), 457.85 kgCO2e/m^2 (medium rise), and 567.51kgCO2e/m^2 (high-rise). Irrespective of the building category, the substructure, frame, upper floors, and external walls were identified as the carbon critical elements, accounting for about 85-95% of overall EC. Internal walls and partitions, stairs and ramps, and roof elements were insignificant carbon elements, contributing less than 20% of EC. This study further revealed some practical indications on optimal EC reduction strategies for office buildings. Importantly, the overall work provided quantitative information that enables the decision-makers to make decisions on reducing EC of buildings in Sri Lanka.

Keywords: carbon critical elements; embodied carbon; life cycle assessment, office buildings; Sri Lanka

1. Introduction

Globally, the buildings and construction sector remains the highest carbon emitter, responsible for 39% of total energy-related emissions [1]. Of this 39%, 28% comes from operational carbon (OC), which is associated with energy use in building operational activities such as heating, cooling, light, and electronic and electrical appliances; the remaining 11% arises from embodied carbon (EC), associated with energy consumption (embodied energy) and chemical processes during the extraction, manufacture, transportation, assembly, replacement, and deconstruction of construction materials or

[1] Embodied Carbon

products [1]. Owing to its larger share, priority until recently has been given to reducing OC [2]. However, successful reduction of OC has caused the EC share of whole life building carbon to increase [3], and attention is now being shifted towards the quantification and reduction of the EC impacts of buildings, while continuing efforts to reduce OC emissions [4]. The efforts of developed countries are widely recognised in the existing literature, but the contribution of developing countries is less well researched. Only a few studies focusing on developing countries are available in the existing literature (e.g. Sheng et al. [5], Mpakati-Gama, Brown and Sloan [6], Zhang and Wang [7], Kumanayake and Luo [8], Kumanayake and Luo [9], Nawarathna et al. [10], and Kibwami and Tutesigensi [11]).

It is acknowledged that rapid development in emerging economies or developing countries is largely responsible for current increasing carbon trends in the global buildings and construction sector [12], [13]. Huang et al. [14] identified that these countries are responsible for 60% of global construction sector carbon emissions, with China being the most prominent contributor. Further, a study done by Yokoo et al. [15] identified that the EC fraction of developing countries is comparatively high due to the extraction and consumption of large quantities of materials and products in these new developments. Thus, EC impacts of buildings in developing countries cannot be overlooked any longer, and it would be prudent to advocate appropriate measures at the earliest possible stage, to facilitate a reduction in EC emissions in developing countries while they continue their development activities.

Sri Lanka is among the fastest developing countries in the Asian region. Its total built floor area is being rapidly increased through development and construction. The growth of high-end residential housing, high-rise buildings and condominiums, commercial office spaces, hospitals, schools and universities, and hotels is mainly due to rapid economic development, associated with: urbanization; increased demand for residential property from the nation’s wealthy and middle-class populations; growing demand for office and commercial spaces from local and foreign corporates; and increasing interest in the country as a tourist destination [16]. Regardless of this rapid development in the Sri Lankan building sector, there is also an appetite for energy-efficient buildings, yet, as with other developing countries, the primary focus is on the reduction of operational carbon (OC) as a means to achieve this, with EC aspects being largely overlooked [17], [18], [19].

It is apparent that EC estimation is one of the main ways to facilitate carbon reduction efforts. Estimation makes it possible to report actual emissions, compare alternatives, develop and deliver the lowest life carbon solutions, and manage performance; without estimation, it would be difficult to inform policy and scope, and influence decision making [20]. Compared to OC, undertaking quantification of the EC impacts of buildings is complex and challenging. Therefore, in many studies, a Life Cycle Assessment (LCA) approach has been adopted to estimate EC, as this enables the thorough assessment of environmental impacts at various stages in the life cycle of a building [21]. However, only a few building LCA studies have been conducted to date in the Sri Lankan context, and the available quantitative information is limited [8]. This paper presents the results of an EC assessment conducted on twenty office building case studies in Sri Lanka, in order to highlight lessons learned and provide some practical indications on EC reduction strategies to optimise buildings. It is anticipated that this research will provide more quantitative data, enabling decision makers to develop policies, regulations, and strategies to reduce the EC of buildings in Sri Lanka.

Abbreviations

BIM	Building Information Modelling
BOQ	Bill of Quantities
EC	Embodied Carbon
EE	Embodied Energy
EPDs	Environmental Product Declarations
GIFA	Gross Internal Floor Area
ICE	Inventory of Carbon and Energy
I-O	Input-Output
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life cycle Impact Assessment
OC	Operational Carbon
OE	Operational Energy

2. Literature review

2.1. Estimating the embodied carbon of construction projects

Life Cycle Assessment (LCA) is the most refined and well-established methodology used for assessing environmental impacts associated with buildings at present [22]. It provides a methodological framework for estimating and evaluating environmental impact throughout a product or service system life cycle from cradle to gate [23]. It makes the estimation process less complicated, and as a result has been extensively used in the energy and carbon estimation of buildings. The International Organisation for Standardisation (ISO-14040, 2006) [24] codifies LCA into four separate phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. Rashid and Yusoff [25] proposed an LCA framework for the building industry adapted from various published research papers (see Figure 1).

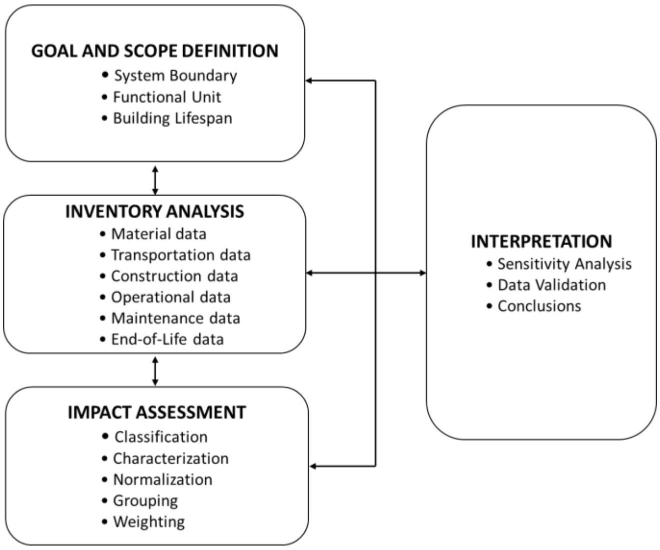

Figure 1: LCA framework for the building sector (Source: Rashid and Yusoff [25] and ISO [24])

Defining the purpose of the study, including system boundaries and functional units, is critical in the first phase of any LCA application, regardless of the subject, as the outputs of the LCA are sensitive to the model and to assumptions adopted to simulate the system around the process, product or service under investigation. This minimises the risk of misinterpretation and/or misuse of LCA results [22]. Buildings are unique products that differ comprehensively from controlled industrial processes [26]. Owing to buildings' long life span, use of many different materials and processes, the unique character of each building, evolution of functions over time, maintenance and retrofitting etc., LCA studies in the existing literature have bound to different goals and scopes, with certain limitations [25], [27], [28], [29]. Pomponi and Moncaster [30] demonstrates that most life cycle assessments at the building scale still include only 20%-40% of life cycle stages, and often focus on the production stage. Similarly, most of the studies related to EC estimation in the existing literature have also been limited to the production stage or the cradle to gate system boundary; for many construction products, data on their impacts after they have left the factory gate is absent [30], [31].

