COMPARATIVE ANALYSIS OF CARBON EMISSIONS BETWEEN REINFORCED CONCRETE AND STEEL STRUCTURES IN A LOW-RISE COMMERCIAL BUILDING

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Abstract

The construction industry's rapid expansion has brought various environmental challenges, such as greenhouse gases, specifically in terms of carbon emissions. Construction industry contributes more than half of the global greenhouse gas emissions, leading to climate change. This study aims to evaluate and compare the embodied carbon emissions of two commonly used construction materials used in Malaysia, which are reinforced concrete and steel structure, applied to a four storeys commercial building. This research utilises a comparative life cycle assessment (LCA) approach to access the carbon emissions during both the construction and demolition phases. Building Information Modelling (BIM) is used to develop the structural models and perform quantity take-off to obtain primary data for the carbon emissions' calculations of the reinforced concrete and steel structure. The study findings indicate that the reinforced concrete structure has carbon emission of 288.71 tCO_2 while the steel structure emitted 32% less carbon of 196.49 tCO_2 during the construction phase. In the demolition phase, the reinforced concrete structure produces 28.87 tCO_2, compared to 19.65 tCO_2 for the steel structure. These results show the potential of steel structures to significantly reduce embodied carbon emissions. This study aligns with Malaysia's sustainability goals, including its commitment to reducing greenhouse gas emissions under the Paris Agreement and its efforts to promote green building practices. By prioritising steel as a primary building material, the construction industry can make substantial progress toward achieving sustainable construction. Practitioners are encouraged to adopt steel and other eco-friendly materials while utilising tools like BIM to facilitate data-driven decision-making and enhance sustainability in design and construction. This research highlights the need for industry-wide advocacy, and policy incentives to drive the adoption of low-carbon construction practices in Malaysia.

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1.0 INTRODUCTION

The construction sector is one of the most active industries in any economy especially in the developing countries experiencing rapid growth and urbanisation. This industry encompasses a variety of activities, including manufacturing, building, renovating, repairing, and demolishing structures and infrastructures, all of which contribute significantly to a country's economic development. Countries such as India, China, Japan, United States, and Canada have made significant contributions to the industry, with an average growth rate of 67% worldwide and a 5.2% annual increase, resulting in substantial improvements each year (Onat & Kucukvar, 2020).

Despite these benefits, the construction industry's rapid growth has led to significant environmental impact, namely, the greenhouse effect, which contributes to global warming. The term "greenhouse" refers to atmospheric gases that are transparent to solar radiation, similar to the effect of glass in a greenhouse (Mitchell, 1989). Some of the most prevalent greenhouse gases are carbon dioxide, methane, and water vapour (Berman *et al.,* 2012). In this regard, buildings are the primary source of greenhouse gas emissions, contributing to 28% of global emissions (Röck *et al.,* 2020). Furthermore, the construction industry is responsible for 37% of global carbon emissions, with developing countries accounting for the majority of the industry's carbon footprint (Zhou *et al.,* 2022).

Construction is considered the most material intensive activity (Bui *et al.,* 2016) and carbon emissions based on different materials used for the construction of a building differs likewise. Although the operational stage in a building's life cycle contributed over 80% of the total energy used including the carbon emissions (Li & Chen, 2017), the main objective in this research would be focusing on the construction and demolition of the multi-storeys building with different materials of reinforced concrete and steel. The development of the Building Information Modelling (BIM) has progressed rapidly and provided efficient methods for the implementation of Life Cycle Assessment (LCA) in recent years (Lu *et al.,* 2019). The combination of BIM and LCA could provide a platform to determine the carbon emissions of the multi-storeys building during the construction and demolition periods.

Low-rise buildings such as terrace houses and shop lots are a dominant feature of Malaysia's urban and suburban landscapes. Terrace houses are among the most common residential developments in Malaysia. They are typically arranged in rows, sharing party walls, which makes them a cost-effective and space-efficient housing solution. Similarly, shop lots are found in towns and cities nationwide, where these low-rise structures serve as a base for small businesses on the ground. It makes them an integral part of local economies, particularly in smaller towns and suburban neighbourhoods. The construction of low-rise buildings in Malaysia has seen a steady increase, driven by the rising demand for affordable and versatile spaces. Developers often choose low-rise projects for their shorter construction timelines, reduced costs, and adaptability to Malaysia's tropical climate (Lapisa *et al.,* 2018).

Malaysia has set a goal of becoming a carbon-neutral country by 2050 (Hamid, 2017). Despite the implementation of several policy frameworks at the national and city-level, there has been a lack of action taken by both industries and communities. This inaction could be attributed to the limited amount of research available that proves that industrial activities in Malaysia are causing serious environmental pollution. As a result, the severity of environmental degradation is not fully understood by both current and future generations. Therefore, this research paper aims to evaluate and compare the carbon emissions of materials of reinforced concrete and steel during construction and demolition for a low-rise four storeys building designed for commercial use. It will provide new insights on the carbon emissions of different building materials in Malaysia, which could help raise awareness among the construction communities. The comparison in this study could act as a reference and assist the selection of structural system of buildings in Malaysia.

2.0 LITERATURE REVIEW

An overview of the greenhouse gases, specifically carbon emissions would be presented next, followed by Life Cycle Assessment (LCA) which serves as the primary tool applied in this study. In addition, Building Information Modelling (BIM) and the use of typical construction materials are briefly explained below.

2.1 Greenhouse Gases

Many studies indicated that the construction industry is the primary contributor of global greenhouse gas (GHG) emissions, which plays a significant role in global warming (Hong *et al.,* 2015). Greenhouse gases are formed by carbon dioxide, methane, nitrous oxide, water vapour, and fluorinated gases, with carbon dioxide as the primary emitted gas. Nowadays, the construction of new buildings as well as for the refurbishment of existing buildings account for 11% of global overall energy thus process greenhouse gases, with more than half of the emissions related to the materials of cement and steel (Röck *et al.,* 2020). Greenhouse gases are also called as the radiatively active gases in the Earth's atmosphere which could increase the global mean surface temperature by 30K. The rise in the gases has led to an increase in radiative heating at Earth's surface, resulting in changes to water vapour, snow cover, sea ice, and cloud patterns, contributing to the observed warming trend to date. (Mitchell, 1989). As it leads to the global-mean surface warming becomes very probable, greenhouse effect comes about where greenhouse gases tend to absorb and keep the energy from being radiated back into the space when solar radiation hits the Earth (Lave, 1988). Based on Lave (1988), greenhouse effect has attributes of being:

- Global: all regions are affected.
- Long term: the impacts are undetectable in the future.
- Ethical: involves human who are not born yet, plants, animals, and the environment.
- Potentially catastrophic: large changes in environment, massive loss of human life and properties.
- Contentious: the difficulty of enforcing agreements even when there are incentives for individual nations to cheat.

2.2 Carbon Emissions in Building Structures

In 2012, global energy-related carbon dioxide emissions reached a historic high of 31.6 gigatonnes with buildings contributed a quarter of the global total carbon emissions (Hong *et al.,* 2015). For instance, China had become the greatest carbon emitter country in the world since 2008 for its continuous economic boom which attracted extensive attentions from academia, politicians, and the public (Zhang *et al.,* 2014). 27.9% to 34.3% of the overall carbon emissions from construction industry are estimated in China between 1995 and 2010 which had resulted in a substantial amount (Du *et al.,* 2018).

Four major emissions sources on construction sites are summarised which are the building materials production and transportation, energy use during construction such as machine, energy use for processing resources, and the disposal of construction waste. There are many methods in measuring the carbon emissions such as the Life Cycle Assessment (LCA) as well as the carbon emissions coefficient method (Hu *et al.,* 2022) which would be presented in this research study. The carbon emissions factors are the coefficients used to measure the amount of carbon dioxide released due to construction activities. There are two types of emissions during construction, which are the direct and indirect emissions as stated as below (Zhou *et al.,* 2022):

1. Direct emissions
   - Energy consumption of construction equipment
   - Onsite transportation
   - Construction electricity usage
   - Assembly and miscellaneous works (welding and thermal insulating)
   - Onsite worker activities
2. Indirect emissions
   - Building materials production and transportation
   - Transportation of construction equipment
   - Offsite staff activities

In addition, the carbon emissions are also categorised into the embodied carbon emission and the operation carbon emission. The embodied carbon emission focuses on the construction phase such as manufacturing, transportation, installation, and demolition while the operation carbon emission emphasis on the energy consumption (Wan Omar *et al.,* 2014). Figure 1 presents the carbon emissions of a building whole life cycle from production to demolition (Zhou *et al.,* 2022). The figure shows that design phases would start by producing the best proposal before the launching of construction phase. The carbon emissions could be calculated based on the figure below for the life cycle of a building to obtain data to reduce the carbon emissions into the surroundings.

