QUANTITATIVE STUDY OF EMBODIED CARBON IN THE HOUSING DEVELOPMENT PROJECT

JORDAN TING CHAO JIEN

A project report submitted in partial fulfilment of the requirements for the award of the degree of Bachelor of Civil Engineering (Environmental) with Honours

Faculty of Engineering and Green Technology
Universiti Tunku Abdul Rahman

April 2024

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

Signature : ____________________

Name : Jordan Ting Chao Jien

ID No. : 1903995

Date : 08 May 2024

APPROVAL FOR SUBMISSION

I certify that this project report entitled **"QUANTITATIVE STUDY OF EMBODIED CARBON IN THE HOUSING DEVELOPMENT PROJECT"** was prepared by **JORDAN TING CHAO JIEN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Civil Engineering (Environmental) with Honours at Universiti Tunku Abdul Rahman.

Approved by,

Signature : ______________________

Supervisor : ChM. Ts. Dr. Tan Kok Weng

Date : 08 May 2024

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ABSTRACT

In Malaysia, the carbon emission from construction sector is not emphasized significantly. However, the carbon emission from the buildings can take up to 39 % of overall global energy-related carbon emissions and contributed by a broad range of stakeholders. Thus, it could be difficult to track and control the carbon footprint in buildings. This study aims to provide a comprehensive understanding on the quantitative study on indirect energy-related emissions, so called embodied carbon in housing development projects using Life Cycle Assessment (LCA) method, and present appropriate solutions for decreasing the embodied carbon. This research is conducted based on a gross floor area with 92.903 m^2 of residential building project in Malaysia. It addresses the challenges faced by Malaysian construction industry in embodied carbon emissions. The embodied carbon within cradle-to-site of the studied building was calculated and reported instead of on-site waste generation. The result shows that a single unit of residential buildings accounted for 68.60 tCO_2e (0.738 tCO_2e/m^2). Embodied carbon released from the material manufacture was consisted by steel (38.12 %), bricks (15.26 %), and concrete (14.16 %). The findings declare that the embodied carbon could be lowered down using low carbon concrete and material minimization through recycling and reuse. In addition, the local material sourcing within distances of 200 km could reduce 11 % of the EC from the material transportation. However, government policy is the crucial key to adopt carbon assessment across the construction industry and make the data collection easier for implementing carbon reduction strategies effectively. The outcome of this study can be used as the reference for Malaysia’s construction companies to start an early embodied carbon assessment. The developed LCA analysis framework may improve residential buildings’ embodied carbon assessment.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS / ABBREVIATIONS

CO_2e	carbon dioxide equivalent
EC	embodied carbon, $kgCO_2e$ or tCO_2e
ECF	embodied carbon factors, $kgCO_2e$/kg
kg	kilogram
kWh	kilowatt per hour
m	meter
m^2	square meter
m^3	cubic meter
t	tonne
TEF	transport emission factors, $kgCO_2e$/kg/km

BIM	Building Information Modelling
BoQ	Bill of Quantity
CCKP	Climate Change Knowledge Portal
CIDB	Construction Industry Development Board
CITP	Construction Industry Transformation Programme
CMIP	Coupled Model Inter-comparison Project
CML	Institute of Environmental Sciences
CoV	Coefficient of Variation
CRU	Climate Research Unit
DESNZ	Department for Energy Security & Net Zero
DOSM	Department of Statistic Malaysia
EC	Embodied Carbon
EE	Embodied Energy
EIA	Environmental Impact Assessment
EN	Euro norm
EPD	Environmental Product Declaration

EPU	Economic Planning Unit
ESG	Environmental, Social, Governance
GDP	Gross Domestic Product
GEV	Generalized Extreme Value
GFA	Gross Floor Area
GHG	Greenhouse Gas
GIFA	Gross Internal Floor Area
GWP	Global Warming Potential
HLCA	Hybrid Life Cycle Assessment
IBS	Industrialized Building System
ICE	Inventory of Carbon and Energy
IEA	International Energy Agency
I-O	Input-Output
IOA	Input-Output Analysis
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MET	Malaysian Meteorological Department
MyCREST	Malaysian Carbon Reduction & Environmental Sustainability Tool
NC	National Communication
NRECC	Natural Resources Environment and Climate Change
OC	Operational Carbon
PAS	Publicly Available Specification
SME	Small-medium sized Enterprise
TC	Technical Committee
UNFCCC	United Nations Framework Convention on Climate Change
VCM	Voluntary Carbon Market

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Overview

Since the 1800s, the commencement of global emissions marked the onset of the first Industrial Revolution. Recognized as the most crucial revolution in human history, it exerted a profound influence on people's daily lives, encompassing both economic and quality-of-life dimensions but the environmental impacts of the Industrial Revolution cannot be overlooked. This revolution was said to be the driver of climate change due to its dependence on fossil fuels like natural gas, coal, or oil. Also, climate change is characterized as the long-term alterations in weather conditions, and temperature patterns. The impacts of climate change are diverse, which include rising sea levels, more severe extreme weather events like heatwaves, and droughts, disruptions in precipitation patterns, etc.

Particularly, human activities are the main donor in causing significant greenhouse gas (GHGs) emissions and excessive waste in landfills. Among the GHGs, specifically for carbon dioxide (CO_2), it captures heat from the sun and contributes to a phenomenon called the greenhouse effect. Additionally, carbon emissions, primarily consisting of carbon dioxide (CO_2), are a form of GHG emissions (IPCC, 2021). The accumulated GHG emissions boosts the ramifications of climate change, resulting in global warming. This phenomenon poses significant threats to both the fulfilment of sustainable development goals and human survival. In order to tackle the global issue of climate change, a legally binding international treaty was proposed, known as the "Paris Agreement". Since Malaysia ratified Paris Agreement on 16th November 2016, Malaysia increased its mitigation ambition with the goal of a 45 % reduction in carbon intensity in relative with the GDP by year 2030 from the carbon intensity levels in year 2005.

Energy, industry, transportation, buildings, agriculture, and land development are the key sectors to emit greenhouse gases. According to the 3rd National Communication (NC) to UNFCCC, Malaysia declared that GHGs emissions contributed by the construction sector is not evaluated separately, instead, they are gathered independently as an aggregate among several sources, this includes the industrial procedures used in the production of building supplies and energy consumption of the buildings. A sectoral GHGs assessment towards the value chain in the construction sector is recommended as to ascertain the best mix of mitigation solutions given the laws, plans, and programs already in place. This assessment would provide a better understanding of the emissions generated at different stages of the construction process in Malaysia. Yet, specific mitigation measures that align with Malaysia's goal under the Paris Agreement can be prioritized.

According to Wang et al. (2018), buildings account for one third of all worldwide energy-related carbon emissions, accounting for 39 % of direct and indirect emissions. Basically, throughout a building's life cycle, we can divide carbon emissions into two categories, namely operational carbon (OC) and embodied carbon (EC). These emissions happen at different times. In their study, Peng, et, al. (2018) claimed that the operational stage took up to 85.4 % of the overall carbon emissions. Moreover, 12.6 % from the total carbon emissions can be resulted from activities such as materials production, transportation of building materials and products, and construction installation, which also comprises waste generation. Carbon dioxide emitted from these activities is called embodied carbon whereas operational carbon refers to the carbon produced from the energy consumed in the operational phase. Despite established dominance of OC over the lifespan of a building, recent research has suggested that embodied carbon (EC) can have intensive annual impacts as it is released within a short time frame. The computation of embodied carbon comes into play during the design to evaluate the carbon emissions associated with the materials consumed in construction.

The quantitative embodied carbon assessment in buildings involves analysis of the carbon emissions associated with the construction materials used across the entire life cycle of a building. By taking formulated life cycle and material data inventory analysis model as basis, carbon footprint resulting from various stages including material production, transportation, construction, and life-end disposal can be measured and quantified. As referring to Construction Industry Development Board (CIDB), a primary embodied carbon assessment had been carried out with approximately 500 records of embodied carbon resulted from construction materials and building elements associated with different carbon factors. Thus, by taking these data, embodied carbon content of the building components and overall structure can be estimated, and thus opportunities for carbon reduction throughout the building's life cycle could be identified. Also, this assessment allows engineers, architects, and policymakers in making environmentally conscious choices from the aspects of material selection, design optimization, construction techniques, and building management practices.

1.2 Problem Statements

Countries worldwide, including Malaysia, has pledged to quantify the direct and indirect carbon emissions embodied in construction materials and their production. However, the assessing indirect carbon emissions can be a challenging task as it involved the extraction of raw materials, transportation to facilities or sites, construction activities, and the end-life of materials, thus it requires extensive data gathering and analysis. Despite the Malaysian government has introduced Malaysian Carbon Reduction & Environmental Sustainability Tool (MyCREST) as a mandatory building rating system for all construction projects, the implementation of this tool might be a constraint for every construction company. Furthermore, the Bursa Malaysia has required all the publicly listed companies to disclose their carbon footprint and their initiatives in carbon reduction. Nevertheless, the construction industry in Malaysia has neglected the quantification of indirect emissions (embodied carbon) associated with buildings, and this embodied carbon assessment was time-consuming process. Consequently, only a limited number of construction companies were starting the early stage of embodied carbon assessments, while the majority focused solely on direct emissions (operational carbon) as required by the Bursa Malaysia. Hence, lack of enforcement mechanisms; resource constraints; and low industry-wide awareness about the embodied carbon are the main problems. This project aims to provide some possible approaches for every Malaysian construction company to conduct a general embodied carbon assessment.

1.3 Aims and Objectives

The widespread adoption of embodied carbon assessments in the Malaysian construction industry was still relatively limited. Although there was growing awareness regarding the importance of considering embodied carbon in building projects, the practice was not yet as prevalent as the direct emissions (operational carbon) assessments. The aim of this thesis was:

i) To identify the challenges faced in computation of embodied carbon in construction sector.

ii) To investigate the embodied carbon value in the life cycle of a residential building in a housing development project.

iii) To suggest carbon footprint reduction strategies.

CHAPTER 2

LITERATURE REVIEW

2.1 Climate Change

Climate change is now one of the major global issues over this century and beyond. As can be seen from the annual temperature anomaly for 25 countries created by Berkeley Earth in **Figure 2.1**, since 1850, the global mean temperature has been risen to highest value of 1.36 °C.

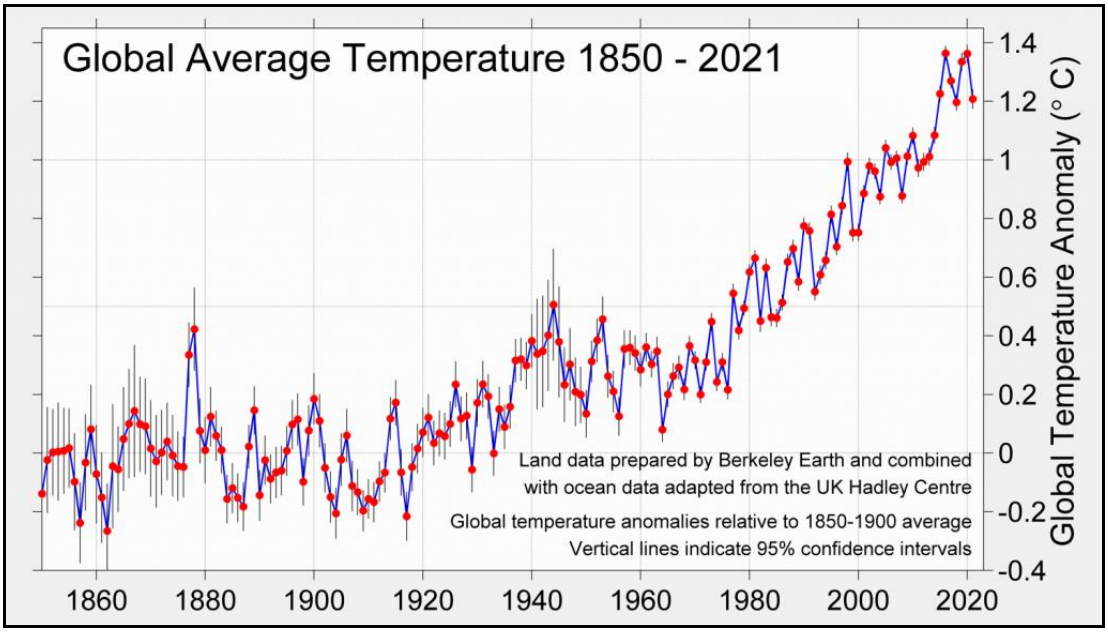


Figure 2.1: Global Average Temperature (Berkeley Earth).

Figure 2.2 demonstrated that the Earth's surface temperature was significantly increased relative to average temperature in 1951s to 1980s and this was broadly distributed, affecting almost all ocean and land areas.

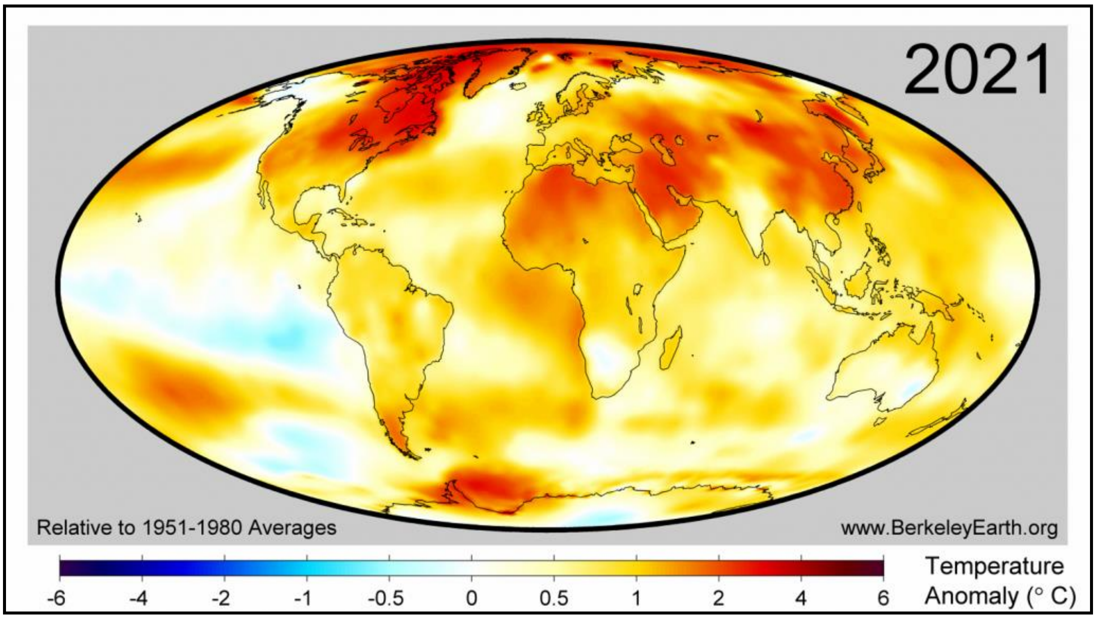


Figure 2.2: Earth's surface temperature in 2021 (Berkeley Earth).

Apart from that, the Intergovernmental Panel on Climate Change (IPCC) has revealed an increase of average global land and ocean temperature by 0.85 °C from 1880s to 2012 (PCC-AR5-WG1, 2013). These are particularly evident in climate change issue. The world has been experiencing the consequences of the climate change such as rising sea level, wildfire, increasing droughts and floods, and bleaching of coral reefs, and this demanded attention worldwide as there is increasing in awareness of the current and future threats to the ecosystems and human civilisation on the Earth. Climate Change Knowledge Portal (CCKP) has assessed the observed annual mean temperature from year of 1991 to 2020 in America as shown in **Figure 2.3**.

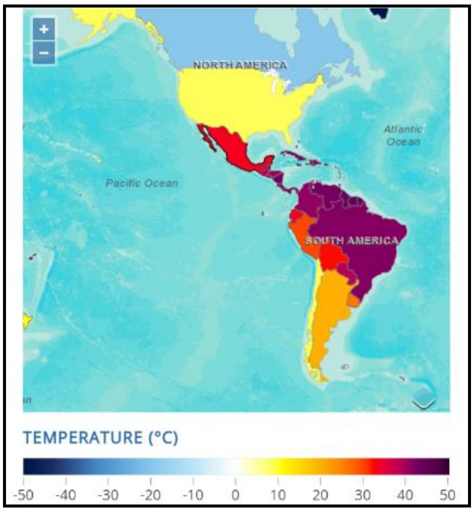


Figure 2.3: Annual mean temperature in United State (CCKP).

The South America faced high temperature ranging from 20 °C to 43°C. Leiserowitz et al. (2018) who is a member of Yale Program, conducted a targeted survey on Climate Change Communication throughout the years, with a recent iteration indicating that 69% of Americans are at least "somewhat worried" about global warming, with approximately 29% saying being "very worried". The climate crisis is proved that it presented a variety of implications to human health, including psychosocial health and wellbeing, especially among young people.

Climate change is defined as the long-term changes in Earth's climate in a way of rapid increasing global temperature. The most significant and influential climate phenomenon can be observed over the 20th century and its impacts unfold regionally. For instance, long-term sustained widespread reduction of iceberg, rising global sea levels, and alterations in atmospheric and ocean circulation as well as regional weather patterns, which lead to seasonal rainfall irregularities. Malaysia, one of the Southeast Asian countries, could be free from climate related disaster, this country however has experienced abnormal warming and rainfall conditions. These phenomena are caused by heat-trapping gases called greenhouse gases (GHG) that existed naturally via processes like volcanic eruptions. These gases allow solar radiation to reach the Earth's surface but absorbed the infrared radiation emitted by the Earth and thus causing greenhouse effect which is the warming of Earth surface. Nevertheless, it is important to know the difference between the natural greenhouse effect and the enhanced greenhouse effect. The 5 key greenhouse gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (NO_x), chlorofluorocarbon (CFC), and ozone (O_3). The researchers from US Environmental Protection Agency have highlighted that human activities are deemed to be the dominant cause or enhancement of this warming with more than 95% of certainty after they analyzed the indirect measures of climate, such as ocean sediments, ice cores, and the Earth's orbit changes in terms of natural variability over diverse time scales. Since the Industrial Revolution, the human activities associated with burning fossil fuels, and deforestation have contributed to continuous rising of atmospheric greenhouse gases concentrations. These gases are radiatively important as they impact the radiation balance, altering net heat balance of the Earth. **Figure 2.4** illustrated the result of a research on spectral distribution of solar radiation done by Hardy, J. T. (2006).

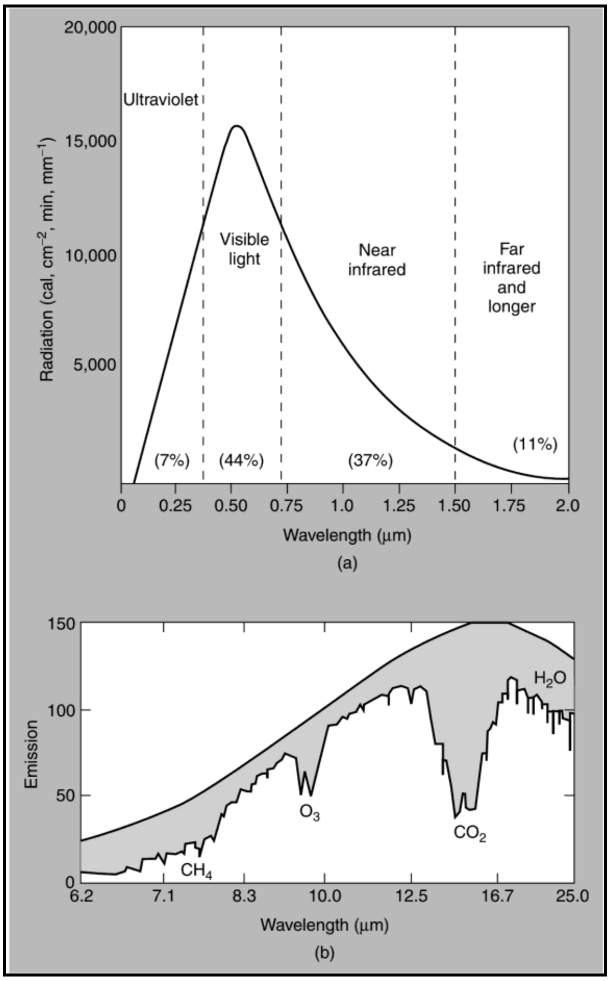


Figure 2.4: Spectral distribution of solar radiation (Hardy, J. T. 2006).

From **Figure 2.4**, the solar radiation is known as the energy distributed across a wide range of the electromagnetic spectrum. It is ranging from short-wavelength X rays to medium-wavelength visible light, to longer-wavelength infrared. According to research studies done by multiple research groups around the world, CO_2 is found to be the most significant among these greenhouse gases because it remains the most abundant in the Earth's atmosphere. As coming solar radiation passes through the atmosphere, CO_2 unable to alter the radiation due to its low absorption. However, after absorption by the Earth's surface, the visible energy radiated as far-infrared radiation at wavelengths greater than 1.5 µm. The notable feature of greenhouse gases is to absorb certain infrared wavelengths and CO_2 absorbs strongly at wavelengths from 12 µm to 18 µm of the outgoing far-infrared radiation emitted as shown in **Figure 2.4 b**. Therefore, the heat was trapped in the troposphere without being radiated out into space. Moreover, the amount of heat escaped from the Earth typically depends on the transparency of the atmosphere. During the last few decades, human activities increased the concentration of atmospheric CO_2, especially transportation and industrial sources. As the consequence, more heat was trapped in the troposphere and thus significant greenhouse effect occurred. Ahmed et al. (2021) claimed that Malaysia is the fourth largest greenhouse gases emitter in ASEAN, contributing to around 0.52% of the world's carbon emissions. Generally, over the years, Malaysia has experienced the impacts of this climate issue.

The rapid urbanization process in Malaysia has made the country more vulnerable to climate issues. The impacts of climate change can be either direct or indirect which encompassing physical and mental health of human, welfare, socioeconomic, and environment. Malaysia is a country located in the equatorial doldrum area, and thus has uniform temperature, high humidity, and copious rainfall throughout the year. Over the last century, Malaysia has become hotter with gradual increase in mean annual temperature as shown in **Figure 2.5**.

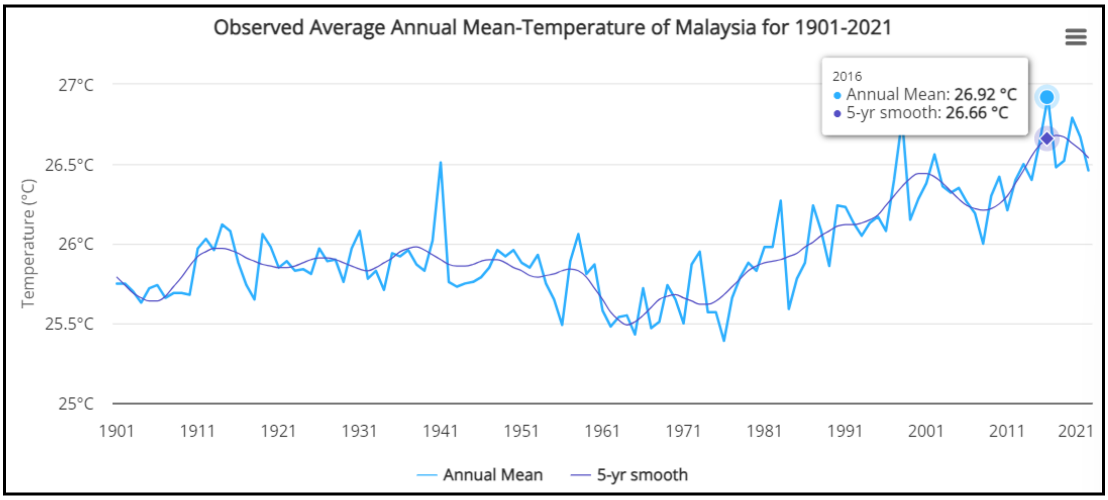
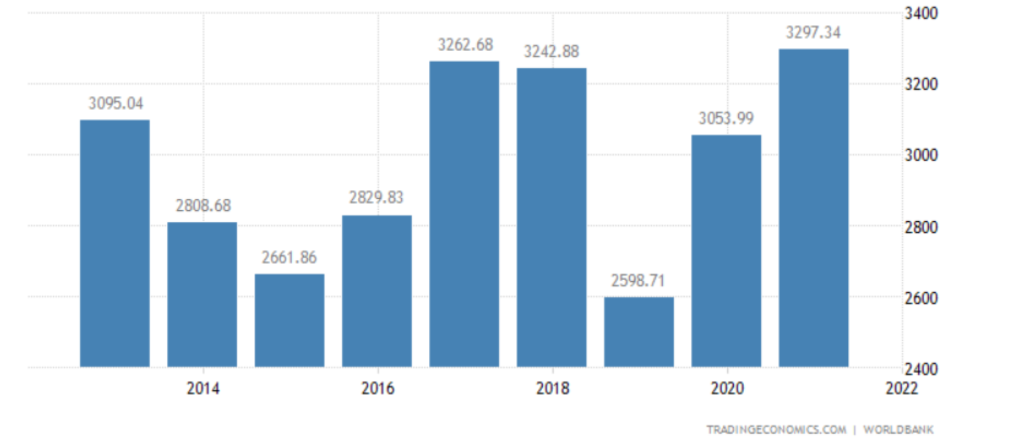


Figure 2.5: Average mean temperature in Malaysia (World Bank Climate Change Knowledge Portal).

CCKP presented that the mean annual temperature of Malaysia is 26.37 °C in the past few decades after analysed the observed historical data (World Bank Climate Change Knowledge Portal). Furthermore, based on the Malaysian Meteorological Department (MET), the temperature distribution across the country currently shows a variation of less than 3 °C ranging from 0.7 to 2.6 °C. This variation is normally expected to be less than 2 °C. The coastal region experiences a temperature range of 5 °C to 10 °C while the interior region sees a range of 8 °C to 12 °C (Malaysian Meteorological Department, 2009). MET Malaysia found that April and May have the monthly temperatures. This aligns with research conducted by the Climate Research Unit (CRU) which confirms that April, May, and June are indeed the months, in Malaysia. According to CCKP's projection, Malaysia might be hotter with an average temperature rise per month of 1.5 °C by 2050 and this climate projection data is derived from global climate model compilations of the Coupled Model Inter-comparison Projects (CMIPs). Since the climate and hydrological cycles have been disrupted due to rising atmospheric temperature, the corresponding intensity and occurrence of extreme precipitation events are likely to increase.

Malaysia is located at latitude 1° - 4.5°N and longitude 100° - 104°E), where receiving high rainfall throughout the year, and thus the humidity is always greater than 68% (Pour et al., 2020). Two monsoons can be observed in the region which are the Northeast Monsoon (November to February) and the Southwest Monsoon (May to September). However, recently, many studies have reported changes in occurrence frequency and strength of heavy rainfall events in Malaysia due to the climate change (Niyogi et al., 2017). **Figure 2.6** illustrated the Malaysia's average precipitation from 2013 to 2021. The highest precipitation amount was in 2021 at 3297.34 mm and the lowest was in 2019 at 2598.71 mm.



Related	Last	Previous	Unit	Reference
Temperature	26.46	26.67	celsius	Dec 2021
Precipitation	3297.34	3053.99	mm	Dec 2021
CO2 Emissions	251555.22	256191.49	KT	Dec 2021

Figure 2.6: Average precipitation in Malaysia from 2013 to 2021 (Malaysian Meteorological Department, 2009).

The difference in precipitation amount is due to the rising temperature. This issue intensified the water cycles (**Figure 2.7**) as it raised the upper limit on the amount of moisture-laden air, and this resulted in increasing the rates of precipitation and evaporation. Increased evaporation will contribute to more frequent and intense storms, as well as droughts.

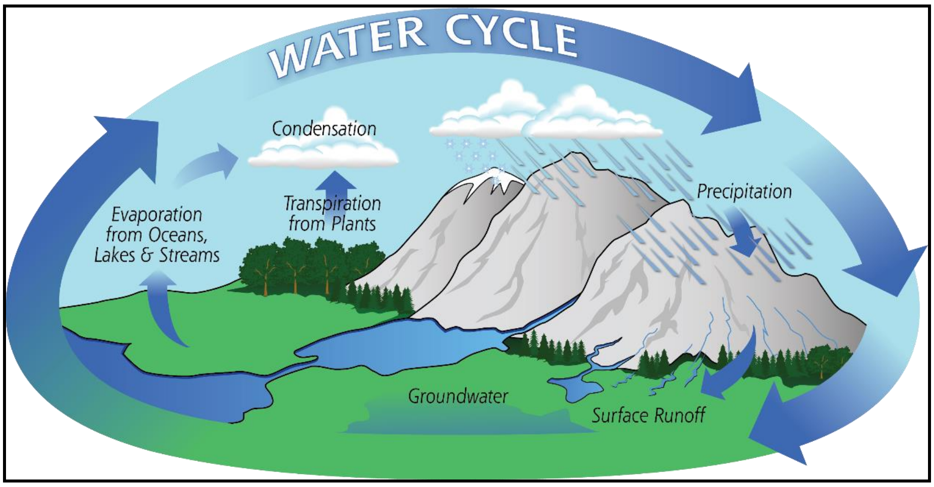


Figure 2.7: Water cycle (Source: https://gpm.nasa.gov/education/water-cycle).