The second phase of any LCA is the creation of a Life Cycle Inventory (LCI), which includes flows of the resources (materials and energy inputs) and externalities (releases to air, land, and water) involved with the product being assessed [22]. Developing an LCI is a time- and resource-consuming activity that requires expert knowledge and a lot of primary data. Inventories or databases have been developed to provide EC coefficients of construction materials, in order to facilitate EC impact estimation. Examples include the Inventory of Carbon and Energy (ICE), EcoInvent 3.3, GaBi, Athena Life Cycle Inventory Product Database, Hutchins UK Building Black book, ÖKOBAUDAT (German National Database), and AusLCI. In addition, environmental product declarations (EPDs) provide an alternative way of finding out EC coefficients of building materials or products [22].

Life Cycle Impact Assessment (LCIA) is the third phase, which uses data from LCI and subsequently evaluates the potential environmental impacts and estimates the resources used in the study. Despite the lack of agreement on the most appropriate methodology for EC assessment of buildings and construction, several methodologies have been well documented. Several standards, guides, and schemes have been developed on how to carry out an EC impact assessment, including: BS EN 15643-2:2011; Sustainability of Construction Works - Sustainability Assessment of Buildings; assessment guidance issued by professional bodies such as RICS [32] & [33], RIBA [34], and UKGBC [35]; and publications by international teams of researchers, such as those who worked on the International Energy Agency Annex 57 [36]. The complicated and time-consuming nature of these EC estimation procedures has led to the development of computer tools to estimate embodied and whole life carbon over the last few years. EC3, SimaPro, One Click LCA, Tally, Athena Eco Calculator, and Athena Impact Estimator and Building for Environmental and Economic Sustainability (BEES) are among the most widely used software tools. Although there are many similar tools, the literature reveals that some of them are not transparent, up to date, or freely available [37].

The last phase of the LCA is interpretation, which identifies significant issues, assesses results in order to reach conclusions, explain the limitations, and provide recommendations relating to the assessment being carried out.

2.2. Status of EC estimation and reduction in Sri Lanka

In response to increasing carbon emissions from the buildings and construction sector, the Sri Lankan government has introduced several initiatives such as building codes, certification policies, standards, projects, and programmes. A summary of these initiatives is shown in Table 1.

Table 1: Initiatives aiming at carbon reduction in buildings in Sri Lanka

Initiative	Purpose	Implementation requirement

Code of Practice for Energy Efficient Buildings [38]	To introduce energy-efficient design and/or retrofits to commercial buildings, industrial facilities and large-scale housing complexes to enable design, construction and maintenance to be carried out under minimal energy consumption without compromising the building's function and/or the comfort and health of occupants	- Voluntary - Currently under review - New code is expected to be mandatory for buildings within its scope
Guideline for Sustainable Energy Residences [39]	To provide essential knowledge and approaches to develop design concepts for small- and medium-scale residences with low energy use. It delivers energy-efficient and sustainable strategies to maintain thermal comfort (shading, ventilation, and materials), integrate lighting and daylight, incorporate solar energy, and optimise water usage	Voluntary
Green building rating certification programmes - Green SL rating system [40] - Green Mark [41] - Building Research Establishment Environmental Assessment Method (BREEAM) [42] - Leadership in Energy and Environmental Design (LEED) [43]	To increase awareness of building performance in the property market and to attract tenants or buyers who are interested in sustainable high-performance buildings	Voluntary
Product labelling schemes - Green SL labelling system [44] - CIOB certification for green building products [41]	To evaluate building products that are manufactured in Sri Lanka for their environmental impact and performance	Voluntary
ISO 50001:2011 Energy Management Systems [45]	To encourage industrial and commercial facilities owners to maintain and improve energy performance, while improving operational efficiencies, decreasing energy intensity, and reducing environmental impacts	Voluntary
Energy Efficiency Labelling Programme [46] - Compact Fluorescent Lamps (CFL) - electric ceiling fans - magnetic/electronic ballasts	To encourage the manufacture and purchase of energy efficient electrical appliances	Mandatory

- double capped tubular fluorescent lamps - LED		Voluntary
Clean energy programmes such as "*Suriya Bala Sangramaaya*" [47]	To promote and implement generation of electricity and heat from renewable sources such as solar, wind, allowing the building and construction sector to reduce indirect carbon emissions	Voluntary

Careful examination of these initiatives reveals that their focus is primarily on operational energy (OE) efficiency (energy used by means of electricity, gas, steam, or fuel to operate building through processes like heating/cooling, lighting, ventilation) and reducing the OC of buildings, suggesting that the importance of EC reduction as a part of the whole building life cycle carbon reduction has not yet been fully realised. Other than promoting the selection of low EC materials, such as high recycled content materials, local materials, rapidly renewable materials, certified wood and green labelled products as an EC reduction strategy in green buildings, it remains difficult to identify any other measures used in the Sri Lankan buildings and construction sector to reduce EC in buildings, and EC remains an under-established concept there. Other than limited research, no standards, policies, or measures have been developed to reduce the EC of buildings in Sri Lanka. Kumanayake and Luo [8], Kumanayake et al. [9], Jaywardana et al. [48] Kumanayake et al. [49], and Nawarathna et al. [19] have conducted studies to assess the EC content of carefully selected buildings. All these studies have followed a LCA methodological framework but were confined to different estimation procedures, based on the availability and accessibility of data. Kumanayake et al. [17] and Nawarathna et al. [50] have introduced two conceptual methodologies to estimate EC in the Sri Lankan context, and Pooliyadda [51] has carried out work to assess the embodied energy (EE) (energy associated with extraction of raw resources, processing materials, assembling product components, transportation, construction, maintenance and repair, deconstruction and disposal of materials) and related EC content of widely used building materials in Sri Lanka. Jayasinghe [52] and Udawaththa and Halwatura [53] have also conducted investigations around selected building materials, but their contents have been limited only to EE content. Reasons for the slow uptake of EC estimations have been investigated by Nawarathna et al. [18], and the perceptions of building professionals on EC strategies have been examined by Abeydeera et al. [54]. This indicates a prominent flaw in research and practice in estimating and reducing the EC of buildings in Sri Lanka. More EC impact assessment studies are needed to provide more quantitative data in order to inform decision makers and policy makers on the importance of EC reduction, so that EC mitigation policies, regulations, and strategies may be introduced.