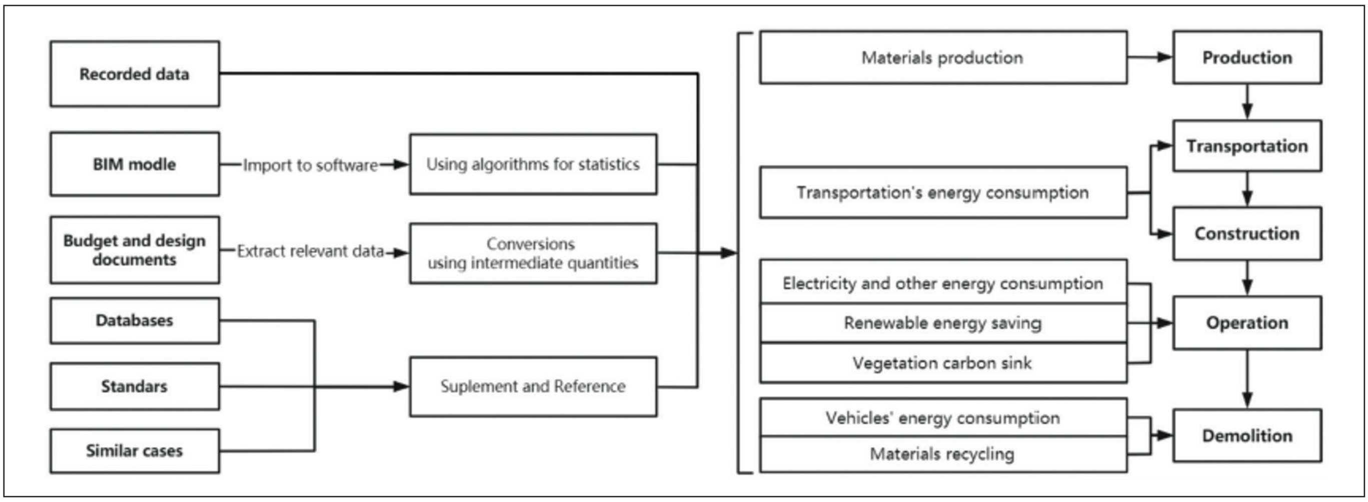

Figure 1: Building whole life cycle carbon emissions framework (Zhou et al., 2022)

2.3 Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is used to examine the environmental and social impacts for a building's entire life cycle (Lu *et al.,* 2019). It aims to evaluate the environmental burdens associated with a product, process, or an activity by identifying and quantifying the energy and material uses that would release back to the environment, as well as evaluate and implement opportunities to affect the environmental improvements (Chau *et al.,* 2015). The interest in LCA has grown significantly since the 1990s when it was met with high expectations, but its results were often criticised. Since then, a strong development and harmonisation has taken effect, produced an international standard and complemented by several guidelines (Finnveden *et al.,* 2009). The first appearance of LCA in its current modern understanding was in a study held by Coca-Cola to assess the environmental impacts of cycle from cradle to grave (Hunt & Franklin, 1996).

There were more initiatives taken to standardise the application of life cycle assessment, such as the Canadian Standards Association released the world's first national LCA guideline Z-760 Environmental Life Cycle Assessment in 1994 (Khasreen *et al.,* 2009). The development of the International Standards for life cycle assessment has become an important move to consolidate the procedures and methods of LCA (ISO, 2016). The organisation has developed with two latest standards that act as references to all stakeholders and the international community:

- ISO 14040:2006, Environmental management- Life cycle assessment
  Principles and framework, offers a clear overview of the practice, applications, and limitations of LCA to a broad range of potential users and stakeholders, including those with a limited knowledge of life cycle assessment.
- ISO 14044:2006, Environmental management- Life cycle assessment
  Requirements and guidelines, is designed for the preparation of, conduct of, and critical review of. Life cycle inventory analysis. It also offers guidance on the impact assessment phase of LCA and on the interpretation of LCA results, as well as the nature and quality of the data collected.

Both standards are the latest updated versions from the previous standards of ISO 14040:1997, ISO 14041:1999, ISO 14042:2000 and ISO 14043:2000 with improvements on the readability and minor amendments. In the construction industry, all stakeholders such as designers, engineers and contractors are all affected by the trend of sustainable production and eco-green strategies. LCA could become a method to assist in achieving sustainable building practices by obtaining environmental-related information such as the amount of carbon emissions for different phases of building's life cycle (Khasreen *et al.,* 2009). Figure 2 below shows the framework of the whole life cycle assessment which could evaluate all resources inputs, including energy, water, materials, and environmental loadings such as carbon dioxide, solid or liquid wastes of a product (Chau *et al.,* 2015).

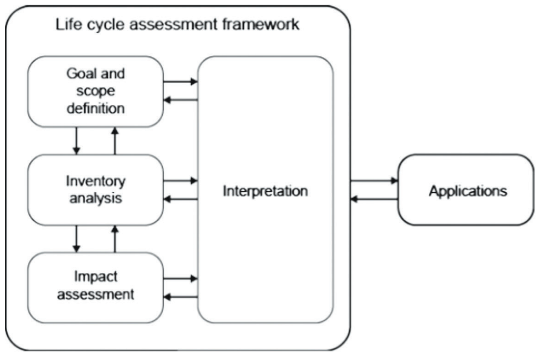

Figure 2: Life cycle assessment framework (Chau et al., 2015)

2.3.1 Integration of Life Cycle Assessment in Environmental Evaluation

Life Cycle Assessment (LCA) is extensively utilised as a method that systematically evaluates the environmental impact of a building throughout its entire life cycle. Xu *et al.* (2022) developed a BIM-integrated LCA solution to automate the environmental assessment of prefabricated buildings based on a five-level framework, consisting of material, component, assembly, flat, and building. The framework was developed based on three modules, such as the BIM data preparation, data extraction and integration, and embodied carbon (EC) assessment. In addition, Kayacetin and Tanyer (2019) developed an integrated LCA-EC assessment method for the built environment at neighbourhood scale which the results were validated based on three neighbourhood-scale mass housing projects in Ankara, Turkey.

Khan *et al.* (2022) aimed to provide a comprehensive and holistic approach to data analysis, including measurement, management, and reduction of embodied carbon. It also analyses the introduction of the assessment process from the early stages of building design and to explore mitigation and management strategies at different levels, such as the neighbourhood, urban, and national levels. Other than that, a study investigates the variations of EC intensities of materials and identifies their parameter variations in hybrid life cycle assessment (Omar, Doh & Panuwatwanich, 2014). The Malaysian Input-Output (I-O) tables are used to derive indirect energy and carbon intensities which are then merged for detailed process LCA analysis. Liang *et al.* (2023) had done further step to account for the embodied carbon emissions in buildings in 2020 for the Guangdong-Hong Kong Macau Greater Bay Area in China (GBA). They integrated remote sensing techniques such as night-time light data (NLT) and building material flows analysis to calculate and spatialise the newly generated building material stocks (MS) using LCA method.

2.4 Building Information Modelling (BIM) in Construction Industry

Building Information Modelling (BIM) is widely seen as a catalyst for innovation and productivity in the construction industry. It could assist for a more sustainable construction process which in turn might contribute to eradicating poverty in developing countries such as Malaysia, China, and India (Bui *et al.,* 2016). Complex construction projects from where buildings are conceived, designed, constructed, operated, maintained, and demolished require inter-organisational associations and to ensure success in project ventures, trust between the different projects partners is a key success factor. Therefore, BIM could be the key approach to create the integration by shifting all data to an Integrated Database paradigm for more efficient communications (Bryde *et al.,* 2013).

BIM software allows engineers and designers to build a 3D virtual model, and it can export information to other computer-modelling platforms to perform data analysis (Hao *et al.,* 2020). Due to the advancements in building materials and technology, the life cycle assessment (LCA) has become a great burden to engineers as the evaluation of environmental issues becomes more complicated. Thus, BIM software could assist in obtaining the information in an easy and accurate manner (Shin & Cho, 2015). Röck *et al.* (2018) proved that the BIM-integrated approach enables identification of design specific hotspots which can be visualised on the building model for communication of LCA results and visual design guidance.

2.5 Construction Material: Concrete

Concrete is the most common construction material in Malaysia. It is the mixed product of water, cement, fine aggregates, and coarse aggregates. The design of right water-cement ratio would produce strong and high compressive strength of concrete to withstand the loads of structures. For instance, the 163 storeys Burj Khalifa in Dubai, world tallest skyscraper was rose with more than 330,000 m^3 of concrete and 39,000 tons of steel rebar (Hamza, 2021). Portland cement is the most frequently seen manufactured finely ground power in the industry. The production of cement, which is an essential constituent of concrete, could lead to the release of significant amounts of carbon dioxide, where production of one ton of Portland cement produces about one ton of carbon dioxide (Naik, 2008). After water, concrete is the most widely used substance on Earth.

If the cement industry is a country, it would be the third largest carbon dioxide emitter in the world with up to 2.8 billion tons, surpassed only by China and United States (The Guardian, 2019). From 2013 to 2022, production of cement in Malaysia is at average of 20 million metric tons. In year 2022, Malaysia had produced 19.86 million metric tons of cement. As concrete is the most common construction material in Malaysia, Malaysia has many top-rated cement manufacturers which produce quality cement such as YTL Cement Berhad and Lafarge Malaysia. The nation's reliance on this material significantly contributes to its carbon footprint. This highlights the pressing need to address the environmental impact of cement and concrete production, particularly in the context of reducing carbon emissions. In the Malaysian context, addressing these challenges is particularly urgent given the country's commitment to international climate agreements, such as the Paris Agreement (Wong *et al.,* 2022). Reducing emissions from cement and concrete production aligns with broader efforts to transition to a low-carbon economy and achieve sustainability in the construction sector.

2.6 Construction Material: Steel

Steel is one of the most sustainable construction materials on Earth. This is due to the reason that many steel frame structures nowadays are designed in consideration for the demolition of the whole structure. Steel has many desirable characteristics which could be exploited in a wide range of construction applications. It is corrosion-resistant and long-lasting, making thinner and more durable structure possible. Furthermore, it could be presented in many possibilities of shapes and forms while being tough, hygienic, adaptable as well as recyclable (Baddoo, 2008). Therefore, using steel as construction materials brings more benefits especially for long life cycle building. The ECSC study has confirmed that steel construction products within Western Europe have high recycling rates with 83% recycling at the end-of-life cycle, 14% are re-used and only 3% are landfilled or disposed (Durmisevic, 2003).