Furthermore, the surge in severe flash floods can be linked to augmented rainfall intensity. As per the information provided by the Ministry of Natural Resources Environment and Climate Change (NRECC) in Malaysia, flash floods can be caused by convection rain that exceeds 60 mm for 2 to 4 hours (average). The heavy rains during the monsoon season, however, are typically long-lasting with intermittent downpours, and the intensity may sometimes exceed several hundred mm in 24 hours. Therefore, floods are normal during the annual monsoon season, nonetheless, a series of severe floods in Malaysia are evident from changing climate. In December 2021, the capital Shah Alam, Klang, and Kuala Lumpur are heavily hit by floods with 27 people killed, and this caused large-scale socioeconomic losses, especially in urban areas (Deutsche Welle, 2023). Other than that, instances of other major floods have previously occurred in Malaysia, such as in December 2006 and January 2007, which had a severe effect on the southern state of Johor in Peninsular Malaysia (Haliza, 2009). To avoid these losses to occur, the frequency or return period of heavy precipitation events can be measured. Determining the return period of rainfall events is essential for forecasting the chance of extreme precipitation events in the future, considering previous data (Nur Khaliesah et al., 2019). There are different methods and theories applied to determine the characteristics of rainfall distribution. Many scientists have determined that Generalized Extreme Value (GEV) is the best approach for examining extreme rainfall in Malaysia (Annazirin et al., 2013). GEV can generate an estimation of extreme rainfall over the 100-years period. The return level of 100-years period extreme events with a probability of 1/100 is being estimated. By applying the L-moment method, the estimation for the distribution parameters can be performed in this study. The L-moment method is a suitable method for parameter estimation in small data samples, especially for estimating extreme parameters. As a result, extreme rainfall events return values during the T-year, x_t can be obtained using the formulae: $x_t = \varepsilon + \frac{\varepsilon}{\kappa}(1 - (-\ln(1 - \frac{1}{T}))^{\kappa})$ and

when the estimates of parameter values of ε, and κ are obtained. After the return level is obtained, return periods maps are developed to evaluate spatial analysis for 20, 50, and 100 years. The map showing the extent of extreme rainfall provides valuable insights into the spatial distribution of precipitation and enables the estimation of potential disaster occurrences in different locations. Moreover, this study has helped identifying stable areas that are suitable for sustainable urbanization, while also highlighting critical zones that require further attention. To better understand long-term risks associated with extreme rainfall, the return period data will be mapped. The resulting analysis can determine the susceptibility of the research area and identify stable zones with varying levels of development and socio-economic activity. Rather than solely increasing the risk of flooding and drought from irregular extreme rainfall events, climate change can also have potential impacts on agriculture.

Climate change has various effects on agriculture in Malaysia, especially in oil palm sector. It reduced yields in warmer regions due to heat stress. Additionally, it can cause crop damage, soil erosion, and land degradation resulting from prolonged drought. Furthermore, heavy precipitation events as mentioned above can also make it difficult to cultivate land. Palm oil is an essential commodity with global usage in approximately 30 % of foods, pharmaceuticals, and cosmetics (Paterson et al., 2009). Moreover, palm oil biodiesel is contributing to Malaysia’s fuel requirements (Lim and Lee, 2012). Consequently, the demand for oil palm will continue to rise, generating high yields at low costs. Despite that, climate change is foreseen to affect food supply and safety. The increase in greenhouse gas concentrations in the atmosphere is causing environmental warming, greater precipitation, and prolonged drought. Oil palm plants become highly susceptible to various fungal diseases with climate change. The most damaging among these diseases is *Fusarium* vascular wilt. This wilt is resulted in decreased cell division that causes reduced size of petiole and leaf lamina. In general, water and climate change are inextricably linked, thus climate change might lead to prolonged and mild water stress. Consequently, the younger leaves of oil palm plants faced a problem of stunting while the older non-stunted leaves are permanently water-stressed, having grown before the pathogen, *Fusarium oxysporum* f. sp. *Elaeidis* becomes established (Paterson et al., 2013). The fungus can grow directly into vascular elements from roots. The host can limit spread by producing gums, gels, and tyloses that impede transpiration (Ploetz, 2006). Nevertheless, in oil palm trees that are susceptible, the production of tyloses, gels, and antifungal metabolites has been slowed down and this enable the further colonization of the fungus. This leads to more vascular occlusion and external symptoms. Non-pathogenic isolates from oil palm plantation soils and healthy palm roots from Malaysia and Zaire may serve as a source of pathogens in response to changing weather (Flood, 2006). Besides, there are another severe fungal disease called *Ganoderma* rots. This disease infections in younger palms and seedlings have increased dramatically in Malaysia. This may be due to the unusual changes in the weather. Although information available for the physiology of growth of *Ganoderma* species involved in oil palm disease is not sufficient, a group of researchers conducted a study on this issue. Prior to the work of Rees et al. (2007), *G. boninense* will die at 45 °C which is the temperature of exposed soil, albeit new strains may emerge. Plant epidemics are affected by climate change, and the altering temperature and rainfall patterns specifically pose a threat to food security (Miraglia et al., 2009). This will cause agriculture growth rate dropped and hence those developing countries including Malaysia might face severe negative economic impact.

Climate change is known in causing both acute and chronic public health through a range of direct or indirect exposures. Climatic influences on environmental systems and social conditions will pose most health risks. In social conditions, the lack of livelihoods, equality, and access to health care and social support structures can undermine most of the social determinants for good health. **Figure 2.8** shown some key examples of direct and indirect health impacts by climate change through various processes and pathways.

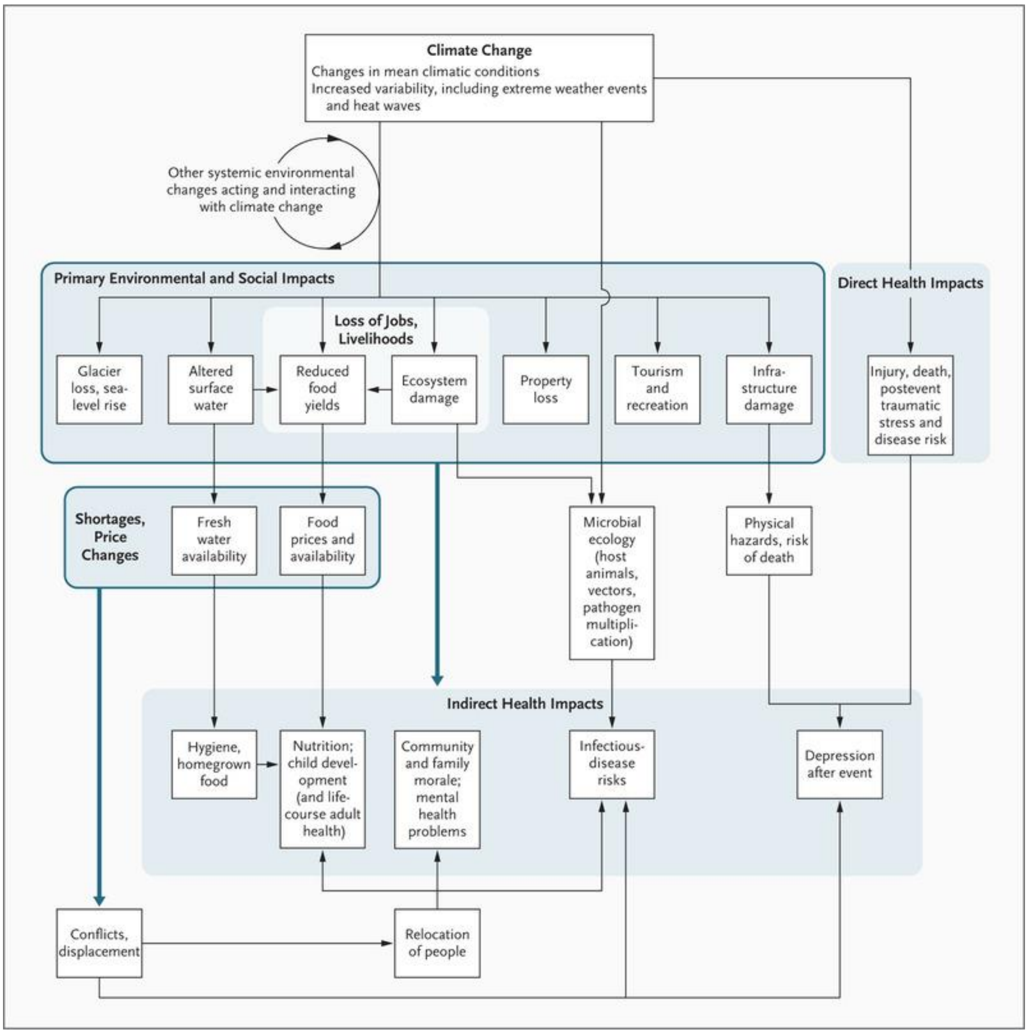


Figure 2.8: Various impacts of the climate change (Butler, 2010).

Directly through flooding, increased frequency and intensity of heatwaves, and extreme events of fire like wildfire haze. Exposure to high temperatures and humidity in a tropical country, like Malaysia can cause heat stress, leading to chronic illnesses and potentially fatal heat stroke or even death. Both indoor and outdoor workers are susceptible to the effects of heat stroke. Working in such environment can increase the risk of health problems and impair the ability to perform work tasks, which increases the accident risk. If exposure to these conditions is prolonged, heat exhaustion or even heat stroke can occur to the workers. Meanwhile, urban air pollution and wildfire haze poses climate sensitive diseases among future generations, elderly, and pregnant women particularly respiratory diseases. In Malaysia, the burden of illness is directly proportional to the intensity of haze as well as the healthcare utilization and costs (Othman et al., 2014). The common respiratory-related illnesses include acute exacerbation of bronchial asthma, acute exacerbation of chronic obstructive pulmonary disease, acute bronchitis, pneumonia, and bronchiolitis in infants (Laumbach and Kipen, 2014). Furthermore, climate change will also have indirect effects like changes in air and water quality due to irregular rainfall pattern, which can increase the risk of food and waterborne illnesses. Alternatively, water-borne diseases are commonly found in the tropical and subtropical regions. These include diarrhoeal diseases caused by microorganisms like Escherichia coli, viral diseases such as hepatitis A, and protozoan diseases like giardiasis. In general, high rainfall can lead to water ponding, and thus resulting in high transmission of dengue. Extreme rainfall events and the change in temperature in Malaysia has created favourable microclimates for Aedes mosquitoes to breed. This statement was supported by Alhoot et al. (2016) who highlighted the positive correlation between rainfall and dengue. Also, the review projected that propagation and spread of dengue viruses is at significant efficiency under climate change characterized by increased rainfall time and surface temperature. As an example, on May 21 of 2023, a total of 43,619 dengue fever cases were reported in Malaysia with 28 deaths, indicating an increase of 170 % compared to the same period in 2022 with reported 16,144 cases and 9 deaths. Following this, climate change would have other indirect effect on socio-economic. Treatment of dengue poses a heavy financial distress on lower-income populations. This is due to the substantial amount of cost of hospitalization, diagnostic tests, medications, and follow-up care. The government will also increase the expenditures spent on managing dengue outbreaks, and thus resources of other essential health services will be diverted. Alhoot et al. (2016) reported that given the rise in ambient temperature by 1.5 °C in 2050, malarial cases are potentially to be increased by 15 %.

Climate change mitigation is a global challenge as its goal is to reduce or limit the extent of climate change by abating the anthropogenic factors. Consequently, an international binding treaty on this issue was proposed, called Paris Agreement. It was adopted by 196 Parties in Paris, France, on 12 December of 2015 under United Nations Framework Convention on Climate Change (UNFCCC). The primary goal of the Paris Agreement is to avoid the global average temperature from increasing more than 2 °C, by pursuing to keep it to 1.5 °C. Malaysia signed up to this treaty in 2015 and ratified it on 16th November 2016. Malaysia pledged to cut carbon intensity against GDP by 45 % by 2030 as comparing to 2005 levels. According to (NRS, 2001), the Malaysian government aims to promote efficient use of resources and environmental conservation via five principles after framing the National Policy on Climate Change in 2009. These 5 principles include development on a sustainable path, coordinated implementation, conservation of environmental and natural resources, effective participation as well as common but differentiated responsibilities and respective capabilities (NRS, 2001). On the other hand, public involvement in mitigating climate change is said to be critical as climate change is not only impacting the environmental but also human health negatively. Hence, to persuade the public participation, improving both formal and non-formal education, training, and public awareness on climate change can be one of the most effective ways.

In view of the literature related to climate change due to increased attention on regional climate change, this review could reveal some of the significant climatic impacts on Malaysia country and face the limitation of not covering all necessary literature on climate change. Moreover, accuracy of the review on temperature rising, rainfall variation, and spectral distribution of solar radiation is dependent on accuracy of the data and simulation models adopted by other researchers in their thesis.

2.2 Greenhouse Gases (GHGs) emission in Construction Sectors

Net Zero Carbon Emissions 2050 is a groupwide goal and extends to operations of all the local public listed construction and property companies. According to Bursa Malaysia, scope 1 and 2 are mandatory to report and evaluate, whereas reporting scope 3 emissions is optional. Carbon emissions can be divided into scope 1, scope 2, and scope 3. To define scope 1 emissions, it is a mandatory scope to be measured as it is the direct emission due to direct use of fossil fuels and relevant activities that controlled by the reporting organisation. For scope 2 emissions, it can be the emissions indirectly caused by the usage of purchased electricity, or heat. In terms of scope 3 emissions, it is the indirect emissions related to all other GHG emissions throughout the companies' operations included use of sold products, business travel, employee commuting, extraction, production, and transportation of purchased materials and fuels which can't be controlled over. This scope 3 emission evaluation is the most time-consuming and difficult task for disclosure. Also, this scope requires measuring embodied carbon (EC) which is currently still new for Malaysia country. Building construction in Malaysia are responsible for producing a large portion of greenhouse gas (GHG) emissions, especially carbon dioxide emissions. 39 % of total direct and indirect global energy-related carbon emissions comes from buildings, making it one-third of the total (Wang et al., 2018). This statement is supported by Klufallah et al. (2014) who stated that more than one third of total energy use and GHG emissions can be resulted from buildings construction in developing country like Malaysia. Malaysian construction sector takes up 24 % of total carbon dioxide emissions (National Master Statistic, 2013). In Malaysia, GHGs are converted into carbon dioxide equivalent (tonne CO_2eq) for evaluation and analysis purposes as covered by the Kyoto Protocol. CO_2 is found to be the most significant GHG in contributing global warming, which in turn of climate change. Carbon emissions throughout a complete building's life cycle can be categorized into embodied carbon (EC) and operational carbon (OC). EC is the sum impact of all the GHG emissions from the materials' life cycle including extraction, manufacturing, construction, maintenance, and disposal, while OC refers to the total GHG emissions occur during the building's operational phase.

Main sources of GHG emissions are basically from energy consumption in different aspects. The cradle-to-site GHG emissions can be divided into 3 aspects as demonstrated in **Table 2.1**.

Table 2.1: The 3 types of GHG emission aspects (Butler et al., 2010).

Greenhouse Gases Emission Criteria	**Greenhouse gases Emission Sources**
1) **<u>EC in the Material</u>** Construction material consumption, e.g., concrete, reinforcement, cement, steel, etc.	"Cradle-to-gate" embodied carbon is generated from the material extraction and manufacturing which release GHG after consumed energy.
2) **<u>Material Transportation</u>** Delivery of the construction materials to the site	The fuel consumption like diesel can be found during the material transportation and this can emit GHGs including those

	released from the combustion, production, processing, and distribution of fuel (well to tank).
3) **Construction Site Emission** Utilization of machinery and equipment in the construction activities including maintenance and renovation, and the waste generation at the site.	Electricity and/or fossil fuel consumed by the machinery and equipment during the construction stage. The GHG from the fuel consumption can be sourced from combustion, production, processing, and distribution of fuel. Disposal of waste can also release the GHG.

The 3 aspects of energy consumption in relation with buildings and construction materials are operational energy, embodied energy, and inherent energy. To define the operational energy, it is the energy required for heating, cooling, lighting, and powering appliances, while inherent energy is the energy embedded in building materials, in other words, the energy content of the raw material. Henceforth, the energy will be released during the disposal of the building through combustion or chemical processing. For example, incineration of the construction waste like debris is inherently energy intensive. For embodied energy, it can be classified into initial and recurring embodied energy. Initial embodied energy is the total energy consumed during activities such as resources extraction, material processing and manufacturing, transportation to construction site and assembly. Meanwhile, recurring embodied energy refers to the energy needed in maintenance and refurbishment of a building. In accordance with (Yim et al., 2018), residential buildings in Malaysia account for around 65 % of the global total sectoral emissions, while commercial buildings represent for the balance of 35 %. In details, the bulk of construction sector's GHG emissions are mostly produced during the operational phase with 80-90 % from energy consumption for lighting, ventilation and appliances, heating, and cooling, whereas the activities like pre-production, deconstruction, transportation of building materials, and demolition produced 10-20 % of its GHG emissions (CIDB, 2020). A broadly similar point has also been made by Peng, Jiang, and Qin (2018), who found that in China construction sector, operational stage gave 85.4 % of the total carbon emissions, and approximately 12.6 % of the overall carbon emissions can be resulted from activities such as materials production, transportation of building materials and products, waste generation, and construction installation. According to the analysis done by CIDB for year 2017 until 2019, there were 5.45 million tonne CO_2eq emitted from construction site. 90 % were from fuel consumption, 6 % from electricity consumption, and 4 % from waste treatment and transportation. In particular to the fuel consumption, bitumen was found as the main contributor (42 %), followed by diesel fuel (35 %), lubricant (12 %), and liquified petroleum gases (11 %) (CIDB, 2020). Besides, between the year 2016 to 2019, embodied carbon in material consumption (cradle-to-gate) attributed to 90 % of the total GHG emissions, while 7% were contributed from the construction site emissions and remaining 2 % was from transportation of construction material. In addition, construction sector stands for approximately 24 % of the total national GHG emissions 2014. The result is tabulated as **Table 2.2**.

Table 2.2: Amount of GHG emissions from three aspects (CIDB, 2020).

Year	**GHG Emission (million $tCO_2eq.$)**				**% compared to National GHG Emissions 2014**
	Construction Material	**Transportation**	**Site**	**Total**	
2016	45.6	1.2	4.9	51.8	16 %
2017	67.9	2.1	5.2	75.3	24 %
2018	71.8	2.3	5.5	79.6	25 %
2019	66.8	2.3	5.6	74.6	23 %
Average (2017 – 2019)	68.8	2.2	5.5	76.5	24 %
Average Distribution (2017 – 2019)	**90 %**	**3 %**	**7 %**	**-**	**-**

Studies claimed that without any action or mitigation, the energy use in building construction sector is expected to increase from 60 % to 90 % as well as GHG emissions between 2005 to 2050 (Urge-Vorsatz et al., 2005). This study is supported by the projection done by CIDB for year 2020 to year 2050. CIDB used econometric approach to estimate the projections of the material consumptions, fuel consumptions, electricity consumptions, and waste up to year 2050. CIDB referred to Department of Statistic Malaysia (DOSM), Economic Planning Unit (EPU), and World Bank to utilize the gross domestic product (GDP) as the economic indicator. With the aid of GDP, the historical correlation between consumption of construction materials and energy demand as well as activity indicators were derived. As the result, the projected total GHG emissions up to 2050 is shown in **Figure 2.9**. As by the year 2050, a total of 147 million tCo_2eq (92 % increment as compared to 2020) will be emitted if no mitigation actions are adopted.

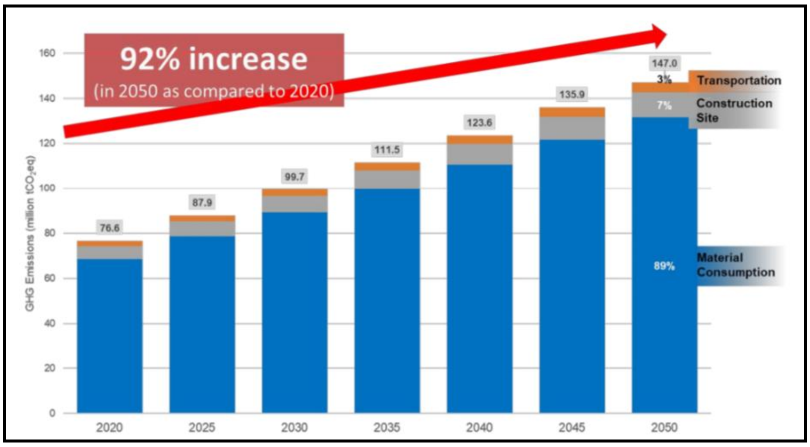


Figure 2.9: Predicted increment of GHG emissions to 2050 (CIDB, 2020).

Building construction and material consumption in construction sector consequently raise carbon dioxide emissions. Therefore, it is not merely important to select wisely the appropriate strategies or technologies, but the correct materials for the local with the aim to lower the overall contribution of the sector to climate change. Many studies suggested that timber, a naturally insulating material, makes a better choice compared to other material such as brick or concrete. This is because timber was found to be more environmentally friendly with its low carbon dioxide emissions. Cole & Kernan (1996) had conducted a study on office building that constructed with different structural frame materials (wood, steel, or concrete) in Canada. The result revealed that the manufacturing and production of concrete frame consumed more energy than production of steel and wood frames about 6 % and 14 %. Similarly, Petersen & Solberg (2002) found that wood has emit much lesser GHG emission than non-wood components in buildings after completed the assessment on application of wood components instead of non-wood components in Norway. Ortiz et al. (2010) have attempted to evaluate environmental impacts from the exterior and interior wall scenarios of typical block during the construction phase. Using CML life cycle impact assessment (LCIA) method, Ortiz et al. have been able to assess the global warming potential or GWP. In terms of environmental impact of GWP, the result indicated that 85% of energy is used during the fabrication of material while the remaining was due to the energy consumed (8 %), transportation (6 %), and waste management (1 %). Peuportier (2001) conducted a life cycle assessment study for 3 different houses: concrete block house, house with solar heating system, and high-insulated wood house. The result proved that highly insulated wood house had just about half of the negative impacts as compared to concrete house. Although the use of wood in Malaysia's building components is more preferrable in reducing GHG emissions, timber structures might face short lifespan problem in terms of material strength and defective. Che-Ani et al. (2008) concluded that timber houses are not being constructed at the present time in Malaysia because the humid weather can lead to structural problems. Defects of timber structures can be attributed to fungal infestations, insect, weathering, and mechanical failure. Therefore, Malaysian construction and development companies prefer using timber as an alternative material for homes in the situation of the land is plentiful in the types of biomass renewable energy resource (Bin Marsono & Balasbaneh, 2015).

In **Figure 2.10**, there are 2 types of building design system in Malaysia: conventional building system, and industrialized building system (IBS).

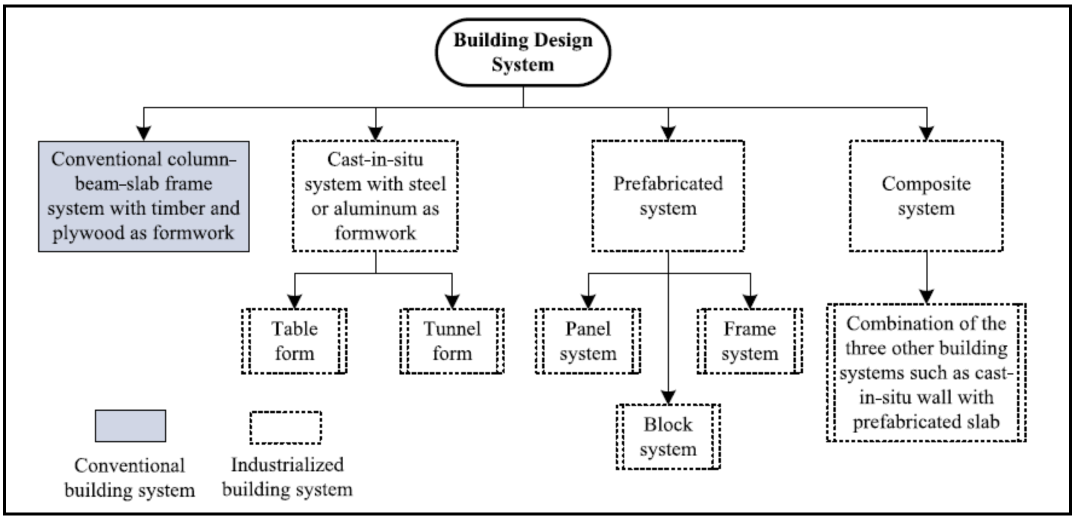


Figure 2.10: Types of building systems in Malaysia (Al-Awag et al., 2023).

In terms of conventional building system, it can be classified into two major components. The first component is defined as the structural system that is consisted of a column-beam-slab frame which involved 4 phases: fabrication of formwork and scaffolding, erection of reinforcement bar, placement of concrete, and dismantling of formwork and scaffolding (Badir et al., 2002). Next, the second component is referred to a wall system which composed of infill materials, non-load bearing brick. In comparison, IBS is an engineering technology consisting of cast-in-situ formworks, prefabricated, and composite systems (Al-Awag et al., 2023). For the cast-in-situ system, it uses a lightweight prefabricated formwork made of steel, fibreglass, or aluminium instead of conventional timber formwork. Other than that, the prefabricated system involves casting a structural element on-site or off-site before installing it at the site, whereas the composite construction method refers to the casting of some elements off-site in the factory, while others are casted on-site. In short, IBS is a system encompassing manufacturing processes of building components in which they are conceived, designed, fabricated, transported, and finally erected on-site (Richard, 2017). Al-Awag et al. (2023) conducted a study on embodied energy (EE) and embodied carbon (EC) intensities of 10 case studies with different building design systems in Malaysia. These systems comprise of conventional, fabricated, and composite systems (a combination of the three other building design systems such as cast in-situ wall with prefabricated slab). Input-output life cycle assessment (I-O LCA) was used in this study. Yet, in accordance with the I-O product items in the Malaysian Standard Industrial Classification, the direct embodied energy intensities included the crude oil, natural gas, coal, petroleum refinery, electricity, and gas supply sectors (Department of Statistics, 2000). Al-Awag et al. (2023) stated that the IBS (residential buildings) have higher embodied energy and embodied carbon intensities as compared to the conventional buildings (office buildings). The reason is that IBS involved usage of a high amount of concrete and reinforcement steel for concrete elements in their panel systems. Similarly, Chau et al. (2017) discovered that using 50 to 80 % off-site prefabricated materials in façade and concrete elements might increase EC intensities accounting for 5% of total carbon emissions. Besides, High EE and EC comes from the application of steel fabricated roof structures and steel roof sheeting, which required large amounts of energy and emitted large portion of carbon embodied in relation to the steel product manufacturing. However, in conventional building design system, largest contribution can be seen in the upper floor element that was a conventional column-beam-slab frame system. Owing to large quantity of concrete and reinforcement steel used, this element represented for 30.4 7 % and 30.75 % of the total EE and EC intensities of a building (Al-Awag et al., 2023). In summary, different building design systems can contribute to different EE and EC intensities either through increment or reduction. However, in Malaysia, concrete and reinforcement steel are used widely, thus IBS will be the best option for building construction as this can reduce wastage of resources and speed up the construction rates which can contribute to a lower embodied carbon emission.

GHG emissions in construction sector is crucial to be taken into account in Malaysia due to current rapid economy growth. In fact, a lot of public-listed construction companies acted on their carbon footprint reduction initiatives. For instance, use of solar energy as alternate energy source, monitoring of diesel and electricity consumption, motion sensors lighting, diverting waste from landfill, and promoting and using local supply chain. Nonetheless, currently there are no construction companies working on embodied carbon evaluation and involvement of IBS technology in construction is not normalized among the Malaysian contractors but only public-listed companies. In terms of cost factors and high availability of resources, the construction sector in Malaysia is less emphasising on carbon reduction, especially embodied carbon.

2.3 Current State of Embodied Carbon Assessment in Malaysia

Quantitative assessment in both direct and indirect carbon emissions embodied in construction materials and their production is becoming a trend in Malaysian construction industry. Earlier studies indicate that indirect emissions may surpass direct emissions for energy-intensive materials like cement and steel reinforcements. Moreover, small-medium companies’ contractors in Malaysia prefer conventional building systems instead of Industrialized Building systems (IBS) due to buyers’ traditional mindset. Also, cost factors unable to motivate developers, especially small and medium companies in shifting the building system from conventional to IBS.

This situation is not only causing obstacles in embodied carbon reduction, but also local contractors struggle to compete with foreign counterparts who implement IBS. Currently, reducing the embodied carbon footprint is one of the major concerns in the Malaysian construction industry. **Figure 2.11** demonstrated that most of the total embodied carbon of a building is released upfront in the product stage at the beginning of building life.

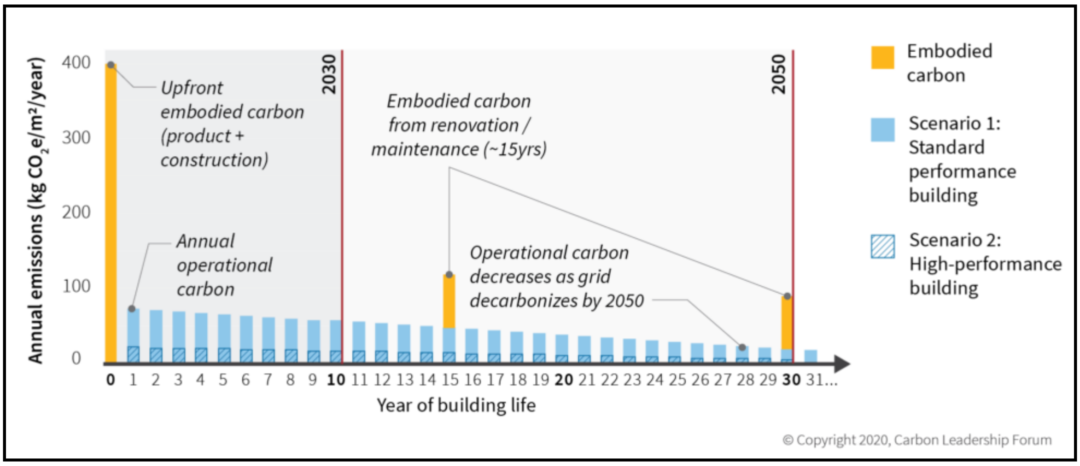


Figure 2.11: Embodied carbon emission during the product stage (Source: https://carbonleadershipforum.org/embodied-carbon101/#:~:text=In%20the%20building%20industry%2C%20embodied,due%20to%20building%20energy%20consumption).