3. Methodology

This section provides an overview of the methodology adopted in the study. Conforming to the LCA approach explained in section 2.1, this study followed the LCA methodological framework, which included goal and scope definition, inventory analysis, impact assessment, and interpretation in estimating the EC impacts of twenty office buildings in Sri Lanka. Following an overview of selected building cases in section 3.1, the LCA phases are discussed in subsequent sub-sections.

3.1 Overview of building cases

The growing demand for office space in Sri Lanka dictated the choice of office buildings as the focus of this study. With the support of several quantity surveying consultancy and contractor practices in Sri Lanka, bill of quantities (BOQ) and architectural drawings of a convenience sample of 20 office building projects were collected as data sources to represent, albeit through non-probability means, office buildings in Sri Lanka. An initial target of gathering details of 30 buildings was not possible due to confidentiality issues regarding client data and missing information in some potential projects. All the buildings in this sample were of concrete frame construction. Data on the materials and quantities used in the buildings were extracted from the BOQ, while key design parameters such as Gross Internal Floor Area (GIFA), total height, and the number of stories were taken from architectural drawings. Buildings were designated as either low-, medium-, or high-rise based on the number of stories, for the purpose of analysis. Buildings with 1-3 stories were categorised as low-rise buildings, those with 4-11 stories were medium-rise, and those with 12 stories and above were deemed to be high-rise buildings. Of the 20 buildings, eight buildings were low-rise, another eight were medium-rise, and four were high-rise buildings. Table 2 provides details on the 20 buildings.

Table 2: Basic information on the building cases

Case study	Building structure	No. of stories	GIFA(m^2)	Total height (m)	Building category
CS-1	Concrete frame	4	2,629.26	19.02	Medium-rise

CS-2	Concrete frame	3	3,100	16.75	Low-rise
CS-3	Concrete frame	4	1,245	17.00	Medium-rise
CS-4	Concrete frame	4	1,916	17.15	Medium-rise
CS-5	Concrete frame	6	3,918	22.95	Medium-rise
CS-6	Concrete frame	3	4,300	11.90	Low-rise
CS-7	Concrete frame	1	284	5.10	Low-rise
CS-8	Concrete frame	2	510	13.25	Low-rise
CS-9	Concrete frame	4	1,786	17.95	Medium-rise
CS-10	Concrete frame	7	5,288	26.37	Medium-rise
CS-11	Concrete frame	16	14,361.30	58.60	High-rise
CS-12	Concrete frame	3	1,110	13.10	Low-rise
CS-13	Concrete frame	2	560	8.12	Low-rise
CS-14	Concrete frame	15	18,172	63.18	High-rise
CS-15	Concrete frame	17	23,033.45	64.20	High-rise
CS-16	Concrete frame	2	1,181	8.70	Low-rise
CS-17	Concrete frame	13	10,151.62	46.10	High-rise
CS-18	Concrete frame	4	8,300	13.20	Medium-rise
CS-19	Concrete frame	7	12,539	28.20	Medium-rise
CS-20	Concrete frame	3	1,000	12.00	Low-rise

3.2 Defining the goal and scope

The goal of this study was to present, evaluate and discuss the EC assessment methodology and the assessment results drawn from twenty office building case studies in Sri Lanka. The scope of the assessment included the boundaries of building development stages, building elements and the building life cycle stages. Figure 2 demonstrates the scope of the study. The building development stages were defined according to the RIBA plan of work [55]. The selected sample buildings were in different development stages, ranging from the design development to the in-use stage. The estimation was therefore bounded by design development to the in-use stage of buildings. As the purpose of this assessment was mainly to investigate the EC content of buildings and to identify key contributing elements to EC emissions, the estimation stage did not affect the final output. However, if an assessment was to be focused on reducing EC, it is recommended to carry out the assessment during the early design stage of buildings so that there are more opportunities to reduce the EC through analysis, decision making and action.

The elemental boundary was defined as the structural elements which cover the skeleton of a building. It included substructure, frame, upper floors, roof, stairs and ramps, external walls, internal walls and partitions. These elements were defined in compliance with the building cost information service (BCIS) element classification developed by RICS [32]. Even though it is crucial to account for all the elements and stages of a building life cycle to get a representative EC value of a building, the lack of availability of required data limited the estimation of this study to structural elements. The boundary of the building life cycle was limited to the product stage of a building, which is known as the cradle to gate (raw material extraction to production of building materials) boundary level, mainly because the EC coefficient database which was used for this study was limited to that boundary level. The building life cycle stages were defined as per BS EN 15978:2011 Sustainability of construction works- Assessment of environmental performance of buildings- Calculation method.