The annual consumption of steel has increased at a compound growth rate of 5% over the last 20 years as steel producers are continually developing the manufacturing of steel with the aims of reducing cost, shortening lead times, and improving quality (Baddoo, 2008). In Malaysia, steel demand is increasing gradually, where Malaysia's apparent steel consumption (ASC) predicted that the nation would reach 12.4 million metric tons in 2025. This increasing demand highlights the need to address the carbon footprint associated with steel production, as the construction industry's environmental impact is one of the largest contributors to global greenhouse gas emissions.

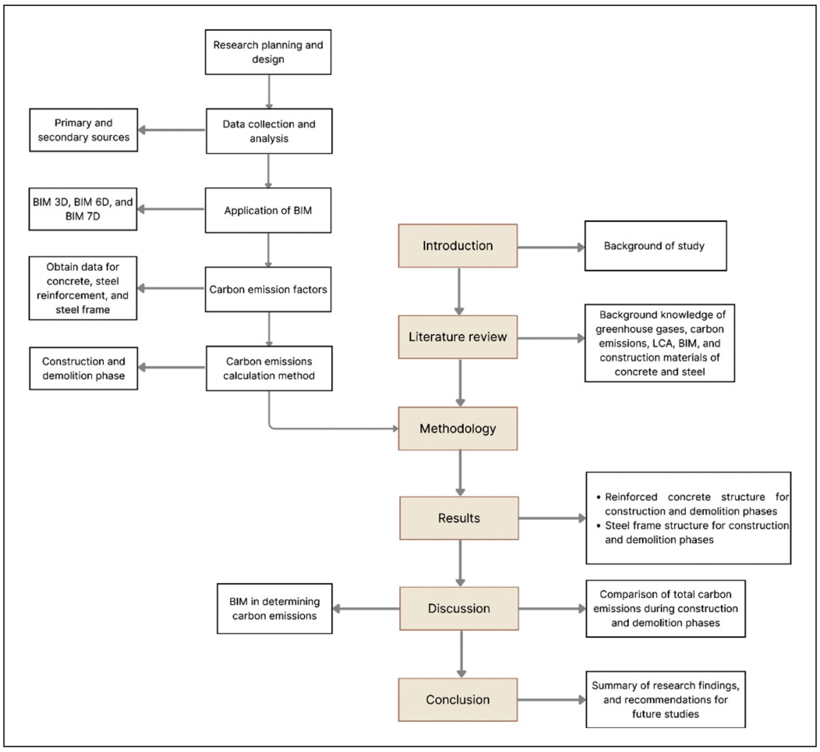

Figure 3: Research framework

3.0 RESEARCH METHODOLOGY

The whole research process would be applied with the Life Cycle Assessment (LCA) for a more detailed investigation on this environmental issue. Life cycle assessment is an important tool to help decision making (Navarro *et al.,* 2020). The overall framework of the LCA is as presented in Figure 2. In addition, a research flow chart, integrating the LCA procedure is presented in Figure 3, to produce a more sequenced evaluation process.

3.1 Research Planning and Design

The research performs a case study analysis, utilising a multi-story building which would give an outcome on the amount of carbon dioxide emitted by both RC and steel buildings, using the units of $kgCO_2$ or tCO_2. In addition, the research further studies the recommendations on the application of Building information modelling (BIM) and its tools in determining carbon emissions.

3.2 Data Collection and Analysis

The data collection is divided into two categories:

- Primary sources
  Two 3D models for reinforced concrete and steel are designed and modelled using Autodesk Revit 2022 to review and obtain the material quantities such as volume used for the whole building through quantity take off method.
- Secondary sources
  The embodied carbon coefficient factors are referred to research articles and journals before selecting the preferred factors to use for concrete, steel reinforcement bar and steel.

  The research is mainly focusing on the materials' embodied carbon emissions; thus it will be categorised under indirect carbon emissions analysis.

The collected data obtained is further analysed using Microsoft Excel. The total carbon emissions of buildings are calculated based on the amount of concrete, steel rebars and the steel structure's components. Discussion is made in depth based on the findings obtained with the comparisons between reinforced concrete and steel structures that are being discussed and studied. Moreover, the application of Building Information Modelling (BIM) for conducting Life Cycle Assessment (LCA) of carbon emissions from buildings is also being evaluated.

3.3 Application of BIM

Figure 4 illustrates the BIM dimensions for the whole life cycle of the buildings. In this research study, some dimensions are included and applied to determine the carbon emissions for the construction and demolition phases of the multi-story building.

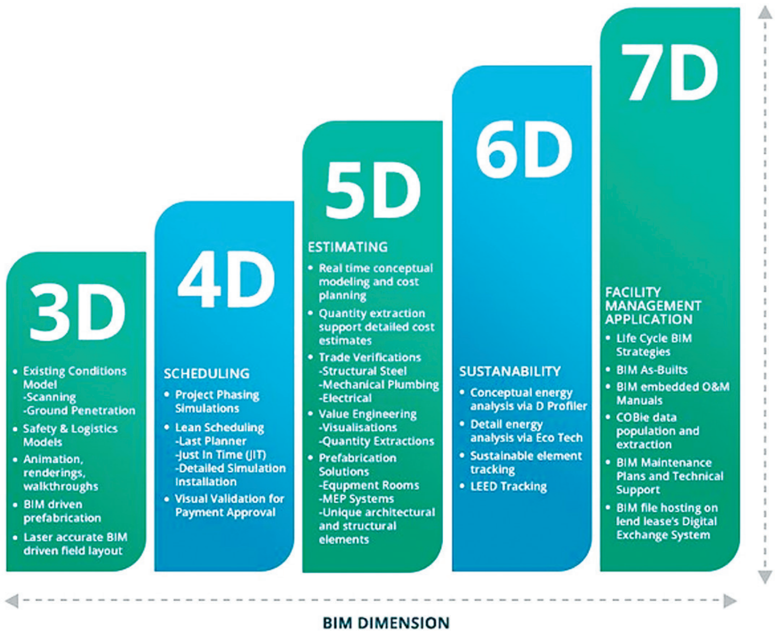

Figure 4: BIM dimensions (Rodriguez, 2022)

1. BIM 3D

3D models of reinforced concrete of steel structures are designed based on loading calculations and detailed calculations on beams, columns, and slabs. The pad foundation of both structures is designed as well but it would not be considered in the comparison due to the same dimension. Autodesk Revit 2022 is used to draw and visualised the two models. After the models are completed, quantity take off is generated from Autodesk Revit 2022 as well to obtain the data as below:

- Construction material name and types
- Columns' locations
- Columns', beams', and slabs' levels

- Types of Universal Column and Beam
- Lengths of column and beam
- Cross sectional areas of concrete columns and beams
- Areas of slabs
- Volumes of columns, beams, and slabs

An example of the information obtained from Revit 2022 is provided in the Appendix.

2. BIM 6D

Both buildings are analysed to obtain the carbon emissions and discuss the comparison between two construction materials for the construction and demolition phases. Moving on, suggestions on approaches to reduce carbon emissions will be made.

3. BIM 7D

BIM 7D mainly focus on the facility management such as operation and maintenance of the building during its life cycle. However, in this research paper, BIM 7D would be focusing on the carbon emissions during the demolition of both buildings.

3.4 Carbon Emission Factors

Carbon emission factor is also known as the carbon intensity and emission coefficient. It is a measure of the amount of carbon dioxide emitted per unit of activity, typically $kgCO_2$/kg, tCO_2/m^3 and tCO_2/t. They are used to calculate the carbon footprint and to assess the environmental impact of the construction materials. Various sources are referred to determine the appropriate carbon emissions factor for this study. As this research focuses on the construction materials, hence the coefficients of concrete, steel reinforcement bar and steel frame are obtained. Based on the design of the reinforced concrete structure, concrete of grade 30 MPa is used.

Tables 1, 2, and 3 show the summarised data collection of embodied carbon emission factors from various sources. The research is an indirect carbon emissions analysis, as the study is focusing on comparing two materials' embodied carbon emissions. Based on the data obtained, it shows that most of the research regarding the carbon footprint in construction industry are carrying out in China, as China is one of the greatest carbon emission countries. The carbon emission factors from Li *et al.* (2021) are adopted for this investigation, because it offers the latest research outcomes, compared to other research papers. This paper has evaluated the impacts and values of carbon emissions by analysing four building projects in the Fujian Province of China. Apart from that, the coefficient from Zhang (2021) with the greatest value of 0.3410 $kgCO_2$/kg is not selected in this paper due to the reason that the coefficient included the production and transportation of the concrete carbon emission.

3.5 Carbon Emissions Calculation Method

3.5.1 Construction Phase

The carbon emissions (ec_i) of concrete, steel reinforcement and steel frame in BIM could be computed using the equation:

$$ec_i = \sum_{j=1}^{n} ecf_j * q_j \quad (1)$$

where $i = 1\ldots\ldots m, ecf_j$ includes the embodied carbon emission factors for different material types used in building component (concrete, steel, etc.) which could be obtained from section 3.4. q_j is the material quantity obtained directly from the BIM model (Eleftheriadis **et al.,** 2018). The resulting values are calculated in $kgCO_2$ using equation above.