Nevertheless, the Malaysia construction sector is still in its early stages of embodied carbon awareness and knowledge. Henceforth, the CIDB Malaysia has developed an embodied carbon inventory to fulfil the need of the construction sector in Malaysia. The early assessment of embodied carbon is within a lifecycle stage including production stage (raw materials extraction, processing, manufacturing, and transportation to factory gate), transportation to site, and construction installation as well as material waste (CIDB, 2021).

Embodied energy is defined as the total primary on-site and off-site energy consumption within the boundaries of cradle-to-gate. The activities included production and manufacturing of building materials (upstream and downstream processes), prefabrication, transportation, construction, and administration.

Obviously, embodied carbon is strongly related to embodied energy. Embodied carbon refers as the sum of fuel related (embodied energy) carbon emissions and process related (chemical processes) carbon emissions throughout whole life cycle (Finnegan, 2018). It can be measured from cradle-to-gate, cradle-to-site, cradle-to-grave, or even cradle-to-cradle (CIDB, 2021). In the past few years, much emphasis has been placed on improving operational carbon. Basic tactics, such as enhancing building insulation and using LED lighting and automatic controls, have been applied for a long time to increase energy efficiency. However, these mitigations still contribute to the embodied carbon of the site through the addition of new products and materials, and the removal and disposal of old ones. While both embodied carbon (EC) and operational carbon (OC) indicate a building's overall carbon footprint, they have different implications for sustainability. It is crucial to prioritise EC as it constitutes a significant portion of overall carbon footprint of a building, especially for materials with high embodied carbon like steel, cement, and aluminium. Referring to Sturgis (2019), the built environment utilizes most of the three materials, which account for 23 % of total global emissions. According to IEA, the built environment generates 40 % of the global CO_2 emissions each year, and 13 % of it is due to embodied carbon from building, and infrastructure materials and construction. Malaysian contractors and developers must address embodied carbon appropriately to meet global and national net-zero targets, whether in anticipation of future regulations or in line with public sustainability agendas.

Although there are a lot of journals proposing the embodied carbon assessment, the embodied carbon computation is still on hold in Malaysian construction industry. This is because measuring and tracking embodied carbon is complex, in contrast to operational carbon that can be extrapolated from energy bills. Furthermore, sustainability reporting methods have only required scope 1 and 2 emissions accounting and disclosures, leading public-listed Malaysian construction companies to prioritize reducing OC emissions. In terms of building design systems, IBS can be one of the best options for Malaysian construction industry in embodied carbon reduction. IBS can be classified into five types: precast concrete system (walls, slabs, columns, 3D components), steel formwork system, steel framing system, prefabricated timber framing systems, and block work systems (Othuman Mydin et al., 2014). With the aid of IBS technology, only minimal installation work is required, and equipment at the construction sites can be reduced. Also, the extra or unused components can be stored for future construction projects that have the similar designs, in other words, enhancing material usage. As a result, low embodied energy consumed lead to low embodied carbon emissions. IBS concept has been introduced in Malaysia since nearly four decades ago, however, its applications are still at low levels. This is because contractors today are not willing to take the risk to implement pre-cast and prefabricated construction as a lot of buyers prefer houses built with brick and mortar and think the pre-cast or prefabricated building elements are always with lower quality (Kamar et al., 2012). Apart from that, higher costs may result from the lack of experience and technical knowledge of contractors in IBS as they unable to manage the costs effectively. Furthermore, conventional building systems have been the norm for many contractors for years and the is an abundance of cheap foreign labour.

Fortunately, IBS implementation has increased to 84 % in 2021, whereas, in private projects, it has increased to 60% in 2021. The Construction Industry Transformation Programme (CITP) 2016-2020, the National Construction Policy 2021-2025, and Construction 4.0 Strategic Plan 2021-2025 boosted the growth of IBS in Malaysia steadily over last 15 years (Shakirah, 2023). Also, the construction industry would widely adopt CIDB's sustainability measures – MyCREST and INFRASTAR as a means of evaluating sustainability. But while the IBS implementation has been increased among Malaysian construction companies, the evaluation of embodied carbon in a building is still not gaining much attention in Malaysia. To determine the embodied carbon of building materials, it required the co-operation of every party and partner. Manufacturers, suppliers, subcontractors, and consultants are essential to be transparent about their processes and conduct self-assessments. However, it is impossible to know from the finished product alone, and they may not reveal their emissions accurately. Other than that, a local comprehensive life-cycle inventory database is still not available for Malaysian construction companies to conduct carbon emission assessment. Therefore, an inventory data with 500 embodied carbon data for various construction materials and building elements was provided by CIDB.

Although accounting for embodied carbon has been a low-priority action item for firms due to the challenges associated with it, proactive construction and property firms will realize that it is now necessary because of some changes in regulatory policies and ESG business trends in Malaysia. As an example, Sunway Construction Group Bhd has started to work on embodied carbon calculation for readily disclosure in their sustainability report. Embodied carbon can be emitted from waste; thus, waste disposal and recycling data is reported in their annual report, and this waste data disclosure is always not available in other construction companies. This data can help to compute the approximate embodied carbon footprint from the waste. Since embodied carbon requires a strong methodological foundation and a lot of input database, this consumes a lot of time and manpower to complete an embodied carbon assessment. Additionally, there are no generalized embodied carbon assessment in Malaysia buildings, but only for few buildings like residential buildings and office buildings. Yet, it is still a long journey to quantify the embodied carbon in Malaysia, especially construction sector.

2.4 Embodied Carbon Assessment

The process of embodied carbon (EC) assessment involves evaluating and measuring all the greenhouse gas emissions, including carbon dioxide, related to every stage of a product's life cycle, from its extraction and production to its recycling or disposal. The assessment considers emissions generated throughout the entire life of a product or system for a holistic understanding of its environmental impact. Different methodologies can be applied for embodied carbon assessment.

There are some standards developed for Life Cycle Assessment (LCA). The basic four-stage framework provided by ISO 14040 in 2006 has been a significant milestone for EC assessment (International Organization for Standardization, 2006). The critical requirements for these assessments were further specified in 2008 by PAS 2050 (Specification, P.A., 2008). The European Committee for Standardization Technical Committee 350 (TC 350) established European standards in March 2011 that specify the stages that need to be incorporated. EN 15978, one of the TC 350 standards, proposes that buildings' environmental performance assessments should combine the human activity scope with an emission factor coefficient (National Standards Authority of Ireland, 2011). Gelowitz & McArthur (2018) discovered discrepancies and inaccuracies in EPD studies due to the use of different methodologies. ‘Carbon management in infrastructure’ was launched in 2016 as a complimentary British publicly available specification named PAS 2080. Reporting, benchmarking, and target setting are all included in its guidance. The associated documents provide an abundance of worked examples and practical tips in the UK. Requirements for organizational level design, development, management, monitoring, quantification, documentation, reporting, and verification were included in the release of the ISO 14064 series in 2018 and 2019. These standards which have been implemented in UK should be considered in Malaysia, however, the embodied carbon assessment is still new for Malaysian construction sector.

The most popular used approach in quantifying embodied carbon is Life Cycle Assessment (LCA). This method requires the assessment of quantitative data on material, energy, and waste flows related to a product’s entire life cycle to determine its environmental impact. Therefore, embodied carbon assessment can be viewed as a subset of a wider LCA methodology. Different impact categories can be employed in the impact assessment methodology to present the outcomes of an LCA study on buildings. Global warming potential, resource extraction, acidification, etc., are among the most common impact categories (Kayaçetin & Tanyer, 2020). The GWP is an essential category that provides valuable data about the embodied carbon in the built environment. The environmental effects of goods and services are quantified using LCA, the most utilized and well-regarded tool. Despite its conceptual simplicity, LCA can be highly intricate, with many crucial assumptions, often specific to materials, that can significantly affect the outcome. To regulate buildings’ EC assessment, Environmental Product Declarations (EPDs) were introduced in 2014, complying with EN 15804 and ISO 14025, and based on European Standard’s core Product Category Rules (Pan & Teng, 2021). The development of Environmental Product Declarations (EPD) not only involves PCR but also the use of LCA methodology. Defining the study's goal and scope is an important first step in any LCA. Key details of the study should be defined by the study's goal and scope. As an illustration, the functional unit that needs to be evaluated, like a ton of structural steel, a square meter of external wall, or a whole building, etc., is analysed over a particular duration, typically 60 years for building assessments. Additionally, the assessment's scope is determined by the system boundaries, meaning what is included/excluded. Also, allocation methods are employed to distribute the environmental load of a process among various products or functions that share the same process. For example, since blast furnace slag is a valuable by-product of steelmaking from iron ore, it should assume a portion of the environmental impact from steelmaking for the product in which it's utilized. Allocation is applied to distribute a portion of the environmental impact of steelmaking to the blast furnace slag (Davies et al., 2018). The process of a Life Cycle Assessment (LCA) includes three key stages. Before that, it is important to note that the term carbon dioxide equivalent or CO_2e is used to describe different greenhouse gases (GHG) in a common unit. CO_2e is a measure of the equivalent impact on global warming of any type and quantity of greenhouse gas. GHG expressed as CO_2e is calculated by multiplying its amount by GWP. "Global warming potential" (GWP) is a measure of a GHG's warming effect over a certain period. CO_2 is assigned an index value of 1 in the GWP index, with all other GHGs assigned a value that represents the number of times they cause greater warming effect than CO_2. For example, 1 kg of nitrous oxide causes 273 times more warming than 1 kg of CO_2. The GWP for each GHG was shown in **Figure 2.12**.

	Greenhouse Gas	Global Warming Potential (GWP)
1.	Carbon dioxide (CO_2)	1
2.	Methane (CH_4)	29.8
3.	Nitrous oxide(N_2O)	273
4.	Hydrofluorocarbons (HFCs)	5 – 14,600
5.	Perfluorocarbons (PFCs)	78 – 12,400
6.	Sulfur hexafluoride (SF_6)	25,200
7.	Nitrogen trifluoride (NF_3)[3]	17,400

Figure 2.12: GWP value of each GHG (source: IPCC 2021 – 6^{th} Assessment Report).

First stage for LCA process is creating an inventory of environmental discharges and energy and material inputs for a particular system as well as resource flows while solid wastes or emissions to air or water may be classified as releases. This inventory is known as life cycle inventory (LCI). LCI includes material and transportation data, construction data, operational data, maintenance data, and demolition data. The standard measurement for embodied carbon is in kilograms of CO_2e per kilogram of product or material. Second stage involves assessing the possible consequences linked to these inputs and discharges, such as the effect of CO_2 and other greenhouse gas emissions on global warming. The third stage is the result interpretation for informed decision-making. In fact, LCA can be calculated using the input-output, process-based, and hybrid methods (Liu, 2021).

The input-output (I-O) method has found broad usage in economic and environmental research. The financial transaction in industrial framework is described using a top-down linear macroeconomic approach (Lenzen. et al., 2003). Moreover, the optimal solution is to accurately gauge the direct influence of carbon emissions and enhance the evaluation methodology within an LCA framework (Williams. et al., 2009). The utilization of I-O data in LCA, as per Crawford (2008), enhances dependability by enhancing the comprehensiveness and reliability of life cycle inventories, which is lacking in traditional inventory analysis. Crawford (2008) discovered that capital inputs accounted for 22 % of the overall input to the I-O table for specific components. An I-O table can be used to show the flow of commodities and services between sectors within an economic system (Treloar, 1997). Tracking the flow of energy throughout an economic structure can be done by analysing the monetary input and output of sectors that generate energy and converting it into a physical energy value. (Alcorn & Baird, 1996). The use of I-O LCA ensures identification and capture of all energy transactions within national economic structures. Using these, the inputs and outputs of energy can be assessed. The advantages of I-O LCA are offset by its limitations, and replacing process LCA with it doesn't always ensure model accuracy. According to Acquaye (2010), the I-O methodology has potential errors that include proportionality and homogeneity function, imports handling, conversion of economic data into physical data, total error, double count for energy supply sectors, and product aggregation in sectors. Pure I-O LCAs face a downward bias because assessments do not take into account emissions from usage to decommissioning (Khan et al., 2022). There has been a continuous improvement in the model’s assumptions, and the progress in compiling input-output tables has been significant. The analysis and measurement of embodied carbon in trade was initially conducted by researchers using single-region input-output models in the trade field (Huang, L. & Zhao, X., 2018). The model considers all external countries/regions as a unit and measures the embodied carbon footprint in the trade between the home country and the external regions (Wang, Z. et al., B., 2019). The I-O LCA computes the material flow in the economy structure to ascertain the primary energy required to generate a particular service or good.

Process analysis has been the traditional method for compiling LCIs. Bullard et, al., (1978) propose that the process life cycle assessment (LCA) is the optimal approach for industrial chains, products, or processes where the physical movement of goods and services can be readily identified and traced. The process of product manufacturing is time and labour-intensive due to the need to identify numerous, sometimes elusive energy inputs (Lenzen & Treloar, 2002). The analysis involves examining resource usage and environmental discharges from on-site manufacturing, as well as the suppliers' contribution of essential inputs. Heijungs (1994) pioneered the matrix inversion technique and the flow diagram approach, which is widely used, are the two common approaches to process analysis (Suh, S. & Huppes, G., 2005). The interdependence among industry sectors in contemporary economies is inescapable, and it extends upstream throughout the entire life cycle of every good, resembling a vast network of tree branches (Rowley, H.V. et al., 2009). According to Nässén et al. (2007), the incomplete definition of system boundary causes systematic truncation errors in process LCA. Since the bottom-up approach can cause the truncation error, the top-down analysis led to around 90% of the specific energy consumption. Nässén et al. (2007) noted that the energy consumed by services and transportation in production stage was underestimated by bottom-up approach in comparison to the use phase. The ease of estimating the use phase through direct energy consumption is the primary reason. Sketching the system's boundaries in a process flow diagram can also lead to a truncation error of up to 50 %, as reported in certain industrial sectors (Lenzen, M., 2000). To address the scarcity of real data in the building sector, a framework for uncertainty analysis was developed by combining data quality indicators with the probabilistic technique and assessing them based on different uncertainty studies conducted for the process-based assessment of the building's embodied carbon (Hong, J. et al., 2016). The truncation issue in the matrix inversion technique used for process analysis is that it does not account for further upstream inputs, although it may take into consideration infinite orders of interactions between the up stream’s boundary (Rowley, H.V. et al., 2009).

Both processes' strength (completeness and IOA specificity) has been primarily directed toward hybrid approach execution (Suh, S. et al., 2004.). Hybrid life cycle assessment (HLCA) aims to merge the benefits of the precise LCA method and a broad system scope of I-O LCA as mentioned by (Mattila, T. J. et al., 2010). It balances system boundaries, model applicability identification, and time and cost efficiency. HLCA allows for the extension of both upstream and downstream manufacturing processes by considering direct and indirect emissions. By using hybrid analysis, curtail errors in terms of time and location in operational analysis can be reduced while still maintaining detailed product information to compare similar products or systems (Heijungs, R. et al., 2002). Meta-hybrid analysis, input-output-based hybrid analysis, and hybrid analysis at multiple levels are the three types of tests consistently employed during the literature review process (Khan et al., 2022). The mining and release phases, along with multiple upstream processes, utilize process-based data in a multi-level combined analysis. The two datasets are combined in this analysis, along with other modelled upstream processes using input-output analysis (Suh, S. & Huppes, G., 2005). The process analysis strategy involves conventional detailing, along with input-output assessment (IOA) to address the process gaps. The I-O LCA framework can minimize aggregation uncertainty by utilizing a more detailed process of LCA data, which provides solutions. Furthermore, HLCA can aid in approximating the degree of immediate unpredictability. Typically, within every 5years, an in-depth I-O LCA will be issued. Quick scoping analysis of temporal variability can be done by gathering prices from a particular time frame. According to Williams et al. (2009), The assessment and handling of geographic uncertainty can be enhanced by HLCA. The requirements of HLCA are known to be data- and time-intensive, in spite of its advantages.

In LCA and embodied carbon studies, determining which parts of the product life cycle to include is a crucial scoping decision. **Figure 2.13** is the life cycle boundaries for a material or product.

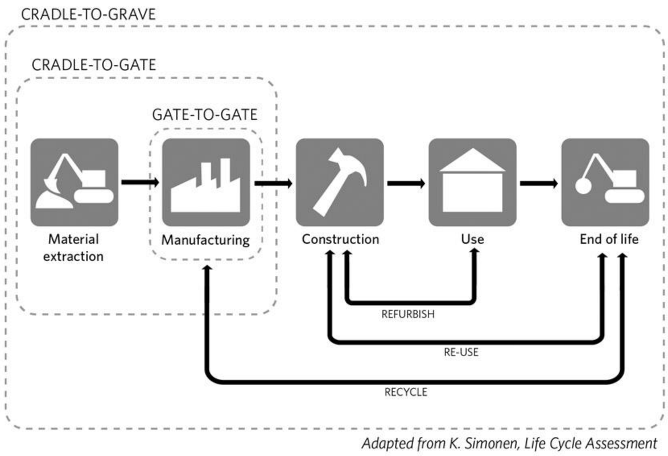


Figure 2.13: Life cycle Boundaries (K. Simonen, 2014).

The term ‘cradle-to-gate’ refers to studies that assess the impacts of a product until it leaves the factory gate. 'Cradle-to-cradle' studies are those that encompass all stages of a building's life cycle, up until its demolition and the disposal or recycling of its materials. Including cradle-to-cradle impacts is widely acknowledged as a requirement for rigorous studies, and there is a growing recognition of the importance of considering the entire life cycle. It is achievable by using both BS EN 15804 and ISO 14044. Wan Omar (2018) conducted a HLCA of embodied carbon emissions in precast concrete wall panels from both conventional and industrialised building systems in Malaysia and detailed out some research on system boundaries. A clearly defined system boundary is necessary to guarantee reliable and consistent results. First step is to establish the boundaries of building materials and goods using HLCA. Relationships between supply chains across industries can be found using this. Cement, aggregate, water, steel reinforcement, and concrete are used in the manufacturing of precast concrete wall panels, which produces both direct and indirect carbon emissions (Wan Omar, 2018). All of these can be traced accordingly. Of the total carbon emissions in upstream processes, 46 % and 31 % are attributed to domestic and imported emissions, respectively (Nässén et al. 2007). **Figure 2.14** displays the complete system boundary in material input required for precast concrete products production.

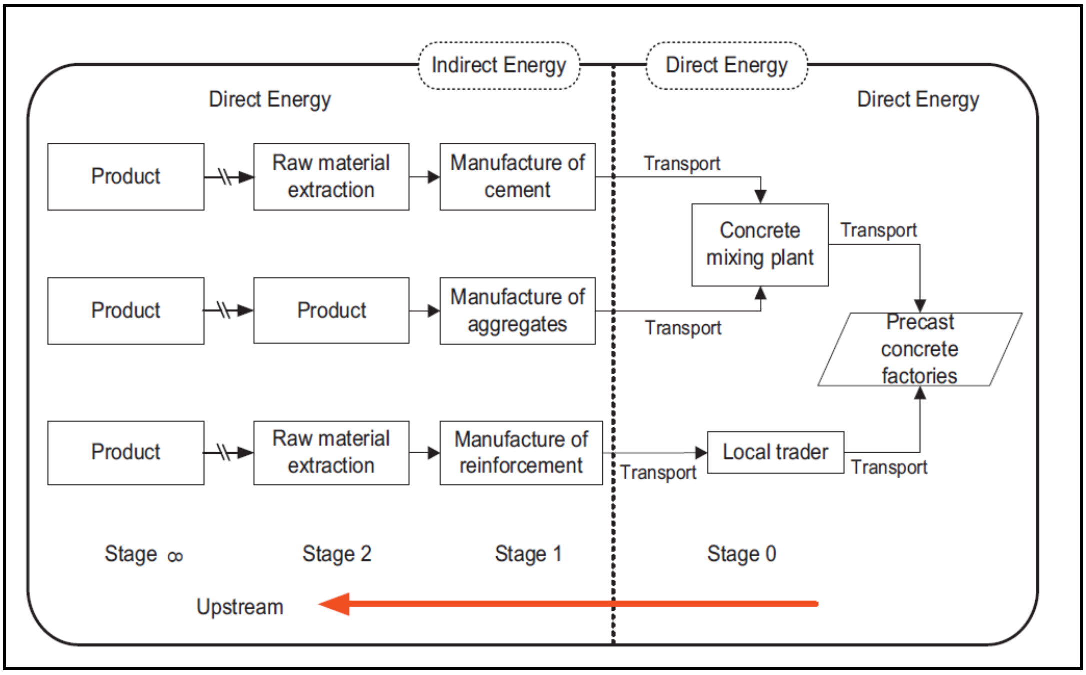


Figure 2.14: Complete system boundary in material input required for precast concrete products production (Nässén et al. 2007).

The following step involves using partial life cycle assessment (LCA) to identify the system boundary from the construction site to the cradle. The life cycle stages did not account for carbon emissions from the usage and demolition periods. The procurement of raw materials, their transportation, and manufacture up to the construction site are all included in the scope of the research. Carbon emissions related to construction product renovation and refurbishment are not included in this research. The main cause for this is the multitude of assumptions necessary to cover the complete life of a building. No replacement precast concrete products are required for the building during its entire service life. As can be concluded from this research, LCI analysis is still incomplete. LCI depends greatly on the accuracy of the data. Incomplete data may lead a revision of the study's objectives and scope, which would result in time waste. In summary, some of the phases cannot be included might be due to lack of data collections and analysis, and hence causing immature EC assessment in Malaysia including developed country.

Embodied carbon assessment allows for informed decision-making by providing a full picture of a product's environmental impact throughout its lifespan. Stakeholders can use this information to identify improvement areas, promote sustainable practices, and contribute to mitigating climate change. Nevertheless, embodied carbon assessment is still incomplete and widely utilized globally, a further improvement is required with the help of researchers in every country.

2.5 Past Studies

Past studies in embodied carbon assessment illuminates both the successes and challenges encountered in quantifying embodied carbon in construction sector. Gaps and inconsistencies can be discovered from existing research, and thus improvement of assessment techniques was done as well. By evaluating the methodologies, findings, and implications, the key drivers influencing embodied carbon can be identified. Consequently, the engineers or professional researchers can explore better design choices, production methods, and innovative mitigation strategies for reducing the environmental impact of this carbon emission across a building’s whole lifecycle. Indeed, a lot of existing embodied carbon assessment can be found beyond national boundaries. In terms of variations in industrial building practices, region-specific factors, and the mitigation strategies effectiveness, past studies from various countries can contribute to a more comprehensive understanding of embodied carbon emissions associated with products or materials, and systems.

2.5.1 China Study

Past studies from other countries are focused on residential buildings but not public educational buildings. Therefore, Liu & Leng (2022) has conducted quantitative embodied carbon assessment on an educational building during the low carbon design phase. The height of the educational building is 23.9 m, and it consists of 6 floors above ground and 1 underground floor. Furthermore, the total land size for this project is approximately 6,800 m^2, and the construction area is estimated to be 1,300 m^2. The building structure is made up of 2 main parts which are the cladding podium section and the upper standards floor section. An atrium of 33.9 m is built throughout the building.

Process-based life cycle assessment (LCA) was used in this study. Before we start to compute the embodied carbon amount, the emissions boundary was set. “Cradle to site” was reported for the carbon emissions from construction materials as this phase contributed to the largest portion of embodied carbon. This boundary included the material production stage to material transportation.

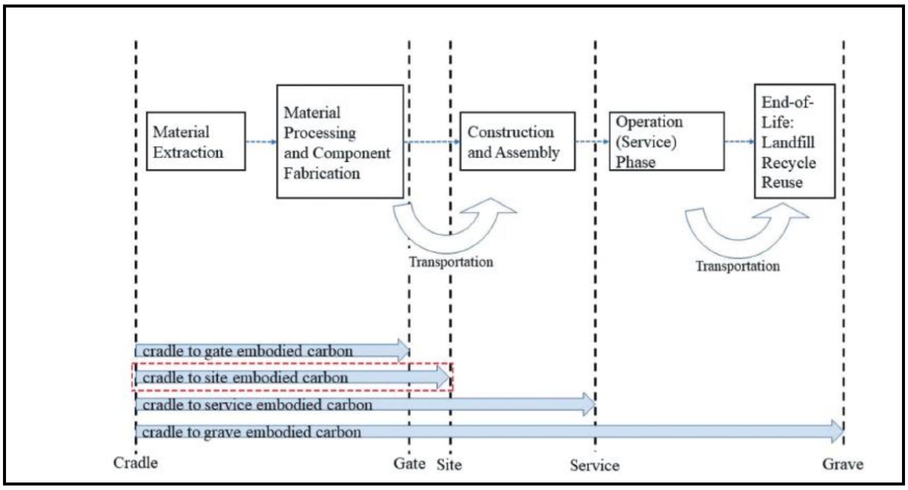


Figure 2.15: System boundaries for embodied carbon calculation (Liu & Leng, 2022).

Liu & Leng (2022) found that measurement of the actual data-related emissions during the design stage of a building is complicated and inconsistent due to the variables in construction stage. Process-based LCA was chosen as the calculation method in this study as it can independently calculate and analyze the carbon emissions at every single stage. Zhang et al. (2019) also supported that process based LCA is the most suitable method for carbon emissions evaluation in design stage.

The main materials for the frame structure of this building are concrete and steel. In this study, major construction materials to be evaluated is determined when the total weight of all the selected materials is not less than 95 % of the total weight of construction materials in the building. Therefore, the materials and elements as shown in **Table 2.3** is the main construction materials being calculated in this study.

Table 2.3: Major construction materials inventory of the educational building.

Material Type	Material Specification
Steel	Large shape steel
	Small and medium steel
	Rebar (Comprehensive)
	Steel truss plate (120 mm)
	Steel of curtain wall
Sand and gravel	Medium (coarse) sand
	Gravel
Cement	Cement Comprehensive
Glass	Plate glass
Concrete	C30 concrete
	C35 concrete
	C40 concrete
	Concrete solid brick
Window frame	Heat-insulating bridged aluminum window frame
Curtain wall	Ultra-high-performance concrete (UHPC)
	Aluminum of curtain wall

All the materials are calculated and recorded in unit of ton while m^2 unit is for frame and plate elements. Comes to transportation carbon emission calculation, Liu & Leng (2022) assume that, by default the concrete transported distance would be 40 km, and 500 km for other materials. According to the previous projects, the transportation mode for this study is heavy-duty diesel wagon transport which is with 0.129 $kgCO_2e/(t.km)$. The carbon emission factors used is in accordance with the Chinese local standards and literature. **Figure 2.16** illustrated the carbon emission factors for each material.

Type of material	Name of material	Unit	Carbon emission factor
Steel	Large shape steel	tCO_2e/t	2.380
	Small and medium shape steel	tCO_2e/t	2.338
	Rebar (Comprehensive)	tCO_2e/t	2.340
	Steel truss plate (120 mm)	tCO_2e/t	2.000
	Steel of curtain wall	tCO_2e/t	2.000
Sand and gravel	Medium (coarse) sand	tCO_2e/t	0.003
	Gravel	tCO_2e/t	0.002
Cement	Cement (Comprehensive)	tCO_2e/t	0.800
Glass	Plate glass	tCO_2e/t	1.130
Concrete	C30 concrete	tCO_2e/t	0.099
	C35 concrete	tCO_2e/t	0.113
	C40 concrete	tCO_2e/t	0.122
	Concrete solid brick	tCO_2e/t	0.160
Window frame	Heat-insulating bridged aluminum window frame (100% native aluminum profile)	$tCO2e/m^2$	0.254
Curtain wall	Ultra-high performance concrete (UHPC)	tCO_2e/t	0.268
	Aluminum of curtain wall	tCO_2e/t	9.500

Figure 2.16: Carbon factors of the construction materials (Liu & Leng, 2022).

With the aid of the process-based method, a total of 13,502.84 tCO_2 was emitted during the material production process and 1,330.19 tCO_2 was found in transportation. As a result, the embodied carbon of the educational building as an overall amounted to a 14,833.03 tCO_2. From this study, steel materials are found to be the largest carbon emitter which contributes up to 60.52 % of total embodied carbon emissions, the second highest would be concrete (24.51 %), and the lowest, sand and gravel (4.19 %). Additionally, further LCA research proved that embodied carbon emissions accounted for around 51 % of the total carbon emissions throughout the whole life cycle of the building (Liu & Leng, 2022).

In this study, Liu & Leng (2022) discovered that the actual distance for transporting construction materials hard to be obtained during the design stage. **Figure 2.17** proved that the production stage was with much higher carbon emissions if compared with the carbon emissions in the materials transportation stage.