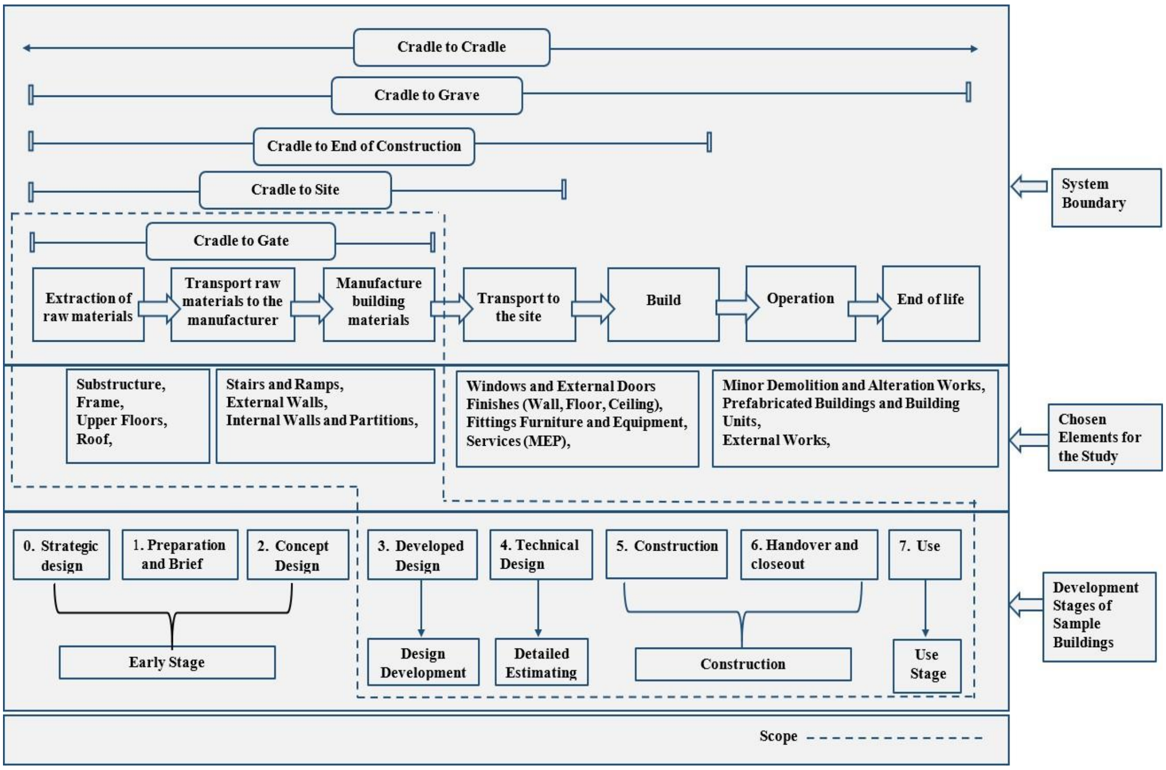

Figure 2: Scope of the study

3.3 Life cycle inventory analysis

In this study, the analysis was based on the Inventory of Carbon and Energy (ICE) version 3.0 developed by Jones and Hammond [56]. Although the EC coefficients of building materials vary from one country to another depending on factors such as raw materials used, material production technologies, energy sources and quality of energy, the lack of availability of an up-to-date country-specific EC coefficient database led the researchers to choose ICE to extract EC coefficients for building materials or products used in the selected elements of sample buildings. Unlike other databases, such as Athena LCI, Hutchins UK Building Black Book, EcoInvent 3.3, and AusLCI, which are either country- or region- specific and have restricted access, ICE is an open-access database that has drawn on data from around the globe. Hammond and Jones [57] suggest that in the absence of country-specific data, as is the case in Sri Lanka, this can be used as 'proxy data'.

3.4 EC impact assessment

In this phase, the EC impacts of buildings were measured using the results of LCI analysis. The EC estimation process introduced by RICS [58] and presented in Figure 3 was adopted in this study. Although numerous software tools have been developed to make the EC estimation process easier (see section 2.1), assessment in this study was conducted manually, due to capability and functional limitations, and the license requirements of those tools.

Accordingly, the key materials and the quantities used in each element were identified using the BOQ. The quantities of various units, such as square meters (m^2), cubic meters (m^3), tons (t), and meters (m), were converted to mass in kilograms (kg) to maintain consistency throughout the estimation. The material quantities were multiplied by the EC coefficient of each material referenced in ICE version 3.0. The EC values of all materials in each element were then totalled to identify the elemental EC. Elemental EC values were added together to arrive at the EC of the building skeleton. The EC impact results were presented as EC in $kgCO_2e$ and EC in $kgCO_2e$ normalised per m_2 of gross floor area ($kgCO_2e/m^2$).

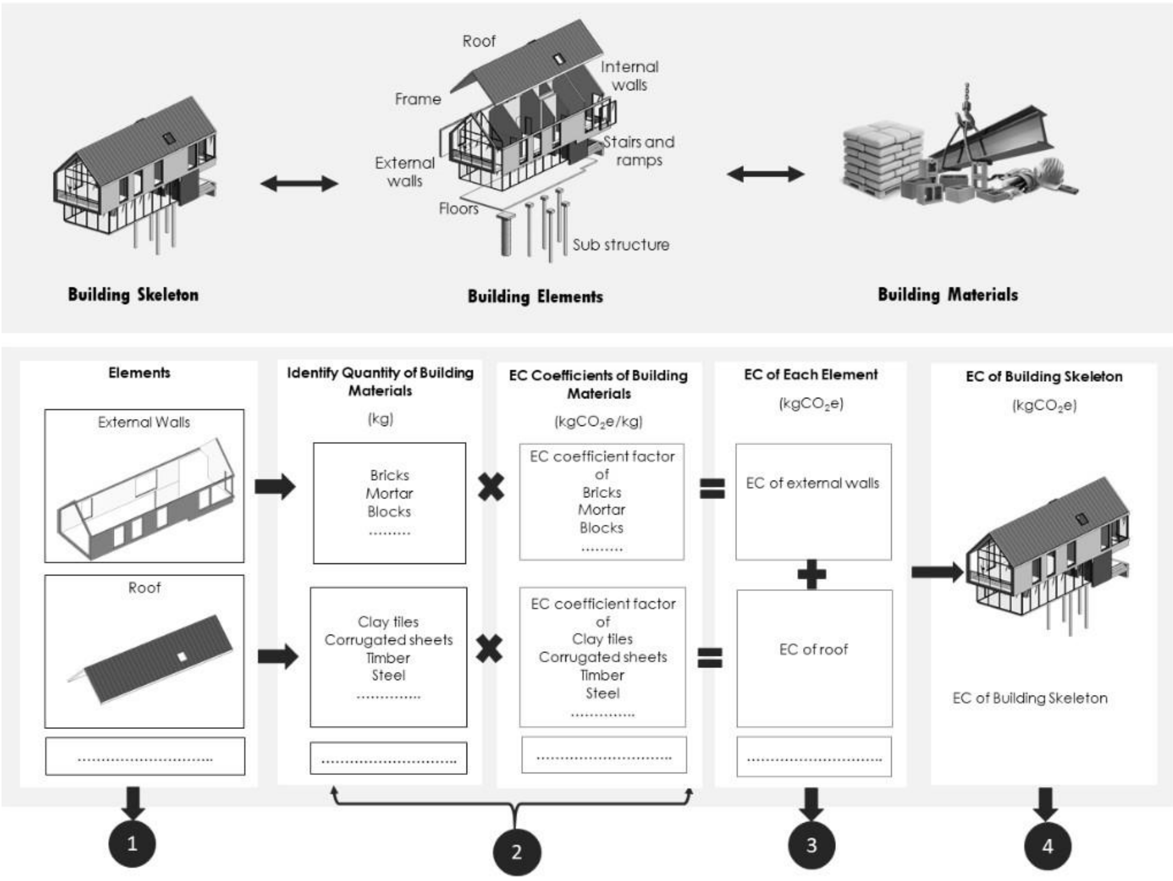

Figure 3: EC estimation process (Adapted from RICS [58])

3.5 Life cycle interpretation

According to ISO 14040:2006, the results of the inventory analysis and impact assessment are summarised during the interpretation phase. Thus, in this phase, a set of conclusions and recommendations were presented within the defined goal and scope of the study.