Based on Eleftheriadis (2018) the total embodied carbon could also be calculated by the sum of the embodied carbon emissions from all the building components divided by the total internal floor area from ground floor (a_1) to the top floor (a_k) using the equation below:

$$EC = \sum_{i=1}^{m} ec_i \,/\, \sum_{z=1}^{k} a_z \quad (2)$$

Where k is the total number of floors. Therefore, in this case the carbon emissions should calculated with the units of tCO_2/m^2 or $kgCO_2/m^2$. Table 4 shows the area for every floor and the total floor area of whole building obtained from the BIM room layout feature. Both building of reinforced concrete and steel frame have the same area for each floor.

Table 1: List of carbon emission factor for concrete

Coefficient	Unit	Publication	Article
0.3410	$kgCO_2$/kg	Zhang *et al.,* 2021	Sustainable design of reinforced concrete structural members
0.1590	$kgCO_2$/kg	Yan *et al.,* 2010	A Case study of One Peking in Hong Kong
0.2700	tCO_2/m^3	Li *et al.,* 2017	A case study in Shenzhen
0.2877	tCO_2/m^3	Li *et al.,* 2021	Using BIM to research carbon footprint
0.1980	$kgCO_2$/kg	Wan *et al.,* 2014	Assessment of the embodied carbon in precast concrete

Table 2: List of carbon emission factor for steel reinforcement

Coefficient	Unit	Publication	Article
1.242	$kgCO_2$/kg	Yan *et al.,* 2010	A Case study of One Peking in Hong Kong
2.206	tCO_2/t	Li *et al.,* 2017	A case study in Shenzhen
2.670	tCO_2/t	Li *et al.,* 2021	Using BIM to research carbon footprint
3.5862	$kgCO_2$/kg	Wan *et al.,* 2014	Assessment of the embodied carbon in precast concrete

Table 3: List of carbon emission factor for steel frame

Coefficient	Unit	Publication	Article
1.722	tCO_2/t	Li *et al.,* 2017	A case study in Shenzhen
1.860	tCO_2/t	Li *et al.,* 2021	Using BIM to research carbon footprint
1.740	$kgCO_2$/kg	Steelconstruction.info, 2013	Embodied carbon data for common framing materials

Table 4: Summary of floors' area

Floor	Level (m)	Floor Area	Unit
Ground Floor	0	297.000	m^2
First Floor	3.0	297.000	m^2
Second Floor	6.0	297.000	m^2
Roof Floor	9.0	76.125	m^2
Total	9.0	967.125	m^2

3.5.2 Demolition Phase

Due to the lack of basic data on building demolition, the relevant studies have widely used the empirical value method to estimate the carbon emissions in this phase (Architectural Institute of Japan, 2003). Based on several literature reviews on previous research articles, the demolition phase is dependent on the construction phase, as data for the demolition stage of buildings are difficult to obtain (Wang *et al.,* 2007). Lu & Wang (2019) had done much research on the demolition stage and found out that the demolition phase is approximately equal to 10% of the construction stage. Yao *et al.* (2023) had also utilised this analysis method to calculate the carbon emission of demolition phase for residential building in n Liaocheng City, Shandong Province, China. Therefore, the formula for the calculation to estimate the carbon emissions at the demolition stage is:

$$C_{dem} = C_{con} \times 10\% \quad (3)$$

where C_{dem} is the carbon emission of concrete, steel reinforcement and steel frame at demolition phase. C_{con} is the carbon emissions at construction phase, which is ec_i from section 3.5.1 above. The demolition phase would be executed at least after 50 years of the buildings' life cycle.

Table 5: Summary of volume and weight for concrete and steel reinforcement

Materials	Components	Volume (m^3)	Density (kg/m^3)	Weight (kg)
Concrete	Column	33.80	2380	80,444
	Beam	77.69	2380	184,902
	Slab	137.22	2380	326,584
	Total	248.71	2380	591,930
Steel Reinforcement	Column	1.41	7848	11,053
	Beam	3.24	7848	25,407
	Slab	5.72	7848	44,872
	Total	10.37	7848	81,331

4.0 ANALYSIS AND DISCUSSION

4.1 Reinforced Concrete Structure

The proposed low-rise multi-storey building is designed as hostel for the accommodation of guests who are visiting The University of Nottingham Malaysia. It has a Gross Internal Area (GIA) of $315m^2$ (15x21m), equipped with 13 deluxe rooms including room for disabled individual at ground floor and few common areas. It takes 6 months to fully construct the building structure. The whole project involves the Building Information Modelling (BIM) dimensions from 3D to 7D and this research engages few parts in it. This structure is designed for a 50-year lifespan.

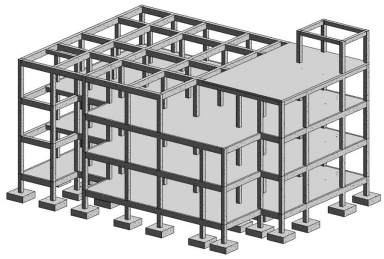

Figure 5: Reinforced concrete structure model

The reinforced concrete structural model is illustrated in Figure 5 and it is modelled using the intelligent 3D modelling in BIM. As shown in Figure 5, only the main construction components are included in the analysis, while other architectural and structural components such as walls, ceilings, doors, roofs, and façade are not included in the analysis. The foundations are not included in this study as both comparing structures have the same pad footing design. All quantities needed for the carbon emissions analysis are obtained from the primary source, which is from the model using quantity take-off method in Autodesk Revit 2022.

4.1.1 Construction Phase

After obtaining the data needed by quantity take-off in Revit 2022, the data analysis is conducted using Microsoft Excel. All components for concrete and steel reinforcement are analysed separately in spreadsheets. Table 5 shows the determination of weight for both materials. The concrete has a weight of 591.9 tons, which is around 7 times greater than the steel reinforcement. Table 6 shows the carbon emissions for each material as well as the grand total carbon emission for the whole reinforced concrete structure.

Table 6: Summary of reinforced concrete carbon emission

Materials	Components	Weight (kg)	Carbon Coefficient	Units	Carbon Coefficient ($kgCO_2/kg$)	Carbon Emission ($kgCO_2$)
Concrete	Column	80,444	287.70	$kgCO_2/m^3$	0.121	9,724
	Beam	184,902	287.70	$kgCO_2/m^3$	0.121	22,351
	Slab	326,584	287.70	$kgCO_2/m^3$	0.121	39,478
	Total	591,930	287.70	$kgCO_2/m^3$	0.121	71,554
Steel Reinforcement	Column	11,053	2.67	tCO_2/t	2.67	29,512
	Beam	25,407	2.67	tCO_2/t	2.67	67,836
	Slab	44,872	2.67	tCO_2/t	2.67	119,807
	Total	81,331	2.67	tCO_2/t	2.67	217,155
					Grand Total:	**288,709**

The carbon emission factors obtained from secondary sources as presented in section 3.4 are first converted to the same unit of $kgCO_2/kg$ before multiplying the weight to obtain the carbon emissions in $kgCO_2$. The grand total carbon emission for the whole structure is 288.71 tCO_2 with the slabs occupying the most quantity for both concrete and steel reinforcement. This is because slabs have the largest areas at every floor with thickness of 150mm.

Based on BS EN 1992-1-1:2004, the maximum percentage of steel reinforcement for column, beam, and slab are 4%. Therefore, it is proven that the volume of steel reinforcement remains as 4% of the volume of the reinforced concrete while the concrete grade 30 occupies the remaining 96% of the total volume. Based on the grand total carbon emission of 288.71 tCO_2, concrete only built up 24.78% from the grand total while steel reinforcement built up 75.22%. Concrete emitted 71.55 tCO_2 while steel reinforcement emitted 217.16 tCO_2. This shows that steel reinforcement is the dominant in the carbon emission of reinforced concrete. One of the reasons of high carbon emission in steel reinforcement might be the relatively high carbon emission factor as shown in Table 4.2. Steel reinforcement has a coefficient of 2.67 $kgCO_2/kg$ while concrete has coefficient of 0.121 $kgCO_2/kg$ only. In the result, the steel reinforcement coefficient is 22 times greater than concrete, conducting to more carbon emission despite having lesser volume than concrete.

As it is proven that steel reinforcement is the major contributor to the carbon emission of reinforced concrete, some approaches must be implemented to reduce the reinforcement carbon emission. For instance, steel could be reused for the cast in-situ construction as steel is very durable and long lasting without losing its properties. Based on the research of Mastali *et al.* (2018), using recycled steel as replacement for the steel reinforcement could reduce the carbon emissions by an average of 20% after conducting several investigations. In addition, proper management of materials should be implemented to avoid any material wastage during construction. The amount of materials needed for construction should be estimated and calculated in detailed and only order the adequate amount of steel reinforcement as well as concrete.