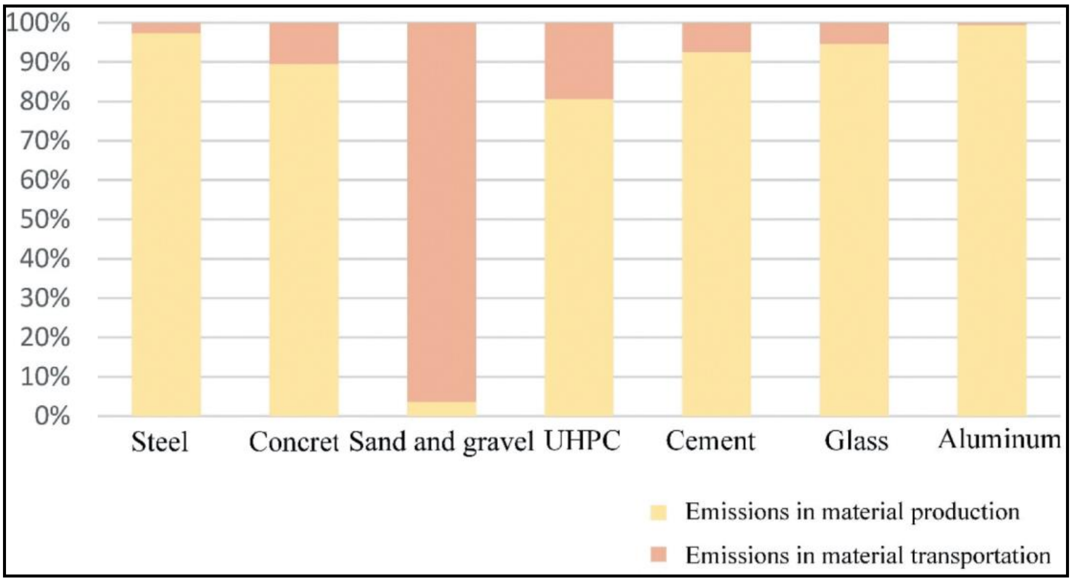


Figure 2.17: Proportion of production and transportation in the embodied carbon emissions of main construction materials. (Liu & Leng, 2022).

Other than that, Liu & Leng (2022) stated that different construction material carbon emission factor databases in China and abroad, normally is associated with large degrees of error up to 30 % in results of embodied carbon emissions. Hence, more localized emission factors are found the be able to improve the accuracy of the results.

2.5.2 United Kingdom Study

A case study was conducted on UK educational building with a gross internal floor area (GIFA) of 1,760 m^2. However, Marsh et al. (2021) claimed that several issues will be faced in embodied carbon assessment: access to data, lack of standardization, data transparency. The majority of products and materials are confirmed; however, some are still in the early stage of estimation with multiple design options such as steel or concrete frames and the final material information is unknown. In the latter case, designers can choose to use a specific manufacturer environmental product declaration (EPDs) prior to confirmation. Marsh et al. (2021) also reported that there are three main types of uncertainty in life-cycle assessments (LCA): parameter (input data like quantities and carbon data), scenario (normative choices such as future scenarios), and model (mathematical relationships). Uncertainty can denote measurement errors such as random and systematic uncertainties as well as unknown factors caused by insufficient data and knowledge (epistemic uncertainty).

The system boundary of the study was set as "cradle-to-gate" approach. This boundary was in range from A1 to A3 product stage embodied carbon (**Figure 2.18**), which is emissions related to raw material extraction and manufacturing, often makes up the majority of EC for various building typologies over 60 years (Pomponi et al., 2018).

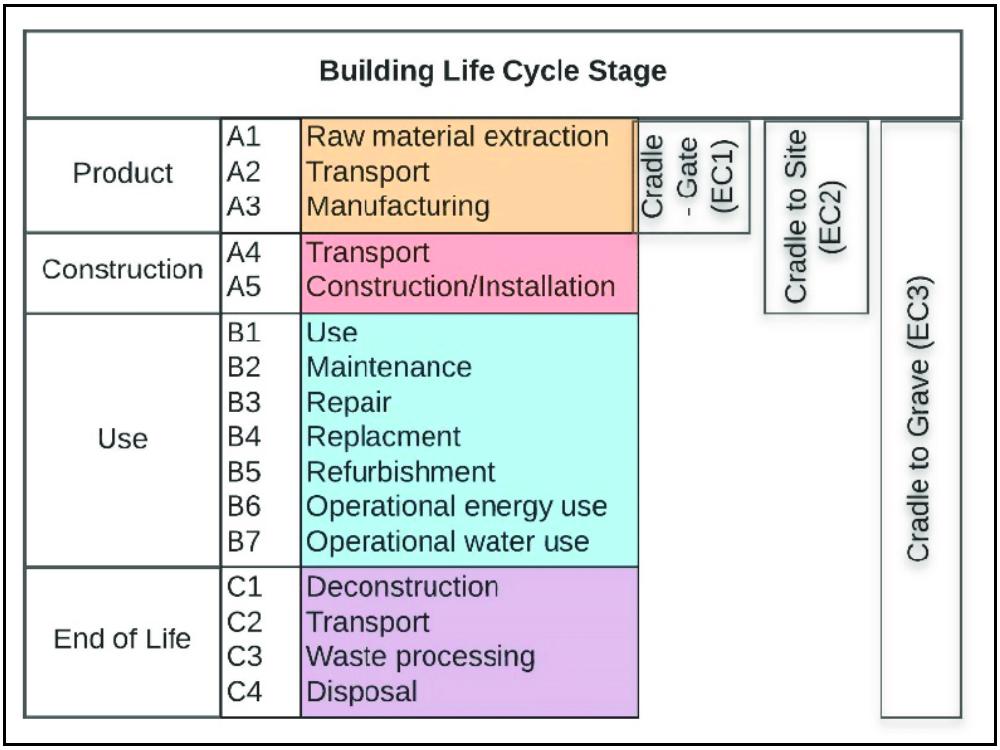


Figure 2.18: Life cycle stages and embodied carbon definition (Pomponi & Moncaster, 2016).

In this study, type of LCA assessment was not specified but in compliance with BS EN 15978:2011 for buildings and BS EN 15804:2012 + A2:2019 for products. This study aims to provide a methodology to quantify uncertainty in embodied carbon assessments for product stage carbon only. Thus, a stochastic modelling called Monte-Carlo simulation was used as the uncertainty propagation method. An uncertainty analysis using this simulation was done in two scenarios: full building, and substructure & structural frame. First, a Life Cycle Assessment (LCA) evaluation for product stages (A1 – A3) was performed in accordance with BS EN 15978:2011; subsequently, Environmental Consequence results will be ranked by the material's highest to lowest GWP impact (kgCO2e), and select the materials responsible for 80% of the EC; proceed to extraction of the mean and standard deviation of the selected materials' embodied carbon coefficient from the ICE material inventory, and in cases of missing data, the average coefficient of variation (CoV) can be utilized; the remaining 20 % of embodied carbon was calculated, applying the average CoV; finally, a Monte-Carlo simulation was carried out with N iterations, aggregating random values from the normal distribution in each iteration to compute the building's total embodied carbon, which will be represented by its mean, standard deviation, CoV, and range. The flow of the methodology was displayed in **Figure 2.19**.

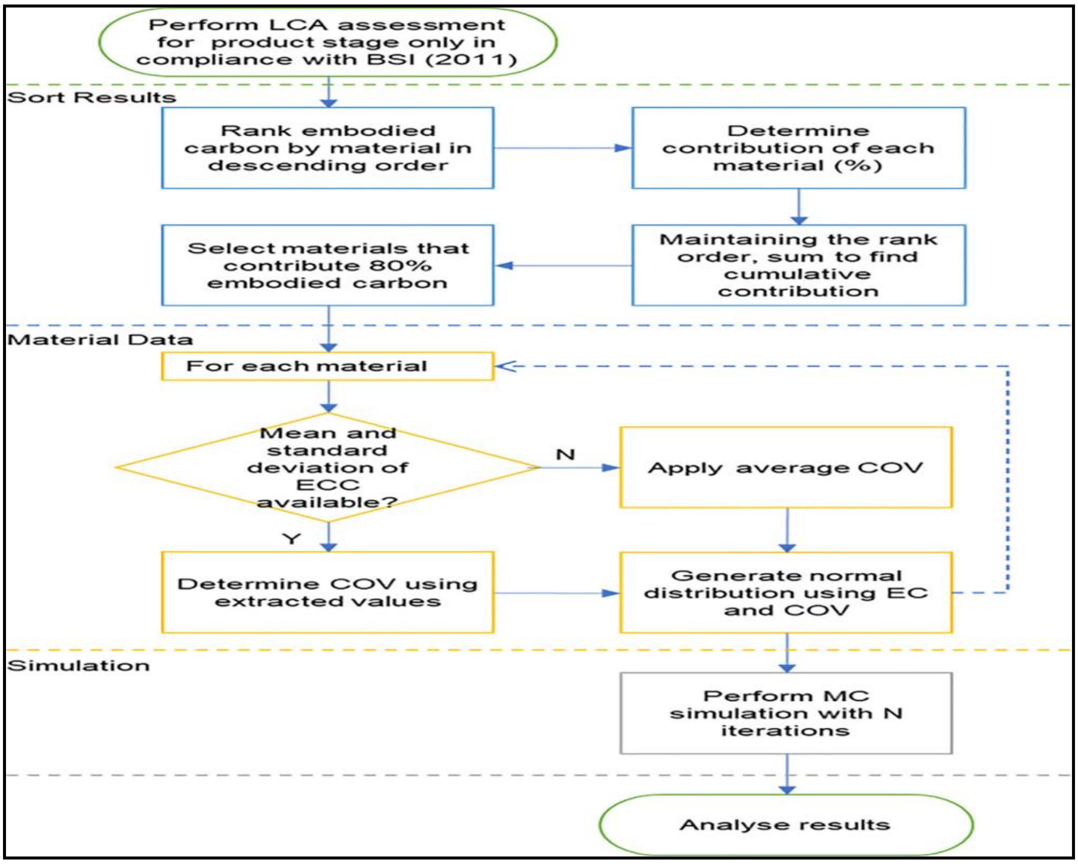


Figure 2.19: BIM-Integrated LCA method flow (Marsh et al., 2021).

In this study, bill of quantity (BoQ) provided the material quantities needed. 93 individual materials were included in the full assessment. **Figure 2.20** presents the building elements that were included and excluded in the analysis. The evaluation was done for two scenarios as mentioned above. Scenario of substructure and superstructure was assessed in frame, upper floors, roof, and stairs & ramps.

	Scenario One – Full Scope	Scenario Two – Substructure and Superstructure (2.1 – 2.4) Only
1 Substructure	Y	Y
2.1 Frame	Y	Y
2.2 Upper floors	Y	Y
2.3 Roof	Y	Y
2.4 Stairs and Ramps	Y	Y
2.5 External Walls	Y	N
2.6 Windows and External Door	Y	N
2.7 Internal Wall and Partitions	Y	N
2.8 Doors	Y	N
3 Finishes	Y	N
5 Services (Lifts only)	Y	N

Figure 2.20: Building components Selection (Marsh et al., 2021).

In addition, this case study considered both products (e.g., windows and doors) and raw materials (i.e. concrete and steel). Moving forward, "construction products" will refer to both raw materials and products. Concrete 1 is specifically designed for substructure, unlike Concrete 2, which has a different specification. Also, the study excluded services (other than lifts) due to insufficient data. The replacement rate and use of high-impact materials in services cause their results to be underestimated in all LCA stages. Other than that, ICE database was used in this study to provide embodied carbon coefficients for product stage. The ICE database, which included UK EPDs, was considered more suitable for this study (Marsh et al., 2021). Nevertheless, EPDs are not consistent in carbon data material, even though product category rules are present. Hence, standard deviations and means are calculated to determine the variability of the material data. The transportation in A2 stage was not mentioned or discussed in this study paper.

The complete building's EC product stage by building element is shown in **Figure 2.21**, in absolute, $kgCO_2e$, and $kgCO_2e/m^2$ GIFA.

	Scenario One ($kgCO_2e$)	Scenario One – ($kgCO_2e/m^2$ GIFA)	Percentage contribution to total (%)
1 Substructure	350,000	198	37.7%
2.1–2.4 Superstructure	200,000	113	21.5%
2.1 Frame			
2.2 Upper floors			
2.3 Roof			
2.4 Stairs and Ramps			
2.5–2.6 Superstructure	227,000	128	24.4%
2.5 External Walls			
2.6 Windows and External Door			
2.7–2.8 Superstructure	80,800	45.9	8.74%
2.7 Internal Wall and Partitions			
2.8 Doors			
3 Finishes	58,800	33.4	6.36%
5 Services (Lifts only)	11,600	6.59	1.26%
Total $kgCO_2e$	928,000	525	–

Figure 2.21: Product stage embodied carbon in full scope scenario (Marsh et al., 2021).

The structural frame (2.1 to 2.4) is responsible for 21.5 % of the product stage EC, while the full superstructure accounts for 54.6 % (2.1 to 2.8). The substructure is the second largest contributor, accounting for 38 % of the total. Thus, the structural frame and substructure comprise 59.2 % of the EC, as depicted in **Figure 2.22**.

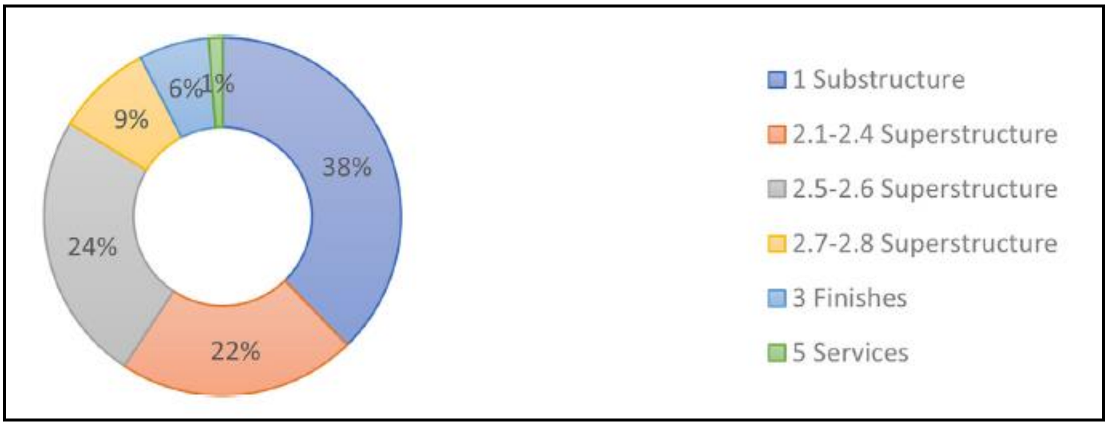


Figure 2.22: Product Stage embodied carbon by building element (Marsh et al., 2021).

Comes to the uncertainty analysis in full scope scenario, the extracted values from ICE database are accompanied by their respective CoV and results. The analysis was determined to require fifty thousand iterations, which were considered adequate in terms of running time, sensitivity, and repeatability, as discussed at the end of this section. **Figure 2.23** illustrated the results of percentage contribution to total EC and cumulative percentage contribution, average and standard deviation EC coefficient from the ICE database, and calculated CoV.

Construction product description	Absolute EC ($kgCO_2e$)	% Total EC	Cumulative EC %	Average EC coefficient ($kgCO_2e/kg$)	Standard deviation EC coefficient ($kgCO_2e/kg$)	Coefficient of variation, CoV (± %)
Concrete 1	187,000	20.1%	20.1%	0.112	0.028	25.0%
Red brick	111,000	11.9%	32.0%	0.225	0.045	20.0%
Concrete 2	99,200	10.7%	42.7%	0.112	0.028	25.0%
CLT	90,900	9.79%	52.5%	1.20	0.136	11.3%
Steel 1	50,800	5.48%	58.0%	2.37	0.645	27.2%
Reinforcement	31,200	3.36%	61.3%	1.09	0.707	64.9%
Window 1	29,800	3.21%	64.6%	N/A	N/A	N/A
Structural steel profiles	27,000	2.90%	67.5%	2.10	0.940	44.8%
Lime mortar	23,600	2.55%	70.0%	0.737	0.319	43.3%
Window 2	21,800	2.35%	72.4%	N/A	N/A	N/A
Glazed door	19,800	2.13%	74.5%	N/A	N/A	N/A
Glulam	19,600	2.11%	76.6%	0.896	0.361	40.3%
Insulation	17,400	1.87%	78.5%	N/A	N/A	N/A
Precast concrete	14,800	1.59%	80.1%	0.152	0.075	49.3%
All remaining items	184,000	19.9%	100%	N/A	N/A	N/A

Figure 2.23: Product Stage embodied carbon by construction product in full scope scenario (Marsh et al., 2021).

The complete building was subjected to an uncertainty analysis on a simulation of 50,000 iterations. The standard deviation of 93,000 $kgCO_2e$ (±10.0%) was observed for the average EC of 930,000 $kgCO_2$-e. The results ranged from 513,000 $kgCO_2e$ to 1,300,000 $kgCO_2e$. **Figure 2.23** revealed the construction products that have the most significant impact, contributing up to 80 % of the total product-stage EC. Their total contribution and cumulative impact on the building was calculated. The top five construction products make up 58.0 % of the estimated total building product stage EC in ranked order. The estimated total is made up of 80.1% from the thirteen construction products listed. CoV values were used to create a normal distribution of possible embodied carbon impacts for each construction product. The average of the overall calculated CoV is 35 % and has been applied to all items or products with no variability information. **Figure 2.24** demonstrated the bar chart for each construction product with CoV error bars indicated.

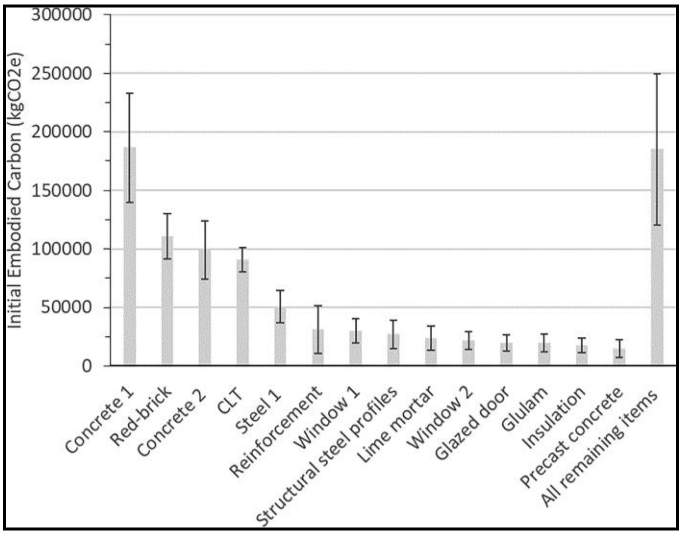


Figure 2.24: Embodied carbon ($kgCO_2e$) for full scope scenario by construction products (Marsh et al., 2021).

Comes to substructure and superstructure scenario, same procedures were conducted. The highest impact construction products contributing up to 80 % of total product stage EC which is similar to full scope scenario. This can be seen from **Figure 2.25**.

Construction product description	Absolute EC ($kgCO_2e$)	% Sup. + Sub EC	Cumulative EC %	Average EC coefficient ($kgCO_2e/kg$)	Standard deviation EC coefficient ($kgCO_2e/kg$)	Coefficient of variation, CoV (± %)
Concrete 1	187,000	33.9%	33.9%	0.112	0.028	25.0%
Concrete 2	98,000	17.8%	51.7%	0.112	0.028	25.0%
CLT	87,800	16.0%	67.7%	1.200	0.136	11.3%
Steel 1	50,700	9.20%	76.9%	2.37	0.645	27.2%
Reinforcement	29,300	5.32%	82.2%	1.09	0.707	64.9%
All remaining items	97,900	17.8%	100%	N/A	N/A	N/A

Figure 2.25: Product Stage embodied carbon by construction product in substructure and superstructure scenario (Marsh et al., 2021).

82.2 % of the estimated total product stage EC was represented by the top five construction products. The CoV for construction products was calculated to be 31%, which has been used for all other items in substructure and superstructure scenario. The bar chart in **Figure 2.26** illustrates each construction product and the CoV errors bar. The product stage EC had an average emission of 551,000 $kgCO_2e$, with a standard deviation of 65,700 kgCO2e (±11.9%). The results ranged from 247,000 $kgCO_2e$ to 858,000 $kgCO_2e$.

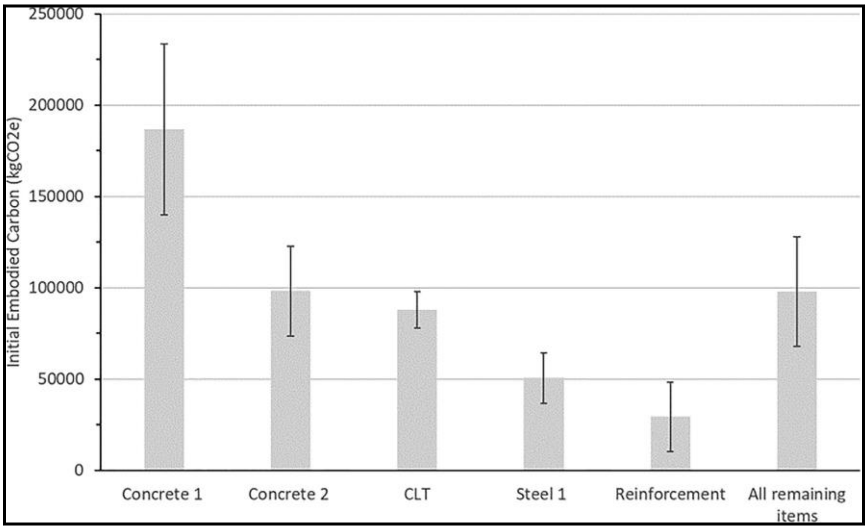


Figure 2.26: Embodied carbon (kgCO_2e) for substructure and superstructure scenario by construction products (Marsh et al., 2021).

This study revealed that assessments that consider only the product stage (from cradle to gate) can overlook nearly 40 % of carbon emissions over the entire lifespan of a product. Other LCA stages can be excluded in substructure and superstructure scenario as the carbon associated with replacement and refurbishment is lower in structures over the 60-year life cycle, in comparison to finishes, façades, and services, making it less concerning. The uncertainty procedure proposed in this study can be improved by including additional LCA stages (Marsh et al., 2021).

2.5.3 Turkey Study

Most of quantitative studies of embodied carbon emissions have focused on a single building perspective. The impact of transportation, distance to the city center, and infrastructure is typically not considered when analyzing a single building. In Ankara, Turkey, 3 neighborhood-scale mass housing projects were the focus of a research. The researchers believed that further understanding the sustainability of the built-environment necessitates research on neighborhood-scale settlements. A reference model for large-scale residential constructions in Turkey is to be developed by analysis of the embodied carbon of these buildings. 3 housing projects that constructed in tunnel formwork system were examined, which project 1, project 2, and project 3 were constructed with two, six, and five building types, respectively. These projects' description is displayed in **Table 2.4**.

Table 2.4: Characteristics of the mass housing projects.

Project type	Area (m^2)	Area of construction (m^2)	Stories amount	Blocks amount	Dwellings number	Other facilities
Project 1	45,812	60,128	18	14	277	3 children's playgrounds
						Walkways
						Driveways
						Car park
Project 2	67,597	166,733	89	32	1,219	6 children's playgrounds
						Seating area
						Basketball courts
						Underground car park
						Technical facilities
Project 3	35,518	57,887	51	13	415	2 children's playgrounds
						Semi-closed seating
						Technical facilities

System boundary of the study was modelled as "cradle-to-site" which incorporates resource extraction, manufacturing, and material transportation to factory gate and site. The study employed hybrid life cycle assessment (LCA) methods, which allowed the researchers to focus on the data that was available and replace generic data for any missing data (Kayaçetin & Tanyer, 2018). In this study, an additional system named GaBi software was used to create life cycle modelling and environmental balances with available data from manufacturers. The assessments were carried out utilizing the GWP impact category and the IPCC characterization elements in accordance with the CML 2001 assessment methodology. The amount of heat trapped in the atmosphere by greenhouse gases within a given period was measured in GWP. Additionally, the building typology cluster and the urban cluster (two major clusters) evaluated the mass housing schemes at various scales.

In this study, BOQ was the data source for the analysis under building typology cluster. The amount of building components can be derived from BoQ. The assessment of 13 apartment blocks was conducted through analysis of 26 building components. **Figure 2.27** demonstrated the quantities of building components used for each block in unit of kg, tonne, and m^2.

Cluster	Building Component	Project 1		Project 2						Project 3					Unit	Kg per unit
		A1	10A	A2	L2	M2	N2	R2	S2	A3	C3	D3	L3	S3		
Roof	Roof Cladding/Sandwich	517	837	301	395	233	221	218	279	250	225	252	442	252	m^2	3.42
	Roof Heat Insulation	517	837	0	0	0	0	0	0	90	72	82	166	108	m^2	1.30
	Roof Waterproofing	543	879	116	271	116	116	103	102	90	72	82	166	108	m^2	2.80
Exterior Walls	Brick Wall 25 cm	976	0	0	185	0	0	45	0	0	0	0	0	0	m^2	96.03
	Brick Wall 20 cm	117	2138	1,592	3,330	1,713	1,296	1,397	1,622	1,376	1,484	1,560	4,159	2,812	m^2	77.00
	Exterior Paint	1,978	6,627	565	1,249	578	570	320	403	714	158	790	2,664	1,685	m^2	0.13
	Exterior Heat Insulation	1,640	5,267	3,406	5,334	3,105	3,789	2,221	2,188	1,536	1,637	1,521	5,274	3,357	m^2	7.00
	Exterior Cladding	1,673	5,436	0	0	0	0	0	0	0	0	0	0	0	m^2	13.50
	Exterior Plastering	1,978	6,627	565	1,249	578	570	320	403	714	714	790	2,664	1,685	m^2	1.00
Interior Walls	Brick Wall 13.5 cm	274	765	12	93	30	20	15	15	0	0	0	0	0	m^2	51.90
	Brick Wall 10 cm	1,430	3,084	1,440	2,653	1,137	1,540	1,683	1,581	729	714	794	1,863	1,703	m^2	38.50
	Ceramic Wall Tile 40 × 40cm	841	3,054	1,919	2,732	1,436	1,440	1,152	,1691	738	608	663	2,260	1,430	m^2	45.00
	Interior Paint	5,949	21,133	11,091	20,925	9,939	10,032	8,662	9,860	4,348	4,813	4,797	19,295	12,320	m^2	0.13
	Interior Plastering	6,161	17,453	13,010	23,693	11,067	11,472	9,814	11,551	4,348	4,839	4,835	19,400	12,392	m^2	1.00
Windows	Window Profile	5,949	10,847	10,320	19,293	7,921	7,907	3972	6,975	5,539	482	547	1638	1,249	kg	1.00
	Window Glass	340	620	936	1461	679	615	385	554	303	244	279	839	733	m^2	8.00
Floors Ceiling	Ceramic Floor Tile 40 × 40cm	717	2,044	2,079	3,731	1,761	1,608	1,257	1,822	1,059	888	818	2,944	1,669	m^2	45.00
	Stone Tile	97	656	507	1664	578	574	599	470	168	235	216	1,150	612	m^2	50.00
	Laminated Wood	1,113	3,860	2,089	4,213	1,932	1,812	1,489	1,919	860	848	1,025	3,656	2,439	m^2	7.00
Basement	Foundation Concrete	384	945	328	516	268	239	253	308	231	215	243	402	253	m^3	2,350
	Foundation Steel Reinforcement	20	67	20	37	18	18	18	22	17	16	18	30	19	ton	1,000
	Basement Heat Insulation	664	1,187	456	641	346	178	322	374	454	553	573	609	631	m^2	7.00
	Basement Waterproofing	975	1,575	898	1,252	678	520	876	825	1,204	1247	1,359	1,919	1463	m^2	2.80
Structure	Structural Concrete	874	3,183	1,995	4,133	1,840	1,791	1,395	1,758	1,042	970	956	3403	2,200	m^3	2,350
	Structural Steel	6	14	11	15	9	8	8	11	5	77	5	9	5	ton	1,000
	Structural Steel Reinforcement	106	243	144	331	147	143	112	141	94	87	86	306	198	ton	1,000
Building Area		2,709	8,257	5,111	10,356	4,718	4,537	3,746	4,781	2,491	2,313	2,464	9,274	5,707	m^2	–

Figure 2.27: BOQ of each block (Kayaçetin & Tanyer, 2020).

Environmental product declaration (EPD) documentation, manufacturer process data, and generic data from the GaBi software database were the sources of the environmental data for these building components (Kayaçetin & Tanyer, 2020). For their specific products, 10 out of 26 construction components have available EPD. EPD documents of comparable building components were used for nine out of the twenty-six building components, and average values from EPD documents of comparable building components were used for the other two. Kayaçetin & Tanyer (2020) created LCA models based on the process data supplied by manufacturers in order to supply generic data in the event that no data is available. The components' effects on the environment for each construction block were shown in **Figure 2.28**.