4. Results and discussion

4.1 Analysis of embodied carbon content of buildings

The results of the EC assessment exercise undertaken for each of the 20 case studies are illustrated in Figure 4. This shows that the EC emissions of low-rise buildings varied from 157,429-1,653,138kg/CO_2e, while mid-rise buildings and high- rise buildings varied from 656,886-6,070,782kg/CO_2e and 3,401,600-13,177,410 kg/CO_2e, respectively. To identify an average EC value for each building category, EC dispersions were displayed via a box plot, as in Figure 5.

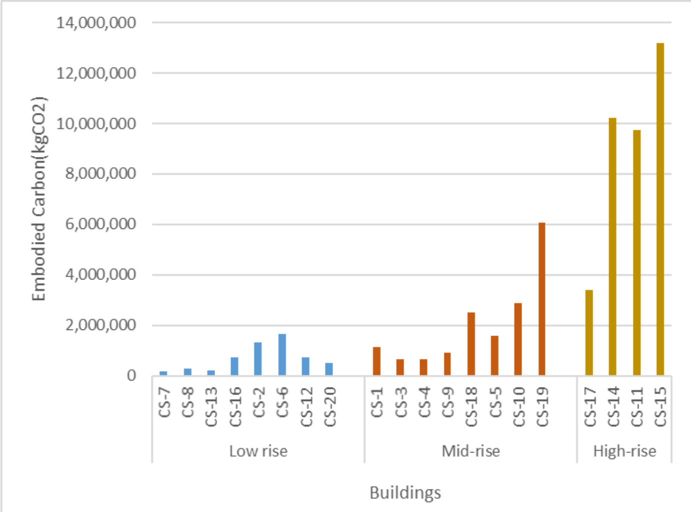

Figure 4: EC contents of 20 building cases

The box plot indicates the central tendency (mean and median), as well as the outliers of these three categories. The central tendency values of these three categories showed a considerable difference, due to the non-normal distribution of the data for EC values. When data are not normally distributed, the mean is particularly susceptible to the influence of outliers, and in this instance, it did not accurately reflect the average EC of each building category. The median is less affected by outliers and skewed data and was therefore considered to represent the best central tendency, indicating an accurate average EC value for each category. The average (median) EC of each building category valued at 613,965 kg/CO_2e (low rise), 1,351,734 kg/CO_2e (medium-rise) and 9,978,936 kg/CO_2e (high- rise). Among the three data sets, only the data set of medium-rise buildings showed as an outlier, and this was attributed to the CS-19 building case, in which EC content was considerably higher than that of other buildings due to its substantially large GIFA. Generally, the boxplots varied in their shapes depending on whether cases tended to be high or low in relation to the median. In Figure 5, the box and the median of low-rise buildings were closer to the bottom end of the data distribution, suggesting less variation among EC values of buildings below the median and more variation above the median. Similarly, mid-rise buildings indicated less variation below the median and more variation above the median line. However, in high-rise buildings, both the box and the median were closer to the top end of the distribution, suggesting less variation among the EC values of buildings above the median and more variation of those buildings below the median line.

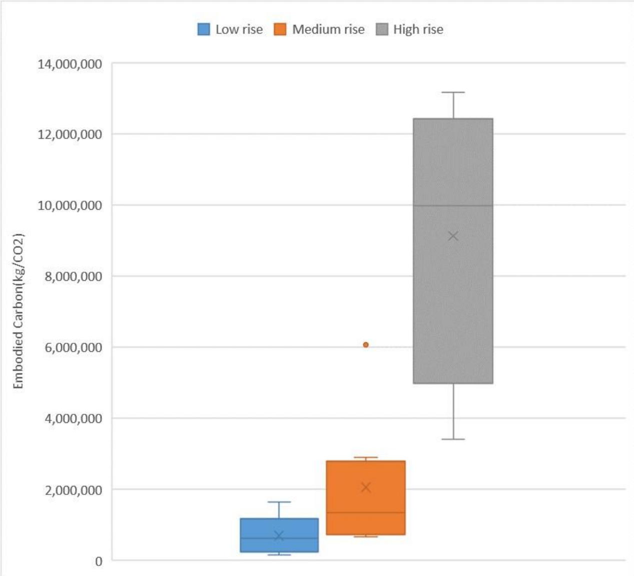

Figure 5: Box plot indicating the EC dispersion of low, medium, and high-rise buildings

EC contents were normalised in terms of the total values per square metre of the overall GIFA of each building ($kgCO_2e/m^2$) to allow for better comparison across the studies. This is illustrated in Figure 6. Accordingly, the EC per GIFA of low-rise buildings ranged from 384.45-674.72$kgCO_2e/m^2$. The medium-rise buildings varied from 304.29-547.44$kgCO_2e/m^2$ and high-rise buildings varied from 335.08-677.39$kgCO_2e/m^2$.

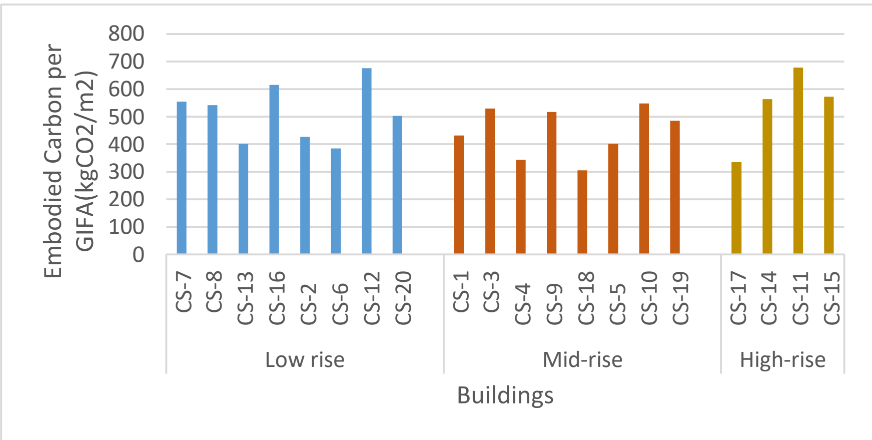

Figure 6: EC per GIFA of case buildings

The box plot in Figure 7 again shows the central tendency of each category. Here, the mean and median value of each dataset showed less difference, indicating that the distribution of EC per m^2 of each building category was less skewed and more normally distributed. However, the average EC per m^2 of each building category against the median was considered the most appropriate measure for use. The average EC per m^2 of the low-, medium-, and high-rise buildings were 522.18, 457.85, and

567.51kgCO2e/m², respectively. These results reveal that average EC per m^2 of all three building categories were within a similar range and showed no considerable differences. This is likely because all of the buildings were considered to be conventionally constructed ones with concrete structures, made from typical building materials. The results show that the average EC of medium-rise buildings was less than that of low-rise buildings. However, it must be highlighted that the results were based on real-time data and as mentioned in section 2.1, buildings are unique products that have unique characteristics and use different types of materials in differing quantities, depending on their purpose, geographical location and occupancy level.