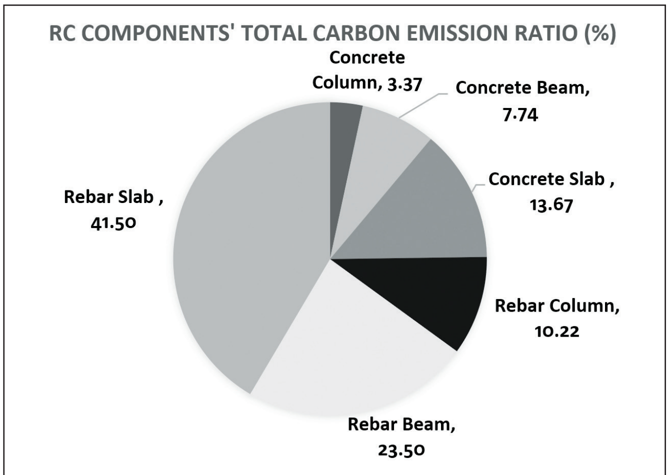

Figure 6: Reinforced concrete components' total carbon emission ratio

Moving on, the total carbon emission ratio for the reinforced concrete is illustrated in Figure 6. Based on the analysis by components, the reinforced slab contributed the most for both concrete and steel reinforcement due to its large volume. However, in this case the amount of steel reinforcement used for the cast in-situ slab is more critical due to the 41.50% of carbon emitted for the entire structure. Therefore, engineers should be more concerned about the reinforcement detailed designs to find a balance between the component's strength and the carbon emission. The greater the amount of volume for slab, the more steel reinforcement needed to increase the strength of the entire slab. In addition, the beam is the second most carbon emitted for the structure, with 31.24% contributed. Column has the least carbon emission with 13.59% emitted due to its lower volume but adequate strength to transfer the loadings to the foundations.

This has proven that Malaysia has emitted million tons of carbon dioxide in construction as reinforced concrete building is the most common structure design in Malaysia, no matter low-rise buildings or skyscrapers. In addition, not only buildings but other structures like bridges and highway flyovers are built with reinforced concrete as well in Malaysia.

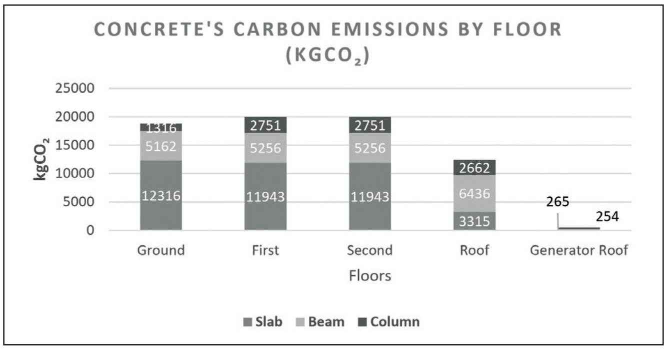

Figure 7: Concrete's carbon emissions by floors

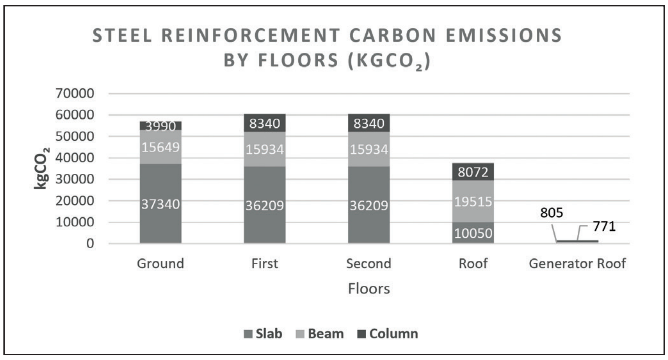

Figure 8: Steel reinforcement's carbon emissions by floors

Figure 7 and Figure 8 show the concrete and steel reinforcement carbon emissions by each floor. As shown in both figures, first floor and second floor have the same carbon emission due to the exact same design and amount of column, beam, and slab. Both floors emitted 19.95 tCO_2 of carbon dioxide from concrete and 60.48 tCO_2 from the steel reinforcement.

In addition, the ground floor emitted slightly lesser carbon dioxide for both materials due to lesser volume accumulated with 75.77 tCO_2 emission. The length of column for the ground floor to the foundation level is shorter with dimension of 1500 mm comparing to other floors' column with dimension of 3000 mm. Therefore, lesser concrete and steel reinforcement used, conducting to lesser carbon emission. The carbon emission for the roof floor is lesser compared to the first three floors mainly due to the smaller area of slab, with 12.41 tCO_2 emitted for concrete and 37.64 tCO_2 for steel reinforcement. Furthermore, the generator roof level without slab only emitted 520 $kgCO_2$ for concrete and 1576 $kgCO_2$ for steel reinforcement.

Based on previous analysis discussions, it still proved that the steel reinforcement carbon emission analysis by floors is greater than the concrete carbon emission. Due to larger coefficient, steel reinforcement emitted 50.44% more carbon dioxide than the concrete.

Tables 7 and 8 show the total embodied carbon emissions of concrete and steel reinforcement by total internal floor area. Determining the value of embodied carbon emissions in this section could observe the carbon emissions per meter square (m^2) for each floor. The embodied carbon emission is analysed by floors as each floor has different values of carbon emissions. The generator roof is not considered in this part as this level does not have slab and an internal floor area. Based on the comparison between the concrete and steel reinforcement embodied carbon emissions by internal floor area, steel reinforcement emitted more carbon dioxide per floor area for every floor comparing to the concrete. The embodied carbon emissions per internal floor area for first and second floor are the same due to same amount of carbon emitted and same floor area designed.

Table 7: Embodied carbon emission of concrete by total internal floor area

Floors	Carbon Emission ($kgCO_2$)	Floor Area (m^2)	Embodied Carbon Emission ($kgCO_2/m^2$)
Ground	18,794	297.000	63.28
First	19,949	297.000	67.17
Second	19,949	297.000	67.17
Roof	12,413	76.125	163.06
		Total:	**360.68**

Table 8: Embodied carbon emission of steel reinforcement by total internal floor area

Floors	Carbon Emission ($kgCO_2$)	Floor Area (m^2)	Embodied Carbon Emission ($kgCO_2/m^2$)
Ground	56,979	297.000	191.85
First	60,482	297.000	203.64
Second	60,482	297.000	203.64
Roof	37,636	76.125	494.40
		Total:	**1093.54**

4.1.2 Demolition Phase

Based on Lu & Wang (2019), the demolition phase is approximately equal to 10% of the construction phase. Therefore, the equation obtained in carbon emission calculation method in section 3.5.2 would be used to determine the carbon emission for demolition at least after 50 years of the building's life cycle. The calculation for this stage only includes the demolishing of concrete and steel reinforcement from the building structure, without considering the transportation, disposal, and recycle process.

Table 9 presented the summary of reinforced concrete carbon emission at demolition phase. The total carbon emission for the whole structure is estimated to be 28.87 tCO_2, where concrete emitted 7.16 tCO_2 and steel reinforcement emitted 21.72 tCO_2 of carbon dioxide. The slab which has the largest volume emitted the most carbon compared to column and beam.

Table 9: Summary of reinforced concrete carbon emission at demolition phase

Materials	Components	C_{con} ($kgCO_2$)	Per (%)	C_{dem} ($kgCO_2$)
Concrete	Column	9,724	10	972
	Beam	22,351	10	2,235
	Slab	39,478	10	3,948
	Total	71,554	10	7,155
Steel Reinforcement	Column	29,512	10	2,951
	Beam	67,836	10	6,784
	Slab	119,807	10	11,981
	Total	217,155	10	21,715
	Grand Total:	**288,709**	**Grand Total:**	**28,871**

4.2 Steel Frame Structure

The steel frame structure has the same architectural design, gross internal area, room layouts and internal facilities as the reinforced concrete structure. The steel frame structural model is illustrated in Figure 9, modelled using the intelligent 3D modelling in BIM. As shown in figure below, only the column, beam, and slab are considered in this analysis, while other architectural and structural components such as foundations, walls, ceilings, doors, roofs, and façade are not included. All quantities required for the carbon emissions analysis are obtained from Autodesk Revit 2022 quantity take-off.

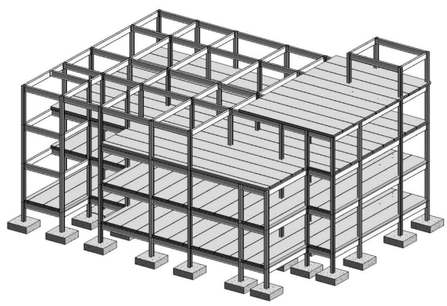

Figure 9: Steel frame structure

4.2.1 Construction Phase

Table 10 shows the determination of weight for the steel structure. The total weight of the entire structure consisting of column, beam, and slab is around 361.76 tons. Furthermore, Table 11 presented the grand total carbon emission for the steel frame. The carbon emission factors for steel and concrete chosen from section 3.4 are first converted to the same unit of $kgCO_2/kg$ before multiplying the weight to obtain the carbon emissions for each component in $kgCO_2$. The equation used to measure the carbon emissions of column, beam, and slab is shown in section 3.5, before summing up to get the grand total carbon emission of the entire structure. The grand total carbon emission is 196.49 tCO_2, with the steel column and steel beam having greater carbon emissions, compared to the precast concrete slab.

The beam emitted the most carbon for the entire structure with 43.31% of total emission following by the column with 39.82% emission. The beam has emitted 85.1 tCO_2 of carbon dioxide while the column emitted 78.2 tCO_2 of carbon dioxide. Despite the high volume of the slab, the slab emitted the least carbon dioxide among the three components with only 16.87% of total emission, 33.1 tCO_2 carbon emitted. This is due to the reason that steel has higher carbon emission factor compared to concrete. Based on Table 11, steel has carbon emission factor of 1.860 $kgCO_2/kg$ while the concrete only has 0.121 $kgCO_2/kg$, which is around 15 times greater than concrete.

This has proven that despite lesser volume of universal column and universal beam, it could still release large amount of carbon dioxide due to its larger carbon emission factor. Therefore, engineers should use the appropriate and sufficient design of structural components which could take the loads designed after considering the safety factors as well.