Building Cluster	Building Component	Component ID	GWP ($kg_{CO2\text{-}eq}$/kg)
Roof	Roof Cladding	Y.18.201	5.09
	Roof Heat Insulation	Y.19.061/004	0.62
	Roof Waterproofing	Y.18.461/005	1.70
Exterior Walls	Brick Wall 25 cm	Y.18.001/C08	0.49
	Brick Wall 20 cm	Y.18.001/C06	0.49
	Exterior Paint	Y.25.004	1.33
	Exterior Heat Insulation	-	1.09
	Exterior Cladding	-	0.77
	Exterior Plastering	27.525/1	0.19
Interior Walls	Brick Wall 13,5 cm	Y.18.001/C04	0.49
	Brick Wall 10 cm	Y.18.001/C02	0.49
	Ceramic Wall Tile 40 × 40cm	Y.26.008/ 405B	1.91
	Interior Paint	Y.25.003	1.88
	Interior Plastering	27,531	0.19
Windows & Doors	Window Profile	Y.23.244	17.42
	Window Glass	Y.28.645	2.15
Floors & Ceiling	Ceramic Floor Tile 40 × 40cm	Y.26.008/ 405A	1.91
	Stone Tile	-	0.43
	Laminated Wood	-	2.59
Basement	Foundation Concrete	Y.16.050/03	0.11
	Foundation Steel Reinforcement	Y.23.014–015	0.85
	Basement Heat Insulation	Y.19.056/013	1.09
	Basement Waterproofing	Y.18.461/005	0.62
Structure	Structural Concrete	Y.16.050/06	0.11
	Structural Steel	Y.23.101	0.31
	Structural Steel Reinforcement	Y.23.014–015	0.85

Figure 2.28: Inventory template (Kayaçetin & Tanyer, 2020).

The GWP category was used to determine the environmental effects. Component impact and quantity were multiplied to determine the environmental impact values. Every building block in the example projects has a template. The structural landscape, which includes parking lots, playgrounds, and small-scale technological areas, was considered under the urban cluster. **Figure 2.29** presented the quantity of each component needed for the landscape work for each project.

Cluster	Landscape Component	Project 1	Project 2	Project 3	Unit
Structural Landscape	Structural Concrete	711	2,201	1,343	m^3
	Structural Steel Reinforcement	31	101	61	ton
	Structural Steel	10	33	20	ton
	Stone Tile	88	281	191	m^2
	Concrete Tile	603	2,210	1,106	m^3
	Pavement Tile	1,940	6,219	3,621	m^3
	RW Concrete	5,950	19,351	12,052	m^3
	RW Steel Reinforcement	411	1,477	950	ton

Figure 2.29: The amount of each component required for landscape works (Kayaçetin & Tanyer, 2020).

In order to evaluate transportation infrastructure, in this study, the calculations were conducted for a period of 50 years in terms of dwellings number, travels frequency, distance to city center, and kgCO_2eq emissions for transportation infrastructure per passenger km travelled (Kayaçetin & Tanyer, 2020). Modes of transportation were assumed as private car, bus, and light-rail system. The statistic data on transportation in Ankara were retrieved from the Urban Transportation Technology Accessibility Implementation and Research Center.

Values of GWP in kgCO_2eq in terms of total and per m^2 on three levels: component, building, and neighborhood. Project 2 accounted for the highest GWP value: 67,774 tons CO_2eq, while the project 1 contributed to the medium value of GWP in 23,094 tons CO_2eq, and project 3 was with the lowest GWP value which was 23,094 tonnes CO_2eq. Embodied carbon in each building component was also calculated in unit of kgCO_2eq/kg. **Figure 2.30** presented the results of EC in building components in unit of GWP (kgCO_2eq/kg). Most of the embodied carbon values were found to be higher than the values in ICE database. This variance might be due to the impact of transportation.

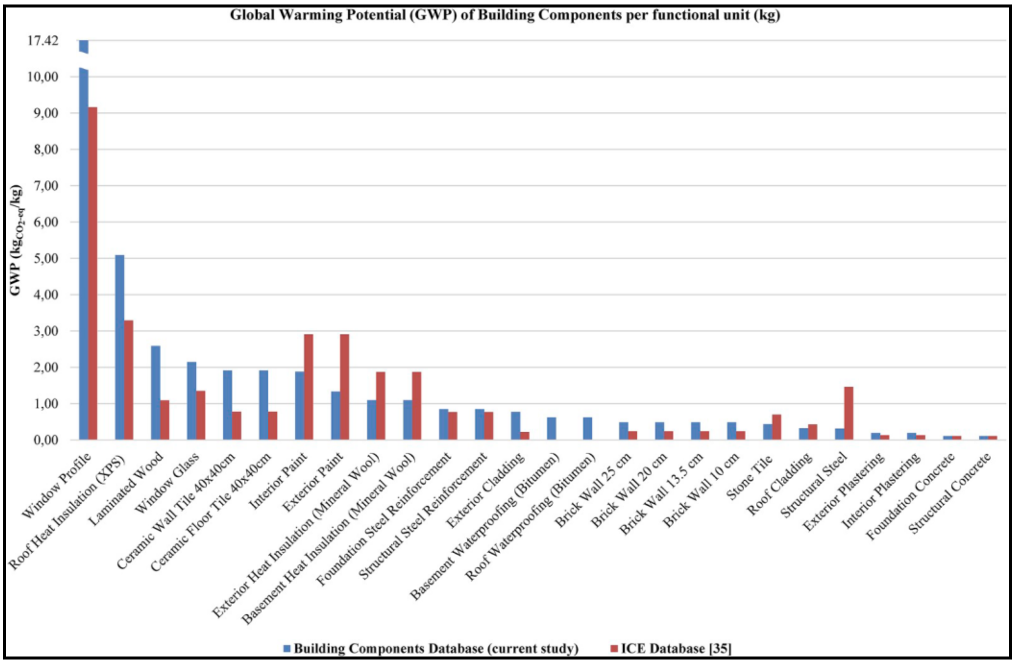


Figure 2.30: Embodied carbon of building components in terms of GWP (Kayaçetin & Tanyer, 2020).

Structural concrete accounted for the largest GWP share ranging from 30 % to 40 %. Concrete is with a low GWP/unit but in large consumption amounts in buildings. Ceramics came in second place because they have high GWP/unit and are commonly found in the case buildings (17-21 %). Steel reinforcement, foundation concrete, and aluminum window profile also cause significant environmental impacts. By multiplying the GWP per kg or m^2 with the precise quantity in the building for each component, the GWP of 13 distinct apartment blocks in these 3 projects can be computed. The results in **Figure 2.31** disclosed that the average GWP per m^2 of these buildings was 273.5 $kgCO_2eq/m^2$, and GWP values for each building type of these housing projects.

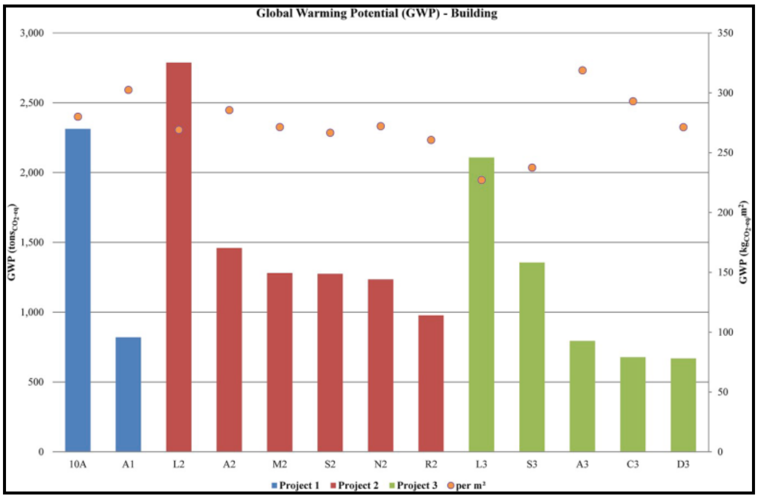


Figure 2.31: GWP of the building in each stage (Kayaçetin & Tanyer, 2020).

In accordance with this study, the increase in the stories number is associated with the decrease in GWP/m^2. This is because the basement components and roof give similar impacts without affected by the increased number of stories; therefore, decreasing the GWP per m^2. Around 9 % of total GWP was attributed to structural landscape in the study. Landscaping emits 37.4 $kgCO_2eq$ per building m^2. Local GWP also increased due to transportation infrastructure. The project findings indicate that the transportation infrastructure's effect on the total GWP was between 22 % and 28 %, which is with embodied carbon of 94.7, 93.1, and 110.6 $kgCO_2eq$ per building m^2. The neighborhood level, which encompasses building, structural landscape and transportation infrastructure, accounts for an approximately 409.2

$kgCO_2eq/m^2$, referring to the LCA analyses of three mass housing projects. Buildings account for 66.6 % of emissions, at an average of 272.4 $kgCO_2eq/m^2$, while 9.1 % of emissions come from structural landscape at 37.4 $kgCO_2eq/m^2$, and 24.3 % come from transportation infrastructure at 99.4 $kgCO_2eq/m^2$.

The embodied carbon of building components was compared to the Inventory of Carbon and Energy (ICE) database while the embodied carbon of buildings was compared to the database of embodied Quantity outputs provided by MIT Building Technology Program. Kayaçetin & Tanyer (2020) stated in their study, there was one of the components, aluminum window profile having significantly different GWP value, measuring at 17.42 $kgCO_2eq$ while the ICE database showed 9.16 $kgCO_2eq$. This difference was attributed to the influence of transportation. The aluminum window profile was imported other countries, and both ships and trucks were used for transportation. In fact, local materials emit much less compared to the emissions produced from transporting materials to the construction site, which was over 11 times greater. An impact of 3.14 $kgCO_2eq$ was caused by the transportation of the aluminum window profile. The differences that are left are within the ICE database range, with a ±30 % tolerance. Hence, local material supply chain is preferred in construction sector to reduce embodied carbon emissions.

2.5.4 India Study

A quantitative study on a high-rise residential building can be used as a model to analyze the majority of the similar buildings in India. This study was conducted by a team of researchers using the building information modelling (BIM) approach to perform life cycle assessments (LCAs) based on existing conditions. CO_2 emissions and other environmental data have been a focus of this research to include in BIM models. A comprehensive BIM-based LCA assessment cannot be carried out due to limitations on object information in building elements. This study is also aiming to use the development of a BIM–LCA integration procedure to gather material quantity information and link it with environmental data. The general idea is to use a neutral file format for open file-based interchange. Subsequently, a visual interface is being developed to improve the documentation and quality of BIM-based life cycle assessment.

The high-rise residential building is with 30 stories, a total height of 109 m, excluding mumty and terrace. Also, the average gross area for this building is 1000 m^2 per story, and the roof area was found to be 635 m^2. There are two housing units with 4 bedrooms on each floor from the ground to the 21st. There are 5 common lifts and 2 common staircases over the 21 stories. In addition, the 22nd floor has a bar and communal hall. The building is 23 floors tall with two apartments per story. Each apartment has two bedrooms, a shared set of stairs, and three shared elevators. There is a single-room apartment with one dwelling unit on the remaining two stories. **Table 2.5** illustrated the building details.

Table 2.5: Details and characteristics of the studied building.

Properties	**Building Specification**
Floors number	30 floors
Dwellings number	56 units
Area of Base	1000 m^2
Roof Area	635 m^2
Floor Height	3.2 m
Total height	109 m

Working drawings also include precise information about architecture, functionality, and operations; a Revit model is created based on the specifications of each piece. According to EN 15978, the building reference service life is 75 years in this study. The key safety precautions comprise the BIM model and information about the mapped and imported material.

System boundary of the study was modelled as “cradle-to-grave” which incorporates material extraction, manufacturing, transportation, construction, operation, and disposal. Maintenance, refurbishment, repair, and replacement were excluded in this study. The phases for this building were A1 to A5 stages (product and construction process stages), C1 to C4 stages (end of life stage), B1 and B6 to

B7 stages (operation stage). The life cycle phases that were considered have been highlighted as shown in **Figure 2.32**.

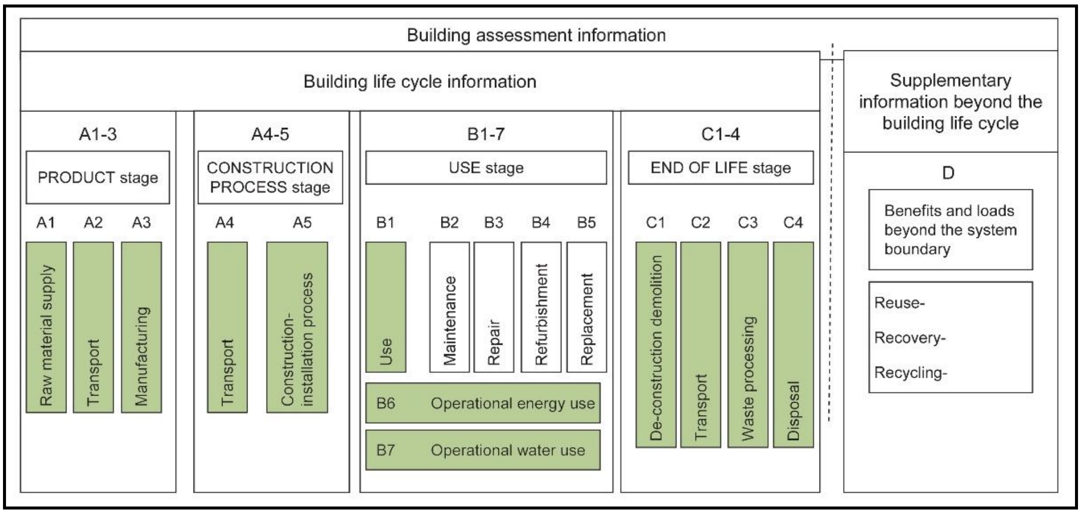


Figure 2.32: Phases selected for the LCA assessment (Alotaibi et al., 2022).

The study applied a BIM-based Life Cycle Assessment (LCA) methodology. By merging process and I-O data, process-based hybrid analysis can remove downstream and horizontal truncation (Atmaca & Atmaca, 2015). An approach consisting of 6 steps is used to assess the requirements for performing a BIM-based LCA analysis. The first step is to combine all the models that will be studied (structural and architectural models, for example). To analyze the consequences of building solutions from different disciplines holistically, a single model that incorporates all the models is required. The second stage is to evaluate the data in the BIM model. If the model's data is exported, this procedure will be easy to complete. Lastly, do the verifications of the exported list. The model may include identically named components from the same family or identical elements from different families. In order to overcome these issues and enable LCA tools to reliably read the bill of goods, it is recommended that the entire project be standardized in the third phase. After making changes to the model, export an updated bill of quantities to assure consistency. To ascertain their applicability to project elements, materials, and future renovations, environmental, economic, and mechanical data will be integrated at the project's fourth stage. The required information for analysis can be added to this list. Using this list, the information in this list can be imported into the

BIM model. Lastly, this data may be leveraged to conduct a complete LCA study using the LCA plugin, similar to the one-click LCA utilized in this case (fifth step). All the workflow in estimation of embodied carbon was concluded in the **Figure 2.33**.

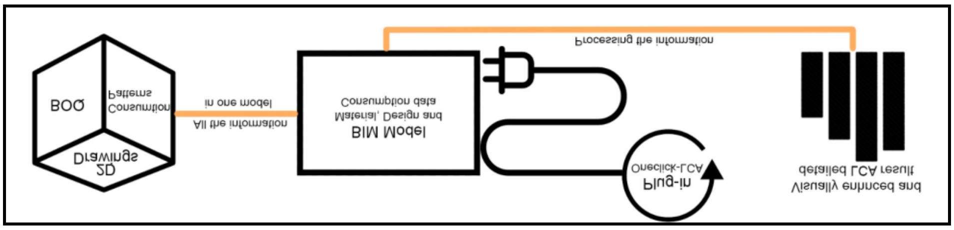


Figure 2.33: Workflow and process in estimating embodied carbon (Alotaibi et al., 2022).

The process of estimating embodied carbon throughout construction, operation, and demolition is fully demonstrated in **Figure 2.34**. Except for the first step of modeling, each step in the table can be easily evaluated using the LCA plugin.

STEPS	GOAL	REQUIREMENT	OUTPUT
Modeling	To develop a model that has all the information in regard to the material and design.	Use of architectural and structural plans on software, such as Revit.	A well-informed BIM model of the building.
Estimate the quantity of material needed and total duration of use	To create an accurate bill of goods.	Estimate the productivity of equipment. Identify temporary material usage/work	Emission due to transportation of material and equipment to the site Emission due to operation of equipment
Estimate the cradle-to-grave embodied carbon	To identify the embodied carbon in the construction and demolition stage.	Manufacture LCA reports. Use of existing LCA Inventories, such as ICE 3.0.	Depreciation in EC of equipment Depreciation in EC of temp. material
Estimate consumption and renovation requirements	To create a consumption pattern of energy and water. To identify the life of equipment over the whole life of buildings.	Annual energy and water bills. Selected equipment details.	Emissions caused by energy and water consumption. Emission caused by renovation changes.
Estimate the embodied carbon	To identify embodied carbon in the operational stage.	Conversion of electricity and other consumption with the fossil used in producing it. Embodied carbon in the renovation.	Increase in EC of consumption Increase in EC of equipment
Estimate the embodied carbon of construction and demolition waste	To identify the carbon emissions incurred in the end-of-life (EOL)	Type of material used and the original design of building component. Availability of required local technologies for reuse and recycling and availability of local market for the product and local landfills for disposal of debris.	Carbon emissions incurred in the EOL phase of building's life cycle.

Figure 2.34: Complete steps to estimate embodied carbon (Alotaibi et al., 2022).

Bill of quantities (BoQ), and the environmental impact assessment (EIA) report were taken as the basis for the methodology in this research. EIA report is used to identify the construction activities. Alotaibi et al. (2022) assumed that all the products manufacturing was took place on-site or transported within a 30 km radius. Besides, materials considered to be evaluated in estimation of embodied carbon were displayed in **Table 2.6**. The main materials used were identified as concrete, steel, wood, and plaster.

Table 2.6: Building elements in the selected building.

Building Elements
Façade, external walls
Slabs, beams, ceiling, roof, and roofing decks
Doors, windows
load-bearing vertical components, columns
Other components

The kilograms (kg) were used to express the amounts unit. Other measurements included meters (m), cubic meters (m^3), tonne (t), and square meters (m^2). The material amounts were multiplied by the EC coefficient for every material mentioned in ICE version 3.0. Subsequently, the EC values of all the components in each element were added to determine the elemental EC. The elements EC values were multiplied to determine the EC of the building skeleton. Units of $kgCO_2e$ and $kgCO_2e$ normalized per m^2 of gross floor area ($kgCO_2e/m^2$) were the reported EC effect statistics. The CO_2 emission factor for the power consumed in the chosen building is determined using the primary emission factor from the IEA 2019. To calculate total demolition emissions, the weight of dismantled building waste is converted to truckloads for transportation.

Figure 2.35 shown the result of embodied carbon in $kgCO_2e$ based on life cycle stages. Materials represent 37.5 % or 11,631,188.20 kg CO2e, while energy accounts for 49.4 % or 15,322,608 kg CO2e. The remaining 13.1 % impact is distributed amongst various stages: 5.5 % for maintenance, 3.4 % for transportation, 2.2 % from water, and 2 % for end-of-life. The materials and energy contributed to major CO_2 in the building LCA assessment. This analysis is analysed considering the embodied energy which is the energy required for the building operation.

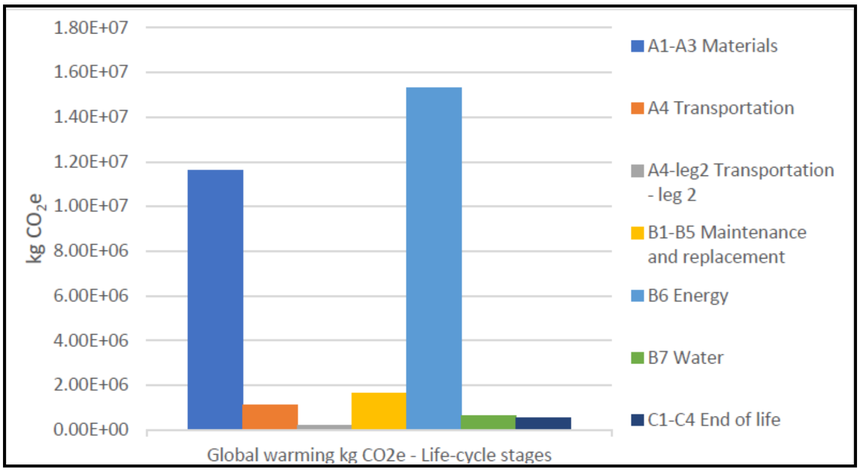


Figure 2.35: Embodied carbon based on life cycle stages (Alotaibi et al., 2022).

Including cooling and heating load, the average energy consumption in a composite climate was found to be 300 kWh (Singh et al., 2018). The energy consumption of the families residing in the chosen building will be 201,600 kWh per year. 4780 kWh of energy is consumed each year by the basements, water pumps, and two remaining floors. The calculation was done in manual by determining the appliance load and usage hours. As a result, complete tower has a total energy consumption of 249,402 kWh. According to the EIA report, the building's water consumption is 34,020 Litre per day and requires 12,417 m^3 annually. The embodied carbon amount in terms of element classification was shown in **Figure 2.36**. Horizontal elements contribute to 55.2 % of the overall carbon emissions, whereas vertical components contribute to 40.9 % of emissions, and the rest of the elements, such as windows, doors, and other structures, account for the remaining emissions. Electricity use was the largest contributor of CO_2.

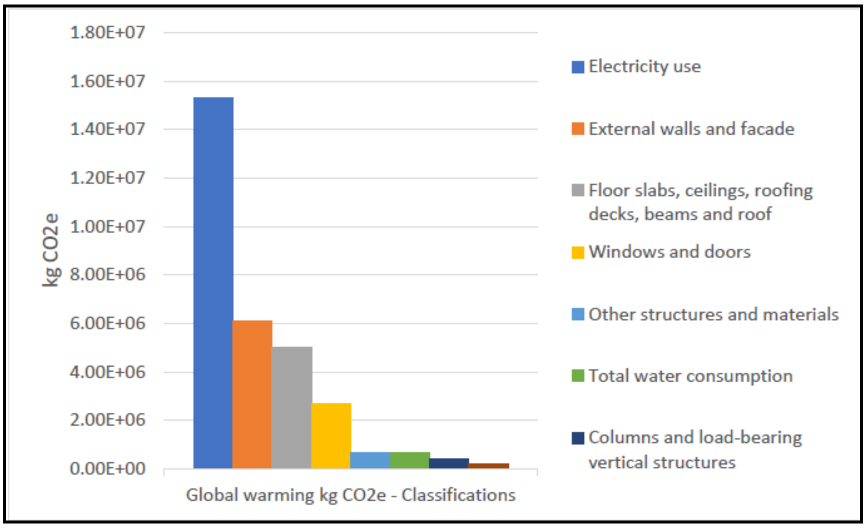


Figure 2.36: Embodied carbon in Construction Element (Alotaibi et al., 2022).

Analysis shows that the carbon emissions from the chosen building in India are 414 kg CO_2e/m^2/year, resulting in 14,196 kg CO_2e/m^2 throughout its lifecycle. Both process-based and hybrid-based analyses of 448 kg CO_2e/m^2/year and 368 kg CO_2e/m^2/year were followed by the selected case studies, and the analyzed data are remarkably close to them.

CHAPTER 3

METHODOLOGY

3.1 Assessment Approach

The embodied carbon is the carbon footprint of a product, building, or infrastructure project throughout the project's life cycle. It can be measured and quantified in terms of all greenhouse gas emissions generated within the boundaries of "cradle-to-site" or "cradle-to-gate". With the aid of this systematic evaluation process, a precise and numerical data can be developed for further mitigation of carbon emissions. The quantitative assessment of embodied carbon was conducted in terms of life cycle assessment (LCA) in accordance with ISO 14040 and ISO 14044. Before quantifying the embodied carbon in a building project, embodied carbon emissions boundary was defined. The operational phase will be excluded, and "cradle-to-site" boundary was chosen in this study. **Figure 3.1** indicates the life cycle stages in terms of A, B, C, and D stages.

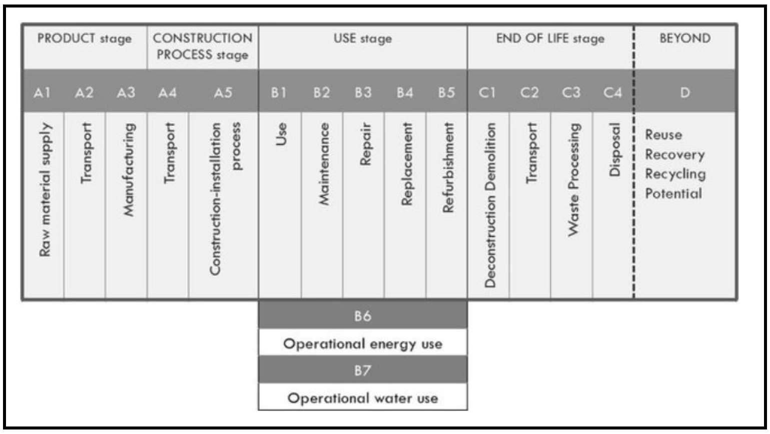


Figure 3.1: Embodied carbon life cycle stages (Moncaster & Symons, 2013).

The process based LCA method was used in this study. This method entailed defining a product system and its boundaries, and then documenting all the inputs and outputs that happen between that system and the environment. Materials and energy are both considered flows, and once the inventory was created, each item's environmental impact was assessed. The corresponding research basis was then established, which involves introducing the project, determining carbon emission inventories, and collecting data on building material consumption and transportation. The gathering of data on system inputs and outputs from primary or secondary sources is necessary for embodied carbon assessment. Collecting primary data requires accessing suitable sources, which can be resource intensive. Secondary data is more easily accessible but may not be fully representative of the process or material being assessed. Carbon factors are reported in units of carbon dioxide equivalent, CO_2e. For example, carbon factors for materials are generally reported in terms of mass or volume, with units of $kgCO_2e$ per kg (or tonne) or per cubic meter (or other appropriate unit) of material; whereas, for energy can be reported per megajoule or kWh of electricity, or per unit of fuel consumed (e.g., liters). The material amounts were multiplied by their respective embodied carbon coefficients, as stated in the data inventories chosen. By adding the EC values of all materials in each element, the elemental embodied carbon was calculated. The elemental EC values were then used to calculate the embodied carbon of the building skeleton. For the construction, installation, and transportation activities, embodied carbon emissions were calculated by multiplying economic activities by their corresponding emission factor. Total carbon emissions for the economic activity process were determined by summing up the emissions of each segment or stage. Also, the results were being displayed in bar charts to show the portion of embodied carbon in each stage and each element. The study flow for this research was summarized as in **Figure 3.2**.

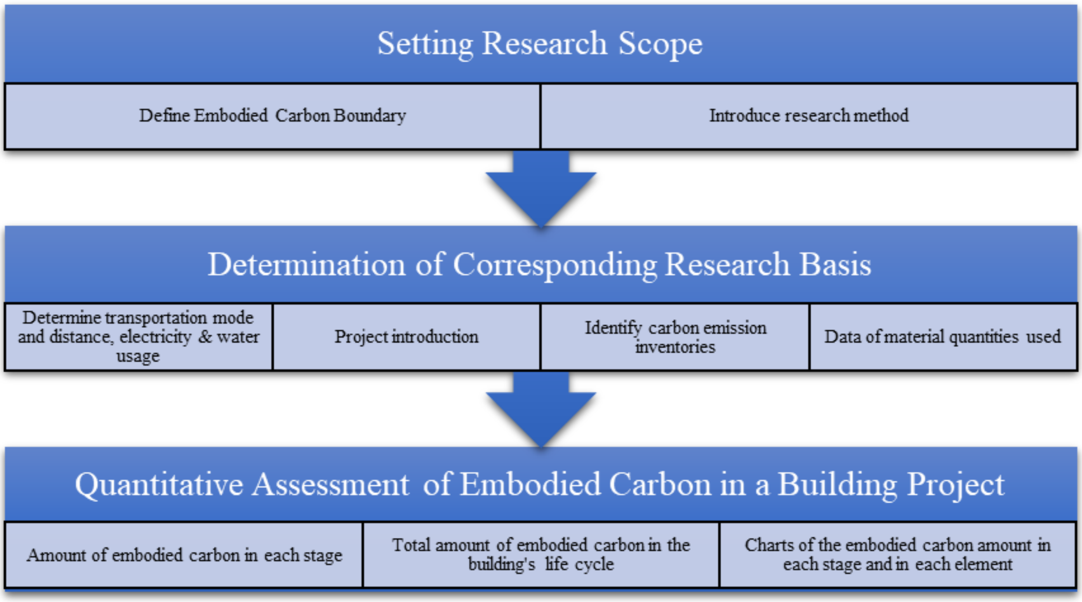


Figure 3.2: Study Flow of Embodied Carbon Assessment.

3.2 Project Description

Table 3.1: The basic information of the case building.

Project Details	Description
Assessment Objective	Embodied Carbon only
Building type	Residential
Location	Kampung Serdang, Manjung, Perak
Size – GFA per unit (m^2)	92.903
Total unit	347
Assessment Scope	A1-A5 stages
Data sources	Material quantities – Bill of Quantity
	Carbon data – CIDB database

The building project selected in this research is a residential building. 347 units of low-cost single-story terrace houses are built in Perak, Malaysia. This building is classified into end unit, inter unit, and corner unit which are different in material usage and the construction area. Corner unit of the building is used in this study to conduct embodied carbon assessment. The gross floor area (GFA) of the corner unit of the building was 92.903m^2.

3.3 Data Collection

First set of data required is the inputs and outputs from the building. Physical quantities of materials and energy at each life cycle stage were used for process analysis. The second set of data needed are the carbon factors corresponding to each input and output. Ideally, data from the Malaysian construction industry, including material properties and prices, was preferred. National average data has been utilized by certain researchers instead of overseas data in order to enhance the reliability of the results. However, no comprehensive life cycle inventory analysis was conducted using data specific to Malaysia. Therefore, this research study utilized both local and international data, including ICE v3.0 and United Kingdom (UK) government data (https://www.carbonfootprint.com/international_electricity_factors.html), for the compensation of a scarcity of local data.