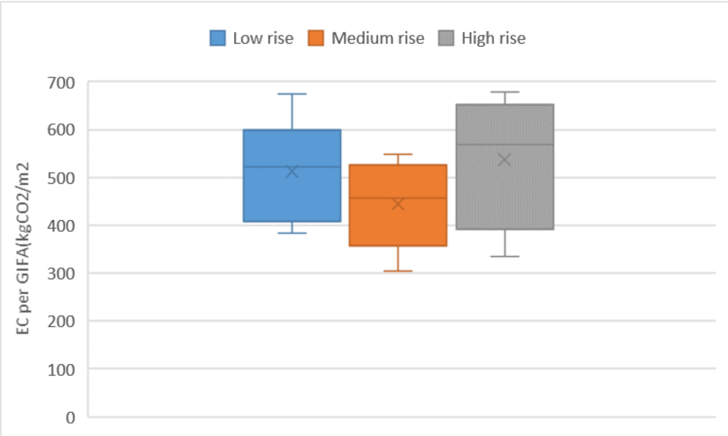

Figure 7: Box plot indicating the dispersion of EC per GIFA of low-, medium-, and high-rise buildings

4.2 Comparison of results in relation to embodied carbon

Comparison between EC studies is not straightforward, as the scope and system boundaries may vary between studies. Although it is difficult to draw definitive conclusions, Table 3 provides a comparison of the EC contents of office buildings in Sri Lanka with previously conducted EC assessments for office buildings worldwide. To ensure consistency across the comparison, where the case studies may have used different definitions of system boundaries and included different levels of detail based on the available data, studies conducted at the building production stage (cradle to gate) were chosen as a common basis.

The comparison revealed a significant discrepancy among the EC contents of case studies. Most of the comparator studies have used process-based LCA, while a few have used input-output (I-O) and hybrid LCA methods, to estimate EC. Using different methodologies with different system boundaries, depending on data availability, is a key reason underlying disagreements between the EC contents of various assessments [21]. De Wolf, Pomponi and Moncaster [37] identify a need for more transparency and better data quality assessment, suggesting that sensitivity analyses and work to resolve uncertainty issues could potentially solve problems relating to non-uniform EC calculations. The same authors go on to suggest that the Green Building Council of each country could disseminate a uniform EC calculation methodology. Dixit et al. [59] also stress that significant variations in EC results among different case studies illustrate inconsistencies in the data used, which come from different sources and countries. De Wolf, Pomponi and Moncaster [37] highlight that the available databases for factors (EC coefficients, transport factors, construction factors, waste factors, etc.) are still inconsistent and sparse and, as a result, the use of outdated or geographically inappropriate data remains commonplace. Sinha, Lennartsson and Frostell [60] emphasise the need for data linked to the location of a project, while De Wolf, Pomponi and Moncaster [37] signify the importance of regulations for mandatory EPD databases to improve the accuracy of EC assessments.

Table 3: Comparison of EC contents of Sri Lankan office buildings with previous studies

Study reference	**Stories**	**Floor area**	**Country**	**Structure**	**Method**	**EC ($kgCO_2$-e/m^2)**
Wan Omar [21]	15	21376	Malaysia	Reinforced concrete	Process LCA	1348.98
	2	1237	Malaysia	Reinforced concrete	Process LCA	987.017
Yokoo et al [15]	Not given	947	China	Reinforced concrete	I-O LCA	761
	Not given	1145	Japan	Reinforced concrete	I-O LCA	566
Victoria, Perera and Davies [61]	8+1 basement	11320	UK	Reinforced concrete/steel	Process LCA	777.92
Chang, Ries and Lei [62]	19-21	49166	China	Reinforced concrete	Hybrid LCA	720.30
Wu, Yuan, Zhang and Bi [63]	13	36500	China	Reinforced concrete	Process LCA	648.63
Wallhagen, Glaumann and Malmqvist [64]	4	3314	Sweden	Reinforced concrete/steel	Process LCA	146.05
Junnila and Horvath [65]	5	15600	USA	Reinforced concrete	Process LCA	279.41
Dimoudi and Tompa [66]	5	1891	Greece	Reinforced concrete	Process LCA	181.43
	3	400	Greece	Reinforced concrete	Process LCA	262.17
Davis Langdon LLP [67]	8	12236	UK	Steel	Process LCA	764
Kumanayake et al. [49]	3+mezzanine	897	Sri Lanka	Reinforced concrete	Process LCA	629.6

Current study	Low-rise (1-3)	284-4300	Sri Lanka	Reinforced concrete	Process LCA	522.18
Current study	Mid-rise (4-11)	1245-12539	Sri Lanka	Reinforced concrete	Process LCA	457.85
Current study	High rise (12 above)	10151-23033	Sri Lanka	Reinforced concrete	Process LCA	567.51

4.3 Identification of key contributors to high embodied carbon intensities

Figure 8 illustrates in detail the proportion of EC accounted for by the different building elements for each case in the three building categories. The elements included substructure, frame, upper floors, roof, stairs and ramps, external walls, and internal walls. As Figure 8 shows, substructure, frame, upper floors and external walls significantly contributed to EC content in all cases except CS-7, in which the upper floor element had been replaced by the roof, as it was a single-story building. Approximately 85-95% of EC was generated from these four elements (See Table 4,5 and 6). These findings agree with previous studies by Victoria and Perera [68] and Wan Omar [21]. These building elements made such a significant contribution to EC due to the large quantities of concrete and reinforcement steel used in them. Concrete and steel are carbon-intensive materials, and consume a significant amount of embodied energy in their production processes [57].