Table 10: Summary of volume and weight for steel frame

Materials	Components	Volume (m^3)	Density (kg/m^3)	Weight (kg)
Steel	Column	5.36	7,848	42,065
	Beam	5.83	7,848	45,754
	Slab	115.1	2,380	273,938
	Total	126.29		361,757

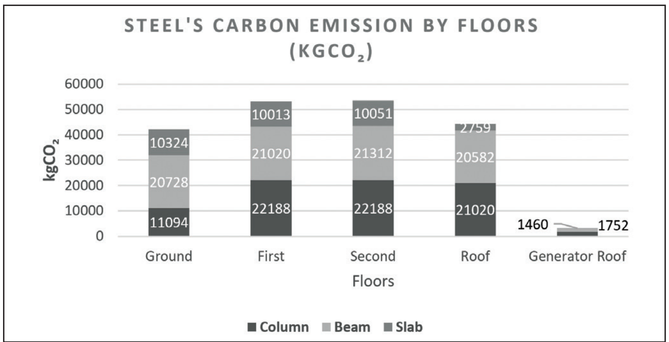

Figure 10: Steel's carbon emission by floors

Figure 10 illustrates the steel's carbon emissions by floors. The first and second floors have similar amount of carbon emissions of 53.2 tCO_2 and 53.5 tCO_2. Next, the roof floor emitted 44.4 tCO_2 of carbon while the ground floor emitted 42.1 tCO_2. By comparing both figures below, it showed that slab which has greatest volume, emitted the least carbon dioxide among the three components for each floor, except the generator roof's floor. As for the ground floor, the carbon emission of column is lesser than beam because the column of the ground floor is shorter with 1500mm only, comparing to other floors' column with length of 3000mm.

Table 12 shows the embodied carbon emission of steel by total internal floor area. The equation used and the total internal floor area obtained from Autodesk Revit 2022 could be found from the carbon emission calculation method in section 3.5.1. The generator roof is as well not considered in this section due to the absence of slab and internal floor area. Based on the table below, roof floor has the greatest embodied carbon emission by total internal floor area due to its large carbon emission but small floor area.

4.2.2 Demolition Phase

The carbon emission of steel frame for the demolition phase is same as the calculation in reinforced concrete structure, which is based on the research of Lu & Wang (2019) in section 3.5.2. The action of demolishing the structure would also be implemented at least after 50 years of the building's life cycle. The calculation for the demolition stage only includes the demolition of steel frame components of column, beam, and slab, without considering the transportation, disposal, and recycling process.

Table 13 shows the summary of steel frame carbon emission at demolition phase. C_{con} indicates the carbon emissions at construction phase while C_{dem} indicates the carbon emissions at demolition phase. Based on the table below, the total carbon emission for the whole structure is 19.6 tCO_2, where the column emitted 7.8 tCO_2 and beam emitted 8.5 tCO_2. The slab has the lowest carbon emission during demolition phase with 3.3 tCO_2.

Table 12: Embodied carbon emission of steel by total internal floor area

Floors	Carbon Emission ($kgCO_2$)	Floor Area (m^2)	Embodied Carbon Emission ($kgCO_2/m^2$)
Ground	42,146	297.000	141.91
First	53,221	297.000	179.20
Second	53,550	297.000	180.30
Roof	44,361	76.125	582.74
		Total:	**1084.15**

Table 13: Embodied carbon emission of steel at demolition phase

Materials	Components	C_{con} ($kgCO_2$)	Per (%)	C_{dem} ($kgCO_2$)
Steel	Column	78,241	10	7,824
	Beam	85,102	10	8,510
	Slab	33,146	10	3,315
	Total	196,490	10	19,649

Table 11: Summary of steel frame carbon emission

Materials	Components	Weight (kg)	Carbon Coefficient	Units	Carbon Coefficient ($kgCO_2/kg$)	Carbon emission ($kgCO_2$)
Steel	Column	42,065	1.860	tCO2/t	1.860	78,241
	Beam	45,754	1.860	tCO2/t	1.860	85,102
	Slab	273,938	287.70	kgCO2/m3	0.121	33,146
	Total	361,757			**Grand Total:**	**196,490**

4.3 Comparison of Total Carbon Emissions during Construction and Demolition Phases

Based on the results and analysis of both reinforced concrete and steel structure above, the grand total carbon emissions for both buildings are summarised in Figure 11 Reinforced concrete structure has carbon emission of 288.71 tCO_2 while the steel structure has 196.49 tCO_2. It shows that the reinforced concrete structure emitted 32% more carbon dioxide than the steel structure. In this case, both structures' carbon emissions do not consider manufactures, materials wastages, use of machines and other construction works that would emit carbon to the surrounding. For the reinforced concrete structure, the maximum cross-sectional area of 4% of steel reinforcement for column, beam, and slab is used. Besides, the reinforced concrete structure has larger volume for each component conducting to more carbon emissions. Therefore, proper and appropriate design for the structure would reduce the carbon emission. For instance, recycled steel could replace newly industrial manufactured for steel reinforcement. In addition, study and design new water-cement ratio for concrete or replacing the elements of concrete (fine aggregates, coarse aggregates, water, and cement) with sustainable materials could reduce the carbon emissions.

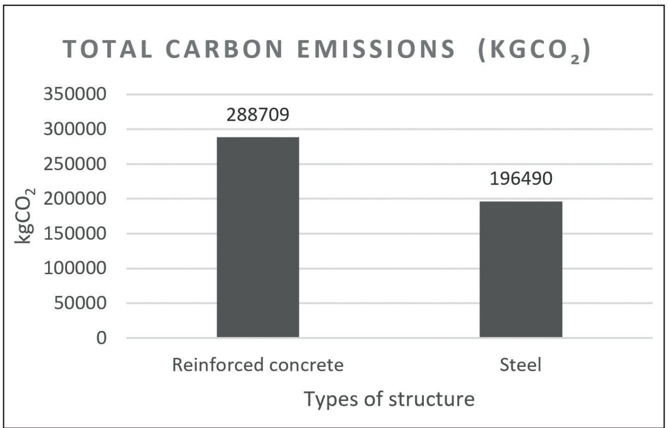

Figure 11: Total carbon emissions of reinforced concrete and steel structure during construction

Based on ISO 14044:2006, the equivalence of the systems being compared shall be evaluated before interpreting the results for different stages. Therefore, the components of reinforced concrete and steel structure involved for both construction and demolition stages remain the same in quantities and properties. The total carbon emissions during demolition phase are dependent on the construction phase. The carbon emission of reinforced concrete structure during demolition stage is 28.87 tCO_2 while the steel is 19.65 tCO_2. This indicates that steel has lesser carbon emission for both construction and demolition phase.

In the result, steel's carbon emission is lesser even at the demolition stage. Apart from that, the steel frame could be removed parts by parts and could be reused for other purposes without losing its properties and strength. The precast slabs which come in pieces could be removed in its original form and could be reused or recycled too. As for the reinforced concrete, the concrete would be crushed and disposed which would produce more carbon emissions. However, the steel reinforcement might be recycled for other usage without consider it as material wastage.

4.4 BIM in Determining Carbon Emissions

BIM is a tool applied since the beginning of the research to build two 3D models of reinforced concrete and steel frame structure. First, the loadings consisting permanent loads and live loads are designed before selecting the sizes of the components. Then, Autodesk Revit has efficiently assisted in building the two models with the exact dimensions of column, beam, and slab. The models created could be easily viewed from every corner which is very convenient to check any minor mistakes. As the models must be tested to ensure that the structure could take the loads, another BIM software which is called Autodesk Robot Structural Analysis is applied to carry out the load testing. At this stage, the ability of BIM in communicating has shown up by creating an integrated data among the Autodesk Revit and Robot Structural Analysis. As both are two different software, one is for creating a 3D model and another for structural load tests, but both software could communicate with only one model, which could save time and avoid doing two times amendment works.

Apart from that, as this research study requires some of the dimensions and measurement data from every single column, beam, and slab of both models, hence obtaining the values of each component manually would take extremely long time. Therefore, BIM could also perform quantity take-off by listing the data of every single component needed such as the length, area, and volume. However, the input of the components' dimensions must be correct when creating the model especially the universal column (UC) and beam (UB) with flange and web. This is due to the reason that the software would automatically generate the area, volume, and all other data needed from the input's dimensions and properties. In addition, additional input such as the UC's and UB's wrapping constant, elastic and plastic modulus as well as the second moment of area are all required to perform the most detailed analysis for load testing. This concludes that Building Information Modelling is very convenient and time saving as different works could be integrated with one model created only, where all could communicate using that single model. When there are some corrections for the main model, other software could update instantly to provide the latest version of the model.

Furthermore, analysing and discussing on the carbon emissions of both model is also part of BIM 6D as the determination of carbon emissions are based on the models. As mentioned above, all works including the sustainability study could be performed by BIM under one data environment. After getting the results, some suggestions are made to reduce the carbon emissions such as using recycled steel. Aside from that, BIM 7D focuses on the facility management after the construction of buildings are completed as well as the demolition of the building after 50 years. As in this case the demolition of construction materials is the focus of this study, thus the carbon emissions during demolishing of the structures are well discussed and compared.

While BIM offers significant advantages in integrating workflows and providing detailed insights into carbon emissions, it is not without limitations when applied to LCA and sustainability analysis. One limitation is its reliance on the accuracy and completeness of input data. If material properties, manufacturing emissions, or transportation impacts are not fully or accurately integrated into the model, the results may underestimate or overlook indirect emissions. While BIM excels in quantity take-offs and structural analysis, it might lack of capabilities for comprehensive LCA, particularly for assessing embodied carbon at a component level or comparing various material alternatives across the entire lifecycle.