This study focused on embodied carbon emissions during some project phases. Additionally, this study did not encompass the recurrent carbon emissions involved in use stage (B1 to B5). The reason was due to the numerous assumptions needed to encompass the complete lifespan of a structure and the project may subject to change locally. Furthermore, stage A5 can be classified into 2 types: A5w (material wastage on site) and A5a (site activities). The Malaysian construction industry does not commonly practice reuse, recovery, and recycling, resulting in insufficient data for calculating the embodied carbon assessment in stage A5w and stage D. Thus, the project phases considered were highlighted as in **Figure 3.3** which are A1 to A5a stages.

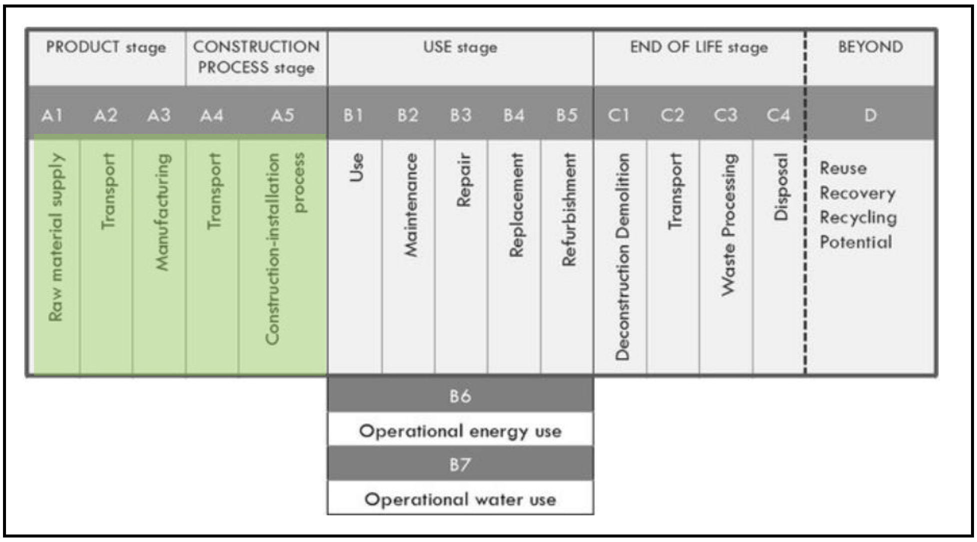


Figure 3.3: The selected project phases.

3.3.1 Construction Material Data

The inventory of building materials, products, and components is required to quantify the embodied carbon footprint during A1 to A3 stages. Material quantities were acquired from quantity survey data, and a standard bill of quantities (BoQ) in several units. These units included kilograms (kg), tonne (t), meter (m), square meter (m^2), and cubic meter (m^3). To ensure the reliability and accuracy of the results, the carbon emission factors of the selected construction materials were extracted from the inventory developed by Construction Industry Development Board (CIDB) Malaysia. However, there are only 500 embodied carbon data information available in this local inventory, thus, Inventory of Carbon and Energy (ICE) ver. 3.0 database was chosen as the backup database to use for addressing the unavailable embodied carbon data.

3.3.2 Transportation Data

Some assumptions need to be made in transportation stage which are A2 and A4 as the actual transport distance, type of vehicles, and mode of transport might be different in some situations. While for amount of fuel consumption were excluded due to unavailable record of the fuel. In Malaysian context, all average mode of transportation used is indicated in terms of heavy goods vehicles, tonnage, etc. The calculation of embodied carbon for transportation within the cradle-to-gate boundary should be based on the mode of transport, emission factors of transport per kg km, and the transportation of 1 kg of materials such as gCO_2/kg/km. Information on body type, distance travelled for material transportation from factories to construction site (in km), and mode of transport will be collected. However, local data is still not available, therefore international transport emissions factors as shown in CIDB inventory will be applied in this research. Also, some transport emissions factors from other literatures will be considered as well. **Table 3.2** is the transport emissions factors for different transport mode.

Table 3.2: Transport emissions factors for different transport mode (CIDB, 2021).

Transport Mode	Transport emission factors ($kgCO_2e$/kg/km)
Road transport emissions	0.10650×10^{-3}
Sea transport emissions	0.16140×10^{-4}
Freight flight emissions	0.59943×10^{-3}
Rail transport emissions	0.25560×10^{-4}

3.3.3 Construction Activities Data

Site activities are indicated in terms of on-site electricity consumption and fuel consumption. Fuel consumption of construction equipment will not be taken into account in this research as Malaysian construction companies has no practice in recording the fuel consumed either in terms of cost or volume. The amount of electricity consumed during the construction activities is extracted from the electricity bill in unit of kWh. Also, type of electricity used need to be determined to multiply with the corresponding carbon emission factors. In Malaysia, coal type fuel is the major generator for grid electricity, but renewable energy is also available in higher cost. Due to the absence of local data, the electricity emissions factors are adopted from (Department for Energy Security & Net Zero (DESNZ, 2023). The electricity emission factor was calculated by assuming the fuel source used is with 38 % from coal, 48 % from gas, 36 % from oil, and 40 % from bioenergy. Based on

2022 fuel data by Malaysia, 41.8 % of coal, 38.1 % of gas, 17.0 % of hydropower, 1.1 % of oil, and 1.1 % of solar energy were utilized as fuel mix used to generate grid electricity. Therefore, the calculated emission factor is acceptable to be used in embodied carbon assessment. **Table 3.3** shows the electricity emission factors for scope 2, scope 3, and the total production fuel. The emission factor calculated from total production fuel. The construction activities also involved water usage for cleaning and cooling down the machinery, thus the carbon emission from water usage might be considered although it is expected to be insignificant in the overall embodied carbon emissions of a construction building. The emission factor for water consumption in Malaysia is 0.344 $kgCO_2e/m^3$ as reported by MOHAMAD ZAMRI et al. (2022).

Table 3.3: Electricity emission factor (DESNZ, 2023).

Generation (Scope 2) ($kgCO_2e/kWh$)	**Transmission & Distribution (Scope 3) ($kgCO_2e/kWh$)**	**Total Production fuel mix (Scope 2 + Scope 3) ($kgCO_2e/kWh$)**
0.45295	0.08539	**0.53834**

A variety of various sources of data existed for this research, the main sources were identified and summarized in **Table 3.4**.

Table 3.4: Data sources for the input of data.

Data Sources	**Data Types**
Government data – carbon factors provided by Construction Industry Development Board (CIDB) Malaysia	Inventory data for construction materials & building elements
	Transport emissions factors
Government data – provided by Malaysian Green Technology Corporation	Electricity conversion factors
Government data - Department for Energy Security & Net Zero (DESNZ) Greenhouse gas reporting: conversion	

factors 2023 by UK government	
Factors derived from literature review	Transport emissions factors
The Inventory of Carbon and Energy (ICE) database	Inventory data for construction materials & building elements
Bill of Quantity (BoQ)	Quantity of materials used
Industry data – information provided by industry body	Transport mode, transport distance
	Project details

3.4 Embodied Carbon Calculation

Fundamental principle of embodied carbon (EC) calculation is multiplying the quantity of a material or product with the embodied carbon factor. The total carbon emissions within the lifecycle of the building project can be calculated from the sum of the carbon emissions of all products used at each stage of the lifecycle. Thus, the equation was shown as:

$$Embodied\ carbon\ (kgCO_2e) = \sum_{each\ stage}(Quantity\ (kg) \times carbon\ factor\ (kgCO_2e/kg)) \quad (3.1)$$

There is an exception for A5a stage which was not calculated based on material quantities as it is the construction site activities emissions.

A1 to A3 emissions for production of the construction material was calculated by multiplying the material quantities obtained from BoQ with the corresponding embodied carbon emission factors (ECF). The equation is:

$$EC_{A1-A3}\ (kgCO_2e) = \sum Quantity\ (kg\ or\ t\ or\ m^3) \times ECF_{A1-A3}(kgCO_2e/kg) \quad (3.2)$$

where

EC = Embodied Carbon

ECF = Embodied Carbon Factors

After getting the information on the transportation mode and delivery distance, the ECF for transportation was calculated by multiplying the transport distance (in km) with the respective transport mode emission factor, TEF (gCO_2/kg/km). The formula can be defined as:

$$ECF_{A4}\ (kgCO_2e/kg) = \sum Transport\ Distance\ (km) \times TEF\ (kgCO_2e/kg/km) \quad (3.3)$$

where

TEF = Transport Mode Emission Factors

Accordingly, A4 emissions for delivering a quantity of materials and elements from the factory gate to the construction site can be estimated by using the equation:

$$EC_{A4}\ (kgCO_2e) = \sum Quantity\ (kg\ or\ t\ or\ m^3) \times ECF_{A4} (kgCO_2e/kg) \quad (3.4)$$

In short, embodied carbon emissions from A1 to A4 can be summarized as the equation where *i* is the number of phases or type of construction materials:

$$EC_{A1-A4}\ (kgCO_2e) = \sum_{i=1}^{n}[Quantity \times \left(ECF_{A1-A3,i} + ECF_{A4,i}\right)] \quad (3.5)$$

where

i = Number of phases or type of construction materials

A5a emissions for the electricity consumption of on-site equipment which denotes the electric use was calculated by multiplying the consumption quantity of resource (kWh) by the emission factor of respective fuel source ($kgCO_2e$/kWh). The equation follows:

$$EC_{A5a(e)}\ (kgCO_2e) = \sum Consumption\ amount\ (kWh) \times ECF_{A5a}\ (kgCO_2e/kWh) \quad (3.6)$$

While for the water consumption was calculated by multiplying the consumption quantity (m^3) with the emission factor ($kgCO_2e/m^3$). The equation is:

$$EC_{A5a(w)}\ (kgCO_2e) = \sum Consumption\ amount\ (m^3) \times ECF_{A5a}\,(kgCO_2e/m^3) \tag{3.7}$$

A total A5a emissions for the construction activities was computed by total up the results from equation 3.6 and equation 3.7. The equation follows:

$$EC_{A5a}\ (kgCO_2e) = EC_{A5a(e)} + EC_{A5a(w)} \tag{3.8}$$

After that, the total embodied carbon of a building is estimated using the equation:

$$EC_{total}\ (kgCO_2e) = EC_{A1-A4} + EC_{A5a} \tag{3.9}$$

Finally, to ensure the consistency of the study, the result is then normalized. The total embodied carbon is then divided by the gross floor area, GFA (m^2). The equation:

$$EC_{total}\ (kgCO_2e) \Big/ _{GFA\ (m^2)} = kgCO_2e/m^2\ \ GFA \tag{3.10}$$

where

GFA = Gross Floor Area

To make comparison with the past study, the kg unit in every equation will be divided by 1000 to convert it into t, tonne.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 The Challenges of Embodied Carbon Assessment in Construction Sector

In Malaysia, carbon accounting and decarbonization is still in its infancy as it requires internal and external support mechanisms that include financial and non-financial resources. Therefore, the availability and quality of data, especially carbon related information, is the biggest problem in carbon accounting. The emissions from various building materials and products associated with subcontractors and the supply chain were difficult to precisely assess and allocate in this project due to the complexity of the supply chains. Some products are made from a combination of different materials and in a ready-to-use state. For these products, the organizations or industries should submit a formal Environmental Product Declaration (EPD), which contains the results of a life cycle assessment for a specific material or product. However, most product suppliers or industries in Malaysia do not bother to collect and report the carbon data of their business activities, which means the adoption of EPDs is relatively low. Although Bill of Quantities (BoQ) is available for data collection to assess embodied carbon, the results may not be entirely accurate as the details of the building elements used are not available. For example, the steel beam used has a hollow cross-section, which means that a detail of the dimensions is required to calculate the actual weight of the beam. However, this is only possible with a BIM model if the suppliers or subcontractors do not provide an EPD.

Although EPDs are not readily available in Malaysia, suppliers, manufacturers, and subcontractors could report the carbon data or LCA studies for their products. Nevertheless, they are unwilling to share the relevant information due to cost and lack of awareness on the importance of carbon disclosure. The Bursa Malaysia has developed a platform for organizations in purchase of carbon credits to voluntarily offset their carbon footprint called Voluntary Carbon Market (VCMs). However, the involvement is relatively low among small-medium sized enterprises (SMEs) because the construction companies in Malaysia are not required to participate in government initiatives as most are voluntary. Without legislation and incentives, small and medium-sized enterprises with limited budgets and resources will not carry out carbon assessments for their projects which can be resource-intensive and costly. In this study, the case building was done by a mid-sized construction company – King Ong Group – which does not prioritize disclosure of environmental performance and carbon emissions, including environmental, social and governance (ESG) reporting, as the Bursa Malaysia only requires this from public listed companies. For example, the company has not recorded its water and electricity consumption of the project in a documented report, making it difficult to track the exact carbon emissions during construction work. Emissions from construction equipment and machinery such as excavators, cranes and concrete mixers can also be difficult to track as the age, efficiency and fuel consumption of the equipment is not disclosed.

Majority of small and medium-sized companies focus on completing the construction project on time and on budget, so waste management and data tracking are not among their main concerns. In addition to the lack of awareness and enforcement of regulations, there are also some ingrained cultural attitudes or habits such as dumping waste in abandoned places and using materials without considering waste generation that can lead to poor waste management. Additionally, the larger construction companies often manage more complex contracts themselves, most small and medium-sized enterprises (SMEs) depend on subcontractors for various tasks and projects. Therefore, coordinating and monitoring waste management across multiple subcontractors can be a challenge, making it difficult to accurately track waste data. In this study, the King Ong Group failed to allocate adequate resources for waste management, hence, making it impossible to quantify greenhouse gas emissions associated with the disposal or recycling of construction waste due to the lack of records on waste disposal. This may also be due to Malaysia's informal waste sector, which influences local waste management practices and makes it difficult to track and record waste generation and disposal.

The Construction Industry Development Board (CIDB) has identified the Embodied Carbon (EC) Inventory data for building materials in Malaysia as the source for calculating embodied carbon for buildings. However, certain materials and products used in the building construction such as aluminium sliding doors, steel truss, PVC door, etc., are not available in this database. This can lead to inconsistencies in the results as data from different sources are combined if the suppliers or manufacturers are unable to provide the details of the materials and products. Furthermore, the carbon footprint of certain materials and products can vary due to different manufacturing processes, transportation routes and energy mixes. This can cause inaccuracies in the embodied carbon results. Besides, since embodied carbon factors from the CIDB carbon inventory are expressed in units of $kgCO_2e$ per kilogram of a material quantity, a geometric conversion of the unit of the materials used may be required to calculate the amount of carbon emitted as the BoQ may use different units for the materials. During this process, the total weight of the materials may vary slightly due to differences in manufacturing technology and raw materials used. To come to the point, these factors can cause uncertainty and impact in the EC results of this case building.

4.2 Embodied Carbon Value Across the Cradle to Site Stage of the Residential Building

4.2.1 Overview of the Results

The embodied carbon (EC) emissions of the residential building were calculated using the corresponding data and reported using LCA methods across cradle to site which are production stage (A1 to A3) and construction stage (A4 to A5) (as shown in **Figure 4.1** and **Table 4.1**).

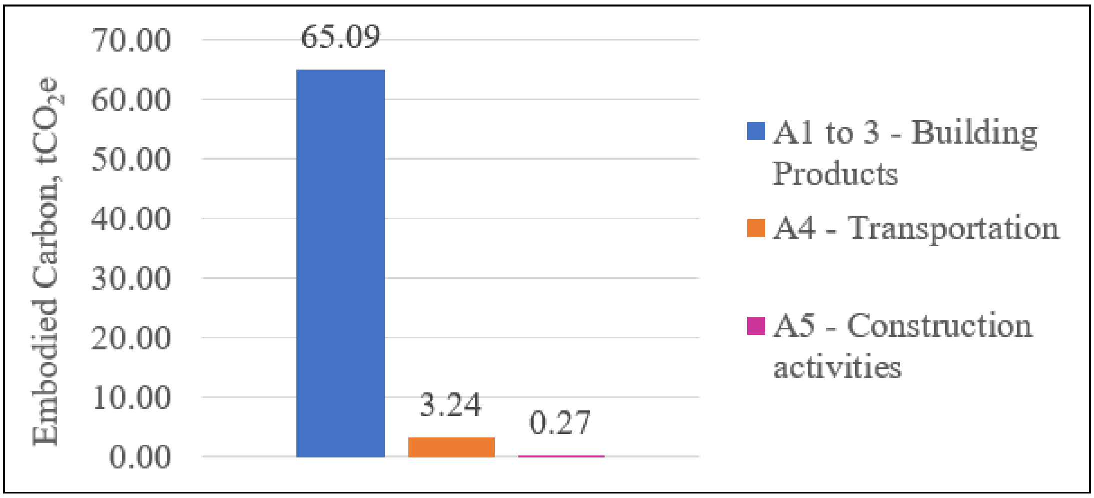


Figure 4.1: Embodied carbon of the residential building by life cycle module.

Table 4.1: Total EC across A1 to A5 stages of one unit of the building.

Assessment Scope	**Total Embodied Carbon [tCO_2e]**	**Percentage contribution to total**
A1 to 3 – Building products	65.09	94.89%
A4 - Transportation	3.24	4.72%
A5 - Construction activities	0.27	0.39%
Total	**68.60**	**100.00%**

The total embodied carbon emission of one unit of building was calculated at 68.60 tCO_2e. The cradle-to-gate emissions for the construction elements (A1-3) have the greatest impact, accounting for just over 90 % of total emissions. The next largest contribution comes from transportation (A4) – 4.72 % and followed by construction activities (A5) – 0.39 %. As almost no data was available for the maintenance or repair of various building components (B1-4), this phase of the life cycle was excluded from the assessment. According to the calculation results and the literature review conducted in Chapter 2, the embodied carbon reduction strategies dealing with carbon-intensive materials and construction were further investigated to determine the carbon reduction potential in Malaysia.

4.2.2 Embodied Carbon from Material Production Stage (A1 to A3 Stages)

The **Table 4.2** demonstrates the production stage embodied carbon (measured in terms of tCO_2e, and tCO_2e/m^2 GFA) for each building element across the residential building. The EC of this stage was 65.09 tCO_2e, which accounted for 94.89 % of overall EC of the cradle to site for this case building (see **Table 4.1**). The embodied carbon emission of the residential building has been classified into 4 major building elements which are substructure, superstructure, finishes, and other services. **Figure 4.2** illustrated that the superstructure in the residential building accounted for more than 50 % of the cradle to grave EC which was found to be 38.00 tCO_2e. Meanwhile, the substructure contributed 18.49 tCO_2e (28.40 % of cradle to grave EC), followed by the finishes with 8.39 tCO_2e emissions (12.88 % of cradle to grave EC), and the services with an EC of 0.22 tCO_2e (0.34 % of cradle to grave EC). This emission is due to the quantities of materials required for the building elements. The larger the quantities, the greater the EC emissions. The materials input for the superstructure was found to be the highest among 4 building elements as shown in the **Table 4.1**.

Table 4.3 demonstrates the embodied carbon emissions of the case building at the material level. Their total contribution to the entire building was presented in **Figure 4.4**. In the ranking, the top five building materials account for 86.14 % of the estimated total EC of the building. These products included steel (38.12 %), brick (15.26 %), concrete (14.16 %), cement (9.36 %) and windows (9.24 %). Glass also contributed to a large proportion of the carbon embodied in the materials (5.26 %), followed by tiles (3.25 %), PVC (1.43 %), timber (1.10 %), other materials (1.06 %), gypsum (0.98 %), and paints (0.79 %).

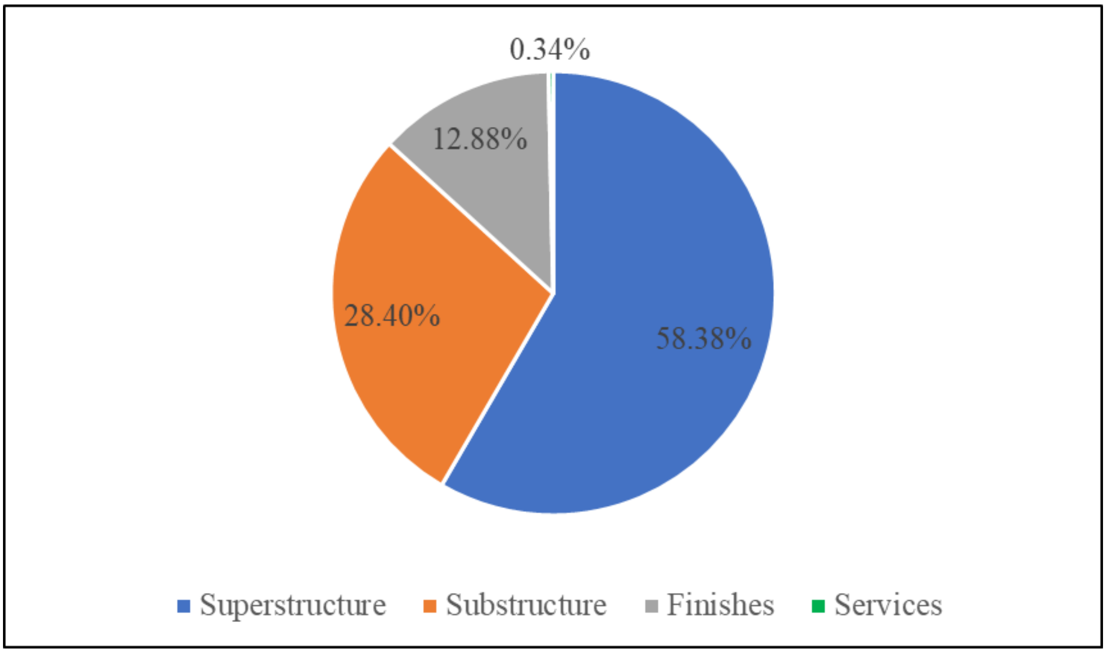


Figure 4.2: Embodied carbon percentages of building elements for cradle to grave (A1 to A3).

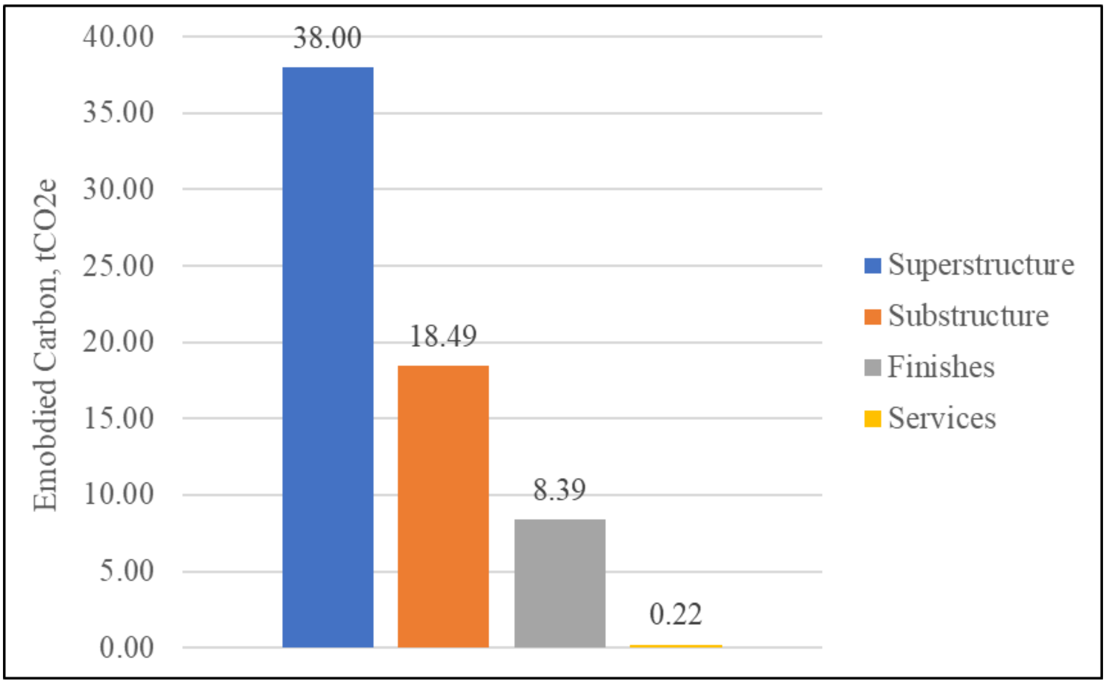


Figure 4.3: Embodied carbon of building elements.

Table 4.2: Embodied carbon by building element for cradle to grave (A1 to A3).

Element Cluster	**Total material used quantity (kg)**	**Total Embodied Carbon [tCO_2e]**	**Total Embodied Carbon per Floor Area (tCO_2e/m^2 GFA)**	**Percentage contribution to total**
1.0 Superstructure	82651.73	38.00	0.409	58.38%
1.1 Doors				
1.2 External Walls				
1.3 Frame				
1.4 Internal walls & partitions				
1.5 Roof				
1.6 Windows				
2.0 Substructure	60709.35	18.49	0.199	28.40%
3.0 Finishes	13649.48	8.39	0.090	12.88%
3.1 External ceiling finishes				
3.2 External floor finishes				
3.3 External wall finishes				
3.4 Internal ceiling finishes				
3.5 Internal floor finishes				
3.6 Internal wall finishes				
4.0 Other Services	134.70	0.22	0.002	0.34%
4.1 Sanitary Appliances				
Total		**65.0946**	**0.7007**	**100%**

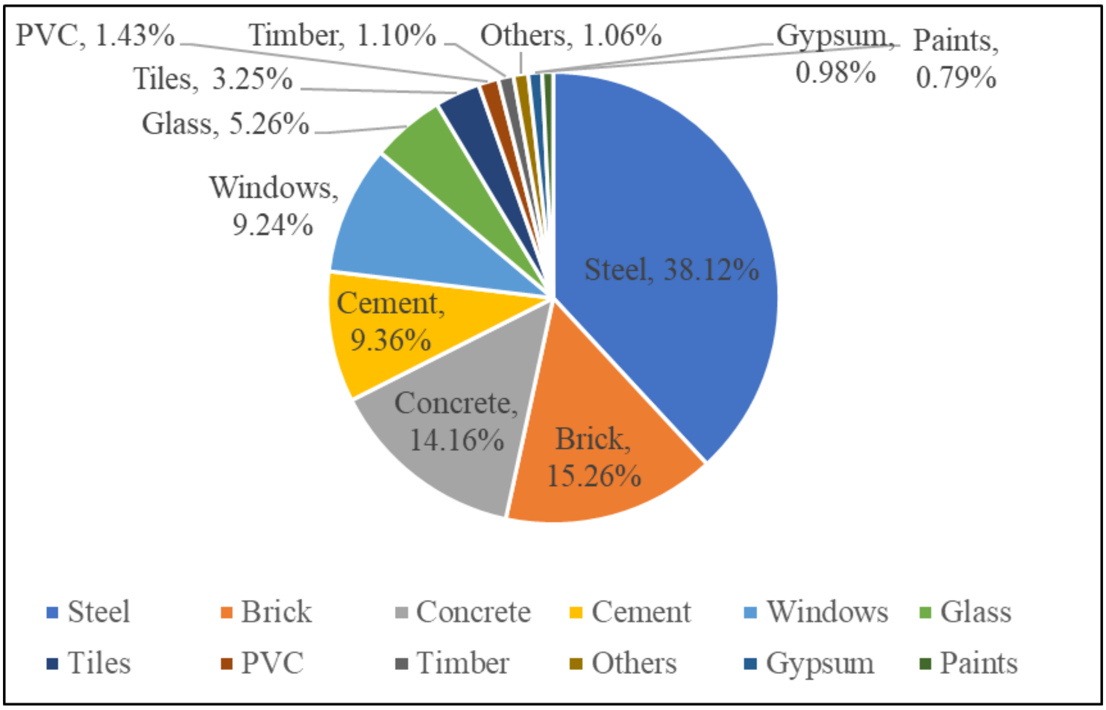


Figure 4.4: Embodied carbon percentages by construction material consumption.

Table 4.3: Major construction material consumption and embodied carbon contribution.

Materials	**Material Quantity**	**Unit**	**Total Embodied Carbon [tCO_2e]**	**Percentage contribution to total**
Steel	13728.44	kg	24.82	38.12%
Brick	41376.60	kg	9.93	15.26%
Concrete	76800.00	kg	9.22	14.16%
Cement	11494.24	kg	6.09	9.36%
Windows	7.98	m^2	6.02	9.24%
Glass	2101.11	kg	3.42	5.26%
Tiles	5193.50	kg	2.11	3.25%
PVC	288.08	kg	0.93	1.43%
Timber	1996.04	kg	0.71	1.10%
Other	2459.70	kg	0.69	1.06%

Ceiling	1490.00	kg	0.64	0.98%
Paints	209.58	kg	0.51	0.79%
Total	**-**	**-**	**65.09**	**100.00%**

4.2.2.1 Details of the Material Production Stage Embodied Carbon

The superstructure in the case building contributed 58.38 % of the total EC intensity at the production stage. This significant contribution is due to the large amount of concrete and reinforcing steel used in this building element. The superstructure was consisted of external walls, frame, internal walls, roof, windows, and doors. These building components were produced with various types of materials associated with high EC intensity. These results are also corresponded with case study done by CIDB (2021) and results of study by Alotaibi et al. (2022). Comes to the material level, the amount of concrete is the highest among these 5 building materials, but not the highest proportion of embodied carbon. Steel, on the other hand, is the greatest embodied carbon contributor, although it has a smaller amount of material. This is because steel has a higher embodied carbon factor value than brick, concrete, and cement without comparing it to the window. This result is consistent with the findings of previous study by Liu & Leng (2022) and supports that steel is the main contributor to the embodied carbon at the material level. Therefore, recycling or reuse of steel products should be more effective to reduce embodied carbon.