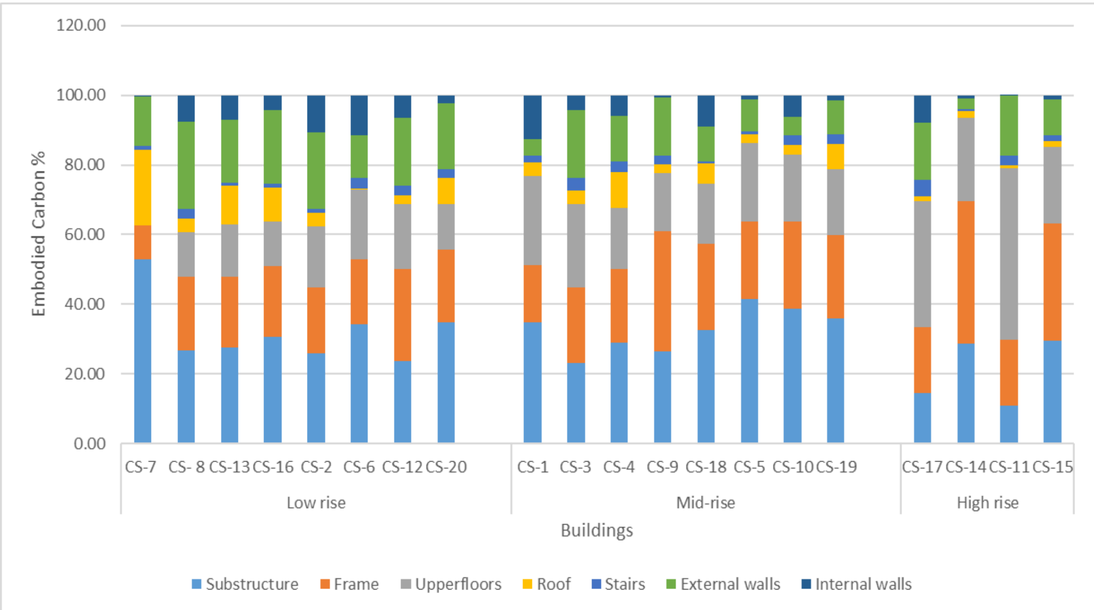

Figure 8: Elemental EC breakdown of case buildings

The hierarchical order of the carbon critical elements of these three building categories did vary, however. Element quantities and material choices were the two main variables contributing to the breakdown of carbon intensive elements [68]. Tables 4, 5, and 6 present the elemental breakdown of each building category in a hierarchical order, subject to the average EC intensities of building elements. The hierarchical order is also graphically illustrated in Figures 9, 10 and 11, to better present the highest and lowest EC contributing elements.

Table 4: Hierarchical order of elements in low-rise buildings

Element	Average EC per GIFA ($kgCO_2e/m^2$)	Element contribution %	Cumulative %
Substructure	164.39	32.08	32.08
External walls	97.60	19.05	51.13
Frame	96.15	18.76	69.89
Upper floors	73.77	14.40	84.29
Roof	39.71	7.75	92.04
Internal walls	30.64	5.98	98.02
Stairs and ramps	10.17	1.98	100.00

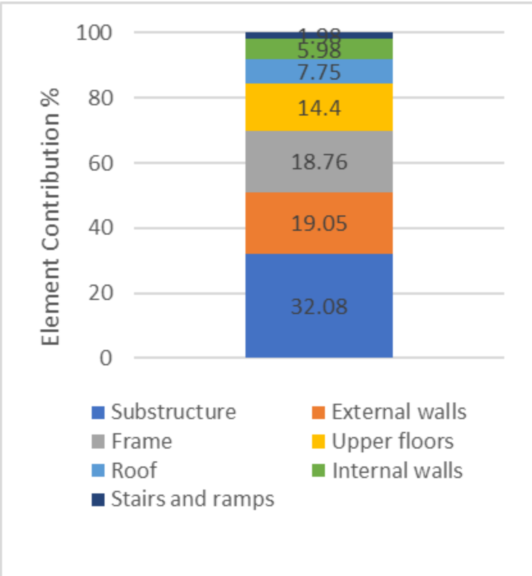

Figure 9: Hierarchical order of elements in low rise buildings

Table 4 and Figure 9 show that substructure, external walls, frame, and upper floors were respectively the greatest EC contributing elements of low-rise buildings. The elemental breakdown of medium-rise buildings is presented in Table 5 and Figure 10, showing that the highest EC contributing elements in order of priority were the substructure, frame, upper floors and external walls. Table 6 and Figure 11 present the elemental breakdown of high-rise buildings, where upper floors, frame, substructure and external walls also made significant contributions to the EC content. The results revealed that the substructure was the highest EC contributing element in low- and medium-rise buildings, whereas the highest EC emitting element in high-rise buildings was the upper floors. High-rise buildings were defined as those with more than 12 stories, and it may therefore be expected that multi upper floor levels would be the highest EC emitters, considering the deployment of large amounts of concrete and reinforcement steel. It was observed that other building elements being studied - the roof, internal walls and stairs, and ramps - made a much smaller contribution to the EC content of all three building categories, accounting for less than 20% of total EC content.

Table 5: Hierarchical order of elements in medium-rise buildings

Element	Average EC per GIFA ($kgCO_2e/m^2$)	Element contribution %	Cumulative %
Substructure	145.07	32.65	32.65
Frame	106.42	23.95	56.61
Upper floors	90.43	20.35	76.96
External walls	49.76	11.20	88.16
Internal walls	21.68	4.88	93.04
Roof	20.19	4.54	97.58
Stairs	10.73	2.42	100.00

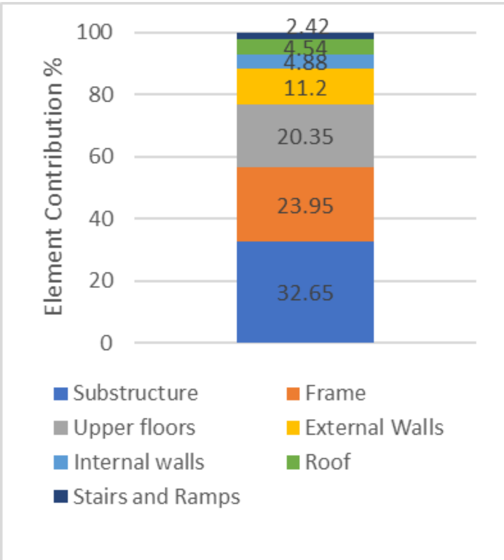

Figure 10: Hierarchical order of elements in medium-rise buildings

Victoria and Perera [68] categorised these elements variously as occupying 'lead', 'special' or 'remainder' positions, based on their carbon intensity. They categorised substructure, frame and external walls as occupying the 'lead positions'; these need to be given the highest priority during design due to their high carbon intensity, and their design should be carefully considered during the concept stage, where the most effective EC savings may be made. Upper floors and the roof were categorised as having 'special positions', thus also requiring careful attention during the concept design stage, for similar reasons. However, in the current study, the roof was identified as occupying a 'remainder position' along with internal walls and stairs and ramps, as these were estimated as generating lower contributions. According to Victoria and Perera [68], remainder positions can be given the lowest design priority, and may be addressed throughout the detailed design and technical design stage of a building.