To improve BIM's capability in sustainability assessments, future developments could include more detailed integration of LCA databases and sustainability metrics into BIM platforms. Enhanced interoperability between BIM tools and specialised LCA plugins would allow for more detailed assessments. Additionally, incorporating real-time environmental data and adopting artificial intelligence for predictive modelling could further refine sustainability analyses. These enhancements would support a more holistic understanding of a building's environmental impact and facilitate data-driven decision-making for greener construction practices.

5.0 CONCLUSION

The objectives of this study are met by comparing the carbon emissions between reinforced concrete and steel for 4 storeys building. In the results, the carbon emission of reinforced concrete during construction phase is 288.71 tCO_2 where concrete contributes to 71.55 tCO_2 while the steel reinforcement contributes to 217.15 tCO_2, which is 67% more than concrete. Furthermore, the carbon emission of steel structure is 196.5 tCO_2, which is 32% lesser than the reinforced concrete structure. The reinforced concrete structure is built with cast in-situ with concrete and steel reinforcement while the steel structure is built with simply supported frame. Based on the results, it is found that the carbon emission factors obtained from Li *et al.* (2021) for steel and steel reinforcement are greater than concrete, leading to higher carbon emissions. The total embodied carbon emissions per internal floor area of reinforced concrete and steel structure are 1454.22 $kgCO_2/m^2$ and 1084.15 $kgCO_2/m^2$.

At the demolition stage, the carbon emission of reinforced concrete structure is 28.87 tCO_2 while the carbon emission of steel structure is 19.65 tCO_2. The carbon emissions of both structures during demolition stage are still relatively high although it is 90% lesser than construction stage. The total carbon emissions per internal floor area of reinforced concrete and steel structure are 145.42 $kgCO_2$ and 108.41 $kgCO_2$ respectively. In summary, steel is a more sustainable construction material compared to reinforced concrete as it releases 32% less carbon. However, steel is not a popular construction material in Malaysia compared to the more common reinforced concrete. Therefore, this research wishes to provide some comprehension of the carbon emissions impacts to the environment based on the selection of reinforced concrete and steel as construction materials in Malaysia.

In general, steel structure induces a better impact on the environment, and it is suggested that construction professionals in Malaysia should consider using steel for building's materials. This would require changes in the traditional practices and perceptions of the Malaysia's construction industry, such as the implementation of green building standards and the promotion of sustainable construction practices. In addition, reinforced concrete structure could also reduce carbon emission by replacing newly manufactured steel with recycled steel as could reduce carbon emission by 20%. However, cost considerations in the Malaysian market play a critical role, as recycled steel and sustainable materials often involve higher initial expenses compared to conventional alternatives. Additionally, the availability and accessibility of recycled steel and advanced construction technologies may vary across different regions, posing further challenges. Addressing these constraints through policy incentives, subsidies, and increased industry awareness could facilitate a smoother transition toward more sustainable construction practices in Malaysia.

Aside from that, BIM has performed greatly throughout each LCA stage. BIM could assist in the initial phase of creating the models, conducting load tests, perform quantity take-off and more until the demolition phase, which is the end-of-life cycle of a building. It creates a single data environment while different types of works in this research study could rely on one source only, which is the model of reinforced concrete and steel structure.

As BIM is not developed to fully integrate with LCA and sustainability analysis, some recommendations could be provided for future studies. Incorporating advanced technologies into BIM tools could facilitate a more effective and immediate response to the environmental challenges (Chew *et al.,* 2024). For instance, plugins available such as One Click LCA, Insight and Tally, which come with LCA and embodied carbon database can be utilised in BIM tools. Autodesk Revit has a visual programming tool called Dynamo that allows users to create custom logic and automate tasks. It can automate repetitive tasks based on own preferences and facilitate embodied analysis workflows by writing their own scripts or using pre-built nodes.

Dynamo can perform generative design which supports the exploration of various sustainable building design options and embodied carbon optimisations. By utilising artificial intelligence (AI) algorithms and parametric modelling, it can suggest alternative structural designs and building materials that minimise environmental impact while maintaining performance. For instance, Dynamo can simulate the effects of replacing conventional materials with low-carbon or recycled alternatives, assess the viability of lightweight structures, or propose design modifications that enhance material efficiency. Moreover, its iterative approach supports the identification of optimal design solutions by analysing the trade-offs between sustainability objectives, construction feasibility, and long-term performance. This capability enables engineers to evaluate multiple configurations, material substitutions, and structural systems to identify solutions that reduce embodied carbon, promoting more sustainable construction practices and aligning with sustainability goals such as Paris Agreement. ■

AUTHORS' CONTRIBUTIONS

- **Zhi Xian Chew**: Study design, data collection, methodology, formal software analysis, and journal writing.
- **Ioannes, Yu Hoe Tang**: Review, editing, final manuscript approval, and supervision.
- **Jing Ying Wong**: Review, editing, final manuscript approval, and supervision.

REFERENCES

[1] Architectural Institute of Japan (AIJ). *LCA Guidelines for Buildings*; Architectural Institute of Japan: Tokyo, Japan, 2003.

[2] Baddoo, N. R. (2008). Stainless steel in construction: A review of research, applications, challenges and opportunities. *Journal of Constructional Steel Research, 64*(11), 1199–1206. Available via https://doi.org/10.1016/J.JCSR.2008.07.011

[3] Berman, E. S. F., Fladeland, M., Liem, J., Kolyer, R., & Gupta, M. (2012). Greenhouse gas analyzer for measurements of carbon dioxide, methane, and water vapor aboard an unmanned aerial vehicle. *Sensors and Actuators, B: Chemical, 169*, 128–135. https://doi.org/10.1016/J.SNB.2012.04.036

[4] Bryde, D., Broquetas, M., & Volm, J. M. (2013). The project benefits of Building Information Modelling (BIM). *International Journal of Project Management, 31*(7), 971–980. https://doi.org/10.1016/J.IJPROMAN.2012.12.001

[5] Bui, N., Merschbrock, C., & Munkvold, B. E. (2016). A Review of Building Information Modelling for Construction in Developing Countries. *Procedia Engineering, 164*, 487–494. https://doi.org/10.1016/J.PROENG.2016.11.649

[6] Chau, C. K., Leung, T. M., & Ng, W. Y. (2015). A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. *Applied Energy, 143*(1), 395–413. https://doi.org/10.1016/J.APENERGY.2015.01.023

[7] *Concrete: the most destructive material on Earth | Cities | The Guardian*. (2019). Retrieved March 11, 2023, from https://www.theguardian.com/cities/2019/feb/25/concrete-the-most-destructive-material-on-earth

[8] Du Q, Lu X, Li Y, Wu M, Bai L, Yu M. (2018). Carbon Emissions in China's Construction Industry: Calculations, Factors and Regions. *International Journal of Environmental Research and Public Health*, 15(6):1220. https://doi.org/10.3390/ijerph15061220

[9] Durmisevic, E. (2003). *Re-use Potential of Steel In Building Construction*. http://www.4darchitects.nl/download/TG39_2003_3.pdf

[10] Eleftheriadis, S., Duffour, P., & Mumovic, D. (2018). BIM-embedded life cycle carbon assessment of RC buildings using optimised structural design alternatives. *Energy and Buildings, 173*, 587–600. https://doi.org/10.1016/J.ENBUILD.2018.05.042

[11] Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., & Suh, S. (2009). Recent developments in Life Cycle Assessment. *Journal of Environmental Management, 91*(1), 1–21. https://doi.org/10.1016/J.JENVMAN.2009.06.018

[12] Hamza, A. S. (2021). Assessment of Carbon Dioxide Emission and Its Impact on High-Rise Mixed-Use Buildings in Egypt. AUC Knowledge Fountain. Retrieved March 8, 2023, from https://fount.aucegypt.edu/etds/1652

[13] Hao, J. L., Cheng, B., Lu, W., Xu, J., Wang, J., Bu, W., & Guo, Z. (2020). Carbon emission reduction in prefabrication construction during materialization stage: A BIM-based life-cycle assessment approach. *Science of the Total Environment, 723*. https://doi.org/10.1016/J.SCITOTENV.2020.137870

[14] Hong, J., Shen, G. Q., Feng, Y., Lau, W. S. T., & Mao, C. (2015). Greenhouse gas emissions during the construction phase of a building: A case study in China. *Journal of Cleaner Production, 103*, 249–259. https://doi.org/10.1016/J.JCLEPRO.2014.11.023

[15] Hu, X., Zhang, X., Dong, L., Li, H., He, Z., & Chen, H. (2022). Carbon Emission Factors Identification and Measurement Model Construction for Railway Construction Projects. *International Journal of Environmental Research and Public Health 2022, Vol. 19, Page 11379, 19*(18), 11379. https://doi.org/10.3390/IJERPH191811379

[16] *ISO - ISO standards for life cycle assessment to promote sustainable development*. (n.d.). Retrieved March 8, 2023, from https://www.iso.org/news/2006/07/Ref1019.html

[17] ISO/TC 207/SC 5. (2006a). *ISO 14040:2006 - Environmental management — Life cycle assessment — Principles and framework* (2nd ed.). ISO Standard.

[18] ISO/TC 207/SC 5. (2006b). *ISO 14044:2006 - Environmental management — Life cycle assessment — Requirements and guidelines* (1st ed.). ISO Standard.