4.2.3 Embodied Carbon from Material Transportation Stage (A4 Stage)

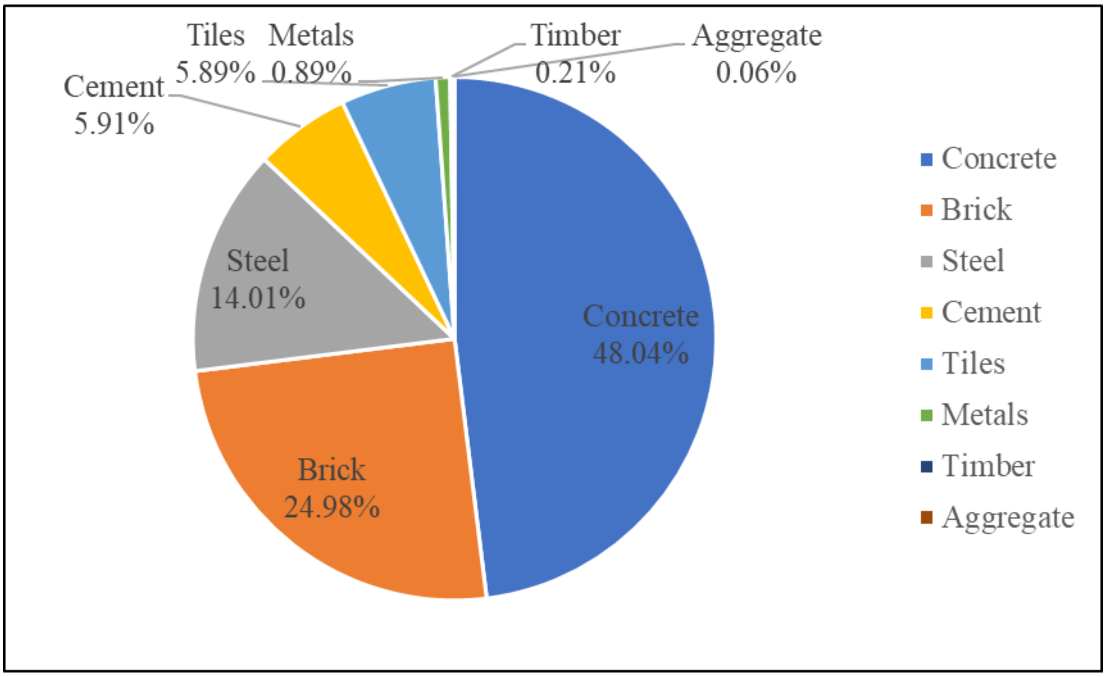


Figure 4.5: EC percentages of each material transportation.

Table 4.4: Transportation emissions and transported distance of the construction materials.

Material Category	Description	Distance – Return and Delivery (km)	Embodied Carbon Emissions (tCO_2e)	Percentage contribution to total
Concrete	From Chemor, Perak to the construction site	190.2	1.556	48.04%
Brick	From Bidor, Perak to the construction site	183.6	0.809	24.98%
Steel	From Petaling Jaya, Selangor to the construction site	402.0	0.454	14.01%
	From Sungai Petani, Kedah to the	428.0		

	construction site			
	From Nibong Tebal, Penang to the construction site	296.0		
Cement	From Ipoh, Perak to the construction site	156.4	0.191	5.91%
Tiles	From Seremban, Negeri Sembilan to the construction site	324.0	0.191	5.89%
	From George Town, Penang to the construction site	392.0		
Metals	From Ipoh, Perak to the construction site	141.2	0.029	0.89%
	From Lumut, Perak to the construction site	11.2		
Timber	From Lumut, Perak to the construction site	20.0	0.007	0.21%
	From Ipoh, Perak to the construction site	162.8		
Aggregate	From Lumut, Perak to the construction site	11.2	0.002	0.06%
Total			**3.238**	100.00%

Since the mode of transportation is the same for all materials, namely road transport, the EC emissions depend on the transport distance and the total weight of the transported material. Based on the data on the total distance from the suppliers to the construction site and the total weight of the transported materials, the EC emissions for the transportation of the materials are calculated and listed in **Table 4.4**. The total EC emissions of the A4 phase amounted to 3.438 tCO_2e, which is 4.72 % of the total

EC emissions from cradle to site for this case building. It should be noted that the weight of the transported materials may differ from the amount of material used for construction, as some of the materials were recycled from previous construction projects and no data is available for this recycling. The transportation distance of steel material was the highest compared to other materials, as shown in **Table 4.4**. **Figure 4.5** shows the overall EC percentage of material transportation. Surprisingly, the transportation of concrete was the highest EC contributor with 48.04% of total EC of A4 stage (see **Figure 4.5**). As can be seen from **Table 4.3**, the amount of concrete used for construction is the highest, so the EC value is greatest during transportation to the construction site. This depends on the amount of material transported. The larger the amount of material, the higher the EC emissions. This also proved that the emissions of the A4 stage depend mainly on the weight of the transported material, but not on the transport distance.

4.2.4 Embodied Carbon from Construction Activities (A5 Stage)

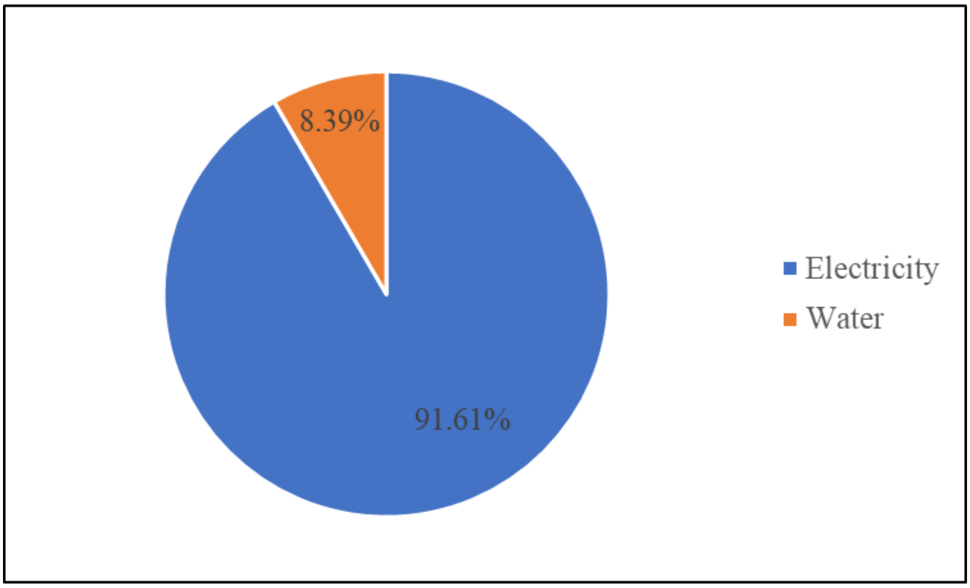


Figure 4.6: EC percentage of the electricity and water usage in the construction activities.

Table 4.5: EC from the electricity and water usage during the construction activities.

Category	Total consumption	Unit	Embodied carbon emissions (tCO_2e)
Electricity	452.756	kWh	0.244
Water	64.927	m^3	0.022
Total	-	-	**0.266**

The EC of this phase amounted to 0.266 tCO_2e, which only accounted for 0.39 % of the cradle-to-site of construction embodied carbon. As no complete electricity and water bills were available and there were no proper records of electricity and water consumption, consumption was estimated on the basis of an electricity and water bill for 2 months and listed in **Table 4.5**. EC generated from the electricity consumption of on-site equipment contributed to 0.244 tCO_2e in this stage which stands for 91.61 % of EC from the construction activities as shown in **Figure 4.6**. Electricity in the location of the case building is generated using coal combustion, so the carbon emissions could be much higher than the water consumption. The EC contribution of water consumption is relatively insignificant as only 0.022 tCO_2e with only 8.39 % of EC is emitted during construction.

4.3 Strategies for Reducing Embodied Carbon Across the LCA of the Case Building

As can be seen from the results presented above, building materials contributed the most to the total carbon content, followed by transportation and construction activities. Therefore, the proposed strategies must be specific to the goal of reducing embodied carbon from sources. They should also deliver benefits to stakeholders in relation to the 5 pillars: People, Planet, Peace, Prosperity, and Partnership, in line with the Sustainable Development Goals. The strategies specifically address EC emissions from the boundary set in this study which is cradle-to-site, including regional sourcing, use of low-carbon materials, material recycling, and control of plant operations. Due to on-site waste generation were excluded, thus the strategies proposed are not covering the waste management mitigation. However, these strategies need to work with some incentives and binding policies to ensure efficiency and more sustainable practices on construction sites.

4.3.1 Policy Measures for Controlling Embodied Carbon in the Construction Industry

Reducing carbon emissions can be achieved by directly reducing the materials used while meeting construction requirements, but this is done on the basis of policy measures. Malaysia should be strategic in implementing policies that support the environmentally friendly practices in the construction sector. As developing countries prepare for a growing demand for buildings, it is important to invest in more energy efficient buildings. The Malaysian government has issued guidelines for green development, the National Policy on Climate Change, and the National Green Technology Policy to promote green and low-carbon development. For example, Green Construction Guidelines provide a comprehensive framework for the implementation of sustainable practices in the areas of materials, waste, water, energy, innovation, and management in the construction sector (Malaysian Green Technology and Climate Change Corporation, 2023). Besides, numerous initiatives and strategic plans for green growth have been developed, as well as a green assessment system, green incentives and financing, a green procurement system and green technology companies (Chua and Oh, 2011). Energy and carbon emissions are linked, so energy efficiency is the key to reducing carbon emissions. In Malaysia, building standards are governed by the Uniform Building By-Laws 1984 and the Construction Industry Standards, neither of which currently have energy efficiency requirements (M. Zaid et al., 2015).

Carbon disincentives schemes should be proposed in construction projects to promote stakeholders in monitoring their construction emissions. Firstly, levying a carbon tax or emissions pricing mechanism that link the EC emissions with construction materials, activities, and procedures. The carbon tax can be set at a low rate initially, and gradual increase may be made over a period. As referring to National Environmental Agency in Singapore, carbon tax can be introduced under a specific legislative act. For the carbon tax rate, Malaysian government can set it at RM5 per tonne initially to give businesses a transitional period to adjust. However, this implementation must take into account of the overall cost burden to the construction companies, especially SMEs. Yet, the government must convince companies to accept this tax, because not all companies can afford to invest in clean technologies, as these require high investments. Consequently, they will consider the low-carbon alternatives such as recycled steel, green concrete containing additional cementitious ingredients, and timber. The revenue raised from the carbon tax is used to assist with decarbonization initiatives, the shift to a green economy, and minimizing the impacts on consumers and enterprises. Also, carbon credits and carbon offsets, or known as a cap-and-trade programs are suitable for the country that intended to reduce carbon footprint. In Malaysia, this measure can be firstly operated for listed construction companies. A company is authorized to produce one tonne of CO_2 emissions when it purchased carbon credits that are provided by the government and the number of credits is typically based on emissions targets. Business can voluntarily buy carbon offsets. A business generates carbon offsets when, as part of daily operations, it removes one unit of carbon from the atmosphere. To decrease their carbon footprints, other companies can buy carbon offsets.

The Malaysian government should introduce regulations requiring construction projects of certain sizes to be completed with embodied carbon assessment and the results reported to the relevant authorities. Hence, the relevant authorities like CIDB can develop standardized methodologies and guidelines to quantify embodied carbon emissions across a project’s life cycle. For instance, in terms of different project types, specific scope boundaries like cradle-to-site or cradle-to-grave can be set for the embodied carbon assessment. Next, the databases or records of data required including carbon factors should be recognized by the relevant authorities to ensure the consistency in the emissions computations. This involves collaboration across a wide range of stakeholders including suppliers, manufacturers, subcontractors, clients, and contractors. Subsequently, the authorities must announce the reporting formats, verification protocols, and disclosure timelines.

The carbon emissions report should contain information on the total consumption of construction materials, construction's activity data of the scope boundaries set, calculation for each element emissions, and the total building emissions. This report must be prepared and submitted by at least one designated representative with relevant experience. Authorized third-party verification should be done for the emissions report to ensure the accuracy and completeness of the report. After that, the companies are required to conduct monitoring on the emission hotspots by describing the sources, streams, quantification methods, and uncertainty. A submission of monitoring plan is voluntary. In this process, government can provide financial or technical support for the companies such as local professional or expertise from other countries can develop a standardized monitoring mechanism such as carbon calculator will help the industry to benchmark, monitor and report their emissions production. Consequently, they are able to avoid the carbon tax and further improve their carbon footprint performance by setting target for embodied carbon reduction in their business operations. Also, this can drive the market demand for low-carbon material or design alternatives.

If the embodied carbon emissions reporting is matured across the whole construction industry, penalties for non-compliance can be imposed to enforce the regulations in effective implementation. The non-compliance includes failure in conducting embodied carbon assessments, late report submission, and underreporting of emissions. In this manner, financial fines, or imprisonment or to both should be imposed to the companies that found to be non-compliant. In order to safeguard the fairness and effectiveness of the penalties, the government authorities should conduct periodic reviews based on compliance rates, and industry feedback. For smaller firms, the penalties can be set at a lower level to motivate their compliance in this embodied carbon emissions reporting. Also, the government may allow for exemptions during early phases, particularly for the SMEs. This is to give time for the industry to adjust and build capacity in terms of their budgets and resources. The fines collected will be used on research funding or training more expertise or professional in the emissions assessment.

4.3.2 Incentive Mechanisms for Adoption in the Construction Sector

To promote green practices in the Malaysian construction industry, an incentive mechanism can be created to encourage the adoption of low-carbon measures, especially for those who adopt these measures early. Increased incentives for construction companies that adopt energy-saving or emissions-reducing innovations encourage company commitment, although this could also mean increased spending on low-carbon products, materials, and green technologies. Thus, monetary incentives such as grants, capital subsidies and low-interest loan programmes can be considered to offset the expenses. For example, the government can fund a part of installation costs of green technologies. The early low-carbon practices adopters may qualify for greater tax credits, grants, or expedited licensing. As reported by International Energy Agency by 2023, the Malaysian government has proposed tax incentive scheme for the companies that participated in Carbon Capture Storage activity. This scheme offered investment tax allowance of 100% for 10 years, full import duty and sales tax exemption on the carbon capture equipment, and tax deduction and exemption (Iea, 2023). The incentive period was set for 5 years which is from 2023 to 2027. SMEs are always burdened with the low-carbon measures adoption due to their limited budgets and resources. For this reason, the government may allocate a certain amount of money to start energy efficiency improvement works among SMEs that are eligible to do so. Other than that, the government may open training workshops for the SMEs with free of charge to raise their awareness in the carbon footprint concept and way to reduce it in their daily business operation. Even so, even if money is allocated from carbon tax revenues, industry levies, or government budgets. the funding sources remain as a significant issue for the government.

4.3.3 Strategies for Mitigating Carbon Footprints in Construction Activities and Transportation

Embodied carbon emission in A5 phase is mainly from machinery operations, thus limiting the machinery productivity can be considered as a measure to mitigate the on-site carbon footprint. According to a study by Mustaffa (2022), reducing machine idle time and optimizing machine utilisation can enhance productivity while reducing emissions and costs. This can make sure the machines are only operating when needed without unnecessary idling. The site officers can also conduct an auditing to identify the inefficient equipment, and these machines should be replaced with more efficient models. This not only saved the cost by reducing the electricity and fuel consumption. Also, adequate equipment maintenance should be provided to optimize the equipment efficiency. As Tang et al. (2013) report, coordinating workflows is more helpful in reducing emissions than working machines. This research suggests that adjusting the control of equipment schedules does not immediately increase the efficiency of pollutant emissions control as this only prevent overlapping operations, which means there are no multiple machines are running simultaneously. So, better management practices such as task scheduling, operational planning and activity planning can boost the emissions reduction during the construction work. Other than that, the companies may lower the energy bills by utilizing smart devices like light controllers, and sensors to save budgets. These devices can automate some processes to ensure efficiency. For instance, motion detectors can be used to automatically turn off lights when an area is not in use.

The emission from the material transportation to site is found to be caused by the fuel consumption of the heavy vehicles. Several strategies can be implemented the reduce the embodied carbon emissions in this phase. As referring to the **Table 4.4**, the transportation distances of steel and tiles are the highest among the other materials, hence material local and regional sourcing can be employed to reduce the transportation distances and associated carbon emissions. In terms of tiles and steel materials, there are a lot of suppliers in Ipoh, Perak area, thus the company can purchase the materials from them. The transportation distance is estimated to be in range of 137 km to 185 km. This might reduce around 11 % of the current EC from the material transportation which reduced from 3.24 tCO_2e to 2.87 tCO_2e. Transportation distances that are within 200 km might emit lower carbon. In addition, the company can have collaboration with suppliers to implement low-emission transportation approaches. For example, suppliers should use fuel-efficient vehicles for transporting the materials or other fuel alternatives like biodiesel. The transporters can also check on tire pressure for optimal fuel efficiency.

4.3.4 Strategies for Decarbonization in Cradle-to-Gate

As can be seen from the results presented above, the building materials contributed the most to the total carbon content, with steel, bricks, and concrete being the top 3 main contributing elements. Carbon reduction can be achieved by directly reducing the materials used, while meeting the structural requirements. Nonetheless, there is still no alternative for mitigating the embodied carbon of steel material as this can only be done on steel manufacturing expect recycling and reuse approaches. Therefore, carbon reduction measures are categorized into three groups: (1) use of low-carbon concrete, and (2) material minimization.

4.3.4.1 Use of Low-Carbon Concrete

Choosing environmentally friendly materials would help minimize the consumption of natural resources, including raw materials, as well as annual energy and water consumption in the manufacturing and construction process. This practice can also be applied to the selection of “green” building materials. For example, low-carbon concrete is recommended to be used in the construction of sustainable buildings. Even if the emissions per tonne are not very high, concrete is the main source of embodied carbon in any project due to its mass and distribution. Currently, YTL Cement which is the largest cement and concrete company in Malaysia, introduces ECO Concrete, an innovative building material designed to solve the environmental problems associated with conventional concrete production. This concrete is found to be more eco-friendly with 20 to 60% less embodied carbon as it incorporates 30 to 70% of recycled materials (YTL Cement, n.d.). A part of the cement in the low-carbon concrete from YTL Cement is replaced with "Green cement", or known as ECO Cem, which containing at least 25% recycled material and with the lower production emission compared to Portland Cement. Since there is not any research on this type of concrete, as according to study by Teng & Pan (2019), they interviewed with the low-carbon concrete production managers and discovered that the recycled materials used are pulverized fly ash, ground slag or blast furnace slag to replace the normal cement. ECO Concrete is suitable for variety of structural components including columns and beams, walls, foundations, and walkways. Therefore, by replacing all the conventional concretes in the case building by the ECO Concrete, and assuming the concretes are with 40% less embodied carbon, the total embodied carbon of the material production stage can be reduced by 5.65 % from 65.09 tCO_2e to 61.41 tCO_2e.

4.3.4.2 Material Minimization

The amount of materials used in buildings is in direct proportion to the total carbon emissions of the building. Therefore, minimizing the use of materials while meeting the structural requirement can be a useful strategy to reduce embodied carbon. With this approach, the design needs to be focused on decarbonizing embodied carbon from the concept phase onwards, as this will allow for an optimal design. By taking the case done by Teng & Pan (2019) as reference, the thickness of slabs and walls can be considered to achieve carbon reduction. However, most of the slabs and walls in the case building were designed with the minimum thickness required by the government. If the thickness of these structures can be reduced, the embodied carbon reduction of the building is assured to be achieved. Another option under this strategy is optimizing the existing and future construction. This can be attained by reuse of the existing infrastructure instead of new infrastructure. Disassembly of abandoned buildings or extra materials from previous projects enable recycling and reuse which can lower the material quantities in new construction. For example, if half of the total reinforcing bar amount can be recycled and reused, it is possible to reduce the embodied carbon by 1%. This measure is supported by CIDB (2021) as the body stated that renovation and reuse projects can save about 50 % and 75 % of embodied carbon emissions, particularly for the substructure and frame.

4.3.5 Carbon Reduction Target

This paper showed that the embodied carbon generated from the cradle-to-site of construction in a residential building in Malaysia was 68.60 tCO_2e, mainly from material consumption. By taking this carbon emission as the baseline study, some decarbonization strategies are assessed across material production, and construction. King Ong Group may consider the strategies to reduce its carbon footprint in future projects, especially when the mandatory carbon tax is implied for SMEs.

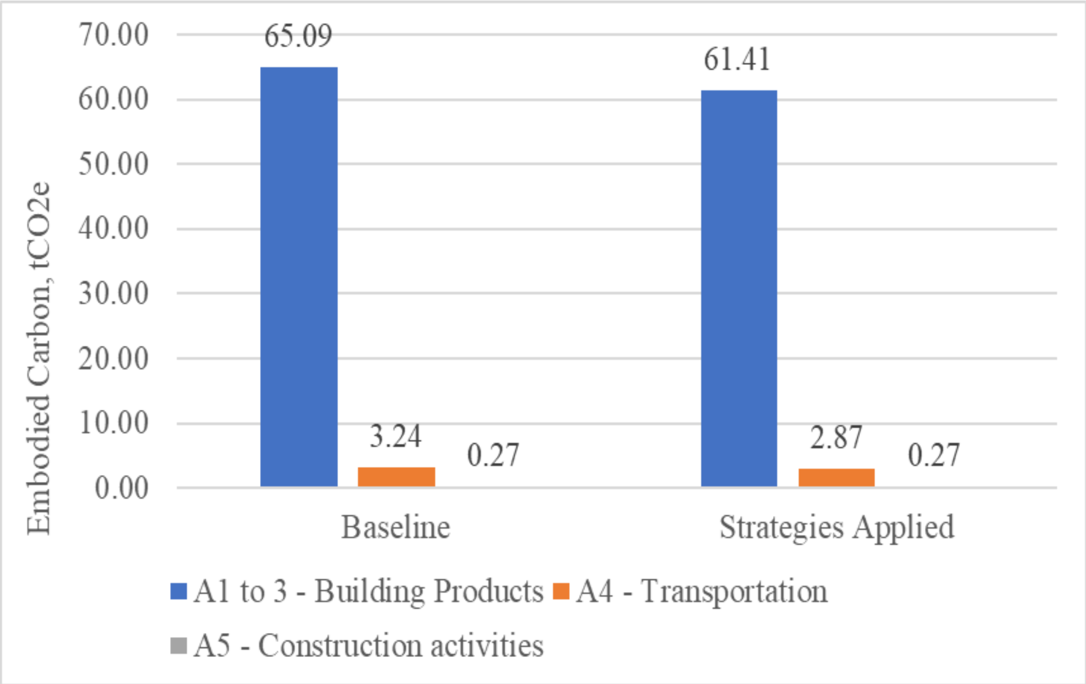


Figure 4.7: Comparison of embodied carbon in the case building between the baseline and situation after strategies applied.

Figure 4.7 demonstrated the maximum reduction for the case building across the cradle-to-site. The total embodied carbon of the building can be reduced by 5.90 % which is from 68.60 tCO_2e to 64.55 tCO_2e. However, from the construction activities stage, the strategies assessed are depending on the government and stakeholder collaboration, thus the embodied carbon of this stage was remained unchanged.

Once we have determined an average of 4 tCO_2e of embodied carbon can be reduced for this individual building, the total embodied carbon amount reduction for the entire project with 347 units of the same building is calculated to be 1,388 tCO_2e. Everyone knows that trees absorb carbon dioxide (CO_2) for photosynthesis. Therefore, planting trees is a popular means of carbon offsetting in developed countries. In Malaysia, some listed construction companies such as Sunway Construction Group are also participating in a tree planting program to offset the carbon emissions contributed by their operations. However, efforts to promote tree planting among the construction industry are insignificant as it could put a strain on their budget and reduce their profit. It should be noted that the CO_2 compensation rate is varied with the species, soil, weather conditions, water, tree age and planting location (*International Institute for Sustainable Development*, n.d.). Therefore, further studies are needed to determine the amount of carbon offset by the trees. Referring to research carried out by an independent agency in Europe called Encon, it was found that a tree can absorb 21.77 kg to 31.5 kg of CO_2 per year. This result can also be confirmed by the research of another European company called EcoTree, which states that a 35-year-old tree can absorb approximately 25 kg of CO_2 per year. Taking this result as a guide, King Ong Group has saved 55,520 of 35-year-old trees need to be planted as carbon offset of this housing project, which is equivalent to 1,388 tCO_2e if they implemented the strategies proposed above.

This study makes a valuable contribution to Sustainable Development Goal (SDG) 13: Climate Action, which states: "Take urgent action to combat climate change and its impacts". By conducting the quantitative assessment of embodied carbon for the construction building, the results provide an understanding that can help develop feasible strategies to mitigate embodied carbon emissions and further address the other environmental issues arise from the construction industry. Precisely, the results in this study in relation to construction practices, inadequate environmental data and manufacturers' awareness will enable stakeholders, including the government, to develop effective strategies and technologies to combat climate change. Similar studies can serve as a guide for evidence-based decision making, promoting progress towards a more sustainable and low-carbon future.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In this study, the embodied carbon evaluation in the housing development project was presented. The LCA framework was used, and this included the emission from cradle-to-site excluding the on-site waste generation, which consisted of material production, transportation to site, and construction activities. This research focused on the development of general standards for embodied carbon of residential buildings. However, this could be challenging in Malaysia due to some issues such as data availability (e.g. EPDs), record keeping of construction activities and material carbon factors, awareness of construction companies and stakeholders, enforcement of regulations and limited budgets and resources. These could lead to inaccuracy and inconsistency in the result of the assessment.

According to the LCA analysis of the construction of residential building, the embodied carbon footprint of the case study in this paper was 68.5989 tCO_2e or 0.738 tCO_2e. An average of 65.09 tCO_2e (0.701 tCO_2/m^2), which was mainly generated by the consumption of materials. It was found that embodied carbon in the production of materials is mainly caused by steel (38.12 %), bricks (15.26 %), and concrete (14.16 %). Also, among the 4 major building elements which are substructure, superstructure, finishes, and other services, over 50 % of the embodied carbon was generated by the superstructure which was 38.00 tCO_2e. While an average of 3.24 tCO_2e (0.035 tCO_2/m^2) originated from material transportation to site, and 0.27 tCO_2e (0.0029 tCO_2/m^2) was emitted from construction activities. Based on these results, the paper concluded that standardized embodied carbon assessment can be achieved by adopting a systematic approach to compute and report the embodied carbon of buildings. Based on the results from the presented study, there are various strategies can be implemented for the construction companies to make informed decisions in embodied carbon reduction. By replacing conventional concrete with the low-carbon concrete – ECO Concrete, recycling and reusing the steel reinforcing bars, and regional material sourcing, an average of 5.90 % of embodied carbon can be reduced. This result shows the great potential for reducing embodied carbon by using materials with low carbon content and adopting recycling and reuse approaches. Nevertheless, these measures are built on the foundation of policymaking. With sufficient incentive mechanism and regulation enforcement, a more comprehensive decarbonization can be achieved and carbon savings might be common among the construction sectors.

5.2 Recommendation

This paper has provided methodological guidance for the quantitative embodied carbon assessment of in a housing development project, and carbon minimization measures were proposed. If the research can be developed further, data points from other companies, especially listed companies would be considered to make comparison and benchmarking. Moreover, the LCA system boundaries will be extended to incorporate the waste disposal stage to identify a more reliable proportion of recycled materials used in the construction. The embodied carbon assessment in this case building did not include the on-site waste generation, and fuel consumption, thus collaborating with the companies that performed carbon reporting may reduce the uncertainty and offer a more comprehensive database required. Future research will look into the uncertainties in the embodied carbon assessment process and extend the LCA stages.