Table 6: Hierarchical order of elements in high-rise buildings

Element	Average EC per GIFA ($kgCO_2e/m^2$)	Element contribution %	Cumulative %
Upper floors	178.28	33.21	33.21
Frame	153.34	28.56	61.77
Substructure	113.49	21.14	82.91
External walls	61.81	11.51	94.42
Stairs	11.55	2.15	96.57
Internal walls	10.22	1.90	98.48
Roof	8.18	1.52	100.00

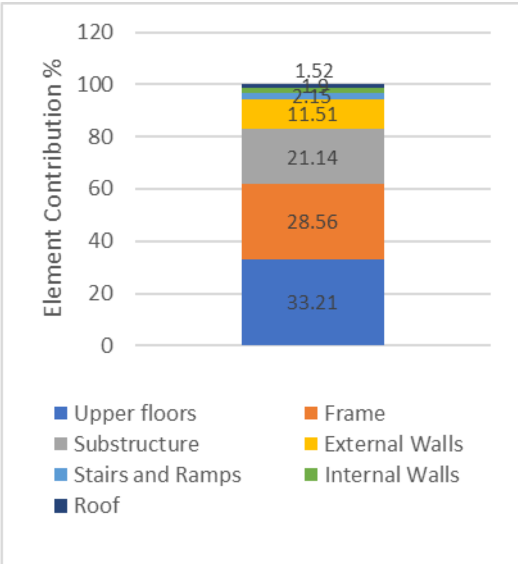

Figure 11: Hierarchical order of elements in high-rise buildings

Building designers generally have more opportunities to reduce EC during the early design and design stages of buildings, by reducing material consumption, minimising waste, specifying higher recycled content, and allocating alternative materials with lower EC content [69], [70]. Previous research has revealed that EC can be significantly reduced by considering optimization designs for structural systems and members and changing the materials and thickness dimensions [7], [71], [72]. Zhang and Wang [7] state that by using high-strength concrete and steel, it is possible to reduce the thickness of these elements, and thereby reduce EC. Victoria and Perera [68] suggest that emission reductions in structural elements such as substructure, frame, upper floors and roof may be achieved through using recycled concrete or steel, light pre-fabricated elements, pre-used materials, and low-energy intensive materials and operations, while the EC of façades can be reduced using recycled glass and low carbon façades, such as bio-based materials.

4.4 Improvements to the design workflow management of buildings

The results of the literature review indicated that a significant amount of a building's carbon can be locked into the structure, and is often unregulated and unaccounted for, while architectural design practices and professionals still focus more on reducing OE in their attempts to reduce carbon. While undertaking EC estimation is labour intensive, and might be conducted at a later stage of the design or on already constructed buildings, the consideration of EC can contribute to and encourage positive benefits on long-term thinking by design teams, in which the whole lifetime, and therefore the longevity and future uses of an asset are taken into consideration [73]. A focus on undertaking EC calculations can also support policy change and priorities besides carbon, such as the creation of benchmarks for EC, use of building components with recycled content, waste reduction targets and moves towards cleaner fabrication and offsite manufacturing. The findings of this research indicate the need for greater automation and industrialisation in the design process and the application of the principles of construction 4.0 [74], which require the transformation of the construction industry towards the 4th industrial revolution, from automated production to a greater level of digitalization. EC needs to be integrated into frameworks such as Building Information Modelling (BIM) for better life cycle analysis [75], and applying modern methods of construction overall, utilising BIM, as we move forward with carbon accounting [76] may be a key way to identify material impact.

5. Conclusions

This research set out to present, evaluate and discuss the results of an EC assessment drawn from twenty office building case studies in Sri Lanka. The office buildings were categorised as either low-, medium-, or high-rise and were assessed in terms of the average EC content of different building categories, enabling the identification of key contributing elements to EC values. The assessment followed an LCA approach, which has been established as the best-practice approach to assess the environment impact of products, processes, or services. The findings revealed that the average EC per m^2 of low-, medium- and high-rise buildings were 522.18, 457.85 and 567.51kgCO2e/m^2 respectively. The medium-rise buildings category indicated a lower average EC content than low-rise buildings, which was unexpected, but remains plausible as these results were derived from the real time data obtained.

The findings revealed that the substructure was the highest EC contributing element in low- and medium-rise buildings, whereas the highest EC emitting element in high-rise buildings was the upper floors. Regardless of building category, the substructure, frame, upper floors, and external walls were key EC contributors, contributing about 85-95% of total EC. These elements were identified as carbon significant elements within this sample, which have a high potential to contribute to reducing the EC of buildings during the early design stage of buildings via effective design alternatives, changing materials and thickness dimensions. The internal walls and partitions, stairs and ramps, and roof were identified as being carbon insignificant elements, whose total contribution was less than 20% of the EC of buildings. These elements were identified as being addressable at the detailed design and technical design stage of a building, to reduce EC.

The scope of this research was limited to the building production phase and the structural elements of buildings, due to the availability and accessibility of relevant data. Future research should consider including the whole building life cycle and all elements of a building, to achieve a more fully representative value of EC. EC coefficients of building materials were taken from ICE V 3.0, in the absence of a national database which may have provided more reliable results; however, it is considered to have provided useful results and conclusions. Regardless of the relatively small sample size, the study findings agreed with most of the literature findings, with the exception of the hierarchical position of roofs. All of the buildings chosen were reinforced concrete structures, representing low-, medium-, and high-rise buildings, and it is considered that the findings can be generalised to a wider context. Despite the limitations mentioned, the study employed a transparent and robust EC estimation method that can be adapted by researchers and practitioners to identify EC carbon content and the key contributing elements to the total EC, not only for office buildings, but also different building types. This study has provided a unique insight into the importance of EC estimation and reduction in developing countries where the building sector is rapidly growing, and the impact of carbon emissions could be devastating to vulnerable sections of the population. Importantly, the findings provide quantitative data that can inform building designers and policy makers in the buildings and construction sector about which aspects of buildings hold the most significant EC reduction potential. This study is part of a longer-term programme of study, and further work will include developing a statistical tool to assess embodied carbon during the early design stage of buildings in Sri Lanka.

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