[19] Kayaçetin, N.C. and Tanyer, A.M. (2019). Embodied carbon assessment of residential housing at urban scale. Renewable and Sustainable Energy Reviews.

[20] Khan, S., Alam, T., Khan, M., Blecich, P., Kamal, M., Gupta, N., and Yadav, A. (2022). Life Cycle Assessment of Embodied Carbon in Buildings:Background, Approaches and Advancements. buildings.

[21] Khasreen, M. M., Banfill, P. F. G., & Menzies, G. F. (2009). Life-Cycle Assessment and the Environmental Impact of Buildings: A Review. *Sustainability 2009, Vol. 1, Pages 674-701, 1*(3), 674–701. https://doi.org/10.3390/SU1030674

[22] Lapisa, R., Bozonnet, E., Salagnac, P., & Abadie, M. O. (2018). Optimized design of low-rise commercial buildings under various climates – Energy performance and passive cooling strategies. Building and Environment, 132, 83–95. https://doi.org/10.1016/j.buildenv.2018.01.029

[23] Lave, L. B. (1988). The Greenhouse Effect: What Government Actions Are Needed? *Journal of Policy Analysis and Management, 7*(3), 460. https://doi.org/10.2307/3323724

[24] Li, L., & Chen, K. (2017). Quantitative assessment of carbon dioxide emissions in construction projects: A case study in Shenzhen. *Journal of Cleaner Production, 141*, 394–408. https://doi.org/10.1016/J.JCLEPRO.2016.09.134

[25] Li, X. J., Lai, J. yu, Ma, C. yun, & Wang, C. (2021). Using BIM to research carbon footprint during the materialization phase of prefabricated concrete buildings: A China study. *Journal of Cleaner Production, 279*, 123454. https://doi.org/10.1016/J.JCLEPRO.2020.123454

[26] Liang, H., Bian, X., and Dong, L. (2023). Towards net zero carbon buildings: Accounting the building embodied carbon and life cycle-based policy design for Greater Bay Area, China. Geoscience Frontiers.

[27] Lu, K., & Wang, H. Y. (2019). Estimation of Building's Life Cycle Carbon Emissions Based on Life Cycle Assessment and Building Information Modeling: A Case Study of a Hospital Building in China. Journal of Geoscience and Environment Protection, 7, 147-165. https://doi.org/10.4236/gep.2019.76013

[28] Mastali, M., Dalvand, A., Sattarifard, A. R., & Illikainen, M. (2018). Development of eco-efficient and cost-effective reinforced self-consolidation concretes with hybrid industrial/recycled steel fibers. *Construction and Building Materials, 166*, 214–226. https://doi.org/10.1016/J.CONBUILDMAT.2018.01.147

[29] Mitchell, J. F. B. (1989). The "Greenhouse" effect and climate change. *Reviews of Geophysics, 27*(1), 115–139. https://doi.org/10.1029/RG027I001P00115

[30] Naik, T. R. (2008). Sustainability of Concrete Construction. *Practice Periodical on Structural Design and Construction, 13*(2), 98–103. https://doi.org/10.1061/(ASCE)1084-0680(2008)13:2(98)

[31] Navarro, D., Wu, J., Lin, W., Fullana-i-Palmer, P., & Puig, R. (2020). Life cycle assessment and leather production. *Journal of Leather Science and Engineering, 2*(1), 1–13. https://doi.org/10.1186/S42825-020-00035-Y/FIGURES/8

[32] Omar, W. M. S. W., Doh, J.-H., Panuwatwanich, K., & Miller, D. (2014). Assessment of the embodied carbon in precast concrete wall panels using a hybrid life cycle assessment approach in Malaysia. Sustainable Cities and Society, 10, 101–111. https://doi.org/10.1016/j.scs.2013.06.002

[33] Onat, N. C., & Kucukvar, M. (2020). Carbon footprint of construction industry: A global review and supply chain analysis. *Renewable and Sustainable Energy Reviews, 124*, 109783. https://doi.org/10.1016/J.RSER.2020.109783

[34] Röck, M., Hollberg, A., Habert, G., & Passer, A. (2018). LCA and BIM: Visualization of environmental potentials in building construction at early design stages. *Building and Environment, 140*, 153–161. https://doi.org/10.1016/J.BUILDENV.2018.05.006

[35] Röck, M., Saade, M. R. M., Balouktsi, M., Rasmussen, F. N., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T., & Passer, A. (2020). Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. *Applied Energy, 258*. https://doi.org/10.1016/J.APENERGY.2019.114107

[36] Shin, Y. S., & Cho, K. (2015). BIM application to select appropriate design alternative with consideration of LCA and LCCA. *Mathematical Problems in Engineering, 2015*. https://doi.org/10.1155/2015/281640

[37] Wan Omar, W. M. S., Doh, J. H., & Panuwatwanich, K. (2014). Variations in embodied energy and carbon emission intensities of construction materials. *Environmental Impact Assessment Review, 49*, 31–48. https://doi.org/10.1016/J.EIAR.2014.06.003

[38] Wang S Q. (2007). Life cycle assessment of residential building energy consumption in severe

[39] Cold Area [D]. Heilongjiang: Harbin Institute of technology.

[40] Wong, F. W. M. H., Foley, A., Del Rio, D. F., Rooney, D., Shariff, S., Dolfi, A., & Srinivasan, G. (2022). Public perception of transitioning to a low-carbon nation: a Malaysian scenario. Clean Technologies and Environmental Policy, 24(10), 3077–3092. https://doi.org/10.1007/s10098-022-02345-7

[41] Xu, J., Teng, Y., Pan, W., and Zhang, Y. (2022). BIM-integrated LCA to automate embodied carbon assessment of prefabricated buildings. Journal of Cleaner Production, 133894.

[42] Yan, H., Shen, Q., Fan, L. C. H., Wang, Y., & Zhang, L. (2010). Greenhouse gas emissions in building construction: A case study of One Peking in Hong Kong. *Building and Environment, 45*(4), 949–955. https://doi.org/10.1016/j.buildenv.2009.09.014

[43] Yao, Q., Yin, Z., Wang, J., Li, J., & Shao, L. (2023). Calculation of Life Cycle Carbon Emissions of Residential Buildings. Journal of Physics, 2534(1), 012015–012015. https://doi.org/10.1088/1742-6596/2534/1/012015

[44] Zakri Abdul Hamid. (2017). Towards A Carbon-Neutral Malaysia By 2050. *New Straits Times*, 14:15.https://www.ketsa.gov.my/msmy/pustakamedia/Keratan%20Akhbar/TOWARDS%20A%20CARBON-NEUTRAL%20MALAYSIA%20BY%202050.pdf

[45] Zhang, Y. J., Wang, A. D., & Da, Y. Bin. (2014). Regional allocation of carbon emission quotas in China: Evidence from the Shapley value method. *Energy Policy, 74*(C), 454–464. https://doi.org/10.1016/J.ENPOL.2014.08.006

[46] Zhi Xian Chew, Jing Ying Wong, Yu Hoe Tang, Chun Chieh Yip, & Maul, T. (2024). Generative Design in the Built Environment. Automation in Construction, 166, 105638–105638. https://doi.org/10.1016/j.autcon.2024.105638

[47] Zhou, Y., Liu, Z., Luo, Y., Zhang, G., Li, B., Pan, Y., Li, L., & Kong, M. (2022). Life Cycle Carbon Emission Assessment of Building Refurbishment: A Case Study of Zero-Carbon Pavilion in Shanghai Yangpu Riverside. *Applied Sciences 2022, Vol. 12, Page 9989, 12*(19), 9989. https://doi.org/10.3390/APP12199989

APPENDIX

<Floor Schedule>

A	B	C	D	E
Structural Material	Type	Level	Area	Volume
Concrete, Precast	Generic 200mm 2	Ground Floor	297 m²	59.40 m³
Concrete, Precast	Generic 200mm 2	First Floor	288 m²	57.60 m³
Concrete, Precast	Generic 200mm 2	Second Floor	288 m²	57.60 m³
Concrete, Precast	Generic 200mm 2	Roof	80 m²	15.98 m³

Example of the slab information obtained from Revit 2022

Concrete, Cast-in-Place gray						
Type	Reference Lvl	Length (mm)	C.S Area (m2)	Volume (m³)	Density (kg/m3)	Weight (kg)
300 x 450mm 2	Ground Floor	15000	0.135	1.55	2380	3689
300 x 450mm 2	Ground Floor	21000	0.135	2.16	2380	5140.8
300 x 450mm 2	Ground Floor	10400	0.135	1.08	2380	2570.4
300 x 450mm 2	Ground Floor	4600	0.135	0.47	2380	1118.6
300 x 450mm 2	Ground Floor	13000	0.135	1.33	2380	3165.4
300 x 450mm 2	Ground Floor	3000	0.135	0.3	2380	714
300 x 450mm 2	Ground Floor	15000	0.135	1.28	2380	3046.4
300 x 450mm 2	Ground Floor	15000	0.135	1.28	2380	3046.4
300 x 450mm 2	Ground Floor	15000	0.135	1.24	2380	2951.2
300 x 450mm 2	Ground Floor	15000	0.135	1.24	2380	2951.2
300 x 450mm 2	Ground Floor	15000	0.135	1.24	2380	2951.2
300 x 450mm 2	Ground Floor	21000	0.135	1.73	2380	4117.4
300 x 450mm 2	Ground Floor	21000	0.135	1.73	2380	4117.4
300 x 450mm 2	Ground Floor	3000	0.135	0.3	2380	714

Example of column analysis spreadsheet

PROFILES

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