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APPENDICES

APPENDIX A: Site Photo

APPENDIX B: Details of Construction Materials Production Amount and Consumption Amount for Single Unit

Element Cluster	Building Cluster	Building Component	Materials	Specification	Material Quantity [m3] or [kg/m]	Density [kg/m3]	Material Quantity [kg]	Embodied Carbon Factor [kgCO2e/kg]	Element Embodied Carbon [tCO2e]
Substructure	Work Below Lower Filling Floor	Filling imported sand	General aggregate and sand	-	1	1602	1602	0.0049	0.0078498
Substructure	Work Below Lower Filling Floor	Half drain	Vitrified clay pipe	230mm diameter	0.249285377	2000	498.5707541	0.5	0.249285377
Substructure	Reinforced concrete G25	Pile caps	Concrete 25/30 Mpa	-	1	2400	2400	0.12	0.288
Substructure	Reinforced concrete G26	Bed and apron and strip footings	Concrete 25/30 Mpa	-	18	2400	43200	0.12	5.184
Substructure	Reinforced concrete G27	stumps	Concrete 25/30 Mpa	-	1	2400	2400	0.12	0.288
Substructure	Reinforced concrete G28	Ground beams	Concrete 25/30 Mpa	-	1	2400	2400	0.12	0.288
Substructure	Reinforcement Steel	Pile caps Y16mm	Reinforcing bar	-	-	-	29	0.68	0.01972
Substructure	Reinforcement Steel	Pile caps Y12mm	Reinforcing bar	-	-	-	11	0.68	0.00748
Substructure	Reinforcement Steel	Pile caps R 10mm binder	Reinforcing bar	-	-	-	6	0.68	0.00408
Substructure	Reinforcement Steel	Strip footings; Y12mm	Reinforcing bar	-	-	-	176	0.68	0.11968
Substructure	Reinforcement Steel	Strip footings; Y10mm	Reinforcing bar	-	-	-	123	0.68	0.08364
Substructure	Reinforcement Steel	Strip footings; R10mm	Reinforcing bar	-	-	-	133	0.68	0.09044
Substructure	Reinforcement Steel	Ground beams; Y 12mm	Reinforcing bar	-	-	-	9	0.68	0.00612
Substructure	Reinforcement Steel	Ground beams; Y 10 mm	Reinforcing bar	-	-	-	6	0.68	0.00408
Substructure	Reinforcement Steel	Ground beams; Y 16 mm	Reinforcing bar	-	-	-	78	0.68	0.05304
Substructure	Reinforcement Steel	Ground beams; R10mm links	Reinforcing bar	-	-	-	26	0.68	0.01768
Substructure	Reinforcement Steel	Ground beams; R6 mm links	Reinforcing bar	-	-	-	6	0.68	0.00408
Substructure	BRC A7 steel mesh	Bed and apron	Steel CA60 rebar, welded mesh and truss	160 m2, 3.02 kg/m2	-	-	483.2	1.62	0.782784
Substructure	Formwork	sides pile caps and stumps	reinforcing bar	3m2, 250mm	-	7850	14.39	0.68	0.0097852
Substructure	Formwork	Sides bed	reinforcing bar	21m2, 220mm	-	7850	43.19	0.68	0.0293692
Substructure	Formwork	sides grd beams	steel section	9m2, 10mm	-	7850	7065	1.55	10.95075
Superstructure	Frame	columns	Concrete 25/30 Mpa	-	2	2400	4800	0.12	0.576
Superstructure	Frame	roof beams	Concrete 25/30 Mpa	-	5	2400	12000	0.12	1.44
Superstructure	Frame	Stiffeners	Concrete 25/30 Mpa	-	1	2400	2400	0.12	0.288
Superstructure	Frame	Roof slab	Concrete 25/30 Mpa	-	2	2400	4800	0.12	0.576
Superstructure	Frame	Lintel	Concrete 25/30 Mpa		1	2400	2400	0.12	0.288
Superstructure	Frame	columns; Y 12mm	Reinforcing bar	-	-	-	274	0.68	0.18632
Superstructure	Frame	columns; R 6mm	Reinforcing bar	-	-	-	71	0.68	0.04828
Superstructure	Frame	roof beams ; Y 16 mm	Reinforcing bar	-	-	-	83	0.68	0.05644
Superstructure	Frame	roof beams ; Y 12 mm	Reinforcing bar	-	-	-	53	0.68	0.03604
Superstructure	Frame	roof beams ; Y 10 mm	Reinforcing bar	-	-	-	213	0.68	0.14484
Superstructure	Frame	roof beams ; R10 mm	Reinforcing bar	-	-	-	44	0.68	0.02992
Superstructure	Frame	roof beams ; R 6 mm	Reinforcing bar	-	-	-	104	0.68	0.07072
Superstructure	Frame	Stiffeners ; Y10mm	Reinforcing bar	-	-	-	40	0.68	0.0272
Superstructure	Frame	Stiffeners ; R 6mm	Reinforcing bar	-	-	-	13	0.68	0.00884
Superstructure	Frame	Roof slab ; Y10mm	Reinforcing bar	-	-	-	218	0.68	0.14824
Superstructure	Frame	Lintel ; Y 10mm	Reinforcing bar	-	-	-	72	0.68	0.04896
Superstructure	Frame	Lintel ; R6mm	Reinforcing bar	-	-	-	48	0.68	0.03264
Superstructure	Frame	Column	Timber/Lumber/Wood	50m2, 14mm	0.7	720	504	0.31	0.15624
Superstructure	Frame	roof beams	Timber/Lumber/Wood	87m2, 14mm	1.218	720	876.96	0.31	0.2718576
Superstructure	Frame	Stiffeners	Timber/Lumber/Wood	6m2, 14mm	0.084	720	60.48	0.31	0.0187488
Superstructure	Frame	sides and soffit Roof slab	Timber/Lumber/Wood	16m2, 14mm	0.224	720	161.28	0.31	0.0499968
Superstructure	Frame	Lintel	Timber/Lumber/Wood	5m2, 14mm	0.07	720	50.4	0.31	0.015624
Superstructure	Roof	Proprietary fabricated roof trusses	Steel hot-dip galvanized steel	85m2	-	-	4100	2.76	11.316
Superstructure	Roof	150mm UPVC	PVC	17m, 150mm, class D, t=9.5mm	5.786672296	1380	98.37342904	3.23	0.317746176
Superstructure	Roof	painting	General Paint	2m2, t=20mils/0.508m	0.001016	1200	1.2192	2.91	0.003547872
Superstructure	Roof	150mm upvc gutter	PVC	12m, 150mm, class D, t=9.5mm	5.786672296	1380	69.44006755	3.23	0.224291418
Superstructure	Roof	Concrete roof tiles	concrete roof tiles	85m2, 42.2kg/m2 elabana	-	-	3587	0.24	0.86088
Superstructure	Roof	Fascia Board	Hardwood (Asian Hardwood)	7.5mm, 230mm, 33m	0.056925	720	40.986	0.31	0.01270566
Superstructure	Roof	Painting to fascia board	Solvent-borne paint	0.12kg/m2, 8m2	-	-	0.96	3.76	0.0036096
Superstructure	External Walls	Half brick wall	clay brick	t=0.127m, 83m2	10.541	1810	19079.21	0.24	4.5790104
Superstructure	External Walls	Glass wall	Glass, Glazing, Double	t=10mm, 83m2	0.83	2512.5	2085.375	1.63	3.39916125
Superstructure	External Walls	Gypsum board with framing	gypsum ceiling (plaster board)	t=17.5mm, 83m2	1.4525	1000	1452.5	0.43	0.624575
Superstructure	Doors	Flush door	Timber, Hardboard	914x2134x38 ,4 units	0.296472352	625	185.29522	0.82	0.15194208
Superstructure	Doors	PVC door	PVC General	813x2134x25 2 units	0.0867471	1380	119.710998	3.23	0.386666524
Superstructure	Doors	Aluminium Sliding door	Glass, General	2000x1093x1.5 1 unit, 2 pcs	0.006558	2400	15.7392	1.44	0.022664448

Superstructure	Doors	Aluminium Sliding door	Aluminum, General	64mm, 40mm, 25mm	0.083122	2700	224.4294	0.93	0.208719342
Superstructure	Windows	Casement window 2 panel	Window frame, aluminium, U=1.6 W/m2K	914x1676x1.8 1unit	-	2700	1.531864	754	1.155025456
Superstructure	Windows	Casement window 2 panel	Window frame, aluminium, U=1.6 W/m2K	914x1219x1.8 4units	-	2700	4.456664	754	3.360324656
Superstructure	Windows	Casement window 2 panel	Window frame, aluminium, U=1.6 W/m2K	914x1372x1.8 1unit	-	2700	1.272288	754	0.959305152
Superstructure	Windows	Top hung window	Window frame, aluminium, U=1.6 W/m2K	600x600 2unit	-	2700	0.72	754	0.54288
Superstructure	Internal walls & partitions	Half brick wall	clay brick	97m2, 0.127m	12.319	1810	22297.39	0.24	5.3513736
Finishes	Internal wall finishes	Ceramic tiles	ceramic tiles	10m2, t=9mm	0.09	2100	189	0.78	0.14742
Finishes	Internal wall finishes	cement plaster	cement	343m2,t=12mm	4.116	1800	7408.8	0.74	5.482512
Finishes	Internal wall finishes	emulsion paints	emulsion paint	343m2,t=0.3mm	0.1029	1400	144.06	2.34	0.3371004
Finishes	Internal floor finishes	anti slip homogenous tiles with skirt and simple patterns	ceramic tiles	17m2,t=9mm	0.153	2100	321.3	0.78	0.250614
Finishes	Internal floor finishes	Homogenous tiles	ceramic tiles	58m2,t=9mm	0.522	2100	1096.2	0.78	0.855036
Finishes	Internal ceiling finishes	Asbestos Free with metal framing	gypsum ceiling (plaster board)	75m2, t=0.50mm	0.0375	1000	37.5	0.43	0.016125
Finishes	Internal ceiling finishes	Asbestos Free with metal framing	Hot dip galvanized steel with pure Zinc coating	51mm width, framing, t=12.7mm	0.023930131	7800	186.6550254	2.56	0.477836865
Finishes	Internal ceiling finishes	Emulsion paint	Emulsion paint	75m2, t=0.3mm	0.0225	1400	31.5	2.34	0.07371
Finishes	Internal ceiling finishes	access panel	Plastic, PVC	600x600, t=1.1mm	0.000396	1400	0.5544	3.42	0.001896048
Finishes	External wall finishes	cement plaster	mortar (1:3cement:sand)	83m2, t-15mm	0.31125	3150	980.4375	0.18	0.17647875
Finishes	External wall finishes	weather resistant paints	Alkyd paint, 60% in solvent	83m2,t=0.3mm	0.0249	975	24.2775	3.21	0.077930775
Finishes	External floor finishes	Cement render	Mortar (1:1:6 Cement:Lime:Sand mix)	69m2, t=25mm	1.725	1800	3105	0.14	0.4347
Finishes	External ceiling finishes	Asbestos Free with timber framing	timber	18m2,t=9mm	0.162	720	116.64	0.31	0.0361584
Finishes	External ceiling finishes	Emulsion paints	Emulsion paint	18m2,t=0.3mm	0.0054	1400	7.56	2.34	0.0176904

Sanitary and Services	Sanitary Appliances	pedestal WC	toilet bowl	2 units	-	-	80	1.61	0.1288
Sanitary and Services	Sanitary Appliances	bib taps	Tap (Brass)	2 units	-	-	0.7	9.2	0.00644
Sanitary and Services	Sanitary Appliances	basin	wash basin	3 units	-	-	54	1.61	0.08694

APPENDIX C: Details of the Material Transportation Stage for Single Unit

Material Category	Description	Road Transport Distance (km	TEF mode (gCO2e/kg/km	Emission coefficient factors (kgCO2e/kg	Material Weight (kg	Embodied Carbon Emissions (tCO2e)
Aggregate	U-Tung	11.2	0.1065	0.0011928	1602	0.0019
Brick	ML Brickworks	183.6	0.1065	0.0195534	41376.6	0.8091
Cement	Tasek Corporation	156.4	0.1065	0.0166566	11494.24	0.1915
Ceramics	White Horse Marketing	392	0.1065	0.041748	1606.5	0.0671
Concrete	YTL Cement	190.2	0.1065	0.0202563	76800	1.5557
Metals	Hock Soon Seng	141.2	0.1065	0.0150378	1893.58	0.0285
Metals	U-Tung	11.2	0.1065	0.0011928	359.13	0.0004
Steel	YL Eminent	402	0.1065	0.042813	7065	0.3025
Steel	Yetta Steel	428	0.1065	0.045582	483.2	0.0220
Steel	Astino Metal	296	0.1065	0.031524	4100	0.1292
Timber	Sim Lee Sawmill	20	0.1065	0.00213	1838.41	0.0039
Timber	IKTA Sdn Bhd	162.8	0.1065	0.0173382	157.63	0.0027
Tiles	Lama Tile (Utara)	324	0.1065	0.034506	3587	0.1238

APPENDIX D: Calculation for the Electricity and Water Consumption Amount for Whole Housing Development Project

RM151,000

RM115233.48 (elec) | RM35766.52 (water)

(2month)
water – RM876.32
electricity – RM2823.35

Rate = 0.4925

bekalan sementara ratio = 0.26735

bekalan sementara total = 0.26735 × RM115233.48 = RM30807.67

RM115233.48 = $[0.016 \times (0.4925x)] + [30807.67 + 0.037x + 0.4925x]$

RM84425.8 = $0.53738x$

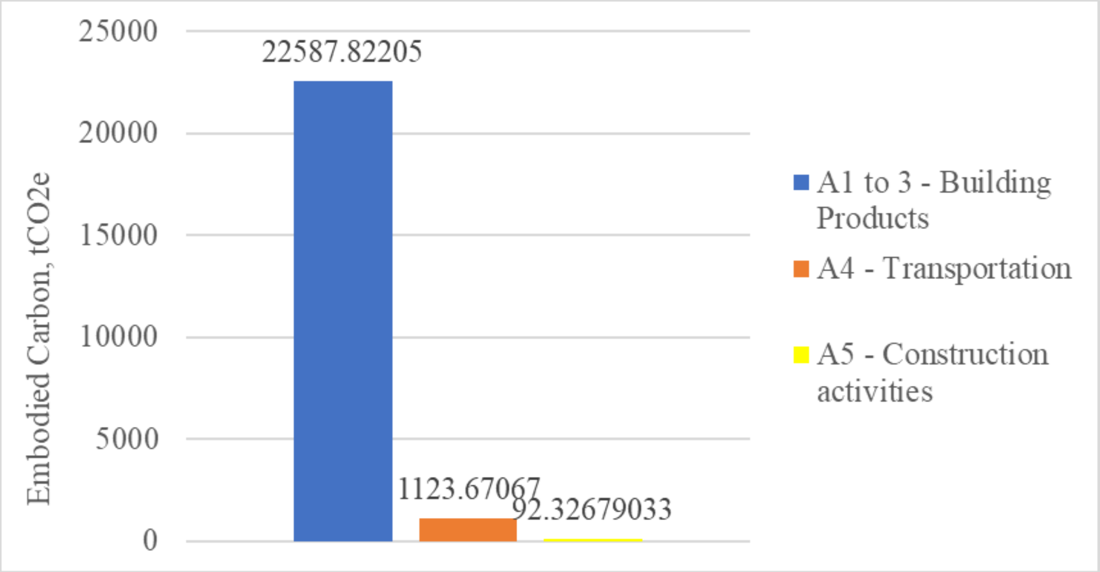
(x = 157106.33 kWh)

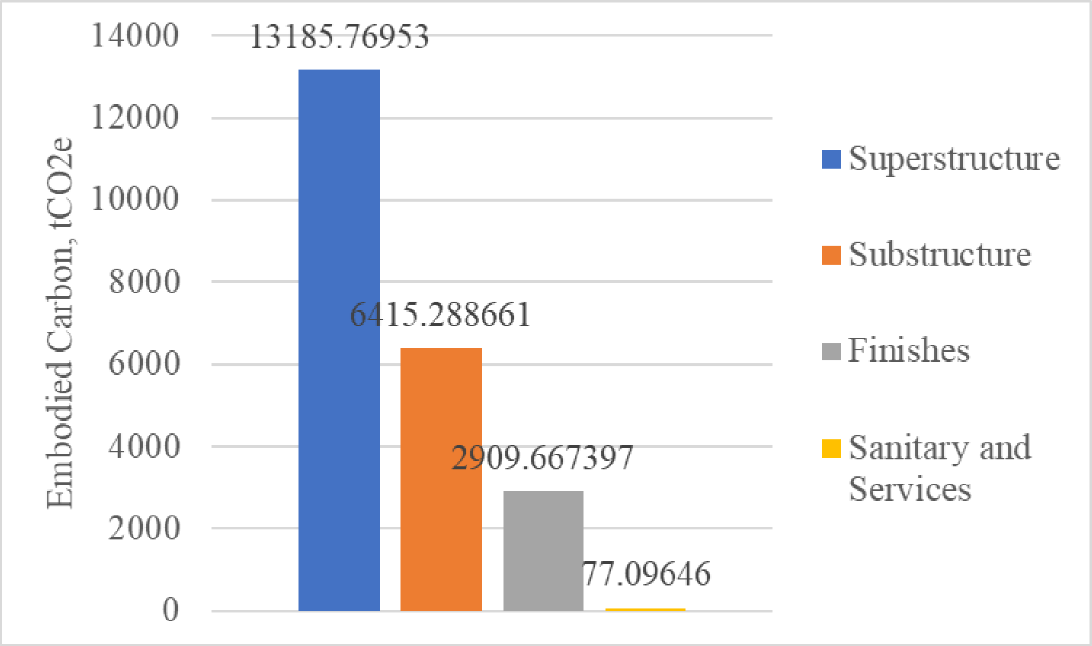
(Water)

RM35766.52 = $(0.036233x \times 1.2) + (0.036233x \times 1.4) + (0.92754x \times 1.61)$

x (= 22529.56 m^3)

APPENDIX E: The Details of each Stage EC for the Whole Housing Development Project





Element Cluster	Building Cluster	Building Component	Materials	Specification	Material Quantity [m3] or [kg/m]	Density [kg/m3]	Material Quantity [kg]	Embodied Carbon Factor [kgCO2e/kg]	EC for whole project (tCO2e)
Substructure	Work Below Lower Filling Floor	Filling imported sand	General aggregate and sand	-	1	1602	1602	0.0049	2.7238806
Substructure	Work Below Lower Filling Floor	Half drain	Vitrified clay pipe	230mm diameter	0.249285377	2000	498.5707541	0.5	86.50202584
Substructure	Reinforced concrete G25	Pile caps	Concrete 25/30 Mpa	-	1	2400	2400	0.12	99.936
Substructure	Reinforced concrete G26	Bed and apron and strip footings	Concrete 25/30 Mpa	-	18	2400	43200	0.12	1798.848
Substructure	Reinforced concrete G27	stumps	Concrete 25/30 Mpa	-	1	2400	2400	0.12	99.936
Substructure	Reinforced concrete G28	Ground beams	Concrete 25/30 Mpa	-	1	2400	2400	0.12	99.936
Substructure	Reinforcement Steel	Pile caps Y16mm	Reinforcing bar	-	-	-	29	0.68	6.84284
Substructure	Reinforcement Steel	Pile caps Y12mm	Reinforcing bar	-	-	-	11	0.68	2.59556
Substructure	Reinforcement Steel	Pile caps R 10mm binder	Reinforcing bar	-	-	-	6	0.68	1.41576
Substructure	Reinforcement Steel	Strip footings; Y12mm	Reinforcing bar	-	-	-	176	0.68	41.52896
Substructure	Reinforcement Steel	Strip footings; Y10mm	Reinforcing bar	-	-	-	123	0.68	29.02308
Substructure	Reinforcement Steel	Strip footings; R10mm	Reinforcing bar	-	-	-	133	0.68	31.38268
Substructure	Reinforcement Steel	Ground beams; Y 12mm	Reinforcing bar	-	-	-	9	0.68	2.12364
Substructure	Reinforcement Steel	Ground beams; Y 10 mm	Reinforcing bar	-	-	-	6	0.68	1.41576
Substructure	Reinforcement Steel	Ground beams; Y 16 mm	Reinforcing bar	-	-	-	78	0.68	18.40488
Substructure	Reinforcement Steel	Ground beams; R10mm links	Reinforcing bar	-	-	-	26	0.68	6.13496
Substructure	Reinforcement Steel	Ground beams; R6 mm links	Reinforcing bar	-	-	-	6	0.68	1.41576
Substructure	BRC A7 steel mesh	Bed and apron	Steel CA60 rebar, welded mesh	160 m2, 3.02 kg/m2	-	-	483.2	1.62	271.626048
Substructure	Formwork	sides pile caps and stumps	reinforcing bar	3m2, 250mm	-	7850	14.39	0.68	3.3954644
Substructure	Formwork	Sides bed	reinforcing bar	21m2, 220mm	-	7850	43.19	0.68	10.1911124
Substructure	Formwork	sides grd beams	steel section	9m2, 10mm	-	7850	7065	1.55	3799.91025
Superstructure	Frame	columns	Concrete 25/30 Mpa	-	2	2400	4800	0.12	199.872
Superstructure	Frame	roof beams	Concrete 25/30 Mpa	-	5	2400	12000	0.12	499.68
Superstructure	Frame	Stiffeners	Concrete 25/30 Mpa	-	1	2400	2400	0.12	99.936
Superstructure	Frame	Roof slab	Concrete 25/30 Mpa	-	2	2400	4800	0.12	199.872
Superstructure	Frame	Lintel	Concrete 25/30 Mpa		1	2400	2400	0.12	99.936
Superstructure	Frame	columns; Y 12mm	Reinforcing bar	-	-	-	274	0.68	64.65304
Superstructure	Frame	columns; R 6mm	Reinforcing bar	-	-	-	71	0.68	16.75316
Superstructure	Frame	roof beams ; Y 16 mm	Reinforcing bar	-	-	-	83	0.68	19.58468
Superstructure	Frame	roof beams ; Y 12 mm	Reinforcing bar	-	-	-	53	0.68	12.50588
Superstructure	Frame	roof beams ; Y 10 mm	Reinforcing bar	-	-	-	213	0.68	50.25948
Superstructure	Frame	roof beams ; R10 mm	Reinforcing bar	-	-	-	44	0.68	10.38224
Superstructure	Frame	roof beams ; R 6 mm	Reinforcing bar	-	-	-	104	0.68	24.53984
Superstructure	Frame	Stiffeners ; Y10mm	Reinforcing bar	-	-	-	40	0.68	9.4384
Superstructure	Frame	Stiffeners ; R 6mm	Reinforcing bar	-	-	-	13	0.68	3.06748
Superstructure	Frame	Roof slab ; Y10mm	Reinforcing bar	-	-	-	218	0.68	51.43928
Superstructure	Frame	Lintel ; Y 10mm	Reinforcing bar	-	-	-	72	0.68	16.98912
Superstructure	Frame	Lintel ; R6mm	Reinforcing bar	-	-	-	48	0.68	11.32608
Superstructure	Frame	Column	Timber/Lumber/Wood	50m2, 14mm	0.7	720	504	0.31	54.21528
Superstructure	Frame	roof beams	Timber/Lumber/Wood	87m2, 14mm	1.218	720	876.96	0.31	94.3345872
Superstructure	Frame	Stiffeners	Timber/Lumber/Wood	6m2, 14mm	0.084	720	60.48	0.31	6.5058336
Superstructure	Frame	sides and soffit Roof slab	Timber/Lumber/Wood	16m2, 14mm	0.224	720	161.28	0.31	17.3488896
Superstructure	Frame	Lintel	Timber/Lumber/Wood	5m2, 14mm	0.07	720	50.4	0.31	5.421528
Superstructure	Roof	Proprietary fabricated roof trusses	Steel hot-dip galvanized steel	85m2	-	-	4100	2.76	3926.652
Superstructure	Roof	150mm UPVC	PVC	17m, 150mm, class D, t=9.5mm	5.786672296	1380	98.37342904	3.23	110.257923
Superstructure	Roof	painting	General Paint	2m2, t=20mils/0.508m	0.001016	1200	1.2192	2.91	1.231111584
Superstructure	Roof	150mm upvc gutter	PVC	12m, 150mm, class D, t=9.5mm	5.786672296	1380	69.44006755	3.23	77.82912212
Superstructure	Roof	Concrete roof tiles	concrete roof tiles	85m2, 42.2kg/m2 elabana	-	-	3587	0.24	298.72536
Superstructure	Roof	Fascia Board	Hardwood (Asian Hardwood)	7.5mm, 230mm, 33m	0.056925	720	40.986	0.31	4.40886402
Superstructure	Roof	Painting to fascia board	Solvent-borne paint	0.12kg/m2, 8m2	-	-	0.96	3.76	1.2525312
Superstructure	External Walls	Half brick wall	clay brick	t=0.127m, 83m2	10.541	1810	19079.21	0.24	1588.916609
Superstructure	External Walls	Glass wall	Glass, Glazing, Double	t=10mm, 83m2	0.83	2512.5	2085.375	1.63	1179.508954
Superstructure	External Walls	Gypsum board with framing	gypsum ceiling (plaster board)	t=17.5mm, 83m2	1.4525	1000	1452.5	0.43	216.727525
Superstructure	Doors	Flush door	Timber, Hardboard	914x2134x38 ,4 units	0.296472352	625	185.29522	0.82	52.7239019
Superstructure	Doors	PVC door	PVC General	813x2134x25 2 units	0.0867471	1380	119.710998	3.23	134.1732837
Superstructure	Doors	Aluminium Sliding door	Glass, General	2000x1093x1.5 1 unit, 2 pcs	0.006558	2400	15.7392	1.44	7.864563456

Superstructure	Doors	Aluminium Sliding door	Aluminum, General	64mm, 40mm, 25mm	0.083122	2700	224.4294	0.93	72.42561167
Superstructure	Windows	Casement window 2 panel	Window frame, aluminium, U=1.6 W/m2K	914x1676x1.8 1unit	-	2700	1.531864	754	400.7938332
Superstructure	Windows	Casement window 2 panel	Window frame, aluminium, U=1.6 W/m2K	914x1219x1.8 4units	-	2700	4.456664	754	1166.032656
Superstructure	Windows	Casement window 2 panel	Window frame, aluminium, U=1.6 W/m2K	914x1372x1.8 1unit	-	2700	1.272288	754	332.8788877
Superstructure	Windows	Top hung window	Window frame, aluminium, U=1.6 W/m2K	600x600 2unit	-	2700	0.72	754	188.37936
Superstructure	Internal walls & partitions	Half brick wall	clay brick	97m2, 0.127m	12.319	1810	22297.39	0.24	1856.926639
Finishes	Internal wall finishes	Ceramic tiles	ceramic tiles	10m2, t=9mm	0.09	2100	189	0.78	51.15474
Finishes	Internal wall finishes	cement plaster	cement	343m2,t=12mm	4.116	1800	7408.8	0.74	1902.431664
Finishes	Internal wall finishes	emulsion paints	emulsion paint	343m2,t=0.3mm	0.1029	1400	144.06	2.34	116.9738388
Finishes	Internal floor finishes	anti slip homogenous tiles with skirt and simple patterns	ceramic tiles	17m2,t=9mm	0.153	2100	321.3	0.78	86.963058
Finishes	Internal floor finishes	Homogenous tiles	ceramic tiles	58m2,t=9mm	0.522	2100	1096.2	0.78	296.697492
Finishes	Internal ceiling finishes	Asbestos Free with metal framing	gypsum ceiling (plaster board)	75m2, t=0.50mm	0.0375	1000	37.5	0.43	5.595375
Finishes	Internal ceiling finishes	Asbestos Free with metal framing	Hot dip galvanized steel with pure Zinc coating	51mm width, framing, t=12.7mm	0.023930131	7800	186.6550254	2.56	165.8093922
Finishes	Internal ceiling finishes	Emulsion paint	Emulsion paint	75m2, t=0.3mm	0.0225	1400	31.5	2.34	25.57737
Finishes	Internal ceiling finishes	access panel	Plastic, PVC	600x600, t=1.1mm	0.000396	1400	0.5544	3.42	0.657928656
Finishes	External wall finishes	cement plaster	mortar (1:3cement:sand)	83m2, t-15mm	0.31125	3150	980.4375	0.18	61.23812625
Finishes	External wall finishes	weather resistant paints	Alkyd paint, 60% in solvent	83m2,t=0.3mm	0.0249	975	24.2775	3.21	27.04197893
Finishes	External floor finishes	Cement render	Mortar (1:1:6 Cement:Lime:Sand mix)	69m2, t=25mm	1.725	1800	3105	0.14	150.8409
Finishes	External ceiling finishes	Asbestos Free with timber framing	timber	18m2,t=9mm	0.162	720	116.64	0.31	12.5469648
Finishes	External ceiling finishes	Emulsion paints	Emulsion paint	18m2,t=0.3mm	0.0054	1400	7.56	2.34	6.1385688

Sanitary and Services	Sanitary Appliances	pedestal WC	toilet bowl	2 units	-	-	80	1.61	44.6936
Sanitary and Services	Sanitary Appliances	bib taps	Tap (Brass)	2 units	-	-	0.7	9.2	2.23468
Sanitary and Services	Sanitary Appliances	basin	wash basin	3 units	-	-	54	1.61	30.16818

Material Categor	Description	Road Transport Distance (kı	TEF mode (gCO2e/kg/kı	ssion coefficient factors (kgC(	Material Weight (k	Embodied Carbon Emissions (tCO2	EC for whole project (tCO2
Aggregate	U-Tung	11.2	0.1065	0.0011928	1602	0.0019	0.6631
Brick	ML Brickworks	183.6	0.1065	0.0195534	41376.6	0.8091	280.7415
Cement	Tasek Corporation	156.4	0.1065	0.0166566	11494.24	0.1915	66.4349
Ceramics	White Horse Marketing	392	0.1065	0.041748	1606.5	0.0671	23.2727
Concrete	YTL Cement	190.2	0.1065	0.0202563	76800	1.5557	539.8223
Metals	Hock Soon Seng	141.2	0.1065	0.0150378	1893.58	0.0285	9.8809
Metals	U-Tung	11.2	0.1065	0.0011928	359.13	0.0004	0.1486
Steel	YL Eminent	402	0.1065	0.042813	7065	0.3025	104.9584
Steel	Yetta Steel	428	0.1065	0.045582	483.2	0.0220	7.6428
Steel	Astino Metal	296	0.1065	0.031524	4100	0.1292	44.8492
Timber	Sim Lee Sawmill	20	0.1065	0.00213	1838.41	0.0039	1.3588
Timber	IKTA Sdn Bhd	162.8	0.1065	0.0173382	157.63	0.0027	0.9484
Tiles	Lama Tile (Utara)	324	0.1065	0.034506	3587	0.1238	42.9492

Cateogry	Total consumption	Unit	Emission Factor kgCO2e/unit	Total embodied carbon (tCO2e)
Electricity	157106.33	kWh	0.53834	84.57662169
Water	22529.56	m3	0.344	7.75016864